DESIGN OF A POWER MANAGEMENT MODEL FOR A SOLAR/FUEL CELL HYBRID ENERGY SYSTEM

by

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A Thesis Submitted to the Faculty of the

College of Engineering and Computer Science

in Partial Fulfillment of the Requirements for the Degree of

Master of Science

Florida Atlantic University

Boca Raton, Florida

August 2010

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This thesis was prepared under the direction of the candidate's thesis advisor, Dr. Ali Zilouchian, Department of Computer and Electrical Engineering and Computer Science, and has been approved by the members of her supervisory committee. It was submitted to the faculty of the College of Engineering and Computer Science and it was accepted in partial fulfillment of the requirements for the degree of Master of Science.

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ACKNOWLEDGEMENTS

First of all, thank you God for what you have offered me in life. I am greatly indebted to my advisor Dr. Ali Zilouchian for all his support, encouragement and guidance. His assistant, from the initial to the final phase of my master program, enabled me to develop this research work. I would like to sincerely thank Dr. Amir Abtahi, my co-advisor for all his help during the entire study of my program especially my work in the FAU fuel cell Laboratory. I appreciate Dr. Negron Erdol's acceptance to be a member of my thesis committee and her patience and help.

I particularly would like to mention my parents, Viola and Hernando. They believed in me and that my dream would become a reality one day. To my siblings, Andres, Lorena, Silvana, for supporting me during the entire project with all their lovely words. In addition, I would like to thank my extended family members in Florida and New York: Eli, Alejandro, Henry, Nathaly, Espe, Mike, Martha, Alvaro, Lina, Jesus, Ramon, Sixta.

In addition I would like to thank Dr. Maria Petrie for all of her encouragement during my study at FAU and Diego Pava, a Ph.D. student candidate at FAU who assisted me since I was in Colombia.

Lastly, I express my appreciation to all of individuals who supported me during the completion phases of the thesis including my friends and all department professors and staff.

ABSTRACT

Author: Rosana Melendez

Title: Design of a Power Management Model for a Solar/Fuel Cell Hybrid Energy System

Institution: Florida Atlantic University

Thesis Advisor: Dr. Ali Zilouchian

Degree: Master of Science

Year: 2010

This thesis proposes a Power Management Model (PMM) for optimization of several green power generation systems. A Photovoltaic/Fuel cell Hybrid Energy System (PFHES) consisting of solar cells, electrolyzer and fuel cell stack is utilized to meet a specific DC load bank for various applications. The Photovoltaic system is the primary power source to take advantage of renewable energy. The electrolyzer-fuel cell integration is used as a backup and as a hydrogen storage system with the different energy sources integrated through a DC link bus. An overall power management strategy is designed for the optimization of the power flows among the different energy sources. Extensive simulation experiments have been carried out to verify the system performance under PMM governing strategy. The simulation results indeed demonstrate the effectiveness of the proposed approach.

DEDICATION

This manuscript is dedicated to my family, particularly to my parents, Viola y Hernando, my grandfather and my grandmother. To God and to all my best friends.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 BACKGROUND AND RESEARCH OBJECTIVES

1.1 Introduction

The population of the United States is projected to increase from the current level of 303 million to 438 million by the year 2050 [1]. The latest Department of Energy (DOE) data confirms that currently 59% of oil consumed in the US is imported as compared to 37% imported at the time of the 1973 oil crisis. Only 2/10 of a percent of all energy consumed comes from solar and wind generation, and only 3.3% is derived from bio-fuels and biomass [2]-[3]. According to a study by Management Information Services Inc., a Washington, D.C. research firm that has been tracking green jobs for two decades, the new industries of environmental management and protection have created 5.3 million jobs in the United States. In the past, environmental jobs were mostly about regulatory compliance; now, they are supporting a wide variety of initiatives, including sustainability, water processing, and alternative energies. By 2010, "green employment" will reach 5.8 million jobs. The technical and scientific challenges to provide reliable and renewable sources of energy for an additional 70 million Americans in a short 30-year period are enormous, especially so when combined with the strategic and economic concerns mentioned above. It is clear that as part of the mix of energy sources necessary to deal with these challenges, alternative energy sources will play a critical or even a central role to address the demand. The US Department of Energy, as well as a number of the national --laboratories and academic institutions, has been aware of the importance of alternative energy sources for some time. Recently, the energy industry, car manufacturers, transportation experts, and even utilities are paying attention to alternative and sustainable sources of energy for the future.

One of the most important aspects in America and Europe is its high dependency on primary energy sources. The European Union (EU) imports around 70% of the oil, 43% of the natural gas and 50% of the coal they need to produce electrical energy for different areas [4]. The current power production capacity installed in Europe is based natural gas (18%), oil (6%), coal (26%), nuclear (33%), hydro (12%) and other renewables (3%) [4]. Actually, the European energy sector is looking for factors such as meeting the Kyoto commitment, solving the issue of security of energy supply, and trying to follow Green energy trends. To succeed on this trend it is completely necessary to implement hybrid energy system. There is an outlined issue behind hybrid energy systems operation: adequate control system. The lack of control systems brings it to non-sustainable scenarios, in which hybrid systems can be implemented but with high operation costs and out of sustainability scenarios. As a consequence, technical requirements should be applied not only to design hybrid systems but also to create the best Power Management Model.

In this study, the optimization strategy from different alternative energy sources is addressed.

1.2 General Overview

Green energy is one of the top research topics around the world and most of green energy systems are denominated as Hybrid Energy Systems. A Photovoltaic/Fuel Cell Hybrid Energy System (PFHES) is a system that takes energy from sunlight and hydrogen to feed a specific electric network (AC or DC load). This hybrid system is compounded by Photovoltaic cells that work as a primary source, converting the energy from the sun into electricity that is given to a DC bus. The second component is denominated as the electrolyzer, a device that produces hydrogen and oxygen from water as a result of an electrochemical process. When there is an excess of solar generation available, the electrolzyer is turned on to begin producing hydrogen, which is sent to a storage tank. This hydrogen is used by the third component of the complete system, the fuel cell stack, which produces electrical energy to feed a DC bus, by using hydrogen as mentioned above.

An overall Power Management Model (PMM) is designed for the PFHES to coordinate the power flows among different energy sources and load, as shown in Figure 1-1.

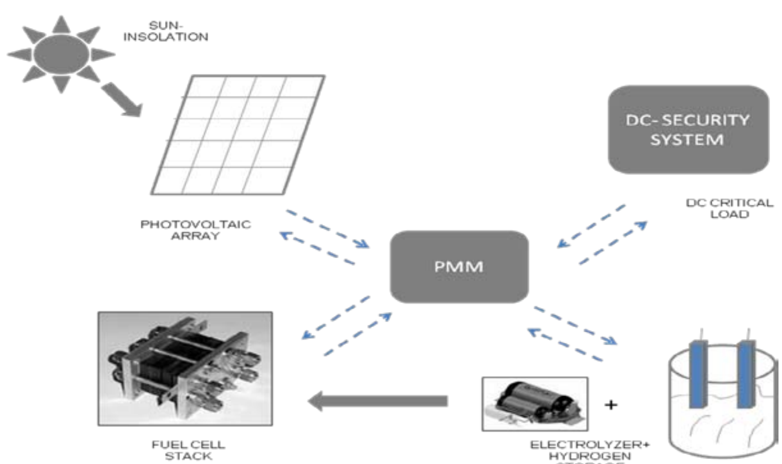


Figure 1-1 Photovoltaic/Fuel Cell Hybrid Energy System Configuration.

PFHES is compounded by some elements identified as subsystems:

- Solar cells (photovoltaic cells).
- Electrolyzer (hydrogen production + storage system).
- Fuel cell stack.
- DC bus and DC electrical load.

DC load is represented by telecommunication systems (DC equipment for security systems).

Figure 1-2 illustrates the system configuration for the proposed hybrid system.

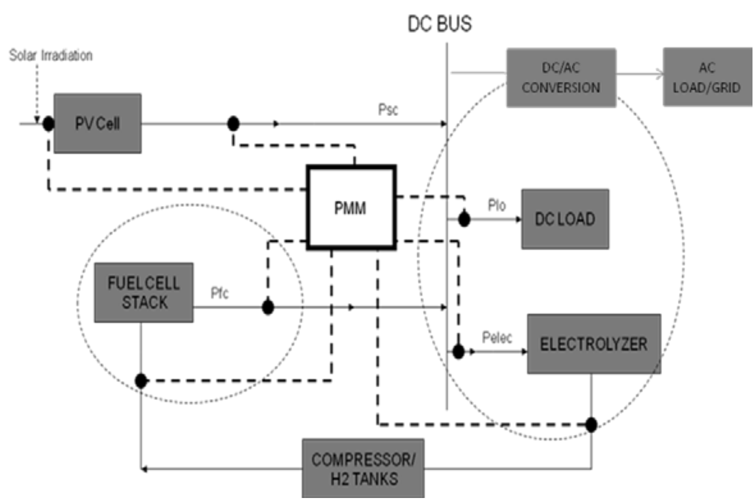


Figure 1-2 Power Management Model Configuration.

As mentioned above, PFHES operation is generally coordinated by using a Power Management Strategy or Model (PMM), which uses a controller to coordinate the combined operation of solar cells, electrolyzer and fuel cells in order to maintain the continuous feeding to an electrical critical DC load and to coordinate the energy flows among the different energy sources.

The PMM is based on a mathematical approach and block diagrams and these elements must be defined as the main PMM components. Additionally it is necessary to establish some initial conditions for the PMM design process:

- Load criteria,
- Subsystems sizing (photovoltaic modules, electrolyze and hydrogen storage tank, fuel cell),
- Control criteria, which are grounded on the continuous power flow between the energy sources and into the load; in general, P_{net} is defined as the sum of all sources' contribution and all loads, at a specific time.
- PMM has to be adequate in order to minimize hybrid system operation costs.

The PMM design process requires that electrical demand must be met while minimizing an objective function, which will be the hourly operation cost of the hybrid system. This function will be identified as C_T. C_T is the sum of capital and maintenance hourly cost.

$$C_T = C_C + C_M \tag{1}$$

These costs can be broken up into the hourly costs for photovoltaic array, electrolyzer – hydrogen storage and fuel cell stack subsystems.

$$\begin{aligned} C_C &= C_{\mathrm{csc}} + C_{celec} + C_{cfc} \\ C_M &= C_{msc} + C_{melec} + C_{mfc} \end{aligned} \tag{2}$$

The objective function C_T is also constrained to minimize the magnitude of the difference between the generated power and the demand over a given period of time (hourly). Power Management Model (PMM) design involves minimizing the Photovoltaic/Fuel Cell

Hybrid Energy System (PFHES) cost function (see equation 3) under Power Management Model (PMM) implementation, which is one of the main purposes of this research work:

$$C_T = \alpha P_{sc} + \beta P_{elec} + \lambda P_{sc} \qquad (3)$$

In the equation, α,β,λ are objective function coefficients or parameters and can be defined under the particular case of study.

One of the approaches for a PMM design process is developed by *Wang and Nehrir* in an illustrative research paper [5]. In this case, a Power Management of Stand-Alone Wind/Photovoltaic/Fuel Cell Energy System is defined under load and weather constraints. An additional and well-developed research was done by Th.F. El-Shatter, M.N. Eskandar, M.T. El-Hagry [6] with a Hybrid PV/fuel cell system design and simulation.

Another good approach is presented by Józef Paska and Piotr Biczel [7], in the paper titled “Hybrid Photovoltaic-Fuel Cell Power Plant”.

1.3 Problem Statement

In actuality, European and American energy sectors are looking for factors such as the Kyoto commitment, to solve the issue of security of energy supply and try to follow Green energy trends. To succeed on this trend it is necessary to implement a hybrid energy system completely. Hybrid photovoltaic/fuel cell energy systems have been studied extensively [8]. Solar energy systems are widely used as an important alternative energy source and, to overcome the problem of intermittent power generation, photovoltaic power systems could be integrated with other alternative/sustainable power sources. Fuel cells represent a fair option because of modularity and fuel flexibility.

Then, the combination of solar energy sources and fuel cells can be used as a reliable power source.

Energy storage is needed in these systems due to the intermittent nature of solar energy. Traditionally, deep-cycle lead acid batteries have been used as the means of energy storage. However, there are environmental concerns associated with the handling of batteries; thus, other alternatives are defined for this application. Fuel cells (FCs), in combination with an electrolyzer (for hydrogen generation) and hydrogen storage tanks, have been considered and implemented for energy storage.

However, there is an outlined issue behind hybrid energy systems operation: adequate control system. With lack of a well-designed Power Management Approach that could control the power flows among energy sources, the operation of an overall hybrid system could be a complete disaster in terms of continuous load feeding and operation cost.

There are many design issues in PMM design process. A continuous DC critical load operation needs to be placed as the number one priority because of special requirements for critical load. The Cost Analysis, intended to minimize hybrid system operation costs, must be studied. Both solar photovoltaic and electrolyzer/fuel cell stack technical performance require adequate control to meet minimum load requirements 24 hours a day. In this thesis, not only power flows simulation but also hybrid energy system unit sizing and economic analysis are performed by applying Labview tools.

1.4 Context and Scope

Some constraints and assumptions may be determined in order to design the proposed PMM.

These constraints are closely related to hydrogen storage mechanism and flow rate controlling. This indicates the following issues:

- PMM design and implementation do not determine the appropriate hydrogen's rate of production/consumption as a function of the system's power inputs and outputs.
- There are no chosen rates applied to the electrolyzer output. The model does not consider how to control how much hydrogen must be produced by the system during at specific interval of time. Therefore, the model will be based on this idea:
    - It is necessary to store the excess energy produced by the photovoltaic array by converting this excess of electrical energy into hydrogen.
- The system should provide energy to the load by reconverting hydrogen into electricity, with the fuel cell stack.

Those constraints are applied to the labview simulations and laboratory experiments, whose results will be presented in Chapter 4.

An additional constraint is also established for hybrid energy system sizing. For this thesis, the proposed hybrid energy system is a small system since a basic power management model is to be created. Actually, in many applications, most of hybrid energy system components such as photovoltaic array and fuel cell stack have large dimensions in terms of output power capacity. In the particular case of this thesis, each subsystem capacity will be calculated in kilowatts.

Finally, supplementary assumptions for PMM design process will be presented in Chapter 3.

1.5 Research Objectives

The objectives of this thesis are:

1. To design a basic Power Management Model (PMM) for a Photovoltaic/Fuel Cell Hybrid Energy System (PFHES). PMM components to achieve this will be defined as:
    a. Mathematical models.
    b. Block diagram.
    c. Strategy or instructions: operation schedule, constraints, among others.
2. To establish a general Cost Analysis by defining cost-related parameters that could be associated with PFHES operation.
3. To define block diagram and strategy associated with the PMM, representing the third objective of this thesis.
4. To run simulations in order to verify the PMM design.

1.6 Significance of the Proposed Research

"Sustainability" has been reinvented as the key word to describe a political discourse concerning quality of life issues, limitation of natural resources and the sense of the commitment to the future generations. In this scenario, the future of energy sources is represented by alternative and sustainable energy systems, not only by the positive impact on the global economy but for the easy operation of this kind of source [9]. It has been proven that a hybrid system driven by a power/control management can combine the advantages of the different renewable energy sources, solar and fuel cells, in order to create a clean system that can supply energy to a critical load. As a consequence of the

PMM operation it is possible to cover peak loads (e.g. the load of the midday) and to store energy that is not needed during quiet time periods.

1.7 Contributions of This Research

There are valuable contributions that this research work could make to the engineering area:

- General advantages of Power Management modules can be implemented as part of large-scale hybrid energy systems.
- PMM application can have positive effects on hybrid systems' component sizing and operation costs.
- The implementation of the Power Management module idea could be employed for systems that include critical DC applications (i.e. Telecommunications systems, transportation) and other AC applications.

One of the expected results is to confirm that the Power Management Model could be implemented to coordinate hybrid energy system performance, in which sufficient electricity is supplied to a DC load, under adequate schedule, weather and power management network conditions.

In actuality, Florida Atlantic University (FAU) graduate students have done some experiments for modeling and implementing alternative/sustainable energy systems. A future implementation of this power management model could be applied in real applications (i.e. other PhD dissertations, FAU Research & Development projects, local energy companies, implementation in some FAU physical locations, among others).

1.8 Literature Survey

The study, planning and operation of Solar/Fuel Cell energy systems with Power Management is a topic that has been studied by many educational, government and professional organizations around the world. Some references and real cases are mentioned.

- Modeling of hybrid renewable energy systems has been developed by many authors. The research documents describe methodologies to model Hybrid Systems components, Hybrid System designs and its evaluation [10]. Authors mentioned renewable energy systems modeling, indicating its popularity in terms of meeting specific energy demands. Penetration levels on network basis is the future of the hybrid power system in power generation capacity of some countries [11].
- Hybrid Wind-PV-Fuel Cells power systems have been designed. In these cases hydrogen production is performed by an electrolyzer, and a fuel cell stack operates as a back-up in case of lack of availability of wind or sunlight. System performance is simulated by using special software such as Simulink (MATLAB) and Hybrid Optimization Model for Electrical Renewables (HOMER), which was developed by the National Renewable Energy Laboratory (NREL). [12]
- Hundreds of papers and research projects about specific control/power management techniques [13] for hybrid systems (PV, Wind, Fuel Cells, biomass, etc.) have been published. Results show a variety of philosophies to control the power flow between AC grid, DC loads and different parts of those systems by

using power electronic devices, special power circuits [14], AC or DC grid synchronization equipment and others.

- Many institutions [15] around the world have experimented and discovered new methods to improve the efficiency of solar panels, electrolyzers and stacks of fuel cells, for many applications in industry, automotive [16] and transportation areas. Those institutions have developed projects to create components and materials for solar cells, electrical power supplies, chemical energy conversion, and energy storage.
- Fuel cells are new and clean DC power sources. Some authors have tested PEM fuel cell Nexa™, produced by Ballard [17], in hybrid solar/fuel cell power systems. First, the mathematical model using Simulink [18] was prepared. It contained PV array model, PEMFC model and power/control unit models. Solar irradiation and ambient temperature were the input parameters. Load power and current of each source currents were output variables. Results showed the way to improve the efficiency of the complete system and the advantage, in terms of cost, for this power plant operation.

1.9 Overview of the Thesis

This thesis is structured as follows: Chapter 2 provides background information on hybrid energy systems as well as main PMM components. Chapter 3 describes in detail the PMM design process. Description and results of laboratory experiments are presented in Chapter 4. Chapter 5 contains the conclusions and general discussion about results and constraints found during PMM design steps and cost analysis.

CHAPTER 2 POWER MANAGEMENT MODEL (PMM) DEFINITION

2.1 Hybrid Energy Systems and Power Management Model

This chapter provides background information on hybrid energy systems as well as main Power Management Model (PMM) components.

A Power Management Model (PMM) [19-20] is a combination of mathematical models, block diagrams and technical requirements or instructions that are defined in order to create a logic operation of a Hybrid Energy System (see Figure 2-1).

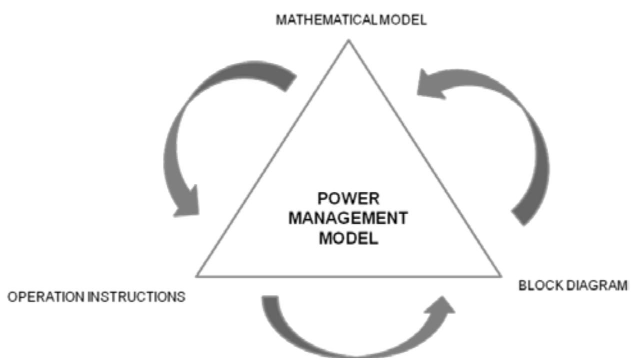


Figure 2-1 PMM Components Interaction Process.

A PMM allows the coordination between different energy sources, such as solar cells, electrolyzers and fuel cells, to maintain the continuous feeding to an electrical critical DC load.

- PMM has to be considered in order to determine when the various components of the system will be used.

- PMM has three components (see Figure 2-2): mathematical model, block diagram and set of system operation instructions.
- PMM has an effect on hybrid energy system operating cost.
- PMM principles of operation are the continuous feeding of the load and the continuous energy flow among energy sources.

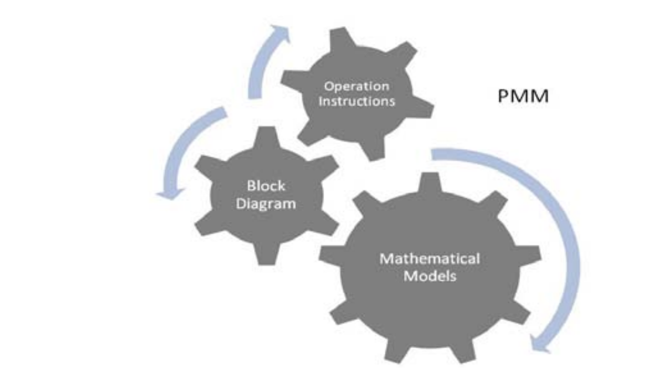


Figure 2-2 Power Management Model - Main Components.

PMM Mathematical model: Mathematical models [21-22] describe a system and its variables; it uses mathematical language (see Figure 2-3) to represent the system. An overall control strategy for power management of different energy sources and loads operation is needed, and math models are one of the more powerful engineering tools to achieve it.

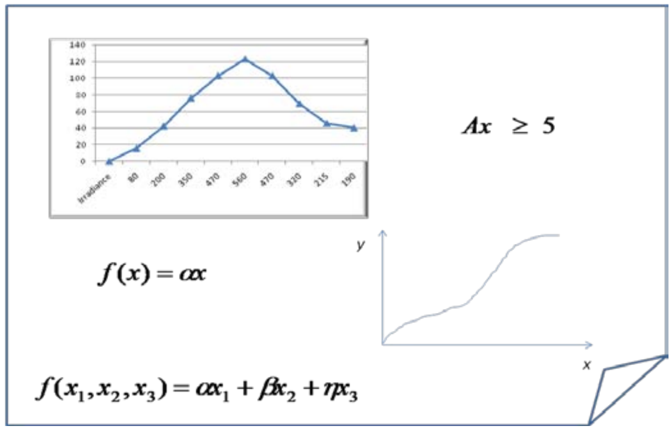


Figure 2-3 Some Mathematical Model Representations.

Input or output power related to Photovoltaic array, electrolyzer and fuel cell stack are defined as the main variables, as well as the power consumed by DC load.

Figure 2-4 shows the proposed system, indicating power variables:

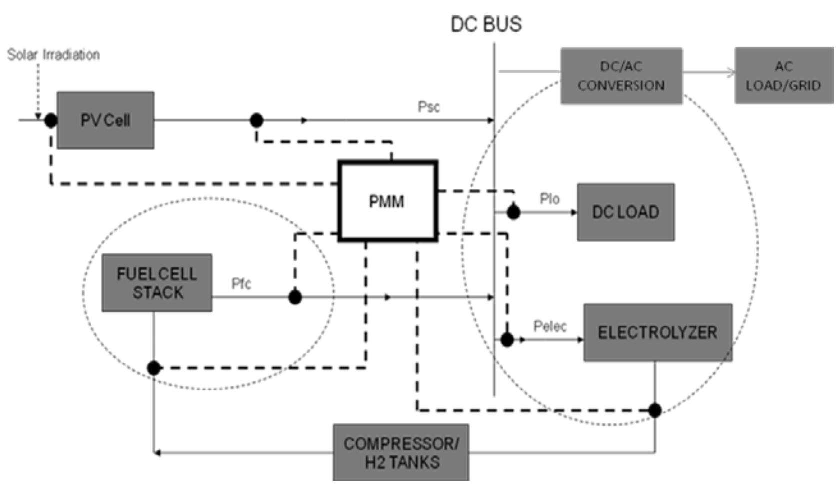


Figure 2-4 Proposed Configuration for PMM To Control Hybrid System Operation.

P_{sc}: Photovoltaic array output power

P_{lo}: DC Load

P_{elec}: Electrolyzer input power

P_{fc}: Fuel Cell Output power

PMM: Power Management Model/System

The PFHES shown in Figure 2-4 consists of a photovoltaic (PV) array, a hydrogen energy storage system (an electrolyzer- storage tank combination) and a fuel cell stack. PMM implementation is based on the proposed hybrid energy system operation:

- Electricity production in excess of demand is converted, using electrolysis of water, to hydrogen gas.
- On the other hand, electricity demand in excess of production is met by converting hydrogen to electricity through a fuel cell.
- If solar energy is being used, then conservation of energy throughout the hour or day requires seasonal energy storage; this is one of the major constraints of PFHES operation.
- Electrolyzer and hydrogen storage tanks accumulate the amount of power generated by PV array for use when needed by the load.

Additionally, it is relevant to identify other Input and Output variables such as time-varying solar irradiation (by hour) and load variations. As a consequence, some important variables that will be used as part of the PMM designing process are Solar Irradiation data and load profile.

Another component for math models are those empirical equations related to solar cells, electrolyzer and fuel cells performance. Those equations are mentioned in this chapter and in Chapter 3. Finally, hybrid energy system Cost Function represents the last component of math approach.

At this stage, Linear programming [22] theory must be mentioned because this particular mathematical tool can be applied when an objective function, such as cost function, wants to be minimized under several constraints. Labview [23] has a tool denominated as a linear programming solving (see Figure 2-5) and this tool can be applied in order to perform cost analysis.

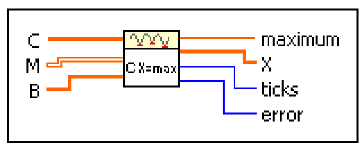


Figure 2-5 Linear Programming Function (Labview, National Instruments).

Some parameters are mentioned:

C: vector describing the linear function to maximize.

M: matrix describing the different constraints.

B: vector describing the right sides of the constraints inequalities.

Maximum: maximal value, if it exists, of x under the constraints.

X: the solution vector.

Linear programming technique applied to cost function will be explained as part of Chapter 3.

Block diagram: A block diagram (see Figure 2-6) is a diagram of the PFHES driving by the PMM, in which the blocks will represent the PFHES subsystems and the lines will represent the relationship between the subsystems and how the power flows among each element. A proposed block diagram is identified in Figure 2-7.

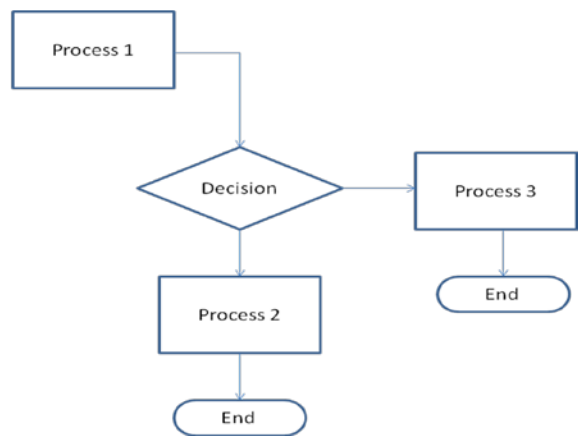


Figure 2-6 Example of a Block Diagram Representation.

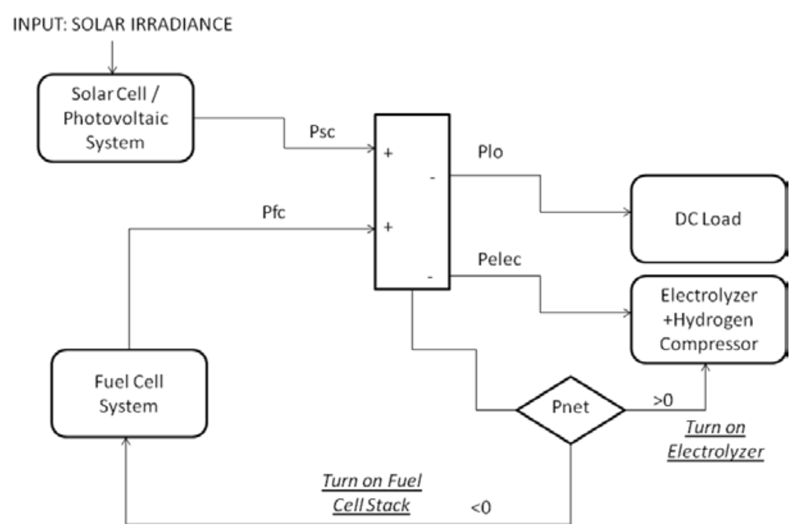


Figure 2-7 Proposed Power Management Model (PMM) Block Diagram.

Logic of PMM implementation is identified by reading the block diagram:

- Solar Irradiation (by hour) is the main input variable.

- Photovoltaic Array subsystem produces energy from sun.
- PMM compares, at a specific time (hourly), load demand and Psc.
- If there is an excess of generated power over load demand, then the electrolyzer is turned on to produce hydrogen.
- If there is a deficit of generated power to meet load requirements, then the fuel cell is turned on to produce power.

In general, the block diagram may be read by defining a set of PMM operation instructions.

PMM strategy or operation instructions: A set of instructions or operation conditions must be identified as part of PMM. Those instructions are based on constraints and simulations results. One of the most important elements of instructions is the PFHES operation schedule.

Some questions must be analyzed as part of PMM strategy definition:

- What happens when power produced by PV array is greater than the power consumed by the DC load?
- What can the system does when power produced by PV array is smaller than the power consumed by the DC load?
- What happens when the hydrogen storage tank is full, and there is also an excess of power produced by the photovoltaic array?
- What are the many technical constraints associated with the PFHES operation?
- Do those constraints affect PMM design process?

The answers to those questions are outlined in Chapter 3.

2.2 Hybrid Energy Systems

Currently we can observe the very fast development of new electrical power sources, denominated as renewable sources. These sources are environment friendly and use primary energy carriers like solar (see Figure 2-8), wind (Figure 2-9) and water flow, biogas, biomass, among others. [24]

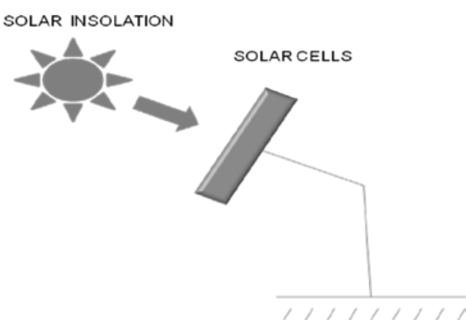


Figure 2-8 Photovoltaic Array Representation.

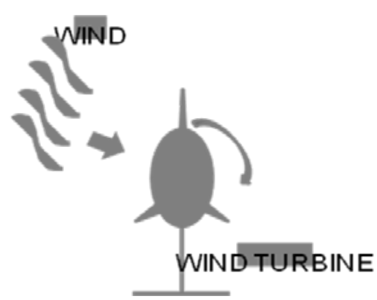


Figure 2-9 Wind Power Representation.

By increasing the use of renewable energy resources it is possible to support sustainable development of the global economy. Renewable energies include hydro power, solid wastes, biomass, geothermal, solar thermal, solar photovoltaic, wind power, and fuel cell (see Figure 2-10).

The particular renewable energies that have shown progress and great potential for market penetration is photovoltaic (PV) and fuel cell.

Figure 2-10 Proton Exchange Membrane Fuel Cell Component.

The energy sources mentioned above can be split into two groups: controlled sources and uncontrolled sources [25]. Controlled sources mean primary energy sources giving possibility to controlling electrical power production, for example coal. Uncontrolled sources are unpredictable and human independent, and a good example of this kind of source is solar energy.

On the other hand, by using controlled sources it allows electrical power to be produced exactly at the same time when it is needed. Sun and wind do not meet this requirement. Therefore special kinds of power systems should be built to avoid shortages of power and to utilize all available energy from sun. There is an option to achieve it: power systems using two primary sources (solar cells and fuel cells) with an additional control scheme. This control scheme is well identified as a PMM implementation.

2.3 Fuel Cells

This item provides basic information about fuel cell operation, types of fuel cells and a description of Proton Exchange Membrane Fuel Cell. In addition to that, the importance of PFHES fuel cell stack subsystem is mentioned.

Operation of fuel cells is such an important factor for a solar/fuel cell hybrid energy system performance (Figure 2-11).

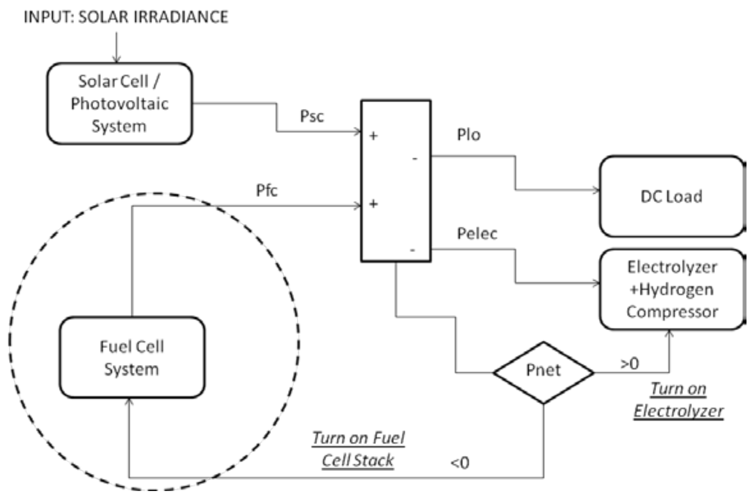


Figure 2-11 Fuel Cell Location in the Block Diagram.

In the scenario of alternative and sustainable energy, the governments of developed countries are working to explore the potential of some sources of energy such as hydrogen. Hundreds of studies also have demonstrated that Fuel Cells, which use hydrogen and oxygen to produce electrical power, represent an essential device for the future large-scale generation of electrical energy. Fuel Cells are useful as power sources in remote locations such as rural farms, military bases, wastewater treatment plants, hospitals, office buildings and many others.

A fuel cell is an electrochemical conversion device [26] that works with a fuel (regularly hydrogen), an oxidant (regularly oxygen) and an electrolyte media; fuel is located in the anode side and the oxidant is located in the cathode side of the device. Additionally, with the urge of a catalyst element, hydrogen atoms are divided in protons and electrons. Protons pass through the cathode and the movement of electrons creates an electrical current utilized before these electrons return to the cathode side. After this step, electrons are reunited with hydrogen and oxygen to form a molecule of water.

A fuel cell can produce Voltage of 1.23V at full rated load; a factor to be analyzed is that Voltage decreases as Current increases because of Ohmic loss (voltage drop due to resistance of the cell components and interconnections) and Mass transport loss (depletion of reactants at catalyst media, which causes loss of voltage). In order to deliver the desired amount of energy, fuel cells can be combined in series and parallel circuits; connection in series results in higher voltage (Kirchhoff's Voltages Law), while connection in parallel allows a stronger current to be drawn (Kirchhoff's Currents Law).

Actually, a variety of fuel cells exist with differences in parameters such as temperature of operation and type of electrolysis media, among others:

- Proton Exchange Membrane Fuel Cell (PEMFC).
- Phosphoric Acid Fuel Cell (PAFC).
- Solid Oxide Fuel Cell (SOFC).
- Alkaline Fuel Cell (AFC).
- Molten Carbonate Fuel Cell (MCFC).
- Direct Methanol Fuel Cell (DMFC).
- Regenerative Fuel Cell.

- Protonic Ceramic Fuel Cell (PCFC).
- Microbial Fuel Cell (MFC).
- Zinc Air Fuel Cell (ZAFC).

Proton Exchange Membrane Fuel Cell will be used as part of the PFHES. Proton Exchange Membrane Fuel Cell is one of the most important types of fuel cells. In this device, a proton-conducting polymer membrane is the electrolyte that separates the anode and cathode sides. In the anode side, hydrogen diffuses to the anode catalyst where it later dissociates into protons and electrons; protons are conducted through the membrane to the cathode and electrons are forced to travel in an external circuit because the membrane is electrically insulated. On the cathode catalyst, oxygen molecules react with electrons (these electrons have traveled through the external circuit) and protons to form water; as a consequence, waste products are liquid or vapor.

The efficiency of a PEMFC is related to the amount of power drawn from it. To draw more power means to draw more current, which increases the losses in the device, thereby reducing efficiency. Most losses manifest themselves as a voltage drop in the cell, so the efficiency of a cell is almost proportional to its voltage; as a result, the denominated Polarization Curves (graph of voltage versus current) are analyzed for every fuel cell. A typical cell operating at 1.2 V has an efficiency of about 50%, meaning that 50% of the energy content of the hydrogen is converted into electrical energy and the remaining 50% will be converted into heat. Production, transportation, and storage processes of hydrogen can generate additional losses.

A description of main PMEFC characteristics and advantages of application is shown in Table 2-1.

Table 2-1 Advantages of PEMFC.

ADVANTAGE	DESCRIPTION	DATA
STATIONARY POWER	Stationary PEMFC produces less emissions than conventional power plants	PEMFC power plant may create less that one ounce of pollution per 1000 Kwh
TRANSPORTATION	Fuel Cell vehicles produce zero pollution	Fuel Cell in trucks can save more than 4.64 million tons of CO2 per year
EFFICIENCY	Fuel cell are most efficient than combustion systems	Fuel cell systems achieve 50% fuel-to-electricty ratio
FLEXIBILITY	Hydrogen can be produces from different sources	Oil demand can be reduced by more than 11 million barrels by 2040.
SECURITY	Need to import foreign oil is eliminated	If just 20% of cars used fuel cells, oils imports decrease to 1.5 million barrels per day
SCALABILITY	This fuel cell is scalable (different sizes and output power design)	Fuel cell can reduce facility energy cost by 40%
WEIGHT	Smaller space in comparisson with batteries	Portable electronic device applications

PEMFC makes energy electrochemically and does not burn fuel, so this fuel cell is more efficient than a combustion system. When the fuel cell is sited near the point of use, its waste heat can be captured for beneficial purposes (for example cogeneration). Efficiencies of 40% to 50% have been achieved utilizing hydrocarbon fuels. Today it is estimated that a typical computer location has 289 power disturbances in one year, which results in a U.S. business loss of $29 billion annually from computer failures; but fuel cells may help to prevent not only loss of power but also loss of money.

Additionally PEMFC can be configured to provide power in a completely new way to customers (independent way to the grid) or the grid can be used as a backup.

Modular installation (the installation of several identical units to provide a desired quantity of electricity) provides very high reliability in specialized applications.

In general PEMFC can offer clean and high quality power, which is crucial to the operation of computers, medical equipment and machines.

In actuality, there a variety of applications of Proton Exchange Membrane Fuel Cells:

- Many automakers are working to commercialize fuel cell cars, buses, boats, trains, planes, scooters, and bicycles.
- Over the last four years, more than 50 fuel cell applications for buses have been developed in North and South America, Europe, Asia and Australia.
- Fuel cell buses can reduce transit CO2 emissions. Emissions are zero if the hydrogen is produced from renewable electricity, which improves local air quality. For example the operation of fuel cell buses reduces noise pollution.
- Telecommunications companies are installing fuel cells at cell phone, radio and 911 towers. With the increase in the use of computers, the Internet, and communication networks, there is a need for more reliable power in comparison to available power from electrical grids. In addition, fuel cells have proven to be up to 99.9% reliable.
- Fuel cells can replace batteries to provide power for 1KW to 5KW without noise or emissions, and are durable as well, providing power in sites that have difficult access or are subject to inclement weather.

There are two important tools to understand the operation and result of internal process in a Fuel Cell: Faraday’s Laws of Electrolysis [27].

- First Law of Electrolysis: The quantity of elements separated by passing an electrical current through a molten or dissolved salt is proportional to the quantity of electric charge passed through the circuit. This fact is represented by:

$$m = (Q/F)*(M/z) \qquad (5)$$

The mass of a substance altered at an electrode during electrolysis (Figure 2-12) is directly proportional to the quantity of electricity transferred at that electrode. Quantity of electricity refers to electrical charge, typically measured in coulombs.

In the equation,

m = mass of the substance altered at an electrode.

Q = total electric charge passed through the substance.

F = 96 485 C mol-1 (Faraday constant).

M = molar mass of the substance .

z = valence number of ions of the substance (electrons transferred per ion).

M, F, and z are constants, so that the larger the value of Q, the larger m will be.

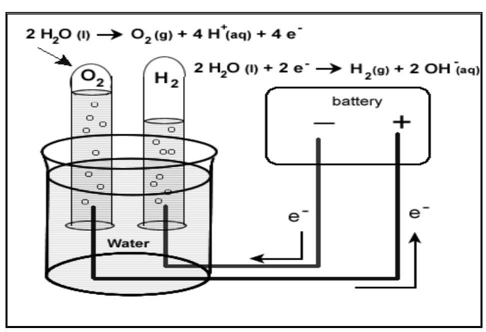


Figure 2-12 Electrolysis of Water Representation.

- Second Law of Electrolysis: Faraday discovered that the current generated in electrolysis is proportional to the mass reacted or produced.

$$n' = (iA/nF)=(I/nF) \quad (6)$$

n' = rate of molar consumption or production of species x.

I = current (A).

A = superficial electrode area.

i = current density.

n = equivalent electrons per mole of reactant x.

F = charge carried on one equivalent mole.

2.4 Solar Cells

In this section, a basic explanation of photovoltaic cells is provided. A photovoltaic array may be one of the most important components of subsystem of a hybrid energy system. Governments around the world have defined global and effective strategies to implement small and large scale photovoltaic systems: *"Now we will work with businesses and communities to use the sun's energy to reduce our reliance on fossil fuels by installing solar panels on 1 million more roofs around our nation by 2010. Capturing the sun's warmth can help us to turn down the Earth's temperature"*. (President Bill Clinton, Million Solar Roofs Initiative Announcement to the United Nations Special Session on Environment and Development, New York June 26, 1997) [28]. One of the Power Management Model (PMM) control variables is the data related to solar irradiance (Figure 2-13) because this variable becomes Photovoltaic subsystem input.

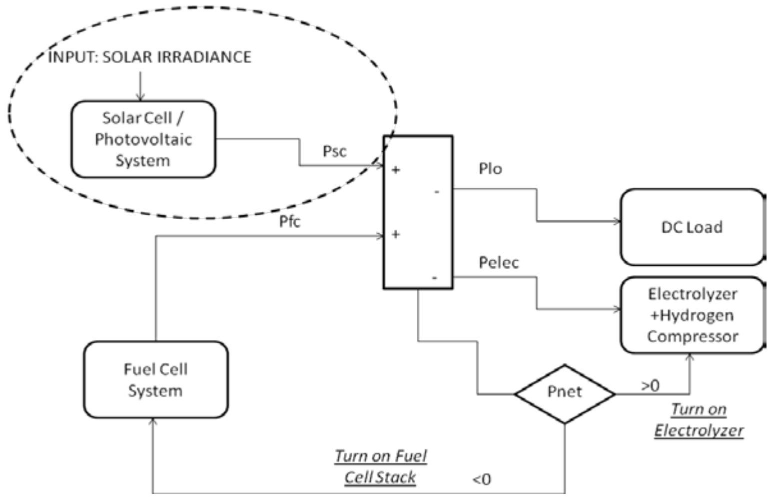


Figure 2-13 Photovoltaic Subsystem Location in the Block Diagram.

In general, it is important to know some issues related to the operation principles for PV systems. The sun provides solar energy through solar irradiation. Irradiation [29] or Insulation is the measure of power density of sunlight and is measured in W/m^2. This is an instantaneous quantity so it has to be measured during a continuous period of time. The solar constant for earth is the irradiance received by the earth from the sun at the top of the atmosphere and is equal to 1367 W/m^2.

Some important points about Irradiation are mentioned here:

- Normally the time period of integration is one day (for daylight hours).
- Irradiation depends on location, weather conditions and time of year, inclined or horizontal surfaces and shaded zones.
- Irradiation on surfaces is related to the angle between the surfaces and the incident beam. The angle of deviation of the sun from above the equator is called declination. The zenith is a line perpendicular to the earth and the zenith angle is defined as the angle between the sun and the zenith. [30]

$$\theta_z = \phi - \delta \quad (7)$$

Where Φ represents the latitude and δ is the declination.

- To specify the position of the sun, it is necessary to mention two coordinates: solar altitude and azimuth. The solar altitude is the compliment of zenith angle. The azimuth measures the angular position of the sun (east or west) of solar noon.
- The numbers of hours of daylight is DH [31]:

$$DH = \frac{48}{360} * \omega_s \quad (8)$$

Where ω_s describes the position of the sun from solar noon, in the plane of apparent travel of the sun.

- Sun shines longer in the summer than in the winter.
- Cloudy places receive less sunlight than sunny places.
- The hours of sunlight over a year are the same for every point on the earth and only the hours between sunrise and sunset are counted.
- Pyranometer is the instrument used to measure solar radiation.

It is important to consider how long the sun shines in a particular place or in a particular day and how much sunlight can be expected during some months at a specific location for Power Management Model (PMM) design stages.

In general the design of a PMM, whose application is intended to control a Photovoltaic subsystem operation, depends on use of data based on measurements averaged over a long period of time:

- To maximize irradiation on the PV collector, it is necessary to track the sun by using a tracking system.

- Solar Cell Current-Voltage Characteristic: For a PV subsystem, we have to measure its I-V characteristic [32]. Both I and V depend on the irradiation level, and the PV output current I is equal to:

$$I = I_l - I_o(e^{\frac{qV}{kT}} - 1) \quad (9)$$

Where I_l is the component of cell current due to photons, q is equal to 1.6×10^{-19} coulombs, k is equal to 1.38×10^{-23} j/K and T is the cell temperature in Kelvin. The product of the voltage and current is the power.

- Generally, a typical PV cell can produce 2 watts, but solar cells can be connected as modules and arrays, so a higher voltage and power can be obtained by using series/parallel connections.
- Most of PV modules are operated at voltages that are multiples of 12VDC. Therefore the idea is to maintain this output voltage under conditions of average irradiation.

Since a PV array produces power only when it is illuminated, PV systems employ a energy storage mechanism to capture energy that can be used in a later time. That storage mechanism may be an electrolyzer with hydrogen storage tanks.

2.5 Electrolyzer and Hydrogen Storage Mechanism

In this section, a basic explanation of electrolyzer and hydrogen storage mechanism (Figure 2-14) are provided.

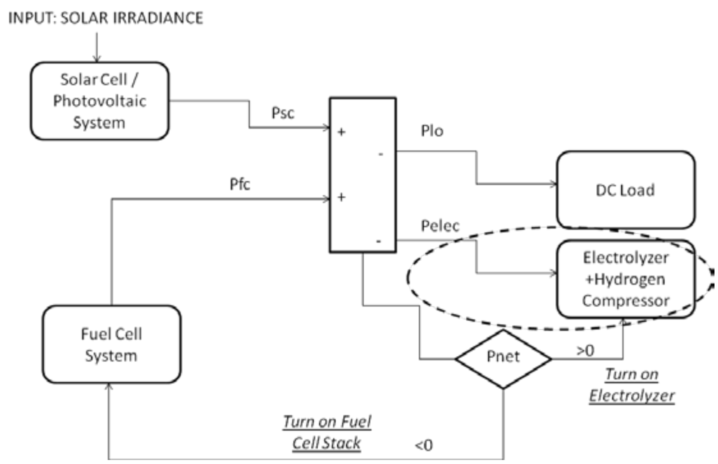


Figure 2-14 Electrolyzer Location in the Block Diagram.

Hydrogen is an energy source. The criterion to select the hydrogen as a transportation fuel is based on versatility, efficiency, environmental compatibility, safety and economics [33].

- Hydrogen is easy to produce and easy to transmit and store.
- Hydrogen is a non-polluting fuel and it is more efficient that other common fuels.
- Hydrogen can be generated by using water electrolysis where water and DC voltage or electricity are the sources for hydrogen generation. In fact, water is the most abundant source of hydrogen on the planet. An energy of 1.229 eV (at 25°C, 1 bar) is required for splitting water into hydrogen and oxygen [34].

Photoelectrolysis [35] integrates solar energy collection and water electrolysis and it is considered the most efficient renewable method of hydrogen production. One kind of photoelectrochemical device is the photovoltaic electrolysis cell, which employs a solid state photovoltaic to generate the electricity that then is passed to a commercial water electrolyzer.

Electrolyzers are used to produce hydrogen in cm^3/min or m^3/hour. Input energy to the electrolyzer could be supplied by an alternative/sustainable energy source such as solar energy.

Electrolysis [36] is a process of dissociating elements and compounds by passing through them an electric current. Water electrolysis decomposes H_2O into hydrogen and oxygen gases.

Electrolysis of water to produce hydrogen and oxygen is a simple technique for water splitting. The general reaction [37] that takes place in this process is:

$$H_2O(liquid / vapor) + electricalenergy \rightarrow H_2(g) + \frac{1}{2}O_2(g) \quad \textit{(10)}$$

Oxygen is the by product. Water electrolyzers satisfy about 3.9% [38] of the hydrogen demand on the planet. An electrolyzer consists of two electrodes, cathode + anode and an electrolyte, whch is water in this case. Reduction and Oxidation reactions take place, forming hydrogen (cathode) and oxygen (anode). Electrolytes dissolve and dissociate into cations (positive ions) and anions (negative ions) that carry the current. Faraday's Laws of electrolysis can be applied to calculate quantity of hydrogen generated by electrolysis of water.

At standard ambient temperature and pressure, electrical energy to chemical energy conversion operates in the electrode solution interface through charge transfer reactions. A potential difference applied between electrodes can be used to produce hydrogen and oxygen and the minimum value of this potential is 1.229Volts. The energy losses in electrolysis are associated with reaction kinetics, charge transport through electrical leads and the electrolyte. The efficiency of electrolysis process is defined as the ratio of energy content of hydrogen (the energy that can be recovered by reoxidation of the hydrogen and oxygen to water) to the electrical energy supplied to the electrolyzer.

The cell must be operated at low voltages and high current densities to obtain high efficiencies and high hydrogen production rates. Practical efficiencies are between 50% to 90%.

2.6 DC Critical Load

Critical loads [39] are those for which the power is required for at least 99% of the time. Non-critical loads require power at least 95% of the time. This means that for the critical load, the system must be available 99%during any period of time at least.

For the specific case of this thesis, critical load (Figure 2-15) will be used; it is represented by some electronic equipment (DC load) that supports security system operation. Also, DC/AC conversion can be included to play with AC load applications.

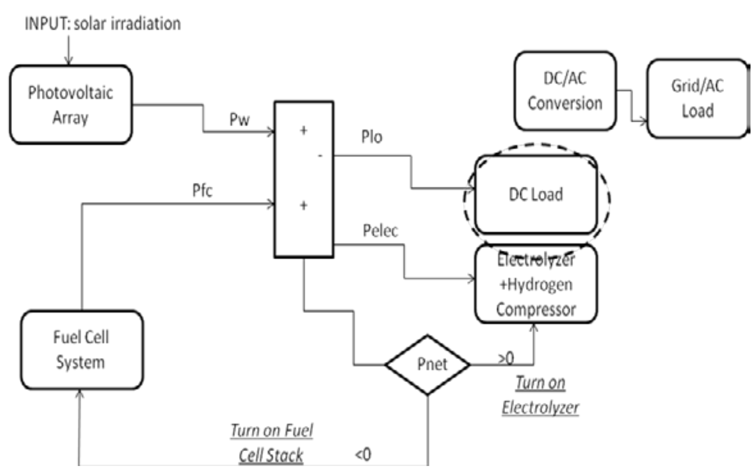


Figure 2-15 Load Location in the Block Diagram.

CHAPTER 3 POWER MANAGEMENT MODEL (PMM)

In this chapter we present the power management model design process for the Photovoltaic/Fuel Cell Hybrid Energy System (PFHES), the case study of this thesis. The PMM mathematical model and block diagram will be elaborated. The simulation associated with PFHES operation under PMM control is presented by using Labview tools. Also, the simulation of the hybrid system is developed by using wind as the primary energy source. Finally, a general cost analysis that is associated with PFHES operation is presented.

3.1 PMM Components and PFHES

The proposed PFHES is shown in Figure 3-1:

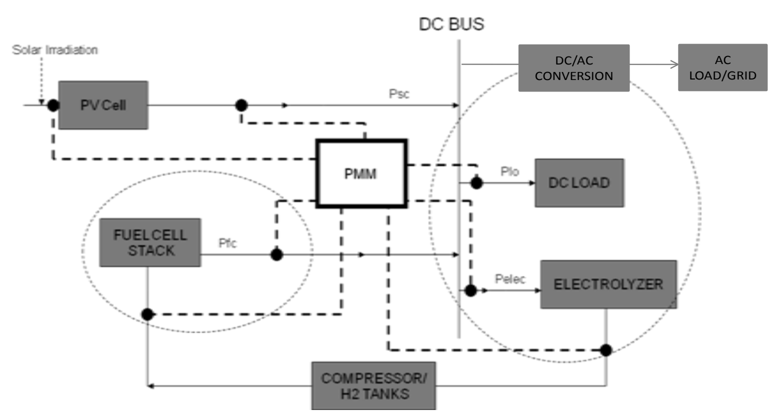


Figure 3-1 Proposed Hybrid System with PMM.

The main input/output variables are:

P_{sc}: Photovoltaic array output power.

P_{lo}: DC Load.

P_{elec}: Electrolyzer input power.

P_{fc}: Fuel Cell Output power.

PMM: Power Management Model/Module.

A Power Management Model has following components:

1- PMM operation mathematical model: The mathematical model can be divided into Power Balance Equation and subsystem model. For the subsystem model, Mathematical Models for fuel cells, electrolyzers and solar cells will be taken from existing technical documentation and from information presented in Chapter 2.

2- Block diagram: The PMM block diagram will show the power flow between subsystems as well as all inputs and outputs system variables.

3- General instructions: General instructions will be established based on initial conditions, load requirements, operation schedule and details contained in items 1 and 2 mentioned above.

A power management strategy will be defined based on the information obtained from items 1 to 3. The first step will be to mark out all initial conditions that could be relevant for system operation and PMM design. These conditions will be explained later in the chapter. One of the most important results of PMM design process is the identification of a particular hybrid system operation schedule.

Mathematical models are based on equations describing subsystem performance and subsystem operation sequence; following are the variables of the PFHES:

P_{net}: is the result of the total power flow from sources to loads. It represents the balance equation.

P_{lo}: power consumed by DC load.

P_{elec}: power consumed by electrolyzer to generate hydrogen.

P_{fc}: fuel cell output power.

P_{comp}: power consumed by hydrogen compressor (this variable is assumed to be included in P_{elec}).

P_{fc}: power produced by the fuel cell stack.

P_{ot}: self consumed power that is related to auxiliary equipment (it is neglected).

The proposed block diagram is shown in Figure 3-2.

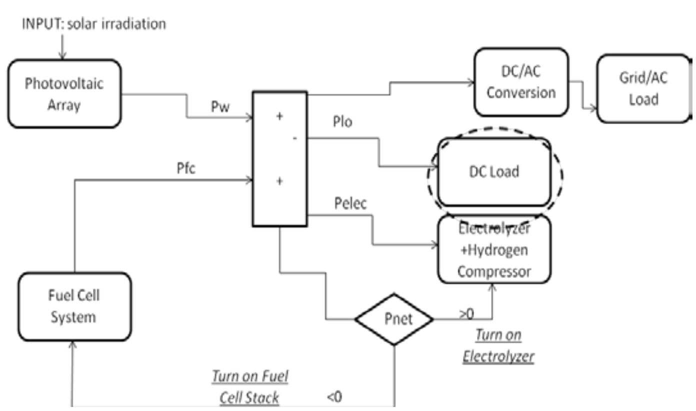


Figure 3-2 PMM Block Diagram.

One of the objectives is to minimize the cost function that typifies the PFHES operation, under PMM control; the cost function is based on capital and maintenance hourly cost components for each of the subsystems.

The PMM design process requires that electrical demand must be met while minimizing an objective function, which will be the hourly operation cost of the hybrid system. This function will be identified as C_T. C_T is the sum of hourly capital and hourly maintenance cost.

$$C_T = C_C + C_M \quad (11)$$

These costs can be broken up into the hourly cost for PV array, electrolyzer+hydrogen storage and fuel cell subsystem.

$$\begin{aligned} C_C &= C_{\mathrm{csc}} + C_{celec} + C_{cfc} \\ C_M &= C_{msc} + C_{melec} + C_{mfc} \end{aligned} \quad (12)$$

The objective function C_T is also constrained to minimize the magnitude of the difference between generated power and the demand over a given period of time (hour). In general, PMM design involves minimizing the PFHES cost function under PMM control.

$$C_T = C_C + C_M \quad (13)$$

$$\begin{aligned} (C_{\mathrm{csc}} + C_{msc})P_{sc} &= \alpha P_{sc} \\ (C_{celec} + C_{melec})P_{elec} &= \beta P_{elec} \\ (C_{cfc} + C_{mfc})P_{fc} &= \lambda P_{fc} \end{aligned} \quad (14)$$

Therefore, the objective is to minimize cost function:

$$\alpha P_{sc} + \beta P_{elec} + \lambda P_{fc} \quad (15)$$

Cost analysis will be presented later in the chapter.

3.2 Explanation and Subsystem Sizing Procedure

For the PMM design it is necessary to follow these steps:

- Conditions Mark Out: Initial conditions.

- Load is DC load and it is variable in time: Hourly load profile is used. DC/AC conversion can be used as part of AC load/Grid connections.
- Load is always "On": It can be DC load or AC load.
- Solar Irradiance must be one of the system input variable.
- DC Voltage of solar PV array is defined before sizing all subsystems.
- PV array, electrolyzer and fuel cell stack sizing procedure must be done by using load profile and other subsystem technical characteristics.
- An automatic solar tracking system is assumed to be part of the Photovoltaic Array, to maximize irradiation on the PV collector.
- Power consumed by hydrogen storage mechanism is already included in the variable used for electrolyzer (P_{elec}).
- Power consumed by other auxiliary equipment that can be part of the system is neglected for all calculations process.

Next, each condition is explained:

- **Load is DC load (variable in time):** There is a load profile (Figure 3-3) [40] (hourly demand) that is related to a particular security system DC electrical portion.

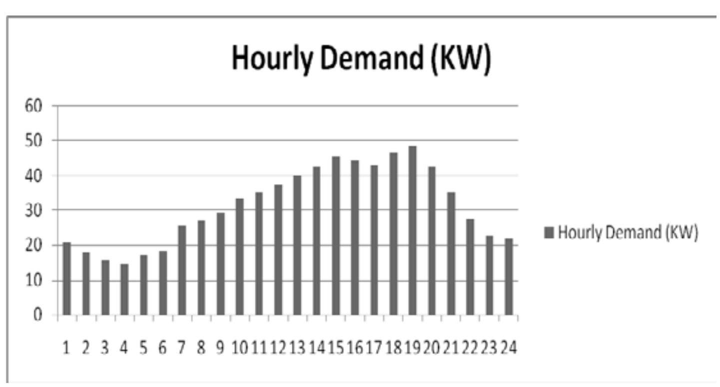


Figure 3-3 Proposed Load Profile (Load Demand).

- **Solar Irradiance must be one of the system input variable:** Solar irradiance data is presented in Figure 3-5.
- **DC Voltage of solar PV array is defined before sizing all subsystems:** 12 DC Volts.
- **Based on this information we size PV array, electrolyzer and fuel cell stack:** The following unit-sizing procedure [41] is used to determine the size of PV array, fuel cell stack and electrolyzer. Capacity factor concept is applied for indicating the overall efficiency and the availability of a renewable energy source.

$$C_{factor} = K_{fac} = \frac{\overline{P}}{P_{rated}} \quad (16)$$

~~P~~ is the actual average output power over a period of time and P_{rated} is the nominal power rating of the renewable energy source. $K_{fac(sc)}$= 10% for solar energy source.

The purpose of unit sizing is to minimize the difference between the generated power (P_{gen}) from the renewable energy and the demand (P_{lo}) over a period of time T (T is taken as 1 hour).

$$\Delta P = P_{gen} - \overline{P}_{lo}$$
$$\Delta P = [K_{caf\,(sc)} * \overline{P}_{sc}] - \overline{P}_{lo}$$
$$\overline{P}_{sc} = \frac{\overline{P}_{lo}}{K_{caf\,(sc)}} \qquad (17)$$

From load profile, the average load demand is 31.4 KW. The size of PV array is calculated to be:

$$\overline{P}_{sc} = \frac{\overline{P}_{lo}}{K_{caf\,(sc)}}$$
$$\overline{P}_{sc} = \frac{31.4kW}{10\%} = 314kW \qquad (18)$$

The fuel cell – electrolyzer combination provides back up for the system. The fuel cell needs to supply the peak load demand when there is no solar power. Therefore the fuel cell stack size is 48.7 kW, because this is the peak load demand value. To leave a safe margin (15%), a 56kW fuel cell stack is used. The electrolyzer should be able to handle the excess of power from the PV array. The maximum possible excess power is:

$$P_{gen,\max} - P_{lo,\min} = 315kW - 14.7kW = 300.3kW \qquad (19)$$

It is known that electrolyzers are very expensive equipment and there is a good probability to obtain high solar irradiance values. Therefore, only 50% of this excess power will be used to define electrolyzer size. Due to the above mentioned reasons, the electrolyzer will be 150.15kW. This means that the system can produce hydrogen until this level.

- **An automatic solar tracking system is part of the Photovoltaic Array, to maximize irradiation on the PV collector:** This tracking system is usually implemented for most of photovoltaic arrays with the objective of tracking the sun. This means that it is necessary to concentrate the solar lens toward the sun because the sun's position in the sky varies with time of day. Therefore, solar cell equipment effectiveness can be increased by operating tracking systems.
- **Power consumed by hydrogen storage mechanism is already included in the variable used for electrolyzer (P_{elec}):** Some assumptions about hydrogen storage mechanism can be made to reduce design complexity. One of these assumptions is that P_{comp}, which is the power consumed by the hydrogen compressor to storage this fuel, is already included in P_{elec} (power consumed by electrolyzer). Thus, it is valid to express the electrolyzer plus hydrogen compressor operation as one (electrolyzer operation). In other words, P_{ot} is represented by P_{comp}, which is already included in P_{elec}.
- **Power consumed by other auxiliary equipment, which can be part of the system, is neglected for all calculations process:** This assumption is also made in order to simplify design complexity.

3.3 PMM Mathematical Model and Block Diagram Components

From item 3.2 we have the information to establish PMM mathematical model and block diagram.

Mathematical models: Mathematical models can be broken up into Power Balance Equations [42] and those equations that characterize PV array, Electrolyzer and Fuel Cell operation.

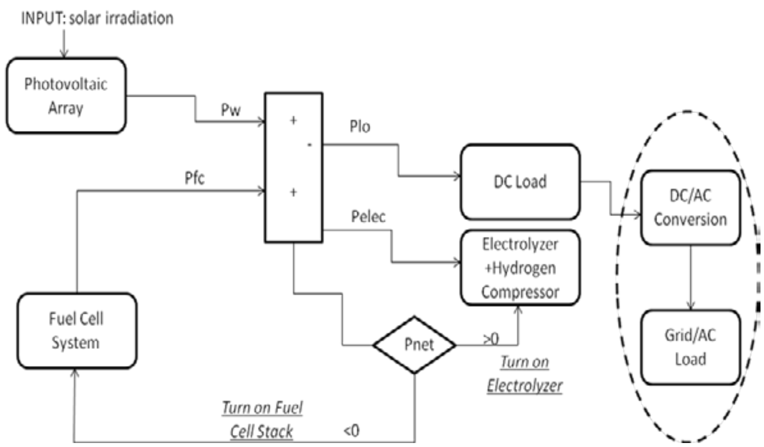


Figure 3-4 PMM Block Diagram.

By following block diagram logic, we see that we can propose a power management equation. The power difference between the generation source and the load demand (Figure 3-4) is calculated as the POWER BALANCE EQUATION,

$$P_{net} = P_{sc} - P_{lo} \qquad (20)$$

The governing control strategy (see block diagram in Figure 3-4) is that, at any given time, any excess of PV generated power (Pnet>0) is supplied to the electrolyzer to generate hydrogen, which is delivered to the hydrogen storage tanks through a compressor. Therefore the power balance equation can be written as:

$$\begin{aligned} P_{sc} &= P_{lo} + P_{elec} \\ P_{net} &> 0 \end{aligned} \qquad (21)$$

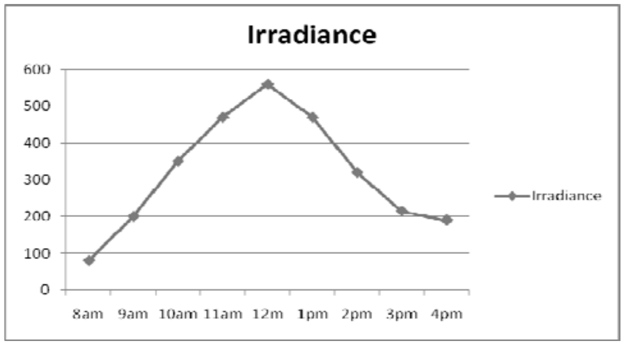


Figure 3-5 Solar Irradiance (Input Data).

When there is a deficit in power generation (P_{net}<0), the fuel cell stack begins to produce energy from the load using hydrogen from the tanks. Therefore, the power balance equation for this scenario can be written as:

$$\begin{aligned} P_{sc} + P_{fc} &= P_{lo} \\ P_{net} &< 0 \end{aligned} \qquad (22)$$

Secondly, those Subsystems mathematical models that represent PV array, electrolyzer and fuel cells operation, are mentioned:

$$I = I_l - I_o(e^{\frac{qV}{kT}} - 1) \text{ : PV array} \qquad (23)$$

$$n' = \frac{iA}{nF} = \frac{I}{nF} \text{ : Electrolyzer and fuel cell stack} \qquad (24)$$

3.4 Labview Simulations and PMM Strategy Definition

The general simulation of PFHES operation under PMM control will be done by using Labview tools. Solar irradiation data (Figure 3-6) and a specific value for DC hourly load (Figure 3-7) will be used as the main input variables.

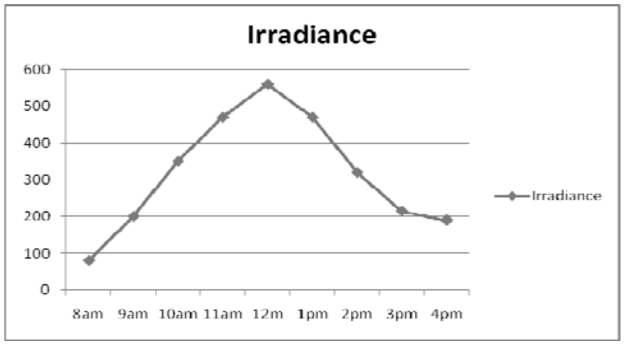


Figure 3-6 Hourly Solar Irradiance.

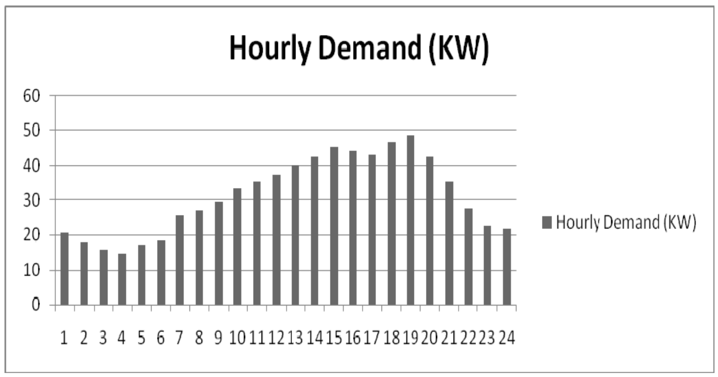


Figure 3-7 Hourly Demand.

It is important to use computer program applications to assist in PMM design. One of the applications is Labview [43] (Virtual Instruments). This program will create a sequence in such a way that some orders could be applied to different parts of the PFHES.

Labview software consists of a great number of functions that are classified as numeric, Boolean, case structures and instrumentation, among others. A group of key functions are those that represent loops running (i.e. while loops); it is possible to run a simulation that can execute a command. For example "***If*** there is a positive difference in the power flowing from the solar cells to the load, ***Then*** the electrolyzer is turned on to produce hydrogen”. Electrolyzer will be turned on/turned off, or electrical circuits for solar panels and fuel cell connection to load will be opened/closed. Simulations by using DAQ modules will be described in Chapter 4.

Simulations operate under schedule constraints, which means that we can obtain an approach for solar cells, electrolyzer and fuel cells operation schedule by using hourly solar Irradiation, for 24 hours a day. Detailed results of PFHES and PMM simulations can be described in Chapter 4, but the general results are presented next.

- **Input data:** One of the input variables for PFHES is solar irradiance (Figure 3-8).

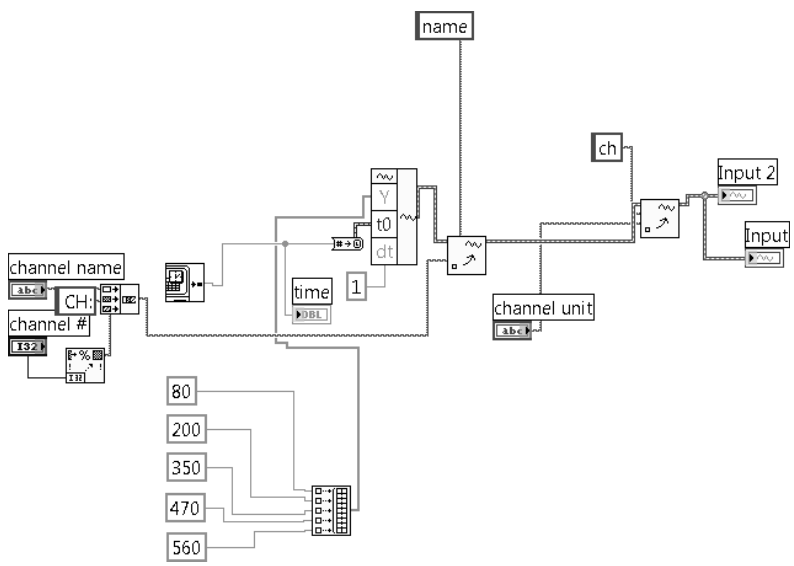


Figure 3-8 Portion of solar irradiance data, as input variable (Labview file)

- **PV subsystem model:** Mathematical subsystem models were inserted as part of the PFHES and PMM simulation (see Figure 3-9).

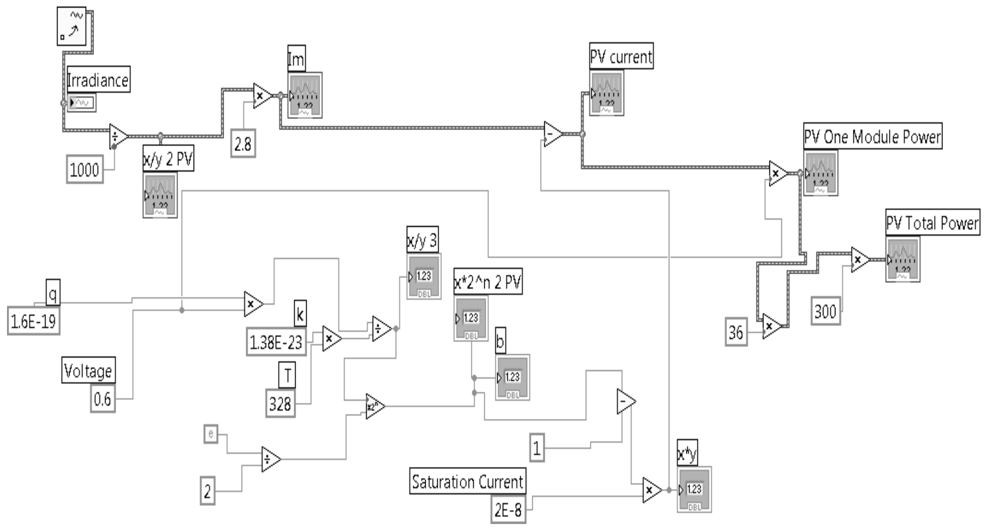


Figure 3-9 Portion of Photovoltaic Array Model (Labview file).

- **Making-decision model:** As part of PMM design process, it is necessary to define making-decision tools based on Power Balance Equations and Conditions (see Figure 3-10).

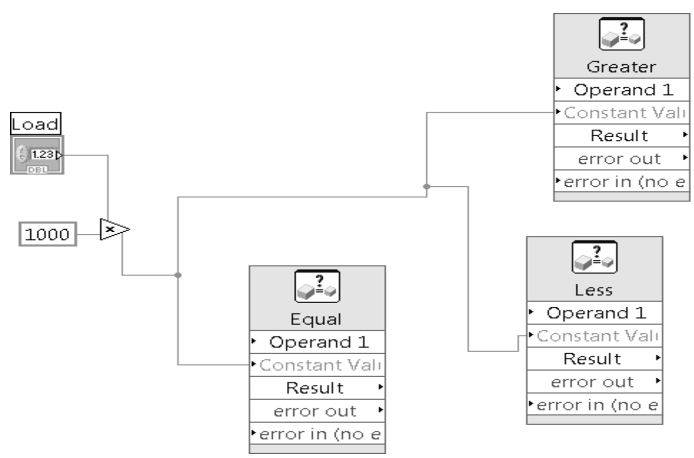


Figure 3-10 Portion of Decision-making Mechanism (Labview file).

- **Electrolyzer model:** Figure 3-11.

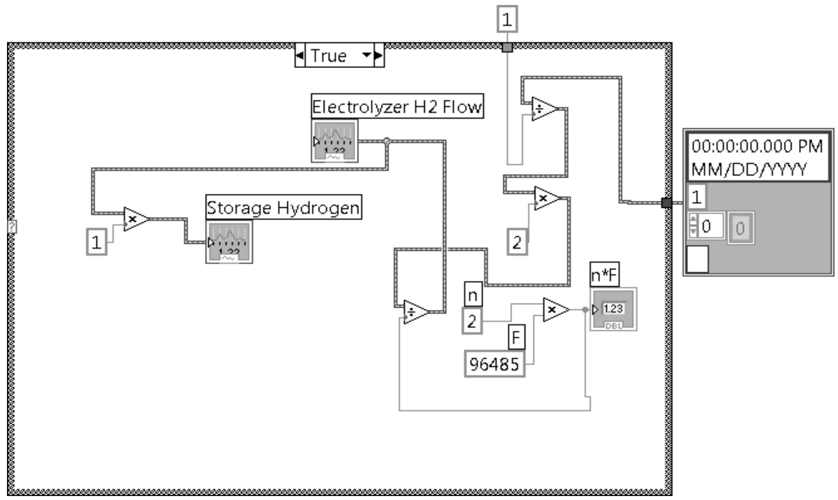


Figure 3-11 Portion of Electrolyzer Model (Labview file).

- **Fuel cell subsystem model:** Figure 3-12.

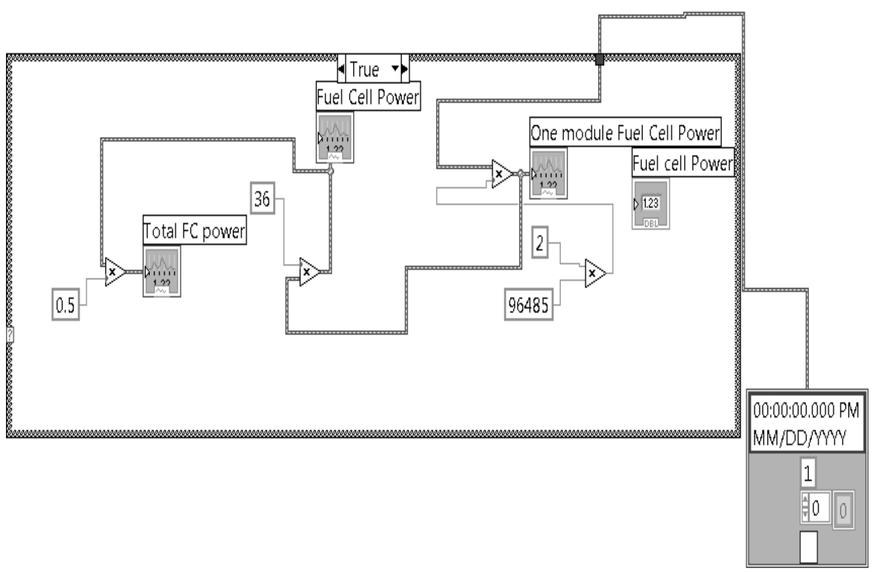


Figure 3-12 Portion of Fuel Cell Stack Model (Labview file).

- **How to read simulations results:** Simulation results can be obtained by opening the window panel (see Figure 3-13).

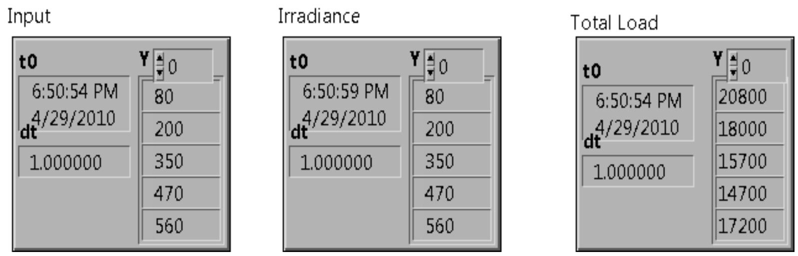


Figure 3-13 Portion of Solar Irradiance and Load Data, as Input Variables of the PFHES and PMM Simulation (Labview file).

The results also can be imported to an Excel sheet (Figure 3-14 and Table 3-1):

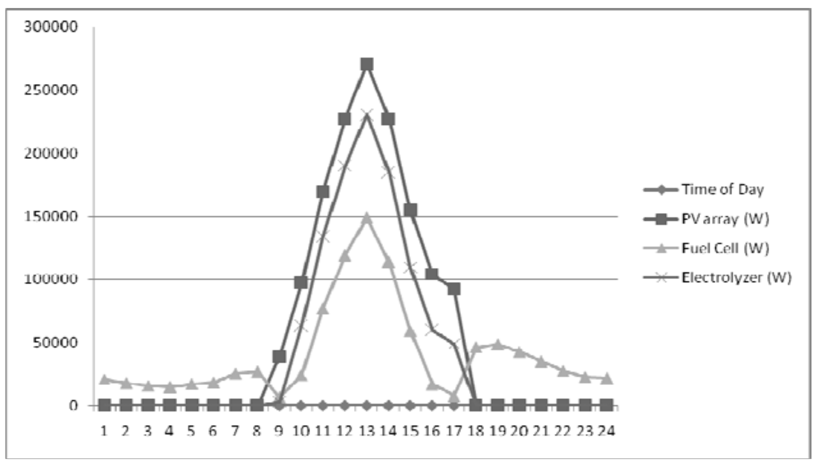


Figure 3-14 Photovoltaic, Fuel Cell and Electrolyzer Output Power, as Variables of the PFHES and PMM Simulation (Labview file).

Table 3-1 Ouput Power Data (Solar Scenario).

Time of Day	PV array (W)	Fuel Cell (W)	Electrolyzer (W)
0	0	20800	0
1	0	18000	0
2	0	15700	0
3	0	14700	0
4	0	17200	0
5	0	18400	0
6	0	25600	0
7	0	27200	0
8	38707	6538	2907
9	96768	24200	63368
10	169344	77191	134044
11	227404	119374	190204
12	270950	149239	230850
13	227404	114110	184904
14	154828	59382	109528
15	104025	16885	59825
16	91929	7476	48829
17	0	46500	0
18	0	48700	0
19	0	42400	0
20	0	35100	0
21	0	27600	0
22	0	22800	0
23	0	21900	0

Next, as mentioned before, the simulation of PFHSE and PMM operation can be elaborated, with Wind power as a primary energy source. To achieve it, wind velocity data (Figure 3-15 and Table 3-2) should be the input variable instead of solar irradiance values; wind power model is placed as part of the system scheme:

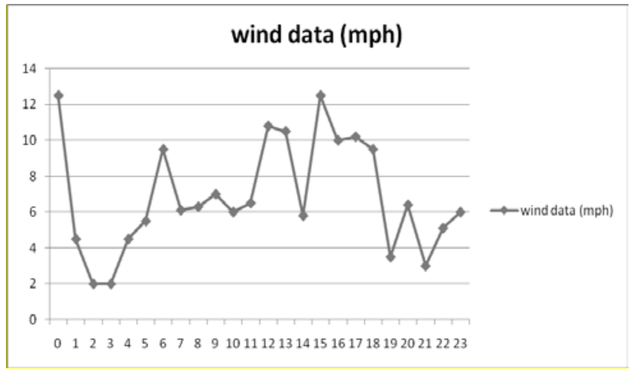


Figure 3-15 Portion of Wind Velocity and Load Data, as Input Variables of the PFHES and PMM Simulation.

Table 3-2 Ouput Power Data (Wind Power Scenario.)

Time of Day	Wind power (W)	Fuel Cell (W)	Electrolyzer (W)
0	177660	0	107645
1	0	18000	0
2	0	15700	0
3	0	14700	0
4	0	17200	0
5	0	18400	0
6	47262	0	47237
7	12512	27200	12485
8	13783	29500	13754
9	18907	33400	18874
10	11907	35300	11871
11	15138	37200	15101
12	69441	0	69401
13	63814	42500	63771
14	10755	45300	10710
15	107660	0	107621
16	55125	0	55081
17	58499	0	58452
18	47262	48700	47452
19	0	42400	0
20	14450	35100	14415
21	0	27600	0
22	7312	22800	7289
23	0	21900	11885

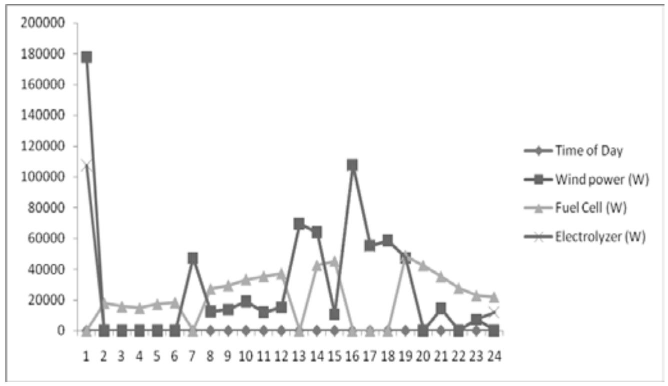


Figure 3-16 Wind Subsystem Power, as Output Variable of the PFHES and PMM Simulation (Labview file).

As we can see, PMM real implementation can be like a “brain” that contains all: math model, block diagram, strategy. Real alghoritms can be written by following Labview diagrams.

The simulation is also developed by using wind (see Figure 3-17) as the primary energy source.

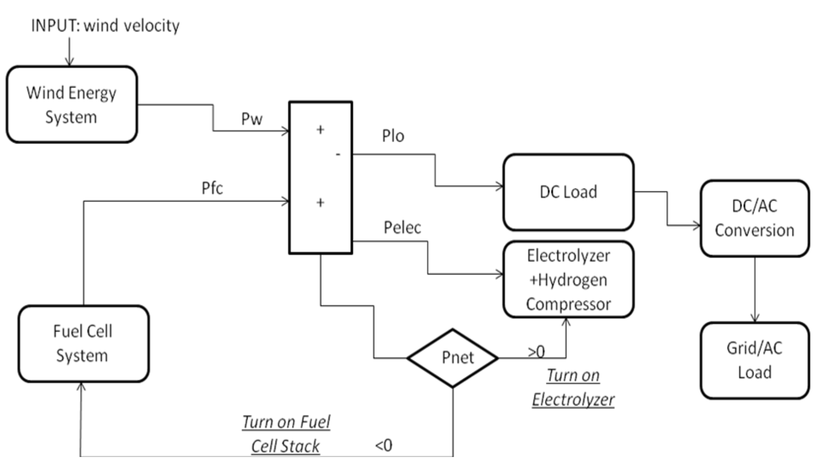


Figure 3-17 Wind Subsystem, as Part of PMM Block Diagram.

The power P_w extracted from wind is:

$$I = \frac{1}{2}\rho A \upsilon^{3} C_{p}$$

(25)

Where ρ is the air density in kilogram per cubic meter, A is the area swept by the rotor blades in square meter, and υ is the wind velocity (see Figure 3-18) in meters per second. C_p is called the power coefficient or the rotor efficiency and is a function of tip speed radio and pitch angle [40]. In other words, the output power of the wind turbine can be regulated by pitch angle control.

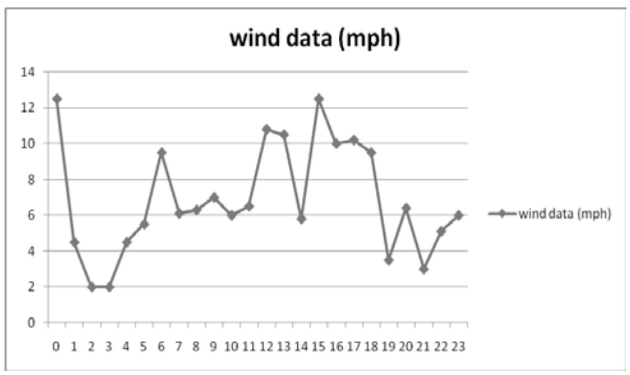


Figure 3-18 Wind Velocity Hourly Data.

Finally, information and results obtained from items 3.1 to 3.4, bring us to the Power Management Model. The results and analysis are shown in Chapter 4 and 5.

3.5 Cost Analysis

Since the Power Management Model implementation has an effect on component sizes and thus system and operating costs, the control strategy must be carefully considered for any system with energy storage. As we mentioned in Chapter 1, Labview linear programming tools are applied in order to find a solution to minimize cost function.

The PMM design process requires that electrical demand must be meet while minimizing an objective function, which will be the hourly operation cost of the hybrid system. This function will be identified as C_T. C_T is the sum of the hourly cost of the capital and the maintenance hourly cost.

$$C_T = C_C + C_M \quad (26)$$

Equation 27 can be expressed as:

$$C_T = \sum (C_C + C_M) \quad (27)$$

These costs can be broken up into the hourly cost for PV array, electrolyzer+storage and fuel cell subsystem.

$$\begin{aligned} C_C &= C_{\mathrm{csc}} + C_{celec} + C_{cfc} \\ C_M &= C_{msc} + C_{melec} + C_{mfc} \end{aligned} \quad (28)$$

The objective function C_T is also constrained to minimize the magnitude of the difference between the generated power and the demand over a given period of time (hour). PMM design involves minimizing the PFHES cost function under PMM control.

There are several methods that can be handled in order to minimize a mathematical function. One of those methods is linear programming, which is a technique for the optimization of a linear function, subject to linear equalities and linear inequalities, known as constraints. The standard form to formulate a linear programming problem is as follow:

- Linear function to be minimized:

$$J = \alpha x_1 + \beta x_2 + \lambda x_3 \quad (29)$$

Where α,β,λ are objective function coefficients or parameters and can be defined under the particular case of study.

- Constraints: Constraints can be delimited by using a matrix notation:

$$\begin{aligned} m_1x_1 + m_2x_2 + m_3x_3 &\geq b_1 \\ m_4x_1 + m_5x_2 + m_6x_3 &\geq b_2 \\ m_7x_1 + m_8x_2 + m_9x_3 &\geq b_3 \end{aligned} \quad (30)$$

And

$$\begin{aligned} x_1 &\geq 0 \\ x_2 &\geq 0 \\ x_3 &\geq 0 \end{aligned} \quad \textit{(31)}$$

Then M and B can be defined as the coefficient-matrix related to both sides of the inequalities.

For the specific case of power management model cost analysis, it is necessary to understand the linear programming tool application. First, the cost function [44],

$$C_T = \sum (C_C + C_M) \quad \textit{(32)}$$

represents the cost for hybrid system operation, where three subsystems can be identified: photovoltaic array, electrolyzer and fuel cell stack. For each one of these, a special notation is used.

C_{csc}= solar cell cost of capital (US$/Watt)

C_{msc}= solar cell maintenance cost (US$/Watt)

$\mathrm{C}_{\mathrm{celec}}$= electrolyzer cost of capital (US$/Watt)

C_{melec}= electrolyzer maintenance cost (US$/Watt)

C_{cfc}= fuel cell cost of capital (US$/Watt)

C_{mfc}= fuel cell maintenance cost (US$/Watt)

In the second place, it is desireable to find the cost of the hybrid system operation. This cost must be determined by subsystems generated power. This indicates that the total cost of solar cells operation may be equal to the cost of generating 1Watt (including capital cost and maintenance cost), multiplied by the total generated power. For example:

Total photovoltaic array operation cost = $(C_{csc} + C_{msc}) * P_{sc}$

Consistently,

Total electrolyzer operation cost = $(C_{celec} + C_{melec}) * P_{elec}$

Total fuel cell stack operation cost = $(C_{cfc} + C_{mfc}) * P_{fc}$

To simplify the model,

$$(C_{\mathrm{csc}} + C_{msc}) = \alpha$$
$$(C_{celec} + C_{melec}) = \beta$$
$$(C_{cfc} + C_{mfc}) = \lambda \qquad (33)$$

Now α,β, and λ parameters must be found. To achieve it, it is necessary to explore technical documentation.

For solar panel [44]: $5 per watt.

For fuel cell [45]: $1000 per kilowatt.

For electrolyzer [46]: $0.02/Watt.

For wind power [47]: $0.06/Watt.

In the third place, the x-variables for linear programming model can be defined as the subsystems power.

$$
\begin{aligned}
x_1 &= P_{sc} \\
x_2 &= P_{elec} \\
x_3 &= P_{fc} \qquad (34)
\end{aligned}
$$

Finally, combining equations defined below, the objective function must be minimized under some constraints that are defined by larger PV array, electrolyzer and fuel cell capacities. Those capacities are mentioned in 3.2.

In general, the formulation of this optimization problem can be presented as follows:

$$
\begin{aligned}
J &= \sum_{i=1}^{3} k_i P_i \\
J &= \alpha P_{sc} + \beta P_{elec} + \lambda P_{fc} \qquad (35)
\end{aligned}
$$

Where,

$$
\begin{aligned}
\alpha &= 5 \\
\beta &= 0.02 \\
\lambda &= 1 \qquad (36)
\end{aligned}
$$

Under the constraints

$$
\begin{aligned}
&P_{sc} \leq 314kW \\
&P_{elec} \leq 150kW \\
&P_{fc} \leq 56kW \\
&P_{sc} + P_{fc} \geq P_{lo} \\
&P_{sc} \geq 0 \qquad (37) \\
&P_{elec} \geq 0 \\
&P_{fc} \geq 0
\end{aligned}
$$

Linear programming application can be found in Labview functions (Figure 3-19).

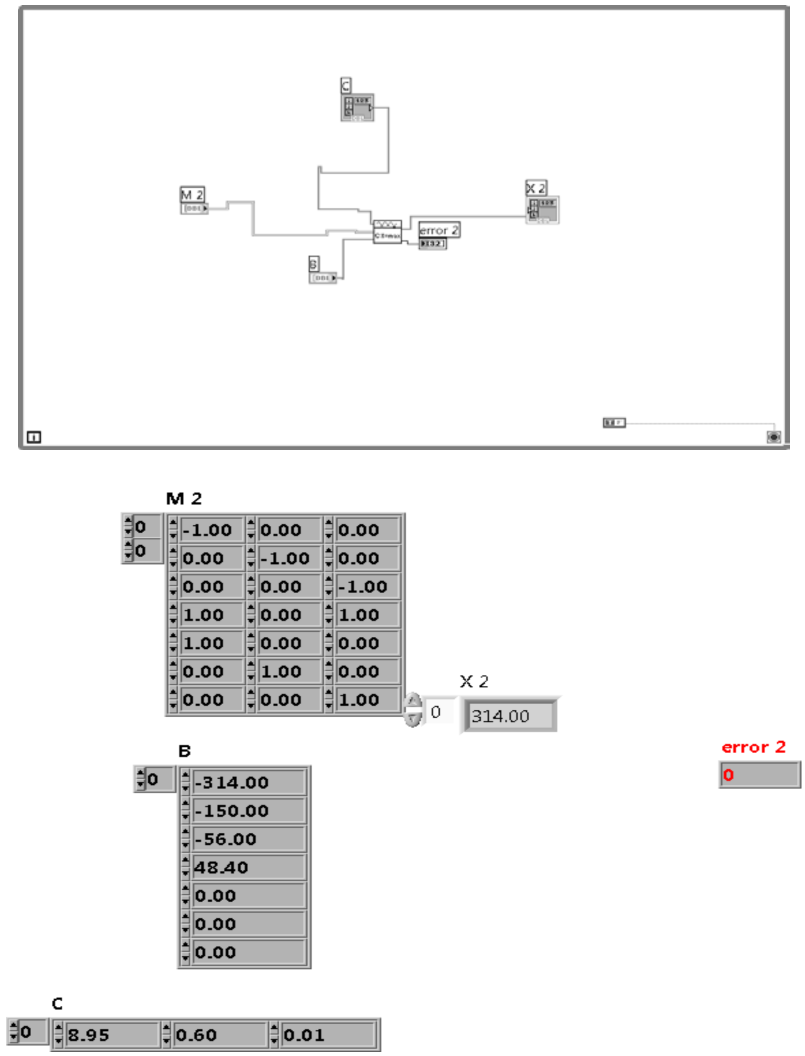


Figure 3-19 General Results for PMM Cost Simulation (Labview file).

The cost (Table 3-3 and

Table 3-4) of components is based on total storage capacity (kWh), while others depend on the rate of use (kW). This warrants developing a model that tracks the storage and use requirements on an hour-by-hour basis.

Table 3-3 Detailed Cost Results (Solar Scenario).

Time of Day	Cost - PV (US$)	Cost - FC (US$)	Cost - Electrolyzer (US$)	Total Cost (US$)
0	-	20,800.00	-	20,800.00
1	-	18,000.00	-	18,000.00
2	-	15,700.00	-	15,700.00
3	-	14,700.00	-	14,700.00
4	-	17,200.00	-	17,200.00
5	-	18,400.00	-	18,400.00
6	-	25,600.00	-	25,600.00
7	-	27,200.00	-	27,200.00
8	193,535.00	6,538.00	58.14	200,131.14
9	483,840.00	24,200.00	1,267.36	509,307.36
10	846,720.00	77,191.00	2,680.88	926,591.88
11	1,137,020.00	119,374.00	3,804.08	1,260,198.08
12	1,354,750.00	149,239.00	4,617.00	1,508,606.00
13	1,137,020.00	114,110.00	3,698.08	1,254,828.08
14	774,140.00	59,382.00	2,190.56	835,712.56
15	520,125.00	16,885.00	1,196.50	538,206.50
16	459,645.00	7,476.00	976.58	468,097.58
17	-	46,500.00	-	46,500.00
18	-	48,700.00	-	48,700.00
19	-	42,400.00	-	42,400.00
20	-	35,100.00	-	35,100.00
21	-	27,600.00	-	27,600.00
22	-	22,800.00	-	22,800.00
23	-	21,900.00	-	21,900.00

Table 3-4 Detailed Cost Results (Wind Power Scenario).

Time of Day	Cost - Wind (US$)	Cost - FC (US$)	Cost - Electrolyzer (US$)	Total Cost (US$)
0	10,659.60	-	2,152.90	12,812.50
1	-	18,000.00	-	18,000.00
2	-	15,700.00	-	15,700.00
3	-	14,700.00	-	14,700.00
4	-	17,200.00	-	17,200.00
5	-	18,400.00	-	18,400.00
6	2,835.72	-	944.74	3,780.46
7	750.72	27,200.00	249.70	28,200.42
8	826.98	29,500.00	275.08	30,602.06
9	1,134.42	33,400.00	377.48	34,911.90
10	714.42	35,300.00	237.42	36,251.84
11	908.28	37,200.00	302.02	38,410.30
12	4,166.46	-	1,388.02	5,554.48
13	3,828.84	42,500.00	1,275.42	47,604.26
14	645.30	45,300.00	214.20	46,159.50
15	6,459.60	-	2,152.42	8,612.02
16	3,307.50	-	1,101.62	4,409.12
17	3,509.94	-	1,169.04	4,678.98
18	2,835.72	48,700.00	949.04	52,484.76
19	-	42,400.00	-	42,400.00
20	867.00	35,100.00	288.30	36,255.30
21	-	27,600.00	-	27,600.00
22	438.72	22,800.00	145.78	23,384.50
23	-	21,900.00	237.70	22,137.70

After sizing the subsystem and seeing the total cost, some sustainability indicators [48] are placed:

- Environment indicator (CO_2) emission: PFHES under PMM control, has 0% of CO_2 emission.

CHAPTER 4 EXPERIMENTS AND RESULTS

In this chapter, the detailed results of laboratory experiments and simulations will be presented and explained, as well as the outcome for the PMM components.

4.1 Laboratory Experiments

Test and simulations are based on Labview tools application. All experiments took place at Florida Atlantic University Fuel Cell Laboratory and Control Laboratory. Some equipment, instruments and devices are mentioned here:

- New fuel cells.
- Basic configurations of DC loads.
- Wiring (control and data communication wiring).
- Data Acquisition modules (National Instruments).
- Electric/Electronic circuits.
- Xantrex solar system.
- Nexa fuel cell.
- Transducers, control valves, hydrogen cylinders, air compressors, electric meters, solar cells, etc.

Results for PMM components are:

- **Block diagram:** Figure 4-1**.**

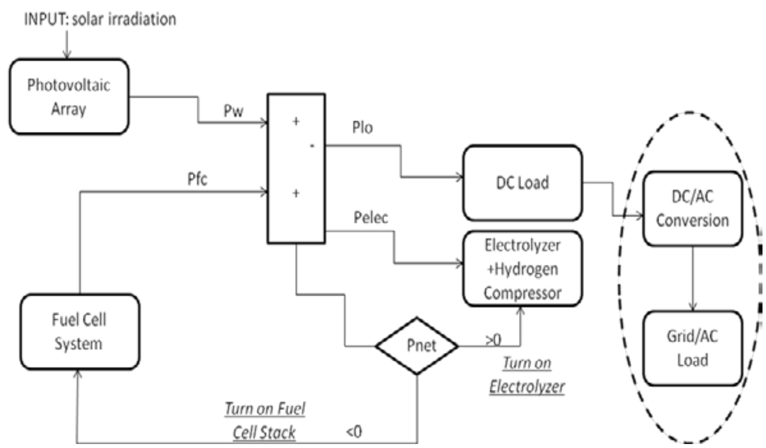


Figure 4-1 PMM Block Diagram.

- **Mathematical Model:** Power balance equation is the main component of mathematical model,

$$P_{net} = P_{sc} - P_{lo} \quad (38)$$

$$\begin{aligned} &P_{sc} = P_{lo} + P_{elec} \\ &P_{net} > 0 \end{aligned} \quad (39)$$

$$\begin{aligned} &P_{sc} + P_{fc} = P_{lo} \\ &P_{net} < 0 \end{aligned} \quad (40)$$

- **Operation schedule and set of instructions for PMM:** Table 4-1.

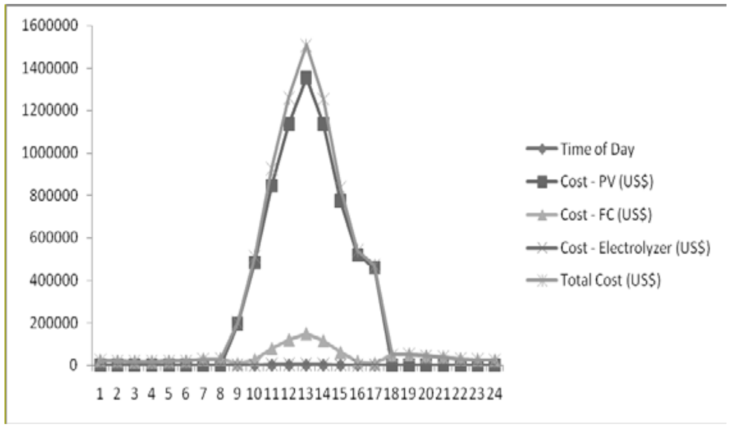
Table 4-1 PFHES Operation Schedule under Power Management.

Time of Day	PV array	Fuel Cell	Electrolyzer
0	Off	On	Off
1	Off	On	Off
2	Off	On	Off
3	Off	On	Off
4	Off	On	Off
5	Off	On	Off
6	Off	On	Off
7	Off	On	Off
8	On	On	On
9	On	On	On
10	On	On	On
11	On	On	On
12	On	On	On
13	On	On	On
14	On	On	On
15	On	On	On
16	On	On	On
17	Off	On	Off
18	Off	On	Off
19	Off	On	Off
20	Off	On	Off
21	Off	On	Off
22	Off	On	Off
23	Off	On	Off

For cases in which Photovoltaic and fuel cell subsystem are "On" at the same time, it is possible to tie the system to the grid and feed an AC load by implementing the DC/AC conversion.

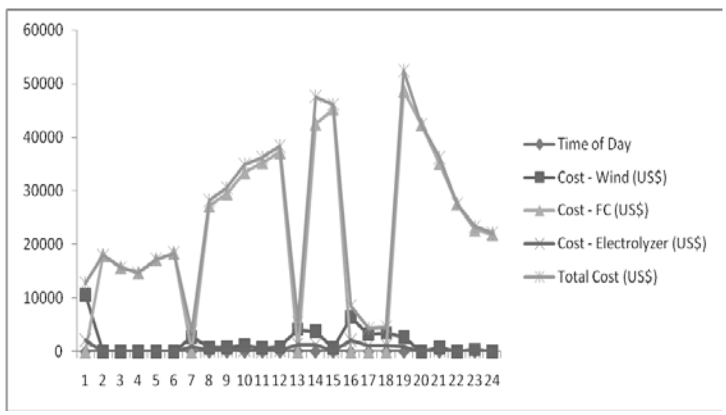
- **Operation cost for the defined schedule:** Table 4-2**.**

Table 4-2 Cost for Solar Scenario.



For the wind power scenario, we obtained the other results: Table 4-3.

Table 4-3 Cost for Wind Scenario.



Cost analysis for wind power scenario shows that this alternative is better than the PV power scenario.

CHAPTER 5 CONCLUSIONS AND GENERAL DISCUSSION

This thesis was intended to be part of the hundreds of research that companies and governments have been developing in the sustainable/alternative energy sources field of study. Thus, a Power Management Model applied to a Photovoltaic/Fuel Cell Hybrid Energy System was designed.

The most important results and suggestions are mentioned:

- PMM modeling and experimental efforts have focused on various aspects of hydrogen storage renewable-based hydrogen generation systems and total system design.
- Power Management Model implementation has been shown to have a large, beneficial effect on operating cost. By performing hourly, monthly or even annual simulations of the flow of energy through a power grid, it could show the mismatches between the generation and demand of electricity.
- To obtain an estimate of the least expensive system (Figure 5-1), the PMM, that uses all available information to control energy storage, is proposed. By adjusting the energy storage strategy to variations in power production and demand, the design can be optimized.

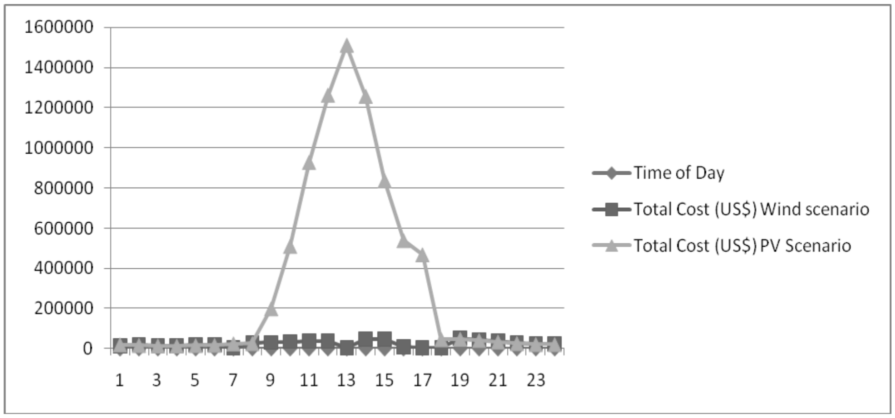


Figure 5-1 Cost for Both Scenarios (PV and Wind).

- Specific design is dependent on geographically dependent parameters such as solar radiation or wind velocity.
- Since electric usage does not follow the variation of solar radiation throughout the day, some PV generated electricity must be stored for use during other times of the day.
- Since the control system has an effect on component sizes and thus system and operating costs, the control model must be carefully considered for any system with energy storage. For this study, a time-dependent (hourly) model of a stand-alone, solar powered, fuel cell hybrid energy storage system was developed to investigate energy storage options for cases where supply and demand of energy are not well hourly matched.
- Improvement of an PMM operation schedule based on simulations results can be made. It is possible to adapt the photovoltaic array or fuel cell stack operation in such a way that the PFHES operation cost can be reduced.

- Identification of main constraints for PMM implementation is one of the basic results for simulations in Labview. Not only the storage mechanism model for hydrogen flow systems, but all calculations formulas used as part of PFHES, can be improved by including more specific parameters. That is the main reason why some assumptions must be taken in order to run the simulations under general conditions.
- General technical requirements for some Power Management Module electronic/electric components that can be used to control the power flow:
    - An important factor affects the electrolysis process, which should be considered in the PMM design. This factor takes place after sunset when the electrolyzer current drops to zero, which means that the electrolyzer must be kept under protective voltage in order to prevent the cathodic potentials from being excessively attacked by active corrosion. To overcome this defect, some electronic circuit must be part of the power management module, to isolate the electrolyte from the electrolysis cell and inject N_2 to the electrolyzer to protect electrodes from corrosion.
- In case the PV module is not illuminated at night, the voltage created in every solar cell can be to 0.388 Volts; then these cells will present discharge currents flowing through them. A way to avoid this is by using blocking diodes. In general for the design of the PMM, this issue will be considered in order to open or close the circuit that connects the PV system with the DC bus and the electrolyzer.

- Hybrid renewable energy systems are becoming popular for power generation applications due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. Economic aspects of these technologies are sufficiently promising to include them in developing power generation capacity for developing countries. Research and development efforts in solar, wind, and fuel cells are required to continue improving their performance and establishing techniques for a more accurate prediction of output. In this case, other future research papers and Ph.D. dissertations can be developed in order to describe, in more detail, methodologies to model hybrid system components and power management system design.

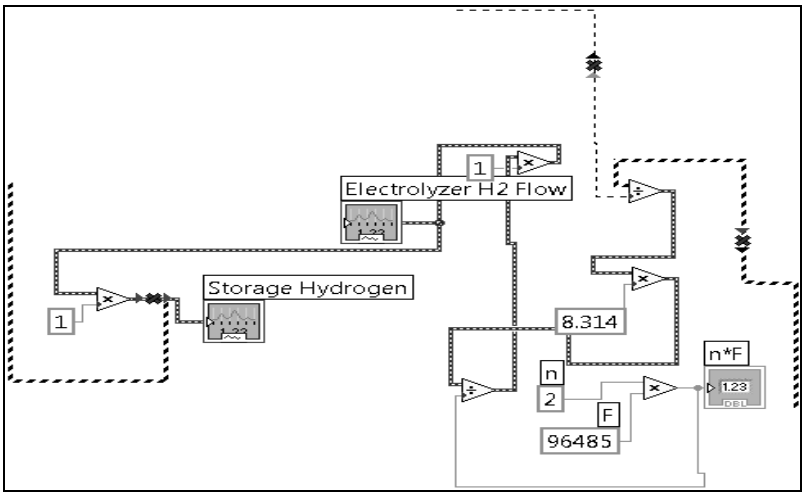


Figure A-1 Electrolyzer (section of Labview modeling).

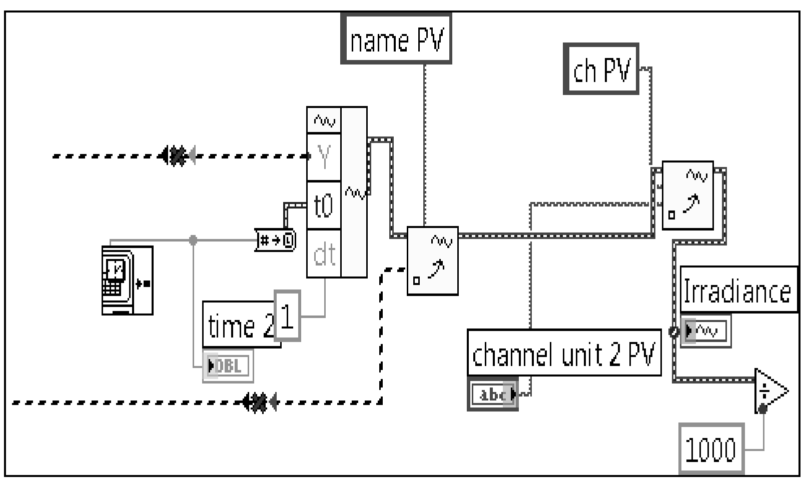


Figure A-2 Input Data - Irradiance (section of Labview modeling).

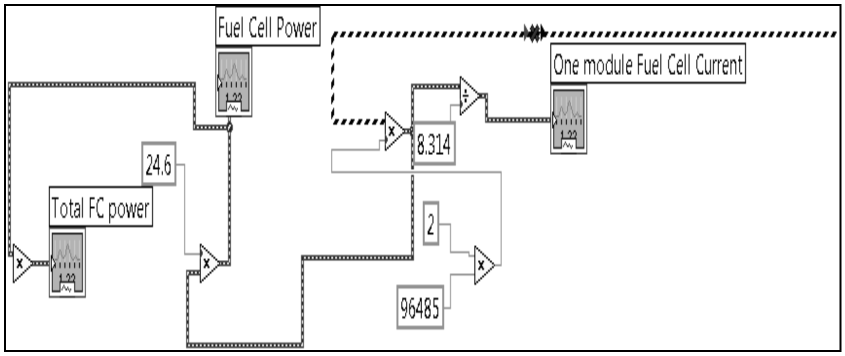


Figure A-3 Fuel Cell Subsystem (section of Labview modeling).

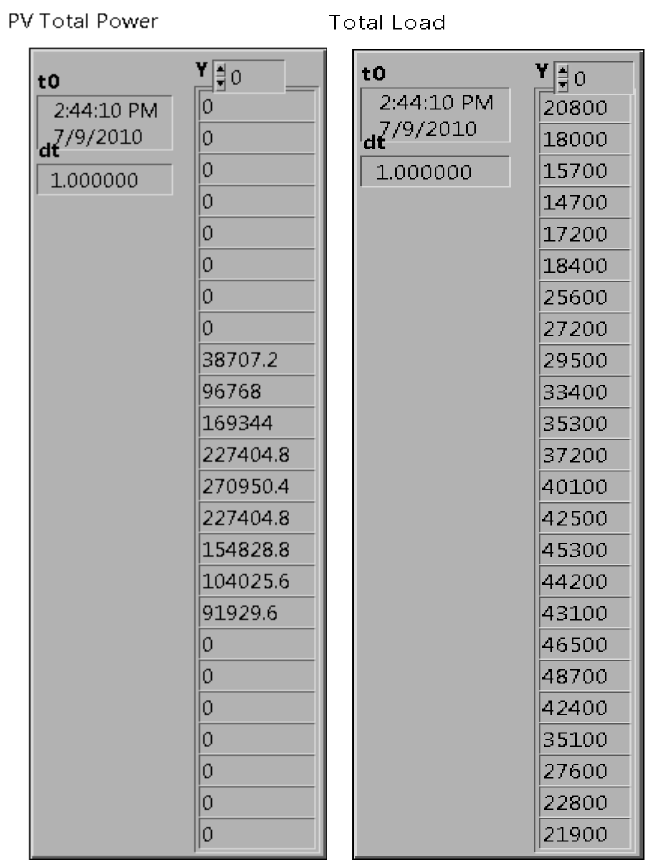


Figure A-4 PV Total Power and Load Values – 24 Hours a Day (section of Labview modeling).

Table A-1 Comparison of PV-Wind Scenarios (Cost Analysis Result).

Time of Day	Total Cost (US$) Wind scenario	Total Cost (US$) PV Scenario
0	12,812.50	20,800.00
1	18,000.00	18,000.00
2	15,700.00	15,700.00
3	14,700.00	14,700.00
4	17,200.00	17,200.00
5	18,400.00	18,400.00
6	3,780.46	25,600.00
7	28,200.42	27,200.00
8	30,602.06	200,131.14
9	34,911.90	509,307.36
10	36,251.84	926,591.88
11	38,410.30	1,260,198.08
12	5,554.48	1,508,606.00
13	47,604.26	1,254,828.08
14	46,159.50	835,712.56
15	8,612.02	538,206.50
16	4,409.12	468,097.58
17	4,678.98	46,500.00
18	52,484.76	48,700.00
19	42,400.00	42,400.00
20	36,255.30	35,100.00
21	27,600.00	27,600.00
22	23,384.50	22,800.00
23	22,137.70	21,900.00

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