Intelligent Algorithms for a Hybrid Fuel Cell/Photovoltaic Standalone System

SYED FAWAD ALI SHAH

May 12, 2010

Master’s Thesis
Computer Engineering

Nr: E3616D
DEGREE PROJECT
COMPUTER ENGINEERING

Programme
Master of Science in Applied Artificial Intelligence

Reg. number
E3616D

Extent
15 ECTS

Name of student
SYED FAWAD ALI SHAH

Supervisor
Pascal Rebreyend

Year-Month-Day
2010-05-12

Examiner
Mark Dougherty

Company/Department
Högskolan Dalarna

Supervisor at the
Company/Department
Pascal Rebreyend

Title
Intelligent Algorithms for a Hybrid Fuel Cell/Photovoltaic Standalone System

Keywords

Abstract:

The Intelligent Algorithm is designed for the Hybrid Fuel Cell and Photovoltaic Cell while using a Battery source. The main function is to automate the Hybrid System through an intelligent Algorithm so that it takes the decision according to the environmental conditions for utilizing the Photovoltaic/Solar Energy and in the absence of this, Fuel Cell energy is used. To enhance the performance of the Fuel Cell and Photovoltaic Cell we used battery bank which acts like a buffer and supply the current continuous to the load.

To develop the main System which could do these intelligent automation decisions, fuzzy logic based controller was used. Fuzzy Logic based controller used to develop this system, because they are chosen to be feasible for both controlling the decision process and predicting the availability of the available energy on the basis of current Photovoltaic and Battery conditions.

The Intelligent Algorithm is designed to optimize the performance of the system and to select the best available energy source(s) in regard of the input parameters. The enhance function of
these Intelligent Controller is to predict the use of available energy resources and turn on that particular source for efficient energy utilization. A fuzzy controller was chosen to take the decisions for the efficient energy utilization from the given resources. The fuzzy logic based controller is designed in the Matlab-Simulink environment. Initially, the fuzzy based rules were built. Then MATLAB based simulation system was designed and implemented. Then this whole proposed model is simulated and tested for the accuracy of design and performance of the system.
Acknowledgement:

With the will and the help of my Lord, Almighty ALLAH i am gratitude and thankful with the depth of my heart for giving me the courage and strength. He gave me strength to complete the goals of this project work.

Thanks to my whole family, especially my lovely parents , by their prayers and well wishes and waiting for me desperately back in Pakistan during my stay abroad, encouraged and supported me every time I needed it. They have always been motivational and have great confidence in myself and always showed me the right path of life to follow.

I obliged all my professors Hasan Feleyh, Yerker, Dr. Mark Dougherty, Seril Yeila and especially my Thesis Supervisor Pascal Rebreyend whose knowledge and guidance for understanding was paramount in the realization of my Thesis objectives and kept me motivated.

I’ll also like to thank the Studera.nu and Swedish Government who gave me this chance to come to Sweden and helped me to earn this degree which is a milestone in my life, also the sweet and helpful Swedish people for their hospitality.

At the end I will also like to thanks all my friends and well wishers who have been supportive with me all the time and never felt me away from my family and home. At the end I would especially like to thank Mr. Atif Ali Khan, who gave me good advices for the development of “Intelligent Algorithms for a Hybrid Fuel Cell/Photovoltaic Standalone System”.
With the depth of my heart

Dedicated

To

MUHAMMAD ALI JINNAH

(1876-1948)

(Founder of PAKISTAN)

“Few individuals significantly alter the course of history. Fewer still modify the map of the world. Hardly anyone can be credited with creating a nation-state. Muhammad Ali Jinnah did all three”

(Stanley Wolpert)
# Table of Contents

1. **Introduction** ................................................................................................................. 11

   1.1 Problem Overview ........................................................................................................ 12

   1.2 Problem Definition ....................................................................................................... 12

   1.3 Brief Description of Thesis Work .............................................................................. 12

   1.4 Goals and Objectives ................................................................................................. 14

   1.5 Literature Study and Previous Work ....................................................................... 14

2. **Solar Cell / Photovoltaic Cell** .............................................................................. 16

   2.1 Introduction .............................................................................................................. 16

   2.2 Average Solar Energy on the Earth Surface .......................................................... 17

   2.3 Incident Solar Energy on the ground ...................................................................... 17

   2.4 Photovoltaic Energy Production ............................................................................. 19

   2.5 Uses of Solar Energy .............................................................................................. 20

       2.5.1 Heat Energy ........................................................................................................ 20

       2.5.2 Photovoltaic Energy ...................................................................................... 20

           2.5.2.1 Silicon ..................................................................................................... 20

   2.6 Photovoltaic Cell .................................................................................................... 21

       2.6.1 Diffused Horizontal Irradiance .................................................................... 23

       2.6.2 Direct Normal Irradiance ........................................................................... 23

       2.6.3 Azimuth Angle ............................................................................................ 23

3. **Fuel Cell** .................................................................................................................. 24

   3.1 Introduction .............................................................................................................. 24

       3.1.1 Types of Fuel Cell ...................................................................................... 26
3.1.1.1 Polymer Exchange Membrane FC (PEMFC) ............... 26
3.1.1.2 Solid Oxide Fuel Cell (SOFC) ........................... 26
3.1.1.3 Alkaline Fuel Cell (AFC) .................................. 26
3.1.1.4 Molten-Carbonate Fuel Cell (MCFC) .................. 27
3.1.1.5 Phosphoric-Acid Fuel Cell (PAFC) ...................... 27
3.1.1.6 Direct-Methanol Fuel Cell (DMFC) ..................... 27

3.1.2 Chemistry of Fuel Cell........................................... 28

4. Battery .......................................................................................................................... 29

4.1 Introduction .............................................................................................................. 29
4.2 Battery Charge/Discharge ..................................................................................... 29
4.3 Battery Capacity ...................................................................................................... 30
4.4 Battery Life .............................................................................................................. 30
4.5 Battery Ratings ........................................................................................................ 31
4.6 Battery Sizing .......................................................................................................... 31
4.7 Battery Interconnect Wiring .................................................................................. 31
4.8 Battery Storage ....................................................................................................... 32
4.9 Battery Protection/ Safety ...................................................................................... 33

5. Algorithm Design ....................................................................................................... 34

5.1 Introduction .............................................................................................................. 34
5.2 Block Diagram ........................................................................................................ 34
5.3 Main Algorithm ...................................................................................................... 35
5.4 Explanation .............................................................................................................. 39

6. Fuzzy Logic .................................................................................................................. 40

6.1 Fuzzy Logic .............................................................................................................. 40

Dalarna University
Röda vägen 3
S-781 88 Borlänge
Sweden
6.2 Why to Use Fuzzy Logic........................................................................................................42

6.3 Fuzzy Rules..................................................................................................................................43

7. Result and Analysis..........................................................................................................................46

7.1 Simulation Results.........................................................................................................................46

7.1.1 PC Generation Graph........................................................................................................47

7.1.2 Solar Radiation Graph.........................................................................................................48

7.1.3 PV T Surface Graph...........................................................................................................49

7.1.4 Power Supply Graph...........................................................................................................49

7.1.5 PV Efficiency Graph..........................................................................................................50

7.1.6 Battery Graph....................................................................................................................51

7.1.7 FC Graph..........................................................................................................................51

7.2 Fuel Cell & PC Consumption....................................................................................................52

7.3 Analysis........................................................................................................................................52

8. Conclusion and Future Recommendations..................................................................................53

8.1 Conclusion.....................................................................................................................................53

8.2 Future Recommendations...........................................................................................................53

9. References.......................................................................................................................................54

10. Reference for Picture and Graph..................................................................................................55
List of Figures:

Figure 1: The Sun ................................................................. 17
Figure 2: Incoming Solar Radiation ................................. 17
Figure 3: World Energy Consumption .......................... 19
Figure 4: World Electricity Generated by Fuel .......... 19
Figure 5: Molecular structure of Silicon ......................... 22
Figure 6: Working of a Photovoltaic Cell ....................... 22
Figure 7: Band Gaps and Efficiency of Different Materials used for Solar Panels .......... 23
Figure 8: Measure of Azimuth Angle ............................ 24
Figure 9: Working of a Fuel Cell ..................................... 25
Figure 10: Battery Box for a Fuel Cell ......................... 30
Figure 11: Two 6-volt batteries in series provide 350 amp-hour capacity at 12 volts ........ 32
Figure 12: Two 6-volt batteries in parallel provide 700-amp-hour capacity at 6 ...... 33
Figure 13: Two sets of two 6-volt batteries wired in series-parallel provide 700-amp-hour capacity at 12 volts ................................................................. 33
Figure 14: Solar Gel Battery Bank ................................ 33
Figure 15: On Left: Catastrophic battery DC safeties fuse. In Centre: Large size of 15-amp DC circuit breaker. On Right: A standard 15-amp AC circuit breaker .... 34
Figure 16: Block Diagram of Hybrid System ................. 35
Figure 17: Linguistic Variable “tall” in Fuzzy Logic ........ 41
Figure 18: (above) Conventional Logic (below) Fuzzy Logic ........................................... 42
Figure 19: Two-valued and Multivalued Logic ............... 43
Figure 20: Binary vs. Fuzzy Logic ................................. 43
Figure 21: Input and output Graphs ............................. 47
Figure 22: Month wise PC Energy generation Graph .... 48
Figure 23: Solar Radiation Graph ................................. 49
Figure 24: Photovoltaic T Surface Graph ...................... 50
Figure 25: Power Supply Graph ................................... 51
Figure 26: PV Efficiency Graph .................................... 51
Figure 27: Battery Consumption Graph ....................... 52
Figure 28: Fuel Cell output Graph ............................ 52
List of Tables:

Table 1: PC Materials & Efficiency..........................................................................................23
Table 2: Types of FC and their Efficiency................................................................................26
1. Introduction

With the passage of time World’s population is rapidly growing and to provide them with the sufficient energy for their needs, we have wasted allot of Earth’s natural resources, which are quite expensive and harmful and are the cause of green house effect. By considering the renewable energy resources the most abundant and economical resource is solar energy also know as photovoltaic energy. The solar radiations are used and can be implemented universally as the alternate of the conventional energy resource.

The sun is the earth’s primary source of radiant energy. A significant portion of the radiant energy from the sun actually gets converted to other forms of energy once it reaches the earth. For example, the process of photosynthesis by plants converts the radiant energy from the sun to chemical energy. Both the atmosphere and the surface of the earth absorb large portions of the sun’s radiant energy and convert it to heat. [1]

Solar radiations can be subdivided in two parts, Sunlight converts into electricity/photovoltaic current and residual as heat energy as usable form. Photovoltaic current as the renewable energy is the most efficient and economical form of energy. The operational cost of the installed system is once (although expensive at time of installation) and it may provide energy for years.

Hybrid systems are considered as the dynamical systems that are involved with the interaction of different types of system. Usually hybrid systems are the combination of more than two different types of systems or subsystems. They have identical use for a specific domain and have common tasks to accomplish. Hybrid systems make the whole process fast and efficient; also can be unique and impressive for users into some specific domain.

The main idea behind our research is to make an intelligent hybrid system which could use photovoltaic cell and fuel cell according to the system demand and somehow it could save the photovoltaic cell and fuel cell energy intelligently, by applying some intelligent algorithms. The system is designed and simulated so that all the testing should be done before the physical development process. All the operational processing time and system stability can be measured by this way.

Dalarna University
Tel: +46 (0)23 77 80 00
Röda vägen 3
Fax: +46 (0)23 7780 80
S-781 88 Borlänge
Sweden
1.1 Problem Overview:

The energy crisis is a huge problem in today’s world were all the natural resources of energy are diminishing rapidly and are expensive too use, for considering this hard fact we should be utilizing alternative renewable energy resources. For that solar energy is the best available source of abundant energy which can be utilized to meet the whole World demands.

Solar energy is clean and free, as we are concerned with the solar energy also named as photovoltaic energy, photovoltaic cells provides energy from solar panels for powering up some system or connected load, we are also know about the fact that the photovoltaic energy depends upon the some certain conditions (solar radiant energy, longitude, latitude, tilt angle of solar panels, weather conditions and solar plates).

1.2 Problem Definition:

Our main goal is to save as much fuel cell as we can in a PV/FC hybrid system by designing any intelligent controller that make decision on the basis of available solar energy, load, battery & time to turn on or off the fuel cell. Intelligent controller should be able to take decision intelligently on different parameters like availability of PV Energy, Variation in load, different battery conditions & time. Intelligent controller must be able to save battery by turning on the fuel cell early before the night start and turned off the fuel cell by fulfilling the load requirement from battery and letting the battery to reach its lower threshold level before the day start so that battery can be fully recharged in the presence of PV energy during day timing. Also simulate this system to analyse its performance.

1.3 Brief Description of Thesis Work:

The hybrid system for photovoltaic and fuel cell uses battery as buffer and intelligent fuzzy controller for making the decisions, for providing the continuous power supply to the load. There have been many hybrid systems which provide continuous flow of the current, but there is not specific description for the holding and distribution of available current management. The main and unique description in this research work is to make an intelligent controller...
which could make decisions for uninterrupted power supply as well as decisions to save particular source of energy. This unique ability addresses the concept to save the cost of Fuel cell and battery at some certain stage, where there it can be saved by utilizing alternatives. Fuzzy logic is used for developing an intelligent controller because; Fuzzy logic can deals with real-time systems having volatile, an imperfect environment of highly variable, or with unpredictable conditions. It generates the optimal solution where it deals with imprecise or vague data.

For developing the system an intelligent algorithm was designed and tested which works on the mentioned principle. The main philosophy of this system is to save fuel cell by turning it off, when it has buffered battery and photovoltaic energy will start in the near future. In viewing the other conditions, for saving the battery for upcoming night, we starts or keep fuel cell on so that battery could be saved for the future load management.

All these intelligent decisions which could help in saving the fuel cell or battery in the presence or absence of photovoltaic energy are managed by the intelligent fuzzy controller. This controller is responsible of making decisions by using certain set of rules. These rules are fired while some specific conditions are met; in response of this information flow from the fuzzy controller all the responsive units perform their specific tasks.

The control scheme running in the hybrid fuel/photovoltaic cell intelligent controller consists of three main control components:

- Fuel Cell control switch
- Battery control
- Load management

The main control strategy of hybrid fuel/photovoltaic system is to provide the photovoltaic energy to the load whenever it is available. In absence of the photovoltaic energy, system is powered up by available battery buffer and available fuel cell. System composed of the fuel cell is used to control and save fuel cell cost when there is alternative available. Battery control keeps the battery available for load while fuel cell can be saved and keeps the battery discharge, although the battery is critical or above critical threshold, by keeping this fact in
view for upcoming solar productions. Load management is to utilize the optimal source of available energy while considering the load behaviour.

1.4 Goals and Objectives:

To deal with this Hybrid Fuel/photovoltaic system, a lot of controls techniques may be used to provide the uninterrupted power to the system, but to deal with the optimal use of the available energy by considering management of these resources in respect of resource, operational cost and energy saving. These problems make it difficult to design such a system where we could utilize hybrid system using these intelligent operational decisions. The basic goal of my thesis work was to design an intelligent algorithm which takes these optimal decisions for saving the fuel cell cost and battery storage. For this purpose fuzzy logic based controller is used. The fuzzy controller is chosen to be feasible in such conditions where real time systems are involved and we have to deal with imprecise or vague data.

This thesis work investigates fuzzy based technique for developing a hybrid system using an intelligent controller. It includes design and simulation of Mamdani controller. The fuzzy logic based controller is designed in the Matlab-Simulink environment. The MATLAB based simulation system is designed and implemented. The proposed model is thoroughly tested for the accuracy of designed algorithm and performance analysis of controller through simulations.

1.5 Literature Study and Previous Work:

There were many different kinds of hybrid systems developed and designed in past, using an intelligent controller with fuel cell, photovoltaic cell and battery hybrid system were not developed before.

Lian Dibo, Feng Xiaoyun, Li Shuichang, GU Bochuan [4] studied the dynamical control of fuel cell and battery hybrid system to supply a frequently changing load. This main study of this paper is to combine a fuel cell and battery in pulse load conditions. Józef PASKA, Piotr BICZEL [5], developed a standalone hybrid solar-wind power plant for supply of
telecommunication equipment. For providing the continuous supply to the said system in
different weather condition was a huge task, for that purpose Hydrogen fuelled fuel cells were
used.
Each one has different topology, but fuel cell, battery and DC/DC are the main parts. The key
point in hybrid system is how to control the power flow in the right way to meet the
requirement of the load.

LI Wei, ZHU Xin-jian, CAO Guang-yi[6]. Their research describes a solar photovoltaic/fuel cell
hybrid generation system consisting of a photovoltaic (PV) generator. The current is supplied
to the load from the PV generator with a fuel cell working in parallel. When there is
excessive PV energy it is converted to hydrogen using an electrolyser, Later this produced
hydrogen is used in the fuel cell as fuel for producing current.
2. Solar Cell / Photovoltaic Cell

2.1 Introduction:

Basics of Solar Energy

Solar Energy is clean and totally free. It is continuous enough for everyone and will not run out. The sun is always producing a lot of energy because of the chemical reaction and explosions on Sun’s surface. Sun has been producing continuous energy in the form of Sunlight and heat since GOD has created the whole solar system. The energy balance in the atmosphere can be shown through the following diagram.

![Fig. 1: The Sun](image)

![Fig. 2: Incoming Solar Radiation](image)
Following are the main components in the above diagram [2/7]:

- Short wavelength (optical wavelengths) radiation from the Sun reaches the top of the atmosphere.
- 17% radiations are reflected back into space from clouds. Cloudier the climate is, the more radiation will be reflected back and less will reach to the surface of the earth.

8% radiations are scattered backwards due to the presence of air molecules.
6% is directly reflected back off the Earth’s surface into space.
So the 31% is the total reflectivity of the earth, which is technically known as an Albedo.

The rest of 69% of the incoming radiation that doesn't get reflected back:
In the upper atmosphere 19% radiations gets absorbed directly by dust, ozone and water vapors.
The 4% radiations get absorbed by clouds located in the troposphere.
The remaining 47% of the sunlight, which incident on top of the earth's atmosphere reaches the Earth surface.

2.2 Average Solar Energy on the Earth Surface:

Energy is measured in units of Watt/hours. A watt is not a unit of energy, but it is a measure of power. So the Energy equation could be

\[ \text{ENERGY} = \text{POWER} \times \text{TIME} \]

Where, 1 Kilowatt Hour (1KWH) = 1000 watts used in one hour, and 1000 watts means lighting up 10 bulbs of 100 watt for an hour.

2.3 Incident Solar Energy on the ground:

- Incident Solar energy on the Average basis over the entire earth is equal to 164 Watts per square meter over a period of 24 hours a day. It means that the entire planet receives about 84Tera-watts of Power, while the current average worldwide total consumption is about 13.5Tera-watts. So by considering this fact, if we start using only solar energy, so that 70.5Tera-watts still remains after meeting up worldwide
total energy consumption and it can still meet the challenges of the upcoming energy consumption growth.

![Increase in World energy consumption](image1)

**Fig. 3: World Energy Consumption**

![Figure 54. World Electricity Generation by Fuel, 2005-2030](image2)

**Fig. 4: World Electricity Generated by Fuel**
2.4 Photovoltaic Energy production:

Considering on a summer day of 8 hours, at the latitude of $(40^\circ)$ the solar energy produced is equal to 600 Watts per square meter.

So over this period of 8 hours day one can receive:

- $8 \times 600 = 4800$ watt-hours per square meter, which is equal to 4.8 kilowatt hours per square meter
- This amount of energy is equivalent to the 0.13 gallons of gasoline
- For considering the above calculations if we have 1000 square feet of horizontal area (typical roof area) the amount of energy is produced about 450 KWH, which is equivalent to 12 gallons of gasoline.

Under optimum conditions, one can achieve fluxes as high as 1000 Watts per square meter

Now considering a sunny day in the winter at the latitude $(40^\circ)$ the solar energy produced is equal to 300 Watts per square meter. The roof receives the illumination for about 6 hours.

So over this period of 6 hours day one can receive is:

- $6 \times 300 \times 100 = 180$ KWH (per day)
- Assume that the roof top will receive about 6 hours of illumination on the area of 100 square meters (about 1100 square feet).

In the winter the sun is lower in the sky, considering the location at 40 degrees latitude, the average flux is received about 300 Watts per square meter

The efficiency of the solar panels so far achieved is indicated below:

- If the efficiency is 5% total energy is produced at the rate of 9 KWH per day
- If the efficiency is 10% total energy is produced at the rate of 18 KWH per day
- If the efficiency is 20% total energy is produced at the rate of 36 KWH per day
2.5 Uses of Solar Energy:

The solar energy can be used into two forms

- *Heat Energy*
- *Photovoltaic Energy*

**2.5.1 Heat Energy:**

A small part of solar energy is converted into heat energy. Solar Collectors are used to collect the sunlight and convert it into the heat, which is used for heating the houses and water from Sun’s energy. The incident solar radiations falls over the Earth’s surface and keeps the Earth warm, causes evaporation when incident on water and can be used according to the requirement. Heat energy from the solar radiation are collected over the flat plate collector for direct heating of water circulation system and may also be used in different systems.

**2.5.2 Photovoltaic Energy:**

Solar radiations are directly converted from solar photons into electrons through some semi-conductor, when the photons strike on a metal, their energy is used to liberate the loosely bound electrons in that metal and a stream of these loosely bound electrons starts inducing an electric current. The efficiency of the current depends upon the material on which the photons strike. So far the average efficiency is measured as 10% while the research is underway and in some advanced materials is developed and the efficiency has reached up to 20%.

**2.5.2.1 Silicon:**

Silicon is considered to be the most effective and economical material for photovoltaic effect. It is a good conductor of electricity and readily available in the crust of Earth and manufactured in bulk at reasonable cost. It has four outer (valence) electrons which bond silicon atoms together in the form of a crystal. Following diagram shows the structure of a silicon molecule.
2.6 Photovoltaic Cell:

Solar Cells also known as Photovoltaic (PV) cells (Photo means “Light” and Voltaic means “Electricity”) it converts sunlight directly into electricity. When these cells are connected together in the form of Array, they are called Solar Panels. When the sunlight falls over the solar panels the freely moved electrons get energy and starts flowing through some semiconductor, the best available material for these semiconductors is known as Silicon. Mostly single-crystal silicon is frequently used in photovoltaic cells but it is not the only material, Polycrystalline silicon is also another material for reducing the manufacturing cost.

The Second-generation of solar cell technology is consists of Thin-film solar cells. They are very cheaper in production and simple to use also very efficient as well. A thin-film solar cell has no crystalline structure, such an example of these materials is amorphous silicon (gallium arsenide and cadmium telluride and copper indium diselenide).

To increase the efficiency of Solar panels another strategy used which consist of two or more layers of the different materials which have different band gaps. The main idea is to
stack the high-energy photons of higher band gap material on the surface, while allowing the lower-energy photons to be absorbed by the lower band gap material beneath). These cells, called multi-junction cells have much higher efficiencies and have more than one electric field. [7]

<table>
<thead>
<tr>
<th>Material</th>
<th>Level of efficiency in % Lab</th>
<th>Level of efficiency in % Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline Silicon</td>
<td>approx. 24</td>
<td>14 to 17</td>
</tr>
<tr>
<td>Polycrystalline Silicon</td>
<td>approx. 18</td>
<td>13 to 15</td>
</tr>
<tr>
<td>Amorphous Silicon</td>
<td>approx. 13</td>
<td>5 to 7</td>
</tr>
</tbody>
</table>

[8]

Table 1: PC Materials & Efficiency

Above table shows that, the material used for solar panels have different level of efficiency. Monocrystalline Silicon has much more efficiency (14-17 %) than the Polycrystalline Silicon (13-15 %) and Amorphous Silicon (5-7 %).

Following Diagram shows the different band gaps and their efficiency relating to the material used for solar panels.

Fig. 7: Band Gaps and Efficiency of Different Materials used for Solar Panels.

Following are the main parameters to calculate the solar radiation.
2.6.1 Diffuse Horizontal Irradiance

Diffused Horizontal Irradiance is the amount of radiation falls over the surface per unit area. That is not a direct radiation from sun but also it is scattered by atmosphere which has molecules and particles.

2.6.2 Direct Normal Irradiance (DNI)

DNI is the amount of solar radiation which is received per unit area by a perpendicular surface, directed towards the Sun rays coming in a straight line. Amount of irradiance can be increased by keeping a surface to normal for incoming radiation. The quantity of DNI is of particular nature which concentrating solar thermal installations and installations that track the position of the sun.

2.6.3 Azimuth Angle

The azimuth angle $\varphi$ is the angle used for measuring the solar radiation falls over a horizontal plane from south to the horizontal projection of the sun's rays. [9]

![Diagram of Azimuth Angle](image)

Fig. 8: Measure of Azimuth Angle.

The sun's azimuth, $\varphi$, is given by the relation:

$$\cos \varphi = \frac{1}{\cos \beta} \left( \cos d \sin l \cos h - \sin d \cos l \right)$$
3. Fuel Cell

3.1 Introduction:

Fuel cells are known as electrochemical devices which converts the chemical energy of a reaction directly into the electrical energy. They use different types of liquid fuels or gases are used for chemical reactions (hydrogen, methyl alcohol, hydrazine, or a simple hydrocarbon). When the fuel is reacted with Oxygen (O\(_2\)) electrons are released through electrolytic chemical reaction.

Mostly in fuel cells Hydrogen (H\(_2\)) is used as fuel, it has many advantages, it is environment friendly, readily available and manufactured and the byproduct of the Hydrogen (H\(_2\)) is water (H\(_2\)O). The ideal standard potential (E) of H\(_2\)/O\(_2\) fuel cell is about 1.22 volts with liquid water product.

During the chemical reaction the irreversible losses of actual cell potential is lower than its equilibrium potential. So for a fuel cell these losses results in a cell voltage (V) which is less than its ideal potential. So the equation will be as below.

\[ E (V = E - \text{Losses}) \]

Fuel Cells (FC) are the chemical device which produces DC (direct current) voltage. It can be used directly and also converted to AC (Alternate Current) through the invertors which can be used for powering up the small appliances to the bigger plants. Performance of FC depends upon the electrolyte they use and the operating temperature depending upon the fuel used. Best performance is attained where the operating temperature is low. Higher the operating temperature means that late generation of electricity, lower the operating temperature means electricity will generate bit quicker.
Following Table shows the types of Fuel Cell and its corresponding values.

<table>
<thead>
<tr>
<th>Fuel cell name</th>
<th>Electrolyte</th>
<th>Qualified power (W)</th>
<th>Working temperature(°C)</th>
<th>Efficiency (cell)</th>
<th>Efficiency (system)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal hydride fuel cell</td>
<td>Aqueous alkaline solution</td>
<td>&gt; -20 (50 % P peak @ 0°C)</td>
<td></td>
<td></td>
<td></td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Electro-galvanic fuel cell</td>
<td>Aqueous alkaline solution</td>
<td>&lt; 40</td>
<td></td>
<td></td>
<td></td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Direct formic acid fuel cell (DFAFC)</td>
<td>Polymer membrane (ionomer)</td>
<td>&lt; 50 W</td>
<td>&lt; 40</td>
<td></td>
<td></td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Zinc-air battery</td>
<td>Aqueous alkaline solution</td>
<td>&lt; 40</td>
<td></td>
<td></td>
<td></td>
<td>Mass production</td>
</tr>
<tr>
<td>Microbial fuel cell</td>
<td>Polymer membrane or humic acid</td>
<td>&lt; 40</td>
<td></td>
<td></td>
<td></td>
<td>Research</td>
</tr>
<tr>
<td>Upflow microbial fuel cell (UMFC)</td>
<td>Polymer membrane (ionomer)</td>
<td>&lt; 40</td>
<td></td>
<td></td>
<td></td>
<td>Research</td>
</tr>
<tr>
<td>Regenerative fuel cell</td>
<td>Polymer membrane (ionomer)</td>
<td>&lt; 50</td>
<td></td>
<td></td>
<td></td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Direct borohydride fuel cell</td>
<td>Aqueous alkaline solution</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td>Commercial</td>
</tr>
<tr>
<td>Alkaline fuel cell</td>
<td>Aqueous alkaline solution</td>
<td>10 – 100 kW</td>
<td>&lt; 80</td>
<td>60–70%</td>
<td>62 %</td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Direct methanol fuel cell</td>
<td>Polymer membrane (ionomer)</td>
<td>100 mW – 1 kW</td>
<td>90–120</td>
<td>20–30%</td>
<td>10–20%</td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Reformed methanol fuel cell</td>
<td>Polymer membrane (ionomer)</td>
<td>5 W – 100 kW</td>
<td>250–300 (Reformer) 125–200 (PBI)</td>
<td>50–60%</td>
<td>25–40%</td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Reformed methanol fuel cell</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct-ethanol fuel cell</td>
<td>Polymer membrane (ionomer)</td>
<td>&lt; 140 mW/cm²</td>
<td>&gt; 25 ? 90–120</td>
<td></td>
<td></td>
<td>Research</td>
</tr>
<tr>
<td>Proton exchange membrane fuel cell</td>
<td>Polymer membrane (ionomer)</td>
<td>100 W – 500 kW</td>
<td>50–120 (Nafion) 125–220 (PBI)</td>
<td>50–70%</td>
<td>30–50%</td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>RFC - Redox</td>
<td>Liquid electrolytes with redox shuttle and polymer membrane (ionomer)</td>
<td>1 kW – 10 MW</td>
<td></td>
<td></td>
<td></td>
<td>Research</td>
</tr>
<tr>
<td>Phosphoric acid fuel cell</td>
<td>Molten phosphoric acid (H₃PO₄)</td>
<td>&lt; 10 MW</td>
<td>150-200</td>
<td>55 %</td>
<td></td>
<td>40% Co-Gen: 90 %</td>
</tr>
<tr>
<td>Molten carbonate fuel cell</td>
<td>Molten alkaline carbonate</td>
<td>100 MW</td>
<td>600-650</td>
<td>55 %</td>
<td></td>
<td>47 %</td>
</tr>
<tr>
<td>Tubular solid oxide fuel cell (TSOFC)</td>
<td>O²-conducting ceramic oxide</td>
<td>&lt; 100 MW</td>
<td>850-1100</td>
<td>60–65%</td>
<td>55–60%</td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Protonic ceramic fuel cell</td>
<td>H⁺-conducting ceramic oxide</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct carbon fuel cell</td>
<td>Several different</td>
<td>700-850</td>
<td>80 %</td>
<td>70 %</td>
<td></td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Planar Solid oxide fuel cell</td>
<td>O²-conducting ceramic oxide</td>
<td>&lt; 100 MW</td>
<td>850-1100</td>
<td>60–65%</td>
<td>55–60%</td>
<td>Commercial/Research</td>
</tr>
<tr>
<td>Enzymatic Biofuel Cells</td>
<td>Any that will not denature the enzyme</td>
<td>&lt; 40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Types of FC and their Efficiency
3.1.1 Types of Fuel Cell:

There are many types of fuel cells which are classified according to their operating temperature, electrolyte used, fuel and which kind of chemical reaction takes place. Each FC has its own advantages, potential and limitations which classifies them in different categories.

Most commonly used FCs’ are as follows.

3.1.1.1 Polymer Exchange Membrane Fuel Cell (PEMFC)

This type of FC normally operates on low temperature around 50 - **100°C** which allows them to start up quickly. They have fast startup time; they are very favorable in terms of power-to-weight ratio and also have low sensitivity to orientation. The PEMFC are considered to be very suitable for the use in passenger vehicles, like cars and buses. Typically pure hydrogen is used as fuel which is supplied from storage tanks or from an on-board reformer.

3.1.1.2 Solid Oxide Fuel Cell (SOFC)

SOFC normally operates on very high temperature around **600 - 1000°C**. Their electrical efficiency is almost 35-43%. They are slow in startup and require significant thermal shielding to protect personnel and retain heat; they may be suitable for the utility applications but not suitable for transportation. However, SOFC are very reliable in terms of continuous use. They have longer operating life and another advantage of SOFC is that they generate steam which can be used for electricity through turbines.

3.1.1.3 Alkaline Fuel Cell (AFC)

AFC are the oldest Fuel cells technology of all the time, they were firstly designed and operated by US space program since the 1960s, Old AFC were considered to be high-temperature AFCs which operated between 100-250°C. However, newer AFC designs has lower operating temperature around 23-70°C. They are considered to be very expensive as pure Hydrogen and oxygen is used as fuel so they were not commonly used or commercialized. Their electrical efficiency is almost 60%.
3.1.1.4 Molten-Carbonate Fuel Cell (MCFC)

These types of fuel cells also considered to be high temperature fuel cells which operate between the temperature ranges of 600 - 700°C. While they have electrical efficiency is around 45-47%. Their design is not very expensive as they operate little lower temperature than SOFC and have internal reforming of hydrogen, so no external reformer is needed. They also produce steam which can be utilized but their durability is less because of the high temperature and corrosion, which reduces the FC life.

3.1.1.5 Phosphoric-Acid Fuel Cell (PAFC)

PAFC are advanced fuel cells and they are considered to be the "First Generation" of modern fuel cells. PAFC are considered to be most mature fuel cell types and are first to be used as commercially. They have electrical efficiency is >40%. The operating temperature of

Phosphoric-acid fuel cell is around 150 - 200°C. They have longer warm-up time. They don’t require more pure Hydrogen as they are very much tolerant to the impurities with Hydrogen. Like PEM fuel cells PAFCs are also considered to be expensive, as they require an expensive platinum catalyst, which is costly. The best operations of PAFCs are for stationary power generation, but they also have been used for large vehicles such as city buses but unsuitable for small cars.

3.1.1.6 Direct-Methanol Fuel Cell (DMFC)

Pure Methanol is used in DMFC along with steam to fed the anode of FC directly, they have some advantages as they methanol is easily carried and transported as fuel like liquid fuel, also Methanol is easily to transferred to public using current infrastructure. Large amount of platinum is used as a catalyst which makes the DMFC expensive. Comparing a PEMFC and DMFC are almost same in regards to operating temperature, but DMFC are not as efficient as PEMFC.
3.1.2 Chemistry of Fuel Cell:

Chemical reactions occurring at the anode and cathode are shown by the following chemical equations.

**Chemical reaction at Anode:**

\[ 2H_2 \rightarrow 4H^+ + 4e^- \]  \( (Four \ Hydrogen \ and \ Four \ Electrons \ ions \ are \ released) \)

**Chemical reaction at Cathode:**

\[ O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \]  \( (Two \ Hydrogen \ dioxide \ ions \ are \ produced) \)

**Net Chemical reaction:**

\[ 2H_2 + O_2 \rightarrow 2H_2O + 4e^- \]  \( (Two \ Hydrogen \ dioxide \ ions \ are \ produced \ and \ electrons \ are \ released) \)

This chemical reaction shows that when Hydrogen is reacted with Oxygen it generates Hydrogen dioxide and electrons are released during the chemical reaction through electrolyte. Until the reactions will take place between these two chemicals, it will keep producing the electric current in the form of electrons.

Single cell produces minimal amount of electricity approximately 0.7 volts and to achieve the much bigger amount of electric current different fuel cells should be combined together with bipolar electrolytes, which forms a Fuel-Cell Stack.
4: Battery

4.1 Introduction:

One of the most important parts of a solar power system is battery or the battery bank. There are different kinds of solar batteries, some solar battery banks use wet cells (like golf cart batteries) while others use sealed or gel cell batteries. They have different requirements such as, different temperature, ventilation and mounting. Each battery is specifically designed for a specific type of charge and discharge cycle. For example thin plates are used in Car batteries for low weight and are designed for heavy discharge which lasts for a few seconds, which is followed by a long period of slow re-charge of the battery.

4.2 Battery Charge/Discharge:

Different batteries have different charge/discharge characteristics depending upon the nature of the battery. For a residential solar application considering the minimum battery of 6-volt (golf cart battery) having the (size T-105) uses very thick plates and are designed for long hours of heavy discharge every day, also followed by a fast recharging for few hours each night. An efficient solar battery must have the following characteristics;

- Should provide long periods of deep discharge each evening and night
- Must be fully recharged only in few available sunlight hours each afternoon

Not all the batteries have these characteristics, only very few batteries can take a cycle of deep discharge-recharge every day. If the battery will overcharge it can evaporate all the
electrolytes although the battery is sealed. Considering a 12-volt battery is powered from a 50-Watt solar panel may discharge the electrolytes if it is over charged.

if the batteries are exposed to extreme temperature swinging between 50° to 80° F range, batteries can lose over half of their charge, to take care of this problem battery box must be insulated accordingly.

**4.3 Battery Capacity:**

Considering a typical battery of 6-volt may store about 1 kilowatt-hour energy. This can be expressed in an equation as below.

\[
6 \text{ volt} \times 220 \text{ amp-hr} \times 80\% \text{ discharge} = 1056 \text{ watt-hours}
\]

Where 80\% is the battery discharge ratio and 220 amp-hours is current flowing through the battery and 1056 watt-hours is the power.

If the required load has more than 220 amp-hr capacities so the desired battery should be a larger size L-16 traction battery, which has current of 350 amp-hours. This battery is almost of the same length and width as a typical golf cart battery, but it is much taller than and almost twice as heavy as a typical battery. System consisting of L-16 batteries may require fewer batteries, and also proven to be an excellent battery for solar applications having very heavy charge-discharge cycle.

**4.4 Battery Life:**

Battery life depends upon the charge and discharge cycle, complete charging of 100\% will increase the life of battery while reverse is the case of battery if it is not discharge below half. Usually a good quality lead acid battery has a 2,000-cycle life when discharged 20\% each time with 80\% charge remaining. However, if the battery goes down to 90\% discharged with 10\% charge remaining, the battery life will decrease to 400-cycle life.

Depth of discharge (DOD) of the battery should be considered in developing the system as at some conditions it may require to be heavily discharged the battery bank. So an average daily discharge should not go below 50\% to 40\%, but a better strategy should be 60\% charge remaining. Battery life may increase by considering charge/discharge cycle or by using more batteries, much stronger batteries, or by reducing load of the system.
4.5 Battery Ratings:

Battery rating can be observed over the battery, sometime it is written as amp-hour (A-Hr) rating which defines its energy storage capacity. Whereas somewhere only amp-hour rating which can be listed for different discharge time periods.

For example, considering an L16 size deep discharge battery which is typically used in solar powered homes has a 259 amp-hour rating when it’s discharged over a period of 6-hour (C6). Similarly 350 amp-hour capacity when it is slowly discharged over a period of 20-hour (C20). Now considering the same battery which has a 460 amp-hour rating when it is discharged over a period of 100-hour (C100).

4.6 Battery Sizing:

Considering a lighting load of 12 amps (4 lights x 3 amps), which operates for six hours per day. The battery system must supply the energy to meet daily power needs of 72 amp-hours (12 amps x 6 hours) per day (taking account the ideal condition of no loss). Now if the selected battery has a 350 amp-hour rating which discharged to 50%, it will deliver 175 amp-hours.

Now, if the 350 amp-hour battery is a 6-volt battery and our load requires double (12-volts) voltage to operate, so two batteries wired in series connection will be used to provide the 12-volts. Here it should be kept in mind that multiple batteries connected in series always have the same amp-hour capacity like a single battery, but multiples of the amp-hour capacity if the batteries are connected in parallel. In this case the battery voltage will not be increased.

4.7 Battery Interconnect Wiring:

The wiring of batteries has a huge impact on Volt or Amp-Hour. If two 6-volt batteries are wired in series will provide 12-volt output with the capacity of 350 amp-hour as shown in figure below.
Similarly if they are connected in parallel we will get an output of 6-volt with the capacity of 700 amp-hour as shown in figure below.

![Fig. 12: Two 6-volt batteries in parallel provide 700-amp-hour capacity at 6-volts.](image)

Now consider, if the system requires an output of 12-volt with the capacity of 700 amp-hour. So to meet the system requirement the batteries must be wired in series-parallel, as shown in figure below.

![Fig. 13: Two sets of two 6-volt batteries wired in series-parallel provide 700-amp-hour capacity at 12 volts.](image)

To increase the battery bank capacity 24-volt and 48-volt versions system should be used. In series, to achieve the higher voltage a battery bank of 24-volt will need four batteries of 6-volt and a battery bank of 48-volt system will need eight batteries of 6-volt. Similarly in Parallel, a Battery Bank of 48-volt requires sixteen 6-volt batteries. Out of Two, Each parallel string requires eight batteries of 6-volts.

### 4.8 Battery Storage:

![Sealed solar gel batteries located in an open basement rack](image)
Expensive gel or absorbed glass matte (AGM) batteries normally do not generate explosive gases, and are more flexible in locating the battery bank. These batteries can be mounted close together in a vertical steel rack as they do not require a vapour proof enclosure for gases or vent pipes.

A battery bank storage system should not be oversized of the designed solar array or fuel cell charger, if the battery bank is bigger than charging array it may not be able to recharge back to 100%, before powering the loads again. If the charging is less than 100% each day so the battery bank voltage will drop down lower and lower until it won’t be able to supply the loads.

4.9 Battery Protection/ Safety:

While considering the hazards related to battery safety or protection following points must be keep in mind.

A fuse should be use with every wire which is connected to the positive (+) terminal of any battery or battery to prevent serious damage in case of a system short.

- In a battery bank proper size and type of cables should be use to increase the voltage and capacity and also keep them as short as possible.
- AC fuse or AC circuit breaker does not safely protect a DC wiring circuit. [11]
5: Algorithm Design

5.1 Introduction:
The suggested algorithm for the problem is to make a hybrid system for Fuel cell and Photovoltaic cell using a battery as buffer. The aim is to make the Algorithm Intelligent so that it could save the Fuel cell cost where as the battery can be utilized. The suggested algorithm is efficient and proven to be operational. It shows the required outputs an also provide an optimal solution which was not yet considered earlier.

5.2 Block Diagram:

The block diagram shows an Intelligent Fuzzy Controller which is connected with the Load, Battery Bank and PC Energy Producer for getting the input and with the Fuel Cell’s Switch for generating the output to keep it “ON” or “OFF”.

The first information of Load for required power (W-h) is transferred to the Intelligent Fuzzy Controller, now the second information of Battery Current State from battery through battery
sensor and third and last information from the PC Energy Producer, that how much Photovoltaic Energy is being produced or even no energy.

Now the Intelligent Fuzzy Controller, which is designed for making the intelligent decisions on the basis of “Fuzzy Rules” makes the decisions and generate the output. These rules considering the all the available input and make the decisions. This outputted information to keep the Fuel Cell switch “On or Off” is used for providing the FC current to the battery if switch is open else it keep at rest.

The main function of Battery is to provide the constant flow of current to the load’s power, here battery acts like a buffer which keeps itself charged or stable if the sources (PC & FC) are constantly providing the current, if there is no back power available then the battery keeps itself discharged as per load requirement and sending this track of battery current state to the Intelligent Fuzzy Controller.

The flow of information is from Load, Battery Sensor and PC Energy Producer to the Intelligent Fuzzy Controller and from here to switch. This information is not exchanging between the hardware components but from there to Fuzzy Controller and from there to some hardware. But the current only flows between the hardware only but not to the Fuzzy controller so that’s why the flow is mentioned appropriately. Current only flows from FC to battery through switch and from PC energy producer to battery and from battery to load, also from battery to its sensor where the battery charged state is transferred as information to the Fuzzy controller.

5.3 Main Algorithm:

Where

**PC: (Watts)**

Low= 0-500  
Medium=300-750  
High=500-1000

**Load: (Watts)**

Low= 0-230  
Medium=130-360  
High=300-500

**Battery (Volts)**

Critical=0-100  
Low= 50-230  
Medium=130-400  
High=300-500

**Time: (Seconds)**

Day
Pseudo-code:

1: Get Input from PC Energy Producer
2: Get Input from Load
3: Get Battery Initial Level from Battery Level Sensor
4: Fuzzy Controller Decisions
5: Generate Output

FIRST REFINEMENT

4.1:
If
{PC is High & Time is Day}
5.1:
Then
Keep FC Switch Off

4.2:
elseif
{PC is High & Time is Day}
5.2:
Then
Keep FC Switch On

4.3:
elseif
{Pc is Low & Battery is Critical & Time is Night End}
5.3:
Then
Keep FC Switch On

4.4:
elseif
{Pc is Low & Battery is Not Critical & Time is Night End}
5.4:
Then
Keep FC Switch Off
4.5:
elseif
{Pc is Low & Load is Medium & Battery is Not High & Time is Night}

5.5:
Then
Keep FC Switch On

4.6:
elseif
{Pc is Low & Load is Medium & Battery is High & Time is Night}

5.6:
Then
Keep FC Switch Off

4.7:
elseif
{Pc is Low & Load is Medium & Battery is Critical & Time is Day}

5.7:
Then
Keep FC Switch On

4.8:
elseif
{Pc is Low & Load is Medium & Battery is Low & Time is Day}

5.8:
Then
Keep FC Switch On

4.9:
elseif
{Pc is Low & Load is Medium & Battery is Medium & Time is Day}

5.9:
Then
Keep FC Switch Off

4.10:
elseif
{Pc is Low & Load is Medium & Battery is High & Time is Day}

5.10:
Then
Keep FC Switch On

4.11:
elseif
{PC is Medium & Load is High & Battery is Critical & Time is Day}

5.11:
Then
Keep FC Switch On

4.12:
elseif
{PC is Medium & Load is High & Battery is Not Critical & Time is Day}

5.12:
Then
Keep FC Switch Off

4.13:
elseif
{PC is Low & Load is High & Battery is Not High & Time is Night}

5.13:
Then
Keep FC Switch On

4.14:
elseif
{PC is Low & Load is High & Battery is High & Time is Night}

5.14:
Then
Keep FC Switch Off

4.15:
elseif
{PC is Low & Load is High & Battery is Not High & Time is Day}

5.15:
Then
Keep FC Switch On

4.16:
elseif
{Pc is Low & Load is High & Battery is High & Time is Day}

5.16:
   Then
   Keep FC Switch Off

4.17:
   elseif
   {Pc is Low & Load is Low & Time is Night}

5.17:
   Then
   Keep FC Switch On

4.18:
   elseif
   {Pc is Low & Load is Low & Time is Day}

5.18:
   Then
   Keep FC Switch Off

   Else
   Then
   Keep FC Switch Off

Explanation:

The main functionality of the designed algorithm is to optimize the cost of Fuel in the Fuel Cell wherever it can be saved. The Intelligent system is responsible for providing the continuous current to the Load/Drain. Also the battery can be saved for the utilization in the night’s late hours. The designed algorithm was implemented through MATLAB/Simulink Model using Fuzzy Logic. The output of the system is discussed in chapter 7 “Result and Analysis”. It is observed that the simulation of the Hybrid system is generating output according to the expectations. It is very handy for saving the fuel. Through the simulation the estimated total Fuel Cell energy consumption in the whole year is 635.31 KW per Year as compared with total Photovoltaic Cell energy consumed to fulfill load requirements is 565.36 KW per Year. Whereas the Total load required was 1200.67 KW per Year. It shows that with the use of this intelligent system the difference between the FC and PC is not much high, as shown in Fig. 22 the graph clearly indicates that the total Energy production varies throughout the year. Where, most of time of the year production of PC was very low. So we can perceive that this Intelligent Hybrid system performed well and utilized all the possible alternatives to save the Fuel and Battery according to the requirement.
6.1 Fuzzy Logic:

A form of multi-valued logic which is derived from fuzzy set theory is called Fuzzy Logic. It accommodates uncertainty where the system’s inputs and outputs are imprecise and uncertain. Fuzzy logic deals with the approximate reasoning, which is approximate but not precise. In classic propositional logic the two truth values range only 0 or 1 contrast with the fuzzy logic where the variables may have a membership value range between 0 and 1, depending upon the degree of truth of a statement.

[12]

Variable “tall” in Fuzzy Logic

Considering the above image as our example, Where the linguistic variable “tall” is used instead of numeric vriable. The length of persons is considered as “tall” if they reaches some defined height like 6 feet and 0 inches or above, but if a person is little short around 5 feet and 9 inches. do we consider him a short person? The answer should be “True” as considering the domain of well-defined (crisp) boundary of a classical set theory. Whereas considering the domain of Fuzzy the word "tall” correspond a curve which defines the degree to which any person is considered to be “tall” who ranges between 5 feet and 8 inches to 6 feet and 0 inches or above.

Furthermore, when these linguistic variables are used, these degrees of membership may be managed by some specific functions.
Above image shows that how the degree of membership in the conventional logic have the Sharpe edged membership function which has “tall” range either “0” or “1”. Where as in Fuzzy logic the membership functions are described as continuous which has “tall” range between really not very tall “µ=0.30” to definitely a tall person “µ=0.95”.

In Fuzzy logic "fuzzy" does not refer to a lack of rigidity in method, whereas “logic” deals with fuzzy concepts - concepts that are expressed as "partially true" but not as straight "true" or "false". Fuzzy logic has advantage over other logics that the solution to a problem can be expressed in terms that a human operator can easily understand, and their experience can be added on for design of the controller. Allowing it easier, to mechanize those tasks which were successfully accomplished by humans.

The following figure shows the Two-valued and Multivalued logic graphed against the values of truth table. The above part of Two-valued logic figure where two fuzzy sets were used to create the one fuzzy set and the below part shows the range between A&B truth values, according to fuzzy set table.
These three functions of AND, OR and NOT can resolve any construction using fuzzy sets and the fuzzy logical operation.

In the above diagram on Left, shows the range of membership function of two-valued functions for identifying the weekend, varying from the range of Friday night to Sunday night. While on Right side of the above diagram it clearly shows the range may be variable as multivalued membership function.

6.2 Why to Use Fuzzy Logic?

There are many reasons for using Fuzzy Logic. Here is a list of some general observations about fuzzy logic:

- Fuzzy logic is conceptually easy to understand. The mathematical concepts behind fuzzy reasoning are very simple. Fuzzy logic is a more intuitive approach without the far-reaching complexity.
- Fuzzy logic is flexible. With any given system, it is easy to layer on more functionality without starting again from scratch.

- Fuzzy logic is tolerant of imprecise data. Everything is imprecise if you look closely enough, but more than that, most things are imprecise even on careful inspection. Fuzzy reasoning builds this understanding into the process rather than tacking it onto the end.

- Fuzzy logic can model nonlinear functions of arbitrary complexity. You can create a fuzzy system to match any set of input-output data. This process is made particularly easy by adaptive techniques like Adaptive Neuro-Fuzzy Inference Systems (ANFIS), which are available in Fuzzy Logic Toolbox software.

- Fuzzy logic can be built on top of the experience of experts. In direct contrast to neural networks, which take training data and generate opaque, impenetrable models, fuzzy logic lets you rely on the experience of people who already understand your system.

- Fuzzy logic can be blended with conventional control techniques. Fuzzy systems don't necessarily replace conventional control methods. In many cases fuzzy systems augment them and simplify their implementation.

- Fuzzy logic is based on natural language. The basis for fuzzy logic is the basis for human communication. This observation underpins many of the other statements about fuzzy logic. Because fuzzy logic is built on the structures of qualitative description used in everyday language, fuzzy logic is easy to use.

The last statement is perhaps the most important one and deserves more discussion. Natural language, which is used by ordinary people on a daily basis, has been shaped by thousands of years of human history to be convenient and efficient. Sentences written in ordinary language represent a triumph of efficient communication. [13]

### 6.3 Fuzzy Rules:

The intelligent Hybrid system is working on the following rules applied using Sugeno based Fuzzy Controller.
Where,

**Inputs**

There are 4 inputs parameters

1. **Photovoltaic Current (PC)** has 3 membership functions along with their ranges are defined as below.
   - **Low** = 0-500
   - **Medium** = 300-750
   - **High** = 500-1000

2. **Load** also has 3 membership functions whose values are defined as below
   - **Low** = 0-230
   - **Medium** = 130-360
   - **High** = 300-500

3. **Battery** has 4 membership functions along with their values as below
   - **Critical** = 0-100
   - **Low** = 50-230
   - **Medium** = 130-400
   - **High** = 300-500

4. **Time** has only 4 membership functions as below
   - **Day**
   - **Day End**
   - **Night**
   - **Night End**

**Outputs**

**Fuel Cell (FC)** has only two outputs

**ON**

**OFF**

**Rules for Sugeno based Fuzzy Controller**

1. If PC is high & Time is Day then FC is Off.
2. If PC is high & Time is Day End then FC is On
3. If Pc is Low & Battery is Critical & time is Night End then FC is ON
4. If Pc is Low & Battery is not Critical & time is Night End then FC is Off.
5. If Pc is Low & Load is Medium & Battery is not high & time is Night then FC is On.
6. If Pc is Low & Load is Medium & Battery is high & time is Night then FC is Off.
7. If Pc is Low & Load is Medium & Battery is Critical & time is day then FC is On
8. If Pc is Low & Load is Medium & Battery is low & time is day then FC is On
9. If Pc is Low & Load is Medium & Battery is medium & time is day then FC is Off
10. If Pc is Low & Load is Medium & Battery is High & time is day then FC is On
11. If PC is Medium & Load is High & Battery is Critical & time is Day then FC is On
12. If PC is Medium & Load is High & Battery is not Critical & time is Day then FC is Off
13. If Pc is Low & Load is High & Battery is Not High & time is night then FC is On
14. If Pc is Low & Load is High & Battery is High & time is night then FC is Off.
15. If Pc is Low & Load is High & Battery is Not High & time is Day then FC is On
16. If Pc is Low & Load is High & Battery is High & time is Day then FC is Off
17. If Pc is Low & Load is low & time is night then FC is On
18. If Pc is Low & Load is low & time is Day then FC is Off

For detailed discussion about the Rule base and their membership functions along with their results, referred to Simulation part of this thesis done by Mr. M. Irshad Ababsi “Simulation of Hybrid Fuel/Photovoltaic Cell Standalone System”. [E3618D]
7.1 Simulation Results:

Following are the results of the simulation based on the intelligent algorithm of a hybrid fuel/photovoltaic standalone system.

![Input and output Graphs](image)

The above Fig. 21 shows the graph of all inputs and output. Here PC, Battery and Load are the inputs and FC is the output.

**PC:**

We can see that simulation of PC started from night and when the graph achieves the gain it started to generate the Photovoltaic energy also marked with arrow as “Day”. And after achieving the peak (380watts) it start declining and reached to Zero (0), which is marked as “Night”. It completes the cycle of 1 complete day. When it started to continue it reaches to another day where the solar energy is produced as very low. This small mountain is because the solar energy is not present because of the cloudy weather or so. This cycle completed at reaching at 5\(^{th}\) mountain where it showed high PC almost 370 watts.
Battery:
The second graph shows the battery behaviour, where it started from initial Zero (0) level and when it get the current from FC it started to charge as the load was starting to decrease and the extra current is used to charge the battery. Going further the battery keep on charging as the solar energy is started to generated from PC and it achieved its level where it is marked as “Medium” and further at “Minimum Threshold” which is set for making the Fuzzy rules.

Load:
Load is the third graph as shown in above fig. It started to simulate at the random values of Required Power in Watts/h, which is almost considered to be “Medium” and is mentioned with the arrow pointing at it. The load varies, as different types of the inputs load may be on or off with the time. The graph shows that the as the demand increases the load shows gain and as the load demand decrease it shows decline, which is mentioned as “Low” and marked with an arrow.

FC:
The last graph shown in the above fig. is FC which is the outputted result on the basis of above the input parameters of PC, Battery and Load. The FC is on in the start as the PC is not available and load is greater than the battery threshold. When the FC is on its value is 1 as shown by arrow “FC ON” and when it is off its value is 0 and marked as “FC OFF”. More the FC will remain on, more the fuel will be used or vice versa.

7.1.1 PC Generation Graph:
The above graph shows the amount of Photovoltaic Energy produced in Watts-h for a period of complete 1 year. It clearly shows that the amount of energy depends on the fall of incident solar radiation. Lower the amount of incident radiation, lower the amount of PC generated. Similarly higher the amount of Incident solar energy, higher the PC generated. Graph shows that initial values and the ending values represent those months where there is less solar energy produced and in middle the higher values shows that more PC is more generated than rest of the months. These higher values represents month of May, June, July, Aug, when there was summer and allot of solar energy was produced. Highest energy level was obtained in May where the PC generation was in almost 13.9 watts/h and lowest value for PC energy generation was observed in Dec where it was almost 1.75 watts/h.

7.1.2 Solar Radiation Graph:

Above graph shows the irradiance of solar energy produced during the whole year, scattered values represent the less amount of solar radiations according fall over the period of low sunshine hours and the low projection shows the less amount of solar energy, whereas the thich and unsaturated thick lines represent the high amount of solar radiation and the high projection represents the solar energy was produced above than 600 to 950Kwh approx. Also this indicate the peak summer months for high performance of soalr panels.

Fig. 23: Solar Radiation Graph
7.1.3 PV T Surface Graph:

The above Graph represents the temperature of the T-surface of a Solar panel, as it is the temperature of the photovoltaic cell for the whole year. The graph clearly shows that when the production of the photovoltaic energy is below the Zero degree Celsius to the 10 degree Celsius there were less amount of energy was produced. Now considering the graph in the middle where the temperature of the T-Surface is above the 15 degree Celsius to almost above 50 degree Celsius, this indicate that whenever the high amount of solar energy is produced, the temperature of the Photovoltaic cell surface rises. The rise in the temperature also indicate that the efficiency of the Solar panel may be decreased, due to the high resistance the average fall in the power loss is almost 40%.

7.1.4 Power Supply Graph:

following diagram of Power Suply shows that how much current was produced during the whole year on the basis of daily production, depending upon the solar radiation, tilt angel and weather conditions. The graph clearly shows uneven flow of lines representing the current production is high at some points, even above 90 W whereas at some times it shows the 0W production of current. This behaviour shows that the data obtained from the graph is good, as there are many factors which causes the increase or decrease of Cureent production.
7.1.5 PV Efficiency Graph:

The efficiency of the solar panel is the amount of electricity produced by the solar panel after capturing the solar energy. Efficiency depends upon the material used in PV and the efficient design, usually the range between efficiency is average 5 %.

Above diagram shows that the efficiency varies throughout the year, it depends upon the solar incident radiations fall over the PV and the temperature of the PV panels. Considering the above graph between the range of 1 to 2 the efficiency drops down from 0.15 to 0.1. It is due to the high production of electric power generated from Solar panels, so the temperature of the PV increases and the high temperature decreases the efficiency.
7.1.6 Battery Graph:

![Battery Consumption Graph](image1)

The above diagram of Battery exhibits the behaviour of charging and discharging throughout the year and maps the output. It shows that in the middle of the graph where the solar energy was high the battery charging ratio was almost equal to full. Whereas at the low production it was not even charged to half.

7.1.7 FC Graph:

![Fuel Cell output Graph](image2)

The above diagram shows the graph of the output for Fuel Cell, when the value is 1 it shows that FC is on and off at 0, comparing the all the respecting graphs will give the clear overview that
how does the FC can be saved while it still has the need, but battery will be used instead of FC to save the fuel.

7.2 Fuel Cell & PC Consumption

After running the simulation for whole year, following result are achieved.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Power Requirement by load</td>
<td>1200.67 KW per Year</td>
</tr>
<tr>
<td>Total Solar energy consumed to fulfill load requirements</td>
<td>565.36 KW per Year</td>
</tr>
<tr>
<td>Total Fuel energy consumed to fulfill load</td>
<td>635.31 KW per Year</td>
</tr>
</tbody>
</table>

7.3 Analysis:

Now we can compare all these graphs so that we could have an overview of our system performance.

I. Considering, the 1st red line on left side which represent the “FC off at Night End”. The intelligent system predicts automatically that if the day is going to be start in near future so keep the FC off so that it could let the battery discharge no matter how much the charge is available. If the battery is below the critical threshold so it can be discharged more, because as the solar energy will start to produce the battery will start to recharge. This intelligent technique can save up the fuel cost.

II. Now consider the 1st green line at left side which represent the “FC on at Day End”. When the day is going to be finished the intelligent system predict it earlier and start the FC well before the PC is going to finish. This will save the battery for the night use, as it will keep the system ready against the demand of heavy load.

III. Now consider the 2nd red and green lines at the right side of the graphs, which is marked as the same tags as discussed above. This also shows that at any instance the system is behaving as desired, so that it can save the FC and battery.

Now compare the both (green and red) marked lines on the left side and right side. Now compare left side with right side. We can observe that as the load was low on right side as compare to left side, the system kept the Fuel Cell off bit earlier to save the FC cost. While on the left side the FC was off when the load started to decrease. This analysis shows that the by checking the demand of power, Intelligent Algorithm works well and shows the prediction by keeping the FC off very earlier than expected.

Dalarna University
Röda vägen 3
S-781 88 Borlänge
Sweden
Tel: +46 (0)23 77 80 00
Fax: +46 (0)23 7780 80
www.du.se
8: Conclusion and Future Recommendations

8.1 Conclusion:

The developed system works well and performs the expected output, the behaviour of the FC and Battery to predict the upcoming events and perform the desired operations. These intelligent operations can save the fuel cost in the fuel cell and battery for the night consumption. The efficiency of the hybrid system increased by using Fuzzy based intelligent controller, also it helped to increase the operability of the hybrid system switching between PC and FC. Although the designed hybrid system was implemented as a simulation in MATLAB/Simulink, it has showed the behaviour that it can be implemented as real time system with little modification. Considering the fact that a battery has longer life cycle if it is properly charged and discharged, keeping the battery below the threshold level at irregular instances may decrease the battery life cycle almost half.

8.2 Future Recommendations:

The system works on the input parameter of PC for particularly one location, the solar data of different geographical locations can be added so that a user can be asked for desired output of the particular or different locations.

The weather is also an important part of this system, by considering the real time metrological data from the website may help to predict that how much energy will be produced from solar panels.

The designed Hybrid system can be modelled with the grid connection so that its performance can be analyzed and compare with the standalone system.
9. References:


[2/7]. The Electronic Universe Project e-mail: nuts@moo.uoregon.edu  
http://zebu.uoregon.edu/1998/ph162/l4.html


[4]. Lian Dibo1, Feng Xiaoyun2, Li Shuichang3, Gu Bochuan4, “PEM Fuel Cell and Battery Hybrid System Studied In Matlab/Simulink”, School of Electrical Engineering, Southwest Jiaotong University


[6]. LI Wei†, ZHU Xin-jian, CAO Guang-yi. “Modeling and control of a small solar fuel cell hybrid energy system”, Journal of Zhejiang University SCIENCE A ISSN 1673-565X (Print); ISSN 1862-1775 (Online)


10. Reference for Picture and Graph:

Fig. 1,2,3,4,5: http://zebu.uoregon.edu/disted/ph162/l4.html

Fig. 6: http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/how_pv_cells_work.htm ©2007 Florida Solar Energy Center (FSEC)

Fig. 7: http://www.solarserver.de/wissen/photovoltaik-e.html

Fig. 8: University of monosota, http://www.me.umn.edu/courses/me4131/LabManual/AppDSolarRadiation.pdf, “Solar Radiation”

Fig. 9: “Types of fuel cell” . http://www.answers.com/topic/fuel-cell

Fig. 10,14: http://www.backwoodshome.com/articles2/yago87.html

Fig. 11,12,13,15: http://www.backwoodshome.com/articles2/yago88.html

Fig. 17, 18: http://www.caspur.it/risorse/softappl/doc/matlab_help/toolbox/fuzzy/fuzzytu3.html

Fig. 19: http://www.caspur.it/risorse/softappl/doc/matlab_help/toolbox/fuzzy/fuzzytu4.html

Fig 20: http://www.caspur.it/risorse/softappl/doc/matlab_help/toolbox/fuzzy/fuzzytu2.html