Fuzzy Logic Control for Stand-alone Photovoltaic Energy Conversion System, and Innovation in Renewable Energy

By

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Abstract

In this dissertation, simulation and hardware emulation was implemented to experiment the operation of a power regulation system for stand-alone PV system with DC loads using Fuzzy Logic Control (FLC). The system encompasses the functions of Maximum Power Point Tracking (MPPT) to bring the power to the maximum value, load power regulation and control of battery operation.

An algorithm that tracks the maximum power, and the corresponding fuzzy logic controller were developed. An improved method for the battery operation regulation including a fuzzy logic controller was applied. Load voltage regulation was achieved by a modified cascaded PI controller.

The power regulation system managed to stabilize the load power, proved fast MPPT tracking and regulation of the battery operation in the presence of fluctuations and fast input variations.

The work included a study of the importance of university-industry collaboration to innovation in renewable energy. The current collaboration channels and the contribution of the current work was analysed through a questionnaire directed to the supervisor.

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June 29th, 2016

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Nomenclature

Solar Photovoltaic Cell

A	Diode ideality factor
I	Load current
I_{mp}	Current at maximum power point
In	Light intensity
I_{PH}	Photocurrent
I_{RS}	Diode reverse saturation current
Is	Diode saturation current
I_{SC}	Short circuit current
K	Boltzmann's constant
h	Rate of switching
n_p	Number of cells in parallel
n_s	Number of cells in series
P_0	Cell generated power in neutral temperature
P	Cell generated power
$Pmax$	Maximum PB power
PV	Photovoltaic
q	Electron charge
R_S	Series resistance
T	Cell temperature

T_r	Reference temperature
V	Cell terminal voltage
V_{mp}	Voltage at maxim power point
V_{OC}	Open circuit voltage

Chapter 1

1 Introduction

The development of the steam engine in the 19th century marked the beginning of the industrial society that we know today. Ever since, humans have been continuously burning fuel substances to produce energy. According to the statistics of the International Energy Agency Federation, the demand on energy is increasing by 2 % yearly worldwide with an even more increase in developing countries. An example can be seen in India with a 6% increase and in China with a 4% annual increase [1]. The current pattern of growth in energy consumption is exponential. For example, in the United States, the rate of energy consumption has been doubling every 15 years in the last 5 decades.

Energy sources can be divided into renewable and non-renewable: renewable energy sources like biomass, wind, hydropower, and solar energy, are sustainable and do not cause harm to the environment [2]. There are attempts to extract geothermal energy from rocks inside the earth, but the main used methods cause water pollution. Hydraulic energy is a source of energy that is highly efficient. It uses the energy of water falling from high distances to produce electricity. Nuclear energy is considered by some as a renewable source due to the long-term availability. While others warn about the hazards of the burning fuel, nuclear waste, nuclear emission and fission associated with nuclear energy production. Non-renewable energy sources are the sources that diminish and cause problems to the environment, like pollution and global warming. The main non- renewable energy sources are: fossil fuel, natural gas and carbon products.

The 2014 International Energy Agency statistics indicated that the consumption of fossil non-renewable energy sources makes around 80% of the total energy consumption, and the percentage of use of nuclear energy is 9.9 % of the total energy use. Renewable and other energy sources are only used by about of the 7 % of the whole energy production sources [3], [4].

Looking at energy use for electricity generation: The consumption of fossil fuel is nearly 70%, while the consumption of nuclear sources is 10.6 %. Renewable and other sources nearly make 20% of the energy use for electricity generation. The percentages are illustrated in the following figures.

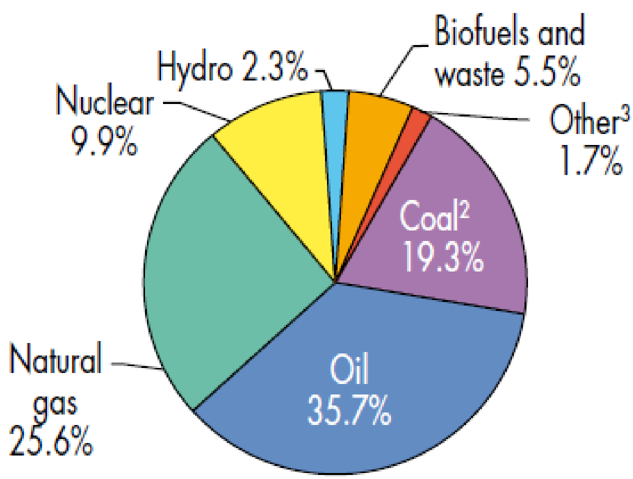

Figure 1 2014 Energy consumption percentages *[4]*.

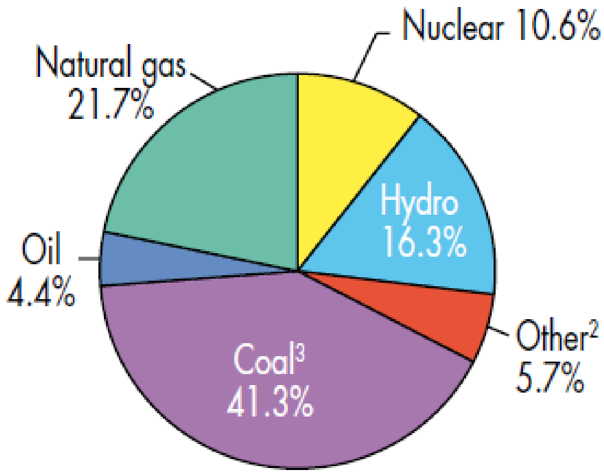

Figure 2 2013 Energy use for electricity generation *[4]*.

The current situation of energy consumption can be referred to as the "Energy Crisis"; a term used by many scholars to point to the present and the future consequences of relying on non-renewable energy sources. The harms caused by depending on non-renewable energy sources are multi-sided: the diminishing of those sources, which took nature millions of years to develop, and the severe consequences on the environment like the production of greenhouse gasses, global warming, and the destruction of plants and animals.

For example; the waste heat generated from factories and generating stations could ruin the earth balance; a rise of 2F in the atmospheric temperature would melt the Arctic Ocean ice peak. In addition to the disturbance to the ecological balance in rivers and ocean life by thermal pollution [5], [3]. Other risks to the oceans reside in the spills of oil from wretched ships and pipelines. Coal mining produces gasses that are high pollutants and harmful to breathing like sulfur dioxide. Smog, particle matter and nitrogen oxides from automobiles and factories contain hydrocarbons, oxides of sulfur and nitrogen that cause cancers and respiratory diseases.

The increase in energy consumption is not only associated with the growth in population, but with the patterns of life and industry demands. If the current trend in energy use continues, the remaining non-renewable energy sources would be insufficient to fulfil the life needs in the near future [3]. Also the extraction of the remaining underground oil would incur very high costs on oil production [6]. The scarcity of energy for basic life needs in the future, would result in negative social and economic consequences.

To solve the problems, caused by non-clean energy consumption, the rising demand of energy on earth has to be met by clean and renewable energy alternatives such as the energy from the sun, wind or other clean sources [6].

One of the most convenient renewable energy sources is the Sun. Photovoltaic (PV) systems convert the energy from the sun into electricity. PV systems are clean and do not have moving parts, nor produce noise. Also, there is very little maintenance cost associated with PV system operation. The difficulty in using solar energy to produce electricity comes from the high initial cost and the variation of the energy supply with the environmental conditions. The low energy density of the solar panel that requires using large size panels to produce sufficient energy is another obstacle. Other challenges are the high cost and expenses associated with setting, operating and controlling storage devices. Also the environmental concerns in manufacturing and recycling secondary storage devices such as batteries.

Despite the mentioned obstacles, the production of more efficient and cost effective solar power generation systems is increasing with the developments in solar panel technologies, control methods, and storage devices.

In order to use the solar system to the utmost efficiency, the maximum power should be extracted at any operating condition. Various techniques referred to as Maximum Power Point Tracking Techniques (MPPT) are applied to achieve this purpose. To guarantee the stability of the power supply, the overall power distribution in the system has to be controlled. The power control operation in a PV system involves regulating the charge and discharge functions of the storage devices, and stabilizing the load voltage. In conditions of non-linearity, high uncertainty, and fast environmental changes; smart technologies like neural, fuzzy and genetic algorithms proved to be more efficient than conventional PID controllers. Fuzzy Logic Control (FLC) algorithms incorporate relatively simple mathematical rules and do not require prior knowledge of the working model. Fast tracking and robust results were obtained from FLC applications in renewable energy systems [7] [6].

In order to develop solar energy technologies and other renewable energy projects, more research should be focused on social and industry needs in the area of renewable energy. To enable the research in universities to turn into innovation (useful products and services); strong collaboration channels between the university and industry should be established. Also initiatives on renewable energy developments should be backed up by supportive rules and investments. The proper definition of research work and its stages, provide the basic information for the scientific policy and rules.

1.1 Problem Definition

For a PV system to provide stable electrical power supply, both the operations of maximum power point tracking and system power regulation have to be maintained at any environmental condition. Some of the challenges with using conventional maximum power point tracking techniques like the incremental conductance the and the perturb and observe techniques are the fluctuation around the optima, and the inability to detect the real maximum power point in a fast manner. Some of the techniques require complicated computations while others are not accurate. Although simple to design, PID controllers do not perform well in multi-input, multi- output (MIMO) nonlinear systems. In conditions of high fluctuations and varying input conditions; conventional PID controllers require frequent calibration and parameter tuning to give the desired performance [8], [9]. Although simulation based research reflects the behaviour of control systems, it does not show the system performance in real time and in actual environmental conditions.

In this work, an artificial intelligent algorithm using fuzzy logic control is developed for the maximum power point tracking operation. The method was able to give efficient response in conditions of high variations, and to drive the system to operate at the maximum power point in all conditions. Good voltage amplification and fast responses in fast changing environmental conditions were attained. A PID fuzzy logic controller for the battery charge-discharge regulation was also modified. The controller provided fast and smooth control of the battery operation in the presence of input power fluctuation.

A cascaded PI controller was used to regulate the load voltage, and was able to stabilize the voltage and current supply to the load when the environmental conditions changed rapidly. The work was implemented using simulation and hardware emulation where the output of the simulated controllers directed the operation of a hardware configuration for the PV system.

The importance of research and experimentation on stand-alone solar systems comes from the wide applications of those systems that range from supplying power to rural areas, water pumping and irrigation, to medical and space solar vehicle systems [10]. In order to transfer the research into industrial products, collaboration channels between universities and industry firms are essential. In this work, the current knowledge transfer channels are investigated as well as the contribution of the current research to the development in PV systems.

1.2 Objective

The objectives of this work are:

1) Develop a fuzzy logic controller and a control algorithm for maximum power point tracking for a stand-alone PV system with DC loads.

2) Modify a PID fuzzy logic controller to regulate the battery charge-discharge operation.

3) Modify a PI controller for the voltage regulation of the DC loads.

4) Explore the type of the current research work and its contribution to future works and developments in renewable energy.

5) Examine current and future industry collaboration channels with connection to the research project.

Chapter 2

2 Stand- alone PV systems with Battery Storage

2.1 Introduction

PV systems can either be connected to the grid, or isolated. In this chapter, the structure and simulation of a PV solar panel is introduced. The electrical characteristics of a PV module, and the construction of the energy conversion system are illustrated. Descriptions of storage devises used in energy systems are also provided. The main parts of a stand-alone PV system are: PV Model, MPPT control system, and the power regulation system. The parts of the power regulation system are the load side and the battery controllers. Challenges associated with using and manufacturing PV systems are also reviewed in this chapter. Applications and developments of PV solar systems and other solar technologies are discussed in the last part. The chapter also reviews the potential of renewable and solar energy is Canada.

2.2 PV Module

2.2.1 PV systems

The sun sends large amounts of energy to the Earth, equivalent to around one hundred million fossil fuels or nuclear power stations, but the majority of the sun's energy fall onto the oceans. The irradiance from the sun differs from one place to another and from one time to another, and is disturbed by buildings and other objects [11]. The operation of the Photovoltaic (PV) cell is based on the Photovoltaic effect; the generation of potential difference in a silicon solar cell due to the falling sun light. The main component of a PV system is the PV panel, which is composed of solar cells [12].

A typical solar cell produces power between 1 and 2 W, which is not enough for most applications; a crystalline silicon solar cell with a typical area of 10×10 cm^2 produces an output power around 1.5 W. In order to be able to use solar energy for actual applications, solar cells are interconnected in series or parallel combinations to form a Photovoltaic (PV) module/panel. The amount of electricity that is delivered by a solar panel depends on a number of factors like: the intensity of sun light that reaches the panel after being scattered by dust, clouds and other particles, the incident angle of the falling light, the time of the day, and the temperature [13]. Other factors called the (Albedo) factors also influence the amount of solar power. The Albedo components are defined as: the effect of the light reflected from the ground and other objects such as trees and building on the power supplied from the solar energy systems. The Albedo effect is usually small, but more significant in locations like the Swiss Alps due to reflections from the snow [6]. The effect of Albedo from the ground and other objects in urban locations is studied by some researches. The influence of different PV material, and topologies on the Albedo effect was investigated [14]. In the following figure, the units of the PV array are shown.

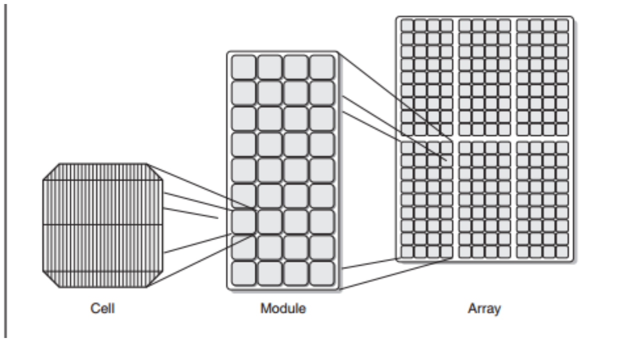

Figure 3 Solar cell, module and array *[15]* .

Some of the practical and technical challenges in using PV systems for electricity production are:

1) The large size of PV panels.
2) The cost of setting the PV system.
3) Difficulty in modelling the PV system behaviour.
4) Recycling after the end of the PV cell life. Recently steps are taken to find solutions for this problem.
5) The appearance of the buildings or sites where PV panels are placed.
6) The space it takes to put the PV panel.
7) The efficiency of the PV system.
8) The dependence of energy on the environmental conditions.
9) The dependence of the efficiency on the power regulation operations and the instruments used [18].

2.2.2 PV Modelling

The electrical circuit simulation of the solar panel includes: A current source, a diode, and a shunt resistance [16], [17].

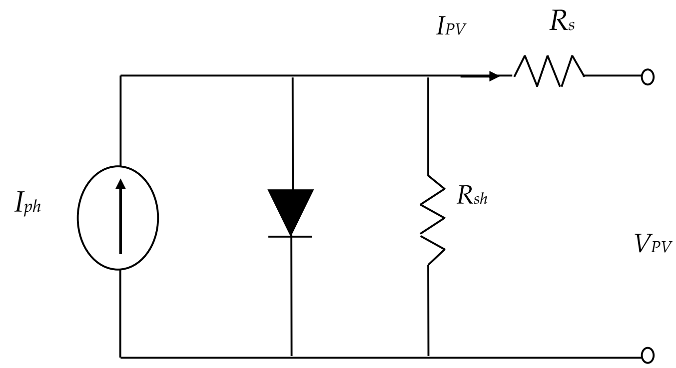

Figure 4 Equivalent circuit of a PV panel *[16]*

The relation between the voltage and current of a solar panel can be represented by the equation:

$$I_{PV} = n_p I_{ph} - n_p I_{sat}\left(exp\left(\left(\frac{q}{AKT}\right)\left(\frac{V_{pv}}{n_s} + I_{PV} R_s\right)\right) - 1\right) - \frac{V_{PV} + R_s I_{PV}}{R_{sh}} \quad (1)$$

where, I_{PV} is the module terminal current, I_{ph} is the photocurrent, I_{sat} is the diode saturation current, V_{PV} is the module terminal voltage, q is the electron charge, A is the diode ideality factor, K is the Boltzmann constant, n_p is the number of cells in parallel, n_s is the number of cells in series, R_s and R_{sh} are the series and shunt resistances respectively, and T is the surface temperature of the PV module.

The current voltage relation from the PV panel can be seen in the following figure.

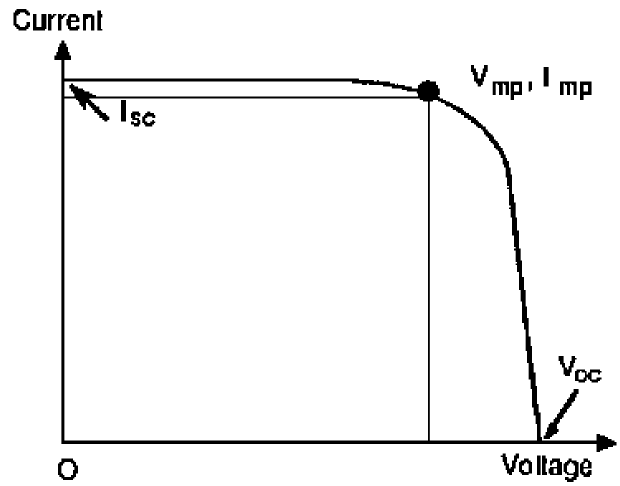

Figure 5 Current- voltage curve of a PV panel *[18]*

It can be seen that the relation between the current and voltage in any operating condition is nonlinear. In different operating conditions, the curve preserves the same shape but the values change. In the following figure, the voltage current curves at different light intensities and temperatures are shown.

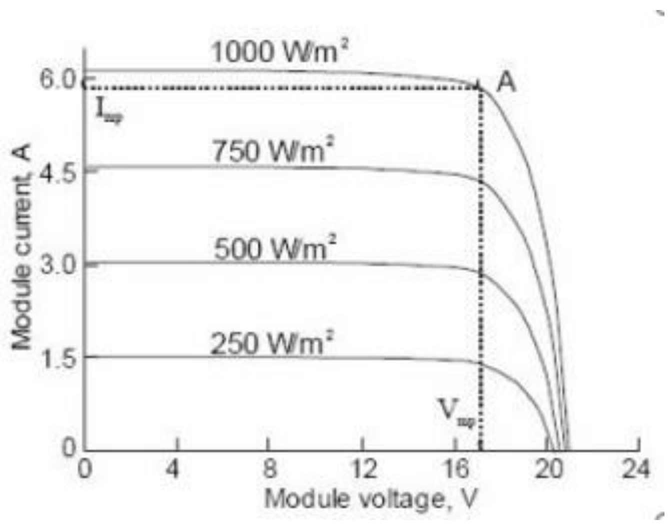

Figure 6 Voltage-current characteristics of a PV panel in different light intensities *[18]*.

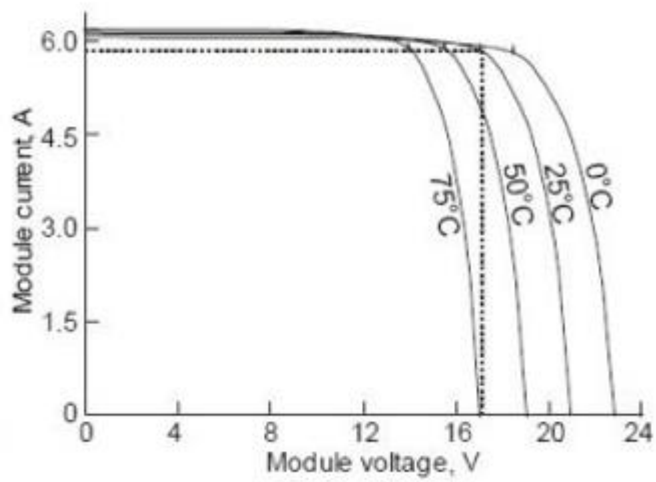

Figure 7 Voltage Current characteristics of a PV panel in different temperatures *[18]*

The electrical characteristics of a solar cell are determined by the short circuit current I_{sc}, and the open circuit voltage V_{oc}. The short circuit current is the maximum current that can be produced by the PV panel when the output terminals are short circuited ignoring the leakage current. The open circuit voltage is the maximum voltage produced by the PV panel when the terminals are open. The main factors that influence the amount of supplied power from the solar cell are the environmental temperature and the irradiance of the sun. When the temperature rises above the reference temperature by one degree Celsius, the cell output power decreases by 0.5%. The relation between the temperature and the PV power is illustrated in the following equations [19].

$$P_{PV} = P_0(1 - 0.005\Delta T) \tag{2}$$

$$P_0 = I_{sc} \times V_{oc} \tag{3}$$

Where, P_0 is the ideal PV power in neutral temperature, I_{sc} is the short circuit current, V_{oc} is the open circuit voltage, and ΔT is the change in temperature.

The temperature effect on the PV power can be explained by: when the temperature increases, the short circuit current increases and the open circuit voltage decreases, but the decrease in the open circuit voltage is more and that drives the power down. This shows that the cell or panel operates better at lower temperatures [20].

Looking at the influence of the incident angle of the sun light, the PV panel supplies the most power when the sun is straight overhead. The power gets less when the sun's position is lower in the sky and the light falls with an angle. The amount of energy reduces with lower sun position, because the light spreads over a large area and the focus is less. The amount of the irradiance of the sun is calculated by multiplying the intensity of the perpendicular irradiance on a certain surface by the cosine of the incident angle. This is called the Cosine Effect, or Lambert's Cosine Law [21].

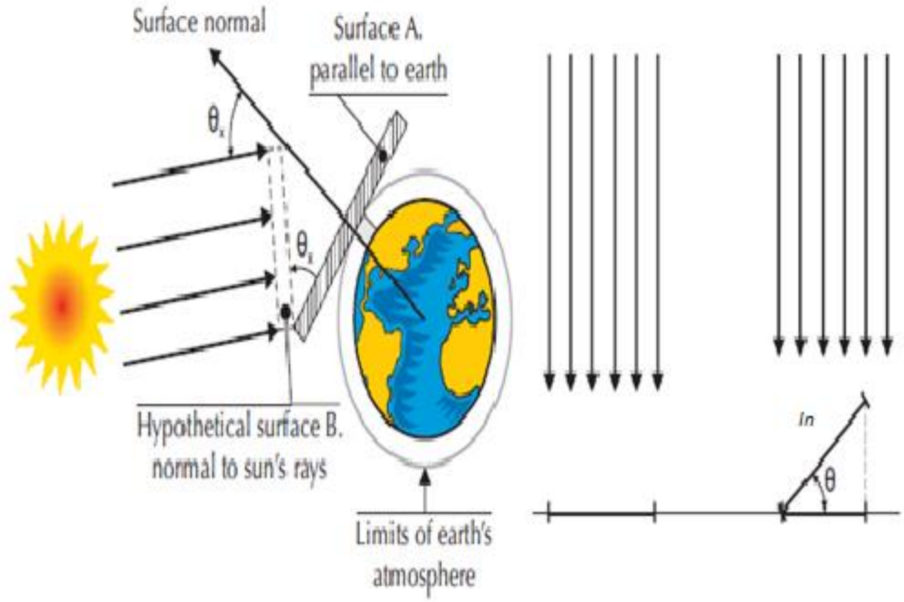

Figure 8 The Effect of incident angle on the PV power *[21]*.

The cosine effect is described by the following equation:

$$I_n = I_{n0} \times cos(\theta) \qquad (4)$$

Where: In_0 is the light intensity when the angle between the falling light and the norm is zero (w/m^2). In is the intensity when the incident angle between the falling light and the norm is θ.

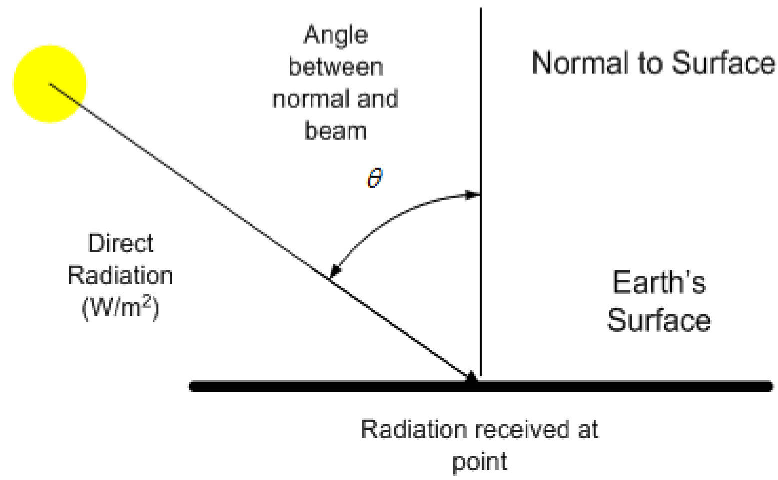

Figure 9 The Cosine Effect *[22]*.

The sun intensity determines the transferred power. For example, if the full bright sun light intensity is represented by a value of 1, less intensities can be represented by a fraction depending on the amount of clouds. The power at bright sun light (sun intensity 1) is higher when there are no clouds, and decreases with increasing clouds as illustrated by the figure (10). The sun intensity influence on short circuit current is more than its influence on open circuit voltage [19].

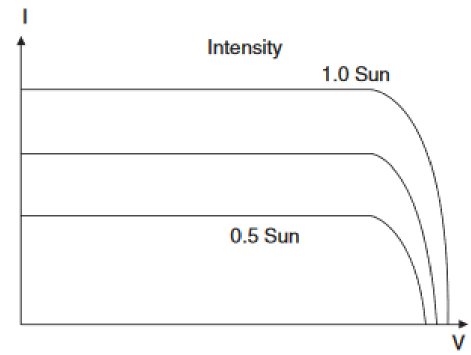

Figure 10 Variation of solar power with sun intensity *[19]*.

2.3 Energy Storage System

2.3.1 MPPT Techniques

The nonlinear characteristic of the voltage current curve for a PV cell, result in uneven power distribution during the operation. The following figure illustrates the relation between the power, voltage and current of a PV cell.

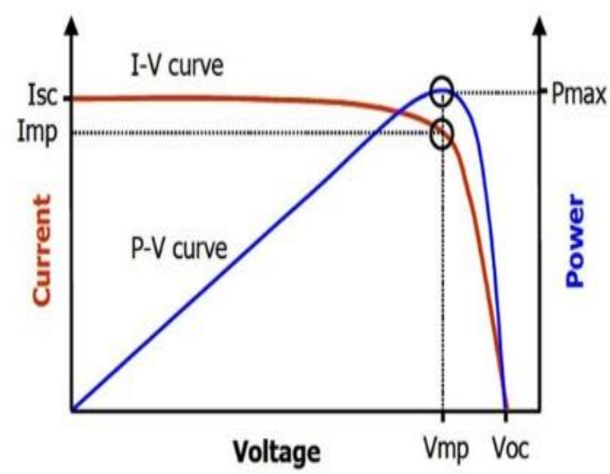

Figure 11 Power voltage-current characteristics of a PV Panel *[23]*.

It can be noticed that there is a point associated with certain voltage and current values that has the highest power. When the PV panel operates at this point, it delivers the maximum available power (Pmax). The point of maximum power is referred to as the Maximum Power Point (MPP), and the current and voltage values at this point are referred to as The Maximum Power Point Current (Imp), and Maximum Power Point Voltage (Vmp). When the operating conditions like the temperature or the sun light intensity change, the values of Pmax, Vmp and Imp change accordingly. In the following figure, the changes of maximum power point with the variations in irradiance levels at the temperature of 25 ^{0} C are illustrated.

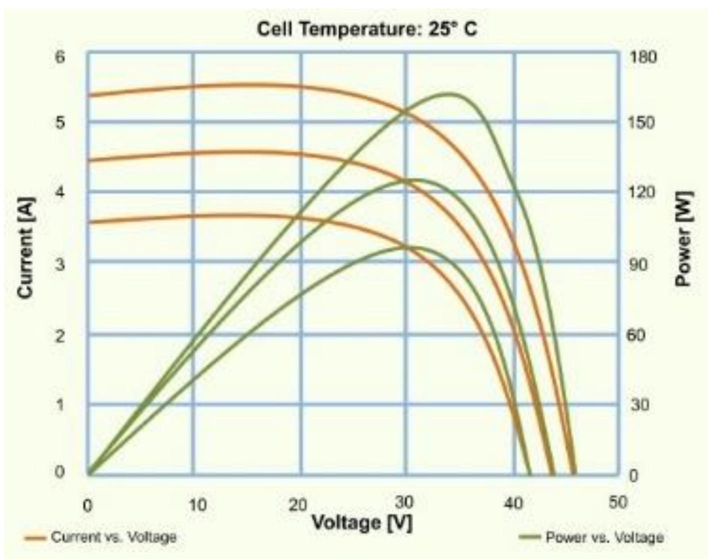

Figure 12 Power -voltage characteristics of PV at different light intensities *[24]*

Maximum Power Point Tracking Techniques (MPPT) are algorithms that find the maximum power point at any operating condition. They are usually simulated by a computer and passed through a controller to the rest of the system. The output signal from the controller directs a pulse width modulator (PWM) to generate control pulses that drive the system to operate at the values of maximum power point voltage and current [25].

MPPT techniques are classified depending on characteristics like:

- The complexity of the technique, and the number of variables.
- The type of the control method used.
- The practical applications of the technique.
- The stability and efficiency of the method [26].

Generally, MPPT techniques are divided into three main types:

- Methods of perturbation and observation.
- Methods of incremental conductance and other incremental methods.
- Artificial intelligence methods [27].

MPPT algorithms can also be divided into indirect and direct algorithms: indirect methods use previous instantaneous information of the PV panel like the voltage, current and power to determine the maximum power voltage and current values. The main disadvantages of these methods are: the PV system may not operate near a maximum power point in a certain interval, they give approximate estimation, and their operation is time consuming. Examples of the indirect MPPT techniques are Curve-Fitting, Look-up Table, PV panel Short-circuit, and Open-circuit methods.

On the other hand, measurements in direct methods are taken during operation and used to direct the system to the maximum power point values. Incremental Conductance (IC), and Hill Climbing (HC) methods are examples of direct methods. Mainly direct MPPT techniques have the ability of more accurate tracking than indirect techniques [28].

Following are brief explanations of some of the popular methods used for MPPT:

The look- up table method is based on storing values of maximum power operation at different conditions. The actual operating conditions are matched with the table values, and the system is driven to operate at the values corresponding to the maximum power. The method needs big storage capacity [29].

The curve fitting algorithm, which depends on finding the maximum point in a simulated power curve, is one of the simplest methods. The values of current and voltage for maximum power point operation are calculated by equalling the derivative of power to zero in equal intervals. The accuracy of this technique is highly effected by the choice of the sampling constants [30].

One of the most used techniques for MPPT is the Perturb and Observe (P&O) technique: first the PV power is measured, then the voltage of the duty cycle is incremented (perturbed) by small amounts in equal intervals. If the power at the new point is more than the previous, perturbation continues in that direction, otherwise, the direction is reversed. The procedure continues till the maximum power point is found. The method has the advantage of simplicity but suffers from negativities such as slow detection and slow adaptability to power variations. The oscillation around the maximum power value and the dependence of the efficiency on the size of the perturbation are other drawbacks [31]. To overcome these drawbacks, adaptive perturb and observe techniques have been used, in which the size of the sample is tuned according to the changes in power [32]

The following figure shows the configuration of the P& O method:

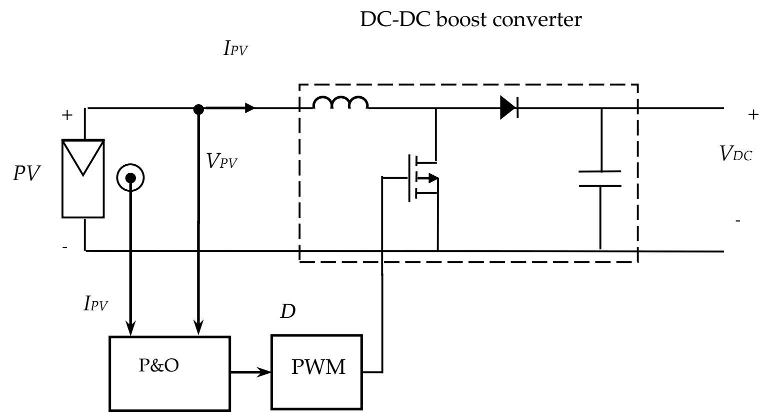

Figure 13 Perturb and Observe method

The Incremental Conductance method is based on observing the direction of the change of the current and voltage values for the maximum power through monitoring the sign of the derivative of the voltage and current [33]. It has good performance under fast changing conditions, and the amount of oscillation is less than the P&O method [34]. The disadvantages are the complexity of the operation and the high cost of the control circuit [35], [36].

The constant voltage method is one of the simplest techniques used; it is based on reducing the error between an estimated maximum power voltage and the actual array voltage at equal time intervals. Usually several trials for the voltage values are done and the one that delivers the maximum power is chosen. Although this technique is fast and simple, it may not give the real value for the MPPT since it is based on estimation. It also neglects the influence of temperature variation on the value of maximum power voltage [31].

Differentiation techniques for MPPT are based on the fact that the derivative of power with respect to time is equal to zero at maximum operating point. These methods require a lot of calculations, measurements, storage space and expensive processors [37].

Open circuit voltage and short circuit current methods are simple methods; they depend on approximation of the open circuit voltage and the short circuit current to the maximum power current and voltage. They can be described by the following equations:

$$V_{mp} = K_1 \times V_{oc} \tag{5}$$

$$I_{mp} = K_2 \times I_{sc} \tag{6}$$

Where: I_{mp} is the current at maximum power point, V_{mp} is the voltage at maximum power point, V_{oc} is the open circuit voltage and I_{sc} is the short circuit current. The factors K_1, K_2 are constants that depend on the characteristics of the cell. They normally vary between 0.68 and 0.9 for multi crystalline PV cells.

In the short circuit method; the short circuit current should be measured at time intervals by disconnecting the PV at each interval. In the open voltage method, the open circuit voltage is measured at time intervals, also by disconnecting the PV circuit. This causes slow response of the system. Also the results of these methods lack accuracy, because the methods depend on approximation [38].

The Temperature Gradient (TG) control method depends on the variation of the open circuit voltage with the temperature of the PV cell. It measures the temperature to determine the open circuit voltage and then the maximum power point. This method shares the same accuracy issues with the open and short circuit methods, but it overcomes the problem of cutting the circuit and taking measurements [35].

The method of Steepest Descent is based on optimization algorithms; it introduces faster response and less oscillations than most of the other methods, as well as better steady state performance. It uses three-point measurements and estimates the value of the voltage at the centre of the three points. It finds the nearest local maximum power point according to the gradient of the voltage curve [39]. A widely used MPPT algorithm is the Newton Raphson or Gaussian Newton Method. It is based on root finding algorithms, and is one of the fastest methods for MPPT [40].

In the feedback voltage or current techniques; the feedback from the panel (voltage or current) is compared with a reference value. The error is used to adjust the voltage and current values for maximum power point. The power feedback method is based on the same principle, but the power is compared instead of the voltage or current. By driving the derivative of the power with respect to voltage to zero, the power to the load is maximized instead of the power to the inverter. The method requires efficient inverters to attain good results [41]. A method that uses a control signal based on the difference of actual to estimated power is proposed. The method estimates a value for the reference maximum power then increments it in intervals until the actual power value gets close to the estimated. Fast convergence and power efficiency was achieved by using this technique [42].

In the sliding mode technique, a variable that links the ratio of current to voltage, and the change of current to voltage is defined. The values are calculated in equal time intervals.

$$h = \frac{I_{PV}}{V_{PV}} + \frac{\Delta I_{PV}}{\Delta V_{PV}} \qquad (7)$$

Where: I_{PV} is the PV current, V_{PV} is the PV voltage, *h* is the rate of switching, ΔI_{PV} is the change in PV current between two consecutive intervals, ΔV_{PV} and is the change in PV voltage in two consecutive intervals.

The method works in a similar concept to the incremental conductance method, but is different in that the variable *h* determines the switching of the converter. This method suffers from the effect of variable operating frequency, which can be overcome by using the discrete version of the method [43].

In order to harness the benefits of more than one MPPT technique, or to avoid the disadvantages of a certain technique, hybrid methods are used for MPPT. For example, the effect of the perturbation step on the performance of the P&O method is improved by using intelligent algorithms such as NN (Neural Networks) to determine the perturbation step [44]. In some applications the constant voltage method is combined with the increment conductance methods to improve the efficiency of the MPPT technique [45].

The ability of the maximum power point tracking technique and control system to respond to fast changing conditions is important to the efficiency of the PV system. This is why it is important to choose the best available method and controller configuration to achieve this operation [38].

a.The Fill Factor

The fill factor resembles the approximation of the voltage-current curve to a square that is the product of the open circuit voltage and the short circuit current. It is found by dividing the actual power from the solar cell by the product of the short circuit current and the open circuit voltage.

$$FF = (I_{mp} \times V_{mp}) / (I_{sc} \times V_{oc}) \qquad (8)$$

The following graph illustrates the concept of the fill factor. The corner of the blue square points to the maximum power value, while the corner of the green square shows the product of I_{sc} and V_{oc}.

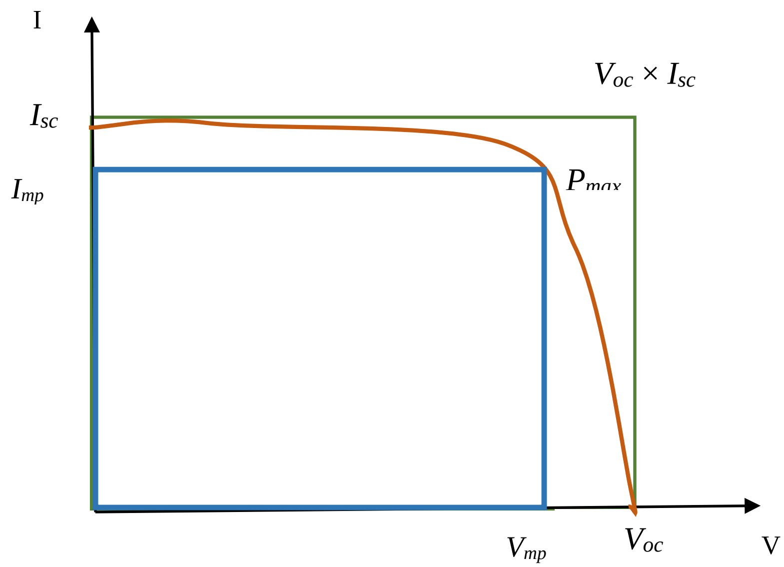

Figure 14 The fill factor

The value of the Fill Factor depends on type of the solar cell [46]. It is an indication of the quality of the PV solar panel. An ideal PV cell would have a fill factor of one. Normally the fill factor is around 0.7 depending on the type and quality of the solar cell [47].

2.3.2 DC-DC Converters

DC-DC converters are used in a variety of applications, like power supplies, calculators, and computers. A DC-DC converter either reduces or increases the input voltage depending on the duty cycle. The later is usually generated by a pulse generator or the Pulse Width Modulator (PWM), that generates signals depending on the output of the controller. According to the relation between the output and the input voltage, converters are divided into Buck, Boost and Buck Boost converters. The principle of operation of the three types of converters is similar [48].

a. Buck Converter

It gives an output voltage that is less than the input voltage according to the relation:

$$M(D) = \frac{V_{in}}{V_{out}} \tag{9}$$

$$M(D) = D \tag{10}$$

Where: V_{in} is the input voltage, V_{out} is the output voltage and D is the duty cycle, and is always in the range of 0 to 1.

b. Boost Converters

The boost converter gives an output voltage that is more than the input voltage according to the following equation [49].

$$M = \frac{V_{out}}{V_{in}} = \frac{1}{1-D} \tag{11}$$

The following is the configuration of the boost converter.

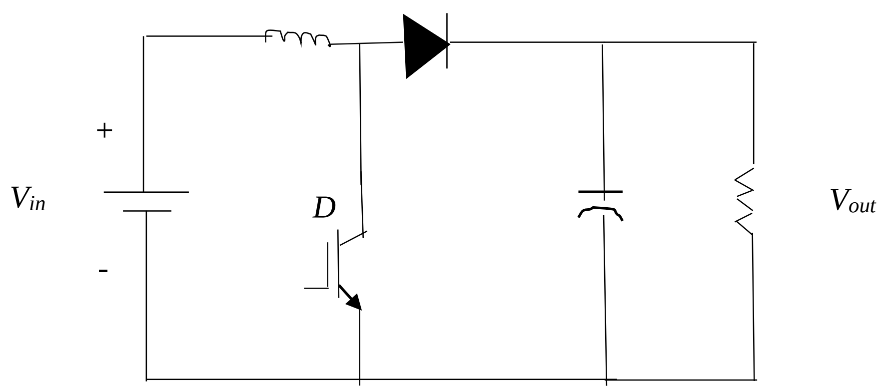

Figure 15 Boost converter configuration.

c. Buck -Boost Converter

The buck boost converter increases or decreases the voltage depending on the duty cycle. Usually the duty cycle for the buck boost converter is determined by the pulse from the pulse width modulator.

The equation that directs the operation of the buck boost converter is:

$$M = \frac{V_{out}}{V_{in}} = \frac{D}{1-D} \tag{12}$$

From the equation, it can be concluded that the magnitude of output voltage is higher than the input (when D > 0.5). The output voltage is lower than the input voltage when (when D < 0.5).

Following is the configuration of a buck boost converter with two IGBTs.

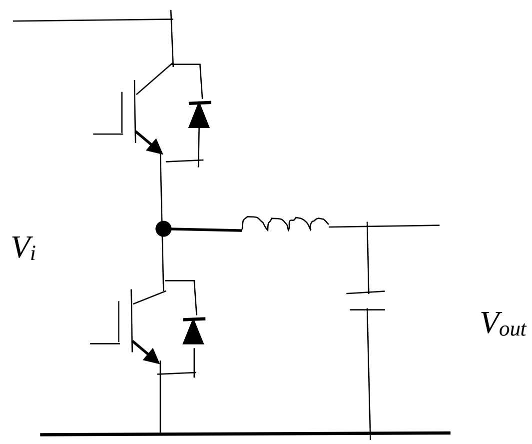

Figure 16. Buck-boost converter configuration.

2.3.3 Storage Devices

For a PV system to work efficiency; uninterrupted power supply has to be provided to the load, also the charge and discharge operation to the battery has to be controlled. This in addition to the control of the maximum power tracking operation. In other words: full power regulation is required in all environmental conditions [50].

Electrical energy storage devices transmit the extra energy from an electric power network to another form to be stored for later use [51]. They are secondary power sources that store and supply power. Batteries in the form of battery banks are the most used storage devices in PV systems. The characteristics of the battery depend on: the technology of the battery, the capacity and the life time of the battery, the tolerance of the battery to environmental conditions, and the speed of the charge-discharge operation [52].

The main types of batteries are:

−Lead acid

−Sodium sulphur

−Lithium ion

−Flow batteries

−Metal air

Lead acid is a popular and safe technology used in power systems. A lead acid battery is made from lead and lead dioxide for electrodes and an isolating material mounted on a plastic container. Lead acid batteries are preferred in many applications due to the low maintenance cost, ability to self charge and discharge, and to operate in different temperatures. It has reasonable installation cost but rather short lifetime [53].

Lithium ion battery electrodes are made from lithium salt cathode and graphic carbon anode. They are newer than lead acid batteries and characterized by high storage efficiency, small size, and small energy density. They have high cost and their life time is affected by repeated discharging. Nickle Cadmium (Ni Cd) batteries are large, have toxic substances and are tolerant to repeated charging [52], [54].

In some applications, alternative storage technologies are used: using Super Conductive Magnetic Energy Storage (SMES) systems to provide better power operation and smooth power distribution under varying load conditions was suggested [55]. An algorithm that regulates the charging of a lead acid battery at day time, and the discharging at night to improve the brightness of the LED lights was proposed [56]. Other technologies that are used for energy storage are: pumped hydroelectric devices, compressed air energy storage devices, flow battery, fuel cell, solar fuel, flywheel, capacitor, and thermal energy storage. A comparison between different energy storage devices is presented in the work by Chen et al. [51].

2.3.4 Power Regulation System

The power regulation control in a PV system is achieved after the MPPT stage and contains: the load voltage regulation and the battery power regulation.

a. Load Power Control System

PV systems supply electrical power to AC, DC or combined loads. Loads for solar systems can be the equipment in a house, lights in solar lighting systems, loads with moving parts like electrical vehicle motors, pumping systems, or others. Whatever is the nature of the load, it has certain limits and requirements for current and voltage. In order to work efficiently, PV systems should be able to keep the power to the load stable at all operating conditions and adapt to load and power supply changes.

When the supplied power is more than the load requirements, the excess power is utilized to charge a battery storage system. When the PV power supply is less than the load requirements, the battery should supply the shortage in power [57], [58]. Many of the used voltage regulation control systems are single-input single-output (SISO) feedback control systems that use PID controllers [59].

The load requirements change with adding or reducing loads, like operating more or less devices. In the presence of multiple loads like house hold loads; a strategy that analyses the load priorities into emergency, necessary and convenience loads was introduced. It enables the system to distribute the power according to load needs in case of supply power shortage [60]. The voltage regulating system should be able to provide good power quality with better stability, and discard any harmonics. Using series compensation to reduce temporary voltage drops and rises, and to decrease the level of harmonics in an isolated PV system was proposed [61].

A method for voltage regulation in an Unmanned Aerial Vehicles (UAV) was proposed. In this method, the maximum power point tracking was implemented using a fuzzy controller [62]. A load voltage regulation systems using a PI controller and a Single Ended Primary Inductor Converter (SEPIC) converter with one control loop was designed [63].

b. Battery Control System

To achieve stable and flawless power supply for the PV system, the charge-discharge operation of the battery has to be controlled in changing conditions. A method that uses the output of the MPPT controller to regulate the battery by changing the polarity of the control signal was introduced [53]. Some applications use a battery state estimator with the charge and discharge control to fully charge and prevent overcharging of the battery [64]. A power control system with a PV panel as the primary energy source, a fuel cell and a battery as secondary sources, and a PID controller was proposed [65]. A technique that consists of cascaded PID controllers for the current and the voltage was applied to control the power flow and the battery operation in an isolated PV system [66]. A power saving method that uses one converter for both the maximum power point tracking and regulation of the battery operation was proposed [56].

Usually, a DC bus is used to connect the MPPT side, the load side and the battery side. The voltage of the DC bus should be kept stable in order to provide stable power distribution in the system. A DC bus signaling method was proposed to direct the operation of the power distribution in a PV system [67].

The configuration of the overall power regulation system for a stand-alone PV system with DC load can be seen in the following figure:

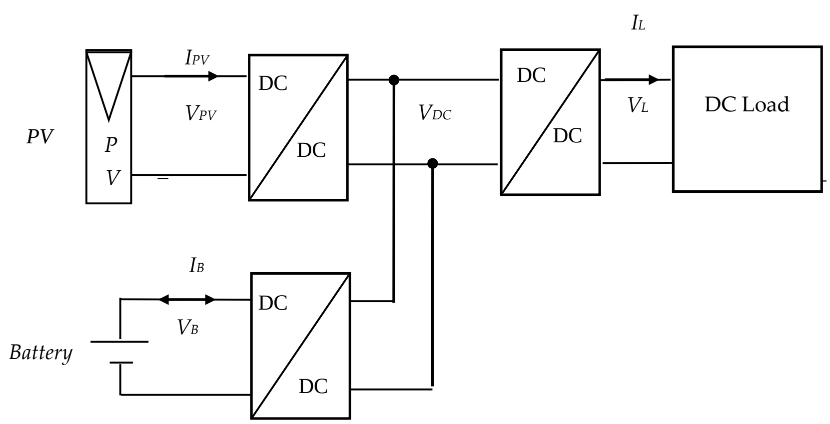

Figure 17 Power Regulation in PV systems.

2.4 Applications

2.4.1 Solar Cell Technologies

A silicon PV solar cell is made from sliced ingots or castings of highly purified silicon. The manufacturing process creates a charge-separating junction, deposits passivation layers and anti-reflective coating, and adds metal contacts. The module is then covered by a transparent glass and a weather proof material and mounted on a surrounding frame [68]. The basic structure of a solar cell can be seen in the following figure:

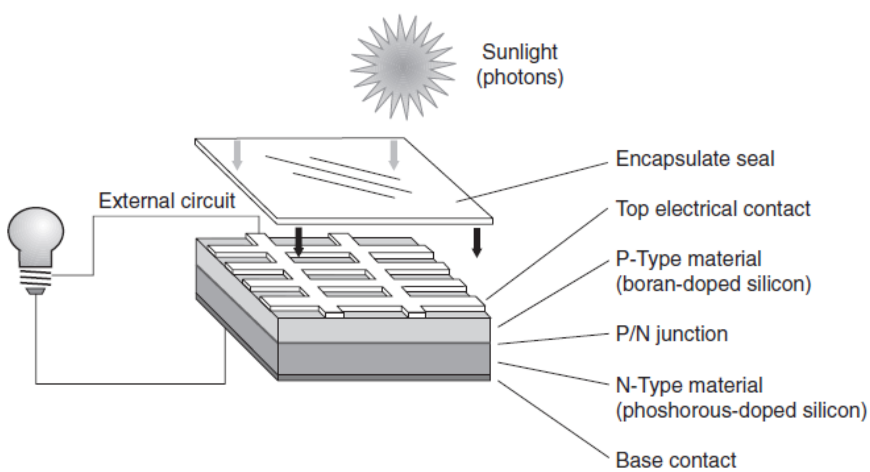

Figure 18 Basic structure of a solar cell *[15]*.

Single Crystalline Silicon (SC-Si) or Multi Crystalline Silicon (MC-Si) are used in manufacturing solar cells. Usually SC-Si cells have higher efficiency than MC-Si cells. Models that use multi crystalline silicon are less expensive, possess a more chaotic composition, and have less efficiency [12]. Micro silicon cells are technologies recently being used in many solar devices [69]. Thin film technology is also used in PV cell manufacturing; the solar cell is made by placing thin micro layers of photosensitive material on a base of a low cost material like glass, stainless steel, or plastic. Thin film solar panels have good performance at high temperatures, low energy efficiency and life, consume less material, and are easy to manufacture and integrate. Due to the low efficiency, the required panel space is more when compared with crystalline silicon panels of same efficiency which incurs more cost. In spite of the mentioned disadvantages, thin film technology production is growing rapidly: in recent years, production units have increased from a pilot scale to 50 MW lines reaching gigawatt (GW) range in some manufacturing units. A significant market share increase for thin film technologies is expected by 2020 [70], [2].

New types of semiconductor thin films which are easy to manufacture, have lower production cost, and relatively low payback period are being developed. Other solar technologies are the Dye Sensitized Solar Cells (DSSC) which were first invented by Michael Grätzel and Brian O'Regan at the Institute of Photonics and Interfaces, Lausanne in 1991. The DSSC technology is based on glass substrate technology and works by the effect of the sun on the Titanium dioxide (TiO2) creating electrons [71]. The disadvantages of this technology is the low efficiency which makes it not practical for large scale use. The dye gets degraded and the sealing of the electrolyte solution is important as it contains volatile organic solvents [72]. New developments in using nanotechnologies in the manufacture of PV cells are happening [73]. Technologies that include both the manufacturing of solar panels and operations used in the control of solar systems are continuously succeeding to overcome many of the obstacles in the use of solar power systems.

2.4.2 Development of Solar Systems

The idea of harnessing solar energy for different uses is not new; references point out that mirrors that collect and condense solar light were used to fight the Roman army back in 214 BC [6].

In 1747 solar furnaces were used by the French scientist George Buffon., and in the 19th century solar stoves were invented and used. Mouchot developed a solar steam engine that operated a printing press in Paris in 1875 [11]. Starting in 1863 in the US, John Ericson worked for 20 years on developing a solar powered engine and then built 9 engines from 1863 – 1883. Water pumping powered by large solar reflectors was invented by Eneas in 1901 and used for irrigation in California. In 1908 Wilson, and John Boyle worked on a solar engine that ran a water pump by the compression of two circulation pumps.

The discovery of the photovoltaic effect was in 1839, while the manufacturing of the first solar cell was in 1952. In 1938 solar houses using a solar collector technology were built in Boston by the Massachusetts Institute of Technology, and in 1947 solar buildings were built [68]. In 1950 Chapin, Fuller and Pearson at the Bell telephone company developed the first solar cell for direct conversion of the sun's energy into electricity. In 1953 more interest in solar production started to grow, and the International Solar Society was established in 1954. In 1959 solar homes, solar thermal collectors, and domestic hot water solar systems were used. Currently, applications of stand-alone PV systems cover a wide range from water pumping systems, rural home supplies, building equipment, traffic controls, street and other lights, to solar cars and radio operating stations. Medical equipment in rural areas, water sanitisation, railway signals, emergency communication, environmental monitoring, drones, solar planes and boats, and communication satellites are other important applications. [3], [10].

An interesting application for PV systems is found in using a hybrid PV storage system in mining operations. It is reported that the method is used in Western Australia, Sand Fire Resource's De Grussa Copper Mine with the installation of 6 MW of storage capacity along with 10.6 MW PV to hybridize an existing 20 MW diesel system. The system gave stable responses, and has a potential to generate $7 million in annual savings that can be realised even in times of low oil prices [74].

Solar energy can be harnessed by two main different ways which are: PV systems which convert solar energy into electricity, concentrated solar power systems that converter solar energy into thermal energy then to electricity.

Concentrated Solar Power Systems (CSP) use mirrors or lenses to concentrate a large amount of sun light onto a small area. The concentrated light is converted to heat to drive a heat engine (usually a steam turbine) connected to an electrical power generator [20]. CSP systems are usually equipped with a tracking system that moves with the direction of the sun [75]. There is good potential to CSP technology due to the high efficiency, and the cheaper prices, but the disadvantages are the dependence of the operation on the reliability of the tracking system and the maintenance requirements. Also the change in solar radiation in cloudy conditions can highly drop the power. It can be said that CSP systems are more suited for solar large-scale farms in sunny locations than for rooftop uses. Improvements to reduce the cost and expand the technologies of CPVs are under development [19]. A new technology that combines both the electrical characteristics of PV systems and the thermal characteristics of heat engines is emerging. It uses the combination of heat and power solar (CHAPS) generators to produce both heat and electricity in the same module where each can be used for the desired application [76].

Solar Towers (Heliostat field collector) are mainly used in places that have large supplies of sun. Mirrors mounted on the solar tower direct the thermal energy to a steam generator in order to produce a steam of high temperature and pressure, which is transferred into a circulating fluid that can be stored and used to produce power [77]. Solar towers are large and can provide more than 10 M watt of energy and thus good economically.

2.4.3 Obstacles and Potentials in the use of Solar Energy

Some of the obstacles that face the efforts in research and development on solar and other renewables are stated by Harrison Brown, Professor of Geochemistry in California Intitule of Technology:

- Taking inexpensive non-renewable energy sources for granted and relaying on them for the long term.
- Not enough attention to the development of renewable energy, accompanied by low priority to research programs in that area.
- Insufficient financial support for renewable energy development.

Government and international policies have great influence on the approaches to energy type adoption, whether renewable or non-renewable. Solar systems can be used as part of a grid, or as isolated systems. In grid connected systems, the grid should be developed to control the alternative use of both the solar and the main electricity supply. Smart technologies, referred to as smart systems, are incorporated to achieve the regulation of power in grid connected systems [78], [79].

Stand-alone systems are used in areas that are not connected to the electrical grid like rural locations or countries where the electrical power is not sufficient for the demand. Stand-alone systems can be divided into: systems that provide energy for single home uses in the range of 1 – 30 W, and systems that supply energy for a collection of houses or buildings in the range between 1-20 k w [6]. Hybrid systems containing more than one renewable source, like solar and wind, can also be connected to grid or off grid. [80]

In addition to the environmental benefits, the use of PV systems for power generation in remote areas adds economic benefits in reducing the cost of supplying electric energy to those areas. It also reduces the dangers and expenses of transferring diesel to locations that use diesel generators. Other economic benefit of stand-alone systems is the reduction of the expenses associated with constructing distribution lines and the power losses in the transmission of conventional power [81], [82].

A stand-alone PV solar system consists of: PV solar panel, controllers, inverters, loads and storage devices. For DC applications, the loads and the inverters would be DC, while for AC applications there would be a DC -AC inverter near the AC loads to transfer the power to AC.

The figure below shows the main parts of a home stand-alone solar system [83], [84].

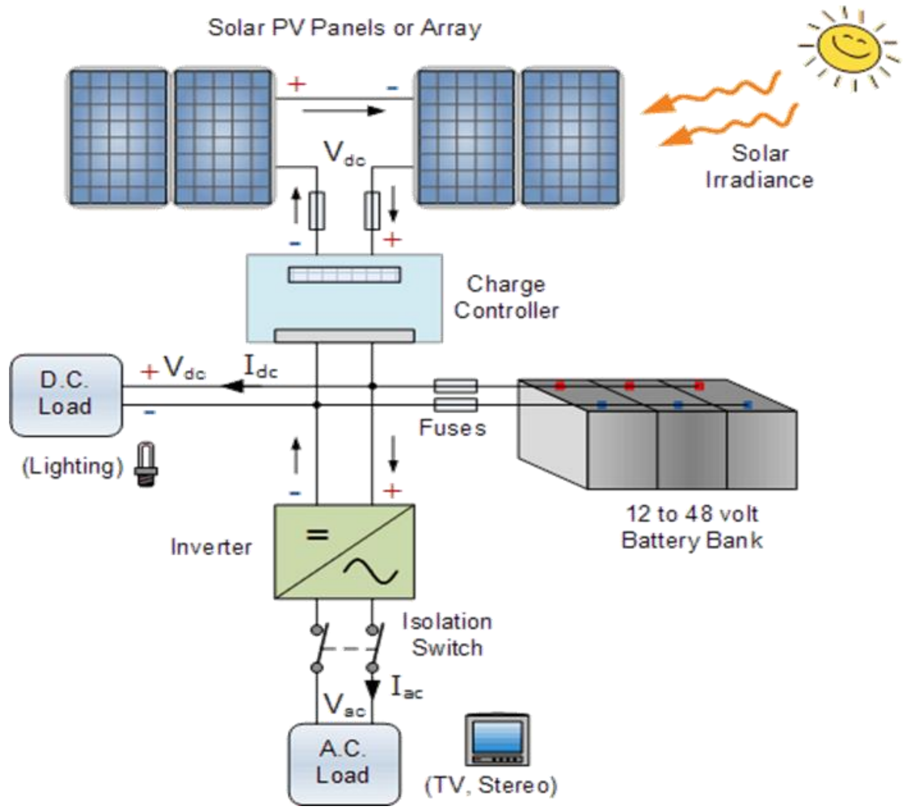

Figure 19 Main parts of home solar system from Alternative Energy Tutorials *[85]*

Scientist are researching on new applications for solar systems such as: solar roadways to use solar panels lined by the roads to supply the grid with electricity**.** The same concept can be applied to floating solar panels. Space solar technologies are supposed to convert sunlight to microwave energy that could be directed to the earth [86]. There is a good potential in using solar energies in a wide range of industries like food, non-metallic, textile, building, chemical, water distillation, and other industries [87].

Germany is considered to be the solar energy leader in the world which produces 768 MW of solar energy. Canada has rich solar resources but the development and investment in solar energy needs to be more. The market is yet not well developed in that area especially for large scale systems. The current energy generation production from solar resources in Canada is around 11 MW [88] [89]. There are good attempts to support the development in solar energy in Canada, but still more has to be done in this area. The future potential of solar and renewable energy development holds a lot of opportunities specially that it is connected to social, environmental, and economical considerations.

In Canada, a great potential in using solar energy lays in off grid applications since large areas are not connected to the grid (around 95 % of the total area), due to the cost of providing electricity to remote areas. Other common uses of solar energy in Canada are in water and home heating. This is not to deny the use of solar energy for electricity production connected to the grid or separate in urban areas, but this area needs a lot of infrastructure and support to provide smart grid solutions and sufficient solar panels or farms. The distribution and the capacity of solar resources in Canada can be seen in the following map [90].

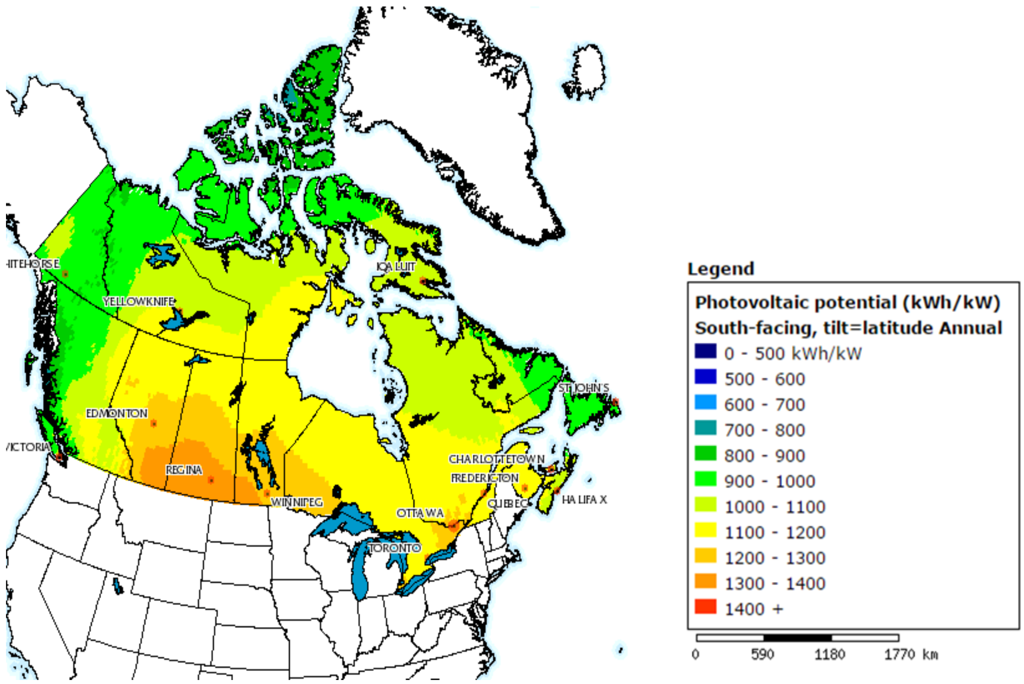

Figure 20 The distribution and the capacity of solar resources in Canada *[91]*.

Canada recognizes the importance of industry research collaboration to develop energy supply systems that depend on solar, wind, and other clean energy sources. Canmet Energy, a leading Canadian research and technology organization in the field of clean energy states: “We are responsible for the scientific aspects of work on photovoltaic energy for Natural Resources”. Canada is involved in several industry partnerships that would lead to innovation in the area. Robust collaboration is established between universities, industry, research groups, public agencies, departments, and governments through mutual research projects. In addition, international links are established by education, project participation, and communication events, and other channels. [92]

Canmet Energy aims to provide the required knowledge and information for partners who work in renewable energies, and has taken an active part in shared research projects. In addition, information is communicated to the decision makers in Canada through Canmet Energy. By cooperation between Camnet, and other similar firms, collaboration channels between industry, government, and agencies are initiated. Similarly, an international network of knowledge and technology transfer in renewable energy is built by establishing international cooperation routes.

2.5 Conclusion

In this chapter, the importance, developments and applications of renewable energy systems and especially solar energy systems including PV systems were demonstrated. The use of solar energy for electricity generation has a lot of potential in reducing the dependence on non-renewable energy sources. Solar PV systems come with challenges like: input power fluctuation, high setting cost, and the low energy intensity. To provide reliable power supply, the power in the system should be regulated, and the system should operate at the point that gives maximum power. In the chapter, technologies for maximum power point tracking and power system regulation were described. The point that PV systems are of the most appealing renewable energy solutions with a wide range of applications, calls for more research and development to improve the efficiency of PV technologies.

In Canada, there is potential for stand-alone PV isolated or hybrid systems in remote areas. Applications of grid connected solar system and large scale solar production still need more attention, and are increasing with the developments of new technologies.

In the next chapter the fuzzy logic principals will be discussed, and the theory and applications of fuzzy logic controllers will be demonstrated. Together with a description of the schematics and the operation of the controllers used in the current energy conversion system.

Chapter 3

3 Fuzzy Control System

3.1 Introduction

Applications of intelligent methods for maximum power point tracking provide a much improved performance in fast changing environmental conditions and uncertainties. The main intelligent MPPT methods are: Fuzzy Algorithms, Genetic algorithms and Neural Networks. Fuzzy Logic Control (FLC) which can detect sudden changes and heuristic variables is very efficient for power control system applications. Fuzzy control is fast and robust and able to follow input changes. It does not need prior knowledge of the system, and uses simple mathematics. Fuzzy logic controllers are suitable for PV systems that are characterized by high non linearity, input fluctuations, and environmental variation [93]. This chapter explains the fuzzy control theory and the structure of the fuzzy logic controller. It then discusses in details the used fuzzy intelligent control methods in the present energy conversion system which contain the MPPT function and the power distribution control. The chapter also reviews other intelligent methods and their applications in control systems.

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3.2 Fuzzy Control Theory

3.2.1 Fuzzy Logic

Fuzzy logic which was first introduced by Zadeh in 1965, is a theory that uses mathematical formulas to explain human reasoning. The computation formulas in fuzzy logic is not complex.

Fuzzy logic interprets qualitative information to mathematical relations. That makes it suitable to explain unpredictable system behaviour that cannot be easily modeled. Fuzzy theory shares the same general concept with the traditional set theory, except that there are no crisp transitions between values. Variables are expressed by functions or curves between two digits, mainly 0 and 1 or any other digits. A series of weights describe the degree of belonging of a variable to a certain value within the assigned range. While, traditional set theory defines a variable by its equality or non equality to a certain value [94].

To define a fuzzy set, both the members of the set (values), and the degree of membership (weights of each value) are needed. Fuzzy logic operations or fuzzy concepts are used to relate fuzzy sets [95], [96]. The main operations of fuzzy sets are:

Union of Two sets: *A and B*: $M(A(x)+B(x)) = max(MA(x), MB(x))$ (13)

Intersection of *A* and *B*: $min(MA(x), MB(x))$ (14)

Negation of *A* $M(A(x) = (1 - MA(x)))$ (15)

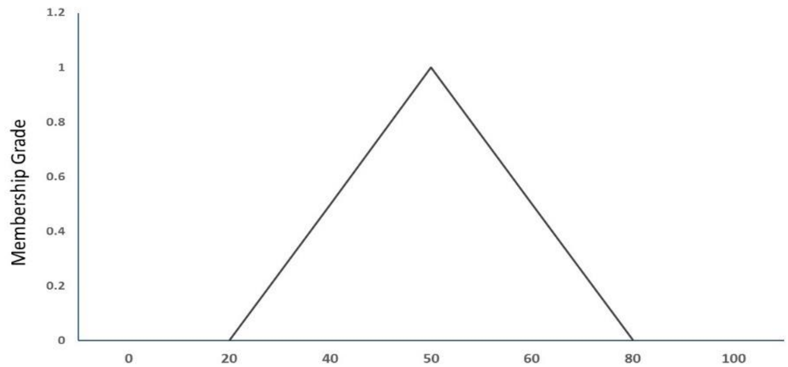
Fuzzy logic interprets real life events which do not have sharp values to mathematical formulas. For example: a room temperature can be represented by fuzzy sets like *warm*, *medium warm*, or *very warm* and these sets can overlap [97].

a. Membership Functions and Fuzzy Rules

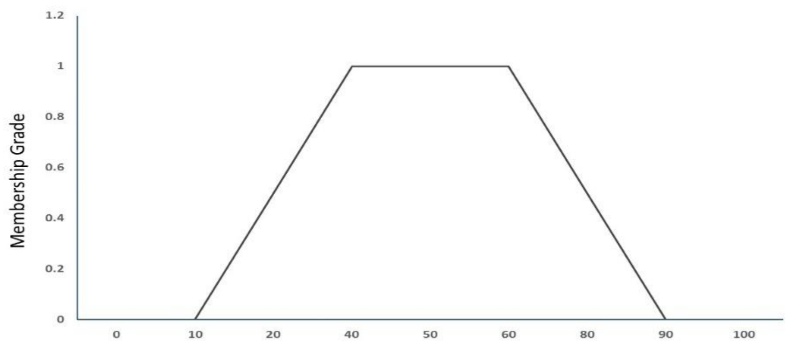
Fuzzy input and output variables are represented by Membership Functions (MF). Membership functions relate each input and output to a weighted variable depending on the shape of the curve [98]. The membership function is usually chosen by the designer of the controller [95]. The most popular membership functions are:

- Triangular
- Trapezoidal
- Gaussian
- Bell
- π shaped membership function
- S shaped membership function

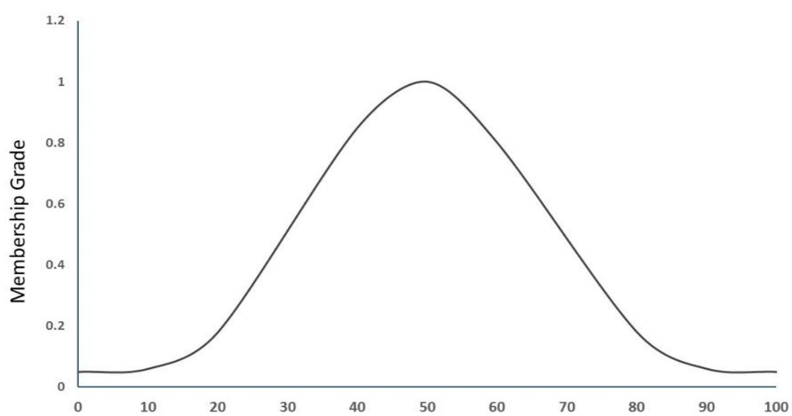
The most used membership functions are the first four due to their simplicity and ability to express most variables. The following figure shows three basic fuzzy functions [99], [100].



Triangular MF



Trapezoidal MF



Gaussian MF

Figure 21 Fuzzy membership functions.

Some references indicate that the shape of the membership function has minimal effect on the operation of the fuzzy controller, while the position and the overlap between functions effects the response. Other references gave merit to the shape of the membership function in determining the system performance. An interesting work investigated the effect of the shape of the membership function of a power system stabilizer for a single machine infinite bus. Comparison between Gaussian, triangular, and trapezoidal functions was conducted: when Gaussian membership function was used, the oscillations were reduced with increasing the spread of the function. When using triangular functions oscillations were generally reduced, and fast convergence was achieved. Trapezoidal membership function resulted in more oscillatory output [101].

Usually the membership function is scaled; many designers use an interval from -1 to 1 which is called (The Universe of Discourse) or (The Standard Universe). When assigning the number of membership functions, a balance has to be acquired between stability and correct outcomes. A small number of membership functions produces unrealistic results, while a large number of membership functions causes instability issues [102]. The main factors that should be considered when choosing a membership function are:

1) Sufficient width of the membership function to allow for noise detection.

2) Sufficient overlapping to correctly define the controller.

3) Gaps between function curves should be prevented, because they result in ill-defined controller

4) A coordination between the number and the width of a set should be achieved [103], [104].

Logical reasoning and understanding of the system helps to design the membership functions. For example, a function that describes human temperature surrounding is different form one that describes the temperature for a furnace [105].

b. Fuzzy Rules

Mandeni Fuzzy

Mamdani Fuzzy is the most used fuzzy membership rule set. It was introduced by E.H. Mamdani [106], [107]. It uses simple methods in designing the membership function and fuzzy rules, and is especially compatible with single input single output systems [108]. Mamdani method is based more on intuitions and human knowledge and it works well with systems that are unpredictable and have high uncertainties. [109]

Takagi Sugeno Fuzzy method

Sugeno fuzzy was first proposed by Takagi and Sugeno in 1985 [110]. In Sugeno fuzzy logic singleton solutions are used to give certain values to the control output [111], [112]. The method is effective in control of complex non linear systems [113]. An advantage of this method is the reduction of the number of rules compared to Mamdani method, which makes it suitable for high order systems. Methods for stability analysis can be developed by using Sugeno algorithms [114].

c. Design of the Fuzzy Logic Controller

In many cases, the design and identification of the fuzzy controller depends on the experience and engineering knowledge of the designer. In some applications, self organization controllers that have the ability to identify and modify their own rules are used.

A convenient method to design the fuzzy controller is to operate the control system with a normal PI or PID controller, then replace the PID controllers with a fuzzy controller and tune if necessary. Noting that this process would be difficult, when the system is ill defined [115]. Likewise, it is impossible to apply the above method if the PID controller cannot be tuned. Building a fuzzy controller that resembles a PID controller makes use of both the fuzzy heuristic characteristics and the PID controller's simplicity, and simplifies the tuning of parameters [116].

Holmblad and Ostergaard proposed the Fuzzy Logic Smith (FLS) controller. Its design is based on the experience and knowledge of the operator that applies three values to resemble a set of measurements, usually, *small*, *medium* and *big* in the control process [117].

Tuning can be applied after assigning the membership functions and rules, based on monitoring the performance of the controller. This process works for systems with a small number of variables, but would be time consuming for larger systems. When the system is complicated and there is a large number of membership functions, mathematical methods should be used to design the fuzzy controller [118].

The use of finite discrete relations to describe the fuzzy concept is proposed in a study by Tong. The used method is simple and provides a technique to analyse closed loop systems by using Zadeh fuzzy sets and an error function [119]. In multi-input multi-output (MIMO) systems, the number of fuzzy rules becomes large and the design process complicated. Methods to reduce the number of fuzzy rules have been used such as the Singular Value Decom (SVD) method which is based on linear algebra [120]. The Combs method simplifies the application of fuzzy rules. It uses Boolean set theory to transfer the MIMO system to a number of single input single output systems to improve system stability [115]. An interesting method for fuzzy controller design is the translation of the relational matrix into sets. This introduces the advantage of not having to change the fuzzy sets in order to optimize the performance, but only change the rules [97].

Although restricted to single-input single-output systems (SISO), an approach of self-organization fuzzy controlled was introduced where an additional fuzzy controller can be used to modify and measure the performance of the original controller [121].

Recently, Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO) were used to select the membership functions and the rule base for a fuzzy logic controller. Larbes et al proposed the optimization of a 25-rule Mamdani FLC for MPPT using genetic algorithms. The membership functions in the controller were triangular and trapezoidal [122]. Another study illustrated using genetic algorithms to optimize a 9- rule base fuzzy controller which was able to meet the desired performance [123]. When the fuzzy controller consists of a large number of parameters, automated tuning becomes crucial. Optimization is mainly done by first selecting a fixed rule base, size and type for the membership functions, then optimizing the FLC parameters. Adaptive neuro fuzzy methods are used to improve the performance of the system. Using fuzzy and neural network technologies combines benefits of neural networks to map input-output non linear functions, with the ability of the fuzzy controller to describe heuristic conditions [124], [125]. Otieno et al presented a fuzzy controller with 21 rules that was tuned using Adaptive Neural Fuzzy Inference System (ANFIS) [126]. A recent publication has also presented a method for tuning a PID fuzzy logic controller for MPPT using swarm intelligence [127].

d. Problems with Fuzzy Sets

Fuzzy sets define input output variables by notations like: *Small*, *Big*, *Negative Small* and so on. Sometimes, the linguistic variables by which fuzzy functions are defined do not reflect the real system variables [115]. Some of the challenges associated with the applications of fuzzy control systems are:

1) Formulating fuzzy sets and rules that would best resemble the control algorithm.
2) The numerical representation of qualitative fuzzy variables in digital computers.
3) The difficulty in determining the range of input output variables in the fuzzy controller that reflects the range of real variables.
4) The difficulty of performance analysis and specially stability analysis of the fuzzy system in some situations [128].
5) Combining engineering control structure and fuzzy algorithms in order to get the best results.
6) The formation of high order problems in MIMO systems, which result in instability, and requires more computation space.

3.2.2 The Structure of the Fuzzy Controller

Fuzzy control is based on incorporating fuzzy logic algorithms in control systems either as dependant controllers or with other types of controllers. A fuzzy controller is composed of the following blocks: the knowledge base, which consists of the fuzzy rule base and the linguistic definitions for the input and output variables. The inference engine, which applies the fuzzy rules to compute the activation of each variable. The fuzzification block which converts the crisp input to a fuzzy variable [7]. The defuzzification block which converts the output of the fuzzy logic controller into a crisp variable.

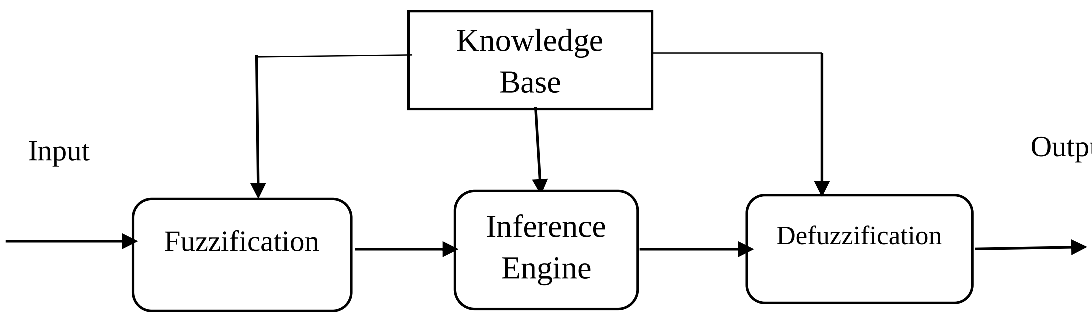


Figure 22 The structure of a fuzzy control system *[7]*.

Defuzzification methods are used to convert the fuzzy variable into a crisp variable for the rest of the control system. The Centroid method, also called the Centre of Area (CoA), or the Center of Gravity is a very efficient defuzification method which can be used with most output membership functions. In the CoA method, the controller calculates the geometric centres of the area under the membership curves [129], [130]. It can be described by the following formula:

$$CoA = \frac{\int_{x_{min}}^{x_{max}} M(x).xdx}{\int_{x_{min}}^{x_{max}} M(x)dx} \quad (16)$$

where CoA is the center of area, *x* is the value of the linguistic variable, *M(x)* is the membership value of *x*, x_{min} and $x_{\max}$ are the minimum and maximum values of the linguistic variable. In the following figure, the CoA method is illustrated:

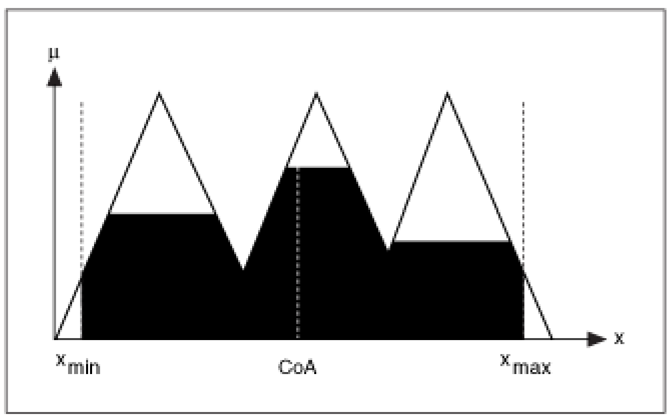


Figure 23 The centre of area defuzzification method *[131]*

A popular defuzzifictaion methods is the weighted average method; it is simple to implement, but can only be used with symmetrical membership functions. Other methods are the Bisector method, the Largest of Maximum, the Smallest of Maximum and the Mean of Maximum method [132].

3.2.3 Applications of Fuzzy Control Systems

Conventional control theory gives good performance in linear systems that have a limited number of variables. It also performs well in optimal control problems that use the maximum principle. Non linear stochastic systems and some deterministic systems can also be controlled using PID techniques [97]. Conventional PID controllers are simple to design and have good ability to estimate the system state from noisy measurements [133].

When the model is hard to simulate, the system is highly nonlinear and subjected to sudden changes, PID controllers are not able to control the system performance efficiently. When the model is complex or unknown, it is useless to design a PID controller using analytical methods [134]. Although adaptive control methods can be applied to solve high order non-linear models with high variations [135], [136], their mathematical formulas get complicated. Fuzzy control methods are more capable when dealing with systems of unknown models, high input variation, and uncertainties [9].

The first application of fuzzy logic control was introduced by Mamdani and Assilian in the control of a dynamic, non linear, and a high coupled process for a simple laboratory steam engine [137]. It was noticed that the fuzzy algorithms performed better than classical control methods and were less sensitive to changes in the operating conditions [138]. In another experiment, Kickert and Lemkef proposed a fuzzy temperature and flow control for a warm water plant. The response to step changes in water temperature set point was fast in the presence of noise, pure time delays, and non-regular gain features. A comparison between fuzzy and PID controllers showed faster step response and better steady state performance for fuzzy over PID controllers [139].

In another work, King and Mamdani experimented the control of the temperature in a non linear pilot state batch chemical reactor with varying gain and pure time delay [140]. Tong studied the control of a pressurized tank that contained liquid which flow is non-linear, and is strongly coupled with two different time constants [141]. Also there are applications of fuzzy logic controllers in speed control of induction-motors either separate or with PID controllers [142], [143]. To sum up, some of the main application of fuzzy control systems are:

- Heat Exchange
- Warm water process
- Traffic control
- Aircraft flight control
- Tuning control
- Robot control
- Automobile speed control
- Water purification process
- Elevator control
- Power and Renewable Energy Systems [144], [145]

Other Intelligent methods have been used separately, or with fuzzy controllers in power regulation and MPPT control systems. Neural Networks (NN) are based on the way the brain processes the signals. They have the ability of self adaptability, can derive models that are non linear, and work well with varying parameters. A Neural Network is mainly composed of input nodes, hidden layers, and output nodes. Hidden layers are composed of a number of nodes each with a weight [146]. Neural networks do not require knowledge of the system model and are relatively easy to design. A neural network was used to find the voltage for the MPPT through detecting the change in the temperature and the irradiance of a PV array [147], [148]. The configuration of a neural network for two inputs and one output is illustrated in the following figure:

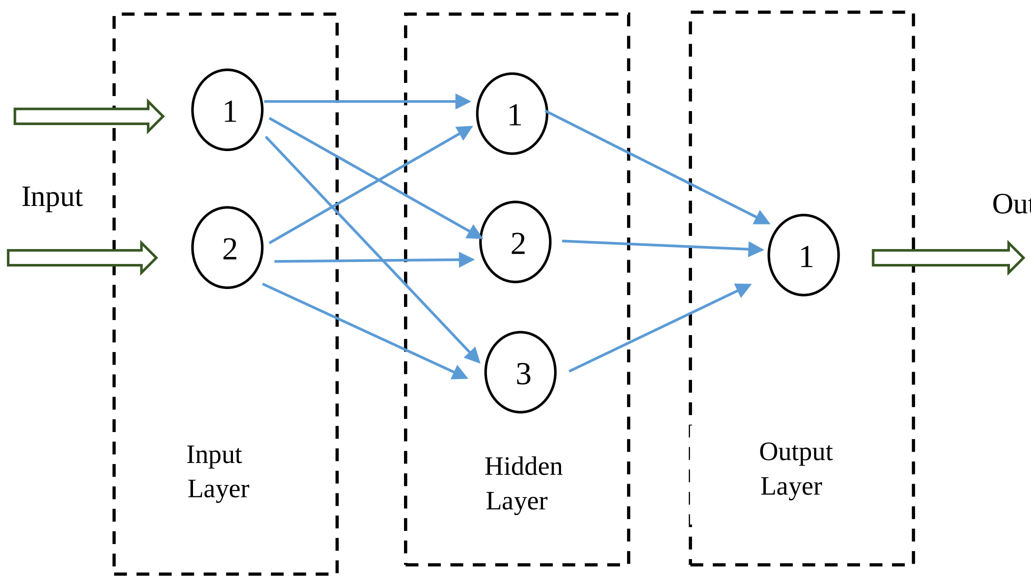


Figure 24 The configuration of a Neural network

Genetic algorithms based on the genetic theory are very fast in finding optimum solutions, although sometimes they have the disadvantage of getting stuck near the optimum value [149]. A genetic based algorithm was used to search for the optimal value, and move from one chromosome to another using the concept of crossover mutation to interchange the chromosomes. A chromosome can be looked at as a string of bits or values and is made of genes which are bytes [150].

Particle Swarm optimization was introduced by Eberhart and Kennedy in 1995 from inspiration of the social behavior of bird flocking or fish schooling. It is based on swarm intelligence which searches for the area where the optimum results can be achieved [151], [152]. An improved method of swarm optimization was applied for maximum power point tracking is stand- alone solar systems [28].

3.3 MPPT Control (Based on FLC)

Fuzzy logic controllers are very suitable for PV systems that are non linear and highly dynamic. Fuzzy sets were designed to represent uncertainty and vagueness, and to perform control operations for such systems [153], [134]. Fuzzy controllers proved to give efficient responses both for the MPPT tracking, and the power regulation of PV systems. Fuzzy logic MPPT tracking applications in PV systems have the advantage of robustness, fast response and are simple to design. It was noted that faster performance and smoother steady state response was obtained when fuzzy logic was used than when normal P&O method was used [154]. A fuzzy logic controller based on voltage detection to improve the performance of maximum power tracking for a hybrid system was proposed [155].

Both types of Fuzzy control, Mamdani and Sugeno were applied to improve the performance of P&O and IC methods. Better time response and less oscillations were noted [156]. A fuzzy logic controller with two input variables: the supply expectancy and the predicted supply expectancy, was applied to control the power in a PV system. The approach set load priorities to supply the power in stand-alone systems with more than one load [109].

a. Maximum Power Point Tracking Algorithm

In this work, maximum power point tracking is implemented using an incremental algorithm and a fuzzy logic controller. The algorithm compares the actual power from the solar panel (P_{PV}) with an estimated value for maximum power (the reference power (P_r)) through the fuzzy logic controller in equal time intervals. The output of the fuzzy controller is used to trigger the reference power to a new level, which is added to the previous value at each interval. The highest value the power can reach is taken as the maximum power. The output signal from the FLC controller directs a PWM to control the duty cycle of a DC-DC boost converter. The DC-DC boost converter converts the voltage to the value that enables the system to operate at maximum power. The following equations describe the algorithm:

$$P_{PV} = I_{PV} \times V_{PV} \tag{17}$$

$$P_{r*} = P_{r(t)} + P_{r(t-1)} \tag{18}$$

$$P_{new} = p_r^{\;*} \times s \tag{19}$$

$$P_r = P_{r(new)} \tag{20}$$

Where: P_{PV} is the actual power from solar panel, I_{PV} is Photovoltaic current, V_{PV} is Photovoltaic voltage, P_r is the estimated reference maximum power and S is the signal from the controller. The MPPT system configuration can be seen in the figure:

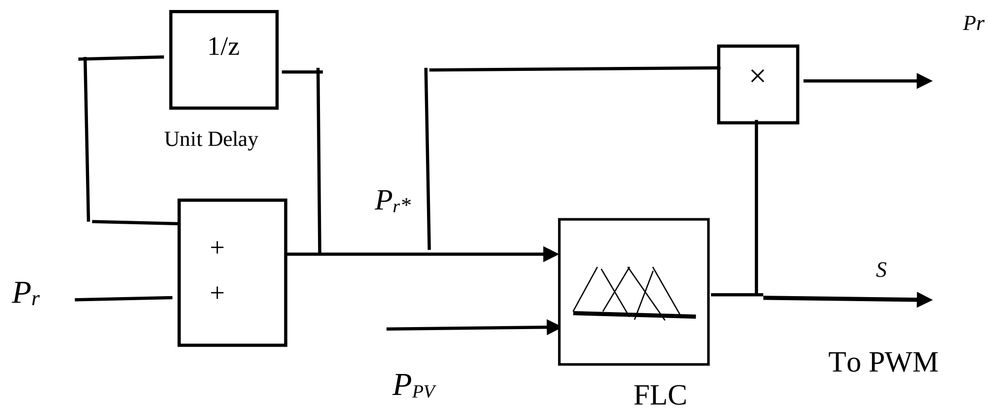


Figure 25 MPPT controller configuration

The flow chart of the MPPT control operation is in the following figure:

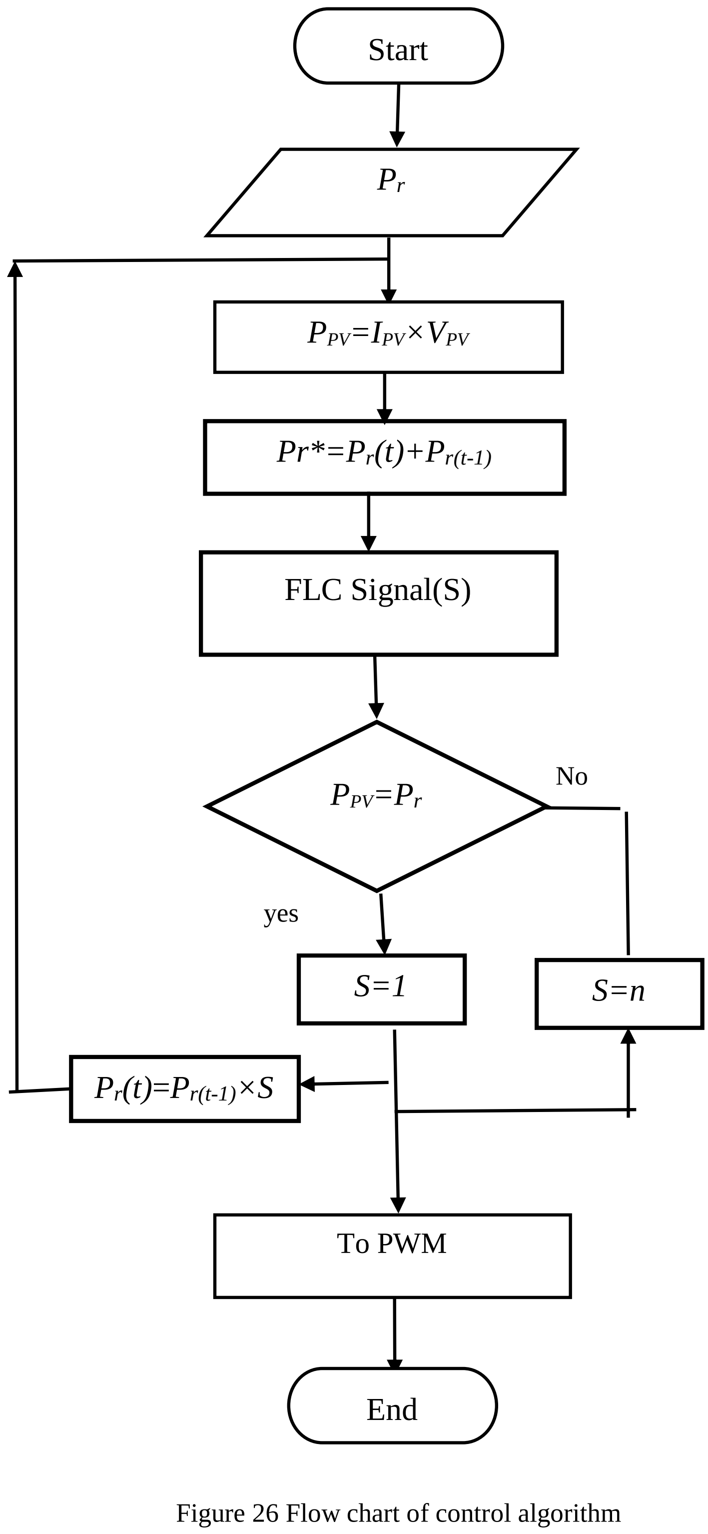
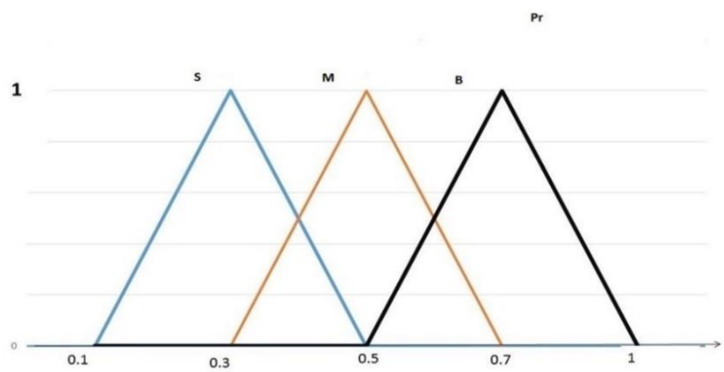


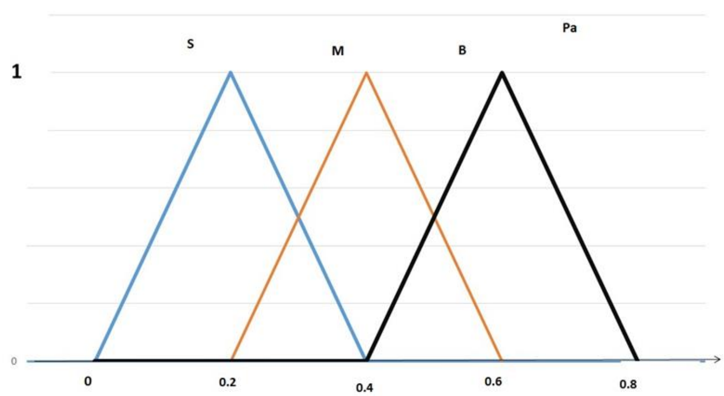
Figure 26 Flow chart of control algorithm

b. Fuzzy Logic Controller and Membership Functions for MPPT

In this work, Sugeno type fuzzy is used for the MPPT controller. The inputs to the fuzzy controller are the estimated reference power (P_r) and the actual PV power (P_{PV}), and the output is the control signal (S). Each input variable is represented by three triangular membership functions: *Small*, *Medium*, and *Big*. The output variable is represented by a singleton function of three variables. *Small* (Sm) at 1, *Medium* (M) at 5 and *Big* (B) at 10. The input membership functions were scaled to the universe of discourse [0 1] using a gain of 0.1. The output of the controller is scaled back to the normal range by a gain of 10. The range was estimated based on the range of the difference between the actual power and the maximum power of real experiments. The CoA method was used for defuzzification. The following figures represent the input and output membership functions for the MPPT FLC.



Fuzzy input membership function, P_r



Fuzzy input membership function, P_{PV}

Figure 27 FLC functions for MPPT

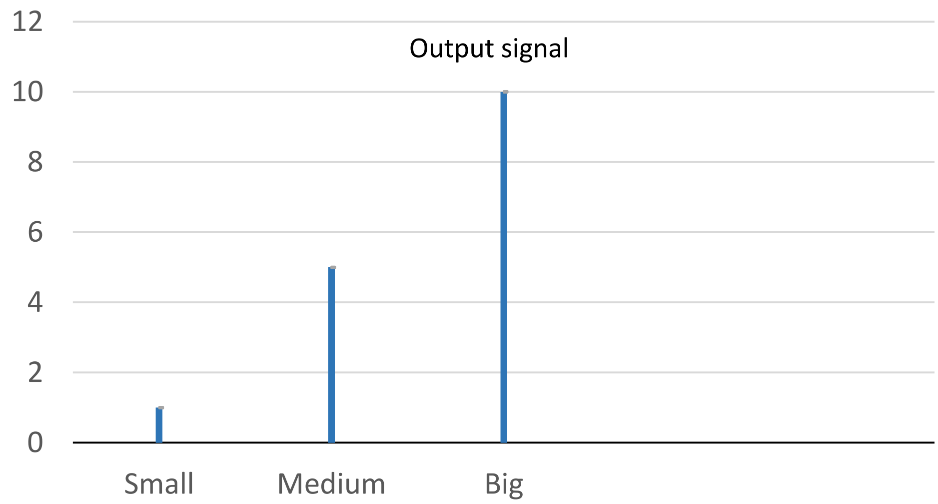


Figure 28 Fuzzy output membership function for MPPT.

The Fuzzy membership rules were derived based on the understanding of the system's operation, and monitoring the behaviour of the system in other experiments. The reasoning that was implied can be summarized in the following points:

- The reference maximum power and the actual power is compared in the fuzzy controller
- The aim of the controller is to determine the control signal that makes the actual power as close as possible to the estimated reference maximum power.
- Usually the maximum power is more that the actual power so only these cases were considered.

- When the actual power is much less than the reference power, the high value of the output is triggered

  - The value of the output signal depends on the variation between the two power values. For example, if the reference power is Big and the actual power is Small, a Big signal is needed to trigger the controller to increase the actual power to the value of the reference maximum power. Below are the abbreviation and the table of fuzzy rules:

  If *(P_r is Small)* and *(P_{PV} is Small)* then *(S is Small)*

  If *(P_r is Medium)* and *(P_{PV} is Small)* then *(S is Medium)*

  If *(P_r is Medium)* and *(P_{PV} is Medium)* then *(S is Small)*

  If *(P_r is Big)* and *(P_{PV} is Small)* then *(S is Big)*

  If *(P_r is Big)* and *(P_{PV} is Medium)* then *(S is Medium)*

  If *(P_r is Big)* and *(P_{PV} is Big)* then *(S is Sm)*

Table 1. MPPT FLC rules

P_r	P_{PV}	S
Sm	Sm	Sm
M	Sm	M
M	M	Sm
B	Sm	B
B	M	M
B	B	Sm

3.4 Battery Regulator (Based on FLC)

The PV panel is the primary source in a PV power system, while the battery is the secondary source. The battery supplies the load with power when the PV power supply is not enough for the load requirements, and stores power when the PV power is more that the load requirements. The operations of the battery charge-discharge and the power transfer happen in fast varying conditions. It can be said that the battery control operation is critical to the efficiency of the PV system. Fuzzy logic control has proven to be able to adapt to fast changing condition and at the same time provide robust response. A Mamdani Fuzzy Logic controller is used to control the operation of the battery. The control is done through controlling the voltage and the power inputs to the battery. The output variables direct the operation of switches before the load [157].

In this work, a fuzzy PID controller is used to control the overall power distribution and the charge discharge operation of the battery. Using a fuzzy PID controller utilizes both the operation of the fuzzy controller and the simplicity of the PID controllers at the same time. It was noted that, when fuzzy PID controller was used, the steady state error was less than when genuine PID controller was used [158]. In many energy distribution and power electronic application, PI /PID fuzzy controllers are preferred over pure fuzzy controllers due to the inherit characteristics of both which enables the system to respond better in case of changing inputs and disturbances. Using fuzzy PID controllers also makes the controller design and parameter tuning easier [102].

a. Battery Operation Control Algorithm

The battery operation can be described by the following modes:

- *Battery charge mode*: In this mode the power from the PV source is more than the load requirements ($P_{PV} > P_L$). The battery is charged which the difference between the two powers, (P_{PV} - P_L).
- *Battery Discharge Mode*: The power from the PV source is less than the load requirements ($P_{PV} < P_L$). The battery is discharged to provide the load demand, (P_L – P_{PV}).
- *No Action Mode*: In this mode, the load demand is equal or nearly equal to the supplied power and there will be no charge or discharge from the battery side.

The battery controller should be able to follow the input power variations and to direct the battery to operate according to the load requirement and the PV supply. In this work, the battery charge and discharge operation is controlled using two imbedded control loops; a PID fuzzy logic controller cascaded with a PI controller are used to control the battery operation. The input to the fuzzy controller is the difference between the desired and the actual battery power. The desired power (P_d) is found by subtracting the power of the load (P_L) from PV Power (P_{PV}). The output of the controller is compared with the battery actual current and passed to a PI controller then to a PWM. The PWM generates the signal that determines the duty cycle of the DC-DC buck-boost converter which changes the current to charge and discharge the battery according to the duty cycle.

The following figure shows the configuration of the battery control circuit.

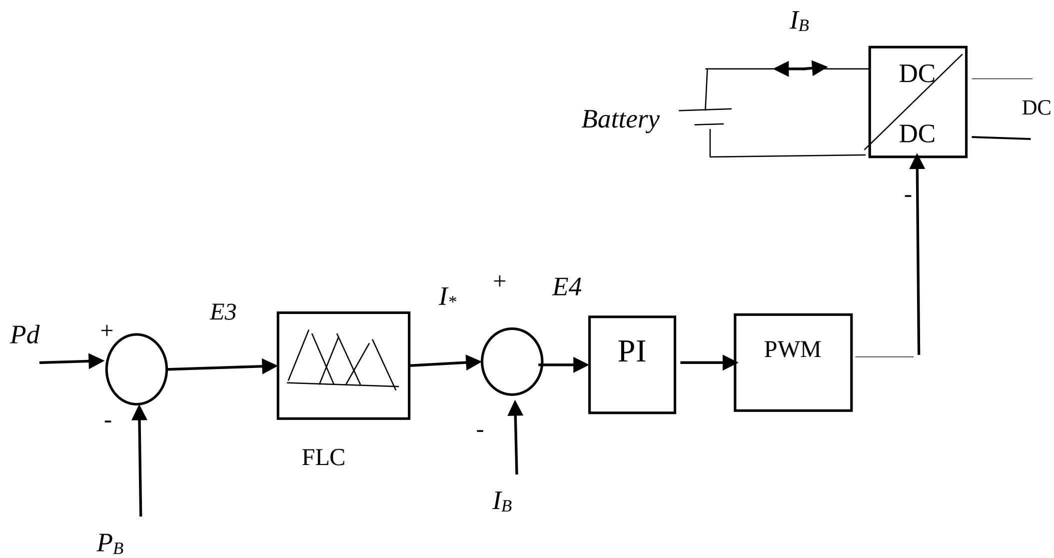


Figure 29 Units of the battery control.

The battery control variables are represented by the following equations:

$$Pd = P_{PV} - P_L \qquad (21)$$

$$E3 = Pd - P_B \qquad (22)$$

$$E4 = I^* - I_B \qquad (23)$$

Where: *Pd* is the desired battery power, P_L is the load power, P_{PV} is the photovoltaic power, I^* is the desired battery current, V_B is the actual battery voltage, I_B is the actual battery current, and *E3, E4* are errors. The operation of the battery charge-discharge can be illustrated in following flowchart:

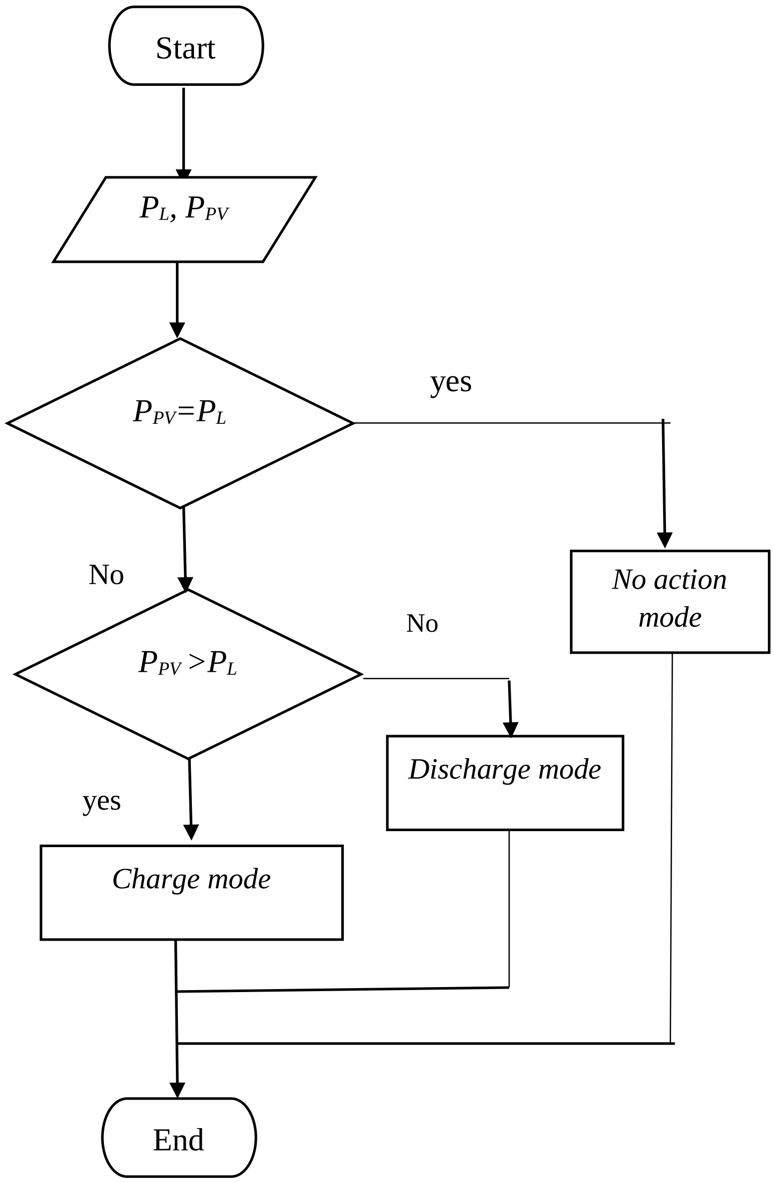


Figure 30 Flow chart of the battery operation

b. Fuzzy Logic Controller and Membership Functions for the Battery Operation.

The inputs to the fuzzy block in the battery controller are the error and derivative of error. The error is integrated and added to the output of the fuzzy block. The output of the fuzzy controller is the signal (*S1*). The configuration of the FLC controller for the battery can be seen in the following figure:

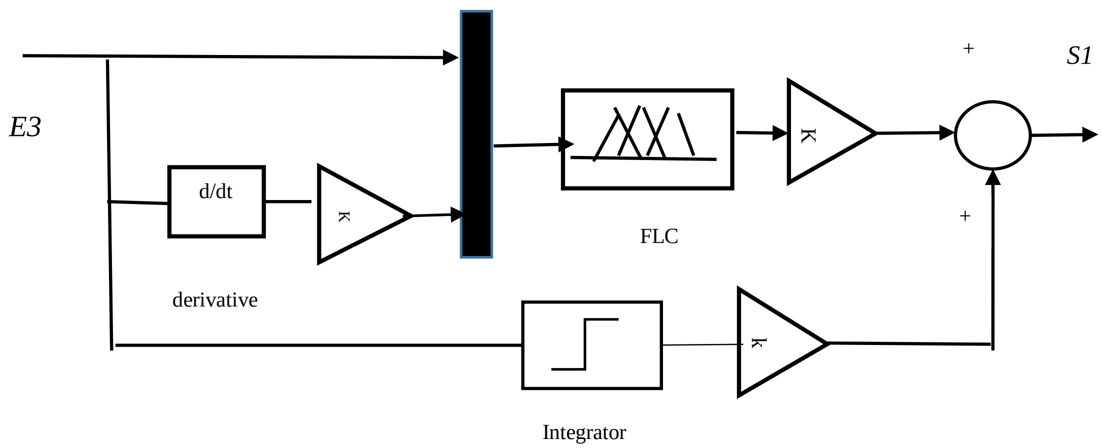
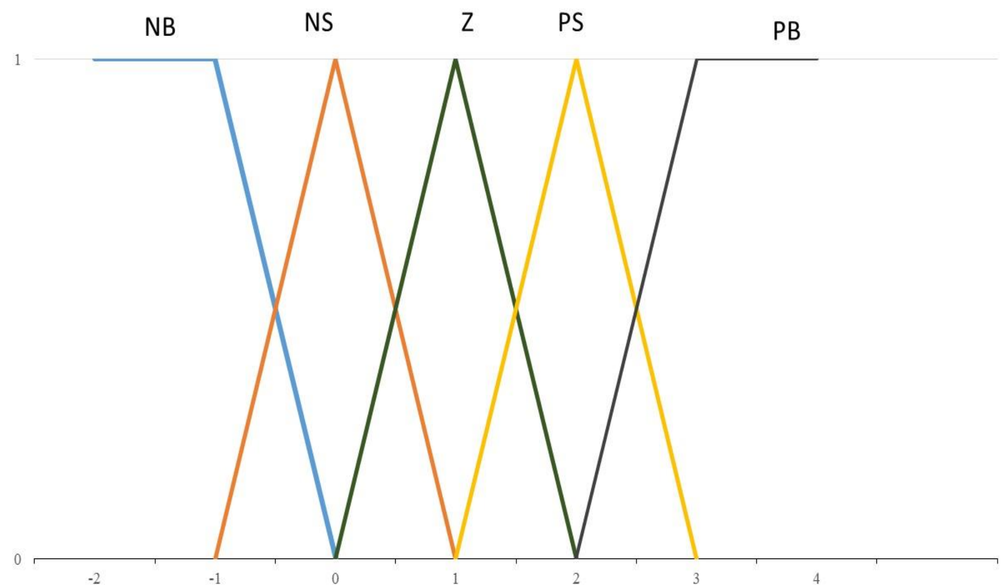


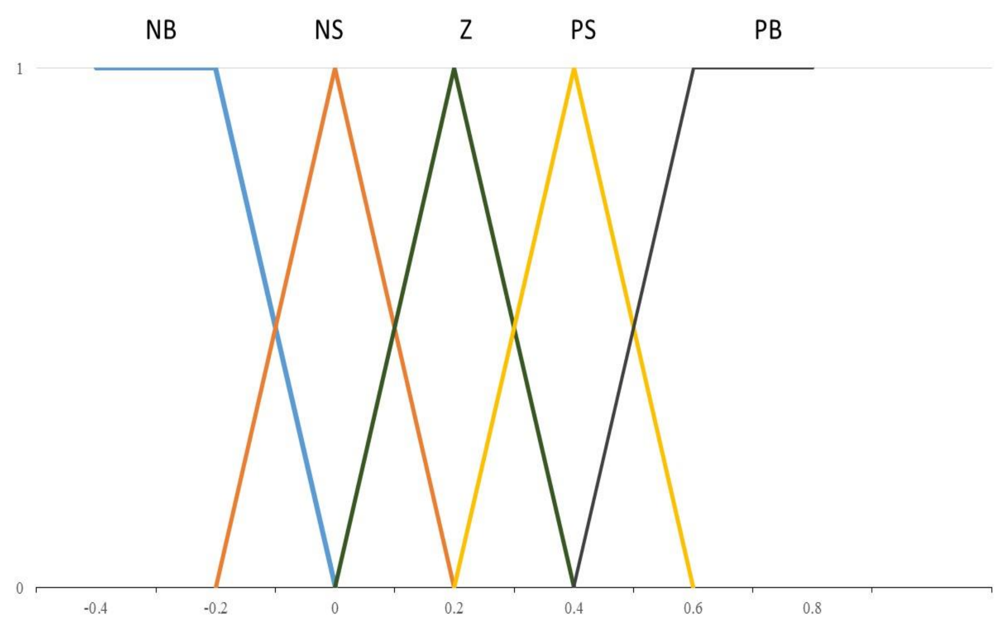
Figure 31 FLC PID Controller

Five membership functions were used to express the input variables (the error (*E3*) and the derivative of error (*dE3*)). Also five membership functions were used for the output variable.

The membership functions are: *Negative Big* (NB), *Negative Small* (NS), *Zero*(Z), *Positive Small* (PS), *Positive Big* (PB). Mamdani fuzzy rules were applied to link the inputs to the output. Following are the membership function for the input and output variables:



MF for the error (*E3*)



MF for the change in error (*dE3*)

Figure 32 Fuzzy input membership functions for the battery operation control.

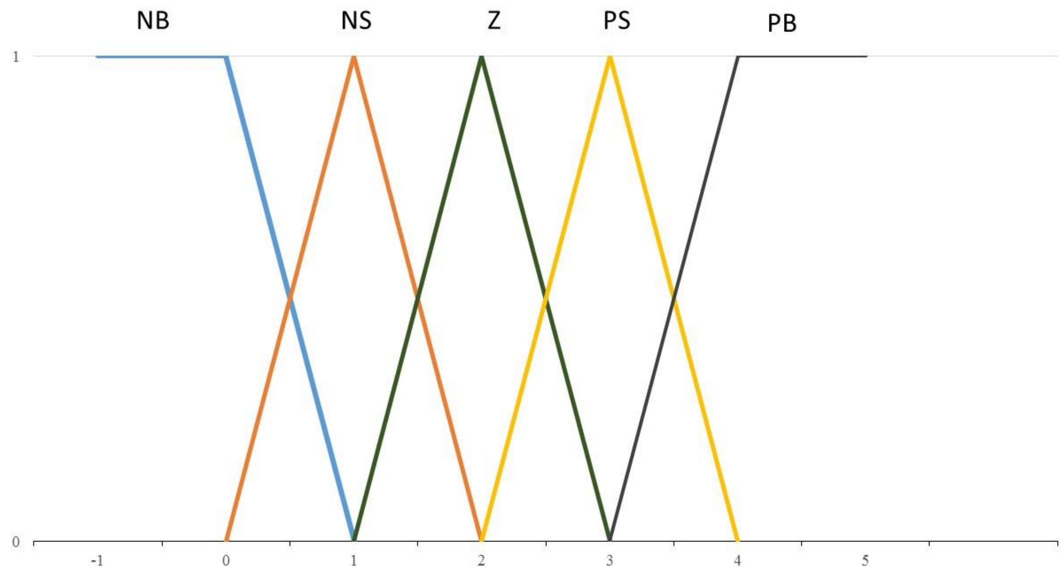


Figure 33 Fuzzy output membership function for the battery operation control.

The fuzzy rule base can be seen in the following table:

Table 2 Fuzzy rule base for the battery control

E3 / dE3	*NB*	*NS*	*Z*	*PS*	*PB*
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PS	PB
PB	Z	PS	PB	PB	PB

The first row is the error(*E3*), the first column is the change in error (*dE3*), and the intersection of a column and row gives the output signal *S1*.

As an illustration the first membership rule can be interpreted by:

(If the *error* is *Negative Big* and the *change in error* is *Negative Big*, then the *Output Signal* is *Negative Big*)

And which can be expressed by the rule:

If *E3* is *NB* and *dE3* is *NB* then *S1* is *NB*

The other columns use the same principal for the other rules.

3.5 Load Side Control

In any load specification there are certain values of current/voltage and power that have to be provided to the load during the operation. In this work, the control of the load voltage and current is done by two cascaded PI control loops. The outer loop is used to control the load voltage, and the inner loop to control the current. The error for the outer loop is found by subtracting the actual load voltage (V_L) from the desired load voltage (V_{Ld}) and then the output is passed to a PI controller. The load current (I_L) is subtracted from the output of the first PI controller to produce the error signal.

The error is directed to another PI controller, then to the PWM and signal generator to produce the control signal. The output of the signal generator determines the duty cycle which determines the amount of voltage increase of decrease for the DC-DC buck-boost converter. Using cascaded controllers improves the performance by minimizing the external disturbances, and reducing the sensitivity to variable gains [159]. The inner control loop operation reduces the effect of disturbances on the output of the first controller [160]. By the used control methods, the voltage, current and power of the load is regulated and stabilized to the set value. In the following graph, the configuration of the load voltage control is illustrated.

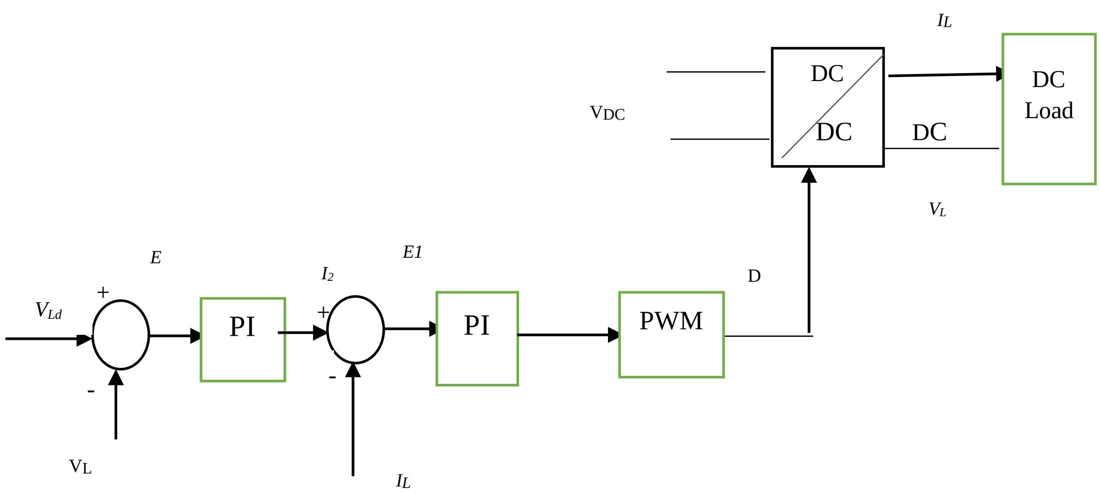


Figure 34 Load voltage control

The following equations illustrate the operation of the load voltage controller:

$$E = V_{Ld} - V_L \tag{24}$$

$$E1 = I_2 - I_L \tag{25}$$

Where: E is the error to the outer PI controller, $E1$ is the error to the inner PI controller, V_{Ld} is the load desired voltage, V_L is the load actual voltage. I_2 is the reference current and I_L is the load current

3.6 Conclusion

The chapter discussed the applications of FLC in PV systems and described the current FLC applied controllers. PV solar systems are non linear systems that undergo a lot of variations related to changes in environmental conditions, and load demands. A PV system is characterised by the interaction of many variables from different parts of the system. For efficient power supply, several tasks have to be controlled such as the MPPT, the load voltage and the battery function. Using conventional controllers have faced challenges in keeping up with the fast variations in PV systems. FLC has proven to be efficient in applications with undefined models and high instability. To develop a fuzzy controller, the input variables and the membership functions have to be identified properly in a way that actually describes the system performance. Many approaches have been used such as trial and error, using past knowledge of the system and using combined intelligent methods. The applications of PID or PI based fuzzy logic have many uses, because they correlate between both the advantages of conventional and fuzzy controllers.

In the next chapter, the experimental aspects of the current work are previewed. Demonstrations of both the hardware and the software of the experimental system will be shown. The results from the experimental application of the system are demonstrated and discussed.

Chapter 4

4 Experimentation and Results

4.1 Introduction

In this work, a complete power regulation control system for a stand-alone PV system with a DC load was implemented by simulation and hardware emulation with OPAL-RT HIL Real-Time Digital Simulator (OP5600). Maximum power point tracking is implemented using FLC. The load power control and the battery operation regulation are realised by using PI and FLC controllers. In this chapter, the parts of experimental system will be discussed including explanations and graphs of the hardware system and the interface. The chapter also includes a description of the simulation software and a discussion of the results obtained from the hardware experimentation.

4.2 Real Time Control Hardware

The hardware experimentation of the PV system that includes battery storage, IGBTs and DC loads was implemented using Opal-RT system. Opal-RT provides efficient real time simulation suitable for complex systems thorough hardware-in-the-loop (HIL) simulation [161], [162]. In the figure below, the HILL application is shown:

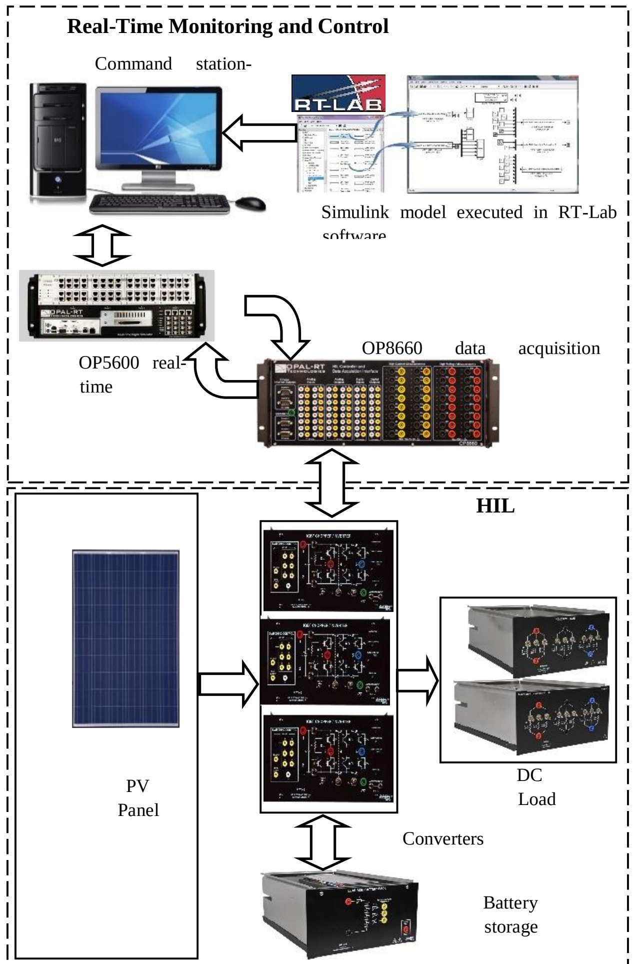


Figure 35 Real time system for the HIL stand-alone photovoltaic energy conversion system.

a. OPAL-RT HIL Real-Time Digital Simulator (OP5600)

The OP5600 is a complete simulation system. It consists of a powerful target computer, a flexible high-speed front-end processor, comprehensive digital and analog I/Os, a signal conditioning stage and FPGA that runs the RT-Lab simulation software platform. The system can run in real time and integrate with Matlab/Simulink models that simulate physical systems. The powerful processor: Intel Xeon QuadCore 2.40 GHz with multi-socket capabilities, higher core counts, and support for ECC memory [163], enables rapid prototyping.

Figure 36 Opal RT interface panel.

b. OPAL-RT Signal Conditioning Module Interface (OP8660)

The OP8660 contains high voltage and current probes specifically customized for Lab-Volt's Laboratory Kit power ratings The OP8660 can direct the output firing pulses to control two IGBT inverter modules and can read two ABZ position encoders. It enables the interaction between the real time simulator (OP5600) and the experimental hardware system.

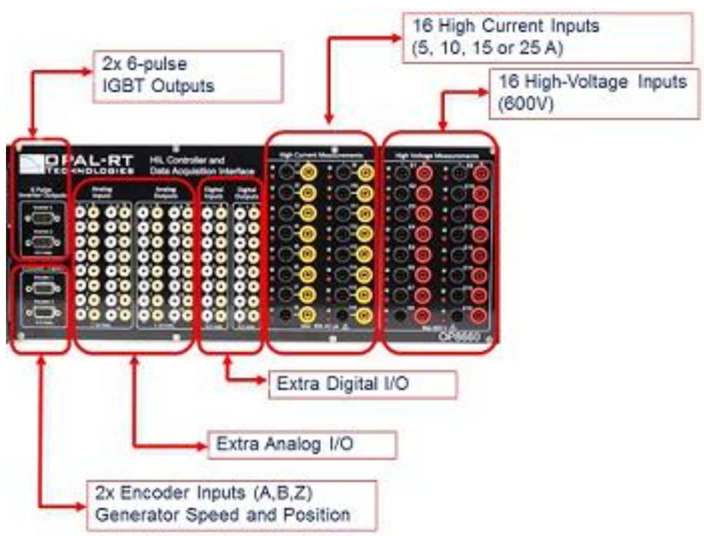


Figure 37 OPAL-RT Signal Conditioning Module Interface (OP8660).

An array of digital and (low power) analog I/O are available for the user that includes the following [164]:

- 2x 6-pulse IGBT outputs

- 2x encoder inputs
- 16 high current inputs
- 16 high voltage inputs
- 48 extra analog and digital I/O
- Speed & torque dynamometer control

c. 200 W Electric Drive Kit

It contains the hardware devises that are used in system connections.

a. AC and DC machines: permanent magnet DC motor, PMSM brushless motor, S.Q. induction moto, four-quadrant dynamometer/power supply
b. Power supply
c. IGBT chopper/inverter
d. Resistive load
e. Lead acid battery

4.3 Real Control Software (RT-Lab)

RT-Lab is the core of the OPAL-RT technology. It is a real time simulator software that can be used in a variety of simulation and control system applications. It has the ability to add more computational power according to system's requirements. Real time simulation can be performed through: Hardware-In-the-Loop (HIL) tests, Power-Hardware-in-the-Loop (PHIL) tests, Rapid Control Prototyping (RCP), Pure simulation to increase calculation speed [165]. The real time software application is developed in MATLAB/Simulink and integrated with the RT-LAB for real time experimentations.

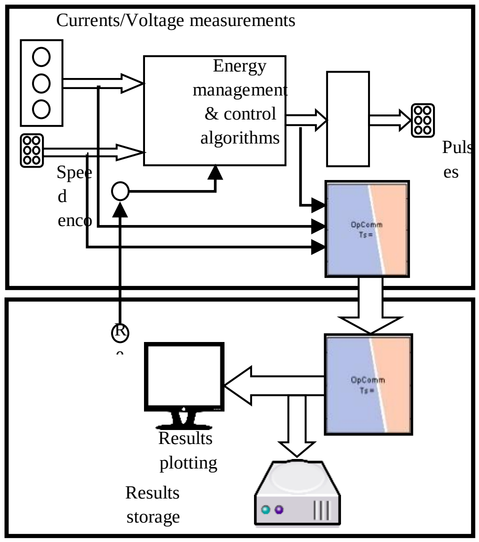
The workflow of RT-LAB to simulate and run a model consists of the following stages:

1) Edit the model
2) Compile the model
3) Load the model
4) Execute the model

The execution model is divided into:

- Console Subsystem: It consists of the user interface blocks and is executed in the command station-PC.
- Master subsystem: Includes the basic elements of the model and the mathematical algorithms and is executed in the CPU.

The synchronising between the two subsystems is performed by the RT-LAB OPComm blocks as illustrated in the figure below:



SM_Control

SC_Monitor

Figure 38 subsystem for OPAL RT LAB

4.4 Experimental PV System with Battery Storage.

a. Overall System Configuration.

In the experimental system for the current dissertation, the controllers were built by Mat Lab/ Simulink software. Power lights were used to produce the lighting to a Solar PV (Canadian Solar) panel. The number and direction of the lights were changed to give the effect of changing sun light intensity and position. The behaviour of the system was experimented in different conditions. Firing signals were send to the hardware part and results collected from the input output interface

The hardware parts of the system proposed in this dissertation are:

- PV Panel
- DC-DC boost converter on the PV side for the MPPT.
- DC-DC buck boost converter on the battery side to control the charge discharge operation and stabilize the DC link voltage.
- DC-DC buck boost converter on the load side for the load voltage and current control.
- Resistive load.
- Lead acid battery model.

The hardware configuration of the system can be seen in the following figure:

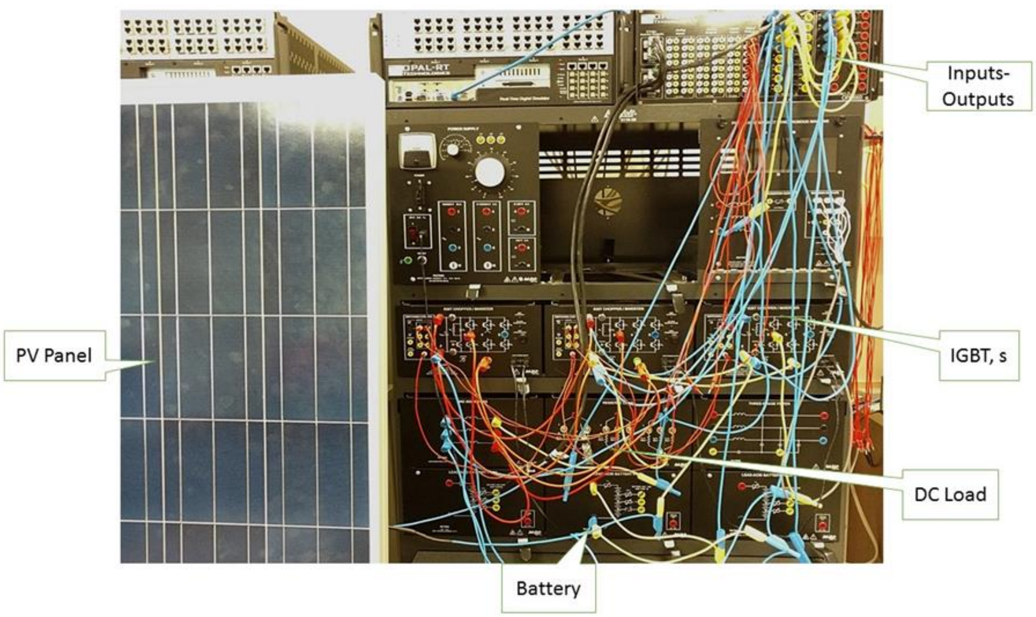


Figure 39 Hardware configuration of the power control system.

The maximum power point tracking system is connected to the overall power control system in the battery and load circuits. The regulation of the battery operation is achieved by a PID fuzzy logic controller that is initially directed by the difference between the desired and the actual battery power. The function of the load side controller is to stabilize the load voltage, current/power with reference to the load requirements. The schematic of the overall system configuration can be seen in the following figure:

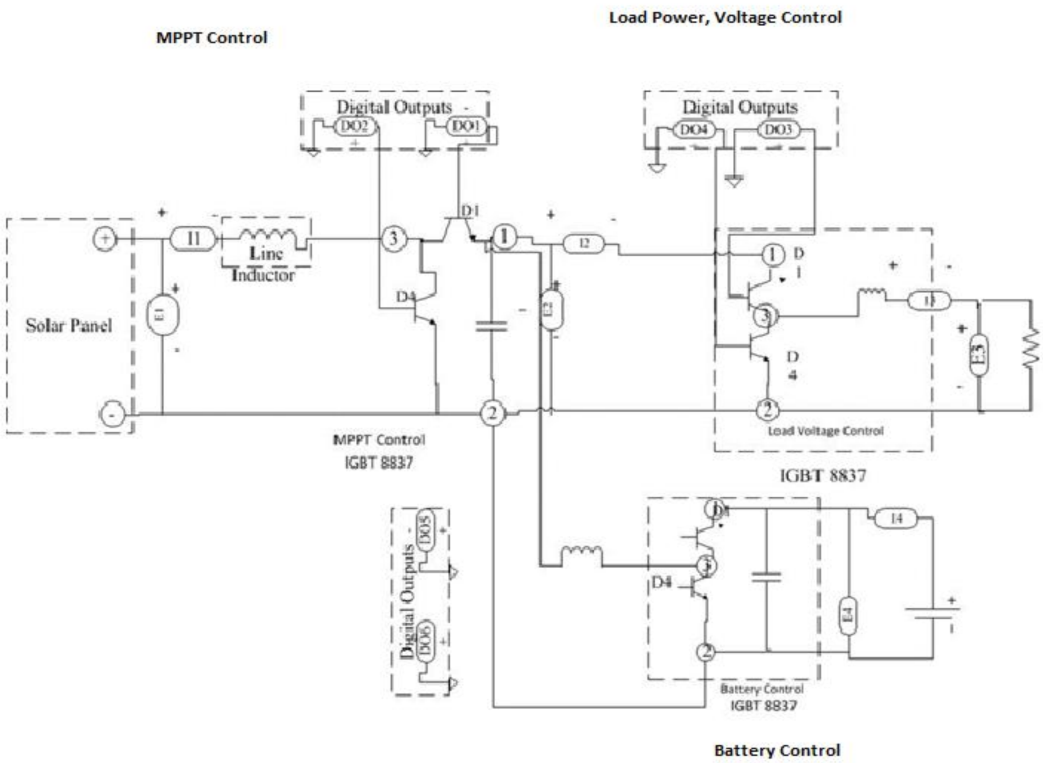


Figure 40 Schematic of the power control system

4.5 Experimental Results

Three sets of readings are illustrated to show the effect of different input variation on the system behaviour. The currents, voltages, and powers for the PV, load, MPPT side, and battery were plotted.

In figures 41, 42, 43 and 44 the first set of experimental responses (*reading 1*), voltages, currents, power at different locations and current at different locations respectively are illustrated. In figures 45, 46, 47 and 48 the second set of experimental responses (*reading 2*), voltages, currents, power at different locations and current at different locations respectively are illustrated. In figures 49, 50, 51 and 52, the third experimental responses (*reading 3*), voltages, currents, power at different locations and current at different locations respectively are illustrated.

From (*reading1*) responses: in figure 41(a), it can be observed that the PV voltage was fluctuating, with a sharp decrease at nearly 50s. In figure 41(b) it can be seen that the load voltage was stabilized at 15v. Figure 41(c) shows the battery voltage is at full charge of 50v, and figure 41(d) shows that the MPPT voltage is relatively stable, following the PV voltage. In figure 42(a), it is illustrated that the PV current followed the pattern of change in the PV voltage, but the fluctuations are more visible in the current. Figure 42(b) illustrates that the battery current followed the pattern of change in the PV current. In figure 42(c), it can be seen that the load current was stable during the process. From observing the power and current variation for the first reading; in figure 43, it can be seen that when the PV power was more than the load power around the interval (20s - 40s), the battery current was positive (figure 44), which indicates that the battery was operating at the charge mode (being charged). When the PV power was less than the power demand of the load, the battery operated in the discharge mode and the battery current was negative.

From (*reading 2*) responses, it can be observed that the PV voltage was fluctuating and sharply decreased at nearly 45s in figure 45(a). The load voltage was stabilized at 15 v in figure 45(b). From the current responses figure 46(a), it can be seen that the PV current was highly fluctuating due to the instability in the PV power supply, and the change in light intensity. Figure 46(b) shows that the battery current followed the PV current, and in figure 46(c), it can be seen that the load current was stable in spite of the variation in the PV current. Figures 47 and 48 show that when the PV power was more than the load power, the battery operated at the charge mode with positive current, and when the PV power reduced at around 25s and became less than the load power, the battery operated at the discharge mode with negative current.

From (*reading 3*) responses, it can be observed that when the PV voltage (figure 49(a)), and the current (figure 50 (a)) started to increase, at around 30s, the PV power followed. From the figures of power at different location (figure 51), it can be observed that when PV power was equal to the load power, the battery was in the no action mode and the battery current was zero (figure 52). When the PV power was more than the load required power, the battery operated in the charge mode and the battery current was positive (figure 52).

The following points can be observed from the results:

The Load voltage, current, and power regulation: The control system managed to keep the current, voltage, and power of the load at a stable level in conditions of high fluctuations and fast changes.

The battery operation: The PID FLC/PI controllers in the battery side, managed to control the battery operation according to the changes in the PV supply, and the load demand. The following was observed:

- The battery was charging when the PV power was more than the load demand, and discharging to the load when the PV supply was less than the load demand.
- The charge and discharge operation was performed according to the difference between the PV power and the load power.
- The current was negative when the battery discharged to the load and positive when the battery was charged from the PV panel.
- The current is more sensitive to the irradiance variations and this correlates with what is stated at the PV characteristics.
- The battery voltage was kept stable.
- The battery control stabilized the DC voltage.

The MPPT Controller: The controller at the MPPT side was able to provide the maximum power at different operating conditions with improved efficiency, and fast tracking ability.

Reading 1

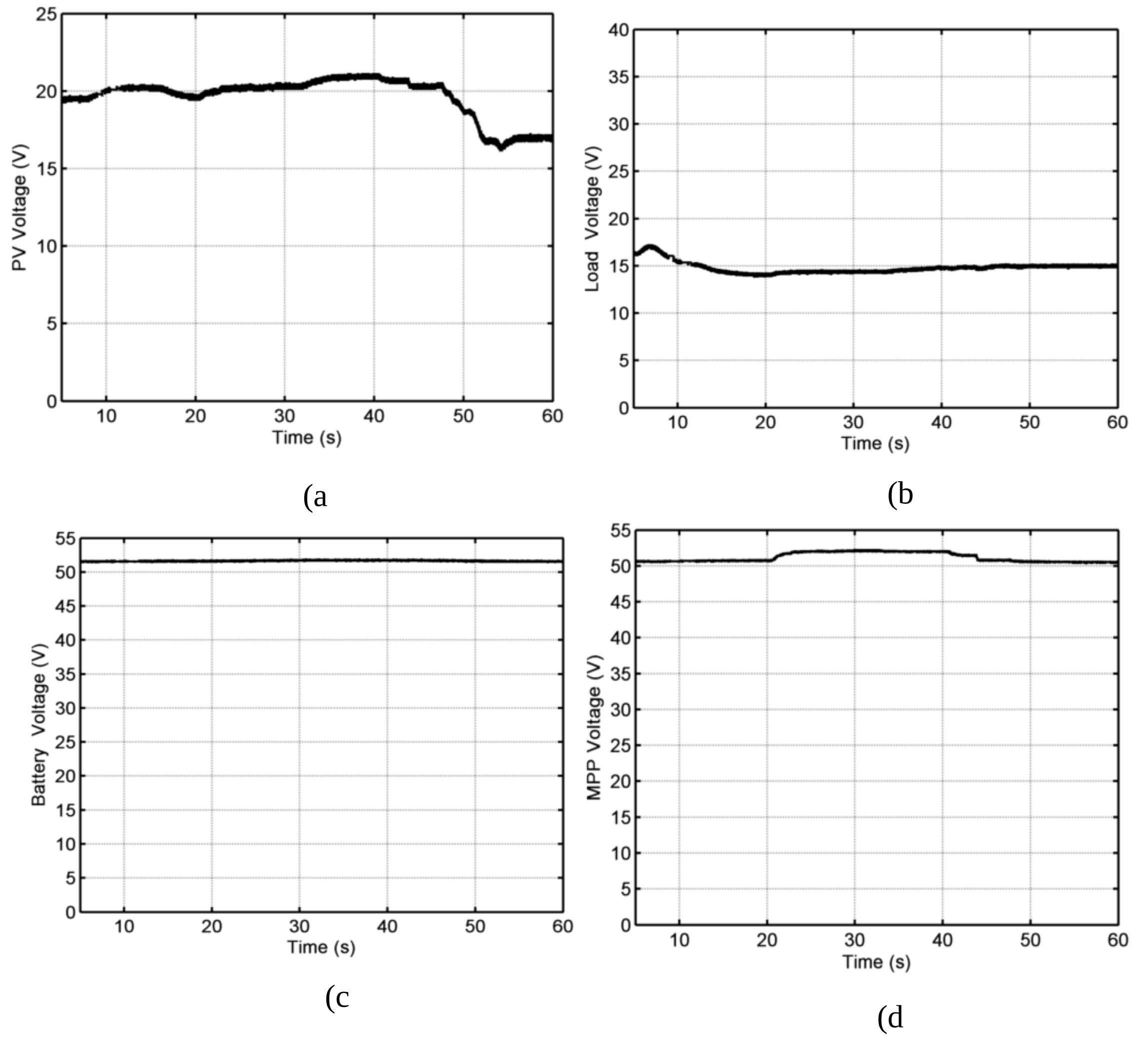
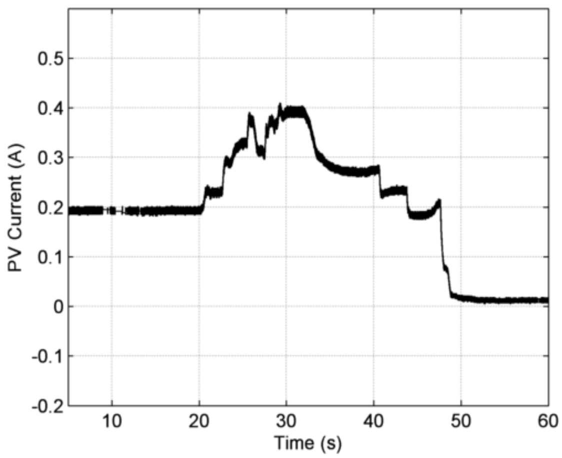
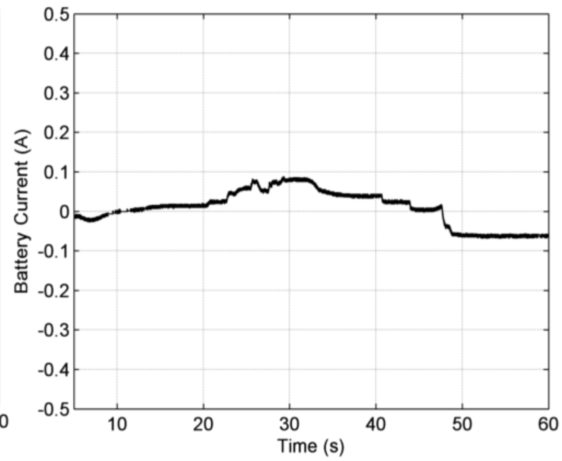


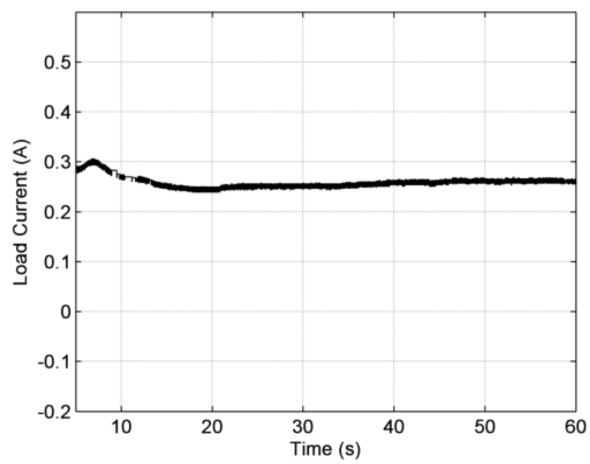
Figure 41 Voltage response in the PV energy system. (a) PV module voltage; (b) Load voltage; (c) Battery voltage; (d) MPPT Voltage, *reading1*



(a)



(b)



(c)

Figure 42 Current response in the PV energy system. (a) PV module current; (b) Battery current; (c) Load current, *reading 1*

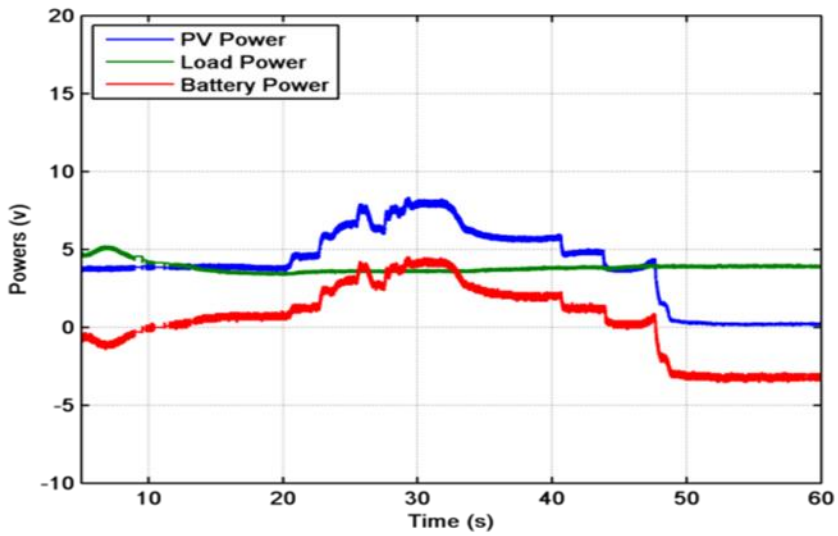


Figure 43 Power at different locations in the PV energy system, *reading 1*

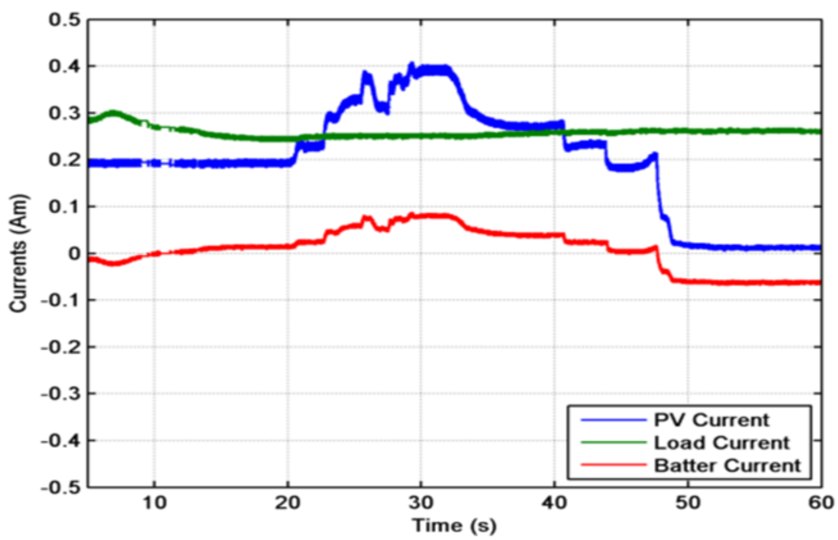
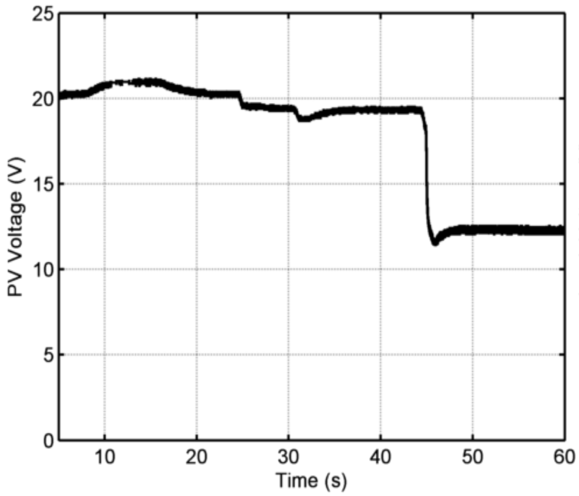
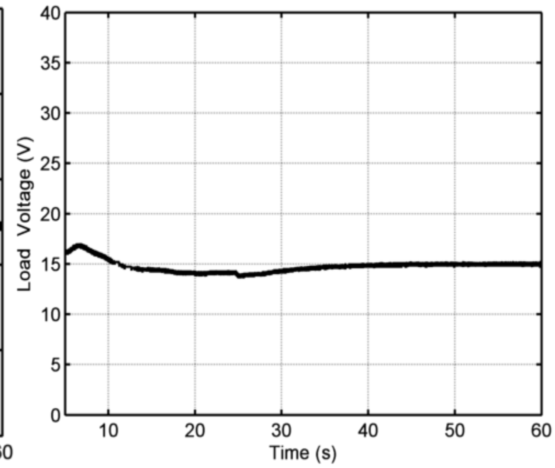


Figure 44 Current at different locations in the PV energy system, reading 1

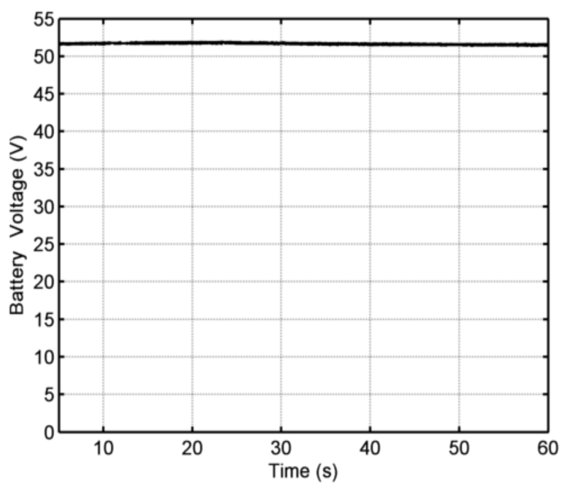
Reading 2



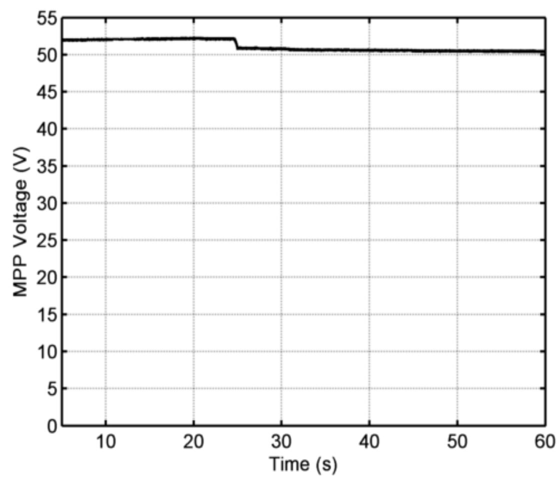
(a)



(b



(c)



(d

Figure 45 Voltage response in the PV energy system. (a) PV module voltage; (b) Load voltage; (c) Battery voltage; (d) MPPT Voltage, *reading 2*.

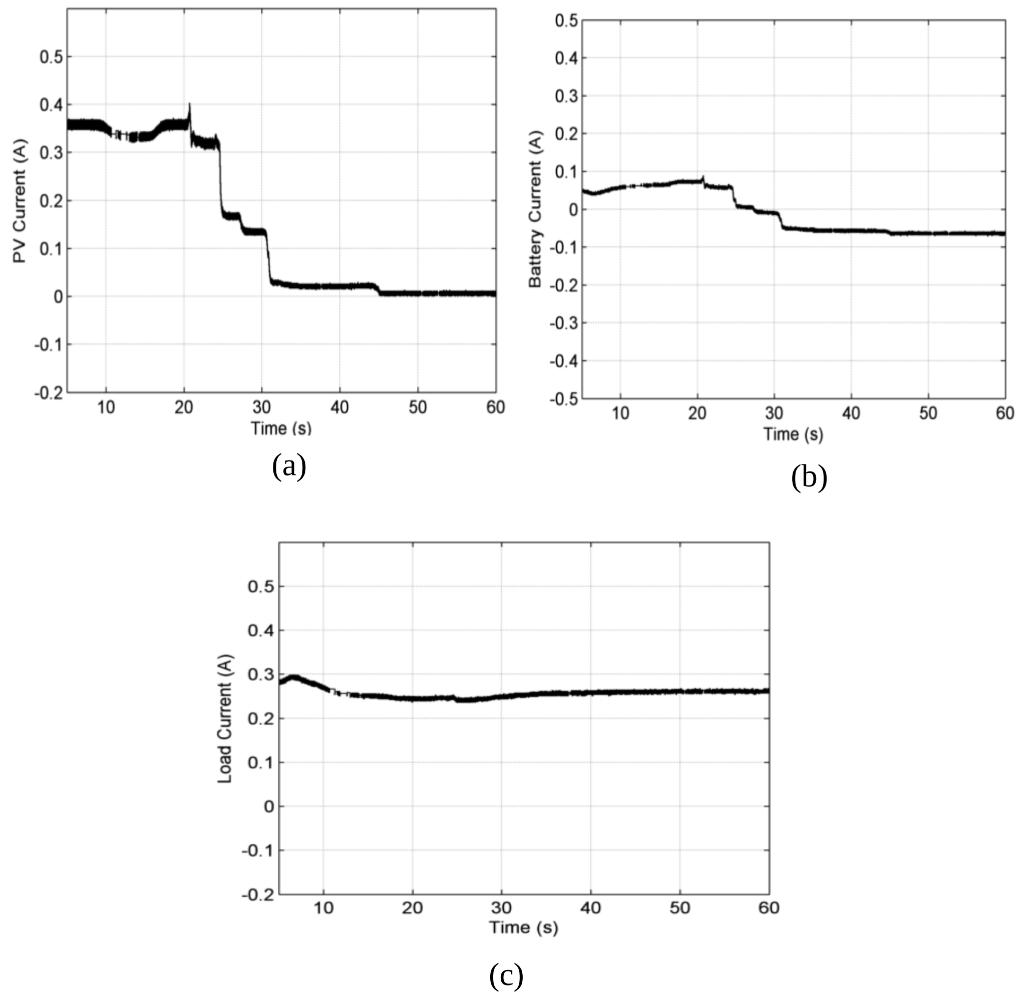


Figure 46 Current response in the PV energy system. (a) PV module current; (b) Battery current; (c) Load current, *reading 2*

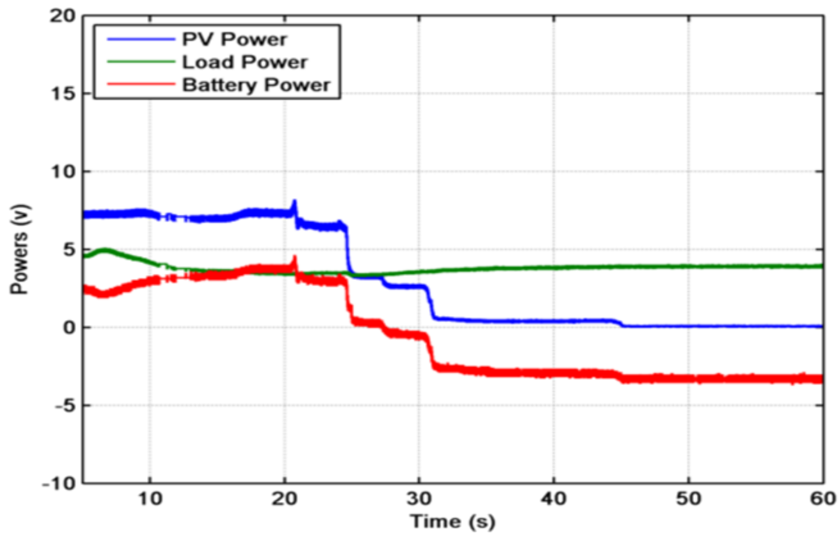


Figure 47 Power at different locations in the PV energy system, *reading 2*.

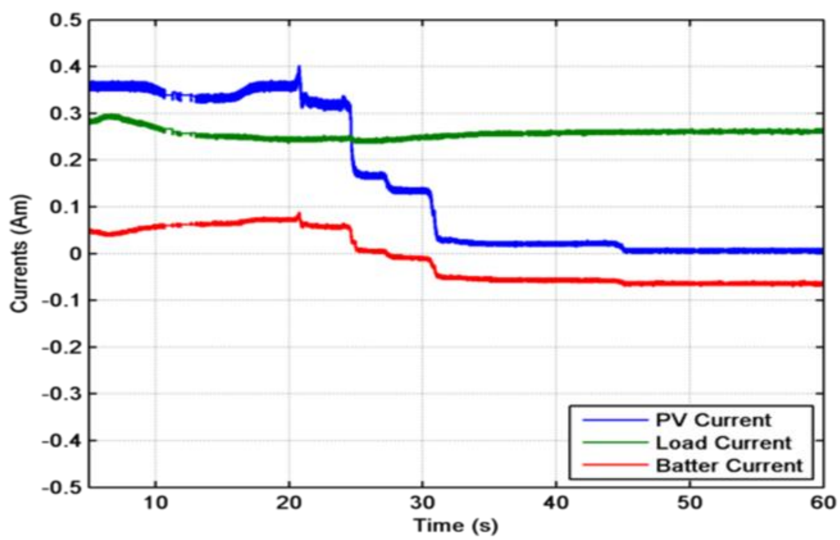


Figure 48 Power at different locations in the PV energy system, *reading 2*

Reading 3

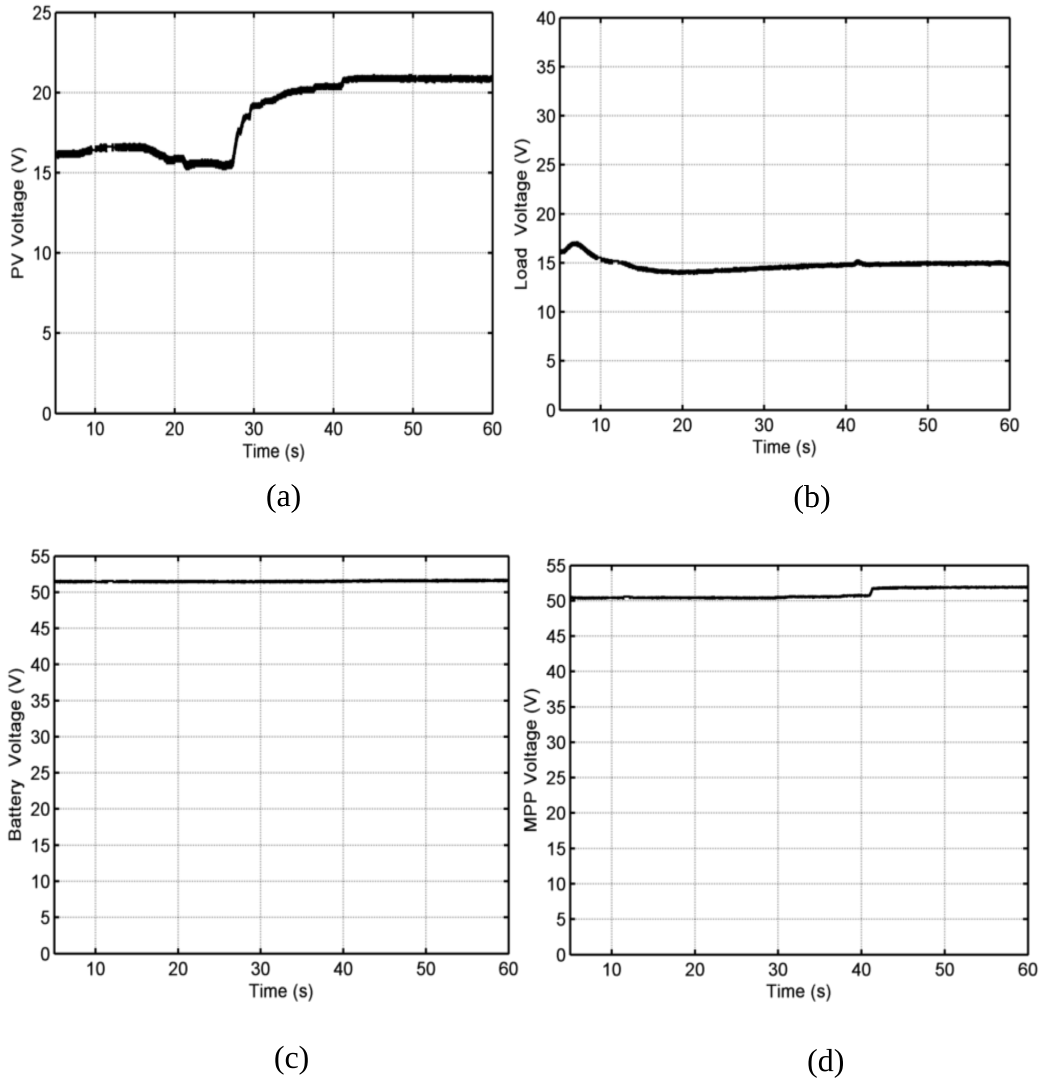
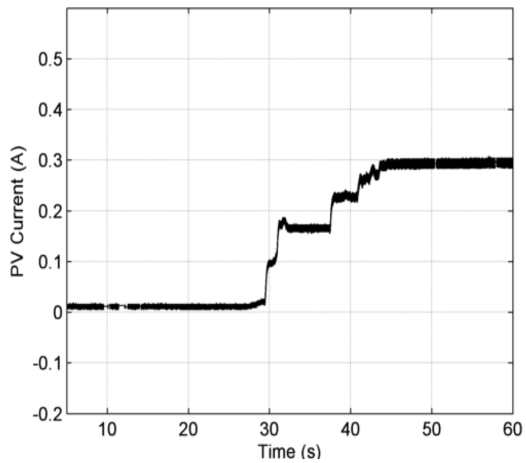
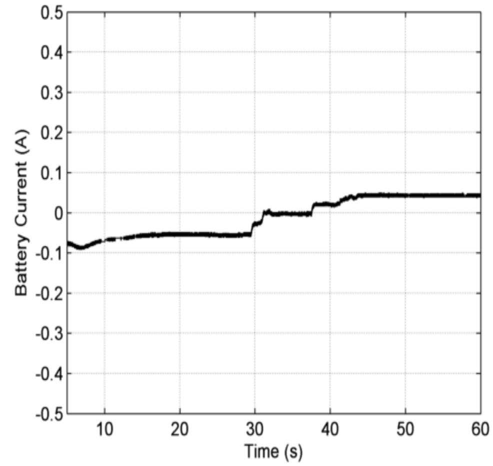


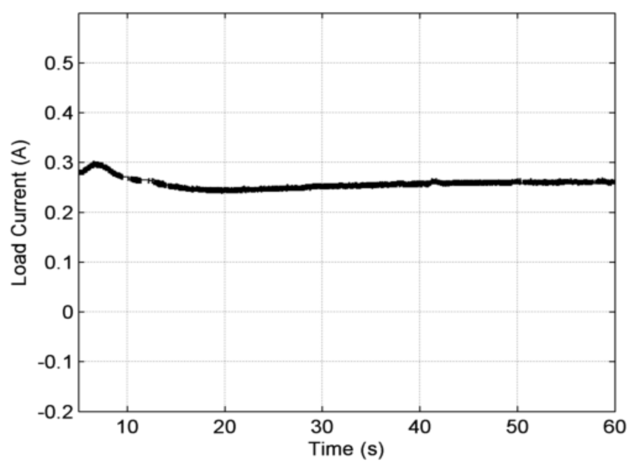
Figure 49 Voltage response in the PV energy system. (a) PV module voltage; (b) Load voltage; (c) Battery voltage; (d) MPPT Voltage, *reading 3*



(a)



(b)



(c)

Figure 50 Current response in the PV energy system. (a) PV module current; (b) Battery current; (c) Load current, *reading 3*

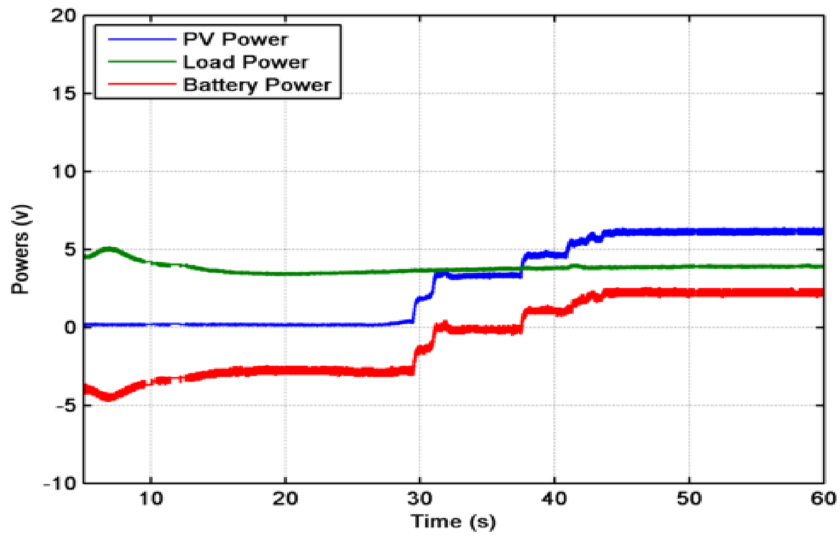


Figure 51 current at different locations in the PV energy system, *reading 3*

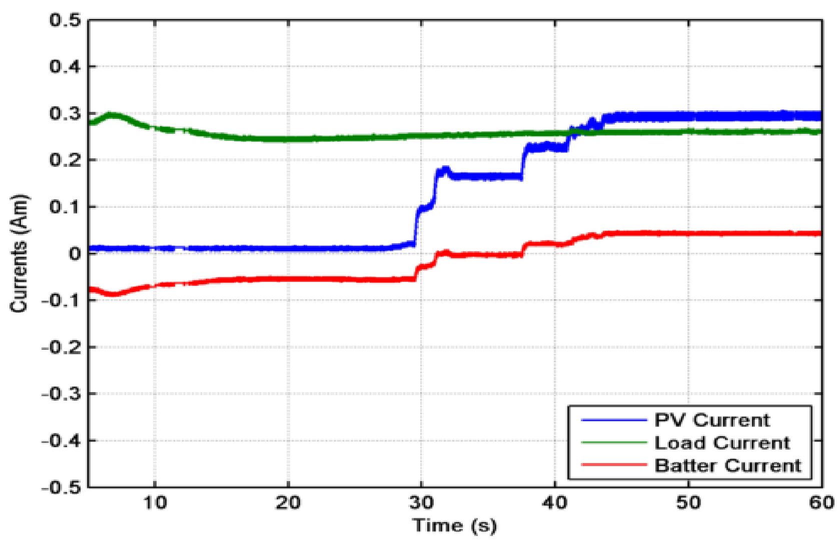


Figure 52 Power at different locations in the PV energy system, *reading 3*

4.6 Conclusion

In this chapter, the system's software and hardware components as well as the practical results were discussed. The experimental implementation with OPAL-RT real hardware components provided a practical study of the system dynamics in real conditions. The capabilities of the OP5600 to perform complete simulation, run the RT-LAB software simulation program through its high -speed processor, and to interface with the 200 W Electric Drive Kit enabled a faster execution as compared with plain simulation.

The variation in the input power was achieved by changing the number and the direction of the power lights providing different light intensities and incident angels. Three sets of results with varying input conditions were obtained to show the response of the system. It can be concluded that the energy control system was able to provide robust power control and distributions in conditions of high variation and non linearity.

In the next chapter, the types of research work and the project contribution to innovation will be investigated. The university-industry (U-I) channels will be studies with relation to the current work, including the present used channels and areas that can be further targeted.

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Chapter 5

5 Innovation and Technology Transfer

5.1 Introduction

Innovation is defined in the Oslo Manual, OECD as:

"The implementation of a new or significantly improved product (good or service), a new marketing method, or a new organizational method in business practices, workplace organization or external relations" (OECD/Eurostat, 2005) [166].

A more general concept of innovation is: it is a better way to do things. But the practical meaning of innovation goes beyond the general understanding in that innovation is linked to an idea or a way that would produce beneficial economic, social, or cultural outcomes or application [167]. A research would lead to innovation if, either the research itself or the future related work of the research is directed to a solution of a problem. It is stated by some scholars that scientific research is the first step to innovation. Others look at the relation between research and production as multisided. This means that basic ideas for industry products could come from scientific research, and also a research can derive its basic idea from an excising industry product.

In other words, the idea of a research could come from a current product, and the research would work on developing that product [168]. Throughout these arguments, there have been many explanations and definitions of the types and stages of research to determine the research and science policy. Moreover, studies on the importance of communication channels between academic institutions and industry, and ways to enhance these channels have been conducted. Renewable energy and especially solar energy has a lot of potential in the future. By conducting research and development on renewable energy, solutions to the current problems of global warming and pollutions would be possible. Areas of research in PV systems range from theory, modelling, control systems and algorithms, measurements, characteristics, and testing [169]. The stages of research can be fundamental, applied, or aimed to development and (R&D).

In this chapter, different theories about research and innovation will be explained. As well as the types of knowledge transfer channels and the importance of those channels according to the view of different scholars. In addition to the nature of the current work and its relation to innovation and industry production. The discussion will be assessed by a questionnaire interview concerning the current work in solar energy technology.

5. 2 The Classical Understanding of Research

The Greeks were the first to use scientific inquiry to investigate natural causes. While in the older civilizations, the tendency was to investigate uses and applications of things, rather than the causes. The Italian renaissance coupled scientific knowledge and action, but generally, the link between science and technology was weak until the 19th century. At that era, the advances in electronic power, health and chemistry that rooted from the research on chemistry, biology and physics were visible [170], [171].

Research is defined as a process of sequential decision making, which has different components in different settings [172]. Whatever is the type of research, basic or applied, it starts by making choices. These choices may include the research area, research problem, models, observations, designs, and interviews.

After World War 2, the Foundation of the National Policy of Research in the US, set a research policy through two cannons suggested by Vannevar Bush: the first cannon stated that the major purpose of the basic research is knowledge and understanding, while applied research is directed to use and applications. The report was submitted to the U.S president in 1945, nominated "Science The Endless Frontier" [173]. By this, a clear distinction between the goals of basic and applied research was drawn. The second cannon specified that basic research is the first step that fuels the applied research at later stages.

Bush described the relation between basic and applied research as a linear relation with stages leading from basic to applied research, then to production. The stages are: basic research, applied research, production or operation [174]. Although Bush emphasized on the importance of basic research as a source of innovation, his theory isolated basic research from production, and put a clear separation between research stages. This view shaped many of the research policies in U.SA and many countries till today. Many R&D managers are still working according to Bush's definition of scientific research [175]. Another explanation of basic research was presented by the Directorate of Scientific Affairs (OECD) which defined the role of basic research in that it extends the understanding of phenomena of a scientific filed. While the role of applied research is understood to convert the possible into actual, and that it works on the feasibility of scientific development. Development is the final stage of the technology sequence, in which research is turned into a useful product or service for the society [175]. This view, although gave more clarity to the roles of each type of research, still isolated basic from applied research.

5.3 The New Understanding of Basic and Applied Research

The definition of research and connection between different stages of research work, influences the basic research policy in a country. Nils Roll-Hansen argued that the proper understanding of the true relation between basic and applied research is a major element in setting the right research policies [176]. The older definition of research has recognised the importance of basic research to developments, but separated between basis and applied research. According to this concept, the process of transferring from basic research to applied research, and then to production can take a long time. According to Bush's definition, the motivation factors for basic and applied research works are diverse [177]. The old definition does not explain the interaction between different types of research and science in the context of scientific advances today. The routs and motivations of different kinds of scientific research and the stages of research work are interacted and connected. This also can be seen in earlier scientific works; for example, it can be observed that the early stages of Pasteur's research work started by questioning. But in later stages the research was more linked to applications. There is no clear distinction between the two stages of his work as basic or applied research. It can be said that the aim of his research was both pure knowledge and the motive to solve practical problems at the same time. The same applies to other fields of research such as social, macroeconomic and life science where it would be hard to distinguish between basic and applied research [175]. A research does not have to belong to one or another definition as in the view of Bush, but can be interrelated. Stokes introduced a new definition of basic and applied research in a new illustrative model. The concept of Stokes better reflects the nature and interactions of the stages of research related to the current nature of scientific advances and extended specification. The interaction and similarities between different types of research work are clearly demonstrated by Pasteur's Quadrant that was introduced by Donald. E. Stokes [178]. Unlike Bush's definition that followed a linear sequential model; Stokes developed a more realistic and interactive approach to describe the relation between basic research and technology innovation in the quadrant model.

In the Pasteur Quadrant Stokes used four example to describe the types of research, and located each example in a quadrant: pure research from Niels Bohr example, who studied the structure of the atom in the last century driven by a motive of pure understanding. On the other practical extreme he used an example of Edison's work which was mainly directed to pure use and ignored looking at the physical phenomena. While Pasteur's work resembles the combination between the use inspired and basic research motives. The bottom left quadrant resembles works like Socrates that purely aims to teaching or philosophy. A research work can be allocated in any of the mentioned quadrants, or can have interrelated characteristics [179].

The following figure illustrated Pasteur's Quadrant.

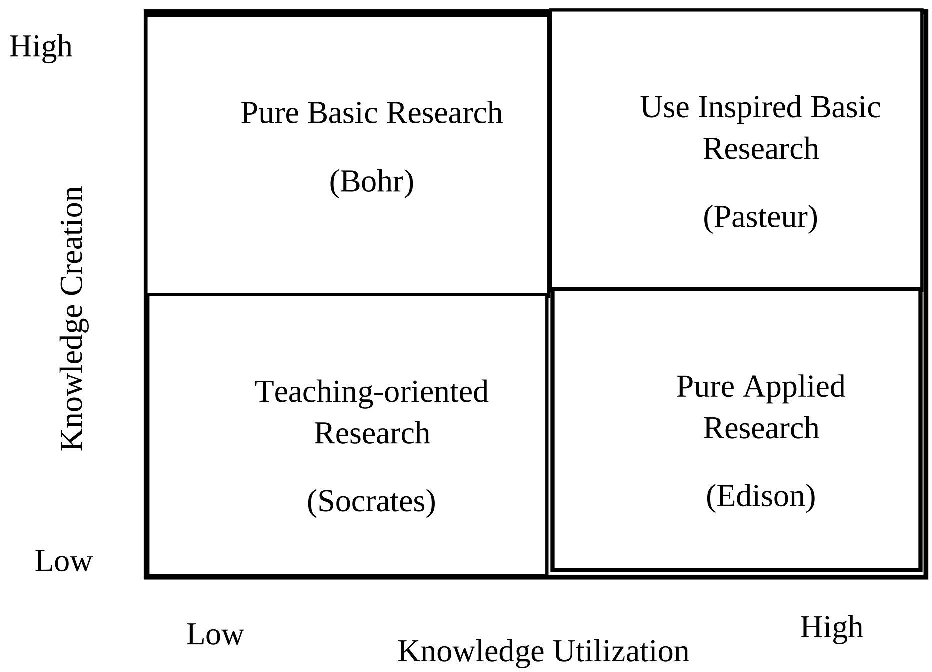

Figure 53 Pasteur's Quadrant *[178]*

Some commented on Stokes' model that although it has made a real transaction in the understanding of basic and advanced research, it only added complexity to the linear model. They claimed that the separation between basic and applied research is still present in Stokes' model, but in a multidimensional rather than in a linear way [180].

A later work, introduced a bidirectional interactive model of discovery and invention. In this depiction, it was pointed out that an invention could be a continuation of other inventions, as well as the result of creating new products. In a very interesting approach, innovation is described as an interlaced complex process in the model "discovery-invention cycle” which represented the interrelation between invention and discovery. Accordingly, ‘invention’ is defined as the creation of a new device that would serve a certain goal, or a new process through the accumulation of new knowledge. On the other hand, discovery is the finding of knowledge to better understand the world. Also mentioned: the process of knowledge movement in the presented knowledge cycle is what leads to successful innovation. Discovery and innovation are considered as mirror images of each other and are not isolated as two sides of a linear process. The model sets a modern understanding that better shapes the era of information, communication technologies and scientific development. [181].

5.4 University-Industry Interaction

Educational institutions and universities are pools of different types of research activities. To be able to integrate the efforts in universities with the industry, and direct them to social and community needs, it is necessary for collaboration between the educational institutes, industry and social organizations. De Fuentes et al indicated that collaboration is achieved through various channels and in many dimensions that differ according to the nature of the institution and the subject of knowledge [182].

There are different channels by which knowledge is transferred between industry and university. The importance and role of industry-university knowledge and technology transfer channels is addressed differently by different firms according to the nature of the industry and the technology [183]. The motives and benefits of collaboration channels differ between universities, research organizations and industry. Understanding the different motives and views towards the collaboration channels between university and industry plays an important role in understanding how to enhance those channels [182]. In the same scope, different scholars gave different degrees of importance to different types of knowledge transfer channels. For example, Narin et al. mentioned that “codified knowledge” in the form of publications and patents are of the most popular types of knowledge transfer channels [184]. While others like Kingsley et al. saw that mutual activities that involve research are more influential in transferring knowledge between universities and industries [185]. Some scholars pointed out that technology transfer between universities and industry is normally achieved through familiarities between both [186], while others gave importance to hiring university researchers in industry [187]. In the same reference it is mentioned that joint research between university scientist and industry is an indicator of the success of an industry firm and its incentive to gain knowledge. Cohen emphasized on the importance of university research on industrial research indicating that the university research sometimes is a driver to R&D and other times it is an initiator to new projects [188]. A paper by Bekkers et al. proposed a view about transfer channels between industry and university by conducting a survey on Dutch universities and industries. Looking at the firm’s side, the paper indicated that firms stated two kinds of knowledge transfer in order to achieve innovation: conducted research and cooperation, patents and listening. On a similar scope, the time and method of knowledge transfer is much related to the context and the field in which the knowledge is transferred. It is interesting to find out that the participation of universities and researchers through publications and conferences is a very common way to provide the industry with knowledge of the research being done in the universities. Another important knowledge source for the industry is the recruitment of master and PhD students [189]. In the work of Arza, the benefits of collaboration channels are divided into two main categories according to the perspectives of the educational organizations and the industry. Each dimension is further divided into two: The main benefits for the educational organizations are: economic and intellectual. While for the industry, the benefits are more proactive and passive in nature. This division leads to a four-dimension quadrant in which each research type can be characterized [190].

A very important point is: understanding the nature of interaction between universities, public research, R&D and production connects to the basic understanding of research. The traditional linear model suggested by Vannevar Bush puts many of the university research at the starting point isolated from technology developments. The new understanding of research by Stokes, then Gibson and Johnson, defines scientific knowledge not only as the information included in publications, but also the information transferred through formal relationships between universities and industry sectors [191]. Rosenberg pointed out that there has been neglect to the industry research, and emphasised on the importance of new care and attention to the university research [192]. Nelson and Von Hippel saw the relationship between different types of research as more interactive, where public research may lead to development of new technologies, or focus on industry problems [193]. Von Hippel also indicated that the source of innovation depends on the type of knowledge involved [194].

Technology achievements like the Apollo Flight to the moon did not appear instantaneously, but was advanced by years of scientific efforts and research which laid the basis for such achievements. In addition to the availability of accumulated expertise in the subject of research. The same applies to other technological inventions like the invention of the transistor in the 50's which really started with research about the solid state of matter in the 30's. Similar evolutions can be seen in renewable energy solutions in reaching more efficient methods and technologies to supply the energy demand and at the same time reserve the environment. Best solutions cannot be found overnight or when there is an urge to use them, but they should be backed up by efforts and research which would lead to the availability of accumulated expertise in related sciences [6].

Continuous research in renewable energy has to be coupled with production efforts in the area. This can be only done through supportive research and development initiatives gained from the right understanding of the role of research, and by initiating affective collaboration channels between university and industry.

A technological system is defined as "Network(s) of agents interacting in a specific technology area under a particular institutional infrastructure for the purpose of generating, diffusing, and utilizing technology" [195]. These approaches of implying channels both national and international participate in enriching the area of interest which is innovation in renewable energy. This agrees with Metcalfe, definition of a system of innovation which is:

> "*A system of innovation is that set of distinct institutions which jointly and individually contributes to the development and diffusion of new technologies,*

and which provides the framework within which government form and implement policies to influence the innovation process. As such is a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts which define new technologies" [196]

In a paper by S. Kyvik, et al, it is mentioned that the attention to applied research in universities is more than that to basic research [197]. This comes from both the research funding as well as institutional policies and academic and individual norms that give more value to applied work in that it leads to innovation. The writer emphasized that there is no clear line between both types of research works, and that research work incorporates both types of activities. He further argues that the distinction between basic and applied research in academic institutions, to some that do basic and other that perform applied research is against reality and that both types are inherited in any work. [197]. It is indicated that universities and research institutions play an active part in encouraging entrepreneurship by understanding research, how technology is transferred from universities to firms, and by setting new policies to go with this understanding [179].

To assess the importance and the kinds of collaboration channels between university and industry in the context of the current work, a questioner was conducted with the supervisor of the research. The questioner also looks at the stages of research and how the sources of knowledge for the present work were initiated.

5.5 Potential in University-Industry Collaboration.

According to the results of the questionnaire and the views of the personnel involved in the project, and related research in renewable energy control systems and in the Laboratory of Control Systems and Mechatronics:

The answer about the university industry collaboration pointed out to current collaboration in research and development of renewable energy through the following projects:

- Project 1: Development of an experimental hybrid wind-solar conversion system with battery storage using Opal-RT Real-Time HIL/RCP Laboratory in collaboration with OPAL-RT Technologies. The aim is to upgrade the OPAL-RT 0.2 KW electric drive system to offer further possibilities of conducting experiments in renewable energy systems.
- Project 2: Development of an interface based on National Instruments technologies for vibration detection to be analysed by data prediction software. The project is in collaboration with Machina Metrica Inc for bearing rolling elements applications.

Relating to the current collaboration channels at the university and research centre level on renewable energy development; there are two joint research projects with Royal Military College (university) and Techno Centre Eolien (not-for-profit organisation). The above comment indicates that research activities are common collaboration channels between university and industry as mentioned by Kingsley [185]. As well as industry collaboration channels, the university has collaboration with other universities and research centres which establishes a base for scientific research network and a system of innovation as defined by Mecalf [196]. The answers also show that joint research projects, and contracted research, are very popular forms of collaboration between the Lab and the industry. This coincides with the comments of De Fuentes at al, about the nature of collaboration channels according to the type of the institution and the area of knowledge [182]. It also correlates with Narin's work that mentioned "codified knowledge" transfer in the form of publications as being the most effective form of knowledge transfer [184]. Also with Pavit who highlighted the importance of different channels of cooperation between university and industry [183]. The type of projects in the university industry cooperation shows that research work can be derived from ideas to test or enhance current devises or methods, and this agrees with the concept of discovery-innovation cycle [181]. The answer to the question about the basic idea of the different projects pointed out that: the idea for the current project with the OPAL-RT technologies started after a discussion with a representative in a conference, and the idea for the project with Machina Metrica started through the industrial liaison office at SMU. The answers agree with the view of Kingsley that gave merit to mutual activities that involve research in transferring knowledge between universities and industries [185]. It also agrees with the opinion of Krahmer in that technology transfer can be achieved by mutual relations between the university and industry [186]. The concept of the bidirectional relation between discovery and invention in that one could be the source of the other, again agrees with the answer [181]. It can be seen that the idea of a research in many cases could start from a current project as mentioned by Elg [168].

The answer to the question about the relation of the current research to previous work pointed to the interaction between the stages of research. It was stated that the work on the solar PV and the hybrid energy system is a continuation of a previous work on wind energy conversion system conducted by the supervisor of the current project. This relates with Stokes understanding of research in the Pasteur's Quadrant. The comment also pointed out to the different and interactive motivations for research work. Research could be a continuation of previous work, a basic idea, or an enhancement of an existing product or service. It also agrees with the view of von Hippel and Nelson about the interaction of different types and stages of research [193], [194].

The comment on the links of the current and similar work to industrial applications mentioned that the cooperation links are present in two different scopes: the first is upgrading the Electric Drive Kit for applications in solar technologies and hybrid systems with the OPAL -RT Technologies. The second is providing a testing physical platform to test the prediction software for Metrica Inc. This shows that the results of research work can contribute to industry in different ways like testing or developing an exciting product. It also relates to the definition of "system of innovation by Metcalfe [196], and that such a system is created between the university, other universities and industries.

The answer about the nature of the research and other research work in the Lab suggested that most of the research work focuses on the development of new control systems and upgrading the existing. From comparing the position of the research with Pasteur's Quadrant, some of the research can be related with the work of Edison in the applied nature, and other research work resembles Pasteur's work. For example, the current project is directed towards the development of the existing device used in renewable energy research (OPAL_RT Lab), as well as the development of a smart intelligence control systems. It can be integrated in PV systems with DC loads like water irrigating systems and street lighting systems, or in the industry of training and experimental devices. Some of the projects have common characteristics from both Edison and Pasteur's work. It can be observed that in many areas including renewable energy and engineering, a research could contain both basic and applied work as indicated by Kyvik et al [197]. Also scientific and engineering disciplines may overlap with other sciences like mathematics and physics. Regarding the contribution of this research to the social needs or a practical industry, the comment indicated that the outcomes of the current research (OPAL-RT technologies and Machina) is directed to the development and improvement of the experimental device, test of a device, and to enlarge the field of application of the equipment. This would itself contribute to the developments in renewable and solar energy systems in creating solutions that would provide more efficient renewable energy alternatives. An important, social, economical and environmental need is provided with using renewable energy alternatives as discussed in chapters 1 and 2. Also the proposed control methods or their applications/developments could be used in PV systems. It is forecasted that the demand on renewable energy sources, realising the advantages of solar energy will highly increase in the future. This would make the industry of renewables one of the most growing among current and future industries [198].

It can be concluded that:

- There are good collaboration and knowledge sharing channels between the university and industry in the field of interest.

- There are established collaboration channels between the university and other universities and research centres in the field of renewable energies.
- Different types of collaboration and knowledge sharing are used like published works, joint events, and contracts.
- Collaboration between the university and other universities could be extended to establish a research network in renewable energies. Also more of the other forms of collaborating like published work and exchange of professionals could be extended.
- The idea generation for future and current research themes is very interesting. It fully considers the needs to further develop previous works to produce new solar and renewable energy technologies, or to enhance the operation of current technologies. The research in the area of renewable energy is part of a well studied sequence that would lead to applied results.
- A very important approach is deriving some of the research ideas from industry and current working systems and working to develop these systems. Developing and extending the scope of renewable energy research technologies, and testing and measurement like the work done on Opal RT Lab and Metrica are very important streams that contribute to development in the area of renewable energy.

Suggestions for further development on the current knowledge network and the collaboration channels between university and industry can be stated in the following:

- Extend the current knowledge and innovation network to include more research centres and universities.

- Expand the innovation network to the international level.
- Explore more variations of methods of knowledge transfer like patents, hiring PhD students and conducting research in industrial locations.

5.6 Conclusion

By analysing the university collaboration channels related to the current project, which include both the links to the industry and other institutions, the work in this chapter practically demonstrated the presence of university industry links in real settings. It also provided a guide to further improve and expand the opportunities in using channels of scientific collaboration in order to produce more innovative solutions in renewable energy and particularly solar energy.

Assessing the contributions of the current project and the position of the research work according to Pasteur's Quadrant by Stokes emphasised the practical nature of the research and the related work. Also it demonstrated the interaction between the different types of research work specially in scientific fields. This can be seen from the indication that a research idea can be basic or can be a development of an existing product. The way knowledge is interchanged and cooperation is held between industry and university shows the multi-directional nature of interaction between those two institutions. Summing up, the chapter provided an examination of the current work to assess the actual university industry collaboration channels and the relation of scientific research to innovation.

The next chapter, includes the general conclusion of the work in this dissertation. It also suggests future works related to the scope of the current dissertation.

Chapter 6

6 Conclusion

The control techniques developed and experimented in this work gave improved PV system power regulation. The developed algorithm and the fuzzy logic controller for maximum power point tracking, delivered more tracking speed, efficient maximum power tracking, and was able to result in more voltage boost. The use of the output signal from the fuzzy controller to trigger the value of the estimated reference maximum power, enhanced the power tracking ability, and extended the range of the maximum power. Using Sugeno fuzzy logic gave the advantage of strong computational capability and fast response. The incremental method to allocate the maximum power extended the range that can be reached in other algorithms. Using the developed PID fuzzy logic controller in the battery management operation provided fast reply to changing conditions and stable steady state response. It also simplified the tuning of variables. The choice of the membership functions was suitable to preserve stability and gave good description of the fast dynamics of the battery operation. The battery charge-discharge operation responded to the change in PV power and load demand in a swift and fast manner. From the results, it can be observed that the load current, voltage and power were stabilized at the required levels in the presence of fast changes and fluctuation. The use of cascaded loops both in the battery and the load controller improved the stability of the system and reduced the sensitivity to input fluctuations. Summing up, by the proposed methods and algorithms; the overall power control scheme of the system was able to track input variations, stay stable in the presence of fluctuations and minimize steady state error. Faster MPPT and battery control were achieved and the whole system response was stable.

The proposed method has evident importance in solar energy systems, specially isolated systems, where it is very important to control the power distribution and to provide maximum power in conditions that could be very instable. The methods can be used to give improved results in areas like: rural areas energy supplies, irrigation, solar vehicles, space systems, street light, drones and others. The suggested control algorithms could also be applied in grid connected PV systems and other renewable systems with minor modifications. The simulation and hardware implementation of the algorithm in real time tested the system and the controller in real conditions with actual hardware equipment and experimented the performance in uncertainties and variations.

The importance of using alternative energy including solar energy solutions calls for more research in the field to develop more efficient systems. The potential in university industry collaboration channels is very high in enhancing research and development. Through university industry collaboration channels, different forms of knowledge are transferred from the university to the industry and vice versa which would enable the transfer of research into innovation. Investigating the current university industry collaboration channels and the applications of the current projects contributes in putting future development plans for other similar work. It can be used as a guide to lay out strategies for collaboration between industry, university and other universities and research institutes in other areas. Understanding the type of research work and the degree of contribution to the industry or social need sets a director on how to choose work areas for similar disciplines. It also demonstrated the position of research in Pasteur's Quadrant and the interactive nature of the research.

In this dissertation both the development of the scientific real time control methods, and the investigation of the context and contribution of the work was studied which adds an important contribution in two directions: development of smart algorithms in PV systems, and investigating the innovative characteristics in the current project. The work has both the features of a scientific experimental work and presents a study of ways to integrate scientific research and production, which contributes to strengthen the links between university research and industry needs.

6.1 Suggestions for Future Work

Applying intelligent algorithms is a promising area of research in PV system operation and other renewable energy systems. Future work can include the use of other smart technologies in real time simulation experiments like genetic algorithms and neural networks. Hybrid method applications that combine two control methods for the MPPT can also be applied. Using optimization and mathematical algorithms like the Gaussian Newton's and singular perturbation methods together with smart and conventional control methods in MPPT tracking and battery operation control is another area to be investigated. The above mentioned work could be applied to PV stand-alone systems, hybrid systems, isolated or grid connected. It also could be experimented with other solar cell technologies, or different kinds of storage devices. Future work could consider the state of charge of the battery in the battery charge- discharge control. Also minimization the number of IGBT s could be investigated by the combination of the load control power and the MPPT function in one IGBT by using smart technologies.

Studying the current status of innovation and university industry collaboration channels in renewable energy in Nova Scotia context would be an interesting scope. By understanding the current statust of cooperation between universities and industry in NS in renewable energy industries, the difficulties and challenges can be assessed. This would provide the reference for setting improvement plans for more productive university industry collaboration methods in the field of renewable energies.

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Appendix A

Acronyms and Abbreviations

AC	Alternating Current
ANFIS	Adaptive Neural Fuzzy Interface System
CoA	Centre of Areas
DC	Direct Current
DSSC	Dye Synthesised Solar Cells
FLC	Fuzzy Logic Controller
GA	Genetic Algorithms
HC	Hill Climbing
HIL	Hardware in the Loop
IGBT	Insulated Gate Bipolar Transistor
MIMO	Multi Input Multi Output
MF	Membership Function
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
PD	Proportional-Derivative
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
P&O	Perturb & Observe
PSO	Particle Swarm Optimization
PV	Photovoltaic

PWM	Pulse Width Modulation
SISO	Single Input Single Output
SVD	Singular Value Decom Position
TG	Temperature Gradient

Appendix B

Specifications of the Hardware Parts

A. Specifications of Solar PVECS

Variable irradiation = 600 to 800 W/m^2

Optimum operating voltage of PV modules = 30.4 V