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Abstract

Concern is growing daily about the dangers of the excessive use of traditional energy resources in conjunction with the exacerbation of global warming. Thus, it has become necessary to move towards the use of renewable and clean energy sources, but the development of renewable energy systems faster has been and continues to be a scientific and technological challenge.

Among the renewable energy sources: Photovoltaic seems to be the most promising source. It has the advantage of being available everywhere, friendly to the environment and easily maintainable. On the other hand, the fuel cell is arguably the most environmentally friendly way to generate electrical energy today. Indeed, apart from electricity, the reaction between hydrogen and oxygen only produces water vapor. As such, the process does not in any case releases any greenhouse gas. However, the main drawbacks to these sources are the high manufacturing cost and non-linear characteristics, and thus the randomness of energy availability. To meet these challenges, sources hybridization and its optimization can demonstrate to be suitable approach for the design of efficient energy solutions.

This thesis deals with the hybridization of two renewable energy sources and improving their performance. The hybrid system comprises photovoltaic solar panels and a fuel cell, in addition to battery, converter, electrolyzer and hydrogen tank to supply cell tower. The objective is to develop new control strategies to extract the maximum power available from the both sources PV/PEMFC and optimize the size of the hybrid system components. As results, some MPPT algorithms have been developed that have proven durability and robust performance under variable operating conditions to extract maximum power, while for second objective, optimization sizing of the hybrid system components have been done using HOMER software.

List of publications

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1. H. Bahri & A. Harrag "Ingenious golden section search MPPT algorithm for PEM fuel cell power system" Neural Computing and Applications, 2020, <https://doi.org/10.1007/s00521-020-05581-4>.
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Nomenclatures

Acronyms and abbreviations

HRES	Hybrid renewable energy system.
DC	Direct Current.
AC	Alternative Current.
LPSP	Loss of Power Supply Probability.
LOLP	Loss of Load Probability.
SPL	System Performance Level.
EENS	Expected Energy Not Supplied.
NPC	Net present cost.
LCOE	Levelized Cost of Energy.
LCC	Life Cycle Cost.
ACS	Annualized Cost of the System.
AGC	Average Generation Cost.
GA	Genetic Algorithm.
ANN	Artificial Neural Net Work.
PSO	Particle Swarm Optimization.
EPSO	Evolutionary Particle Swarm Optimization.
FL	Fuzzy Logic.
SA	Simulated Annealing.
ACO	Ant Colony Optimization.
MOPSO	Multi-Objective Particle Swarm Optimization.
TS	Tabu Search.
NSGA	Non-dominated Sorting Genetic Algorithm.
CDIP	Continuous Domain Integer Programming.
HOMER	Hybrid Optimization Model for Electric Renewables.
HOGA	Hybrid Optimization by Genetic Algorithm.
HYBRIDS	Hybrid Power System Simulation Model.
RAPSIM	Remote Area Power Supply Simulator.
TRNSYS	Transient Energy System Simulation Program.
GAMS	General Algebraic Modeling System.
ORIENTE	Optimization of Renewable Intermittent Energies with Hydrogen for Autonomous Electrification.
SOMES	Simulation and Optimization Model for Renewable Energy Systems.
INSEL	Integrated Simulation Environment Language.
NREL	National Renewable Energy Laboratory.
PV	Photovoltaic.
FC	Fuel Cell.
Win	Wind.
Bio	Biomass.
Hyd	Hydro.
Die	Diesel.
R. E.	Renewable Energy.
R. & S. E. Rev.	Renewable and Sustainable Energy Reviews.
A. E.	Applied Energy.
E.	Energy.
E. C & M.	Energy Conversion and Management.
E. P.	Energy Policy.
E. R. J.	Energy Research Journal.
E. Rep.	Energy Reports.

E. S. D.	Energy for Sustainable Development.
I. J. E. R. T.	International Journal of Engineering Research & Technology.
I. J. H. E.	International Journal of Hydrogen Energy.
I. J. R. E. Res.	International Journal of Renewable Energy Research.
IEEE	Institute of Electrical and Electronics Engineers.
J. E. & C. E	Journal of Electrical and Computer Engineering.
R. & S. E.	Renewable and Sustainable Energy.
R. & S. E. Rev.	Renewable and Sustainable Energy Review.
R. E.	Renewable Energy.
S. C & S	Sustainable Cities and Society.
S. E.	Sustainable Energy.
S. E. T. & Ass.	Sustainable Energy Technologies and Assessments.
Sus	Sustainability.
PHOEBUS	Photovoltaic electrolysis fuel cell system technology.
SAPHY	Stand-Alone small size Photovoltaic Hydrogen energy System.
HARI	Hydrogen and Renewables Integration.
FIRST	Fuel cell Innovative Remote energy System for Telecom.
PV	Photovoltaic.
EJ	Exajoule.
PWh	Petawatthour.
c-Si	Crystalline silicon.
sc-Si	Monocrystalline.
mc-Si	Multicrystalline.
a-Si	Amorphous Silicon.
CdTe	Cadmium telluride.
CIGS	Copper indium gallium diselenide.
GaAs	single-junction Gallium Arsenide.
EVA	Ethyl Vinyl Acetate.
PVB	Polyvinylbutyral.
BIPV	Building integrated photovoltaic.
CEO	Chief Executive Officer.
NASA	National Aeronautics and Space Administration.
AFC	Alkaline Fuel Cell.
PAFC	Phosphoric Acid Fuel Cell.
DMFC	Direct Methanol Fuel Cell.
MCFC	Molten Carbonate Fuel Cell.
SOFC	Solid Oxide Fuel Cell.
PEMFC	Proton Exchange Membrane Fuel Cell.
EDF	Electricity of France.
GDF	Gas of France.
GE	General Electric.
BP	Bipolar Plates.
MPL	Micro-Porous Layer.
GDL	Gas Diffusion Layer.
GDML	Gas Diffusion Medium Layer.
GDBL	Gas Diffusion Backing Layer.
PTFE	Polytetrafluoroethylene.
FEP	Fluorinated Ethylene Propylene.
CL	Catalyst Layer.

Pt	Platinum.
PFSA	Perfluorinated Sulfonic Acid.
MPPT	Maximum Power Pont Tracking.
MPP	Maximum Power Pont.
P&O	Perturbation and Observation.
IC	Incremental Conductance.
SCC	Short-Circuit Current.
OCV	Open-Circuit Voltage.
CV	Constant Voltage.
SC	Soft Computing
AI	Artificial Intelligence
BI	Bio-Inspired
GWO	Grey Wolf Optimization
CSO	Cuckoo Search Optimization
IPSO	Improved particle swarm optimization
QIPSO	Quantum inspired particle swarm optimization
VEPSO	Vector evaluated particle swarm optimization
PSOTVAC	Particle swarm optimization with time varying acceleration coefficients.
PID	Proportional Integral Derivative.
SMC	Sliding mode controller.
T_r	Time response.
Red	Reduction.
Vss	Variable step size.
Fss	Fixed step size.
SF	Scaling factor.
SS	Sing sensor.
RT	Response time.
1S	One sensor.
2S	Two sensors.
GSS	Golden section search.
O&M	Operating and maintenance.
h	Hours.
yr	Year.
SOC	State of charge.

Notations and Symbols

I_{ph}	Photo-current.	A.
I_d	Diode current.	A.
I_p	Parallel current.	A.
I_{pv}	net output current of PV cell.	A.
$I_{sc,ref}$	Short-circuit cell current at reference temperature and irradiance.	A.
T_{pv}	PV cell temperature.	K.
T_{ref}	Reference cell temperature in STC.	K.
G	Instantaneous solar irradiance.	W/m^2 .
G_{ref}	Reference solar irradiance $1000W/m^2$.	W/m^2 .
σ_i	Relative temperature coefficient of the short-circuit current.	%/K.
I_s	Saturation current.	A.

V_t	Thermal voltage.	V.
V_{pv}	Voltage across the photovoltaic cell.	V.
$V_{oc,ref}$	Reference open-circuit voltage.	V.
R_s	Parallel resistance of the photovoltaic cell.	Ω .
R_p	Series resistance of the photovoltaic cell.	Ω .
$I_{sc,ref}$	Reference short-circuits current.	A.
$\tilde{\lambda}$	Diode ideality factor.	/
ϖ	Boltzman's constant.	J/K.
q_{el}	Charge of one electron.	Coulombs/electron.
E_{gap}	Gap energy.	eV.
FF	Fil factor.	%
η_{pv}	Photovoltaic efficiency	%
S	Area of the PV module	m ² ;
N_s	Number of series connected cells	/
N_p	Number of parallels connected cells	/
M	Index to the module	/
O_2	Oxygen.	/
H_2	Hydrogen.	/
H_2O	Water.	/
KOH	Potassium hydroxide.	/
H_3PO_4	Phosphoric acid.	/
SiC	Silicon carbide.	/
CH_3O	Methanol.	/
H		/
Cr_2O_3	Chromium oxide.	/
OH^-	Hydroxide ions.	/
CO	Carbon monoxide.	/
CO_2	Carbon dioxide.	/
CO_3^{-2}	Carbonate.	/
K_2CO_3	Potassium carbonate.	/
Na_2CO_3	Sodium carbonate.	/
δQ	Exchanges of heat.	J.
δW	Exchanges of work.	J.
ΔG	Gibbs free energy variation.	J.
ΔH	Enthalpy variation.	J.
ΔS	Entropy variation.	J.
W_{elec}	Electrical work.	J.
q	Total charges.	Coulombs/mol.
n_e	Number of electrons per molecule.	/
N_{Avg}	Number of molecules per mole (Avogadro's number).	mol ⁻¹ .
q_{el}	Charge of one electron.	Coulombs/electron.
F	Faraday's constant.	C/mol.
E	Reversible cell voltage.	V.
E_{Nernst}	Nernst voltage.	V.

E°	Reference voltage.	V.
R	Universal gas constant.	J/mol K.
T	Temperature.	K.
n_e	Number of electrons.	/
a	Activity of species.	/
c_i	Stoichiometric coefficient of species.	/
P_{H_2}	Pressure of hydrogen.	bar.
P_{O_2}	Pressure of oxygen.	bar.
T_{FC}	Temperature of fuel cell.	K.
T_0	Temperature of fuel cell at STC.	K.
∂_{act}	Activation overvoltage.	V.
$\xi_{(i=1 \text{ to } 4)}$	Parametric coefficients for each cell.	V/K.
C_{O_2}	Oxygen's concentration.	mol/cm ³ .
∂_{ohm}	Ohmic overvoltage.	V.
R_c	Contact resistance.	Ω .
R_m	Equivalent membrane resistance.	Ω .
l	Thikness of polymer membrane.	cm.
σ	Cell active area.	cm ² .
ρ_m	Membrane specific resistivity.	Ω cm.
φ	Membrane water content.	/
∂_{conc}	Concentration overvoltage.	V.
J_{max}	Maximum current density.	A/cm ² .
η_{FC}	Efficiency of the fuel cell.	%.
P_{stack}	Power output of a fuel cell stack.	W.
N_{cell}	Number of cells in the stack.	/
U_{cell}	Voltage per cell.	V.
U_{FC}	Voltage PEMFC stacks.	V.
J	Density current.	A/cm ² .
σ_{cell}	Cell active area.	cm ² .
Ψ_{H_2}	Rate of hydrogen consumed.	mol/s.
Ψ_{O_2}	Rate of oxygen consumed.	mol/s.
Ψ_{H_2O}	Rate of water generated.	mol/s.
$\mathcal{M}_{H_2}$	Molar mass of hydrogen.	g.
$\mathcal{M}_{O_2}$	Molar mass of oxygen.	g.
$\mathcal{M}_{H_2O}$	Molar mass of water.	g.
m_{H_2}	Mass flow rate of hydrogen consumed.	g/s.
m_{O_2}	Mass flow rate of oxygen consumed.	g/s.
m_{H_2O}	Mass flow rate of water generated.	g/s.
V_{output}	Output voltage.	V.
ΔV_{output}	Output voltage ripple.	V.

I_{output}	Output current.	A.
ΔI_L	Inductor current ripple.	A
D	Duty cycle.	/
L	Inductor.	H.
C_2	Capacitance.	F.
f_s	Switching frequency.	Hz.
Γ	Length	/
Φ	Golden ratio.	/
ϕ	Golden section.	/
ε	Current precision.	A.

General Introduction

General Introduction

0.1 Context

Like water, energy is indispensable as it is a necessary form of life for all living beings. Energy takes five main forms: mechanical, chemical, thermal, nuclear, and electrical. The latter, considered the most important and most common, is the main driver of this life at the present time that man cannot do without, as it can easily be transported, transformed and stored. Electrical energy has changed human life for the better and pushed it towards developing at a steady pace to practice all economic and social activities. With the gradual development in addition to the industrial revolution, the total consumption of electrical energy worldwide has increased, and has doubled in recent years. Fossil fuel sources such as coal, oil and natural gas remain after the first decades of the 21st century the main source of total electrical energy generated by them. The availability of electrical energy has greatly contributed from these conventional sources to the increase in population growth, technological development, and economic prosperity. However, on the environmental and health side, it had serious consequences such as environmental degradation, exacerbation of global warming, biodiversity loss and the spread of diseases as a result of carbon dioxide gas emissions [1]. In addition to these disadvantages, the total dependence on fossil fuel resources throughout these decades has led to decrease in their reserves and depletion. In the face of these challenges, international interest has emerged through concluding agreements such as the Kyoto Protocol, ratified by 141 countries, which obligated industrialized countries to make greater efforts to reduce greenhouse gases and preserve traditional resource reserves. However, this policy has led to an increase the prices of electrical energy as well as creates a kind of imbalance, as reducing the rate of these emissions is closely related to energy production and its rapidly increasing consumption [2].

Science and technology offer diverse responses, both in production and in applications. Researchers in this field have begun to focus on renewable energy sources and production methods by harnessing these sources such as solar, water, wind energy, geothermal energy ... etc, to produce electrical energy due to its inexhaustible nature and being clean, and through which can be reduce the demand for energy from conventional resources. Despite the economic, political, geographical and technological obstacles facing the rapid global development, but renewable energy technologies have known remarkable development and are on the right path, as their productive contributions have become clear with their multiple uses [3].

0.2 Hybrid renewable energy systems

Nowadays, solar energy has proven to be one of the most popular among all clean energy resources because it is non-depletable and non-polluting, that used the photovoltaic (PV) modules to produce electricity. PV power contributes to meeting a pretty percent of the whole world electrical power energy requirements. However, the era of PV energy faces great challenges as the energy produced by a PV station changes permanently according to the weather changes such as solar radiation and temperatures, which may lead a mismatch between output PV energy with the time distribution of load [4].

In fact, renewable energy sources cannot be used individually as primary power source to guarantee continuous load feeding because of low reliability and high investment cost [5]. One strategy to beat this issue is to combine renewable, traditional energy sources and energy storage systems in one system to ensure a ceaseless supply of electrical power during a full day. This topology is known as Hybrid Renewable Energy Systems (HRESs) [6].

0.3 Hybrid renewable energy systems optimization

HRESs are used in remote and rural regions as standalone mode, as well as are used in grid connected mode in some places such as factories, hospitals, universities, and cities. In addition to reduce greenhouse gases, HRESs provide valuable benefits, for example, decline cost of energy, enhance power quality and reliability, possibility of feeding remote and rural areas with electricity, further developing services and setting new jobs [7]. In this way, one might say that the HRES satisfies the three measures for sustainable development, which incorporate financial, ecological and social aspects.

The main areas of research in HRES in accordance with recent trends have been divided into several categories including performance assessment and size optimization. The performance assessment of the HRES is mainly based on the performance of its individual components whereby the benefit of optimizing the performance of each component is the improvement of the performance of the entire system. On the other hand, to ensure reliability of supply while keeping system cost low, size optimization of hybrid systems is absolutely essential. The work done is mainly centered on the improving individually both parts PV/PEMFC and the optimization sizing of the HRES.

HRES contains many types of clean energy sources, with wind, solar and hydrogen energy being the most widely used renewable energy generation technologies. PV and wind energy have both developed so rapidly that they have surpassed all estimates. Simultaneously with this, fuel cells (FCs) have entered the line to be one of the clean energy sources due to their many advantages such as high efficiency, negligible environmental effects and no noise [8]. Moreover, the process of controlling each of these sources that make up the hybrid system, allows raising the efficiency and energy of the system as a whole. This process aims to extract the maximum energy that can be obtained from renewable energy generators. In fact, the extracting the maximum power from PV and wind have been solved, and many works in the literature are devoted to it. As for fuel cells, which have become realistic solutions for the future for their use in mobile and stationary applications; the problem of extracting the maximum power and optimizing the fuel consumption raises the challenges that make fuel cells among the sources of hybrid energy systems.

In this section of the study, a system sizing optimization is performed. Its core objective is the exploitation of the electricity generate from HRES with dependable performance and at a competitive financial values; the criteria for optimal component selection and optimization sizing a significant role, e.g., number and capacity of renewable energy sources, battery bank and converters so that these components are selected according to the load requirements. Thus, an optimum sizing process is significant for utilizing renewable energy resources with good efficiency and at the lowest financial cost over the lifetime of the system [9, 10]. Thus, this type of optimization carries economic objectives, and requires an analysis of system performance in order to reach the best

match between reliability and cost. As result, several optimization ways have been referenced in several papers like: Simulated Annealing (SA), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO). Moreover, these methods were enhanced with one of the sizing tools, which has been applied in many issues is the Hybrid Optimization Model for Electric Renewables (HOMER) [6].

0.4 Overview of the chapters

The rest of this thesis is organized as follows:

Chapter I: In the first chapter, we will give an overview of hybrid renewable energy systems. In the first part, we will highlight the HRESs in terms of architecture, classification, criteria and methods of optimization.

Chapter II & III: In the second and third chapters, the description and modeling of PV/PEMFC system will be presented. We will do a study the techniques of converting solar energy and chemical energy into electrical energy and then show the impact of solar radiation and temperature for PV system as well as the impact of pressure, temperature and membrane water content on PEMFC system on the Voltage/Current/Power characteristics. Finally, we will conclude that MPPT must be applied to improve the output power.

Chapter IV: In the fourth chapter, we will give an overview of the maximum power point tracking techniques used for PV and fuel cell. In the first part, we will highlight the main MPPT techniques used in the PV system and more comprehensively for MPPT techniques used in the fuel cell.

Chapter V: In this chapter, we present the results of simulation for different MPPT developed for PV and PEMFC that includes: Variable step size based MPPT for PV system; Novel neural network IC-based variable step size fuel cell MPPT controller, A Novel Single Sensor Variable Step Size MPPT for PEMFC and Golden Section Search based MPPT for PEMFC.

Chapter VI: In this chapter, we present sizing optimization and technico economic for the hybrid renewable energy system includes PV and PEMFC to supply cell tower using HOMER software.

Finally, our thesis ends with a conclusion including the main contribution as well as the future perspectives pour this research work.

Chapter I

Hybrid Renewable Energy Systems: State of Art

I.1 Introduction

Renewable energy sources have penetrated the electric power production sector all over the world. As of late, Solar and hydrogen-based power generation are viewed as the promising technologies in the era of sustainable energy. The PEMFC that used the hydrogen to convert the chemical energy to electrical energy display big potential to be sustainable power sources of the future. However, each of the PV and PEMFC technologies has some challenges at the end users. For instance, PV and PEMFC output power are mainly depend on the operating conditions. The variation of the output power is function of temperature and irradiation for PV, and pressure, temperature and water membrane content for PEMFC [11]. Nevertheless, as a result of the intermittent nature of renewable energy sources, exploiting a single renewable energy source is problematic in terms of energy productivity and operational cost. Thus, multi-source hybrid power systems can possibly give better, more reliable and more dependable capacity to clients than a system that depends on a solitary provider during an entire day [12].

In this chapter, we will present description about the hybrid renewable energy systems with overview of optimization method by using HOMER software.

I.2 Pros and cons of HRESs

The hybrid renewable energy systems have various advantages and some disadvantages. Let's have a look at few of them:

I.2.1 Pros of HRESs

Among HRESs pros, we can mention [13, 14]:

- Reduced losses in lines and transformer.
- Possibility of integrating two or more renewable energy sources into one system.
- Reduced atmospheric contamination.
- Increased system reliability.
- Increased overall efficiency of system.
- Improved power quality.
- Savings on maintenance.
- Quiet and no noise system.
- Possibility to connect to other power sources.
- Multiple uses, especially providing electricity in remote areas.

I.2.2 Cons of HRESs

Among HRESs cons, we can mention [14, 15]:

- Renewable energy sources, especially photovoltaic, need to raise their efficiency.
- The capital cost is high to achieve a hybrid system.
- The storage devices, for example, battery bank, need to expand their life-cycle.
- Appropriate safety devices must be installed for the components of the hybrid system.

- Several power electronics converters are utilized, which generate harmonic components.
- Complex control process between the different energy sources used.

I.3 Hybrid system coupling architectures

It has proven, the multiplicity of power sources in the hybrid system is one of the most important points to make the system more reliable. Since all power sources have various working attributes, it is important to choose sample connection architecture for these resources through the use of converters and buses to feed load. There are various architectures to combine different sources energy into a workable hybrid system. Energy storage units are also connected through a bidirectional converter; it utilized to store energy, and can deliver the requirements of the load when there is a shortage supply. The main objective of these structures are to ensure best flow energy power to end users, minimize the complexity, reduce the conversion losses, make the system highly reliable and cost-effective [16]. The different architectures of a hybrid system are divided into three families as follows:

I.3.1 Coupling DC bus architecture

Figure I.1 illustrated the coupling DC bus architecture [17-19], where the various parts of the hybrid system sources are coupling in single DC bus line. In this architecture, through rectifier the AC resources are associated to the DC bus. While, the DC energy sources are associated to the DC bus directly or by using DC/DC converter in order to obtain the required voltage by the loads. Through bidirectional converter can be connected the battery bank to maintain a stable supply demand for load. The power delivered by each source is centralized on a DC bus to supply end users in the form of DC energy in the case of DC load or AC energy in the case of AC load by using single DC/AC inverter. The AC bus feeds the AC load and also has the possibility to integrate with the utility grid. Notwithstanding, this topology is straightforward and does not need to synchronize the bus to the power frequency (AC load), it also has its drawbacks. In which, the system relies on a single inverter to supply AC loads, and this is not convenient when the system inverter is malfunctioning, resulting in no AC power delivery. On the other hand, a proper control scheme is necessary that allows for good power distribution to be achieved.

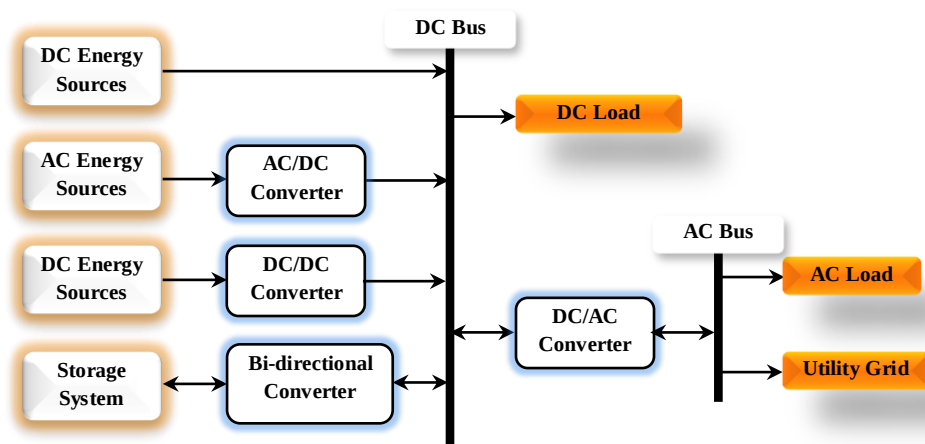


Figure I.1 DC bus hybrid system architecture.

I.3.2 Coupling AC bus architecture

In the coupling of AC bus architecture [18, 20], all sources of the hybrid system are connected to the AC load, as shown in figure I.2. This architecture shows better performance contrasted with the DC architecture, where the problem of synchronizing each converter with its source can be overcome, therefore it can be fed the loads autonomously and at the same time with the other converters, that it provides flexibility for the sources energy to satisfy the needs of load. In the event of low demand rates, some sources are disconnected with leaving a source capable of covering the load consumption rates. However, during acute load requirements i.e. peak hours, the sources of the hybrid system with battery bank work in parallel to fulfill the load needs. The embodiment of this architecture is comparatively considered complex due to the synchronization of the result voltages at the AC bus with the load voltages.

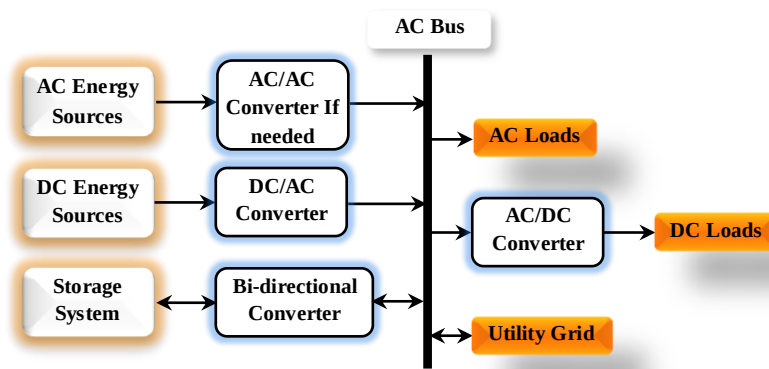


Figure I.2 AC bus hybrid system architecture.

I.3.3 Coupling DC/AC bus hybrid architecture

The coupling DC/AC bus hybrid architecture [18, 20] contains of AC and DC buses as shown in figure I.3. In which, the different sources of the whole system can be associated to the DC or AC bus with or without converters. The interconnection between the two buses can be achieved through bidirectional converters. This configuration has possibility integrated some energy sources directly without the need for converters. Therefore, it provides higher efficiency and low cost.

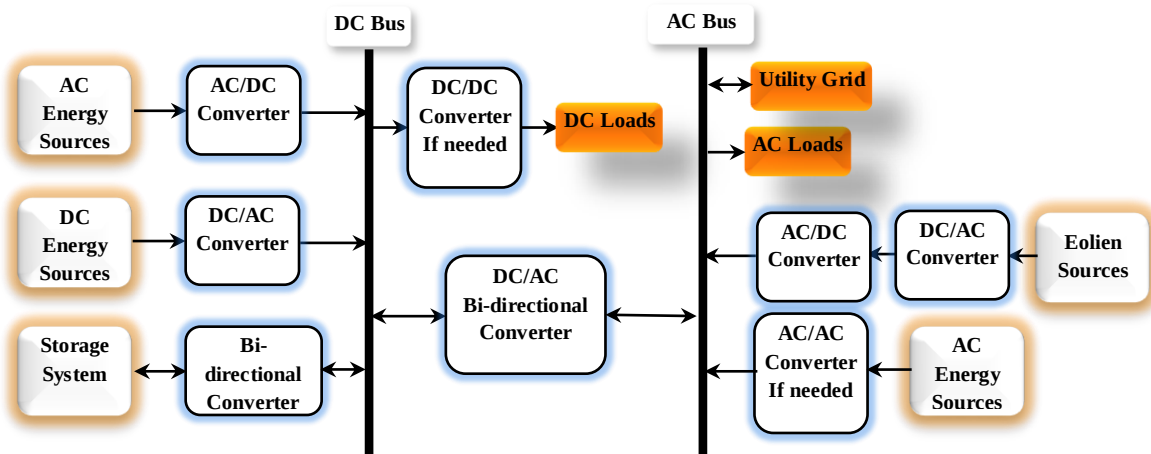


Figure I.3 DC/AC bus hybrid system architecture.

For the situation of the hybrid system connected to the utility grid, it gives a special advantage to the hybrid system where the size of the storage unit can be decreased, and in some applications it can be dispensed with completely. Also, the hybrid system resorts to taking advantage of the power sent from the utility grid when there is a deficit in the ability of power generators to meet the load requirements. While, the opposite occurs when an overproduction of the energy released by the hybrid system is recorded where it can be returned to the grid. Therefore, this architecture is an attractive alternative, especially from an economic perspective, as it reduces the size of storage units, and profit achieved by selling the energy back to the utility grid. Despite, of these advantages it shows difficulty in controlling and management energy compared to DC and AC architectures.

I.4 Classification criteria for HRESs

In the literature, several classifications of HRESs have been carried out according to well-defined criteria. A generalization of the most answered classifications is illustrated in figure I.4 below [21].

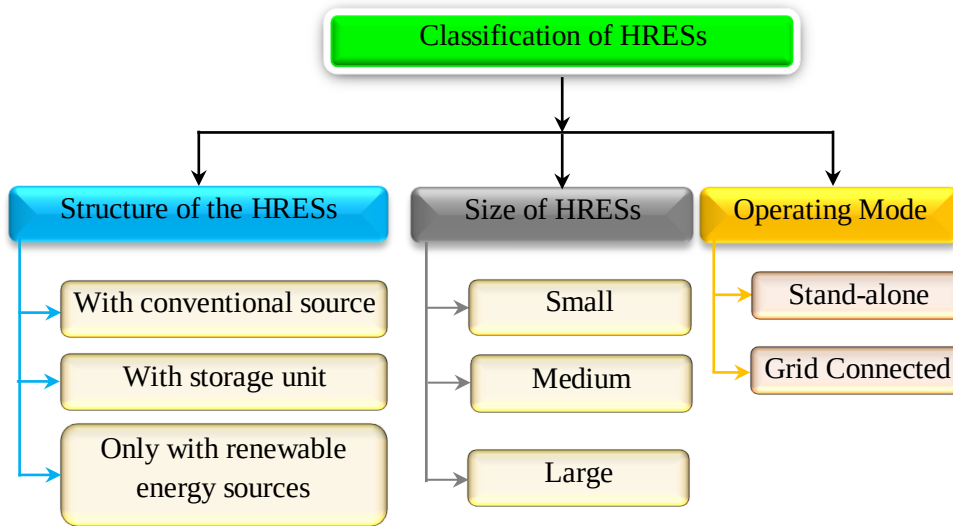


Figure I.4 Classification of HRESs.

I.4.1 HRES operating mode based classification

HRESs are used to meet the requirements load, which can be found into two categories: stand-alone and grid connected modes. The determination of the operating mode is based on various criteria like climatic conditions, application site, grid availability and the cost of kilowatt-hours provided by the electrical grid.

The first category that includes the stand-alone HRESs, in which found in rural and remote areas, due to the he unavailability of an electrical network in these areas, as well as to the high cost of its delivery as a result of long distances, and irregular topography [22]. Therefore, the use of stand-alone hybrid systems mode is an attractive solution to deal with the electrical energy requirements of these areas [9]. In this mode, conventional energy resources and energy storage units can be employed as buck-up resources. Indeed, this process occurs in the case of inability renewable energy resources to meet the requirements of the load, that the required energy is compensated through buck-up resources. On the other hand, when excess power is registered above the load requirements, this will be directed to store the battery bank.

For second mode, HRESs that are connected to the grid; they operate in parallel with the network. This mode is designed to meet power requirements in Factories, universities, hospitals and town applications [23]. An important feature in this mode is the energy exchange between the HRESs and the grid that based on the electricity prices [23]. Therefore, if the grid electricity prices are high, the HRES feeds load and the excess energy for charging the storage units as well as it sells to the grid. On the contrary, when the grid electricity prices are low, the load requirements are assured through grid as well as the process of charging the storage units. In this mode, hybrid systems have more performance appropriate than only renewable energy systems, and also in terms of economic.

1.4.2 HRES size based classification

The size of the HRES is another criterion for its classification [24]. HRES size is based on the load that feed, it ranging from a couple of kW up to many of kW. Therefore, the HRES can be classified into three kind's small, medium and large size. For the small size HRESs with limit power range under 5 kW that used generally to feed the homes located in remotely areas. Whereas, the second category is characterized by a capacity of in excess of 5 kW and under 100 kW, which known as medium HRESs, these are intended to feed a significant number of homes and some amenities located in remote areas. It should be noted that the medium HRESs category in all cases are located in stand-alone mode and are rarely associated to the utility electrical grid. Finally, for systems have power superior to 100 Kw, in which named as the huge systems. It can be associated to utility grid for exchange the electrical energy between the grid and the HRES in the event of a surplus or shortage.

1.4.3 HRES structure based classification

HRES combines various energy sources (conventional and renewable), and often integrate energy storage systems, to ensure maximum reliability of the power supply. Some types of combination between energy sources are described briefly in the following subsections:

1.4.3.1 Combination of renewable energy with conventional sources

In this case, a HRES integrates a conventional power source such as a diesel generator, a gas turbine to have an uninterrupted and permanent power supply. This system can combine several types of energy sources to build a more powerful, reliable and secure system [25].

1.4.3.2 Combination of renewable energy with storage unit

The presences of storage units are indispensable in the HRESs, especially in the stand-alone HRES mode. There is different means of storage divided in short-term storage unit such as battery bank and long-term storage unit such as hydrogen produced through electrolyzer. The combination of short-term and long-term storage devices with renewable energy sources can ensure the reliability and safety of the HRESs. Therefore, the storage unit satisfies the load requirements in the event of an insufficient primary source [25].

I.4.3.3 Only with renewable energy sources

HRES structure consisting of renewable energy resources only must include two or more renewable energy sources such as PV source, wind turbine, biomass or other sources. The type of sources is selected according to their availability. In particular, coupling between PV and Wind are considered the most widespread hybrid systems due to the availability of energy potential solar irradiation and wind speed. The complementarity of these two sources is very significant, whether on an annual or daily scale. This integration of PV and wind energy sources, allows for more reliable energy provision to isolated areas [26].

I.5 HRESs optimization criteria

Recently several areas of research related to HRESs have emerged, which include: control strategies, size optimization, configurations, converter design and performance assessment. All this comes down to two important issues for any HRESs are the search best power reliability and to guarantee the lowest cost of the system [27]. Therefore, they are two criteria by which a HRES can be optimized with the based on one or both of them. The reliability criteria focus on energy continuity to meet load requirements with highest efficiency, whereas the economic criteria prioritize system cost or in some case the size of the whole system [27].

I.5.1 Reliability based criteria

Because of the unpredictable nature of the environmentally friendly power resources like PV and wind systems, reliability analysis plays an essential role in designing of hybrid systems. To assess the reliability of hybrid systems, one of the following parameters is used to complete the reliability analysis; Loss of Power Supply Probability (LPSP), Loss of Load Probability (LOLP), System Performance Level (SPL) and Expected Energy Not Supplied (EENS). These criteria's are briefly defined as follows:

- **LPSP:** is considered as the most popular method that is applied. It is defined as the potential for a power supply shortfall due to the inability of HRE system to ensure the load requirements [28, 29].
- **LOLP:** is defined as a proportion of the likelihood that a hybrid system will not be able to meet maximum (peak) load requirements during a given time period, it happens when the system load surpasses the obtainable generation capacity. It is often expressed in terms of the number of days in a year, hours in a day, or percentage of time [30].
- **SPL:** is defined as the probability that a system will fail to provide load requirements due to a qualifying incident [31].
- **EENS:** is the anticipated energy that won't be provided due to those circumstances when the load requirements surpass the available electrical power [32].

I.5.2 Economic based criteria

Despite the low costs related to operation and maintenance as well as fuel costs, hybrid systems face the challenge of the high cost of the system capital, which requires looking at the optimum value of the cost, to achieve the best possible unit for the hybrid system. A number of economic

optimization criteria's have been mentioned in the literature to achieve optimum designing, configuration and sizing for hybrid systems such as:

- **Net present cost (NPC):** is characterized as the sum of the cash flows spent during the life of the project, which incorporates three costs are: the primary cost of the all components, the replacements cost for any part and the maintenance cost that happen throughout the project lifetime. In most studies, the life of the project is often estimated to be the same as the life of the PV modules, being the components that have the longest life. On the other hand, some other costs such as salvage costs are taken into consideration, which is the worth stayed from the components of the HRES at the last the project lifetime [33, 34].
- **Levelized Cost of Energy (LCOE):** is given as the average cost per kilowatt-hour of beneficial electrical energy delivered by the HRES system [35]. Mathematically is expressed as the total annualized cost of the whole hybrid system divided by the energy delivered by the hybrid system [36]. LCOE is a critical decision whether or not to proceed with the realization of the project.
- **Life Cycle Cost (LCC):** in general, this parameter has a more comprehensive analysis compared to the parameter NPC. In which, the LCC includes the total cost of the HRE system with all expenses incurred over its life, we find some initial costs that have not been taken into account since the beginning of the project and that must be included in the costs [37]. This parameter is usually used for two main reasons are: To compare different power technology options and to define the most cost-effective system [36].
- **Annualized Cost of the System (ACS):** is another parameter that has been developed to be benchmark of hybrid system cost analysis. The ACS is sum of three annual costs include the annualized capital cost, the annualized replacement cost and the annualized maintenance cost [38].
- **Average Generation Cost (AGC):** is defined as the average cost of energy production for all sources included in the design of a HRE system [39].

I.6 HRES optimization methods

There are several objectives in a hybrid system, which needs optimization such as: Sizing, Power quality and cost control, Power dispatch control, Energy management control ... etc. Among this multitude of targets, the size optimization is one of the critical areas of the HRESs. Therefore, to exploit electricity generate from HRESs with trustworthy performance and at a feasible cost; the choose an optimum sizing for the HRESs to satisfy the load demands, should be done based on the criteria's of power reliability along with system cost [40]. Likewise, the results of the research have given the availability of many methods to achieve this optimum sizing of the systems, in which can be broadly categorized into four groups as shown in figure I.5: traditional methods, artificial intelligence methods, hybrid methods [41, 42], and software tools [43].

From literature, software tools are overall broadly utilized in the domain of HRES sizing and optimization because of its accuracy, straightforwardness, and the time wanted for optimization [44]. As result, one of the main impressive strong sizing tools have been released and exceedingly applied in numerous fields of hybrid systems is Hybrid Optimization Model for Electric Renewables (HOMER) software that was created by National Renewable Energy Laboratory

(NREL), United States [6]. Similar to simulation, HOMER permits several tasks to be finished. It gives the most ideal doable configuration possible setup so there is a match among consumption and production, optimization the size as well as provides the financial analysis of the whole system, Managing the energy produced from sources to feed the load at the most appropriate time, calculation the energy produced, consumed and efficiency of each component as well as the entire system [45, 46].

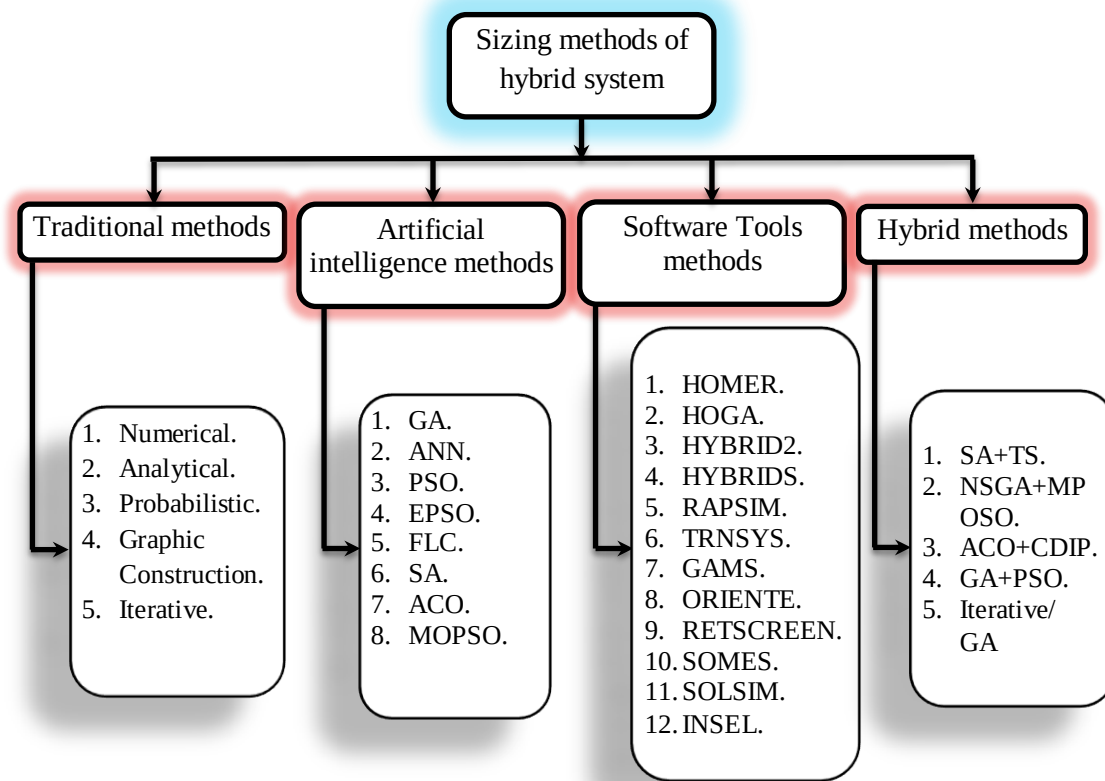


Figure I.5 Hybrid system sizing methods.

In this thesis, the HOMER software will be used for the optimization sizing of the HRES, and identifying the optimum hybrid configuration and their applicability, among various hybrid systems that developed, considering some parameters such as NPC and COE. Therefore, we have done a comprehensive review of all papers that utilized HOMER for optimal planning of HRESs as described in the next section.

I.7 Literature review for HOMER software

From all these papers, the HOMER program assists for designing and the technico-economic analysing of hybrid power systems in order to find the best possible configuration. As results, this program gives several designs, sometimes up to 100, all of which meet the consumer's requirements of electrical energy, depending on the input parameters of the system components, but these systems are different in terms of quantity and some economic criteria. In library of HOMER contains some traditional generators, green generators, electronic power devices and storage units, we can mention such as: Diesel generators, Fuel cell stack, PV module, Biomass, Wind, Hydropower, Electrical grid, Battery bank, Electrolyzer, Hydrogen tank and DC/AC Converters.

Thus, HOMER can be employed to improve the HRES for vast modes: whether stand-alone or grid connected. Simulation, optimization and sensitivity analysis are the main tasks that can be implemented by HOMER software.

Substantial research has been conducted focusing on the feasibility of renewable energy sources in many countries, and perhaps the tropics are the most important areas that focus on the use of hybrid systems based on renewable energy sources due to the difficulty of connecting electrical networks to remote areas, especially islands. In the last two decades, numerous papers have been released to assess these hybrid systems utilizing HOMER. The table I.6 below shows a summary of this research, which included 129 papers from various journals. We aim from this summary to help any researcher to design hybrid system with a specific combination according the type and region of load as well as know several points as follows:

- All papers mentioned in table I.6 are extensions from around 19 journals, its main are Energy Policy (7 papers), Energy (15 papers), Renewable and Sustainable Energy Review (16 papers), Renewable Energy (28 papers) and Institute of Electrical and Electronics Engineers (35 papers) as represented in figure I.6.a.
- HOMER software includes Renewable/Non renewable energy sources like: PV, Wind, FC, Hydro, Biomass, Diesel and Electrical Grid. Several configurations as presented in table I.6 used to feed load considered. Figure I.6.b, represent the configurations used, where PV/Win, PV/Diesel and PV/Win/Diesel are among the most prevalent configurations as HRESs in distant areas, islands, villages, hotels, universities and residences. On the other hand, PV system is regarded as the most sharing source of every past configuration, due to the availability of solar energy, followed by diesel generator, wind and electrical grid as represented in figure I.6.c. In recent years, new resources are integrated such as biomass and hydro power as well as fuel cell.
- Power converters and storage units are among the critical parts in a HRES configurations. DC/DC converter is competent of feeding continuous power to the load and it works to raise the voltage but the load is AC based. Hence, an inverter is necessary for the DC to AC power conversion. As for storage components, battery bank and hydrogen tanks are employed to store energy.
- Hybrid system works in stand-alone or grid connected mode. From figure I.6.d Stand-alone HRE systems are viewed as the most mode employed contrasted with grid connected HRE systems, in which the studied cases amounted to 77.52% of the 129 cases shown in the table I.6. In particular, islands are a great application opportunity for testing hybrid systems in standalone mode.
- Four criteria's are utilized to evaluate the optimization results obtained for every configuration developed to supply the load, these criteria's are: initial capital cost, O&M, NPC and COE. The best configuration given by HOMER is based on the lowest value of NPC and COE. From table I.6, it is shown that the NPC as well as COE are predominant in the literature compared to the other criterions to choice the best configuration.

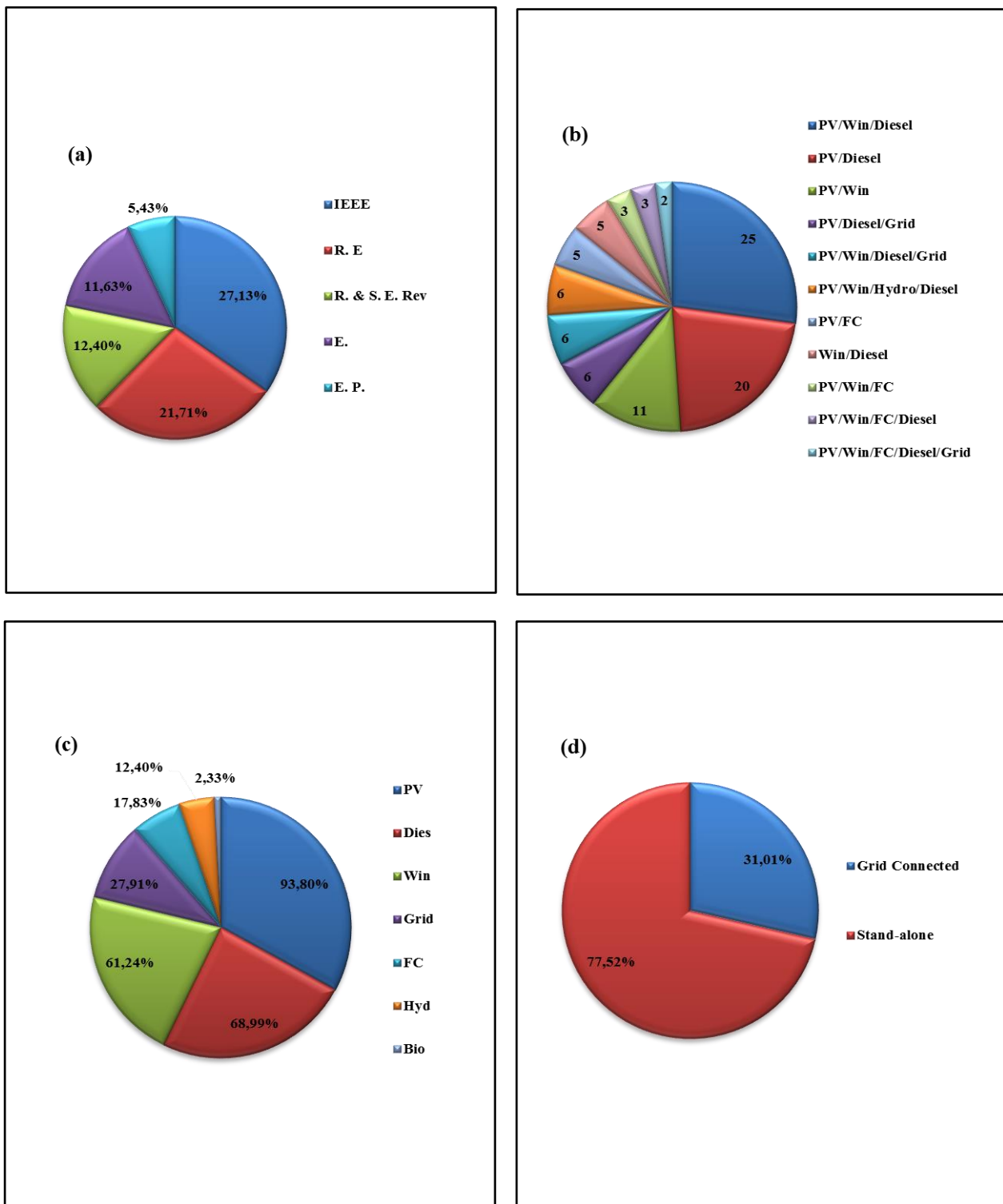


Figure I.6 Statistic for hybrid systems: **a)** Publications per journal, **b)** Number of configurations, **c)** the most contributing energy sources, **d)** Connected mode.

Table I.1: Description hybrid renewable energy systems in different articles.

Year	Ref Number	Journal	Sources							Converters		Storage units		Optimized system outcomes				Connected modes		Demand Load (kW/d)	Peak demand (kW)	Nature of load	Location
			PV	Win	FC	Hydro	Biomass	Diesel Generator	Electrical Grid	Converter	Electrolyzer	Battery	Hydrogen Tank	Initial Capital (\$)	Operating Cost (\$/y)	Total NPC (\$)	COE (\$/kWh)	Grid connected	Stand-alone				
2002	[47]	IEEE	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	542 027	0.554	/	✓	306	/	Island	Thailand
2004	[48]	R. E.	✓	✓	/	/	/	/	/	✓	/	✓	/	/	/	/	/	✓	/	/	11	Typical R-2000 house	Canada
2005	[49]	R. E.	✓	✓	✓	/	/	✓	/	✓	✓	✓	✓	/	/	41 424	0.427	/	✓	25	4.7	Remote area	Canada
2005	[50]	E.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	675 682	0.11	/	✓	/	9.6	Desert agricultural area	Egypt
2007	[51]	R. & S. E. Rev.	✓	/	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.149	/	✓	1689	159	Commercial building	K. S. A.
2007	[52]	R. & S. E. Rev.	/	✓	/	/	/	✓	/	/	/	/	/	/	/	10 158 187	0.041	/	✓	44000	4231	Village	K. S. A.
2007	[53]	R. E.	✓	/	✓	/	/	✓	/	✓	✓	✓	✓	/	/	/	/	/	✓	50	8.3	Small community	Kythnos
2007	[54]	IEEE	✓	✓	✓	/	/	/	/	✓	✓	✓	✓	/	/	/	/	/	✓	150	10.9	/	USA
2008	[55]	R. E.	✓	/	/	✓	/	✓	/	✓	/	✓	/	/	/	/	0.296	/	✓	111	12	Remote area	Cameroon
2008	[56]	R. E.	/	✓	/	/	/	✓	✓	/	✓	/	✓	/	/	/	0.16	✓	/	5300	356	Remote area	Canada
2008	[57]	R. E.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	/	/	/	✓	15000	966	Hotel	Australia
2008	[58]	R. & S. E. Rev.	✓	/	/	/	/	✓	/	✓	/	✓	/	/	/	98 911	0.178	/	✓	97	9.3	Residential consumers	K. S. A.
2008	[59]	IEEE	✓	/	/	/	/	✓	/	✓	/	✓	/	/	/	/	/	/	✓	809	110.9	Remote area	Malaysia
2009	[60]	E. P.	✓	✓	/	/	/	/	/	/	/	✓	/	223 143	6 144	319 132	0.363	/	✓	169	61	Rural	Bangladesh
2009	[61]	E. P.	✓	✓	/	✓	/	/	✓	✓	/	✓	/	/	/	/	0.774	✓	✓	/	/	Village	Portuguese
2009	[62]	R. E.	✓	/	/	✓	/	✓	/	/	/	✓	/	/	/	119 180	0.352	/	✓	73	8.3	Remote villages	Cameroon
2009	[63]	R. E.	✓	/	/	/	/	✓	/	✓	/	✓	/	357 200	/	/	0.425	/	✓	/	24	Rurale	Senegal
2009	[64]	R. E.	✓	/	/	✓	/	✓	/	✓	/	✓	/	28 143	/	54 636	0.234	/	✓	45	7.5	Village	Cameroon
2009	[65]	R. E.	✓	✓	/	/	/	/	✓	✓	/	✓	/	/	/	/	/	✓	/	15000	966	Hotel	Australia
2009	[66]	R. E.	✓	✓	/	/	/	✓	/	✓	✓	/	✓	/	/	/	0.231	/	✓	/	8080	Island	Greece
2009	[67]	R. E.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	/	/	/	✓	/	297.2	Hotel	Australia

2009	[68]	E. S. D.	✓	/	/	/	/	✓	/	✓	/	✓	/	19 702	3 301	66 227	0.297	/	✓	43	6	Remote area	Jordan
2009	[69]	R. & S. E. Rev.	✓	/	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.170	/	✓	44000	4200	Remote area	K. S. A.
2009	[70]	IEEE	✓	/	✓	/	/	/	/	✓	✓	✓	✓	/	/	163 957	0.706	/	✓	50	4.2	Kolkata city	India
2009	[71]	IEEE	✓	/	/	✓	/	✓	/	✓	/	✓	/	87 720	/	132 826	0.197	/	✓	146	15	Remote area	South Africa
2010	[72]	A. E.	✓	✓	/	/	/	✓	/	✓	/	✓	/	58 320	/	201 609	0.322	/	✓	142600	43.05	Remote area	Ethiopia
2010	[73]	E	✓	/	/	/	/	✓	/	✓	/	✓	/	50 000	112 056	1 482 455	0.275	/	✓	1156	84	Remote area	Malaysia
2010	[74]	E	✓	✓	/	/	/	/	/	✓	/	✓	/	231 225	10 259	391 492	0.47	/	✓	160	32	Remote area	Bangladesh
2010	[75]	E	✓	/	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.19	/	✓	47000	4400	Remote area	K. S. A.
2010	[76]	E. P.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.42	/	✓	160	23	Island	Bangladesh
2010	[77]	E. P.	✓	/	✓	/	/	/	/	✓	✓	✓	✓	50 504	3 707	84 142	1.072	/	✓	/	/	Island	Brasil
2010	[78]	I. J. H. E.	✓	✓	/	✓	/	✓	✓	✓	/	✓	/	/	/	/	1.3	/	✓	392	34	Urban area	UK
2010	[79]	E. S. D.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.37	/	✓	50	11	Remote area	Bangladesh
2010	[80]	E. R. J.	✓	✓	✓	/	/	✓	✓	✓	/	✓	/	/	/	53 197	0.57	✓	✓	20	3.1	Coastal residential area	Malaysia
2010	[81]	S. E	✓	/	/	/	/	✓	/	✓	/	✓	/	50 700	/	60 375	0.238	/	✓	31.6	/	Rural area	Iraq
2010	[82]	R. & S. E. Rev.	✓	✓	/	/	/	✓	✓	✓	/	✓	/	/	/	32 537 056	0.174	✓	✓	46000	3500	Island	Turkey
2010	[83]	IEEE	/	✓	✓	/	/	/	/	✓	✓	✓	✓	/	5 414	159 713	0.785	/	✓	44	4	Remote area	India
2010	[84]	IEEE	✓	✓	/	/	/	✓	/	✓	/	✓	/	328 613	54 051	726 433	0.216	/	✓	1253	197	Island	Malaysia
2010	[85]	IEEE	✓	✓	✓	/	/	/	/	✓	✓	✓	✓	/	/	2 258 233	0.398	/	✓	623	65	Village	Iran
2011	[86]	R. E.	✓	/	/	/	/	✓	/	✓	/	✓	/	40 726	/	/	0.65	/	✓	48	16	Electric Machinery Laboratory	Greece
2011	[87]	R. E.	✓	/	✓	/	/	✓	/	✓	✓	✓	✓	/	/	/	0.871	/	✓	42	4	Remote area	Greece
2011	[88]	E. P.	✓	✓	/	/	/	✓	/	✓	/	✓	/	1 392	/	3 549	1.19	/	✓	3.2	0.626	Rural areas	Algeria
2011	[89]	R. E.	✓	✓	✓	/	/	/	✓	✓	✓	/	✓	/	/	/	0.307	/	✓	627	329	University	Turkey
2011	[90]	E. P.	✓	✓	/	/	/	/	✓	✓	/	/	/	2 096 097	13 020 268	1 685 358	0.379	✓	/	95	7.7	Arid region	Algeria
2011	[91]	IEEE	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	147	4 402	/	/	✓	910	144	Hypothetical building	India
2011	[92]	IEEE	✓	/	/	/	/	✓	/	✓	/	/	/	843 5000	734 8362	1 232 316	0.272	/	✓	79000	7100	University	Malaysia
2011	[93]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/	/	/	6 940 033	0.095	✓	/	16000	982	Industry area	Malaysia
2011	[94]	IEEE	✓	✓	/	/	/	/	✓	✓	/	✓	/	641 600	218820	3 151 453	0.196	✓	/	3800	325	Residential consumers	Hypothetical
2011	[95]	IEEE	✓	✓	/	/	/	/	/	✓	/	✓	/	/	/	/	0.172	/	✓	39000	5300	Island	USA
2012	[96]	R. & S. E. Rev.	✓	✓	/	/	/	✓	✓	✓	/	✓	/	15 000	17 870	177 208	0.369	✓	✓	/	13.4	Village	Iran
2012	[97]	R. & S. E. Rev.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.436	/	✓	763	77	University	Malaysia

2012	[98]	R. & S. E. Rev.	✓	/	✓	/	/	✓	✓	✓	✓	✓	✓	300 000	29 075	838 768	0.256	✓	✓	/	36	University	Turkey
2012	[99]	R. E.	✓	✓	/	✓	/	✓	✓	✓	/	✓	/	/	130 000	166 100 033	0.071	✓	✓	5000	1183	Rural community	Canada
2012	[100]	R. E.	✓	✓	/	/	/	✓	/	✓	/	/	/	13 764 080	2 408 521	41 389 628	0.212	/	✓	47000	4400	Village	K. S. A.
2012	[101]	R. & S. E.	✓	✓	/	/	/	/	/	✓	/	✓	/	22 998	218	24 623	1.655	/	✓	5.5	0.495	Portable police building	Iran
2012	[102]	A. E.	✓	✓	/	✓	/	✓	/	✓	/	✓	/	/	/	246 787	0.101	/	✓	571	82.8	Rural	Ethiopia
2012	[103]	I. J. E. R. T.	✓	/	✓	/	/	/	/	✓	✓	✓	✓	/	/	/	0.431	/	✓	140	13	Agricultural application	India
2012	[104]	IEEE	✓	✓	/	/	/	✓	✓	✓	/	✓	/	/	/	/	/	✓	/	/	1030	University	Iran
2012	[105]	IEEE	✓	/	/	/	/	✓	/	✓	/	✓	/	/	/	/	/	/	✓	580	91	Sebira Island	Indonesia
2012	[106]	IEEE	/	✓	/	/	/	✓	/	✓	/	✓	/	942 000	138 204	2 708 705	0.232	/	✓	2500	207	Remote Area	India
2013	[107]	E.	✓	✓	/	/	/	/	/	✓	/	✓	/	42 300	860	53 296	1.045	/	✓	11	5.6	Remote area	China
2013	[108]	E.	✓	✓	/	/	/	✓	/	✓	/	✓	/	17 414	776	3 0921	0.751	/	✓	6.5	56	Village	Indonesia
2013	[1]	R. E.	✓	✓	✓	/	/	✓	/	✓	✓	✓	✓	1 971 000	45 624	2 554 228	1.104	/	✓	/	7109	Island resorts	Malaysia
2013	[109]	A. E.	✓	✓	/	/	/	/	✓	✓	/	✓	/	/	/	/	/	✓	/	97	9.97	Hotel	Jordan
2013	[110]	I. J. R. E. Res.	✓	✓	/	/	/	/	/	✓	/	✓	/	29 361	220	34 861	1.051	/	✓	3.7	1.1	Urban areas	India
2013	[111]	IEEE	✓	✓	/	/	/	✓	/	✓	/	✓	/	1 209 696	272 417	5 049 133	18.589	/	✓	53	10	Island	Bangladesh
2014	[112]	E.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.2	/	✓	120000 & 12000 & 24000	11000 & 1137 & 2300	Remote areas	UAE
2014	[113]	E.	✓	✓	/	✓	/	✓	/	✓	/	✓	/	28 988	1 143	43 599	0.265	/	✓	/	3.8 & 5.6	Rural	South Africa
2014	[114]	R. E.	✓	✓	/	✓	/	✓	/	✓	/	✓	/	/	/	673 147	0.42	/	✓	493	159	Village	India
2014	[115]	R. E.	✓	✓	/	/	/	✓	✓	✓	/	✓	/	/	/	13 044 109	0.174	✓	✓	11000	550	Island	South Korea
2014	[116]	R. & S. E. Rev.	✓	✓	/	✓	/	✓	/	✓	/	✓	/	/	/	/	0.048-0.078	/	✓	82191	5665	Urban areas	Serbian
2014	[117]	R. & S. E. Rev.	✓	✓	/	/	/	✓	/	✓	/	✓	/	367 102	106 803	1 723 403	0.288	/	✓	1289	211	Urban area	Somali
2014	[118]	A. E.	✓	✓	/	/	/	/	/	✓	/	✓	/	608 932	/	693 114	0.595	/	✓	250	27	Remote island	Hong Kong
2014	[119]	E. P.	✓	/	/	✓	/	✓	/	✓	/	✓	/	35 183	1 307	51 887	0.189	/	✓	/	/	Rural	South Africa
2014	[120]	E. C & M.	✓	✓	/	/	/	✓	/	✓	/	✓	/	1 163.8	143.8	3 905.6	0.281	/	✓	2000	83	Remote areas	Ghana
2014	[121]	E. S. D.	✓	/	/	/	/	✓	/	✓	/	✓	/	845 000	149 000	344 1000	0.364	/	✓	1500	236	Rural areas	Nigeria
2014	[122]	IEEE	✓	/	/	/	/	✓	/	✓	/	✓	/	843 000	2 013 815	26 586 316	12.098	/	✓	471	145	Technical college	India
2014	[123]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/	4 900	/	4 113	0.075	✓	/	12	1.7	House	India
2014	[124]	IEEE	/	✓	/	/	/	/	✓	/	/	/	/	1 262 190	962 804	13 570 056	0.043	✓	/	67000	4600	Small village	Algeria
2015	[125]	R. E.	✓	✓	/	/	/	✓	/	✓	/	✓	/	196 000	/	752 290	0.344	/	✓	589	44.4	Village	Bangladesh
2015	[126]	R. E.	✓	✓	/	✓	/	✓	/	✓	/	✓	/	/	62 568	881 829	0.2	/	✓	856	92	Island	Scotland

2015	[127]	R. E.	✓	/	/	/	/	/	✓	✓	/	/	/	/	/	/	/	✓	/	32962000	2213000	Urban area	Saudi Arabia
2015	[128]	R. E	✓	/	/	/	/	✓	/	✓	/	✓	/	/	/	62 772 746 624	0.369	✓	/	32962000	2213000	Urban area	Saudi Arabia
2015	[129]	R. E	/	✓	✓	/	/	✓	/	✓	✓	/	✓	1 592 307	124 939	3 025 344	0.295	✓	/	2400	175	Island	Iceland
2015	[130]	R. E	/	✓	/	/	/	✓	/	/	/	/	/	/	/	/	/	/	✓	/	/	Rural areas	Canada
2015	[131]	R. & S. E. Rev.	✓	✓	✓	/	/	✓	✓	✓	✓	✓	✓	/	2 614	75 515	0.997	✓	/	13	1.3	Rural telecom	India
2015	[132]	R. & S. E. Rev.	✓	/	/	/	/	✓	/	✓	/	✓	/	15 650	41 329	188 863	0.142	/	✓	/	/	Research unit	Algeria
2015	[133]	R. & S. E. Rev.	✓	✓	/	/	/	/	✓	/	/	/	/	/	/	1 250 212 736	2.79	✓	/	/	/	Coastal site	Algeria
2015	[134]	R. & S. E. Rev.	✓	✓	/	✓	✓	✓	/	✓	/	✓	/	/	/	1 886 000	5.6 4	/	✓	653	52	Rural areas	India
2015	[135]	E.	✓	✓	/	✓	/	✓	/	✓	/	✓	/	/	/	31 901 944	0.145	/	✓	25000	2700	Resort Island	Malaysia
2015	[136]	E.	✓	/	/	/	/	✓	/	✓	/	✓	/	/	/	656 858	0.569	/	✓	593	50	Island	Malaysia
2015	[137]	E.	✓	/	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.048	/	✓	248	25	Rural area	Bangladesh
2015	[138]	I. J. H. E.	✓	✓	✓	/	/	✓	/	✓	✓	✓	✓	/	/	11 960 698	0.83	/	✓	1875	135	Island	Turkey
2015	[139]	A. E.	✓	/	/	/	/	✓	/	✓	/	✓	/	119 400	2 918	150 552	0.707	/	✓	56.1	8	Laboratory complex	Congo
2015	[140]	E. C & M.	✓	✓	/	/	/	/	✓	✓	/	✓	/	8 370	82	9 656	0.488	✓	/	3.5	1.4	Urban area	India
2015	[141]	E. C & M.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	/	/	/	✓	/	13	Village	Algeria
2015	[142]	S. E. T. & Ass.	✓	✓	/	/	/	✓	/	✓	/	✓	/	270 500	17 262	552 752	0.336	/	✓	320	25	Rural areas	Sri Lanka
2015	[143]	IEEE	✓	✓	/	/	/	/	/	✓	/	✓	/	2 550/1 250	/	4 256/1 501	0.259/0.108	/	✓	4.2 & 3.6	0.6 & 0.639	Irrigation Pump	India
2015	[144]	IEEE	✓	✓	/	/	/	/	✓	✓	/	✓	/	600 000	/	53 5661	0.095	✓	✓	654.73	101. 32	Rural area	Bangladesh
2016	[145]	E	✓	/	✓	/	/	/	✓	✓	✓	✓	✓	13 938	7 245	106 ,551	0.091	✓	/	250	22	Hospital building	Malaysia
2016	[146]	E. Rep.	✓	/	✓	/	✓	/	/	✓	✓	✓	✓	2 681 000	/	5 189 003	15.064 Rs	/	✓	101	5	Educational institute	India
2016	[147]	Sus	✓	✓	/	/	/	/	/	✓	/	✓	/	/	22 555	2 224 835	0.247	/	✓	755/1385	45/67	Two islands	Korean
2016	[148]	R. & S. E. Rev.	/	✓	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.487	/	✓	8000	537	Remote area	Canada
2016	[149]	R. E.	/	/	/	/	/	✓	/	✓	/	✓	/	4 207	5 459	72 232	0.306	/	✓	54	2.8	Remote area	Norway
2016	[150]	S. E. T. & Ass.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	/	0.324	/	✓	/	/	Rural areas	Nigeria
2017	[151]	R. & S. E. Rev	✓	/	✓	/	/	✓	/	✓	✓	✓	✓	162 800	79 149	335 297	0.323	/	✓	140	21	Rural areas in	Malaysia
2017	[152]	S. C & S.	✓	✓	/	/	/	✓	/	✓	/	✓	/	/	/	17 150 000	0.279	/	✓	13,048	1,185	Commercial	Malaysia
2017	[153]	S. E. T. & Ass.	✓	/	/	/	/	✓	/	✓	/	✓	/	243 000	/	412 104	0.760	/	✓	2/104	1.3/34	Community	Ghana
2017	[154]	S. E. T. & Ass.	✓	/	✓	/	/	✓	/	✓	✓	✓	✓	/	/	/	0.212	/	✓	350000	19000	Remote area	Ghana
2017	[155]	IEEE	✓	✓	/	/	/	✓	✓	✓	/	✓	/	50 770	/	34 660	0.0618	✓	✓	11.26	2.09	Residential	Georgia
2018	[156]	J. E. & C. E.	✓	✓	✓	/	/	/	/	✓	✓	✓	✓	465 100	6 215	544 550	0.313	/	✓	375	39.7	Rural village	Ethiopia

2018	[157]	E.	✓	✓	/	/	✓	/	/	✓	/	✓	/	/	16 354 571.09	180 290 247 40	0.0574	/	✓	/	73600	Residential	Pakistan
2018	[158]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/	/	/	47 770 000	0.0401	✓	/	281680.80	25212	University	Egypt
2018	[159]	IEEE	✓	✓	/	/	/	✓	/	✓	/	✓	/	40 000	81 312	202 618	0.541	/	✓	566.72	105.22	Rural remote	India
2018	[160]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/	12 000	0.681	11 993	0.0316	✓	/	67	16.29	Technical institute	India
2018	[161]	IEEE	✓	/	/	/	/	✓	✓	✓	/	/	/	459	3 347	43 728	0.1	✓	✓	91.7	21.58	Superior Livestock Breeding Center	Indonesia
2019	[162]	S. E. T. & Ass.	✓	/	/	/	/	/	/	✓	/	✓	/	82 018	1,264	109 856	0.059	✓	/	/	/	Irrigation	Egypt
2019	[163]	R. E.	✓	/	/	✓	/	✓	/	✓	/	✓	/	/	/	1 13 210	0.054	✓	/	/	34.34	Rural remote	Iraq
2019	[164]	E.	✓	✓	/	/	/	/	✓	✓	/	✓	/	48 497	/	82 734	0.207	✓	/	108	19.6	rural electrification	Ethiopia
2019	[165]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/	/	/	/	/	✓	/	846.3	206.02	University	India
2019	[7]	IEEE	✓	/	/	/	/	✓	✓	✓	/	✓	/	85 000	643 000	168 000	4.64Rs	✓	/	4443.15	2005.11	University	India
2019	[166]	IEEE	✓	✓	/	/	/	✓	✓	✓	/	✓	/	/	/	/	/	✓	/	250	30.92	Technical Institution	India
2019	[167]	IEEE	✓	/	/	/	/	✓	✓	✓	/	/	/	821 000	918 118	16 700	4.95	✓	/	852.19	163.29	Educational institute	India
2019	[168]	IEEE	✓	/	/	/	/	/	✓	✓	/	/	/	707 530	226 263	3 156.31	0.104	✓	/	6200	502	University	India
2019	[169]	IEEE	✓	/	/	/	/	✓	✓	✓	/	✓	/	/	/	11 4000	3.1	✓	/	480	134.63	Educational campus	India
2019	[170]	IEEE	✓	/	✓	/	/	/	/	✓	✓	✓	✓	39.930	946	5.028	0.426	/	✓	27	4.2	Laboratory	Algeria
2020	[171]	S. E. T. & Ass.	✓	✓	/	/	/	✓	/	✓	/	✓	/	880 103	1 456 296.72	8 649 053 62	0.382	✓	/	2422.06	407.71	Rural remote	Ghana
2020	[172]	E.	/	✓	/	/	/	✓	/	✓	/	✓	/	3 980 200	/	8 674 269	0.528	/	✓	3484	1400.44	Central city	China
2020	[173]	IEEE	✓	/	/	/	/	✓	✓	✓	/	/	/	/	/	/	/	✓	✓	13848	1151.75	National Institute of Technology Campus	India

Among all the configurations shown in figure 6.b, which combined many sources whether it was a mixture between conventional and renewable or renewable alone or connected to the electrical network to form hybrid systems, we focused on the hybrid system that combines the PV system with PEM fuel cell. Solar system has been on the increase all over the globe to produce electric power in the past decade. While hydrogen has recently emerged as an energy carrier in which a fuel cell uses to convert a chemical energy into electrical energy. This type of HRES includes both sources PV and PEM fuel cell, battery bank, electrolyzer and hydrogen tank to store hydrogen generated as well as other components. Therefore, this configuration of the HRES based PV/PEMFC was installed in various projects. The section below, presents some real projects that combine the components of this type of HRES.

1.8 Projects on based PV/FC Hybrid systems for power production

The combination of PV systems with fuel cells is one of the projects that came to light in the early nineties of the last century, as some of them were installed for stationary power production. In fact, these projects receive financial support from governments and some institutions, due to the high costs of realization. Currently, some research and development studies are urgently needed to use these systems on a large scale and to look for ways to reduce costs.

Table I.2: Real Projects hybrid system based PV/PEMFC.

Ref	Project name	Country	Project time		Components of system					Observation
			Start-up	End	PV Power (kW)	PEMFC Power (kW)	Capacity Battery (kW h)	Elec Power (kW)	Hydrogen Tank Volume Capacity (Nm ³)	
[174]	Schatz	USA	1989	1997	9.2	1.5	20	6	60	The Schatz Solar Hydrogen Project was installed at the Humboldt State University (HSU), Telonicher Marine Laboratory, since the fall of 1989. It is equipped to continuously supply power to the air compressor (load), which aerates the lab's aquaria. The goal of this project at that time was to demonstrate the possibility that hydrogen produced through electrolyzer can function as an energy storage in the medium term, and used later by fuel cell to convert chemical energy to electrical energy. After 7 years of operation until 1996, the PEMFC stack was removed from the system due to the appearance of deterioration on it.
[175]	Freiburg Solar House	Germany	1992	1995	4.2	3.5	20	2	15	The project aims for energy autonomy under Central European climatic conditions that require seasonal energy storage. The project is directed to feed a dwelling in Freiburg that was created by the Fraunhofer Institute for Sun Energy Systems.

[176, 177]	PHOEBUS	Germany	1993	2003	43	5.6	304	26	3000	During the ten years between 1993 and 2003, the PHOEBUS factory located in Germany supplied the central library of Forschungs zentrum Julich with electric power generated from a HRES based on PV/PEMFC. The purpose of this system experiment was to test the effectiveness of hydrogen as an energy carrier. The results showed that it is possible to supply the central library with electric power through two sources of renewable energy without resorting to the utility grid. In the initial step, a 6.5 kW alkaline fuel cell was included in the system, but it was not sufficiently reliable. In the finish of 1999, a new type of FC called PEMFC has been introduced, which worked without issues till the terminus of PHOEBUS tasks.
[176-178]	SAPHY	Italy	1994	1997	5.6	3	51	5	120	The SAPHYS project was upheld by the European Commission under the Joule II of the Non-Nuclear Energy Program, and is a joint project between Ente per le Nuove Tecnologie l'Energia l'Ambiente in Italy (ENTEA), Institutt for Energiteknikk in Norway (IFE), and Forschungszentrum Julich in Germany (KFA). The first aim of the project was to examine and prove the usage of hydrogen as a storage medium for electrical energy produced from photovoltaic systems in the long term, and secondly, a small stand-alone system was designed and tested. The system includes PV array of 5.6 kW to supply the load and the alkaline electrolyzer of 5 kW. Through this project, it has been shown that the electrolyzer is a sufficiently mature and reliable technology to produce hydrogen as a power carrier, and that the PEM fuel cell incorporated in this HRES is suitable for small-scale systems.

[179, 180]	HARI	United Kingdom	2002	/	13	7	120	36	2856	In Leicestershire located at United Kingdom, the project of HARRI directed to the West Beacon Farm has been set up. The objective of this program is to enhance the feasibility of a stand-alone hybrid power system, while gaining sufficient knowledge in the design of HRESs. The project has been running since 2002, and it is oriented to supplying commercial centers and homes on a local micro-grid. The HARI project gave the concept of hybrid systems utilization and energy storage in the form of hydrogen, with the ultimate goal of achieving self-sufficiency for the West Beacon farm.
[180]	FIRST	Spain	2002	2004	1.4	0.42	20	1	70	The project test two hybrid power systems intended to meet the requirements of telecommunication units in Madrid, Spain. The first hybrid system includes PV, battery, electrolyzer and fuel cell, where the primary target of the FC is to provide backup power in the happening of power insufficiency in the battery bank. While, the second test was a completely independent system to exhibit the process of hydrogen production by means of water electrolysis during the sunny periods, after that the hydrogen is stored in tank to employ in a long-term as an energy storage system, in which used later via a fuel cell to provide electricity required by the users. Generally, the main objective is to examine the reliability and maintenance service desired to design this system, compared to traditional backup models for telecom applications in far areas by using the PEMFC to be as backup power in the event of a power lack in the battery bank.

[181]	Hybrid energy storage system at NFRC, California	USA	2010	/	5	1	/	7	0.5	The system is built and tested to provide electrical power in residential applications. The hydrogen created by means of the electrolyzer is used by the FC running in parallel with the battery to meet the dynamic demand for energy. The project showed the specialized technical feasibility of working HRE systems under the simultaneous dynamics of irradiation, temperature and load.
[182]	Bozcaada	Turkey	2011	/	20	20	/	50	667	The Bozcaada Hydrogen Island project is the considered as the first project of its kind in Turkey. This project belongs to the list of projects approved by the United Nations Industrial Development Organization, as it was installed by the International Center for Hydrogen Energy Technologies in Bozcaada Governor's building in 7 October 2011, with the support of the Turkish Ministry of Energy and Natural Resources. The project aims to support energy production in stand-alone applications for the powering of island communities by integrating hydrogen technologies and renewable energies. In the case of a grid failure or peak demand, the fuel cells start supplying uninterrupted electricity to the equivalent of 20 households for up to 24 hours.
[181]	MYRTE, Corsica	France	2012	/	560	210	/	56	494	The MYRTE platform is installed grâce the commitment of four partners, the National Center for Scientific Research, the University of Corsica Pasquale Paoli, AREVA Energy Storage, and the Atomic Energy and Alternative Energies Commission. This project aims to enhance the quality and reliability of French Electricity System network through the energy stored in hydrogen. The power plant produces the equivalent of the electrical consumption of 200 homes.

I.9 Conclusion

In this chapter, overviews for HRESs have been done, that included several aspects as follows:

The mode of coupling architectures and classification of HRES, the criteria and the methods of optimization used are essential part. The criteria by which HRES is improved fall mainly into two categories: economic and reliability. Both include several criteria such as LPSP, LOLP, SPL and EENS for reliability criteria, while the economic criteria include NPC, LCOE, ACS and AGC. However, LPSP and NPC are considered the main criteria generally used in determining system reliability and cost, respectively. On the other hand, to ensure the reliability of the supply while keeping the cost of the system low, the optimization sizing of HRES is very much necessary. Various techniques and tools have been developed to achieve this optimum sizing of the systems. In fact, all methods or tools mentioned above have their own advantages, in addition to the possibility of their use in the future in this aspect. However, choosing the appropriate approach is usually due to the type of application, user needs, etc. Therefore, the HOMER software will be used for the optimization sizing of the HRES. As result, we presented 129 papers, all dealing with the use of the HOMER software in the sizing optimization of the HRESs. These papers demonstrate several points among this: HOMER performs three main tasks simulation, optimization and sensitivity analysis for wide modes of designs: whether stand-alone and grid connected modes according to the criteria of NPC and COE to obtain the optimization results. In the last part, we presented some real projects that combine PV and PEMFC, as these projects show the goals of system in the production and storage energy in long-term by using hydrogen as an energy carrier, which is later exploited by PEMFC. This system is very promising, especially for stand-alone systems, but the high cost of the project hinders its implementation in several applications, and for this we find that the majority of projects had financial support from international unions and governments.

Chapter II

Description and Modeling of PV System

II.1 Introduction

The sun shines every morning to send its energy towards the earth. Solar energy is defined as the amount of radiation emitted from nuclear reactions that occur in the core of the sun, and solar energy or sunlight reaches earth through space in the form of bundles of photons or electromagnetic radiation. Although the sun is up to 150 million kilometers away from the Earth [183], it has amazing power. Theoretically, scientists claim that the big quantity of solar energy that arrives at the Earth is able to give the energy necessities of the entire world, only if advanced technologies exist to harvest and use it appropriately [184]. The amount of sun energy directed towards the Earth varies between 15750 EJ to 49837 EJ (which is around 4375-13843 PWh per year), and the received energy per square meter of the land atmosphere is estimated at about 342 W/m^2 , but the amount of energy which passes through Earth's atmosphere is only about 70% or 239 W/m^2 available for exploitation, and the remaining 30% spreads again through space [185]. Unluckily, this potential is not fully exploitable, whether it is by humans or because it is considered an intermittent energy source controlled by several factors such as the Earth's rotation and weather fluctuations that block solar radiation.

The importance of the sun was known to mankind from ancient times. For example, the Romans used glass, which allowed them to trap the sun's heat [186]. After that, the matter passed to the issuance of a law that criminalizes the blocking of sunlight on homes among neighbors so that everyone benefits from sunlight [187]. With the passage of time, it was found that the energy sources currently on our planet are mainly due to solar energy and have been transformed into other energy sources such as thermal energy in the ground and energy generated by precipitation, coal, and timber, and it is also the main initiator of cycles that constitute fossil fuels.

The idea of converting solar energy to other sources of energy is the subject of several studies among scientists and engineers. Currently, we have two main technologies for using sunlight based energy is: Active as well as Passive solar technologies [187, 188].

- Passive solar technologies: This technology does not depend on the use of mechanical devices or equipment through which the sun's energy is converted into power. Greenhouses and heating of homes are considered exemplifies a form of passive solar technology.
- Active solar technologies: in this category of technology, solar energy is transformed into either electrical or thermal energy through the use of special mechanical and electrical equipment. In general, active solar energy technology can be classified into two categories: (1) photovoltaic (PV) technology and (2) solar thermal technology.

Solar technology in its two categories is one of the most promising renewable to meet the future global energy demand. In this study, we will address PV technology in several aspects.

II.2 Brief history

Photovoltaic technologies are devices that convert light or radiation coming from sun into electricity. The history of this system dates back to the years of the last century and have evolved through several historical stages, from these references [189-195] we can mention the following:

- **In 1818:** as early as of this year, scientists issued their observations regarding the electrical conductivity of some materials, such as selenium, where an improvement in conductivity was observed, meaning a decrease in their resistance when exposed to sunlight.
- **In 1839:** by highlighting a metal electrodes immersed in a conductive solution, the result was an electric current passing. This remark was recorded by the French scientist Alexander Edmund Becquerel, and the phenomenon of the PV effect was announced after that for the first time. This phenomenon means the direct diversion of sunlight into electrical power.
- **In 1877:** the first model of a solar cell made of selenium becomes available, and this cell was made by the scientist G. W. Adams.
- **In 1883:** Charles Fritts made an improvement to the selenium solar cell, where plated the semiconductor of selenium with a extremely fine and sheer coat of gold to compose the junction. This process gave the first real solar cell which was only about 1% effective.
- **In 1887:** Heinrich Hertz proved the ultraviolet light have the potential to change the voltage at which sparks between two metal electrodes would be initiated.

In short, it can be said that this stage was marked by the disclosure of essential phenomena and the properties of various materials.

- **In 1904:** Albert Einstein gave the most comprehensive concept and description of the phenomenon of PV effect. As a result of his theoretical interpretation, he was awarded the Nobel Prize in 1921.
- **In 1927:** Based on copper and semiconductor copper oxide was made another solar cell.
- **In 1930:** At the beginning of this year, the both solar cells of selenium cell and the copper oxide cell were used in the light-sensitive devices, such as photometers for use in photography.
- **In 1941:** Silicon cells created for the first time in this year played an effective role in overcoming twice the energy conversion efficiency of solar cells made of selenium.
- **In 1954:** Three American researchers developed silicon solar cells with an energy conversion efficiency of 6% when exposed to direct sunlight.
- **In 1958:** After improving the efficiency of solar energy to be eligible for marketing and use, this technology was rewarded with the support of the government, especially after using it to operate space exploration equipment to be the beginning with the first solar powered satellite, Vanguard1. Reducing costs and increasing production were challenging for the coming years.
- **In 1963-1969:** This period saw some applications of solar cells such as:
 - ✓ With a power of 242 watts, PV system was set up in Japan.
 - ✓ With a power of 470 watts, PV system in the Nimbus space project was installed.
 - ✓ OVI-13 satellite launch with two panels of PV system.
 - ✓ Spire Corporation was founded by Roger Little to produce solar cells.
- **In 1970-1980:** When oil prices rose, necessitated the resort to other energy resources. Some companies have funded research to obtain silicon solar cells at the lowest costs. The results reduced the price per watt from 100\$ to just 20-40\$.
- **In 1980-1990:** There have been many important changes during this decade, and the focus was on raising the production capacity and diversifying the areas of use. For example, we mention that the PV power plants increased and their production capacity reached a maximum value of 1 MW. Some companies have tested these PV systems on cars such as Volkswagen and

the Challenger Company that made the first solar powered plane. Establishing solar cell production companies such as Helios Technology.

Photovoltaic cells in electricity production have come a long way in the past two hundred years, both in quantity and quality, as they show no signs of slowing down and advancing at an unprecedented rate in the global market. Currently, this technology is available in all countries of the world, but it varies in terms of the degree of exploitation to produce electric energy. The period between 1990 and 2000 as well as after 2000 was distinguished to the following:

- Expanding the use of solar energy to reduce carbon emissions, and many major countries have increased the capacity of PV energy facilities. For example, China contributed the largest proportion of the new facilities with a production capacity of about 80 GW, followed by Japan, Germany and the United States.
- Increasing competition among manufacturers in producing highly efficient solar cells.
- The solar market has experienced significant growth, with the market value of solar energy expected to exceed 140 billion dollars in the beginning of 2023.
- The rate of solar energy employ is supposed to rise in the industrial, commercial and residential sectors, such as hotels, hospitals and homes.

II.3 What are the main pros and cons of PV systems?

The employ of PV as an electrical energy source has several pros, we mention the following [194, 196]:

- A promising resource available and is among the renewable energy sources.
- It does not make any noise at all.
- Do not need much maintenance to keep its operating.
- Do not cause any pollution and emissions harmful to the environment.
- It produces electricity near the site that needs energy and to the extent required, as it is easy to extend and install.
- Allows it to be integrated with other power sources to raise system reliability.
- It has lifetime up to 20 years.

Despite the positives, there are some disadvantages too. For example [195, 197]:

- The output power is linked to climatic conditions.
- The need for energy storage systems for night employ, which leads to increased cost and intricacy of system designing and establishment.
- To generate small energy from PV systems, we need a significant area compared to other energy sources.

II.4 Types of light absorbing materials

All PV cells need a light-absorbing substance (semiconductor), which generally resides in their midst. It used to absorb photons beams, which gives the electrons energy that they free under

phenomenon of PV effect. A diversity of semiconductor materials is hired when manufacturing PV cells. Some of these semiconductor materials are developed long ago, and others that are relatively new. These types of semiconductor materials using in PV cell are classified into three generations of technology [198-200]:

- First division: PV models that encompass the material of crystalline-silicon (c-Si) both in its Monocrystalline form (sc-Si), as well as in the Multicrystalline form (mc-Si).
- Second division: PV models that generally comprise on thin-film innovations such as: Copper Indium Gallium diselenide (CIGS), Amorphous Silicon (a-Si), Cadmium Telluride (CdTe) and single-junction Gallium Arsenide (GaAs) cells.
- Third division: PV systems that generally include organic and the multi-junction cells technologies. It should be noted that this generation hasn't been vastly marketed and is a new technology in the path of development.

In civil applications, both technologies crystalline silicon and thin-film are dominated in utilization. However, 93% of the total production capacity comes from crystalline silicon cells distributed between Multicrystalline cells by 69% and 24% for Monocrystalline, while thin-film species make up only 7% of the overall fabrication divided as follows: 3% of a-Si, 2.5% of CdTe, and less 2% of CIGS. [201]. On the other hand, in space energy applications that require high efficiency, both have been used technologies of GaAs and multi-junction cells [201]. Monocrystalline, Multicrystalline and amorphous Silicon technologies are presented from references [195, 202-204].

II.4.1 Monocrystalline silicon PV cells

Monocrystalline, also called single crystal offer the highest efficiency of converting solar energy into electric energy, which is typically around 20.4%. In addition, it is widely available in the market and reliable. The main disadvantage of this type of PV cell material is that the manufacturing costs are rather high as a result of the complex manufacturing process, which leads to its limited use.

II.4.2 Multicrystalline silicon PV cells

Due to the high production costs and the need to cover the market requirements of the PV cells the efforts made by the PV industry led to the development of new technologies. Multicrystalline, also called polycrystalline, and currently accounts for two-thirds of silicon cell production, has been developed, outperforming monocrystalline cells due to the uncomplicated manufacturing process, which lead to lower manufacturing cost. However, this technique has a rather low efficiency, with an average efficiency of about 18%-20%.

II.4.3 Amorphous Silicon PV cells

It is one of the elements that belong to the technology of thin films, which is one of the first developed and most popular elements of this technology. Generally there are two differences

between these cells and silicon cells, where the first difference is in the structure. Instead of the crystal structure, the amorphous silicon cells consist of silicon atoms in a thin homogeneous layer, and the second difference is the rate of light absorption, where we find that the amorphous silicon attracts light beams extra effectively, unlike the crystalline silicon. The low efficiency, which generally around of 5%-7%, is considered the main obstacle to the widespread employ of this technology.

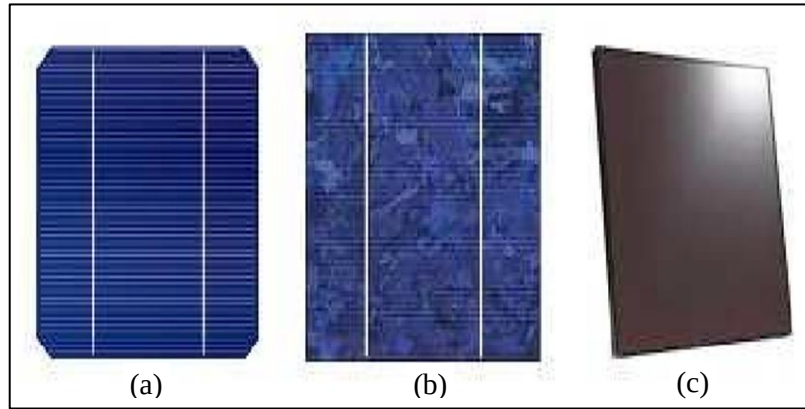


Figure II.1 Types of PV cells: **a)** Monocrystalline Silicon, **b)** Multicrystalline Silicon, **c)** Amorphous Silicon.

II.5 Basic Structure of PV Cell

A PV cell is a group of layers stacked together; each guarantees a particular objective it for optimum performance during its working. The PV cell consists of the following layers [205-209]:

- At the heart of the PV cell is a layer that is considered the most important because during which the phenomenon of photoelectric effect occurs leading to the production of electricity. It is constituted of two layers of semiconductors (p-type and n-type), with a mixture of small quantities of Phosphorus and Boron. The topmost layer (*n*-type) is made up of silicon mixed with little amounts of phosphorous, which makes the silicon negatively charged. While the layer that comes underneath (*p*-type), usually made by mixing silicon with small amounts of Boron, which makes the silicon positively charged.
- On either side of the heart of the cell, we will find a small mesh pattern, which is a conductive layer, in other words a metal grid, since this layer must be well conductive, not subject to corrosion, stable at elevated temperatures and high ultraviolet exposure. Ethyl Vinyl Acetate (EVA) and Polyvinylbutyral (PVB) materials are usually the most commonly applied.
- Behind the positively type semiconductor there is a last layer named the back sheet of PV cell. It usually consists of a layer of: aluminum or molybdenum metal, since allowing light to bounce longer in it to improve performance.
- The topmost layer which is located in front of the illuminated side of the cell is usually made of glass or another transparent material coated. The glass protects the materials beneath it from damage coming from the environment. On the other hand, silicon is very reflective, so an anti-reflection coating is placed down of the glass layer helps sunlight to reach the semiconductor in greater quantities.

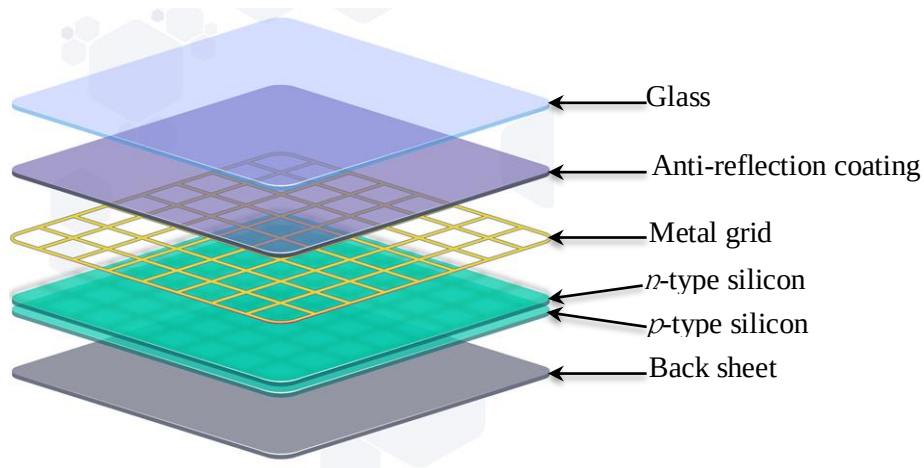


Figure II.2 Components of PV cell.

II.6 Working principle of PV cell

The operating principal of PV cells depends on the PV effect [210-212], i.e. electric current flowing from PV cell in response to its exposure to sunlight. As a result of this effect, PV cells are useful, as the materials that make up the plate convert sunlight into electrical energy. French physicist Alexandre Edmund Becquerel was the first to discover the PV effect for the first time in 1839, by doing several successive experiments on wet cells, which ended with the observation that the cell voltage rises as the surface of the silver cells is exposed to the sunlight.

Silicon is a semiconductor widely used in building a PV cell. The silicon atom has 14 electrons distributed over three energy levels of which four valence electrons are present in the outer layer. The silicon atom seeks to complete the diminution in the number of electrons at the outer level. To do this, it shares four electrons from neighboring silicon atoms, thus the silicon atoms are bound together in the form of a crystalline structure. A pure silicon crystal cannot conduct the electrical current efficiently because there are simply no free electrons as all of the electrons are bound in the crystal structure. Thus, in order for silicon to be used in solar cells, a slight modification of the crystal structure must be made.

This modification is the addition of pentavalent atoms such as phosphorous within the crystal structure of silicon, creating new bonds. Thus, this process allows the sharing of four electrons in the outermost layer of the phosphorous atom by covalent bonds with four neighboring crystal silicon atoms, while the fifth electron remains free and has no any chance of creating a bond with its neighboring atom. Added atom in semiconductors is known as impurities, while the process is recognized as doping. The pentavalent atoms that give up their fifth electron to the semiconductor material is famed by the name of donors. The semiconductor resulting from this process is named as n-type or negative part. So, if this n-type layer is supplied with sufficient energy, whether it is thermal energy or photon energy this will leads separate the comparatively baggy fifth electron from its atom. Many release electrons separated from atoms of phosphorous are always responsible for conducting electrical current in semiconductors. That is why silicon doped by phosphorous is better conductor than pure silicon.

In addition to the doping of silicon in which provides additional electrons. There is another doping with atoms that have provides fewer electrons. The materials resulting from this vaccination are called the p-type, that is, the positive type. In this case, some trivalent atom such as boron is substituted for a silicon atom in the crystal lattice. Consequently, a new configuration will appear by bonding three electrons from the outer layer of the boron atom with one electron from every three silicon atoms close to it by creating covalent bonds, while the unbound electron from the silicon atom behaves as an incomplete bond, and thus the boron atom can accept an electron One to complete the fourth bond, leading to the formation of a hole.

Sunlight is made out of photons, which are basically small packets of electromagnetic rays that have a certain amount of energy. Materials don't absorb all the photons that fall on them, but they are distributed into three parts, one part of which is reflected, another part is transmitted through the material and the rest is absorbed. In case the photon is absorbed by an electron from the outer layer of a semiconductor, then the energy of the electron will increase according to the amount of photon absorbed. This electron can move freely and with enough energy it will cross the band gap to move into the conduction band of the semiconductor.

Electrons and holes move by diffusion in these two layers. Near the interface, diffusion leads to recombination between electrons and holes. So, electrons and holes cancel each other out. This phenomenon produces an electrically non-neutral zone of positively charged phosphorus atom, and an electrically non-neutral zone of negatively charged boron atom. We obtain an electric field within the semiconductor (P-N junction). This electric field is accompanied by the appearance of a difference potential between the both zones. When the solar radiation hits the PV cell, the photons of light transfer their energy to the electrons, freeing them from their atoms and leaving gaps in their place. The electrons and the holes thus formed tend to recombine, but when the phenomenon takes place in the vicinity of the PN junction, the electric field will on the contrary contribute to separating the positive and negative charges, the electrons repelled towards the N layer, and the holes to the P layer. The electrons seeking to combine with the holes are then forced to pass with an external circuit to join the holes creating a continuous electric current that is called the photo-current, and the electrons are delivered under the voltage created in the PN junction which is called the photo-voltage.

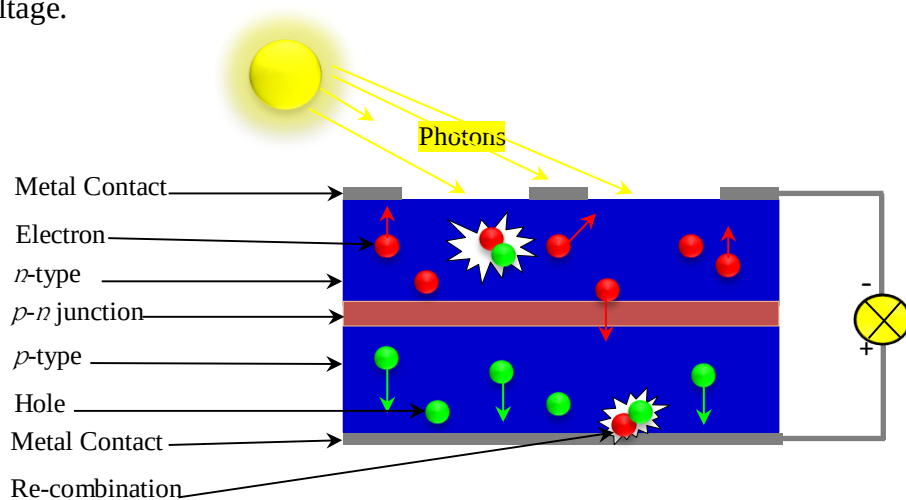


Figure II.3 Photovoltaic cell principle.

II.7 Application of PV system

Fossil fuels are still required for several applications but the PV systems have also found room for application in wide ranges which has given a positive impact social, economic and environmental such as the construction of facilities for social activities, a decrease in the distribution and transfer of the cost of electricity, an improvement in environmental sustainability and an improvement in the quality of life of the rural population. There are several primary applications for PV power systems, among these:

II.7.1 Grid-Connected PV Systems

Grid-connected PV systems are typically designed according to the ambit of power afforded, from a few hundred watts up tens and hundreds of megawatts of large ground mounted systems [213]. Currently, the association of PV systems to the electricity network has become a normal, by providing an integrated system that guarantees this, as the PV systems connected to the network operate in parallel with the electrical utility grid [214], and they supply energy to the utility grid when the energy generated is higher than the assumed consumption [214]. The primary parts of a grid-connected PV system vary according to the size of the system and often include the following: PV system, the filters, transformers and the conversion technologies includes the boost converter and inverter power electronics based converters [213].

II.7.2 Water pumping

The requirements of pumping water supplies, whether for domestic consumption or used for irrigation of farms, were affected by the high costs of electricity and diesel [215]. In contrast, with the low price of PV panels, their use as a source of energy for water pumping is the most attractive solution as a hoped-for alternative to water pumping systems based on traditional electric sources such as Diesel [216]. With the good design and periodic maintenance of these solar systems, they provide the necessary energy when needed. PV systems, after testing all over the world, have proven their effectiveness and reliability in terms of cost, and have proven their effectiveness in terms of raising levels of agricultural production [217]. The design of this system includes PV panels as electrical source to feed a DC or AC motor. The latter converts the electrical energy into mechanical energy, which is then converted to hydraulic energy using the pump. [218].

II.7.3 Photovoltaic system in Space

Photovoltaic cell technology has been used in spacecraft since 1958 (NASA Vanguard satellite). The PV panels placed on the spacecraft are used to provide the ability to operate sensors and telemetry, as well as the propulsion power of the spacecraft [219]. PV cells used in this application require withstanding high temperatures and therefore are completely different from those used in terrestrial applications. Gallium arsenide, indium phosphide and Tandem cells appears as one of the main technologies used in this application for their good efficiency despite their high cost compared to silicon cells [198].



Figure II.4 Photovoltaic system in space.

II.7.4 Building integrated PV systems

One of the most promising technologies in the development of modern PV cell systems is the use of Building integrated PV (BIPV) systems. PV systems built into buildings boil down to exploiting PV panels to be architecturally integrated into building design to become part of their exterior coverage such as windows, roofs, skylights, balcony fences, or facades, and even walls, this idea has become popular among architects and design engineers [220]. Thus, this technology provides electrical energy to the building, reduces the temperatures absorbed by providing shade and air conditioning, in addition to reducing the cost of construction as well as decreasing land use [221]. Researchers are currently interested in providing units to the market that are cheaper, lightweight, transparent and bright in color, and new materials are being tested for PV cells, such as organic PV [222]. Examples of BIPV embedded solar cells are shown in figure II.5 [222, 223].

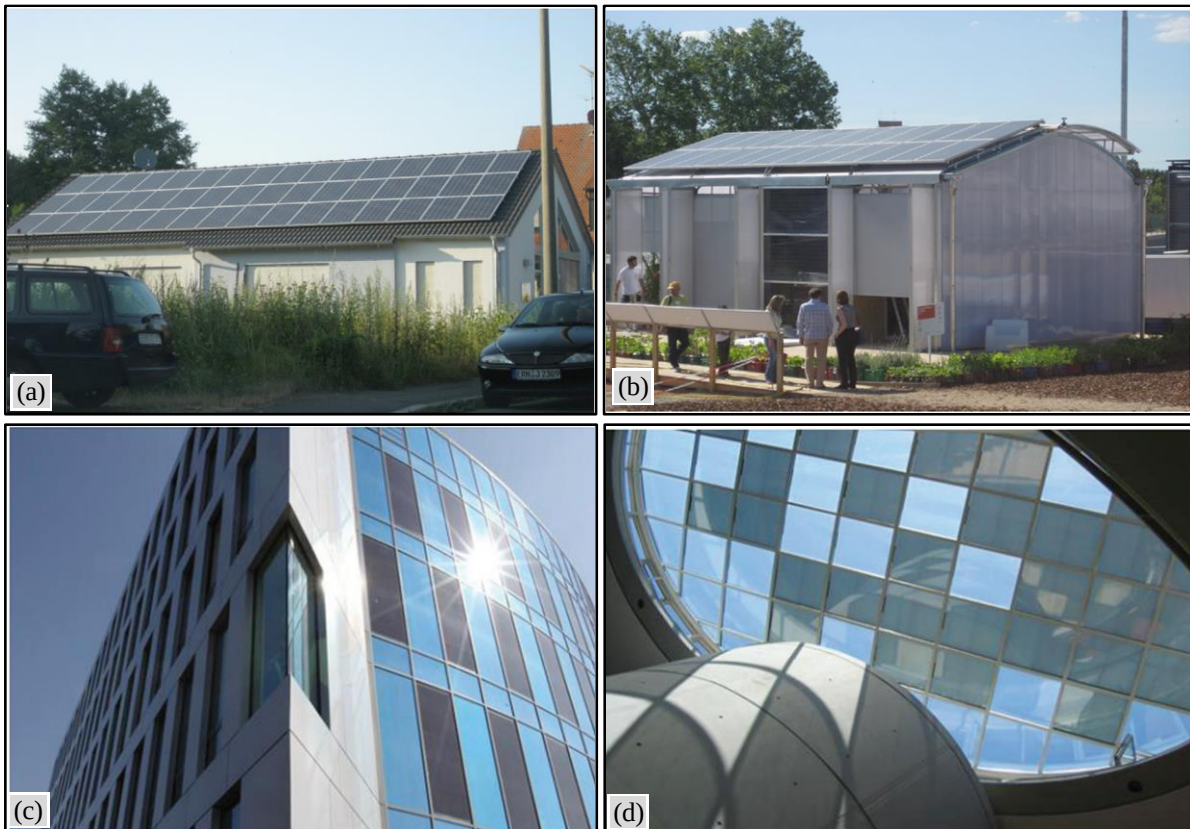


Figure II.5 BIPV system: **a)** in a house in Germany, **b)** in a prototype house Spain, **c)** glazing for facades, and **d)** for roofs.

II.7.5 Photovoltaic for electric vehicles

The transportation sector is one of the driving sectors of the economy for progress, and one of the most challenging sectors in terms of combating the clear climate changes the world is witnessing due to its dependence on fossil energy sources polluting the environment. Therefore, it is necessary to direct energy rationalization in the transportation sector to achieve sustainable development through the incorporation of clean alternative energy. Especially a transition to electric vehicles can support this goal [224]. Consequently, it will inevitably reduce our dependence on oil. Many prototypes of PV powered electric vehicles have been built and tested since the 1970s, but these vehicles were not intended for daily use, but are illustrative vehicles and engineering exercises, to motivate students and researchers toward energy saving and applications the vehicles [225]. Currently, these technologies have become available on the market, the number of electric vehicles has increased rapidly in the world, and more than 565,000 vehicles were sold worldwide from 2011-2015 [226]. In 2016, sales jumped to 750,000 vehicles [226].

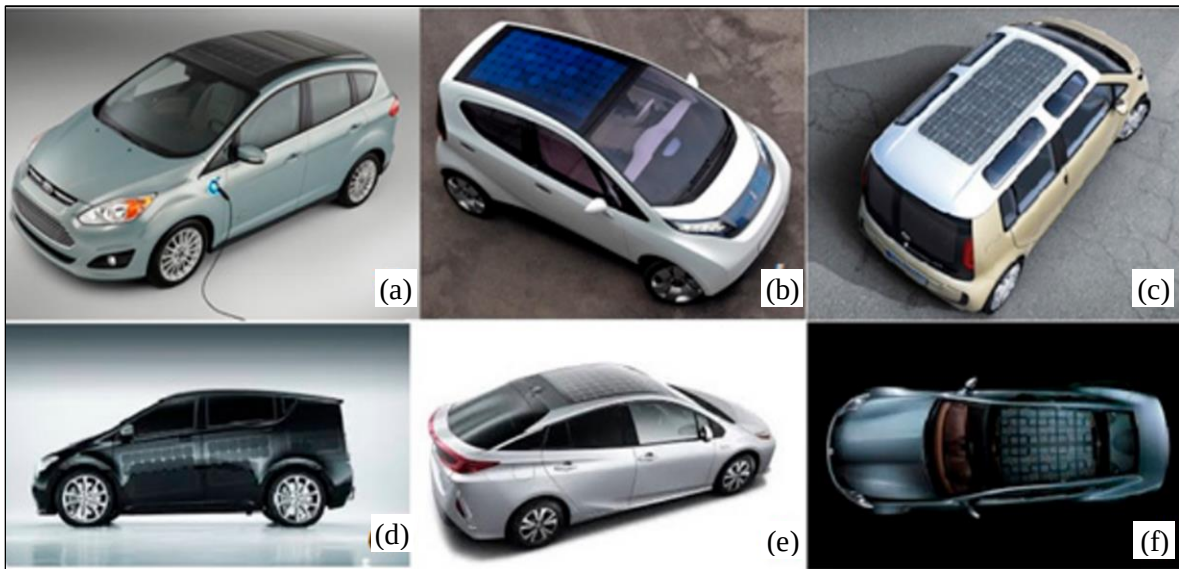


Figure II.6 Electric vehicles: **a)** Ford C-MAX, **b)** B. Pininfarina Zero, **c)** Volkswagen Space Up Blue; **d)** Sono Sion, **e)** Prius and Auris Toyota, **f)** Fisker Karma hybrid [227].

II.8 Equivalent circuit and modeling of a PV cell/module/array

II.8.1 Mathematical model of a PV cell

As we know previously, the PV system converts direct sunlight into pollution-free electrical energy. This particular process lies in the PV cell. In addition to several materials used in manufacturing a PV cell such as: sc-Si, mc-Si, CIGS, a-Si, CdTe, GaAs and GaS...etc. A PV cell is a semiconductor diode, its p-n junction exposed to sunlight. Under the influence of the sunlight falling on the area of PV cell, about 0.5 Volt can be generated by a one cell.

The input of the equivalent circuit model of the PV cell is temperature with sun irradiance, while the output is the current, the voltage and the electrical power. In the scientific papers as well as in technological implementations, the single diode model, also recognized as five-parameters model, is considered the most popular used as equivalent circuit for modelling the output characteristic of a PV cell compared to other models suggested such as: two and three-diode ones

model due to its simplicity [228]. Four principal elements are involved in structuring of the model single PV cell (Figure II.7). Photo-current source coupled in anti-parallel with one diode plus two resistors, one placed in series and another placed in parallel [229]. The series resistance (R_s) is considered as losses by Joule effect, that represent the resistance offered to the current flow, it is primarily due to resistance inside each cell such as metal-semiconductor contact of layer p and n , also metal grids and all interconnection resistances between cells [230-232]. Therefore, the effect of series resistance is more apparent in PV module due to the multiplication of cells resistance [232]. On the other hand, parallel resistance (R_p) is a loss related with a slight seepage of current across the p - n junction and relies upon the he manufacture process for the PV cell [230-232]. Unlike, parallel resistance becomes conspicuous in the large PV system, viz when a certain number of PV modules are placed in parallel [232].

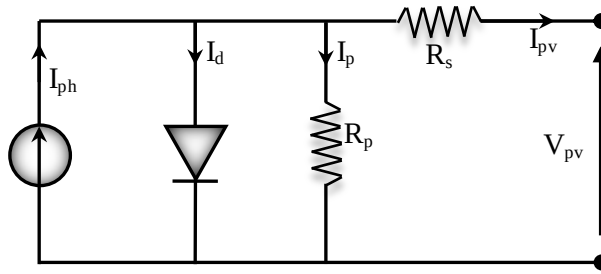


Figure II.7 Equivalent circuit of PV cell.

If we apply the Kirchhoff's premier law to the equivalent circuit of PV cell, the equation (II.1) is obtained as follows:

$$I_{ph} = I_d + I_p + I_{pv} \quad (II.1)$$

Where:

I_{ph} : is the Photo-current.

I_d : is the diode current.

I_p : is the parallel current.

I_{pv} : is the net output current of PV cell.

The photo-current relies linearly upon how much incident sun irradiance, and is additionally impacted by the temperature as presented in the equation (II.2), which is described as [233, 234]:

$$I_{ph} = \left(I_{sc,ref} + \sigma_i (T_{pv} - T_{ref}) \right) \frac{G}{G_{ref}} \quad (II.2)$$

Where:

$I_{sc,ref}$: is the short-circuit PV cell current at T_{ref} and G_{ref} .

T_{pv} : is the PV cell temperature in Kelvin (K).

T_{ref} : is the reference cell temperature in STC, usually 298K (25°C).

G : is the instantaneous solar irradiance (W/m^2).

G_{ref} : is the reference solar irradiance, usually (1000W/m^2).

σ_i : is the relative temperature coefficient of I_{sc} , given by the manufacturer in the datasheet ($\%/K$).

By using the Shockley diode current equation, the fundamental mathematical equation that describes diode current as illustrated in equation below [233, 234]:

$$I_d = I_s \left(\exp \left(\frac{V_{pv} + I_{pv} R_s}{\lambda V_t} \right) - 1 \right) \quad (\text{II.3})$$

Where: I_s and V_t are the saturation current and the thermal voltage respectively, which expressed as follows:

$$V_t = \frac{\varpi T_{pv}}{q_{el}} \quad (\text{II.4})$$

$$I_s = I_{rs,ref} \left(\frac{T_{pv}}{T_{ref}} \right)^3 \exp \left(\left(\frac{q_{el} E_{gap}}{\lambda \varpi} \right) \left(\frac{1}{T_{pv}} - \frac{1}{T_{ref}} \right) \right) \quad (\text{II.5})$$

While reference reverse saturation current $I_{rs,ref}$ is calculated by using the following equation [235, 236]:

$$I_{rs,ref} = I_{sc,ref} / \left(\exp \left(\frac{q_{el} V_{oc,ref}}{\lambda \varpi} \right) - 1 \right) \quad (\text{II.6})$$

Regarding to the parallel current I_p , it writes as follows:

$$I_p = \frac{V_{pv} + R_s I_{pv}}{R_p} \quad (\text{II.7})$$

Where:

V_{pv} : is the voltage across the PV cell.

$V_{oc,ref}$: is the reference open-circuit voltage.

R_s : is the series resistance.

R_p : is the parallel resistance.

$I_{sc,ref}$: is the reference short-circuit current.

λ : is the diode ideality factor.

ϖ : is the Boltzman's constant, which equal $1.381 \times 10^{-23} \text{J/K}$.

q_{el} : is the charge of one electron, which equal $(1.602 \times 10^{-19} \text{Coulombs/electron})$.

E_{gap} : is the gap energy, for crystalline silicon equal to 1.12 eV.

Finally, the equation of the PV cell can be illustrated with $I_{pv} = f(V_{pv})$ characteristic as:

$$I_{pv} = \left(I_{sc,ref} + \sigma_i (T_{pv} - T_{ref}) \right) \frac{G}{G_{ref}} - I_s \left(\exp \left(\frac{V_{pv} + I_{pv} R_s}{\lambda V_t} \right) - 1 \right) - \frac{V_{pv} + R_s I_{pv}}{R_p} \quad (II.8)$$

II.8.2 Mathematical model of PV module/array

For practical use of voltage and current, PV cells are electrically connected in diverse combinations. To raise voltage, the PV cells are connected at series. While, to raise the output current, the cells are connected at parallel. Several cells are packaged together to form a module. In turn, these modules are wired together at series and at parallel combinations to form an array.

II.8.2.1 Photovoltaic module

Photovoltaic modules (M) comprise of numerous PV cell circuits in the form of sheets, which are the basic commercially available building unit for PV power generation stations. Figure II.8 shows the equivalent circuit of PV module, which are electrically arranged in series (N_s) and parallel (N_p) of PV cells [237].

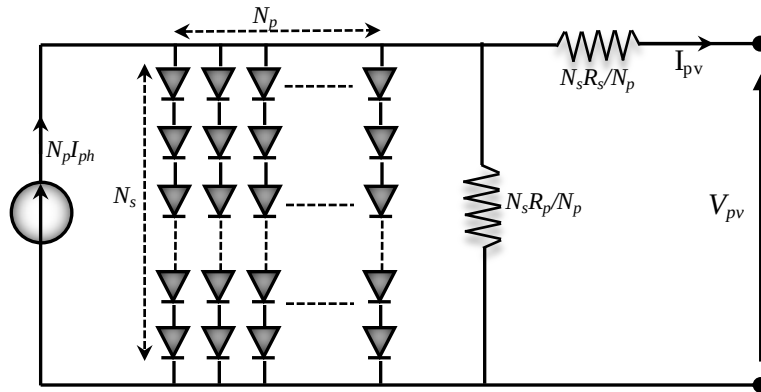


Figure II.8 Equivalent circuit of PV module.

The relationship between the parallel connection currents sum and series connection voltages sum are given by:

$$\begin{cases} I_{pv,M} = N_p I_{pv} \\ I_{sc,M} = N_p I_{sc} \\ I_{s,M} = N_p I_s \end{cases} \quad (II.9)$$

$$\begin{cases} V_{pv,M} = N_s V_{pv} \\ V_{oc,M} = N_s V_{oc} \end{cases} \quad (II.10)$$

The equation (II.8) can be expressed as below [237]:

$$N_p I_{pv} = N_p I_{ph} - N_p I_s \left(\exp \left(\frac{V_{pv} N_s + \frac{N_s R_s}{N_p} N_p I_{pv}}{\lambda V_t N_s} \right) - 1 \right) - \frac{V_{pv} N_s + \frac{N_s R_s}{N_p} N_p I_{pv}}{\frac{N_s R_s}{N_p}} \quad (II.11)$$

This equation (II.11) can be simplified as follows:

$$I_{pv,M} = N_p I_{ph} - N_p I_s \left(\exp \left(\frac{\frac{V_{pv,M}}{N_s} + \frac{R_s}{N_p} I_{pv,M}}{\lambda V_t} \right) - 1 \right) - \frac{N_p V_{pv,M} + R_s I_{pv,M}}{R_p} \quad (II.12)$$

This equation is a non-linear mathematical expression; it depicts the electrical demeanor and determines the relationship between $V_{pv,M}$ and $I_{pv,M}$ supplied by a PV module.

II.8.2.2 Photovoltaic array

The power that one PV module can output is within hundreds of watts. Therefore, it is not intended to feed high power applications. The PV array is installed to produce more power. The architecture of the PV array as shown in figure II.9 is composed of many of strings installed in parallel, while every string is composed of number of PV modules installed in series [238]. Generally, all PV array applications use an inverter to use alternating current that can power the motors, loads, lights ...etc.

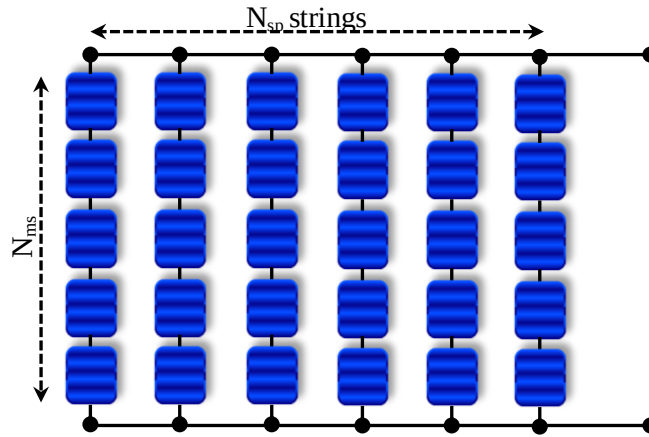


Figure II.9 Physical configuration of the PV array.

For a string of N_{ms} identical modules, the equation (II.12) can be rewritten as follows [238, 239]:

$$I_{pv,M} = N_p I_{ph} - N_p I_s \left(\exp \left(\frac{\frac{N_{ms} V_{pv,M}}{N_s} + \frac{R_s}{N_p} I_{pv,M}}{\lambda N_{ms} V_t} \right) - 1 \right) - \frac{N_p N_{ms} V_{pv,M} + R_s I_{pv,M}}{R_p} \quad (II.13)$$

For an array of N_{sp} identical strings in parallel, the current-voltage relationship is [238, 239]:

$$I_{pv,arr} = N_p N_{sp} I_{ph} - N_p N_{sp} I_s \left(\exp \left(\frac{\frac{V_{pv,arr}}{N_s N_{ms}} + \frac{N_{ms} R_s}{N_{sp} N_p} \frac{I_{pv,arr}}{N_{sp}}}{\lambda N_{ms} V_t} \right) - 1 \right) - \frac{\frac{N_p N_{ms} V_{pv,M}}{N_s} + \frac{N_{ms} R_s}{N_{sp}} \frac{I_{pv,arr}}{N_{sp}}}{\frac{N_{ms} R_p}{N_{sp}}} \quad (II.14)$$

II.9 The electrical characteristic of a PV module

A PV module is made up of a set of PV cells. In the presence of the sun, each of these cells produces a current (in amperes) and a voltage (in volts). The product of these two quantities gives a power, expressed in Watt. The most important performance specifications of the PV module are summed up in the relation between the characteristic of current-voltage ($I_{pv,M} - V_{pv,M}$), and power-voltage ($P_{pv,M} - V_{pv,M}$). For this project, the Bp SX150S module, which contains 72 cells, has been chosen to draw the PV characteristics, where its STC parameters are listed in table II.1 [239].

Table II.1 PV module parameters at STC.

Parameters	Value	Unit
Maximum Power (P_{max})	150	W
Voltage at P_{max} (V_{mp})	34.5	V
Current at P_{max} (I_{mp})	4.35	A
Open-circuit voltage (V_{oc})	43.5	V
Short circuit current (I_{sc})	4.75	A
Temperature coefficient of V_{oc}	(-160±20)	mV/°C
Temperature coefficient of I_{sc}	(0.065±0.015)	%/°C
Temperature coefficient of Power	(-0.5±0.05)	%/°C
NOCT	47±2	°C

On the other hand, other parameters of this module are shown in Table II.2, in which extracted based on datasheet values and it was taken from the reference [239].

Table II.2 Model parameters of BP SX 150s module.

Parameters	Value	Unit
I_{sc}	4.75	A
R_s	0.6279	Ω
I_s	$2.3539e^{-6}$	A
λ	1.3696	/

The behavior of the proposed PV model has been implemented in Matlab environment based on previous mathematical equations that characterize the PV module. The bellow curves display the current-voltage and power-voltage characteristics of a PV module operating under normal conditions, i.e. $G = 1000 \text{ W/m}^2$, and $T = 25 \text{ }^\circ\text{C}$.

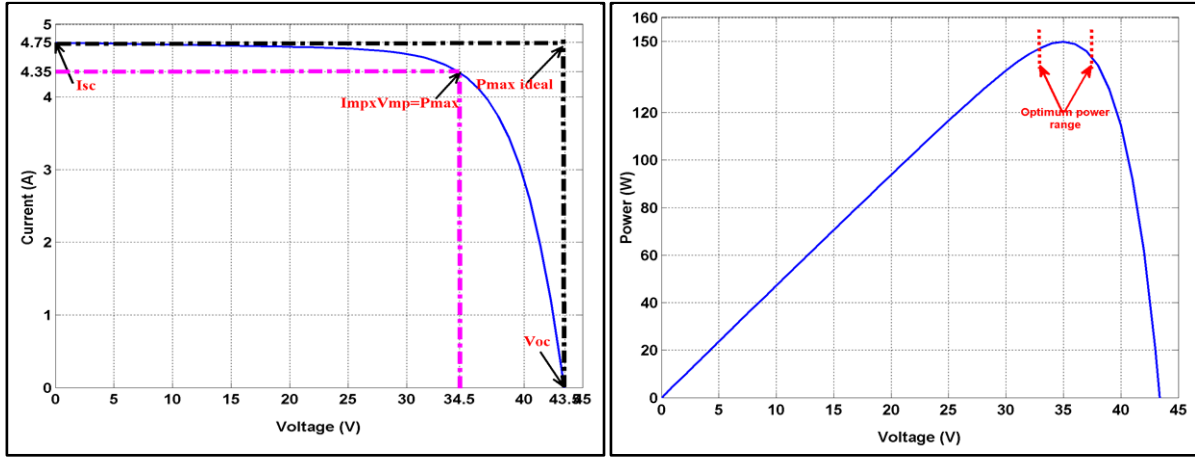


Figure II.10 Current-voltage and power-voltage characteristic of the PV module.

From the curve of electrical characteristic current-voltage of the module, it turns out that the curve is determined by two factors, the short circuit current, i.e. the point at which the curve intersects with the vertical axis and the open circuit voltage i.e. the point at which the curve intersects with the horizontal axis. Therefore, no electrical power is produced at these two points, but it is assumed that there is a point on the curve, where the PV source generates its maximum power. Of course, there is one specific value of current and voltage for which the output power arrive its maximum value, being near the bend in the current-voltage curve of the PV source. In addition, the PV source is most efficient when operating at the maximum power point, which is located in the optimum power range.

The both productivity of PV module current and voltage depend essentially on the environmental circumstances like temperature, the power of the sunlight and other parameters intern such as serie and parallel resistance. For this purpose we can use the characteristics curve of PV module to show how these intern or extern parameters affect the performance of the PV module, as explain in the next section.

II.10 Parameters of PV module

There are many parameters that characterize a PV module. These parameters are called PV parameters and are deduced from the current-voltage characteristic. In addition to the all parameters presented in the figure II.10, two principle parameters usually used through the characteristic current-voltage to evaluate the performance of PV module, are:

II.10.1 Fill factor

The area of a rectangle, specified between points $[0, I_{sc}, P_{max_ideal}, V_{oc}]$ as presented in the figure II.10 are determines the maximum power from an ideal PV module. This is the ideal current-voltage curve that will provide 100% fill factor. Practically, the current-voltage curve is shown in the figure II.10 by blue line, this decrease of curve compared to ideal module is result of the losses, therefore the curve cannot have 100% fill factor. On the other hand, if we draw a rectangle specified by the points $[0, I_{mp}, P_{max}, V_{mp}]$ to cover the area under the current-voltage curve, we will find that the area under the curve decreases followed by a decrease in fill factor. So, the fill factor is often

referred to by the following abbreviation FF ; it is defined in the equation below as the ratio of the area of the two rectangles [240].

$$FF = \frac{I_{mp,M} \cdot V_{mp,M}}{I_{sc,M} \cdot V_{oc,M}} \quad (II.15)$$

The fill factor indicates the quality of the PV cell; the more it approaches to the unit value, the more PV cell is efficient, it is around 0.7 for efficient cells; and decreases with increasing temperature, ideality factor and series resistance [241].

II.10.2 The efficiency of conversion

PV module efficiency alludes to its ability to convert the maximum amount of photon energy into usable electricity. Mathematically, the efficiency of a PV module is defined as the quotient between the maximum electrical power that can be transferred to the load and the power of the solar radiation falling on the PV module area; it is expressed by the following equation [240, 241]:

$$\eta_{pv,M} = \frac{P_{\max}}{P_{in}} = \frac{I_{mp,M} \cdot V_{mp,M}}{G \cdot S} \quad (II.16)$$

The equation (II.16) can also be reformulated as function of fill factor (FF) as follows:

$$\eta_{pv,M} = \frac{I_{sc,M} \cdot V_{oc,M} \cdot FF}{G \cdot S} \quad (II.17)$$

Where S : is the area of the PV module (m^2).

II.11 Influence of external parameters on the characteristics of the PV module

II.11.1 Effect of irradiation

The values of irradiation falling to the land vary according to the seasons of the year and during the day, in which the irradiation varies greatly beginning at $0W/m^2$ just after daybreak and scaling to reach at higher value than $1000 W/m^2$. In this part, we represent the results of simulation concerning the characteristics current-voltage and power-voltage of the PV module by using the MATLAB simulation for various values of irradiation, but the temperature is kept constant at $25^\circ C$ to evaluate the performance of the PV module in this situation.

Figure II.11 shows how the both curves are affected by changes in the irradiation. Through the curve of current-voltage, we can view how the curves change in the vertical axis much more than they change at horizontal axis during applied different values of the irradiation. Therefore, an increase in the irradiation values doesn't significantly influence PV module voltage, in which the open circuit voltage increases slightly. Otherwise, the short circuit current increments extremely sharply, since it is a linear function of the irradiation. As can be seen from the curve of power-voltage, the result power is incrementing with the incrementing of the irradiation values. By and large, raising the level of irradiation has a favorable influence on the result power, as it pushes the value of the maximum output power to rise.

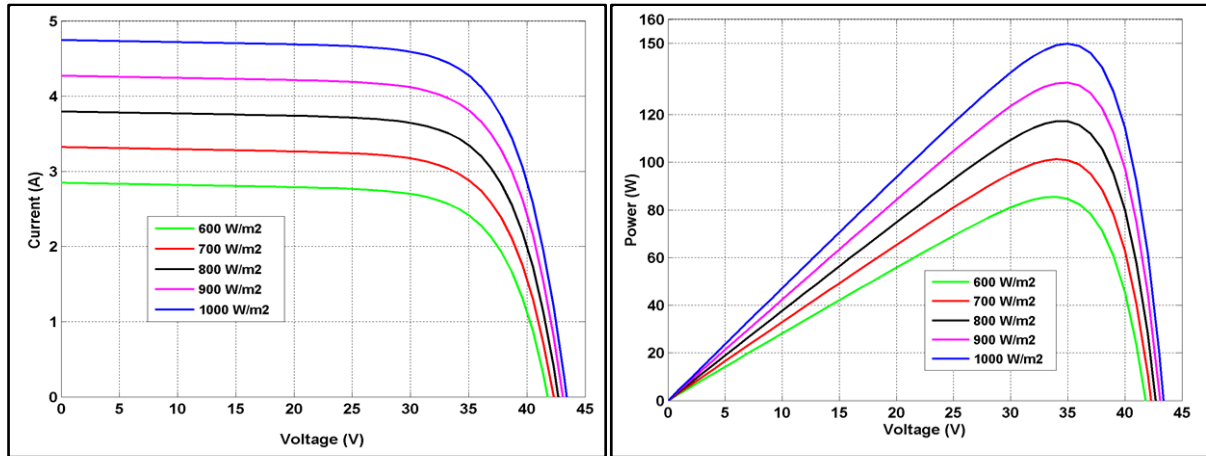


Figure II.11 Current-voltage and power-voltage characteristics of PV module under various irradiances.

II.11.2 Effect of temperature

Temperature is a very important parameter in the behavior of PV module. The both figure below describes the behavior of the module under three different values of temperature 25°C, 50°C and 75°C, while the irradiation stays constant at 1000W/m². Notice how the curve moves strongly to the left and right along the axis of the horizontal voltage other than that it moves on the vertical current axis where its movement is relatively few. Already, with rising temperature the short circuit current rises slightly, while the open circuit voltage reduces strongly. Therefore, changes in temperature straightforwardly impact the voltage output, which in turn directly affects the maximum output power in the same way. The PV module, as a rule, works low efficiently with expanding temperature. However, the cause of that is due to rises in temperature will inevitably increase in the band gap energy of the semiconductor material and thus more photons energy is required to cross this barrier and to create electron-hole pairs [242].

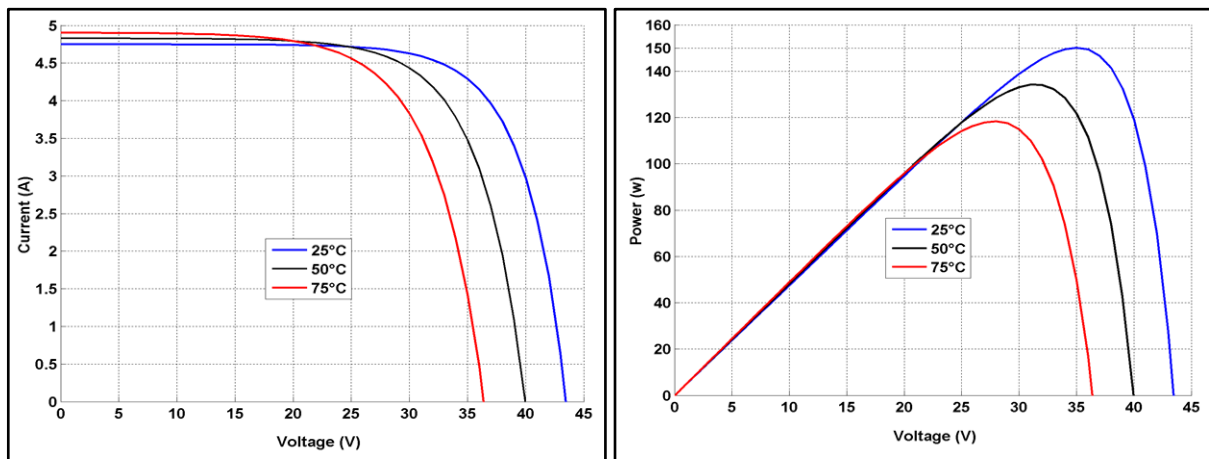


Figure II.12 Current-voltage and power-voltage characteristics of PV module under various temperatures.

II.12 Influence of internal parameters on the characteristics of the PV module

II.12.1 Effect of series resistance

The performance of PV cells is limited for different energy losses, these losses are linked to the physical and technological parameters of the PV cell; the series resistance of a PV cell is a parasitic,

power consuming parameter. A small variation in the value of serie resistance leads to decrease the maximum achievable output power, and hence, a large impact on the slope of the current-voltage curve. Indeed, raising the serie resistance leads to decrease in the slope to inside of the area selected by the current-voltage curve. It means decay in fill factor of the PV module. From [243], each increase in resistance by 0.1Ω corresponds to it decreases in the fill factor of a PV cell about 2.5%.

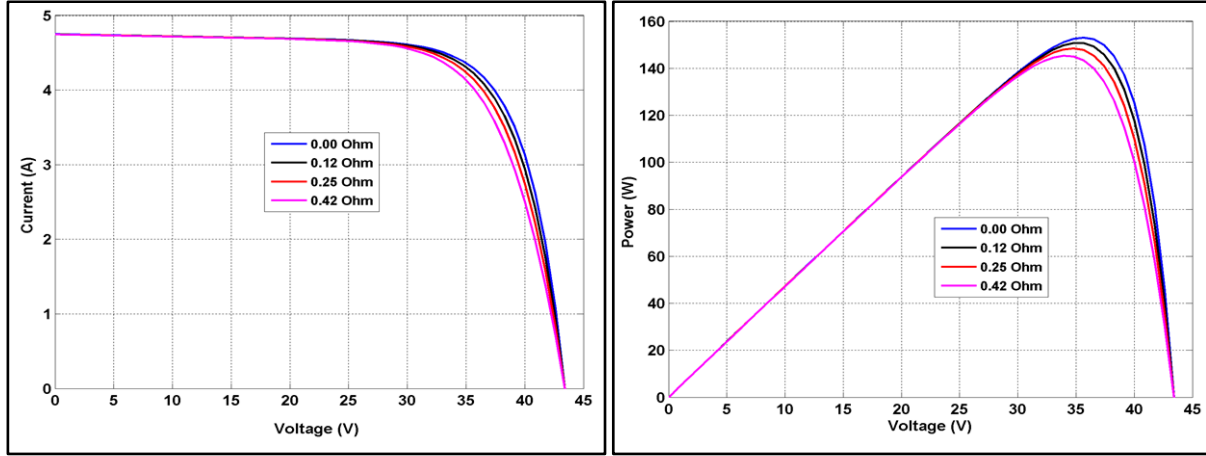


Figure II.13 Current-voltage and power-voltage characteristics of PV module under various series resistance.

II.12.2 Effect of diode ideality factors

In order to see the impact of ideality factor, the both parameters of temperature and irradiation values are kept constant at 25°C and 1000 W/m^2 respectively. The simulation results of both characteristic curves of current and power as function of voltage are illustrated in figures below for various values of ideality factor, in which takes values between one and two ($\lambda = 1, 1.3, 1.6, 1.8$ and 2). The ideality factor is a parameter contained within the Shockley equation, and is an empirical factor is done through it reproduce the real behavior of a PV cell. Through figures, the increase in the ideality factor decreases the values of voltage and current in the zone of the slope of the curve, i.e. at the region relating to the maximum output power, which leads in a decrease in power at the level of the operating zone.

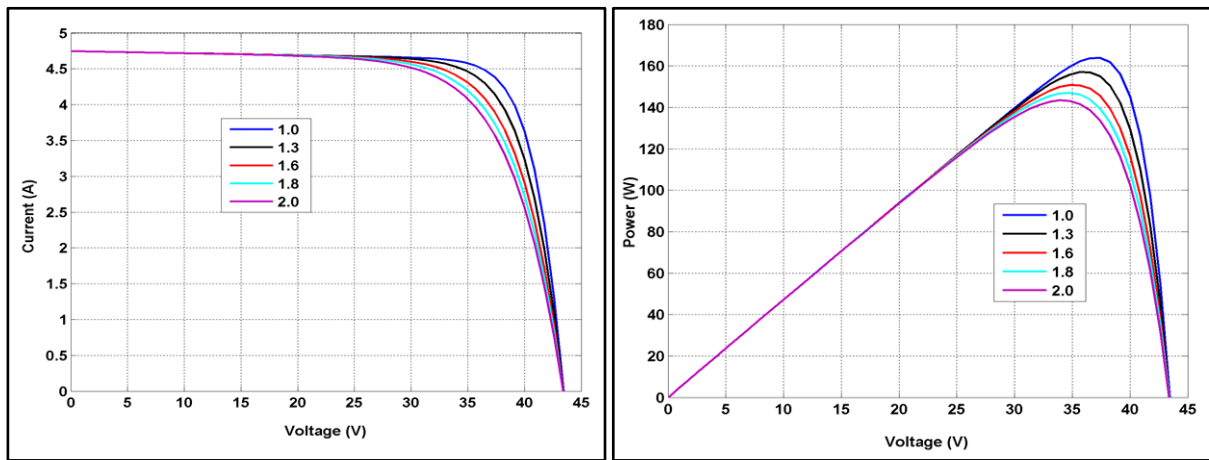


Figure II.14 Current-voltage and power-voltage characteristics of PV module under various ideality factors.

II.13 Conclusion

At the beginning of this chapter, we have known that the PVs are one of the categories of solar energy technology and we have given a historical overview of some of the stations where this technology has known the most important recorded developments. Add to that, due to its several advantages, especially as it is friendly to the environment, has increased interest in it and the development of its components to raise its efficiency especially semiconductor materials. For this reason, three types of semiconductor materials using in PV cell are developed. Foremost among them are Multicrystalline cells classified from the first generation as one of the most technology used in the PV systems. We then presented the basic structure of PV cell as well as its operating principle by explaining the principle of the PV effect. For the second part of this chapter, we have seen the modeling of the PV module using the equivalent a single diode PV cell model. This modeling is an essential step to assess the characteristics of a PV module through representation graphic of both characteristics current-voltage and power-voltage. We have seen that the PV module has a non-linear characteristic, has a maximum power point characterized by a maximum voltage and current. Add to that, the maximum power point changes according to the operating conditions i.e. the performance of the PV module is affected by the external parameters such as variations of irradiation and temperature, as well as the internal parameters such as series resistance and diode ideality factors. However, environmental conditions have more influence on the performance of the PV module. The power generated from the PV module is directly proportional to the irradiation and inversely proportional to the temperature. Hence it is important to have the system operate at the maximum power point in order to get the maximum power from the PV module.

Chapter III

Description and Modeling of PEMFC System

III.1 Introduction

When we look at the history of global energy policies, we can obviously notice that an alternate source is selected every some decades, reflecting our inventive development over time. On 23 October 2018, the first international conference on the prospects for the use of hydrogen gas was held in Tokyo, attended by more than 300 members from car manufacturers, utilities, government institutions and research centers [244]. In January 2017, the Hydrogen Council was established, a global initiative led by the Chief Executive Officer (CEO) of a company of 60 leading companies in the fields of energy, transportation and manufacturing. The functions of the hydrogen Council were defined in two things [245]:

- Accelerate the evolution and commercialization of the hydrogen and fuel cell sectors.
- Encouraging increased hydrogen subsidies as section of a sustainable energy future.

Hydrogen is the simplest substance component known to chemists, where it comprises of just a proton and an electron, which makes it the lightest. Also, it is viewed as the most plentiful component, making up over 90% of the total chemical [246]. But despite its abundance, hydrogen does not exist individually and naturally as a gas on earth, it is always coupled with other elements such as a water atom, as well as found in many organic compounds, especially hydrocarbons that make up many fuels such as gasoline, gas natural, methanol and propane.

Hydrogen is considered as an energy-carrier element and not a source of energy [247]. At present the best method for taking advantage of hydrogen energy is by utilizing fuel cells (FCs) devices, since they convert chemical substance energy into electrical energy. Inside fuel cell, hydrogen and oxygen consolidate into an electrochemical reaction and the outcome is the creation of electrical current, water and heat [248]. FCs mimic batteries because they convert the energy from the electrochemical reaction into electrical energy. Fuel cells are a potential technology to provide a source of electricity and heat in several applications. Fuel cells have great potential as sources of green electricity because of the many advantages they offer, such as high overall efficiency, low pollutant emissions, zero noise and a flexible modular structure.

In this chapter, we present in the first part overview about of fuel cells in terms of: History of its discovery and development, its main pros and cons, classification, description of its types and applications. While, in the second part, we will focus on one type of fuel cell is Proton Exchange Membrane Fuel Cell (PEMFC), in which we will discuss the working principle, describe all the basic components, and finally we will address the mathematical modeling of the type considered.

III.2 History of the fuel cell

In the 18th century and exactly in 1839 the world witnessed with the British lawyer and the chemistry researcher Sir William Robert Grove realizing the first fuel cell. This achievement was based on the idea of the principle of operation of FCs which found by the German researcher Christian Friedrich Schönbein put forward in 1838 [249]. Through his trial, which two electrodes of platinum were submerged into a beaker of aqueous sulfuric acid, and after that the tubes were reversed over every one of the electrode, Mr. Grove noticed the flow of electric current, so that both contain a different gas from the other, one contain hydrogen and the other contain oxygen. To increase the voltage produced, he placed several of these devices in series and produced what he called a gas battery (figure III.1), which will in future be called the FC [249].

Parallel to this discovery, this period saw a rapid development in the exploitation of fossil fuels and engines, so the discovery of Mr. William was however not exploited. During the first century of research around the FC we can say that the research results are modest, despite the remarkable evolution in the hydrogen sector [250, 251].

In 1930 at Cambridge University, the British engineer Thomas Francis Bacon resumed its research on the FCs. His scientific efforts culminated in the completion of the first fuel cell with a capacity of 6 kW in august 1959. His work developed the first FC made of hydrogen and oxygen, has operating characteristics such as temperature between 80-200°C, gas pressure of 40atm, and drew for practical use to power a welding machine, a circular saw and a forklift truck [252].

The works of Thomas Francis Bacon was attracted the attention of NASA in the early 1960, to find alternatives to producing electrical power to its space flights instead of using batteries, nuclear power and energy solar, that's because of the difficulties of use such as heaviness, their seriousness and high cost. Consequently, huge funds were channeled towards the development of space-fueling cells [253].

In 1973 oil crisis and the interest of NASA opened the field to FC development in particular and gave it great importance as an alternative energy source, and focused on reducing manufacturing costs, increase the lifespan and reliability of the systems. FC technology developed and expanded during the 1980s, but marketing of the technology was discontinued due to cost. NASA's FCs were expensive for public use. Despite these efforts, the results haven't been achieved as hoped [251].

The FC became an increasingly popular topic of research from the early 1990s, this was the result of technological advances in (vehicles, laptop battery chargers, and power generation and heat systems), and also search for clean energy to fight the environmental problems.

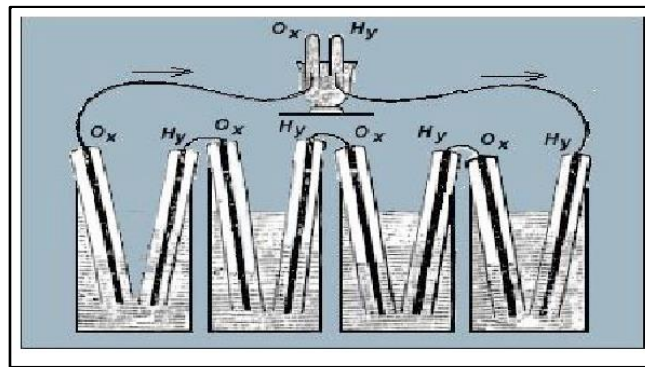


Figure III.1 Fuel Cell of Sir William Robert Grove.

III.3 Why do we need Fuel cells?

Fuel cells are a very promising energy technology with abundant of possible applications. FCs enjoy many pros that make them adequately appealing, among them [254]:

- The conversion efficiency into electrical energy is usually high.
- The heart of a FC does not produce any noise when it is turned on; only compressor, pumps and ventilation produce a slight noise.
- FCs are environmentally friendly, and there are no emissions if we use pure hydrogen.
- FCs provide the required power from a few kilowatts up to megawatts.

- The ability to operate in low or high temperature degrees.
- The designing of fuel cells are very simple.
- Do not need recharging.

III.4 What are the challenges facing fuel cells?

Despite the many advantages of FCs, they face some challenges such as [254]:

- 1- The FC is very expensive because of the precision required in their manufacture and the materials that compose it such as platinum.
- 2- Weight and size limit its use in the transportation.
- 3- Using a fuel other than hydrogen decreases gradually their performance because of catalyst degradation.
- 4- The FC uses hydrogen as fuel, the most abundant element on earth, but on the other hand hydrogen is highly flammable, so it must be handled safely.

III.5 Fuel cell classification

Over time, the development of FCs has given many kinds. They are generally classified by three criteria [255]:

- **Nature of electrolyte:** Electrolyte technology is divided into two parts, solid and liquid. On the other hand, in the electrolyte liquid technology, there are two categories classified according to the value of PH; acids or alkalis. So the mobile ions in the electrolyte liquid are cations or anions.
- **Operating temperature:** Generally, there are two kinds of fuel cell according to the operating temperatures. Class of fuel cells that operate at low temperature which below 250°C and the second class that operate at high temperature which exceeding value 250°C until 1000°C.
- **Nature of fuel:** fuel cells used directly hydrogen in reaction chemical. However, there are other types used internal reforming for converting other gas such as methanol or ethanol into hydrogen.

III.6 Types of Fuel Cell

There are six sorts of FCs, a simplified explanation will be provided on five types, while the PEMFC will be addressed in this thesis from several aspects:

III.6.1 Alkaline Fuel Cell (AFC)

This sort was invented in 1950s by F. BACON, they are considered among the first technologies developed. AFC use hydrogen and oxygen as fuel and oxidant respectively and generally use a solution of potassium hydroxide (KOH) in water as the electrolyte [256]; their electrical efficiency is 60%. The operating temperature is classified in low temperature; it is between (60°C-90°C). AFCs have many pros, including low cost, long life and high stability. They have been widely used in many practical areas like space missions (NASA) and electric vehicles [257].

III.6.2 Phosphoric Acid Fuel Cell (PAFC)

This sort was the first FC technology to be commercialized. It developed since the 1970s, which requires hydrogen as fuel with operating temperature between 150°C-210°C, and used solution phosphoric acid (H_3PO_4) saturated in a silicon carbide matrix (SiC) as liquid electrolyte [258]. PAFCs have an electrical efficiency between 37-50%, and an overall efficiency of cogeneration (electricity and heat) about 87% and for this reason, a large number of them are exploited in stationary applications with cogeneration in electricity and heat [258]. PAFCs have the advantage of working with reformed fossil fuels or oxygen in the air because the carbon dioxide does not affect the performance of the electrolyte or react with it.

III.6.3 Direct Methanol Fuel Cell (DMFC)

This sort is considered relatively new compared to the AFC and PAFC, it has been discovered and studied since the early 1990s. DMFC is invented to remove storage issue of hydrogen and to eliminate the necessity of a reformer to convert methanol to hydrogen, DMFC fed from the anode with a liquid mixture of water and methanol (CH_3OH) [259]. The hydrogen ions produced in the anode migrate to the cathode through the electrolyte and is considered, the standard polymer electrolyte membrane so-called Nafion 117, the most widely used as electrolyte [260]. DMFCs operate at low temperature generally between 70°C to 90°C and their efficiency up to 45% [261]. Its applications are directed to the field of modest power requirements such as mobile phone charger, computer, camcorders; these fuel cells could replace normal batteries in the various electrical appliances [260].

III.6.4 Molten Carbonate Fuel Cell (MCFC)

The development of MCFCs started in 1951, which belongs to high temperature fuel cells exceeding value 650°C, and are using an electrolyte composed of a molten carbonate salt mixture suspended in a ceramic matrix solid electrolyte which is chemically inert and porous [262]. The electrical efficiency of the MCFC systems is around 45-47% and 30-35% as a thermal efficiency, and as an overall energy efficiency of the system may reach between 80-90% [262, 263]. This type of fuel cells are mainly used stationary either as power plant or for generation combined power (heat and electricity) as well as industrial and military applications.

III.6.5 Solid Oxide Fuel Cell (SOFC)

SOFC works at up temperature, typically between 600 and 1050°C, and this type of fuel cell is characterized by their overall efficiency which reaches 90% if the reaction products are exploited together (Electricity and Heat), while its electrical efficiency alone reaches more than 60% [264]. The current SOFC is made out of an electrolyte made of Yttria stabilized zirconia is considered as the most preferred at high temperatures because of its high ionic conductivity, high chemical and mechanical stability [265]. SOFC are used in several applications because of their high efficiency, it could be used as power systems for trains, ships and vehicles; provide electrical energy for residential or industrial purposes.

Additionally, table III.1 summarized the main characteristics of these types of FC.

Table III.1 Fuel cells characteristics.

Technology	AFC	PAFC	DMFC	MCFC	SOFC
Electrolyte	KOH (Liquid)	H ₃ PO ₄ (Liquid)	Proton Exchange Membrane (Solid)	Molten carbonate salt (Liquid)	Yttria stabilized zirconia (Solid)
Fuel	H ₂	H ₂	CH ₃ OH+H ₂ O	H ₂ , CO, CH ₄	H ₂ , CO, CH ₄
Temperature	60°C-90°C	150°C-210°C	70°C-90°C	650°C	600°C-1050°C
Catalyst	Pt	Pt	Pt	Ni	Pervoskites
Electrical Efficiency	60%	37%-50%	45%	45%-47%	60%
Efficiency with Cogeneration	70%	87%	70%	80%-90%	90%
Charge Carrier	OH ⁻	H ⁺	H ⁺	CO ₃ ⁻²	O ⁻²
Power range	1 kW-100 kW	200 kW-10 MW	1 kW-1 MW	500 kW-10 MW	1 kW-10 MW
Application	Space & Transport	Stationary & Transport	Portable & Stationary	Stationary & Transport	Stationary & Transport

III.7 Applications of fuel cell

Generally, FCs can be utilized in a vast scope of implementations, but the applications of transportation, stationary and portable, are the most commonly used [266]. In this part, we will present description for these applications as follows:

III.7.1 Transportation applications

The transport sector is growing rapidly and is one of the main factors that have contributed to the well-being of mankind over the past years. However, this development had negative repercussions such as congestion and dioxide carbon emissions. In 2015, the transportation sector accounted for about 24% of CO₂ emissions, and vehicles contributed up to 70% of these emissions [267]. FC vehicles have the potential to significantly reduce our dependence on benzene, because the technology of FC vehicles used hydrogen gas as fuel, thus decreasing CO₂ emissions. In addition, they help reduce noise in crowded cities. However, some challenges must be overcome for FC vehicles to be competitive with conventional vehicles such as weight, volume, the complexity of design, reducing maintenance costs and manufacturing as well as must be safe to operate with high efficiency [268]. Figure III.2 summarizes the development of FC vehicles during two decades by several automakers from different countries such as Germany, the U.S.A, Japan, Korea and China [267].

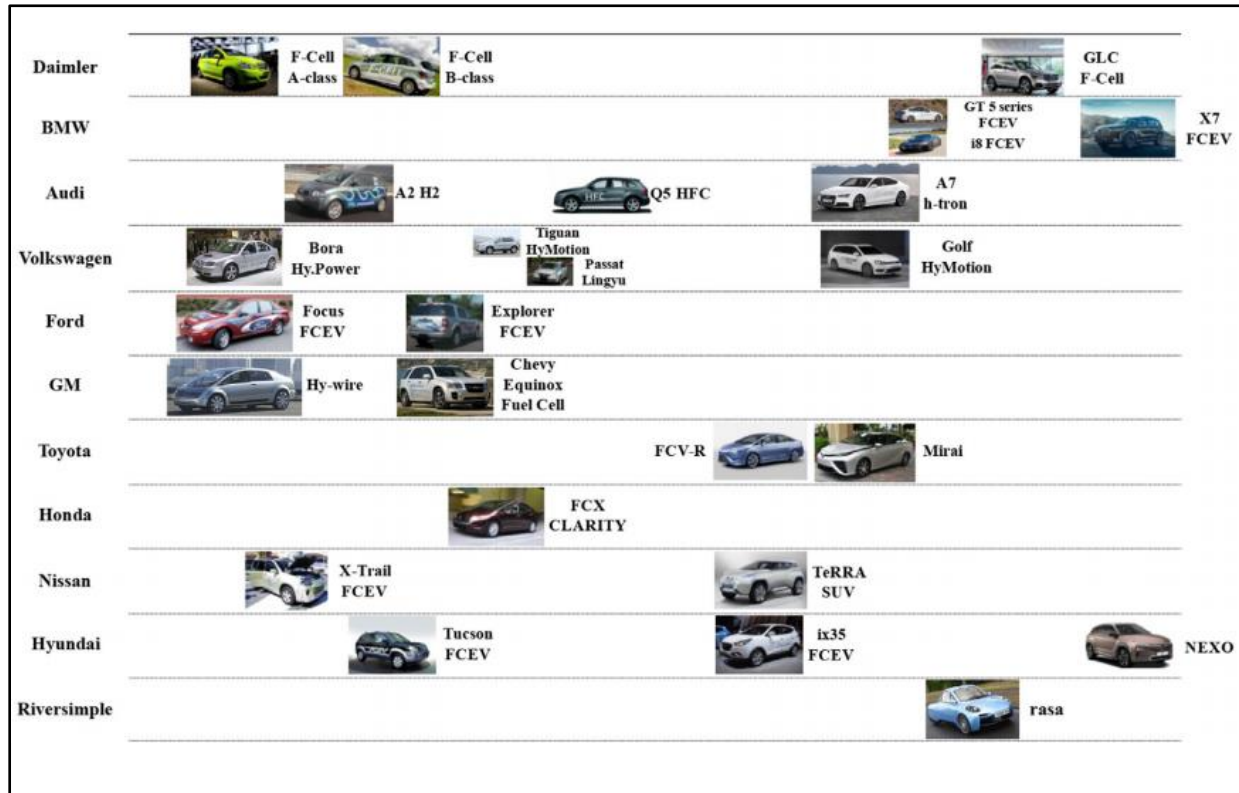


Figure III.2 Fuel cell vehicles models.

III.7.2 Stationary applications

Stationary applications fuel cells are units that provide electricity and sometimes heat in a specific location. This application is used in many ranges such as hospitals, schools, shelters, hotels, companies and centers for elderly care, in which about 2500 stationary FC sources have been put into operation worldwide [269]. In recent years, the uses of stationary FCs have expanded in several implementations, either as principal power generator rather than the grid or on remote areas, or in the case of generating combined power also known as cogeneration (electrical and heat), or as backup power supply, and in hybrid power systems [270]. On the other hand, three kinds of FC stationary can be distinguished accordingly to the power produced: large FC stationary plant from 300 kW up to 20 MW, medium FC stationary plant from 10 kW up to 300 kW, and small FC stationary plant up to 10 kW [271]. Among a large number of installations, we mention the following stationary applications:

- Figure III.3 a) presents the installation of a FC RCU-4500 with electrical power of 3.5 Kw and a thermal power of 5.6 Kw at the National Polytechnic Institute of Lorraine (INPL) in Nancy aims to feed the INPL building with electricity and hot water. The unit is supplied with natural gas and is connected to the hot water and electricity outlets [272].
- Figure III. 3 b) shows SOFC units. It includes 3 units, which able to produce 58 kW of each. This SOFC can cover around 30% of the electrical needs for Waste Water Treatment Plant located in Collegno, in Torino Italy [273].



Figure III.3 a) Fuel cell unit installed in Nancy, b) SOFC module installed in Waste Water Treatment Plant.

III.7.3 Portable applications

The density, quality and time needed for energy supply are among the important elements of the portable power production market such as laptop computers and mobile phones....etc [274]. On the other hand, electricity supply to the telecommunications sectors has become necessary in order to maintain the continuity of internet and social networks services, and this means the need for a source that guarantees the reliability electricity supply. Fuel cells are the bright future of portable power systems due to its several potentials: energy density, durability, simple design and higher power output. In addition, the FC can continue to supply the devices with electricity as long as there is fuel, and this is often done by providing a small lightweight bottle [275]. An enormous number of models have been made by different companies working on these types of fuel cells in the low power range, from a few milliwatts to some hundred watts. Liquid-feed DMFC and PEMFC are the predominant technologies for such applications as shown in figure III.4 [276].

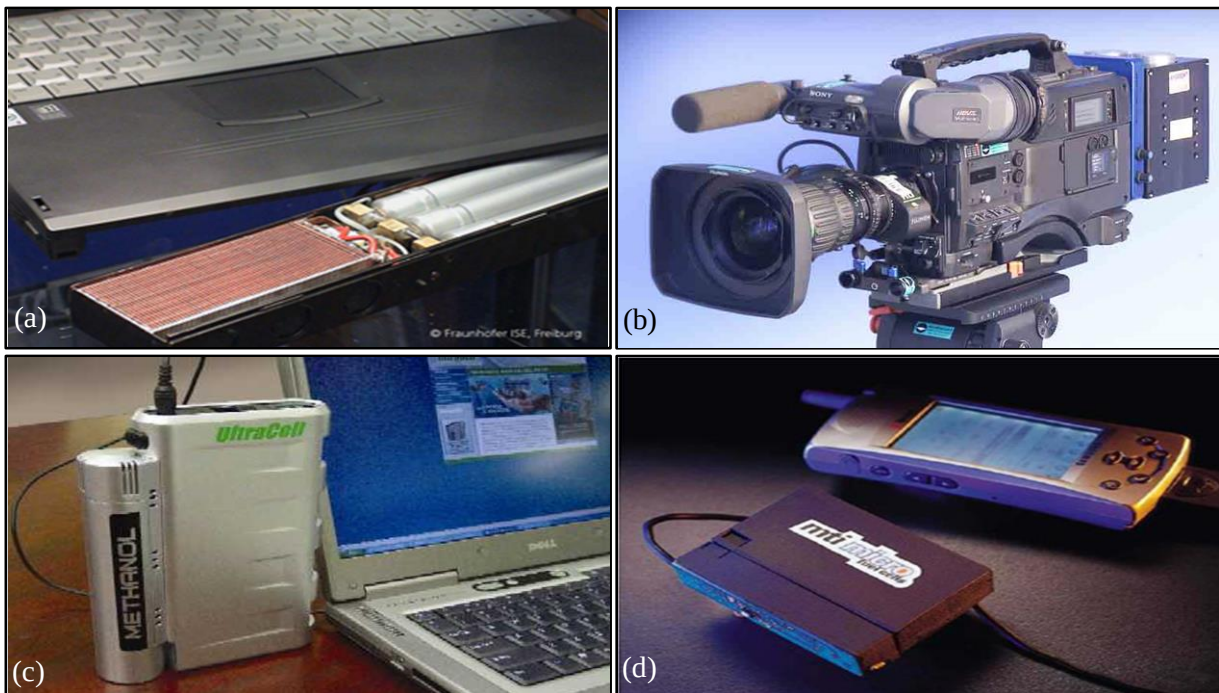


Figure III.4 a) PEMFC system integrated into laptop, b) PEMFC for professional cameras, c) DMFC Ultra cell fed laptop, d) DMFC Battery charger for mobile phones.

III.8 Description of PEM Fuel Cell

III.8.1 Principle operating of PEMFC

PEMFC is an electrochemical system that produces electricity, heat and water from two separated chemical reaction and this is done only by presence two chemical elements H_2 and O_2 [277]. The hydrogen employed as a fuel is introduced on the side of the anode, while oxygen as an oxidant is introduced on the side of the cathode.

Under constant supply of hydrogen, the hydrogen dispartes through the anode and the diffusion layer up to the platinum catalyst whose role is to trigger the chemical reaction and to divide the hydrogen molecules into protons and electrons, so that this process is called the oxidation of hydrogen. The hydrogen ions on its way to the cathode pass through the polymer membrane while the electrons are pumped through way outer circuit. On the side of the cathode, we find the other half-chemical reaction, which is called oxygen reduction reaction. In this side, the oxygen diffuse through the cathode is combined with hydrogen ions and electrons to form water [278, 279].

The sum of these hydrogen and oxygen reactions is shown in the figure III.5 and by the following equations [278]:

The half-reaction of oxidation of hydrogen will be as follows:



The half-reaction of reduction of oxygen will be as follows:



Therefore, the gross chemical reaction happening between the two electrodes of PEMFC is:

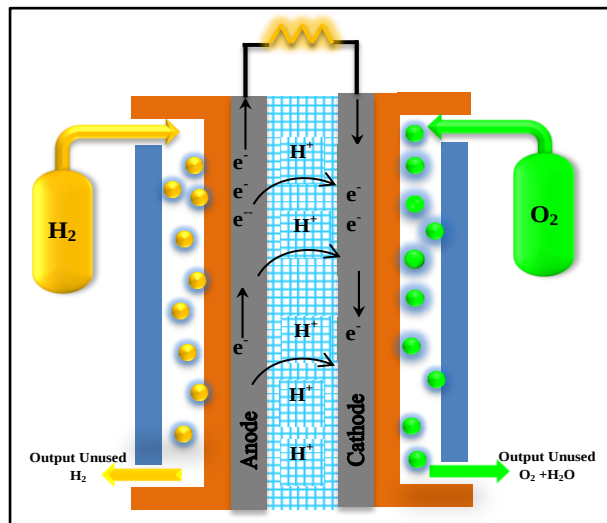


Figure III.5 Schema of operating principle of a PEM Fuel Cell.

III.8.2 Description of the basic components of PEMFC

The overall chemical reaction in the fuel cell stack is located in each primary cell. Therefore, the primary cell requires several of basic constituents and has mechanical, chemical and electrical properties specific to ensure a good performance in the fuel cell stack. Figure III.6 below shows components of the elementary cell, which contains generally the principal elements following: electrolyte (membrane), electrodes (anode and cathode), and bipolar plates [280].

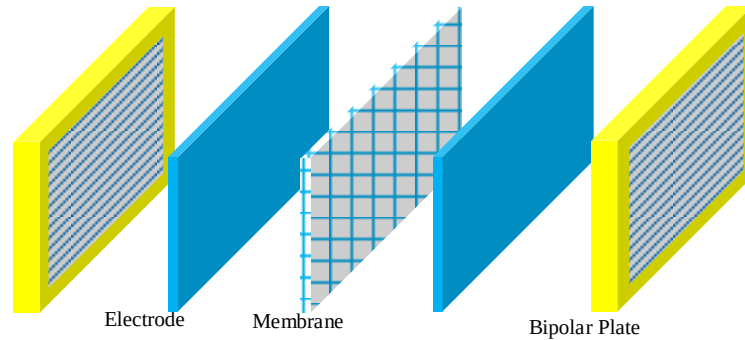


Figure III.6 Main components of a PEM Fuel Cell.

III.8.2.1 Bipolar Plates (BP)

The bipolar plates are located in the end of each cell at anode and cathode sides, they are considered as an outer covering which includes all the elements located inside the cell. BPs are looked as one of the main parts in the manufacture of PEMFC, they represent about 30 to 35% of the cost of the PEMFC and 60 to 85% of their weight, and an optimal design of the bipolar plates can greatly improve the overall performance of the PEMFC stack [281]. These BPs provide multiple functions of vital importance for long-term operation are [281, 282]:

- Distribute the reactant gases homogeneously over the active sites through flow channels.
- Directing electrical current between cells.
- Achieve cohesion and mechanical support of all the components.
- Facilitate the water management and thermal produced.
- Separate individual cells.

As result of their many functions inside the cell, the BPs must meet strict series of properties, particularly with regard to the nature of its constituent material. These properties are listed as follows [282, 283]:

- Have high electrical conductivity.
- Have low interfacial contact resistance.
- Have high resistance anti-corrosion.
- Impermeable to reactants gases.
- Have good thermal conductivity to evacuate the heat of reaction.
- Requires high mechanical strength and lightweight.
- Use of low cost materials.

Several materials were used to make this BPs, so that they meet the previous properties. One of the first materials used in the fabrication of BP is graphite due to its availability, high electrical and thermal conductivity, good chemical stability and superior corrosion resistance in an acidic fuel cell operating environment [284]. However, the graphite is fragile, has a high permeability to reactive gases, their current manufacturing processes are also long and expensive [284]. In order to avoid the inherent disadvantages in graphite, other materials have been used such as stainless steel, titanium, titanium alloys, nickel and aluminum alloy. Stainless steel and titanium are more suitable than other metals because they have the properties required by this BPs, after they are reinforced with protective coatings such as carbon, metallic nitride, carbides and noble metals to reduce both resistance interfacial contact and corrosion, because of the easy formation of a non-conductive oxide layer such as chromium oxide (Cr_2O_3) on the surface of stainless steel and titanium when in contact with air and water [285, 286].

Like materials, the shape of the channels on the surface of the plates and the space between them are very important parameters for the PEMFC stack to work properly at its maximum potential. The flow channels in the plate are used for the evacuation of water, as well as for the supply and distribution of reactants in the diffusion layer, while the space between the flow channels are used for collection and transmission of current from one cell to another, in addition to the transfer of heat generated in the electrochemical reaction [287]. Various topologies for the BPs channels were proposed by the researchers, and they differ among themselves in terms of pressure drop, water removal, reactants distribution, temperature distribution...etc. The pin, parallel and serpentine is the most dominant designs in the current BPs channels [287].

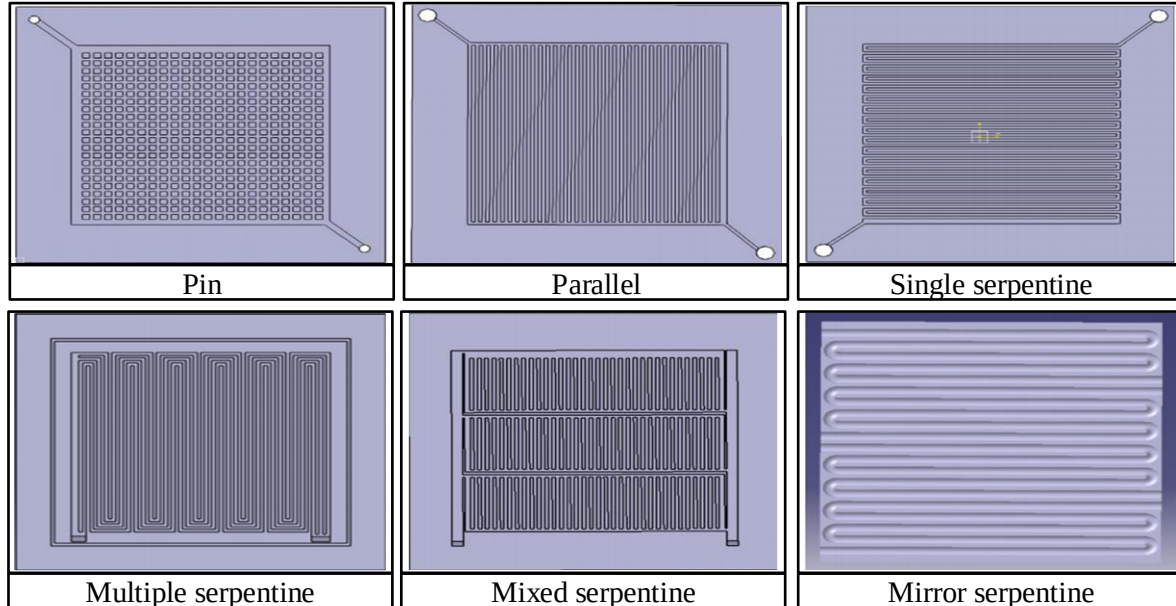


Figure III.7 Flow field design for bipolar plates in PEMFC.

III.8.2.2 Electrode

The electrodes (anode and cathode) are located between the BPs and the membrane, which are the areas of occurrence of electrochemical reactions in the PEMFC. In order to meet these functions, both electrodes must satisfy the following aspects [288]:

- Must have the necessary pores to allow the reactants to move.
- Must contain a catalyst layer (CL) to achieve chemical reactions.
- Must transfer electrons from the CL to the external circuit.

Figure III.8 presents the structure and summarizes the functions resides in the electrode, while their descriptions have taken below [288]:

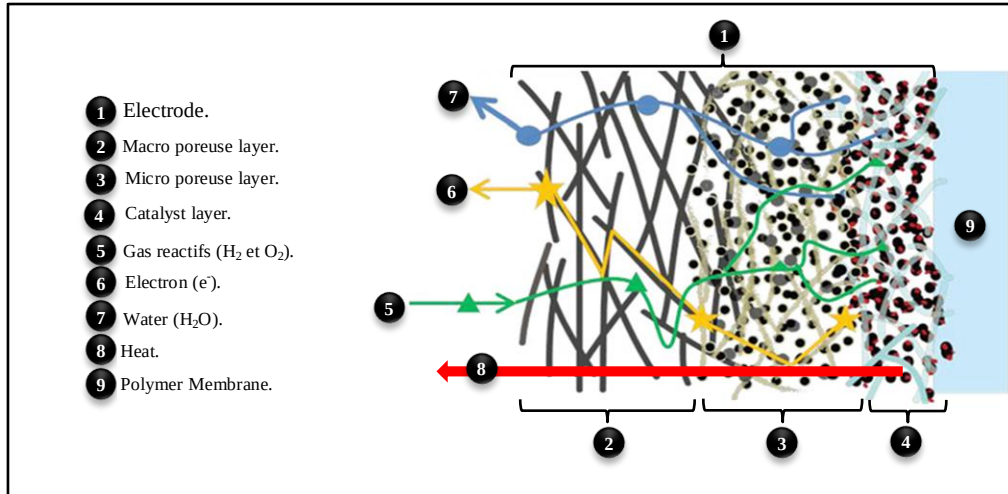


Figure III.8 Components of the electrode and its function [289].

III.8.2.2.1 Gas diffusion layer (GDL)

The GDL connects the BPs with the catalyst layer and is considered an intermediate between them. The GDL is typically a dual-layer consists of macroporous layer and micro-porous layer (MPL). Some researchers call the macroporous layer the name of the gas diffusion backing layer (GDBL) or the gas diffusion medium layer (GDML). The thickness of GDL is usually in a range of 90-350 μm , and it takes a significant role in the PEMFC [290, 291]:

- Transportation reactant gases from flow fields to CL.
- Conducting the electrons from the CL to the BPs.
- Evacuate of excess water and dissipate heat generated from the catalyst layer to the BPs.
- Providing strong mechanical support to the CL and polymer membrane.

To perform its role well, GDL is made of carbon in the form of a porous fiber material. It takes two microstructures, woven and nonwoven. A woven GBL forms a carbon paper with uniform style across its surface area as shown in figure III.9 (b), while nonwoven GBL, which considered the more commonly used are found in two categories: a carbon cloth and carbon felt, as shown in figure III.9 (a) and III.9 (c) [361]. These structures differ among themselves in terms of pore sizes and distribution. Usually, the pore sizes range from 2 to 100 μm [291].

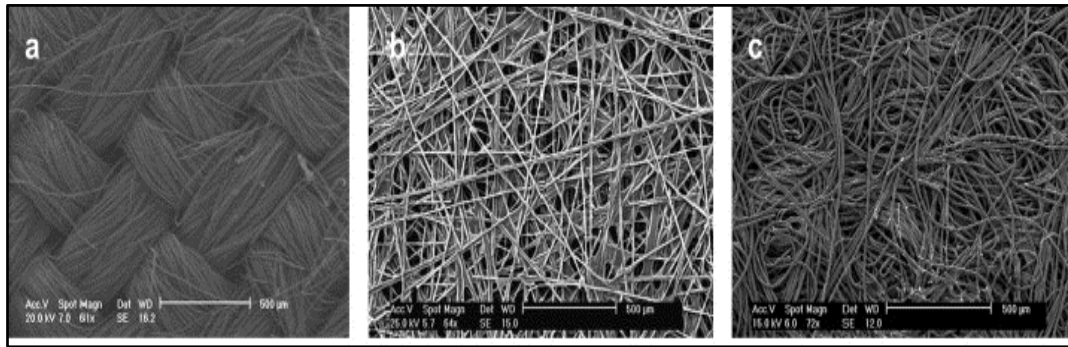


Figure III.9 Gas diffusion backing layer (GDBL) structure.

The movement inside the GDBL is as follows: the reactant gases and water produced pass through the pores, while the electrons are transferred into the highly conductive carbon fibers. The management of water in the GDL is the major problem which makes the use of this structure alone is unfavorable, the water condenses into a liquid prevents the transport of reactants gases through the pores available. This phenomenon extremely influences the performance of the cell and is called the phenomenon of flooding water in the GDL [292]. Therefore, to eliminate this phenomenon was resorted to treatment of these layers with materials hydrophobic agents such as polytetrafluoroethylene (PTFE) or fluorinated ethylene propylene (FEP) to prevent partial closure in the layer pores [292].

III.8.2.2.2 Catalyst layer (CL)

The CL is a key component in the electrode because, at its level, it allows the electrochemical conversion of hydrogen and oxygen into electricity and water. The Figure III.10 presents the structure of the CL; it consists of a catalyst, carbon particles, a hydrophobic substance and an ionomer such as Nafion [288]. The CL is located between the membrane and the GDL, its thickness usually ranges from 5-100 μm [288].

In the CL, the catalyst molecules are placed on the carbon substrate, which together forms the so-called the electrocatalyst. This latter, is responsible to accelerate the process of electrochemical reaction in the anode and cathode. Based on this, the catalyst in the PEMFC is classified into three groups as follows [363]: platinum based catalysts, platinum based catalysts that are alloyed and non-platinum based catalysts, such as non-noble metal. In terms of performance of improving reaction kinetics, the platinum based catalysts is considered the most excellent material used in the CL [293].

The second element in the electrocatalyst is carbon substrate. Generally, catalyst support must have some conditions in order to achieve the best performance under PEMFC operating conditions, which among these: high specific surface (to allow a good distribution of catalyst particles), good electrical conductivity, sufficient porosity to allow access of gases, corrosion resistance, and able to prevent water flooding [294]. Carbon black is currently the most used among carbon-based supports because it includes the majority of the previous characteristics required in catalyst support as well as it is available and its low cost [294].

Nafion among the types of Polymer Ionomers, which is added to the catalyst layer to improve its performance. The Nafion insert not only serves as a physical binder for carbon support particles,

but helps to facilitate hydrogen ions to flow across the path from its production site (the anode), membrane and then cathode [295]. The kinetics of hydrogen ions is related to the optimal amount of Nafion that has been introduced into the catalytic layer, so this is a crucial point to control. Indeed, if large amounts of Nafion are introduced into the catalyst layer, negatively affect the absorption and activating hydrogen. On the contrary, a too small quantity of it will limit the contribution of protons in the membrane [295].

In addition, during the manufacture of the CL, an amount of hydrophobic substance must be added, generally PTFE to improve the porosity of the CL and enhance the reactant gases transport and water resultant during electrochemical reaction [296].

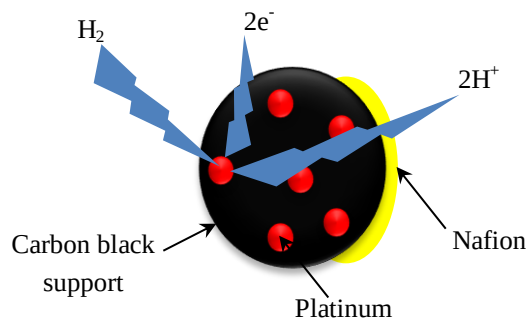


Figure II.10 Structure of the CL.

III.8.2.3 Membrane

The membrane is the central element of the PEMFC, which divides this latter into two halves, the compartment of anode and cathode. It also sets the cell operating field in terms of the permissible temperature, as well as the pressure and humidity of the gases. In addition to its principal function of proton conduction and the essential propriety of chemical stability, it must fulfill a numerous restrictive specification to be applied in PEMFC [297]:

- The highest possible of protonic conductivity.
- The highest possible of electronic resistance.
- Must have impervious to reactant gases (fuel or oxygen).
- Good chemical and thermal resistance under acidic operating conditions.
- Must have sufficient mechanical strength.
- Better to be low cost.

Because it is able to guarantee and in large proportion the requirements mentioned above, Nafion one of Perfluorinated Sulfonic Acid (PFSA) materials appears among a wide range of polymers used in PEMFC as membrane, which has been widely adopted in PEM fuel cell applications [298]. Nafion consists of three parts, polytetrafluoroethylene (PTFE) polymer like backbone, that ensure chemical stability during oxydo-reduction of hydrogen and oxygen; while the second part is represented by the fluorinated carbon side chains, that works to connect the molecular backbone with third part, which consisting of sulfonic acid groups ($-\text{SO}_3\text{H}$) [299]. Hydrogen ions move as the membrane becomes wet by bonding to water molecules and then move between sulfonic acid groups, chemical structure is given by the following figure III.11 [299].

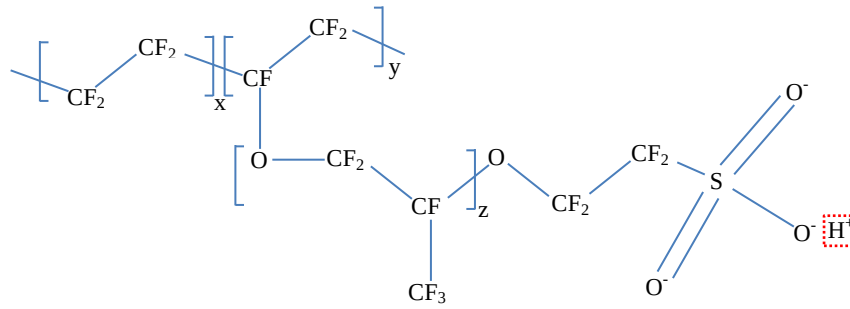


Figure II.11 Chemical structure of Nafion.

In general, there are two elements that will be transported across the membrane. The first moves in one direction from the anode towards cathode which is the proton, while the water swims in both directions. Protons come from the oxidation of hydrogen, while water comes from the humidification gases and the results of reaction in the side of cathode. The transport and management of these quantities in membrane are of the utmost importance; in which water contributes to hydration of the membrane to facility the transporting protons across it. Therefore, three mechanisms that contribute to the transfer process; mechanism to transport proton and water all separately, and other mechanism shared between them [300-303]:

- **Electro-osmosis:** is defined as the movement of liquid according to an applied electric field across a membrane, which is considered as one of the major water transport forces in the membrane. Indeed, when PEMFC begins generate electrical current; an electric field creates between its electrodes, ions of hydrogen moves across the membrane accompanied with water molecules, in response to electromotive forces applied across the membrane. In this process, the proton binds to one or more water molecules that then form hydrogen water ions ($H^+(H_2O)_x$) such as hydronium ion (H_3O^+), Zundel-ion ($H_5O_2^+$) and $H_9O_4^+$. This process is also known as vehicular mechanism.
- **Back Diffusion:** this process responsible only to transport water in the direction perpendicular from cathode to anode through the membrane, which happens when there is concentration gradient. As long as the water comes in large quantities from the side of the cathode, the center of its production, this means that it will create a difference in concentration and be on the side of the cathode greater than the focus on the side of the anode, causing the water to move according to the concentration gradient.
- **Grotthuss mechanism:** This process depends on the proton exchange, by jumping step by step between a wet ionic site and another until reaching the catalyst layer from the side of the cathode by a series of hydrogen bonds formations and breakage. The proton created by oxidation of hydrogen in anode adheres to water molecule creating a hydronium ion (H_3O^+), and can also be created Eigen-ion ($H_9O_4^+$) by creating hydrogen bonds between (H_3O^+) and three water molecules. Then, the proton can move to a new position between two water molecules to form Zundel-ion ($H_5O_2^+$). Also, another ($H_9O_4^+$) can be created but at different site. These transitions between the ($H_9O_4^+$) and ($H_5O_2^+$) are caused by the processes of hydrogen bond formation and breaking, which mainly lead to proton transfer.

III.9 Mathematical Modeling of PEM fuel cell

In general, the PEMFC is a system for converting energy from a chemical form to an electrical form, thermodynamics having the power to analyze this transformation of energy. In reality, thermodynamics makes it possible to give the value of the maximum electric voltage generated during the chemical reaction which takes place between hydrogen and oxygen. However, this maximum value is practically not available, it is necessary to take into account the kinetic and transport aspects.

III.9.1 Operating cell voltage

Energy is conserved in any transformation; this is stated by the first law of thermodynamics. The equation (III.4) translates the first principle of thermodynamics, in such a way that the variations of energy of a system correspond to exchanges of heat and/or work [304].

$$dE_n = \delta Q + \delta W \quad (III.4)$$

Where: δQ and δW are the exchanges of heat and work respectively.

In steady state, the first law of thermodynamic equation (III.4) can be expressed by equation (III.5) using the enthalpy function (H).

$$\Delta H = Q + W \quad (III.5)$$

Our target is to know the maximum amount of electrical energy sent to external circuit by the PEMFC during the oxidation of hydrogen. Assuming that the chemical reaction inside the PEMFC takes place at constant temperature and pressure, the enthalpy of the reaction provides the maximum amount of energy that can be recovered in the form of heat and electricity. The enthalpy of the reaction is given by the difference between the heat of formation of products and reactants as presented in the equation (III.6) [305].

$$\Delta H_r(T, P) = \Delta H_f(H_2O) - \left(\Delta H_f(H_2) + \frac{1}{2} \Delta H_f(O_2) \right) \quad (III.6)$$

At standard condition ($T^\circ = 298K$ and $P^\circ = 10^5 Pa$), the both species (H_2 and O_2) have enthalpy of formation equal to zero. Therefore, the enthalpy of reaction become equal to the enthalpy of formation of water and its value is related on the state in which it is liquid or vapor [305].

- In the state liquid: $\Delta H_r^\circ = -285.83 \text{ kJ/mol}$.
- In the state vapor: $\Delta H_r^\circ = -241.82 \text{ kJ/mol}$.

On the other hand, extensive studies in the world of thermodynamics have added to our information that not all of this resulting energy can be converted into useful work. According to the second principle, part of this energy released during the reaction will be transformed into heat and the rest into work. The second principle of thermodynamic is defined by using two state functions called entropy and free enthalpy. The part which expresses free enthalpy also known as Gibbs free

energy variations (ΔG) characterizes the exploitable net electrical work. It is calculated from the difference between variations in enthalpy (ΔH) and entropy (ΔS) [306].

$$\Delta G(T, P_i) = \Delta H(T, P_i) - T \Delta S(T, P_i) \quad (III.7)$$

The Gibbs free energy variation (ΔG) which is the maximum theoretical electrical work a system can make at any given constant pressure and temperature from a given reaction [304, 306]:

$$W_{elec} = -\Delta G(T, P_i) \quad (III.8)$$

The equation of the electrical work (W_{elec}), when PEMFC faced with a potential difference E (Volts) is given by [304, 306]:

$$W_{elec} = q E \quad (III.9)$$

The total charges q , which are considered electrons resultants from PEMFC reaction is given by:

$$q = n_e N_{Avg} q_{el} \quad (III.10)$$

While:

$$N_{Avg} q_{el} = F \quad (III.11)$$

Where:

n_e : is the number of electrons/molecule.

N_{Avg} : is Avogadro's number, which equal 6.022×10^{23} molecule/mole.

q_{el} : is the charge of one electron, which equal 1.602×10^{-19} Coulombs/electron.

F : is the Faraday's constant, that equal 9.6485×10^4 C/mol.

Finally, by combining the equations (III.8), (III.9) and (III.10) it appears to us the expression of the reversible cell voltage E at standard condition:

$$E = \frac{-\Delta G}{n_e F} \quad (III.12)$$

The (ΔG) takes different values, and this energy changes with the temperature and thus with the state of water product (liquid or gas). Table II.2 below shows these values at various temperatures for the basic PEMFC reaction as well as the corresponding value for reversible cell voltage [307].

Table III.2 (ΔG) and (E) for reaction $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$.

Form of water product	Temperature (...°C)	ΔG (kJ/mol)	E (V)
Liquid	25	-237.2	1.229
	80	-228.2	1.182
Gas	100	-225.3	1.167
	200	-220.4	1.142
	400	-210.3	1.089
	600	-199.6	1.034
	800	-188.6	0.977
	1000	-177.4	0.919

From the table II.2 and at temperature 25°C, we have the value of free enthalpy is equal to (-237.14 kJ/mol). Thus we can determine the reversible cell voltage under the same conditions:

$$E_{th}^{\circ} = \frac{-\Delta G}{n_e F} = \frac{237.14}{2 * 96.485} = 1.229 \text{ V} \quad (\text{II.13})$$

This value of (E_{th}°) is the maximum voltage of a PEMFC obtained under standard conditions. This is why it is also called reversible open circuit voltage.

III.9.2 Operating cell voltage at non-standard conditions

Indeed, in practical cases, the PEMFC is subjected to operating conditions different from the standard conditions. In addition to both temperature and pressure, reactant concentration impact Gibbs free energy value. This will lead us to introduce one of the important electrochemistry equations known as the Nernst equation [308].

$$E_{Nernst} = E^{\circ} + \frac{RT}{n_e F} \ln \left(\frac{\prod_i a_{reactant_i}^{c_i}}{\prod_j a_{product_j}^{c_j}} \right) \quad (\text{III.14})$$

Where:

E° : is the reference voltage.

R : is the universal gas constant that equals 8.314 J/mol K.

T : is the temperature (K).

n_e : is the number of electrons result during reaction.

i, j : is the numbers of reactant and product species.

a : Represents the activity of species.

c_i : is the stoichiometric coefficient of species i .

The theoretical voltage (E°) at standard state is taken to be 1.229V. On the other hand, this theoretical voltage changes as a function of the temperature according to equation below [308]:

$$E^{\circ} = E_{th}^{\circ} + (T - T^{\circ}) \left(\frac{\Delta S^{\circ}}{n_e F} \right) \quad (\text{III.15})$$

E_{th}° is equal to 1.229V at $T_0 = 298K$, and ΔS° is the change in entropy. The expression of (a) can be given as function of partial pressure as follows [308]:

$$a_{i,j} = \frac{P_{i,j}}{P^{\circ}} \quad (III.16)$$

To put standard state pressure $P^{\circ} = 1 \text{ atm}$, and in the case of the oxydo-reduction reaction between hydrogen and oxygen in PEMFC, which the product is water ($a_{H_2O} = 1$), so the Nernst equation is written as follows:

$$E_{Nernst} = E^{\circ} + \frac{RT_{FC}}{n_e F} \ln(P_{H_2} \sqrt{P_{O_2}}) \quad (II.17)$$

From the work of Amphlett and al. [309], the general form of Nernst equation is given according to the semi-empirical relationship shown in equation below:

$$E_{Nernst} = 1.229 - 0.85 \times 10^{-3} (T_{FC} - T_0) + 4.3085 \times 10^{-5} T_{FC} \left[\ln(P_{H_2} \times P_{O_2}^{0.5}) \right] \quad (III.18)$$

Where:

P_{H_2} & P_{O_2} : are the pressure of H_2 and O_2 respectively.

T_{FC} & T_0 : are the temperature of FC and at STC respectively.

III.9.3 Actual operating cell voltage of PEMFC

The output cell voltage which expressed by the equation of Nernst is function of current being provided, temperature and reactant gases pressures. Owing to unavoidable losses during the operating of PEMFC, there are three sorts of voltage losses inside PEMFC namely activation, ohmic, and concentration voltage losses or drops [307]. Therefore, the voltage of the PEMFC is written as follows:

$$U_{FC} = E_{Nernst} - \partial_{act} - \partial_{ohm} - \partial_{conc} \quad (III.19)$$

Where:

∂_{act} , ∂_{ohm} and ∂_{conc} : are the activation, ohmic and concentration voltage losses respectively.

III.9.3.1 Activation Losses

This corresponds to the reality that the FC needs amount of energy to ensure electrons move, and create/break chemical bonds in the both electrodes anode/cathode [310]. The activation loss is appears in the both electrodes, while it is higher at the cathode side due to the difference in the speed of the two reactions, where the oxygen reduction reaction is significantly slower compared to the rapid hydrogen oxidation reaction [311]. In addition, they are significant at low current densities. The voltage drop resulting from the activation losses in both electrodes can be given by the equation below [312, 313]:

$$\partial_{act} = -\left(\xi_1 + \xi_2 \times T_{FC} + \xi_3 \times T_{FC} \times \ln(C_{O_2}) + \xi_4 \times T_{FC} \times \ln(I_{FC})\right) \quad (III.20)$$

Where:

$\xi_{(i=1 \text{ to } 4)}$: are parametric coefficients, where:

$$\xi_1 = -0.948, \xi_2 = 0.00286 + 0.0002 \ln(\sigma) + 4.38 \times 10^{-5} \ln(C_{H_2}), \xi_3 = 7.6 \times 10^{-5} \text{ and } \xi_4 = -1.93 \times 10^{-4}.$$

I_{FC} : is the cell current (A).

σ : is the cell active area (cm²).

C_{H_2} and C_{O_2} : are the hydrogen oxygen's concentration (mol/cm³), given by:

$$C_{H_2} = 9.174 \times 10^{-7} P_{H_2} \exp\left(\frac{-77}{T_{FC}}\right) \quad (III.21)$$

$$C_{O_2} = 1.97 \times 10^{-7} P_{O_2} \exp\left(\frac{498}{T_{FC}}\right) \quad (III.22)$$

Substituting the parametric coefficients of $\xi_{(i=1 \text{ to } 4)}$ with the expression of C_{H_2} and C_{O_2} in the equation (III.20), the activation losses equation becomes:

$$\begin{aligned} \partial_{act} = & -0.948 + \left(0.00286 + 0.0002 \ln(\sigma) + 4.38 \times 10^{-5} \ln(C_{H_2})\right) \cdot T_{FC} + \\ & 7.6 \cdot 10^{-5} \cdot T_{FC} \cdot \ln\left(1.97 \times 10^{-7} P_{O_2} \exp\left(\frac{498}{T_{FC}}\right)\right) - 1.93 \cdot 10^{-4} \cdot T_{FC} \cdot \ln(I_{FC}) \end{aligned} \quad (III.23)$$

III.9.3.2 Ohmic Losses

Two processes participate to the overall ohmic losses of a PEMFC; the first process is mainly due to the ionic resistance of the polymer membrane to the flow of protons, while the second process is related to the resistance of the anode/cathode materials and the bipolar plates resistance to the movement of electrons [311]. The both resistances affect the PEMFC voltage, while the losses that appear at the level of the membrane to be the largest and can be decreased by reducing the thickness of the membrane and by ameliorating its ionic conductivity. Therefore, the voltage drop resulting from the ohmic losses is calculated as follows [312-314]:

$$\partial_{ohm} = (R_c + R_m) I_{FC} \quad (III.24)$$

Where:

R_c : is the contact resistance represent the sum resistance of the components electrode materials and bipolar plates.

R_m : is the equivalent membrane resistance which can be expressed by:

$$R_m = \rho_m \times \frac{l}{\sigma} \quad (III.25)$$

Where:

l : is the thickness of polymer membrane (cm).

ρ_m : is the membrane specific resistivity ($\Omega \text{ cm}$), defined by:

$$\rho_m = \frac{181.6 \left[1 + 0.03 \left(\frac{I_{FC}}{\sigma} \right) + 0.062 \left(\frac{T_{FC}}{303} \right)^2 \left(\frac{I_{FC}}{\sigma} \right)^{2.5} \right]}{\left[\varphi - 0.634 - 3 \left(\frac{I_{FC}}{\sigma} \right) \right] \exp \left(4.18 \left(T_{FC} - \frac{303}{T_{FC}} \right) \right)} \quad (\text{III.26})$$

Where:

φ : is the membrane water content (MWC). It is considered to be 14 for fully hydrated and 23 for fully saturated.

Finally, we find the expression of ohmic loss by substituting the expression in (III.26) into (III.25), and then the result obtained is substituted in the equation (II.24).

$$\partial_{ohm} = \left(R_c + \frac{181.6 \left(1 + 0.03 \left(\frac{I_{FC}}{\sigma} \right) + 0.062 \left(\frac{T_{FC}}{303} \right)^2 \left(\frac{I_{FC}}{\sigma} \right)^{2.5} \right)}{\left(\varphi - 0.634 - 3 \left(\frac{I_{FC}}{\sigma} \right) \right) \exp \left(4.18 \left(T_{FC} - \frac{303}{T_{FC}} \right) \right)} \frac{l}{\sigma} \right) I_{FC} \quad (\text{III.27})$$

III.9.3.3 Concentration Losses

At the surface of the catalyst layer, the concentration of the reactant gases changes during the electrochemical reaction due to the inability of the reactant to maintain its initial concentration i.e. it cannot be delivered from BPs until CL by a constant pressure due to the flow resistance [311, 312, 314]. This decline in the concentration gradients leads to the occurrence of the concentration voltage loss at higher currents density. The voltage drop resulting from the concentration losses is given by the expression follows [311, 312]:

$$\partial_{conc} = - \frac{RT_{FC}}{n_e F} \times \ln \left(1 - \frac{I_{FC}}{\sigma \times J_{max}} \right) \quad (\text{III.28})$$

Where:

J_{max} : is maximum current density (A/cm^2).

III.9.4 Polarization curve

Figure II.12 shows the polarization curve of a PEMFC voltage which includes all the characteristic points and the three regions of the voltage losses. The polarization curve is illustrated according to the expression of the output voltage presented in the equation (III.29), and the PEMFC stack adopted in this thesis with the characteristic mentioned in the table (III.3).

$$U_{FC} = \aleph_{cell} \left(\begin{array}{l} 1.229 - 0.85 \times 10^{-3} (T_{FC} - T_0) + 4.3085 \times 10^{-5} T_{FC} \left[\ln(P_{H_2} \times P_{O_2}^{0.5}) \right] \\ - \left(\xi_1 + \xi_2 \times T_{FC} + \xi_3 \times T_{FC} \times \ln(C_{O_2}) + \xi_4 \times T_{FC} \times \ln(I_{FC}) \right) \\ - \left(\rho_m \times \frac{l}{\sigma} \right) - \left(-\frac{RT_{FC}}{nF} \times \ln \left(1 - \frac{I_{FC}}{\sigma \times I_{max}} \right) \right) \end{array} \right) \quad (III.29)$$

Where $\aleph_{cell}$ is the Number of cell in the PEMFC stack.

Table III.3 PEMFC parameters.

Parameters	Value	Unit
Maximum power at MPP.	7	kW
Cell open circuit voltage.	1.29	V
Number of cells.	50	/
Cell active surface.	200	cm ²
Hydrogen partial pressure.	2.6	bar
Oxygen partial pressure.	0.3	bar

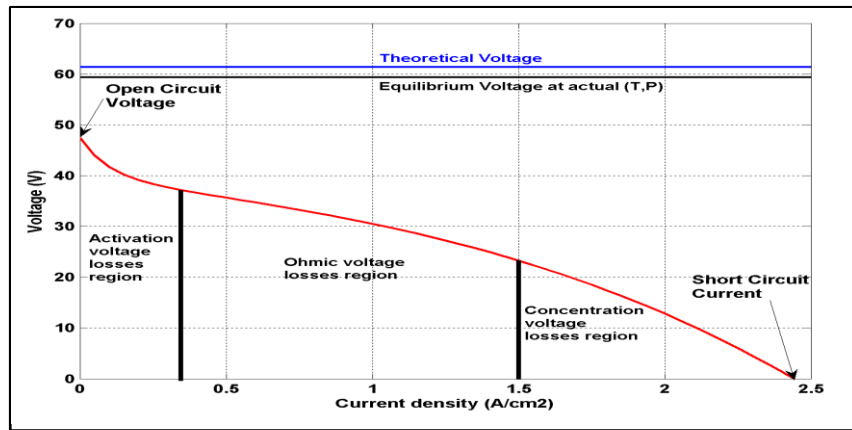


Figure II.12 PEM Fuel Cell polarization voltage curve.

As shown in the figure III.12, the polarization voltage curve can be partitioned into three regions. At the first region, which corresponds at low current density, the curve knows an abrupt and non-linear drop in the voltage of the PEMFC starting from the open circuit voltage, which can be explained mainly by the effect of the activation losses. After this, the polarization curves enter in the second region where current densities to be into its intermediate values, a nearly linear diminution in voltage is observed, which is resulted fundamentally by the ohmic losses. The cell voltage continues to decrease steeply and non-linearly in the last part of it (at high current density), which is caused by insufficient transport of reactant gases to the CL; the concentration losses are considered the most prevalent in this region.

The figure III.13 a), b) and c), present the PEMFC output voltage when considered only the activation losses, ohmic losses and concentration losses respectively in order to illustrate the area of influence of each part of these three losses.

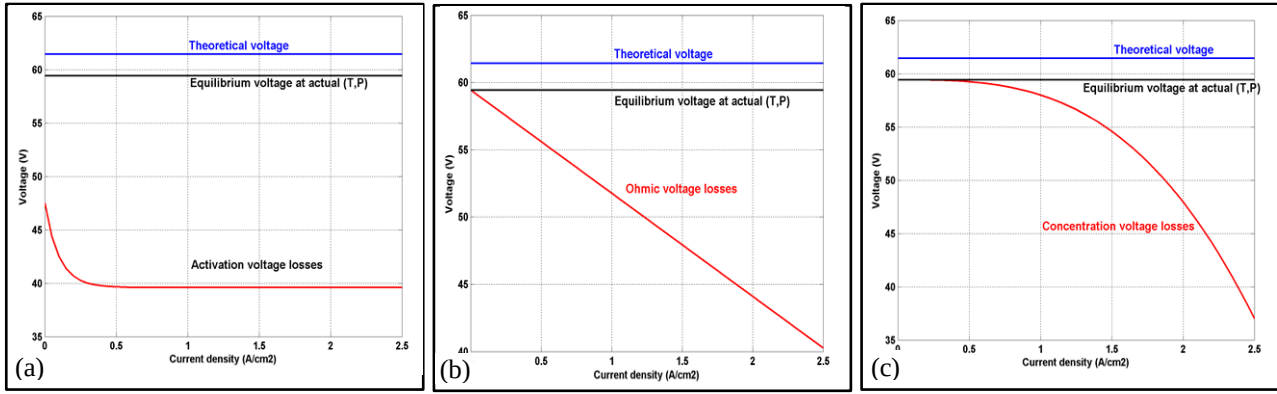


Figure III.13 PEMFC voltage losses.

In addition, from polarization curve of voltage, it can be utilized to extract a power curve of PEMFC stack. The figure III.14 below represents the curve of power as function of the current density, which takes the form of a parabola passing through the maximum power of PEMFC stack. Indeed, the power gradually increases according to the evolution of the current and goes through a maximum at a certain time then begins to decrease. This behavior is due to the voltage losses inside PEMFC which are directly linked to the current.

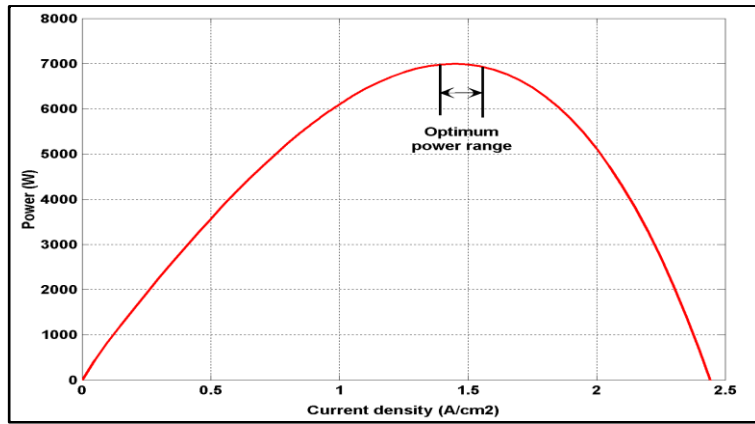


Figure III.14 PEM Fuel Cell Power curve.

Finally, the polarization curves of PEMFC given in figure III.12 and figure III.14 are nonlinear, and functions of PEMFC current, temperature and pressure of H_2/O_2 gases.

III.9.5 Theoretical efficiency of FC

In PEMFC, the enthalpy of hydrogen is the energy input while the helpful energy yield is the electrical energy. If we assume that most of the Gibbs free energy is changed to electrical power, then the maximum efficiency of the PEMFC is expressed as [315]:

$$\eta_{FC} = \frac{\Delta G}{\Delta H} = \frac{237.14}{285.83} = 83\% \quad (III.30)$$

Another expression can be reached for efficiency of a PEM fuel cell through quotient of voltages by using Farady's constant and two electrons which outputs during the reaction:

$$\eta_{FC} = \frac{\Delta G}{\Delta H} = \frac{\Delta G/2F}{\Delta H/2F} = \frac{1.229}{1.482} = 83\% \quad (III.31)$$

In this way, the efficiency of the cell at any condition can be obtained from the voltage at its output terminals:

$$\eta_{FC} = \frac{U_{FC}}{1.482} \quad (\text{III.32})$$

III.9.6 Determination of the flow rates of reactants and product

From the half-reaction of oxidation and reduction, two electrons are transferred and one mole of water is produced for each mole of hydrogen and half mole of oxygen consumed. So, the rates of reactant gases consumed and water generated are determined according to Faraday's law as follow [316]:

$$\begin{cases} \Psi_{H_2} = \frac{I_{FC}}{2F} \\ \Psi_{O_2} = \frac{I_{FC}}{4F} \\ \Psi_{H_2O} = \frac{I_{FC}}{2F} \end{cases} \quad (\text{III.33})$$

The mass flow rates of reactants consumption and the water generated in (g/s) can be expressed as follows [316]:

$$\begin{cases} m_{H_2} = \frac{I_{FC}}{2F} \mathcal{M}_{H_2} \\ m_{O_2} = \frac{I_{FC}}{4F} \mathcal{M}_{O_2} \\ m_{H_2O} = \frac{I_{FC}}{2F} \mathcal{M}_{H_2O} \end{cases} \quad (\text{III.34})$$

Where: $\mathcal{M}_{H_2}$, $\mathcal{M}_{O_2}$ and $\mathcal{M}_{H_2O}$ is molar mass of hydrogen, oxygen and water respectively.

By substitution the values of the Faraday constant and molar mass of reactants as well as water generation in both equations (III.33) and (III.34). The consumption of the reactants gases (H_2/O_2), and water generation in the PEMFC is summarized in table below:

Table II.4 Reactants gases consumption and water generation.

Unit	Hydrogen consumption (H_2)	Oxygen consumption (O_2)	Water generation (H_2O)
mol/s	$5.18 \times 10^{-6} I_{FC}$	$2.59 \times 10^{-6} I_{FC}$	$5.18 \times 10^{-6} I_{FC}$
g/s	$10.4 \times 10^{-6} I_{FC}$	$82.9 \times 10^{-6} I_{FC}$	$93.3 \times 10^{-6} I_{FC}$

III.10 PEMFC operating conditions

The output electrical voltage of the PEMFC is not constant and is greatly dependent on the physical operating conditions such as temperature, pressures and MWC, which that affect PEMFC performance, in which using the correct operating condition for each parameter is critical to obtain the best performance. Therefore, three parameters will be discussed about their impact on the performance of PEMFC.

III.10.1 Effect of the operating pressures

As the main condition through which the process of pumping both hydrogen and oxygen begins, the operating pressure plays a serious part in setting PEMFC performance. The performance of PEMFC is affected by the operating pressure, as the latter have an effect on both the open circuit voltage according to the equation of Nernst, partial pressures of the reactant gases, current densities and mass transfer in the catalyst layers [317]. Therefore, any increasing or decreasing in the operating pressure will inevitably lead to variation in the output voltage. Through series of experiments realized by Hsieh and al concerning to study the pressure effect on the PEMFC performance, it was discovered that the quickening of reaction by the enhanced partial pressure is the significant reason for the improvement of PEMFC performance [318].

In this part, progression of tests was performed to comment the impact of the operating pressure. The temperature of the cell and some parameters are remaining constant, while the pressure values are changed on both the anode and the cathode, which takes values expressed in unit of (bar) as follows: Pressure for anode = [1 1.5 2.6 3.5 4.5] and Pressure for cathode = [0.1 0.2 0.3 0.4 0.5].

III.10.1.1 Effect of pressure on the voltage losses

Activation losses are stemmed from to sluggish electrode kinetics. The rising of the operating pressure is reducing the impact of the activation over voltage; this is confirmed by the simulation results. Figure II.15 (a) allows an overview of the magnitude of pressure effect on the activation voltage losses.

As previously mentioned, concentration losses are caused by the mass transport limitations in both surface catalyst layers of anode and cathode, and climax increases when the reactant concentration is minimum in the catalyst layers at high current densities. Therefore, when pressure begins to raise, the rate of gas molecules diffusion increases simultaneously, this will lead to a reduction of the concentration losses. We can clearly see this in figure II.15 (b).

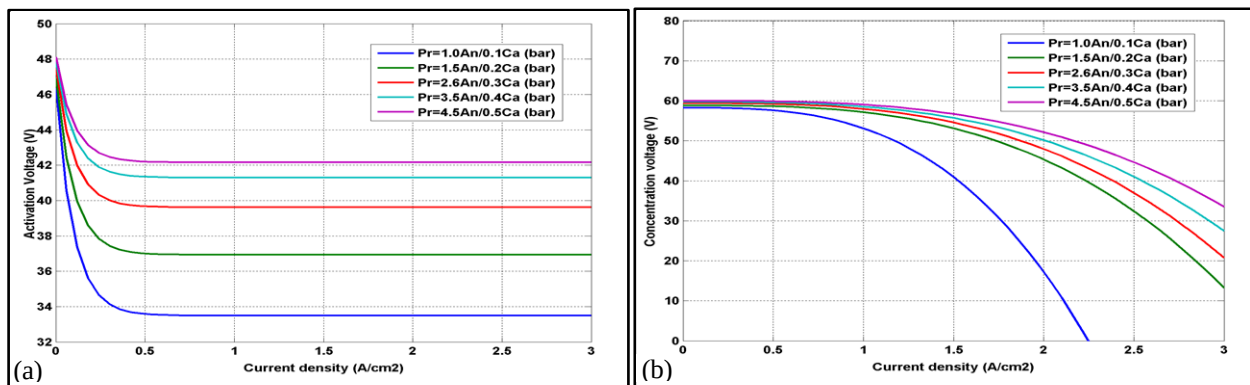


Figure III.15 a) Activation voltage losses and b) concentration voltage losses in PEMFC at different pressure.

III.10.1.2 Polarization curves depends on operating pressure

Through figure III.16 (a), it can be seen that PEMFC performance has improved whenever there is an increase in anode and cathode pressure. An equation III.29 represent output voltage of PEMFC contains two parts, Nernst equation and the voltage losses. Both influenced by operating

pressure positively, in which Nernst voltage increases while that losses decreases. Therefore the output voltage is improved when the operating pressure is increased.

In figure III.16 (b), we also find the output power at different operating pressures, the effect of this one similar to its effect in polarization curve of voltage, in which can increase the maximum output power of PEMFC. As result, at each operating pressure applied there is a corresponding maximum output power. For example, when PEMFC working at operating pressure 1.5/0.2 bar for anode and cathode respectively, the corresponding maximum output power is 6050 W; when the operating pressure 3.5 bar for anode and 0.4 bar for cathode, the corresponding maximum output power is 7738 W. This indicates that the PEMFC can further improve its maximum output power by raising its operating pressure appropriately.

Finally, through these figures it is obviously shown that the increasing of the pressures increase the maximum output power. And, they decrease the voltage loss of the PEMFC.

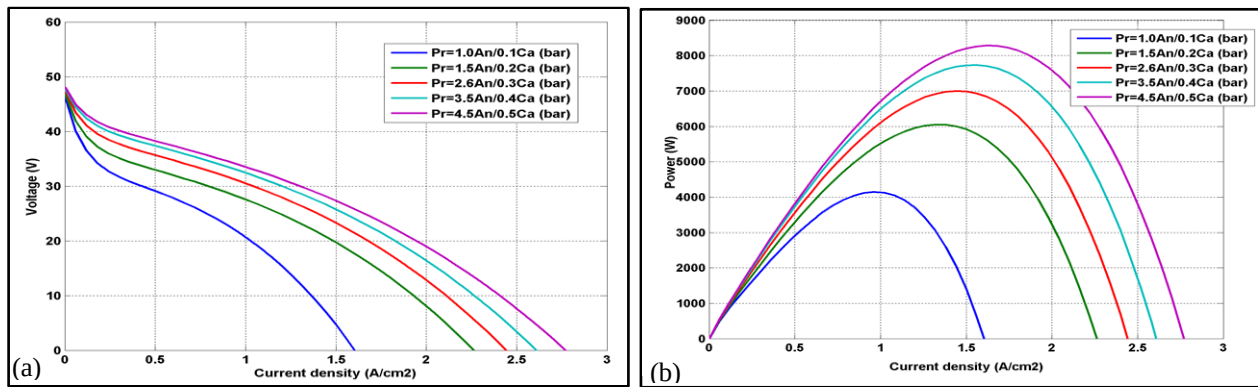


Figure III.16 PEM Fuel Cell: **a)** Voltage and **b)** Power curves under variation of pressure.

III.10.2 Effect of the operating temperatures

Inside the PEMFC, the temperature takes various values. The superior limit of operating temperature is fixed by the effectiveness of membrane, because the main function of the PEMFC depends at over the elasticity of the kinetics of protons through the membrane. Practically, membrane cannot function in a medium with a temperature above 100°C without being dehydrated and damage at the end. At this threshold the water will evaporate which will result dry the membrane and impede the penetration of protons, thus reducing the overall performance of the PEMFC. Several papers were devoted to study on how the operating temperature impacts PEMFC performance [319-323]. Through these studies, temperature variations have major important to improve performance inside PEMFC, which affect all transport phenomena and electrochemical kinetics.

In this part, a progression of tests was performed to comment the impact of the operating temperature. The pressure of the cell and some parameters are remaining its values constant. The temperature values are changed as follows: T (Kelven) = [310 325 353 360].

III.10.2.1 Effect of temperature on the voltage losses

Figure III.17, shows the temperature effect on the voltage losses. For activation voltage losses, it is evident that the rising of temperature has a positive effect, in which a decrease in the activation losses is recorded; this is due to the acceleration of the reaction kinetics with rising of temperature.

The ohmic voltage loss is the most significant parameter in this part. Ohmic voltage losses are takes linearly forms as function of current densities, and also affected by temperature as shows in figure III.17 (b), where we notice diminishing in this losses by increases in the operating temperature, due to this latter improves the ionic conductivity for the membrane in particular. Therefore, it can be said that the positive effect of temperature on the ionic conductivity of the membrane prevails over the negative effect of a decrease in the membrane water content as the temperature rises. With excellent external humidification, the problem of dry membrane can be overcome when PEMFC operated at high temperatures [324]. As mentioned previously, the principal cause of concentration voltage losses at high current densities is the slow mass transportation of fuel and oxidant to the reaction locations. Originally, the temperature has potential to progress the diffusion of molecules inside PEMFC leading to improve and quickly supply of reactants gases. Therefore, rising of temperature reduces the concentration voltage losses slightly as shown in the figure III.17(c) below.

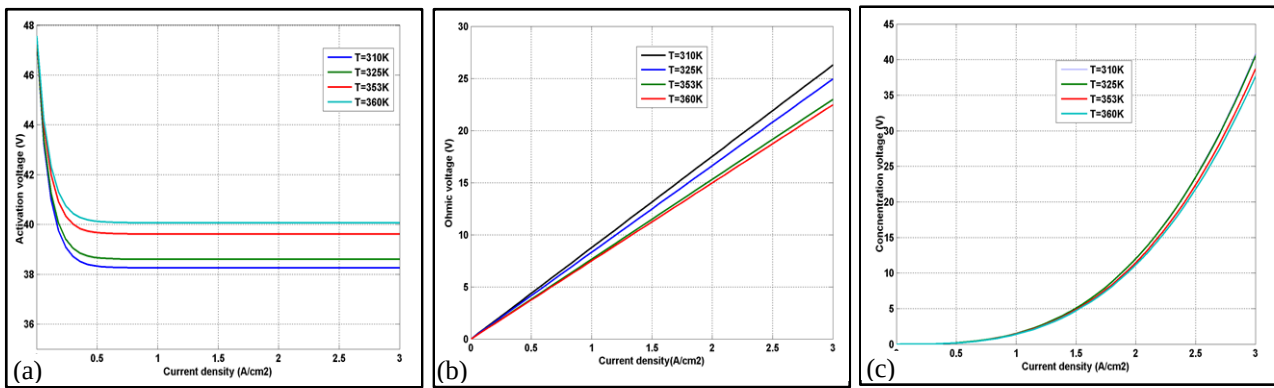


Figure III.17 a) Activation, b) Ohmic and c) concentration voltage losses in PEMFC at different temperature.

III.10.2.2 Polarization curves depends on operating temperature

The effect of the operation temperature on the PEMFC performance was looked, in which were used five operating temperatures 310K, 325K, 353K, 360K and 373K. Figure III.18 (a) represented the polarization voltage curves under changing values of temperatures. From these results of simulation, it is clearly noted that the PEMFC is sensitive to variations of temperature, which drives to improvement its performance when recording an ascent in the temperatures. In addition, in the region of weak current densities ($<0.5\text{A/cm}^2$) the divergence between the performance curves at different cell temperatures are not considerable, activation voltage losses are dominated in this part adjusted directly on the non-linearity of voltage curves. In the second range, where higher current densities ($>0.5\text{A/cm}^2$), the divergence between the performance curves becomes more significant, which resulted from the effect of membrane ionic resistance. The PEMFC in this section also provides its maximum output power, which rises with the rise of the temperature. Therefore, if the PEMFC is operated at a temperature of 310 K, the maximum output power is 6129W; and it rises to 7000 W at a temperature of 353 K. From the results obtained, rising the operating temperature of the PEMFC has a positive effect on the output power, but within an appropriate working range.

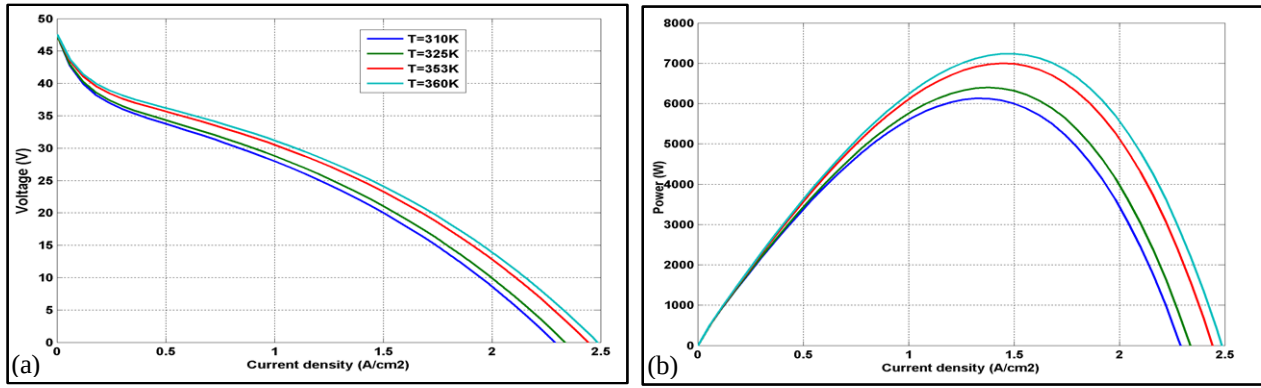


Figure III.18 PEM Fuel Cell: **a)** Voltage and **b)** Power curves under variation of temperature.

III.10.3 Effect of the operating water membrane content

The membrane, one of the main components of the PEMFC, has a fundamental part in its operation, when PEMFC begin deliver current to the load, the protons move through the membrane. The movement of this latter depends entirely on the hydration state of the membrane and more accurately the water content in the membrane. Therefore, with large water content this will leads in diminishing membrane resistance to the protons and then the PEMFC is acquired better performance [325, 326]. However, in some cases, membrane dryness occurs under certain operating conditions and load requirements, where dehydration will lead to decrease in proton conductivity and greater ohmic loss [395, 396].

We will look at this part, the impact of the change of MWC in the performance of the PEMFC, thus certain values choose of MWC (ϕ) getting between [7 10 14 18 23] will applied.

III.10.3.1 Effect of water membrane content on the ohmic losses

The MWC takes values between 0 to 23, which is equivalent to the relative humidity of 0 and 100%. The various curves of voltage ohmic losses are illustrated in figure III.20 according to different MWC. From this figure shows how with increase in the MWC will lead to decrease in voltage ohmic losses due to improve the traffic of protons. Finally, the water content is closely linked to the membrane resistance.

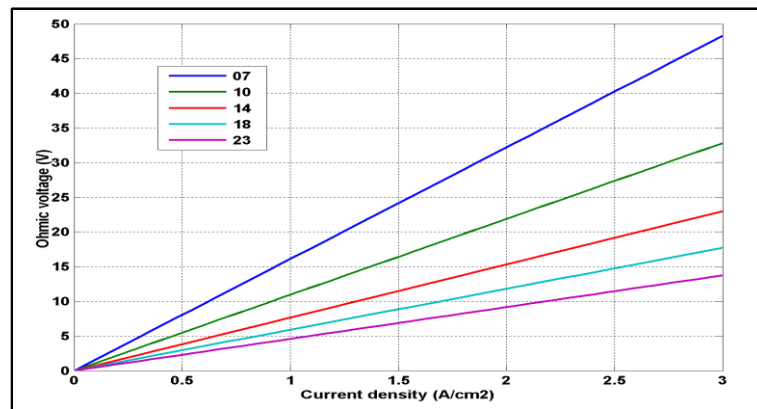


Figure III.19 Ohmic voltage losses in PEMFC at different MWC.

III.10.3.2 Polarization curves depends on operating membrane water content

Figure III.20 shows PEMFC performance at different MWC. As predictable, the PEMFC performance raises emphatically with increasing the MWC. Therefore, PEMFC voltage will be improved, at current density 1.5 A/cm^2 , the cell voltages are 10V with ($\phi = 07$), 18V with ($\phi = 10$), 23V with ($\phi = 14$) and 27V with ($\phi = 23$).

As can be seen from the same figure, the polarization curves of power are affected in the same way of voltage. In which, the raising of MWC will improve the maximum output power. When ($\phi = 07$), the maximum output power becomes 4415W; and it continues to take higher values 5778W, 7000W and 8458W with a raising values of MWC ($\phi = 10$), ($\phi = 14$) and ($\phi = 23$) respectively. Water management between the anode and cathode through membrane is crucial for gains more performances to PEMFC. Therefore, controlling water content inside membrane during the operating can operatively improve the optimal maximum output power of the PEMFC.

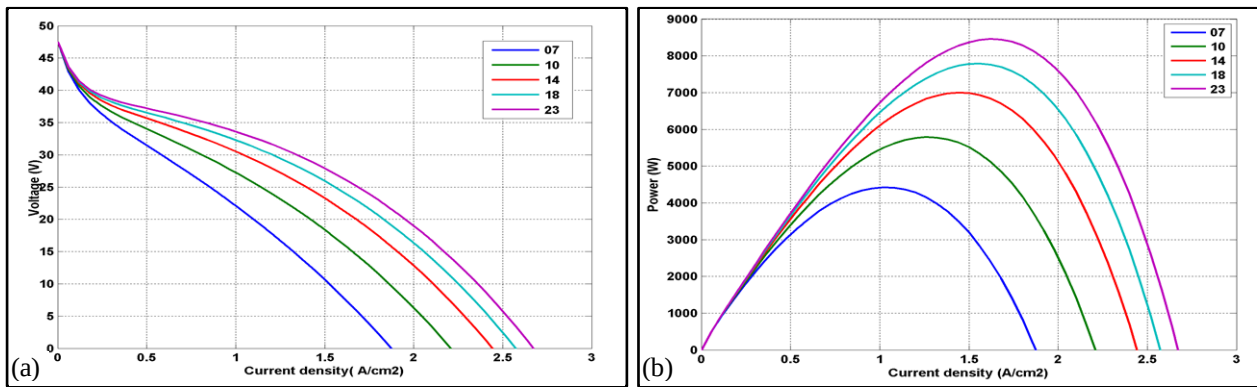


Figure III.20 PEM Fuel Cell: a) Voltage and b) Power curves under variation of MWC.

III.11 Conclusion

At present, the efficient exploitation of energy sources is a critical aspect of ensuring sustainable development and reducing the share of fossil fuels. This position motivated researchers to develop fuel cells. At the beginning of this chapter, we provided a brief history of the fuel cell and its stages of development since 1839. The different sorts of FCs were presented according to several criteria: the type of electrolyte, operating temperature, the nature of the fuel, power and efficiency ... etc. Next, an overview of the three applications: transportation, stationary and portable in which fuel cells are used.

Two sorts of FCs are widely employed. The first is SOFC, which operates at a high temperature, while the second sort is PEMFC, which operates at a low temperature. However, PEMFC technology continues to dominate the market especially in the field of transportation. For this, a large part of this chapter focuses on the PEMFC, and the most important points have been summarized as follows:

- Each component of the PEMFC like BP, GDL, CL and membrane represents a broad field of scientific research.
- Many phenomena interfere during the operation of the PEMFC, which makes its work is very complex, for example, water management. Where for best conduction protonic, the

hydration of the membrane must be excellent. On the other hand, excessive increase of liquid water may block gases from reaching reaction sites.

- The modeling of PEMFC resulted in writing non-linear equation of voltage. The polarization curve presents the voltage-current relationship as a function of the conditions of use such as operating temperature, pressure and MWC...etc. The voltage drop phenomena which cause the voltage to decrease when the current density increases mean that the fuel cell must be used outside the limit zones (very low or very high current densities). In general, the optimal point is chosen in the linear zone, which corresponds to the maximum output power.
- The performance of the PEMFC is affected by several operating conditions, the main of these are: operating pressure, operating temperature and MWC. The increasing of these parameters improves the performance of the PEMFC, especially in terms of the maximum output power. But, using the correct operating condition for each parameter is critical to obtain good PEMFC performance. Hence it is important to have the system operate at the maximum power point in order to get the maximum power from the PEMFC.

Chapter IV

Maximum Power Point Tracking: State of Art

IV.1 Introduction

Since the first publication of the Maximum Power Point Tracking (MPPT) command adapted to a photovoltaic energy source in January 1968 by A. F. Boehringer and up to this day several MPPT control algorithms to track the MPP have been studied, developed and published in the literature [327]. Even though these algorithms are proposed for the same purpose, they vary tremendously in many aspects such as simplicity, efficiency, steady-state oscillations, complexity, hardware implementation, tracking speed, accuracy, sensors requirement and cost [328]. Through these important factors each one can be make an informed decision on the right MPPT algorithms for practical uses. Moreover, the performance and effectiveness of each method differs from the other, and this determines by the operating conditions. We may find MPPT methods that have better performance under stable operating conditions. On the contrary, under rapidly changing operating conditions, these algorithms show low performance and thus unsatisfactory results. Many methods of MPPT have been advanced and implemented to extract the MPP from PV/PEMFC, in which each of these methods has its advantages and disadvantages. The principal errand of MPPT is to ensure that the MPP value is found quickly with minus oscillations and less response time and immense accuracy to improve power generation [329]. Below, we will present an overview about the MPPT in terms of classification and the various techniques of MPPT that applied in PV and PEMFC.

IV.2 Classification of MPPT

IV.2.1 Classification based on Modernity

In this part, the MPPT techniques are grouped on three families categorized on their modernity. The methods of MPPT that have emerged with the beginnings of exploiting the PV systems as stand-alone or grid-connected systems to excerpt the MPP are called conventional methods. This latter that use very simple algorithms. This latter that use very simple algorithms. Years later, the so-called soft computing methods emerged, that came to improve the flaws recorded in conventional methods, which require complex calculations but are distinguished by their accuracy. The third category included hybrid methods that combined the previous two methods. Figure IV.1 shows the different families of MPPT methods. Brief descriptions of these methods are presented in the next section [330-332].

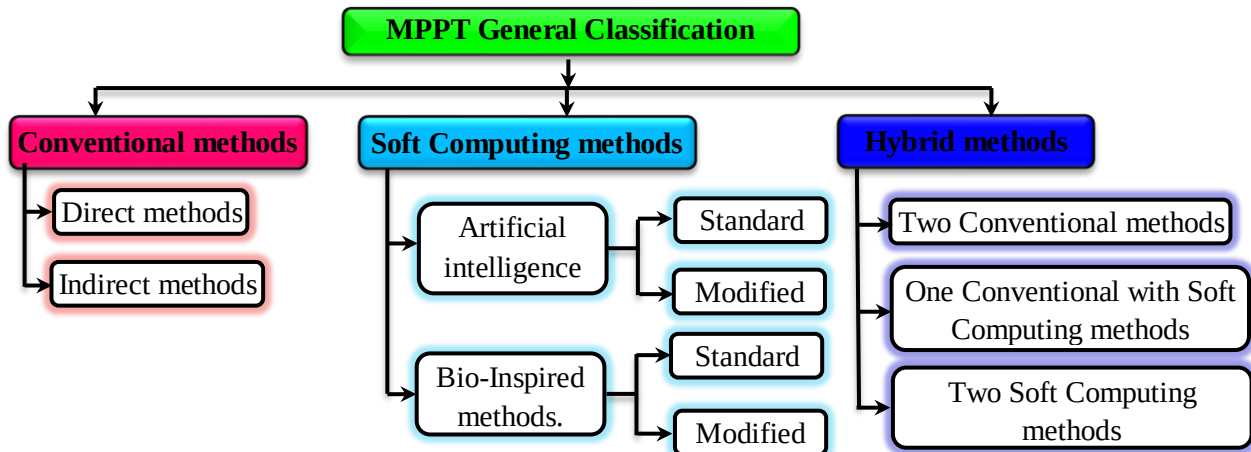


Figure IV.1 General MPPT methods classification.

IV.2.1.1 Conventional MPPT methods

Conventional MPPT methods are the first group that has been used since the first use of the MPPT algorithms, which includes the most popular techniques. The main advantages of these methods are relatively simple to implement on a digital controller and low cost [333]. Moreover, this sort of MPPT exhibits slothful convergence, languid tracking speed, some oscillations and low efficiency [333]. Therefore, under severe operating conditions, conventional methods need to be optimized to achieve better performance. Mostly, the traditional methods are divided into two groups, namely direct and indirect methods. The most MPPT algorithms used in direct methods can be summarized as: Perturbation and Observation (P&O), in addition to the Incremental Conductance (IC) [334]. Whereas, indirect methods include both Short-Circuit Current (SCC), Open-Circuit Voltage (OCV) and Constant Voltage (CV) [334].

IV.2.1.2 Soft Computing methods

As mentioned previously, the conventional MPPT methods under difficult operating conditions suffer from many drawbacks. Therefore, with the advancement of computing fields and the decrease of its cost in recent, Soft Computing (SC) methods have been introduced as an alternative solution for these issues. Moreover, SC methods are known for its many advantages, it can transact with complex non-linear systems; powerful performance, search speed and coherent skill to achieve optimal solution [335, 336]. Therefore, has captured the interest of researchers, many works have been registered on MPPT using SC with over 45 works published in various academic journals [337]. Artificial Intelligence (AI) methods and Bio-Inspired (BI) methods are two subcategories of the SC family. Among, the principal MPPT techniques that enter into this subcategory are: Fuzzy Logic Control (FLC) and Artificial Neural Network (ANN) [338]. While, the most commonly used BI MPPT methods are Particle Swarm Optimization algorithm (PSO), Grey Wolf Optimization (GWO), Cuckoo Search Optimization (CSO) and Genetic Algorithm (GA) [339].

IV.2.1.3 Hybrid methods

In hybrid methods that includes a three families resulting from combining two individual MPPT techniques either between: two Conventional methods, two Soft Computing methods or from two different groups; viz one Conventional and the other from Soft Computing methods. This category is introduced to overcome the incompetence of a few individual MPPT methods to give a powerful tracking performance through targeting the overall benefits of every individual MPPT technique with disposing of their downsides. Several hybrid techniques of MPPT published and discussed in different literatures, among these: P&O with IC [340], P&O with FLC [341], P&O with PSO [342], P&O with ANN [343], and finally FLC with ANN [344]. The latter method showed many advantages such as lessening response time, lessening ripple ratio in the output power, powerful tracking of the MPP under operating conditions changes or converter load changes, and finally, growing the efficiency of the MPPT controller.

IV.2.2 Classification based on tracking mechanism

On the basis of this principle, the MPPT methods have been divided into five groups according to the literature. This number of categories is due to the difference in tracking principle from one

method to another in the MPPT algorithms used. These methods are classified based on: predefined fixed parameters, measurement and comparison with a pre-known MPP, trial and error or calculation and observe; mathematical calculation and intelligent prediction [345].

- **MPPT algorithms with constant parameters:** MPPT control with constant voltage, MPPT control with open-circuit voltage and MPPT control with short-circuit current are among methods that enter within this classification, in which these methods used predefined fixed parameters like: the open circuit voltage and short circuit current, maximum voltage and current that defined location of the MPP.
- **MPPT algorithms with measurement and comparison:** These algorithms mainly depend on measuring the parameters that characterize the system itself like voltage and current, in addition to some external parameters of operating conditions like sun radiations and temperature in the case of PV system and contrasting them with the previously known MPP. Among of the methods that uses the principle of this technique is Look-up table and Load current or load voltage maximization.
- **MPPT algorithms with trial and error:** These algorithms utilize a preliminary calculation and look at the result obtained later. This latter decides the direction criteria for calculation the next step in order to arrive at the MPP. In general, the P&O algorithm is the most widely utilized in this set, it relies on both a trial-and-error process to find and keep track of the MPP.
- **MPPT algorithms with mathematical calculation:** These algorithms are based on the mathematical computation of the various available equations that combine current, voltage, power and various other data in order to search MPP. IC based MPPT algorithm one of these techniques, in which based on the mathematical computation of the slope dP/dI or dP/dV of the power characteristic curve. Accordingly, MPP is found when the result of calculating dP/dI or dP/dV is zero.
- **MPPT algorithms with intelligent prediction:** These algorithms employ an intelligent learning process, in which that presents good convergence, high accuracy for determined the location of the MPP. FLC and ANN are considered among several MPPT found within a smart tracking techniques.

IV.3 Overview of the various MPPT algorithms for photovoltaic

Presently, we find the use of PV plants categorized into two categories, either stand-alone or grid-connected. MPPT techniques have been sophisticated by researchers because of its multiple pros in terms of improving power cost and performance, by providing maximum power under changing operating conditions. What highlights the importance of this technique in the field of PV system is the rapid growth in the total number of publications in the last decade, where it was estimated in tens of thousands for the most important publishing houses such as Elsevier and IEEE [346]. Therefore assorting and summarizing the MPPT methods applied for PV systems is very substantial for research. To date, more than 60 algorithms of MPPT have been accounted in published works, all of them applied to the PV systems to extract the MPP [329, 347]. In actuality, every MPPT has its own particularizations, constraints and implementations. In literature, the prevalent MPPT methods used are:

IV.3.1 Perturbation and Observation algorithm (P&O)

Because of its clarity, ease of execution and low cost, the P&O method is considered as one the most popular methods, available in commercial products and it is also an essential portion of the more advanced algorithms offered in the papers [348, 349]. For these reasons, P&O has been considered by a number of researchers, among these:

P&O technique has been broadly carried out with sundry techniques and power converters. The experimental work presented in paper [350], aims to authenticate the performance of both the P&O suggested and also the snubber circuit. Where, the P&O implemented on real time using single-chip microcontroller 80C51, and the snubber circuit introduced to improve the boost converter efficiency through minimization switching losses, therefore increase the amount of power transferred to the resistance load. The experimental results accomplished show with utilization P&O algorithm and the snubber circuit in the PV system, both operate to increase the amount energy transferred to the load, where the suggested MPPT improved the transfer of power from the PV panels to the considered load by about 45%, and the utilize of the snubber circuit raised the efficiency of the power converter by about 4%.

In this paper [351], using FPGA circuit to execute the P&O method based MPPT of a real time for the sake of tracking the MPP. The architecture of system includes four main blocks as follow: Current/voltage measurements of the PV module, Boost converter, Analog to digital converter, a control instrument (P&O MPPT) applied on the FPGA. Where the total financial value of most of these devices prepared for this work was estimated at 30\$. The performance of the MPPT suggested was tested for various level of sun radiation, and for two perturbations step 0.4 and 0.5. The results showed that when a perturbation step of 0.5 is applied, the PV system converges to the MPP value quickly (0.1736 ms), while it slows down to take a time (0.2198 ms) to reach the MPP when a perturbation step of 0.4 is applied. On the contrary, when observed to the state of power oscillations and the efficiency of the MPPT algorithm for both perturbation steps, in which the efficiency reached at 96.13% for the 0.4 perturbation step and 95.23% for the 0.5 perturbation step.

In this paper [352], the authors aim to study how to increase the efficiency of energy conversion from source towards load considered by using a soft-switching boost converter instead of traditional boost converter in PV system. The authors have presented the various practical modes of the considered converter, and we employed P&O algorithm to deliver the duty cycle required. Moreover, simulation under Matlab/Simulink and experimental results for this system was verified under operating conditions 900 W/m² and 25°C for the sun radiation and temperature respectively. The experimental results showed that 4% is the percentage of improvement in the overall system performance as a result of using the considered converter, the output voltage is 194.3 V and current is 3.6 A. In addition, the MPP value reached at 700 W with low oscillation and good convergence speed.

Finally, from these papers and other works, the method has made some gains, but it suffers some drawbacks. The table IV.1 shows pros and cons of this method.

Table IV.1 Pros and Cons of P&O.

Ref.	Pros	Cons
[336, 341, 342]	• Simple structure. • Simple implementation. • Few control parameters required. • Acceptable accuracy and performance without Partial Shading.	• The controlling of perturbation size is hard. • Low precision. • Slow dynamic response. • Oscillations around MPP.

IV.3.2 Incremental Conductance algorithm (IC)

Like the P&O algorithm, the IC-based MPPT algorithm has been tested on a wide range of PV patterns. Where, this sort of MPPT ways is treated as effective technique to track mightily the MPP under rapidly varying conditions. Somewhat, IC-based MPPT is more refined contrasted with P&O-based MPPT. However, because of the progression of digital signal processors, it is easy to implement. Many works have been done about this technique among them:

A hardware implementation of MPPT either on microcontroller, FPGA, DSP or by using Arduino devices. The work presented by the authors in paper [353], is the implementation of IC algorithm based MPPT for a PV system using Arduino board. Where, this latter is utilized as the connection part between the PV system, the Simulink control model and load. This implementation requires four parts are: PV source, power converter, Arduino uno board and load. Through the outcomes obtained of simulation/Implementation, it showed that this sort of MPPT can achieve lower oscillations around the MPP, minimize transmitted energy losses and improving the efficiency to ensure the perfect employ of source.

Stand-alone PV pumping units have turned into a suitable resolve for water provide. The use of the MPPT algorithm allows improving the energy utilization efficiency for PV pumping systems. This topic has been studied in paper [354], in which presents a comprehensive analysis and experimental evaluation of the tracking algorithms for a standalone PV pumping unit by adopting the both ways: increment conductance (IC) and constant voltage (CV). This study is based on utilizing MATLAB software and dSpace DS1104 to execute the both algorithms. The results showed the successful implementation of a stand-alone PV unit for water pumping operation. As for the insertion of MPPT, this has increased the energy efficiency of PV generator, in which the MPP was obtained under various climatic conditions of sun radiation levels and temperatures. Still, the methodology and the stability of the MPP are not accomplished within the same level, where the IC- based MPPT is more suitable, low oscillations, high accuracy and presents good efficiency for rapid changes of operating conditions. Therefore, the IC-based MPPT had good effect on the whole water pumping system.

Generally, the traditional IC-based MPPT can be established with perturbation methodology to raise or decrease the reference current or voltage through power stage DC/DC converter duty cycle, so the whole system operate in closed loop. On the other hand, it can be established with perturbation methodology adjusted directly to the duty cycle, so the whole system operates in open loop. In paper [355], the authors proposed a discussion of IC-based MPPT algorithm with reference voltage perturbation and comparing it in the same technique with duty cycle perturbation. The principal contrast of these two techniques is that the reference voltage perturbation way

incorporates a PI control system loop. While in the second method, the control loop is dispensed and the perturbation step alteration is adjusted straightforwardly through the IC algorithm. Results show the better performance of the reference voltage perturbation method, in which exhibits a momentous devaluation at the MPP in terms of oscillations, and wonderful tracking beneath the variation of sun radiation.

Table IV.2 shows the main pros and cons of the IC-based MPPT technique:

Table IV.2 Pros and Cons of IC.

Ref.	Pros	Cons
[336, 343-345]	• Oscillations around MPP are depressed. • More accurate. • Reliable and efficient. • Good tracking efficiency. • Response acceptable.	• It takes more time to compute MPP. • Speed and accuracy to achieve MPP depends on step size. • Response time is longer under partial shading.

IV.3.3 Variable Step Size P&O and INC MPPT Algorithms

Generally, the well-known P&O and IC control techniques are applied with fixed step-size to adjust the duty cycle of the PV-interfacing boost converter. The step dimension of P&O/IC-based MPPT decides how performance can be possible in terms of response speed and the oscillation around MPP. Indeed, the output power resulting through PV module with a big step size has a fast response to achieve the MPP, but in return the output power does not kept exactly constant in the vicinity of the MPP and lurch about itself; consequently, this leads to a decrease in efficiency [356]. On the other hand, the inverse happens while the MPPT is operating with a smaller step size [356]. Hence, a compromise between the lurch and response speed has to be done for MPPT with fixed step size (Fss). In order to overcome the drawbacks of the Fss algorithm, a variable step size (Vss) MPPT algorithm has been recommended, in which operates with a Vss, where the duty cycle is adjusted directly with large step size when distant from the MPPT point and with slight step size about the MPPT point [357]. The subject of Vss based MPPT algorithm was discussed in the literature. The performance of Vss P&O and IC MPPT algorithm is evaluated in both papers [358, 359]. The simulation results clearly show that, this method has the competence to optimize both the speed and accuracy simultaneously of the PV power system; it also gives good results under rapidly changes in conditions climatic. Furthermore, it is straightforward and can be effectively implemented with low cost in microcontroller, FPGA, DSP and Arduino.

IV.3.4 Fuzzy Logic Control (FLC)

Over the last decade, FLC has been frequently used to track maximum power from the PV system, especially with existing powerful computing for microprocessors. Trackers established on this technique are viewed as intelligent, because they follow the MPP regardless of whether the data sources are imprecise. In addition, the FLC does not need any technical knowledge for the mathematical model. However, the designer should know some advance information about how the system reacts qualitatively to the inputs. For FLC-based MPPT, it needs two inputs, the error and its change; it has been frequently used for MPPT in several papers:

In paper [360], the authors presented two methods of control: P&O and FLC. The two of them were implemented on a system of energy conversion composed of PV-Boost converter-electric load. The simulation results were compared between the MPPTs suggested, through exposing the whole system to similar environmental working circumstances. The productivity of the entire system has been improved by demeaning the power losses when using FLC under frequently changing of the irradiance level. Therefore, the FLC based MPPT has an excellent performance. It diminishes the dynamic responses as well as removes the oscillations about the MPP. The goodness of the results obtained shows the effectiveness of the proposed FLC method in terms of finding a compromise between the convergence speed in dynamic response and stability in steady-state.

In paper [361], the conduct of the FLC based MPPT is evaluated in the case of isolated PV system under different operational circumstances, like changes in weather conditions and load. The system includes a 110-watt PV power supply, battery bank of lead-acid, two power DC/DC converters and an electric load. Two tasks can be completed by these converters; the first boost converter is used to extract the MP from the PV source, while the second converter is employed to guarantee continuous power supply to the electric load through battery bank in the event of a shortage of the PV source. The simulation outcomes achieved show the feasibility of FLC-based MPPT. The experimental results show the robustness of the FLC method when compared with P&O for the same operating conditions. In which, the PV module is constantly working at the MPP with quick and accurate tracking no matter what changes in climatic conditions and this indicates the elasticity of FLC.

In paper [362], shows the analysis, design, simulation and hardware implementation of the conventional FLC and the proposed FLC sort II based MPPT for isolated PV system. Under different climatic conditions, the results obtained from simulation via MATLAB/ Simulink and experimental are compared to the IC based MPPT. FLC sort II is the best MPPT technique, where the value of the efficiency from experimental result reached at 95.4%, other than conventional FLC and IC, where the efficiency obtained are 94.14% and 90.14% respectively. In addition, it presents top performance and ensures a perfect tracking of MPP with a fast dynamic response; it shows great effectiveness during weather fluctuations.

Table below shows the main pros and cons of the FLC-based MPPT technique:

Table IV.3 Pros and Cons of FLC.

Ref.	Pros	Cons
[336]	• Less oscillation and significantly during changing climatic conditions. • Highly robust and accuracy, quick response, better dynamic and steady-state performance. • Doesn't require an exact mathematical model of the system. • It gives good efficacy when combined with other techniques.	• Implementation is complex and expensive. • Rules cannot be varied during the operating. • The performance quality of the PV system is related to the accuracy of the selection of the rules.

IV.3.4.1 Fuzzy Logic description

FLC has extensive variety of utilizations in environmentally friendly power applications. FLC depends on a mathematical paradigm that arrangement with uncertainty and imprecision, disarray, commotion or shortage of inputs information data [336]. It compares two inputs, the error input as analog signal with change in error, which coincides to values between 0 and 1. Fuzzy logic aims to model thinking or imitating human-like decisions in vague or absolutely undefined terms in order to apply it in a control system [336].

The primary function of a FLC is to provide relationships between the input and output in terms of fuzzy rules and convert it into a fuzzy amount that the system can recognize. The process of FLC includes four stages in real-time. These different stages of FLC and its general structure are presented in figure IV.2 [360].

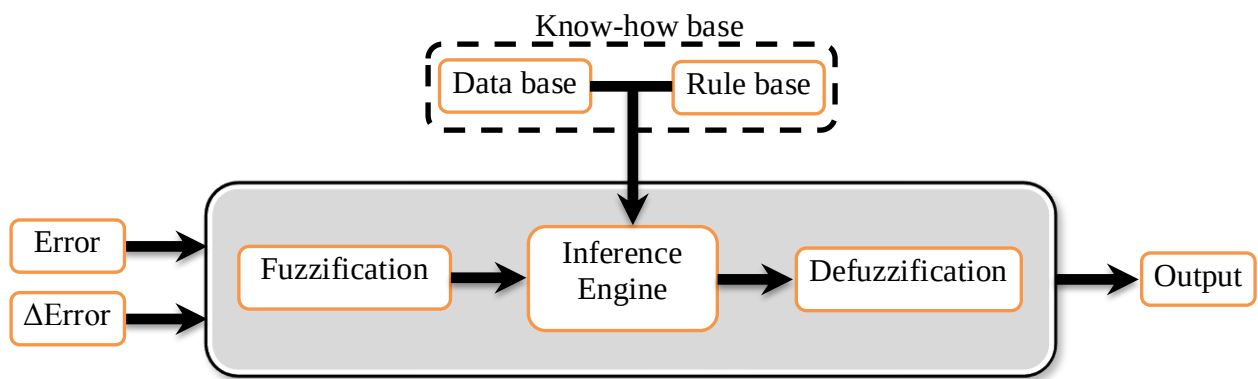


Figure IV.2 General block diagram of a FLC.

The characteristics of each of the blocks constituting the general structure of a fuzzy controller are presented, namely [360-362]:

IV.3.4.1.1 Fuzzy know-how base

The fuzzy know-how base is one of the essential, if we did not say is the fundamental, part of the fuzzy control system. The fuzzy know-how base includes the both data base as well as rule base in the structure of FLC. It stores the necessary knowledge about all the error/change of error and the output fuzzy relationship functions. It also has the membership function which defines the input variables to the fuzzy rule base and the output variables to the plant under control.

IV.3.4.1.2 Fuzzy inference engine

The fuzzy Inference engine is considered as the heart of FLC system, it is eligible to formulate the decision-making from a given input by the human being based on the fuzzy concepts and the rules of inference in FL. In this part of the regulator, the values of the input and output linguistic variables are linked by several rules as well as adjustment goals envisaged in particular. The adjustment circuit must be stable and well damped. The adjustment strategy depends essentially on the inferences adopted. It is not possible to give precise rules; experience plays an important role here. To express the inferences, there are several possibilities namely by linguistic and symbolic description, as well as by table and matrices of inference.

IV.3.4.1.3 Fuzzy fuzzification

Fuzzification stage process is a delicate phase, that represents the transition from the input data received from sensor measurements at form of real (or physical) grandeurs such as change in the power, voltage or current into fuzzy values. Therefore, to achieve this process, membership function must be primary determined for all inputs. The fuzzification is often done iteratively and requires experience. When the membership functions are determined, fuzzification process works taking a real time set inputs and compares it with the stored membership function information to deliver FL input value.

IV.3.4.1.4 Fuzzy defuzzification

The last step of the control, called defuzzification consists in defining precisely what should be the action on the process. Indeed, the process cannot interpret commands of the “Small” or “big” type, etc., it must be sent a physical value. Inference methods provide a resulting membership function for the output variable. The defuzzification operation makes it possible to calculate from the latter the real value of the output variable to be applied to the process. It is often necessary to provide an output signal processing and its digital-analog conversion. The choice of a defuzzification method is a very delicate point when developing a control technique in fuzzy logic. This will in fact greatly condition the dynamic evolution of the control. There are three different methods: that of the maximum, that of the average of the maxima and that of the center of gravity. However, it is recognized that the center of gravity method gives the best results.

IV.3.5 Artificial neural network (ANN)

ANN is technique inspired from the way of behaving of neurons. Where appears as one of the SC MPPT methods, its applications have been increasing in several fields because that has the ability to solve nonlinear problems. For this reason, this technique has been employed for PV systems in several areas like: identification parameters, improve sizing, structure optimization of PV system and MPPT techniques. Among the research mentioned in ANN based MPPT for PV system are:

In paper [363], authors discuss two SC techniques are ANN and FLC, concerning their effectiveness to fulfill the MP transferred to the electric load. Both methods are implemented and their performance is analyzed and tested under variable irradiation conditions. Through simulation results it is shown that both methods have the ability to track the MPP effectively, but in terms the response and the level of oscillation around MPP, the ANN has better performance in both of them compared to FLC method.

In paper [364], to increase the efficiency the whole PV system, authors proposed new solar cell structure based on Multi-junction cells because characterized by its high efficiency and is currently known for its utilizes in aerospace applications, while ANN has been introduced as MPPT technique. The whole PV system with ANN-based MPPT is implemented in MATLAB software. The results of simulation disclose quality of use the ANN based MPPT, as it actually further promotes tracking speed and increments daily yield power from 3.37 kWh to 3.75 kWh for each PV

module. Therefore, the increasing in the output power reflects the superiority of the suggested technique contrasted with P&O technique.

In the paper [365], the authors developed a new MPPT control technique for PV system employing a DC/DC buck converter to extract the maximum available power. This new technique is called as a novel direct adaptive neural control (DANC). The DANC strategy works on MPP and aims to optimize the efficiency of the energy transferred from PV source to the electric load. The online adaptation procedure is based on learning law of the delta rule where only the system output error is required. The simulation results affirm the viability and effectiveness of the suggested DANC method in both cases of steady-state and dynamic response under climatic conditions variations. The MPP value is captured extremely quickly with very low fluctuations in the steady state; In addition, the DCNA technique gives an extremely short time response in the transient states. The outcomes likewise show a striking enhancement of dynamic performance of the suggested technique contrasted with the P&O-based MPPT.

Table below show the main Pros and Cons of the ANN-based MPPT technique:

Table IV.4 Pros and Cons of ANN.

Ref.	Pros	Cons
[336]	• Swift tracking with appropriate exactitude. • Fewer lurches, forceful with good efficiency in varying operating condition. • Can be trained offline and employed in the online environment.	• Intricate and expensive to implement. • Needed wide data around PV parameters. • High cost of temperature and sun radiation sensors.

IV.3.5.1 Artificial neural network description

Artificial neural networks are a fundamentally new approach to information processing. They are parallel, adaptive and distributed systems whose functioning mimics that of biological neural networks while reproducing their basic characteristics [338]:

- Knowledge is acquired by the network through a learning process.
- Connections between neurons, called synaptic weights, are used to store knowledge.

Structurally, a neural network is a number of simple processing units called formal or artificial neurons. The latter are interconnected so as to produce the response corresponding to the inputs received by the network. Several models of artificial neurons have been developed, inspired by the operating principle of the biological neuron which essentially provides the following functions [338]:

- Reception of signals from neighboring neurons.
- Integration of these signals.
- Generation of a response.
- Transmission of it to other neurons.

IV.3.5.1.1 Basic structure model

The first model of the formal neuron dates from the 1940s. It was presented by McCulloch and Pitts. Inspired by their work on biological neurons, they proposed the following model [343]:

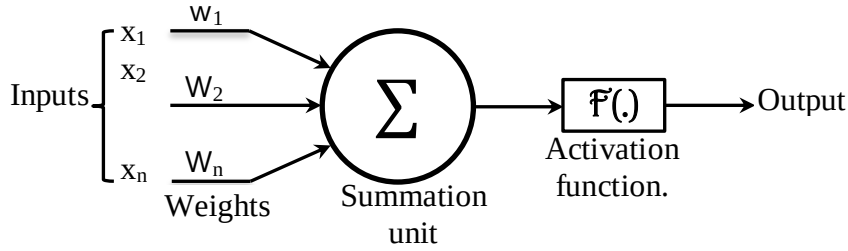


Figure IV.3 The formal neuron.

A formal neuron is a non-linear and bounded algebraic function, whose value depends on parameters called connection weights. More generally, a formal neuron is a processing element with multiple inputs and a single output.

IV.3.5.1.2 Activation function

The activation functions generally represent certain forms of nonlinearity. One of the simplest forms of nonlinearity, and which is appropriate for discrete networks, is the sign function, figure IV.4.a. Another variant of this type of nonlinearity is the Heaviside function, figure IV.4.b. For the majority of learning algorithms it is necessary to use differentiable sigmoid functions, such as the unipolar sigmoid function, figure IV.4.c and the bipolar sigmoid function, figure IV.4.d. The most used class of activation functions in the field of modeling and control of nonlinear systems is the bipolar sigmoid function [343].

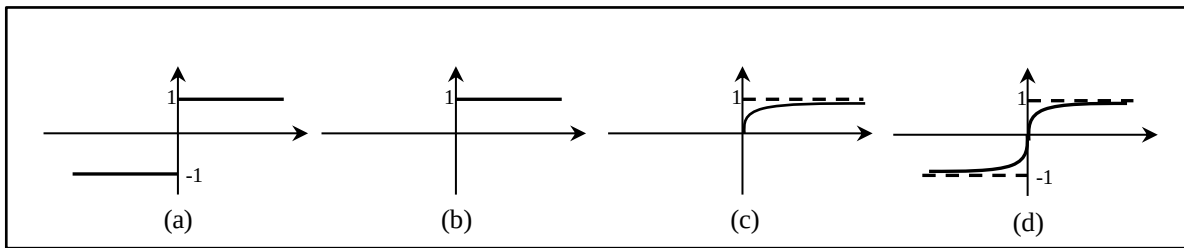


Figure IV.4 Different activation functions.

So a neural network is a set of information processing elements, with a specific topology of interconnections between these elements and a learning law to adapt the connection weights, it is characterized by a very fine gain parallelism and high connectivity. By this we mean that in a given neural network, the information is processed by a large number of very simple elementary processors, each one being linked to other processes. This very simple process is a formal neuron, so its operation is inspired by the modeling of biological cells. They are endowed with two important properties which are at the origin of their practical interest in very diverse fields [344]:

- Ability to adapt or learn which allows the network to take into account new constraints or new data from the outside world.

- Generalization capacity which is his ability to give a satisfactory answer to an input that is not part of the examples from which he learned.

IV.3.5.1.3 Training neural networks

The information that a neural network can acquire is represented in the weights of the connections between the neurons. Learning therefore consists of adjusting these weights in such a way that the network exhibits certain desired behaviors. In other words, training neural networks consists of adjusting the weights in such a way that the outputs of the network are as close as possible to the desired outputs. There are two types of learning [363]:

- **Supervised training:** for which we have the desired output and which consists in adjusting the synaptic weights in such a way as to minimize the difference between the desired output and the output of the network.
- **Unsupervised training:** for which the neural network itself organizes the inputs presented to it in such a way as to optimize a given performance criterion.

The supervised and unsupervised training schemes are shown in figure IV.5.a and IV.5.b respectively [364].

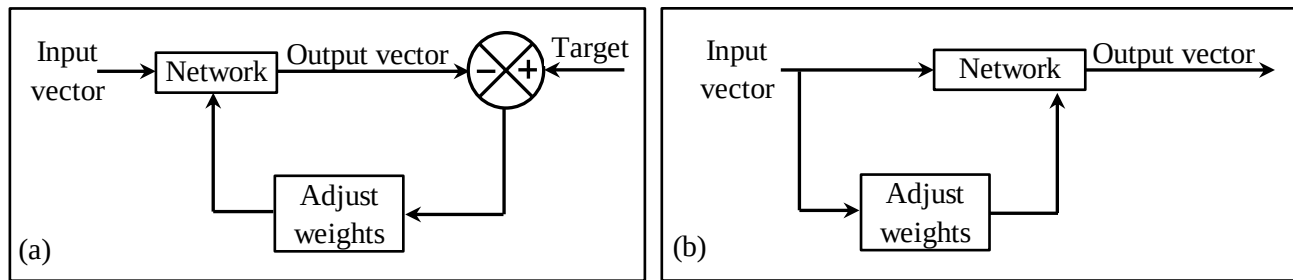


Figure IV.5 a) Supervised training scheme and b) Unsupervised training scheme.

Among several sorts of algorithms are mentioned in the literature like: backpropagation algorithm, Delta-bar-Delta, Quasi-Newton algorithm, conjugate gradient algorithm, Kohonen training that used to train the ANN, the Levenberg-Marquardt is the algorithm the most utilized due to its pros such as: robustness, provides rapid convergence and it is not mandatory for the user to configure any strange design parameters [364, 365].

IV.4 Overview of the various MPPT algorithms for PEMFC

The idea of extracting the maximum power from PEMFC has drawn the attention of researchers. In fact, the voltage produced from PEMFC during its operation affected by some operating parameters such as temperature, pressure, relative humidity and water membrane content. However, for constant operating conditions, there is only one unique point on Voltage-Current curve, which represents the MPP at which a PEMFC produces its maximum power. Therefore, when applied MPPT algorithm for PEMFC, the controller generates instructions for the DC/DC converter to extract the maximum power. The part underneath shows a review of a few studies on fuel cell MPPT:

In the paper [366], the authors study the idea of maximizing the output power of the PEMFC based on MPPT techniques, where the method is designed whose basic principle is to calculate the optimum value of the oxygen stoichiometry reference. The suggested MPPT shows that this method permits rising the outcome PEMFC power by more than 10%. Also, it permits the decline of the hydrogen consumption ratio, if the outcome PEMFC power is fixed and forced by the electric load.

In the paper [367], the authors suggested two methods of MPPT to extract the MPP from FC source, voltage-based MPPT and current-based MPPT. The suggested techniques have been implemented in Matlab/Simulink, and tested under different values of temperature. The results obtained achieve the desired goals in terms of dynamic response, steady-state oscillations as well as the precise tracking.

In the paper [368], the authors suggested new hybrid approach to extract the MPP from PEMFC power source that combined P&O technique to adjust duty cycle for a DC/DC buck converter with a fuel flow rate controller. Under various fuel flow rates, this hybrid technique has proven its high performance to achieve the MPP delivered from PEMFC. Moreover, through the obtained results, the application of this approach gave protection from the deterioration of the mechanical structure and membrane layer of the PEMFC by avoiding overheating and the phenomenon of water flooding.

In the paper [369], the authors employed 50 W/10 A fuel cell as power source, DC/DC boost converter and a dSPACE DS1104 board to implement the suggested MPPT technique. This latter, includes on two-loop cascade controllers, one outer and the other inner. The main purpose of using outer loop is to evaluate the real-time MPP point by employing the extremum seeking control; the estimated value of MPP by the outer loop is used as a set-point for hysteretic control for inner loop in order to oblige the FC work at the estimated MPP. In general, the results obtained are very satisfactory.

In the paper [370], the authors suggested an effectiveness method to extract the MPP based on sliding mode controller (SMC). This latter, it is utilized to adjust the duty cycle for power converter. The authors relied on evaluating this technique through comparing it with P&O-based MPPT under various operating conditions like membrane water content and temperature variations. The results of the comparison show the superiority of the proposed algorithm from several aspects, and one of the most important advantages mentioned is the speed of access to MPP in a fast time and with low tracking error. While, the SMC-based MPPT is characterized by its simplicity and low implementation cost.

In the paper [371], the authors address two main ideas concerned with the FC system, the first is to use energetic macroscopic representation, and the second is to create the MPPT algorithm for strategic management of low speed vehicle and to extract the MPP, respectively. The suggested approach highlights the energy gain with the knowledge of the MP obtainable online by controlling a power interface to tardy down the discharge of battery bank. The employed MPPT technique drives to an raise of the FC output power about 10%.

In the paper [372], the authors employed Matlab software to implement SMC-based MPPT to adjust the power boost converter duty cycle. The purpose of this work is to verify the robustness of

SMC to achieve MPPT under changing working conditions. The suggested way giving the quickest convergence with high accuracy under the three various operational conditions: temperature, membrane water content and electric load variation.

In the paper [373], the authors suggested one of the SC methods for tracking maximum power point of a fuel cell source. This sort of SC is the fuzzy logic controller (FLC) based MPPT. Under severe working conditions, the FLC-based MPPT algorithm has been tested with the help of Matlab/Simulink software. The reported results show that the system efficiency has improved as a result of using the proposed fuzzy logic MPPT controller, increasing from 35% to 55%.

In the paper [374], the authors chose among soft computing methods in order to track the maximum output power from PEMFC source by the driving the duty cycle of the chopper DC/DC converter, the PSO based MPPT algorithm. In addition, some sorts of PSO algorithms are introduced in this paper, which include : simple PSO, quantum inspired PSO (QPSO), improved PSO (IPSO), vector evaluated PSO (VEPSO) and PSO with time varying acceleration coefficients (PSOTVAC), which used for the same purpose to track the MPP. Finally, from the curves that shown the comparative outcomes between the all suggested algorithms and the traditional P&O-based MPPT; The suggested techniques demonstrated good performances. However, among the suggested algorithms of PSO-based MPPT, the both algorithms traditional PSO and PSOTVAC presented fast response time and accurate response respectively.

In the paper [375], the authors aim to keep the PEMFC works at the MPP with rational use of hydrogen consumption under different operating conditions by combining two techniques. The first technique called as quadratic polynomial fitting (QPF) that employed to approximate the output power density curve and to estimate the maximum power efficiency point. While, the second technique called improved generalized predictive control (GPC), used for tracking the changing set-points. The outcomes obtained when applying the suggested strategy show the achievement of the desired goals with satisfactory performance to track the MPP and efficient use of hydrogen energy.

In the paper [376], the authors suggested powerful MPPT method to track the MPP of PEMFC power source, this MPPT called eagle strategy (ES). This latter, it compared with P&O and FLC MPPT algorithms utilizing Matlab/Simulink software. Through the outcomes obtained, the ES-based MPPT algorithm surpasses the both techniques of P&O and FLC MPPTs in terms of the speed and accuracy of MPP tracking under various operating conditions adopted.

In the paper [377], in order to improve and make the FC output power stagger very little at the point of maximum power point, the authors suggested an MPPT based on extension sliding mode controller to achieve these purposes [378]. This work has been implemented using experimental platform includes a 200 W PEMFC. The obtained results prove that this technique has a tracking speed of MPPT value of 0.95 seconds in addition to a high conversion efficiency of 94.5%, which enhances the performance of the system as a whole contrasted with traditional MPPT algorithms.

In the paper [379], incremental resistance based MPPT has been suggested using two approaches, one fixed and variable step size for PEMFC power source. On the other hand, the authors employed a simple static PSIM model of PEM fuel cell. The both suggested methods to

extract the MPP from a PEMFC source producing 613 W at 50°C and 1.5 atm considering various operating condition confirm the powerful of the MPPTs to achieve of their desired goals in terms of enhancing tracking speed and reducing steady-state oscillations.

In the paper [380], the authors proposed a new MPPT technique called water cycle algorithm (WCA) that utilized current FC, temperature and water membrane content as inputs to calculate the reference voltage as output that corresponds to the MPP of FC. This voltage is employed as input of the PID controller in order to adjust the DC/DC power converter duty cycle. To show how effective this technique, it has been compared with three traditional MPPT algorithms: P&O-based MPPT, voltage and current based MPPT. Gotten results demonstrate that the suggested MPPT algorithm has a high reliability; accuracy and a quick dynamic response time on the contrary with the performance of the others three MPPTs.

In the paper [381], the authors aim to diminish the hydrogen consumption consumed by PEMFC source through suggesting a control system includes three subsystems, linear quadratic regulator controller, a Kalman filter/estimator and a P&O-based MPPT in order to determine the optimal value of the oxygen excess ratio. The suggested P&O-based MPPT method gave procedure that satisfies the required total power supply by the electric load with lower hydrogen consumption under any operating circumstance. The authors note in their paper that the P&O algorithm has a drawback of small oscillation around the MPP, which causes a slight drift from the optimal operating point.

In the paper [382], the authors show hybrid system composed of FC/wind with novel unified MPPT method. This latter, it utilized to track the MPPs of the both renewable energy sources of FC and wind. This hybrid system is constructed experimentally in laboratory to supply the load considered. Gotten results show the robustness and reliability of the proposed MPPT algorithm in achieving high conversion efficiency for both sources FC stack and wind, which reached at 99.41% and 99.28%, respectively. In addition, this technique achieved a convergence time of 15 ms, which is considered a basic reference as the shortest convergence time that can be achieved compared to the rest of the techniques, whether traditional or modern.

In the paper [383], the authors utilized a similar way to develop a unified MPPT algorithm for HRES includes two sources PV/FC. Experimentally applying this technique made it possible to obtain a conversion efficiency of 99.60% for the PV system and 99.41% for the FC system, and a good convergence time to reach MPP, which were 12 ms for the PV system and 33 ms for the FC system. Thus, this approach shows its high efficiency in power conversion to the load with almost the shortest convergence time compared to other modern MPPT algorithms.

In the paper [384], the authors suggested the second SMC-based MPPT approach known as super-twisting algorithm in order to extract the MPP produced from the PEMFC source with reliable performance under electric load variations, disturbances and strict chemical reactions. The main purpose of this technique is to improve the classical SMC-based MPPT approach in terms of reduction the chattering phenomenon. The outcomes obtained show net benefits contrasted with the traditional SMC-based MPPT; it has high reliability, accuracy, robust dynamic against electric load varieties.

In paper [385], the authors aim to provide a model a Fractional Order High Pass Filter (FO-HPF) MPPT based on the Extremum Seeking Control (ESC), so as to develop the performance and reliability for the better under unstable operating conditions. The idea of the suggested algorithm lies in the substitution of the ordinary high pass filter in the original extremum seeking control system by employing integer order integrator and low pass filter together with fractional order high pass filter. Gotten results show in the presence of disturbances a strong performance and achievement the required specifications.

In paper [386], the authors suggested a Vss IC-based MPPT algorithm for the green energy source PEMFC. The whole system is realized by employing Matlab/Simulink software, in which composed of 7 kW PEMFC source, power boost converter to feed the electric load. The results obtained under pressure and temperature variations demonstrate the efficiency of the suggested method compared to the Fss IC-based MPPT with regard to the response time, overshoot and lurch about MPP prompting a general amelioration of the output MPP.

In the paper [378], the authors suggested three approaches for power tracking of PEMFC source, which take account the oxygen starvation and system efficiency. Due to the variation between the slow air mass flow rate dynamics control variables and rapid load current, a cascade control structure has been resorted. This structure includes two blocs; the first also includes two loops outer and inner that utilizes to track the maximum power demand and to regulate the air mass flow rate respectively. While, the second bloc aims to realize rapid response and the stable error by using feed forward-feedback composite control. From the results obtained under two scenarios for tracking power and PEMFC degradation, the suggested methods allow to extend the life of the PEMFC, improve its performance while keeping the excess oxygen content constant during the short life of the PEMFC, thus maximizing system efficiency.

In paper [388], the authors suggested one of the soft computing techniques called particle swarm optimization (PSO) and proportional integral derivative (PID) controller in order to extract the MPP from the PEMFC power source. The suggested PSO-PID based MPPT method has been tuning the boost power converter duty cycle in order to kept the output power of the PEMFC at the maximum. The authors made a comparison between the suggested technique i.e. PSO-PID based MPPT with the P&O as well as the SMC-based MPPTs in the presence of various operating conditions. The outcomes obtained prove the high performance of the suggested PSO-PID based MPPT compared to the others MPPTs regarding to the rapidity of the convergence, high reliability and ultra-low output power oscillation around MPP.

In paper [389], the authors suggested four MPPT techniques to guarantee a high efficiency conversion from PEMFC power source to the electric load. These MPPT techniques are: traditional Fss IC, Vss IC, the FLC auto-scaled Vss IC and the suggested method Vss fuzzy based MPPT algorithms. A comparative study has been made to show the better performance between them using Matlab/Simulink software under temperature variations in term of dynamic, static and efficiency performances. From results obtained the suggested method Vss fuzzy based MPPT outperforms the other three MPPTs; it reduces response time, overshoot, ripple and improving efficiency conversion.

In paper [390], the authors aim to make the PEMFC source permanently functioning at maximum power point by using a new MPPT controller. The suggested MPPT controller includes two parts, the current reference estimator and the backstepping technique. The current reference estimator uses current and voltage as input to compute the reference current. This latter, it uses by the backstepping technique with measured current in order to adjust the duty cycle to drive the boost converter feeding the electric load. The whole system has been implemented utilizing Matlab/Simulink software to compare the suggested technique with PI controller. From simulation tests, it can be seen the backstepping technique outperforms the PI controller in numerous points, it displays quick convergence, very lower overshoot, quick stability time, high control fineness and good react in the case of sudden disturbances.

In paper [391], the authors implemented a new MPPT control architecture by using Matlab/Simulink environment. The suggested MPPT contains two-level architecture. The first architecture includes the technique of perturbation-based extremum seeking (PES), which uses to calculate the duty cycle to drive boost power converter powering the electric load in the steady state. While, the second architecture contains model reference adaptive control implemented to obtain the required dynamic response of the system. The results presented in this paper show comparative studies between two controllers, the suggested MPPT and the combination of PES-PID controller, it can be seen the MPPT technique proposed outperforms under both scenarios of PEMFC parameters and load variations in order to track the maximum power.

In paper [392], the authors presented HRES includes a three renewable energy sources are PV, FC and wind to give maximum power at DC-link. The suggested HRES utilizes a FLC-based MPPT algorithm to extract the MPP from each source to improve HRES and make it highly reliable. Gotten results using three resistance loads (Load1 = 15 Ω , Load2 = 25 Ω and Load3 = 35 Ω) show an amelioration of the output power from FC source around 28.61%, 33.18% and 24.45%, respectively, compared to uncontrollable output power of the fuel cell subsystem.

In paper [393, 394], the authors presented one of the soft computing method called NN-based MPPT for the grid connected PEMFC system based on the radial basis function network algorithm. The main idea of this work revolves about the application of the NN-based MPPT to adjust the duty cycle of the new converter named interleaved boost converter instead of using the normal boost converter due to its ability to reduce the PEMFC current ripples. The system PEMFC grid connected has been implemented and simulated using Matlab/Simulink software under sudden variations in PEMFC operating temperature. The results show that the suggested MPPT keeps the stability during these operating conditions by the injection of both active and reactive powers over a wide range of load conditions.

In paper [395], the authors suggested PID controller whose purpose is to extract MPP from FC power source. Generally, the main problem of the PID controller is determines the best gain parameters to give best results. Therefore, the authors proposed Sine Cosine Algorithm (SCA) to tune and to optimize the gain parameters of PID controller. The SCA-PID based MPPT has been implemented and validated by comparing with P&O-based MPPT. The curve of the output power shows the suggested MPPT algorithm gives an output power of 1.096 kW, whereas P&O-based

MPPT gives 0.343 kW; So the suggested MPPT presents an immense improvement in term of maximum output power.

In paper [396], the authors study two controllers to extract the MPP from PEMFC power source by applying them to a DC/DC boost converter in the case of hydrogen and load variations. The whole system and the both controllers, classical PI and SM controllers based MPPT are implemented using MATLAB/SIMULINK software. Gotten results show the outperforms of the SMC-based MPPT than classical PI in term of finding the MPP with powerful performance, accuracy, short convergence, and lower overshoot.

In paper [397], the authors suggested FLC-based MPPT using the both types Takagi Sugeno's and Mamdani fuzzy controllers to find the MPP of 50 kW PEMFC stack, that used to feed DC load through power converter. Gotten results show that the Sugeno-type MPPT compared to the Mamdani-type controller gives quicker convergence time and lower oscillations about the signal of the output power.

Table IV.5 Literature review summary of FC based MPPT controller.

N° Ref.	MPPT suggested.	Results obtained.	Controller parameters.	Sort of study.		Sensors number.
				Simulation	Experimental	
[366]	P&O.	Power raises about 10%.	Oxygen stoichiometry.	✓	/	2.
[367]	FOCV & FSCC.	No notes.	U_{FC} & I_{FC} .	✓	/	1/2.
[368]	P&O.	No notes.	I_{FC} & fuel flow.	✓	/	2.
[369]	ESC and Hysterisis.	Amelioration ripple value (9%-10%).	U_{FC} & I_{FC} .	/	✓	2.
[370]	SMC.	High accuracy reached at 97.98%-98.97%.	U_{FC} & I_{FC} .	✓	/	2.
[371]	P&O.	Power raises about 10%.	U_{FC} & I_{FC} .	✓	/	2.
[372]	SMC.	Quickest convergence time 0.1s.	U_{FC} & I_{FC} .	✓	/	2.
[373]	FLC.	Efficiency rising about 35–55%.	I_{FC} & fuel flow rate.	✓	/	2.
[374]	PSO, IPSO, QPSO, VEPSO & PSOTVAC.	Accuracy between 97.24% until 98.67%.	U_{FC} & I_{FC} .	✓	/	2.
[375]	QPF & GPC.	No notes.	Inlet molar flow rates of hydrogen and coolant.	✓	/	2.
[376]	ES	Accuracy between 99.7% and 99.8%.	T_{FC} & stoichiometry.	✓	/	2.

[377]	Extension theory control.	- Tracking speed 0.95s. - High conversion efficiency is 94.5%.	U_{FC} & I_{FC} .	/	✓	2.
[379]	IC.	No notes.	U_{FC} & I_{FC} .	✓	/	2.
[380]	WCA.	Accuracy 99.96%.	U_{FC} & I_{FC} .	✓	/	2.
[381]	LQR & P&O.	No notes.	Oxygen excess ratio.	✓	/	2.
[382]	Unknown MPPT.	99.41%.	U_{FC} & I_{FC} .	✓	/	2.
[383]	Unknown MPPT.	99.41%.	U_{FC} & I_{FC} .	✓	/	2.
[384]	Second order SMC.	No notes.	U_{FC} & I_{FC} .	✓	/	2.
[385]	FO-HPF & ESC.	No notes.	U_{FC} & I_{FC} .	✓	/	2.
[386]	IC.	Amelioration: - Tracking time 20.69%-49.31%. - Steady state oscillation 25%-37.5%.	U_{FC} & I_{FC} .	✓	/	2.
[387]	Oxygen excess ratio constrained strategy, oxygen excess ratio invariant strategy, and mixed-sensitivity strategy.	No notes.	Oxygen excess ratio.	✓	/	2.
[388]	PSO & PID	No notes.	T_{FC} & stoichiometry.	✓	/	2.
[389]	FLC.	- Reduce response time 3.6%-82.35% - Decrease reduction 70.93%-100%.	U_{FC} & I_{FC} .	✓	/	2.
[390]	Current reference estimator and backstepping.	No notes.	U_{FC} & I_{FC} .	✓	/	2.
[391]	PES & MRAC.	No notes.	U_{FC} & I_{FC} .	✓	/	2.
[392]	FLC.	Power raises between 24.45% and 33.18%.	U_{FC} & I_{FC} .	✓	/	2.
[393, 394]	NN.	Power raises between 4.35% and 8.34%.	U_{FC} & I_{FC} .	✓	/	2.
[395]	SCA & PID.	Power raises 219.62%.	U_{FC} & I_{FC} .	✓	/	2.
[396]	PI & SMC.	- Robustness. - Good accuracy. - Tracking time 0.2s.	U_{FC} & I_{FC} .	✓	/	2.
[397]	Sugeno's and Mamdani FLCs.	Rise time 207.461 μ s-398.196 μ s Falling time 542.94-501.13 μ s Overshoot 4.8%-30.9%.	U_{FC} & I_{FC} .	✓	/	2.

IV.5 Conclusion

In this chapter, overviews about MPPT algorithms developed for PV array and for fuel cells systems to extract as possible power from these systems. Two criteria's adopted to classify this number of MPPT methods, in which includes tracking mechanisms and modernity. For PV systems more than 60 MPPT methods are mentioned in the literature. P&O, IC, FLC and ANN based MPPT are considered the most popular according to literature reviews for both conventional and SC methods. In fact, this is not always an indication of the superiority of these algorithms, but they can have a suitable solution for manufacturers and the end user. On the other hand, the use of MPPT algorithms for fuel cell systems have begun recently, it provides the capacity to protect the fuel cell from degradation and raise its lifetime by preventing the FC voltage collapse and preventing the current to go beyond critical limits. The controller parameters that used to implement the MPPT vary between the PV and FC. Four controller parameters can be found in the PV system; two inputs (sun radiation and Temperature) and two outputs (Voltage/Current). While, the FC contains several controller parameters due to its complexity of operating such as voltage and current, temperature, oxygen stoichiometry, Oxygen excess ratio, Inlet molar flow rates of reactant gases, fuel flow and partial pressure of H_2/O_2 . Therefore, the FC requires a large number of sensors compared to the PV system.

Chapter V

Results and Discussions: MPPT techniques

V.1 Introduction

Power generated from PV module and PEMFC stack varies with variation in set external and internal parameters as presented in the end of each of the previous two chapters. The analysis of curves showed that these curves are nonlinear functions and there is only one operating point called the MPP. At the same time, this MPP keeps shifting its position when any operating conditions change occurs. In addition, depending on the characteristics of the load on which the PV/PEMFC source delivers, we can find a very large difference between the potential power of the generator and that actually transferred to the load in direct connection mode. In order to extract at each instant the maximum power available at the terminals of the PV/PEMFC source and to transfer it to the load, the technique conventionally adopted consists in using an adaptation stage between the PV/PEMFC source and the load as described in figure V.1 below. This stage acts as an interface between the two elements by ensuring, through a control action, the transfer of the maximum power supplied by the generators so that it is as close as possible to the maximum available power.

In this chapter, we present the results of simulation obtained by using MATLAB/SIMULINK for different MPPT developed in order to extract the MPP from PV and PEMFC.

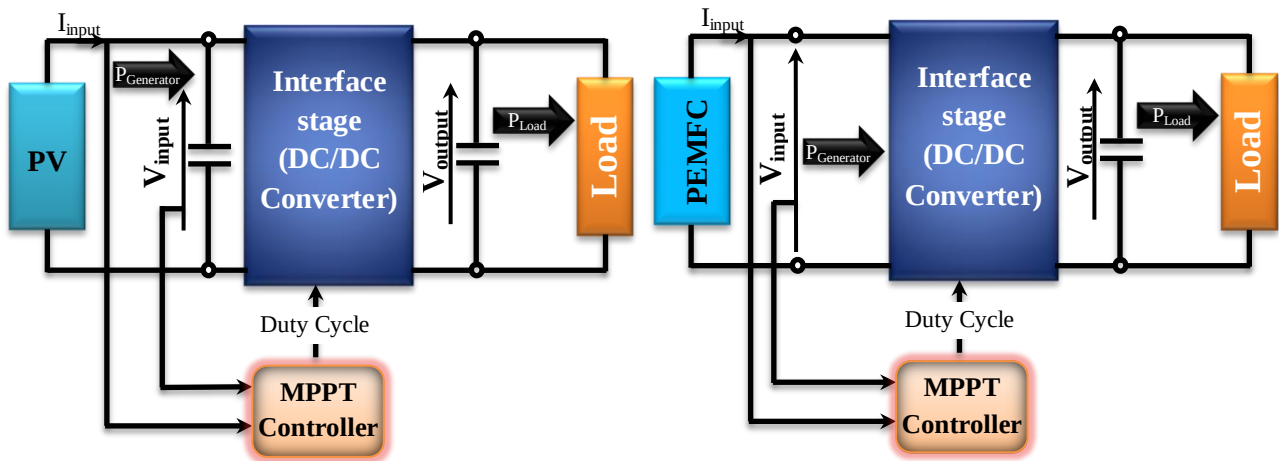


Figure V.1 Adaptation stage between PV/PEMFC and load.

V.2. Adaptation stage between generator and load

The field of power electronics offers several potential solutions in the form of static converters, in which DC/DC converter is presented for the switching circuits, with it transforms the form of input voltage to another output voltage. Indeed, this type of (DC/DC) converter more commonly known as chopper.

A DC/DC converter is a circuit that converts the DC voltage from one level to another. It involves controlling of the average output voltage to a desired value. Several kinds are classified for the converter according to their design specifications, position of components, switching devices output and input voltage relationship and values of voltage, current and power generated by each, DC/DC converters are having following three basic types in field of photovoltaic and PEM fuel cell: step up (boost), step down (buck) and step down and up (buck boost) converters [398]. In the following, the operating principle of a DC/DC converter of the Boost type is described only.

V.2.1. DC/DC Boost converter

A Boost converter also called as step up converter or parallel DC/DC chopper is a switching power supply that converts a DC voltage into another DC voltage of higher value. Therefore, voltage in the terminals of load will be always greater than the input voltage; it follows then that the load current will be lower than as compared to source current [398]. Figure V.2 shows the circuit topology of Boost converter.

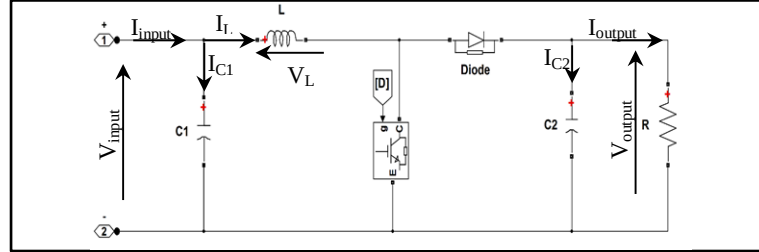


Figure V.2 Boost converter equivalent circuit.

The output voltage is given as a function of the input voltage and the following duty cycle according to the following equation [399]:

$$V_{output} = \frac{V_{input}}{1-D} \quad (V.1)$$

Also, the expression of the output current is given as follows:

$$I_{output} = (1-D) \times I_{input} \quad (V.2)$$

The capacitance must be properly dimensioned to maintain a voltage at its terminals with a tolerated ripple. Likewise for the inductor, it must be equally sized to keep a constant current with a maximum permissible corrugation [400]:

$$L = \frac{V_{input} \times D}{\Delta I_L \times f_s} \quad (V.3)$$

$$C_2 = \frac{I_{output} D}{\Delta V_{output} \times f_s} \quad (V.4)$$

Where ΔI_L is inductor current ripple, ΔV_{output} is the output voltage ripple, f_s is switching frequency and D is duty cycle.

V. 3. Perturbation and Observation PV MPPT

V.3.1 Description of P&O algorithm

One of the most popular algorithms for the class of traditional MPPT approaches is the P&O-based MPPT [401-403]. The year 1970 marked the first year that this technique was used to track MPP in PV systems, when it was used extensively for space applications. P&O is basically iterative method, in which operating point of solar PV oscillates around the MPP. The tracking algorithm

starts with measuring the present value of the operating V_{pv} and I_{pv} , then ΔP_{pv} is calculated. The P&O method's basic tenet is purposefully perturbed on a periodic basis by applying a series of minor and constant perturbations to the operating point step by step, and following each perturbation, the control algorithm compares the values of the P_{pv} fed by the PV source before and after the perturbation. Thus, if after the perturbation the P_{pv} has increased ($\Delta P_{pv} > 0$), this means that the operating point has been moved toward the MPP from the left side; hence further, the perturbation applied to the V_{pv} will have the same direction as the previous one to reach MPP. Conversely, when ($\Delta P_{pv} < 0$) i.e. the P_{pv} become decreases, this indicates that the operating point has been moved far, and is located in the right side of the MPP. Therefore, the sign of the subsequent operating point perturbation must be changed in the opposite. Note that this process keeps repeating, as once the region aligned to MPP is reached, with each new perturbation; the algorithm will go back and forth around the MPP. Hence, it will not stick exactly at MPP; instead of, it oscillates around that point indefinitely. Table V.1 provides a summary of this method.

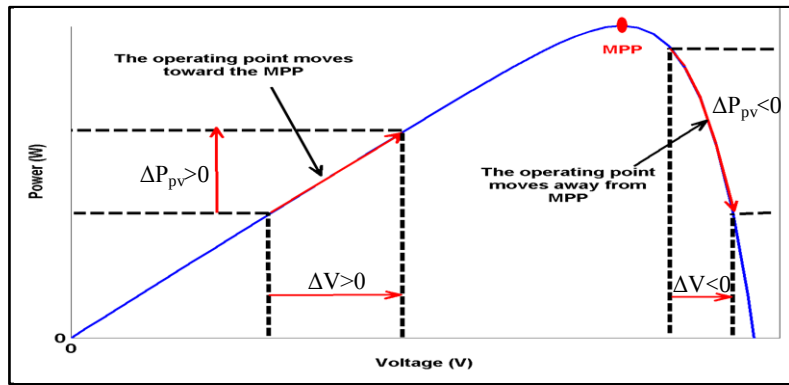


Figure V.3 The movement of operating point in P&O MPPT.

Table V.1 Principal of P&O method.

Case	Perturbation in voltage	ΔP_{pv}	Direction of Tracking	Next perturbation
1	+	+	Good direction	+
2	+	-	Bad direction	-
3	-	+	Good direction	+
4	-	-	Bad direction	-

V.3.2 Variable step size P&O based MPPT algorithm

In general, the traditional P&O technique with Fss tracking has two principal defects described by the interrelation between the lurch around the MPP and response quickness as mentioned in chapter IV i.e. with Fss there is no instantaneous accommodation to quickly reach MPP and to reduce fluctuations around it. Therefore, to beat the flaws of the Fss P&O-based MPPT, a Vss P&O is enforced, where the duty cycle is adjusted immediately with large step size when away from the MPP and with small step size around the MPP. The novel step size is given by:

$$D_k = D_{k-1} \pm \mathcal{N}^* \left| \Delta P_{pv} / \Delta D \right| \quad (V.5)$$

ΔP_{pv} : is the change in power of PV module.

ΔD : is the step-change in duty cycle in the previous sampling period.

$\mathcal{N}^*$: is the scaling factor which is tuned at the design time to adjust the step size.

V.3.3 Results of simulation

To confirm the powerful of the Vss P&O-based MPPT algorithm, the whole system incorporating PV source, DC/DC boost converter derived by the aforementioned MPPT technique and resistance load are modeled employing Matlab/Simulink environment.

Figure V.4 displays the maximum output power for both traditional Fss and suggested Vss P&O MPPT when the sun radiation level alters. Through figure V.4, we can view that both MPPTs track the MPP in each situation of changeful sun radiation levels with robust performances for the suggested MPPT technique compared to the Fss technique in term of quickness and overshoot.

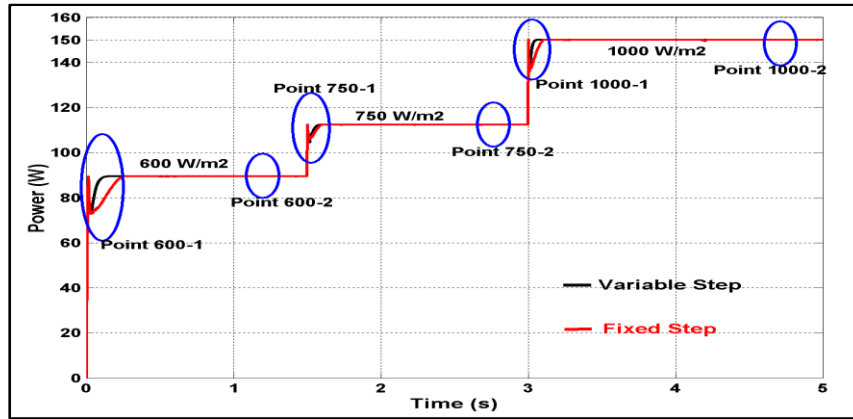


Figure V.4 Output power of PV module.

- **Dynamic Performance**

Figures V.5 display the comparative study of dynamic response i.e response time between both techniques traditional Fixed P&O MPPT (Tr-Fss) and the suggested Vss P&O MPPT (Tr-Vss) in three points 600-1, 750-1 and 1000-1 corresponding to sun radiation levels 600 W/m^2 , 750 W/m^2 and 1000 W/m^2 , respectively. From figure V.5, it can be view the suggested Vss P&O-based MPPT outperforms the Fss P&O-based MPPT in situation of variations sun radiation levels from 600 W/m^2 to 750 W/m^2 and from 750 W/m^2 to 1000 W/m^2 . Table 2.V summarized response time reduction, in which the Vss MPPT shows reduction ratio between 13.86% and 45.28%.

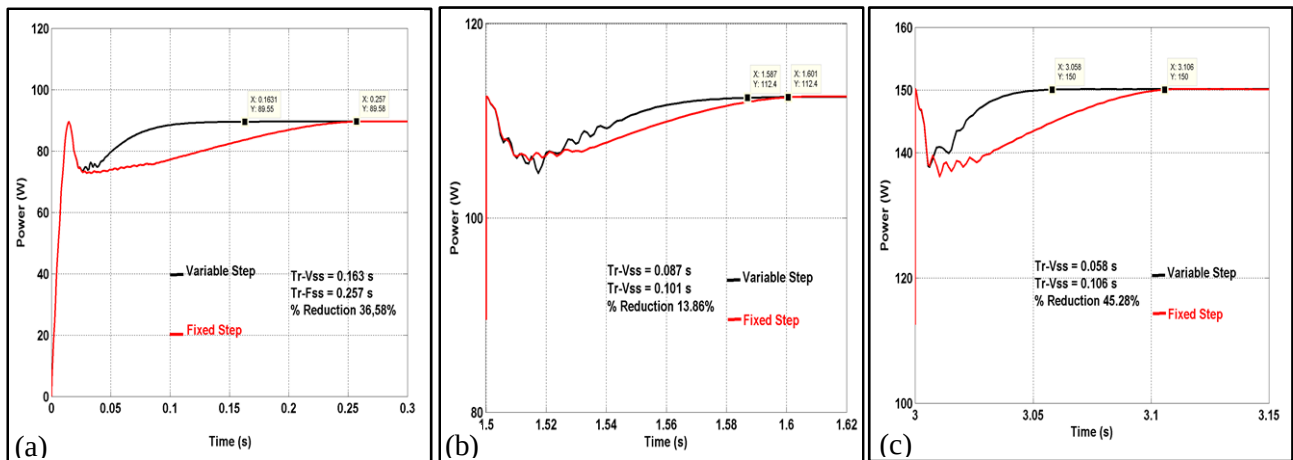


Figure V.5 Output power: Zoom in: a) Point 600-1, b) Point 700-1 and c) Point 1000-1.

- **Steady State Performances.**

Figure V.6 display comparative study regarding to steady state response i.e oscillations around the MPP of both methods: traditional fixed P&O-based MPPT (Osc-Fss) and the suggested Vss P&O-based MPPT (Osc-Vss) in three points 600-2, 750-2 and 1000-2 corresponding to sun radiation levels 600 W/m², 750 W/m² and 1000 W/m², respectively. Through figures V.6, it is obviously if different sun radiations levels from 600 W/m² to 750 W/m² and from 750 W/m² to 1000 W/m² are imposed during simulation, the suggested Vss P&O-based MPPT shows strong performance than the Fss P&O-based MPPT. Table 3.V summarized the main results of steady state oscillation reduction for both techniques, in which the suggested MPPT shows generally reduction ration between 83.33% and 100%.

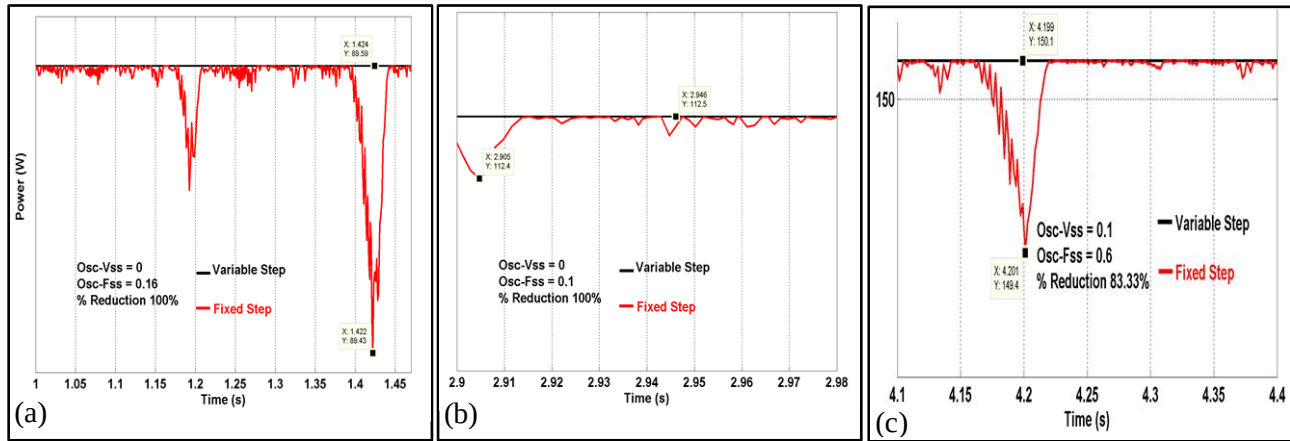


Figure V.6 Output power: Zoom in: **a)** Point 600-2, **b)** Point 700-2 and **c)** Point 1000-2.

- **Course Around MPP**

Figure V.7 displays the P-V characteristics at irradiation level variations from 600 W/m² to 750 W/m² and from 750 W/m² to 1000 W/m² for both P&O-based MPPTs. In this situation we assess the course of the MPP point (Osc-MPP) for each method either: the standard Fss P&O-based MPPT or the suggested Vss P&O-based MPPT. Through figures V.8, we can view obviously that the suggested Vss MPPT method shows lower oscillations around the MPP point compared to the Fss MPPT method, it reached about 0.0001 W and 0.0225 W for Vss P&O MPPT and Fss P&O MPPT respectively.

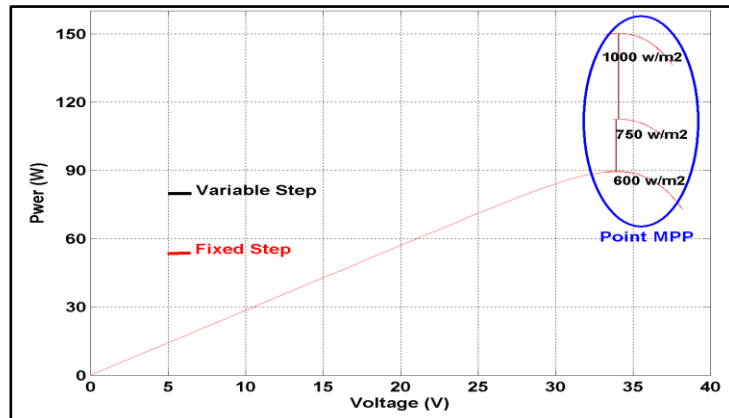


Figure V.7 P-V characteristics at irradiation level variations.

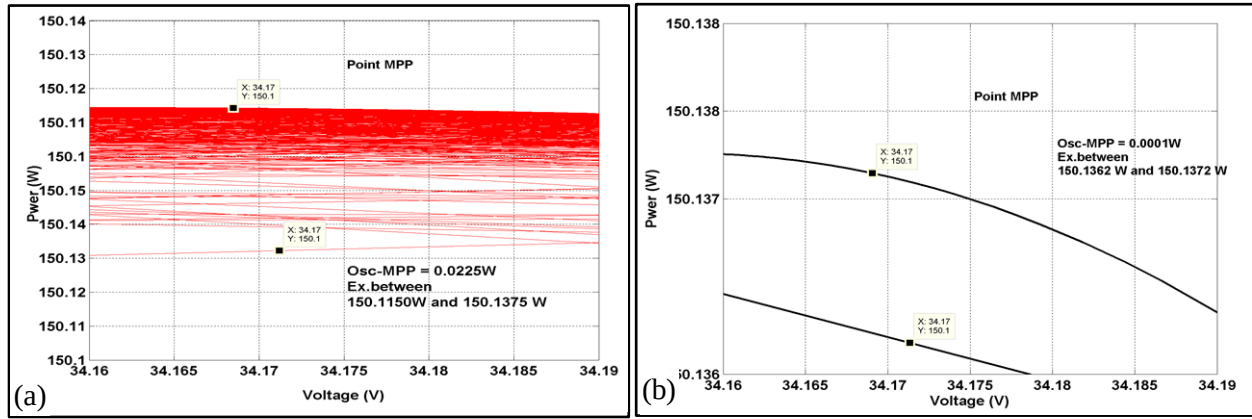


Figure V.8 P-V characteristics: Zoom in Point MPP **a)** oscillation in the case of the Fss MPPT and **b)** oscillation in the case of the Vss MPPT.

The primary effects of this strategy on the response time reduction and the oscillation around the MPP are outlined in Tables 2.V and 3.V.

Table 2.V Response time reduction.

	T_r -Fss (s)	T_r -Vss (s)	Red ratio (%)
Point 600-1.	0.257	0.163	36.58
Point 750-1.	0.101	0.087	13.86
Point 1000-1.	0.106	0.058	45.28

Table 3.V Steady state oscillation reduction.

	Osc-Fss (s)	Osc-Vss (s)	Red ratio (%)
Point 600-2.	0.16	0.00	100
Point 750-2.	0.10	0.00	100
Point 1000-2.	0.60	0.01	83.33

V.4 Novel neural network based IC variable step size MPPT for PEMFC

V.4.1 Neural network

Neural network is considered a smart tracking techniques based on several learning process on the environment. They are popular because of their ability to imitate some of the brain's creative processes, albeit in a simplistic way, that cannot be imitated by existing mathematical or logical methods. Such capabilities are essential for solving many complex problems. The figure V.9, show the architecture of the neural networks, it have three layers, called input, hidden and output layers [404]:

- **Input Layer:** Neurons in this layer receive input values from the PEMFC system and pass them on to hidden neurons. Each neuron receives a value, so it does not make a summation.
- **Hidden layers:** each neuron in this layer receives information from several previous layers, performs the weight-weighted summation, and then transforms it according to its activation function, which is usually a sigmoid function. Subsequently, it sends this response to neurons in the next layer.

- **Output layer:** it plays the same role as the hidden layers; the only difference between these two types of layers is that the output of the neurons from the output layer is not linked to any other neuron.

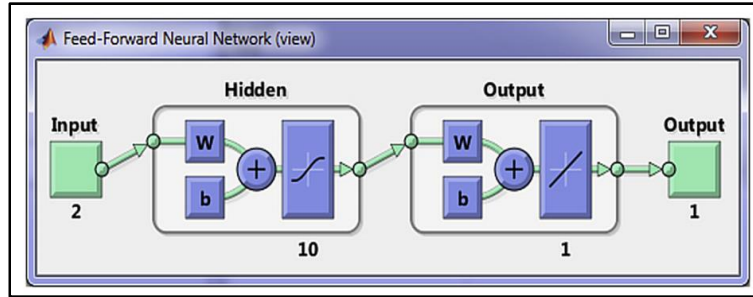


Figure V.9 Architecture of the neural network.

V.4.1.1 Methodology

The first phase of our methodology consists of developing the proposed neural network IC-based variable step size MPPT controller in the offline mode which is required for testing different set of neural network parameters to find the optimal neural network controller architecture. These parameters will help in second phase related to the online mode to track the output power of the fuel cell power system under different conditions. The inputs variables for the neural networks are the same as for the IC algorithm inputs i.e. I and V, current and voltage of fuel cell); while the output power is the PWM ratio used to drive the DC/DC boost converter.

V.4.1.2 Training

The training process used for weights determination is based on the mean squared errors (MSE) for minimizing the overall error measure between the neural networks output and the data generated previously using the variable step size IC MPPT.

V.4.1.3 Implementation

Once trained, the optimized network is used in the online mode for MPPT performance testing using different scenario simulating the change in the conditions.

V.4.2 Fixed and variable step size IC MPPT for PEMFC

Like P&O algorithm, the IC algorithm remains one of the most employed MPPTs [386, 405] due to its simplicity and easy implementation. This technique is based on power variations directly. The output current and voltage of the PEMFC are measured using sensors to calculate conductance and incremental conductance. Using these two values, the algorithm determines the location of the operating point of the PEMFC stack in the current-power curve. Then, tracking the MPP point corresponds to [404]:

$$\frac{dP_{FC}}{dI_{FC}} = 0 \quad (V.6)$$

Equation (V.6) can be rewritten as follow:

$$\frac{dP_{FC}}{dI_{FC}} = \frac{d(I_{FC} \cdot U_{FC})}{dI_{FC}} = U_{FC} + I_{FC} \frac{dU_{FC}}{dI_{FC}} = 0 \quad (V.7)$$

Equation (V.7) can be rearranged in the following form:

$$\frac{dU_{FC}}{dI_{FC}} = -\frac{U_{FC}}{I_{FC}} \quad (V.8)$$

Note that the left-hand side of equation (V.8) represents the incremental conductance of the PEMFC stack, while the right-hand side represents its opposite instantaneous conductance. Therefore, analyzing equation (V.8), the first derivative can test whether the PEMFC stack is operating at its MPP or far from it. At the MPP, these two quantities must be equal in magnitude, but opposite in sign. If the operating point is off of the MPP, a set of inequalities can be derived from equation (V.8) that indicates whether the operating current is above or below the MPP current. These relationships are summarized in the following equations:

$$\left\{ \begin{array}{l} \frac{dU_{FC}}{dI_{FC}} = -\frac{U_{FC}}{I_{FC}} \Rightarrow \text{at the MPP} \end{array} \right. \quad (V.9a)$$

$$\left\{ \begin{array}{l} \frac{dU_{FC}}{dI_{FC}} > -\frac{U_{FC}}{I_{FC}} \Rightarrow \text{at the left of MPP} \end{array} \right. \quad (V.9b)$$

$$\left\{ \begin{array}{l} \frac{dU_{FC}}{dI_{FC}} < -\frac{U_{FC}}{I_{FC}} \Rightarrow \text{at the right of MPP} \end{array} \right. \quad (V.9c)$$

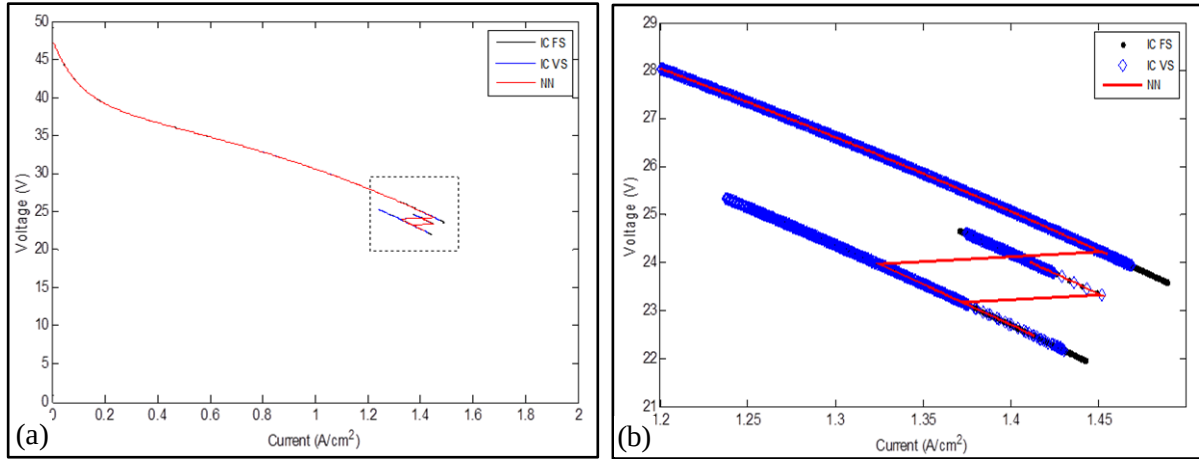
Equation (V.9a) is a repeat of equation (V.8) for convenience. Equations (V.9b) and (V.9c) are used to determine the direction in which a perturbation must occur to move the operating point toward the MPP, and the perturbation is repeated until equation (V.9a) is satisfied. Once the MPP is reached, the MPPT continues to operate at this point until a change in voltage and current are measured. This change in voltage and current will correlate to a change in operating conditions. The algorithm, then, tracks the MPP by applying decreases or increases to current. The size of the increment or decrement determines how rapid the MPP is tracked. Rapid tracking can be achieved by applying larger increments, but the system may not operate exactly at the MPP and oscillations around the MPP may result. That is, use of the fixed step size IC MPPT involves a trade-off between speed of convergence and the likelihood of appearance of oscillations around the MPP. Therefore, a good calculation of step size provides a high performance of PEMFC system. The proposed variable step size IC MPPT algorithm is given as follows:

$$D_k = D_{k-1} \pm \mathcal{N}^* \left| \frac{P_{FC}(k) - P_{FC}(k-1)}{I_{FC}(k) - I_{FC}(k-1)} \right| \quad (V.10)$$

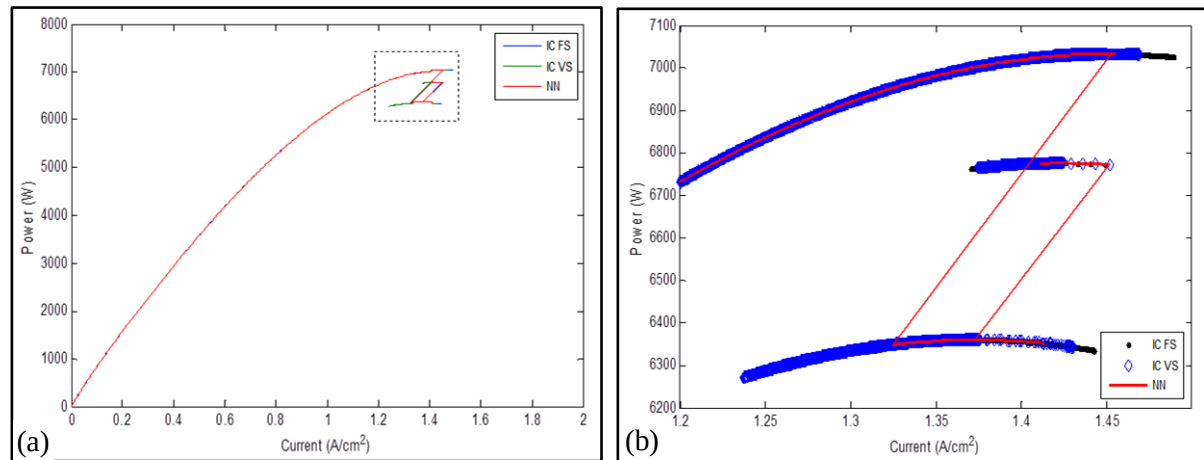
4.3 Results and discussions

In this part, the entire system is designed and analyzed using the Matlab/Simulink software. The PEMFC source is utilized to feed electric load through DC/DC boost converter that driven using two techniques: fixed and new suggested neural network IC-based Vss neural network IC-based. Response time, overshoot and ripple are the three parameters that employed to analyze and decide the performance of the suggested MPPTs. Figures (V.10) and (V.11) display the U_{FC} - I_{FC} and P_{FC} - I_{FC} characteristics when applied fixed and Vss MPPT techniques under changing values of temperature. The PEMFC stack works at different temperature, it decreases and returns to increase between these values 353K, 323K and 343K during three periods 0 to 0.6s, 0.6s to 1.2s and 1.2s to 1.8s respectively.

Through figures (V.10) and (V.11) displaying the characteristic curves of U_{FC} - I_{FC} and P_{FC} - I_{FC} , we can obviously view that the suggested neural network IC based Vss method has the robust performance regarding to the speedy tracking of the MPP, and low oscillation around it in steady state compared to the traditional fixed and Vss IC algorithms.



Figures V.10 a) PEMFC U_{FC} - I_{FC} characteristics and **b)** Zoom at MPP.



Figures V.11 a) PEMFC P_{FC} - I_{FC} characteristics and **b)** Zoom at MPP.

Figure V.12 displays the maximum output power from PEMFC stack utilizing three sort of MPPT: Fss IC, Vss IC and neural network IC-based Vss MPPTs. By applying a variable operating temperature to PEMFC stack in order to analyze and discuss the performance of both Fss and Vss MPPT techniques. Figures V.13 to V.21 display the zoomed in points (A-F), in order to give insight into the performances of the MPTT techniques regarding to the response time, overshoot and ripple as follows:

- **Overshoot:** Through figures V.13 to V.15, we can view obviously that the both classical techniques Fss and Vss show more overshoot compared to the suggested neural network IC-based Vss MPPT, see the (Points A, C and E).
- **Response time:** Through figures V.16 to V.18, we can view directly that the suggested neural network IC-based Vss MPPT is better in term of response time when compared with the both traditional Fss as well as the Vss IC MPPTs controllers, see the (Points A, C and E).
- **Ripple:** Through figures V.19 to V.21, which displays the corresponding ripple state of the three MPPT methods simulated, it can see obviously the suggested neural network IC-based Vss MPPT minimizes the power ripple in comparison to the classical IC MPPT algorithms, see the (Points B, D and F).

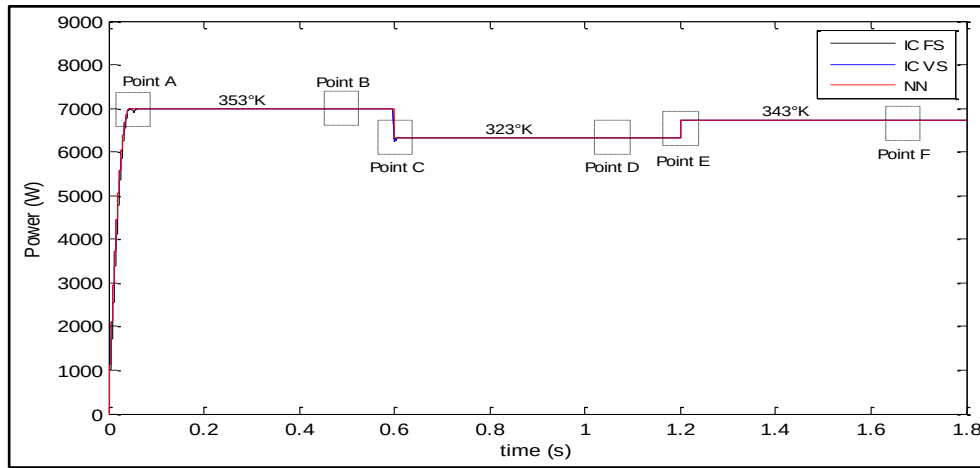


Figure V.12 PEMFC output power at different temperatures using IC Fss, IC Vss and NN based MPPT.

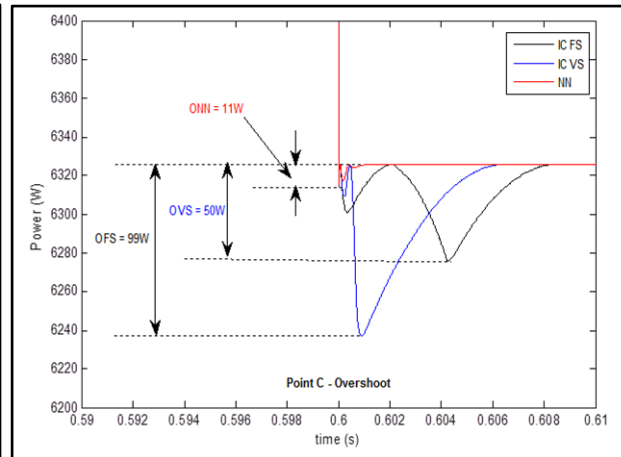
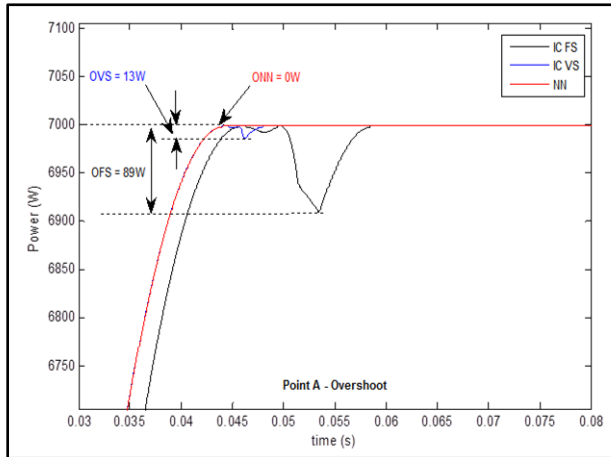


Figure V.13 PEMFC output power: Point A-Overshoot. **Figure V.14** PEMFC output power: Point C- Overshoot.

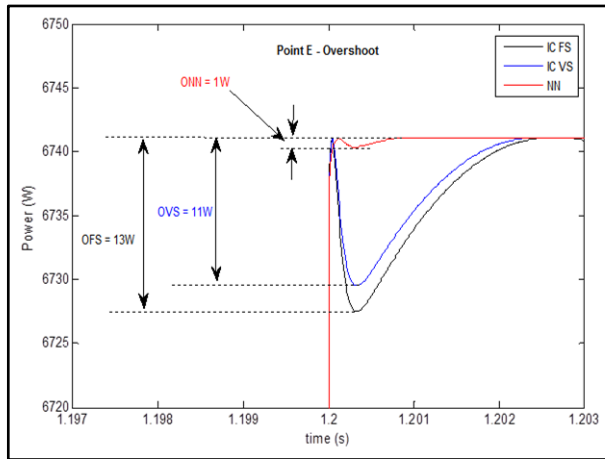


Figure V.15 PEMFC output power: Point E-Overshoot.

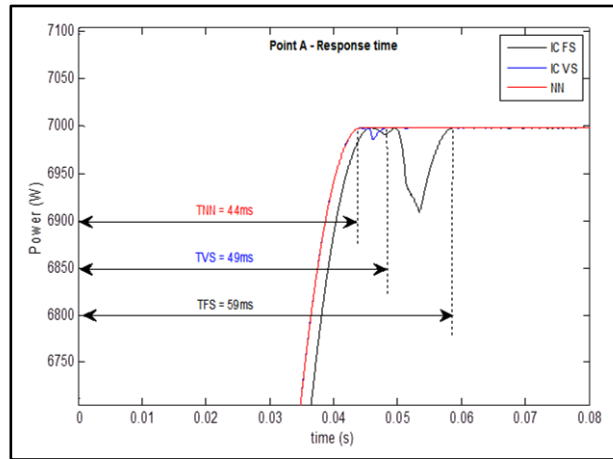


Figure V.16 PEMFC output power: Point A-response

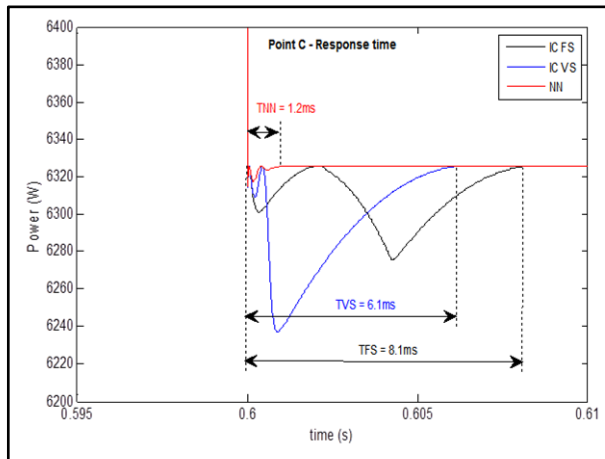


Figure V.17 PEMFC output power: Point C-response time.

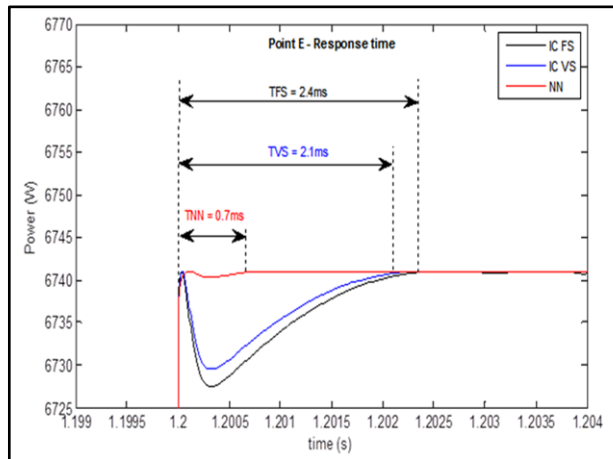


Figure V.18 PEMFC output power: Point E-response time.

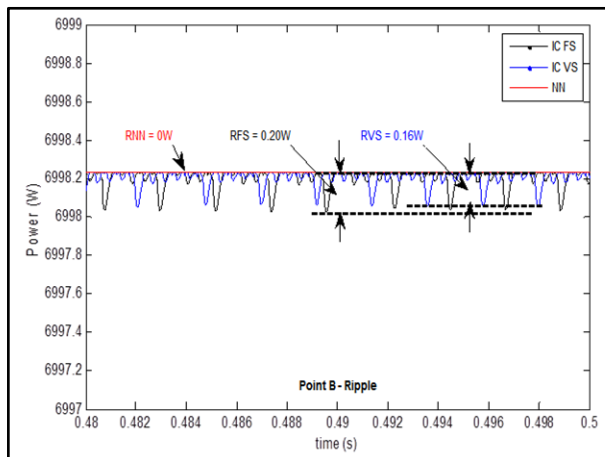


Figure V.19 PEMFC output power: Point B-Ripple.

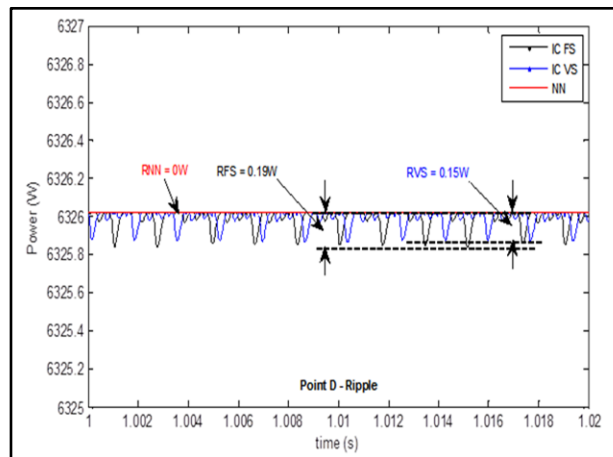


Figure V.20 PEMFC output power: Point D-Ripple.

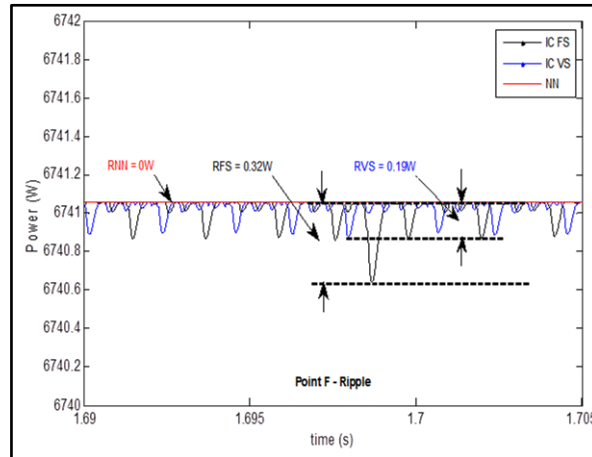


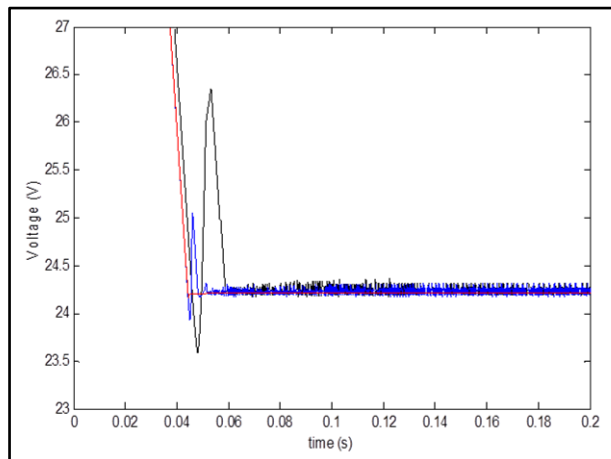
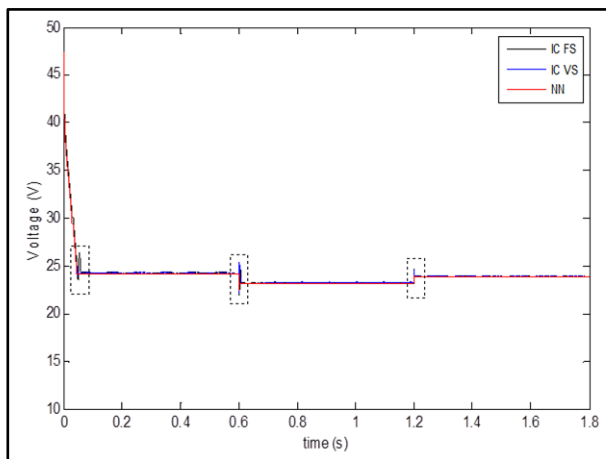
Figure V.21 PEMFC output power: Point F-Ripple.

The most important results presented on the previously figures have been summarized in Table V.4. Through this latter, the performance regarding to the dynamic and steady state responses of the suggested neural network IC-based Vss MPPT outperforms the Fss as well as the Vss IC MPPT controllers.

Table V.4 Summarized results for IC Fss, Vss and NN MPPT.

		Fss IC MPPT	Vss IC MPPT	NN MPPT
Overshoot	Point (A)	89	13	0
	Point (C)	99	50	11
	Point (E)	13	11	01
Response time	Point (A)	59	49	44
	Point (C)	8.10	6.10	1.2
	Point (E)	2.40	2.10	0.7
Ripple	Point (B)	0.20	0.16	00
	Point (D)	0.19	0.15	00
	Point (F)	0.32	0.19	00

The curves of PEMFC voltage and current are displayed in figures V.22 and V.23 respectively. It is undeniably clear that the suggested neural network IC-based Vss MPPT algorithm diminish exceedingly the voltage and current ripple.



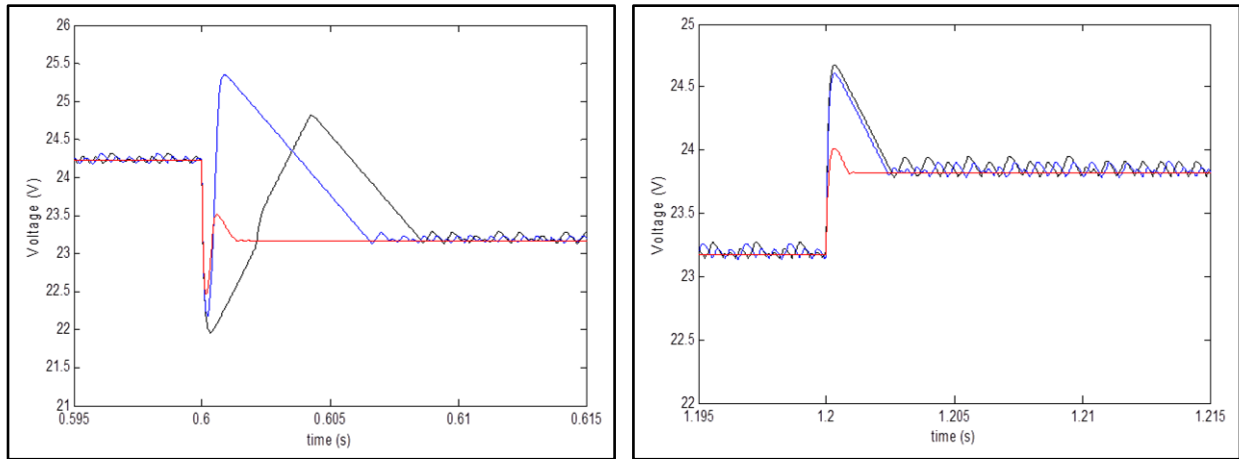


Figure V.22 PEMFC voltage using IC Fss, IC Vss and NN based MPPT.

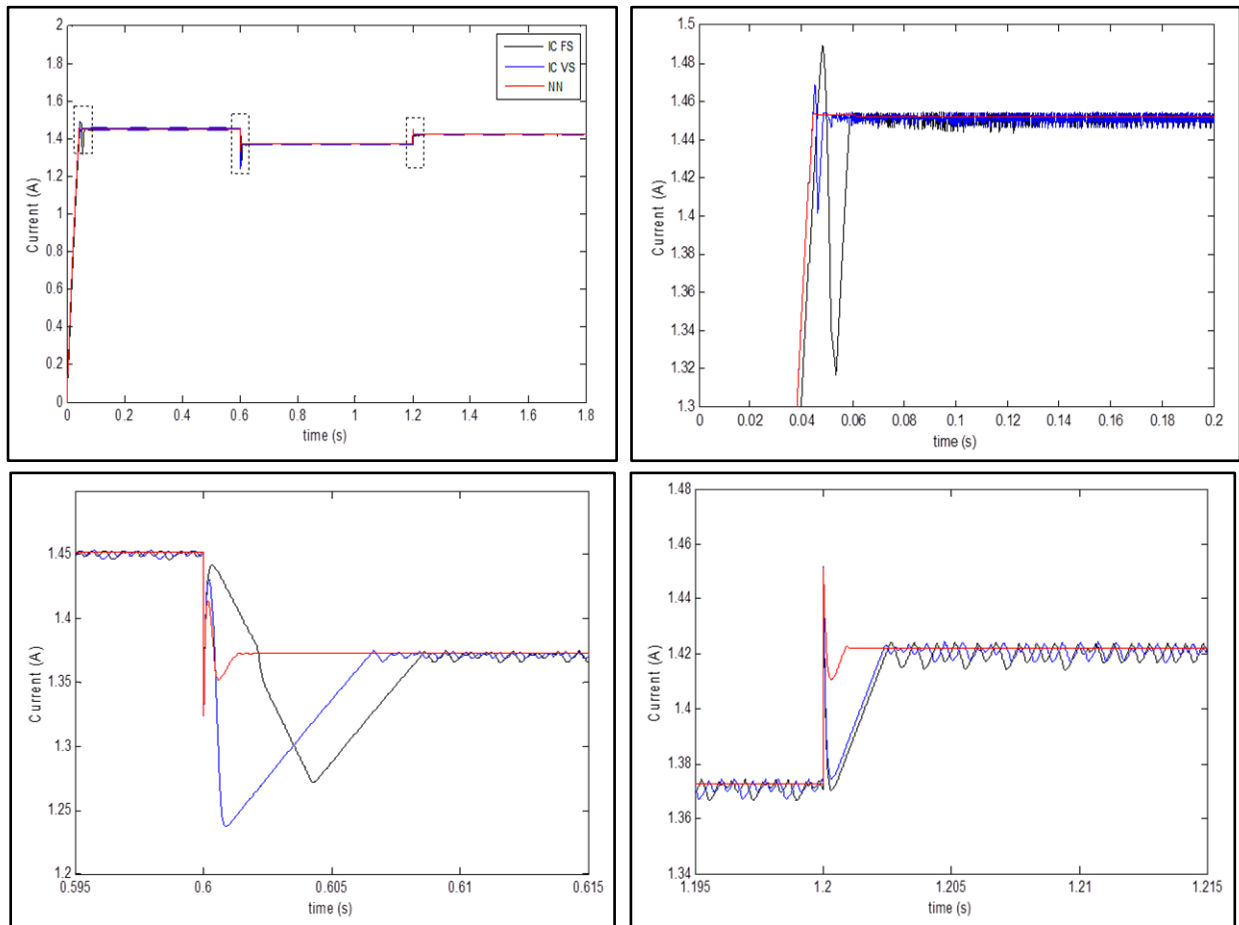


Figure V.23 PEMFC current using IC Fss, IC Vss and NN based MPPT.

V.5 Single Sensor based MPPT Controller for PEMFC

The maximum output power of the PEMFC stack depends on the parameters of the dynamic system and the basic requirements of the electrical load. The cost of a PEMFC system to feed electric load includes the cost the PEMFC source with its auxiliary, the DC/DC converter and the MPPT controller to drive the DC/DC converter. The finally cost of the whole system varies with the size of PEMFC, the electronic power components and the MPPT developed. This latter play important part to reduce the cost of whole system; this has driven to a continual development and improvement of their control systems [406]. The majority of MPPTs used for FC power system require at least two sensors, one for the current sensing and another to sense the voltage and a relatively complex control strategy, as shown in figure V.24 (a). To decreases the cost and complexity of the PEMFC power system; we proposed a single sensor MPPT that uses only a current sensor in order to reduce the cost and the complexity of the MPPT controller, as shown in figure V.24 (b).

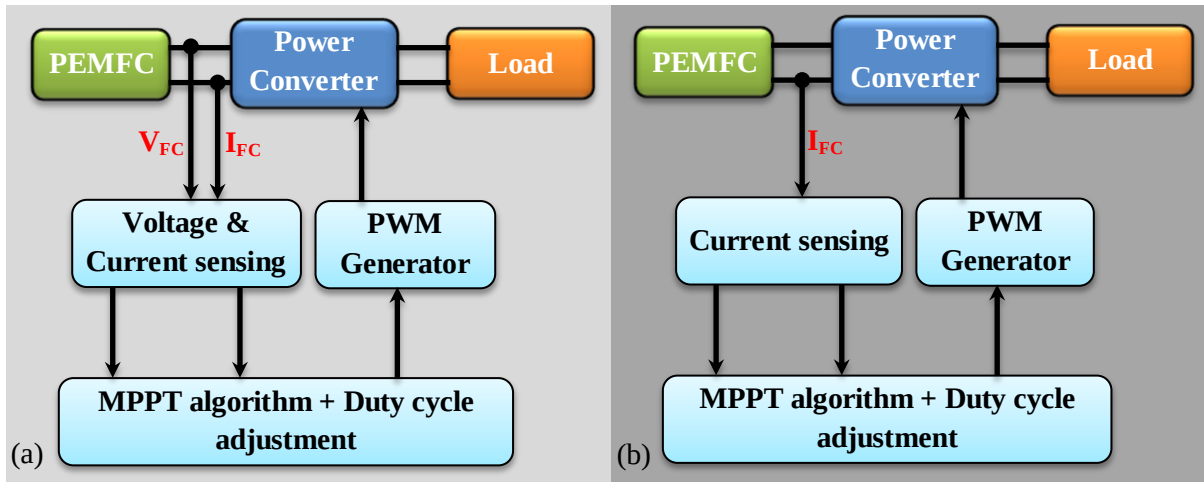


Figure V.24 a) Two sensors MPPT and b) Single sensor MPPT [407].

Based on [406, 407], the PEM fuel cell output power from boost converter to a resistive load is given by equation (V.11):

$$P_{out} = \frac{V_{out}^2}{R_{load}} = I_{out}^2 \cdot R_{load} \quad (V.11)$$

Where:

P_{out} and I_{out} are the output power and current respectively.

The expression of the output current through the boost converter is given by the following equation:

$$I_{output} = I_{FC} (1 - D) \quad (V.12)$$

Tracking the maximum of P_{out} reduced to resolve equation (V.13):

$$\frac{dP_{out}}{dD} = \frac{dI_{out}}{dD} = 0 \quad (V.13)$$

By substituting the expression of the output current in equation (V.13), we will obtain:

$$\frac{dI_{out}}{dD} = \frac{d(I_{FC}(1-D))}{dD} = 0 \quad (V.14)$$

The equation (V.14) becomes:

$$(1-D) \frac{dI_{FC}}{dD} + I_{FC} \frac{d(1-D)}{dD} = 0 \quad (V.15)$$

After simplification of the above equation, we get the following equation:

$$\frac{dI_{FC}}{dD} - \frac{I_{FC}}{(1-D)} = 0 \quad (V.16)$$

Finally, the duty cycle is adjusted as follows:

$$\begin{cases} \frac{dI_{FC}}{dD} < \frac{I_{FC}}{1-D} \rightarrow D_{k+1} = D_k - SF * D_k \\ \frac{dI_{FC}}{dD} = \frac{I_{FC}}{1-D} \rightarrow D_{k+1} = D_k \\ \frac{dI_{FC}}{dD} > \frac{I_{FC}}{1-D} \rightarrow D_{k+1} = D_k + SF * D_k \end{cases} \quad (V.17)$$

Where: SF is the step size scaling factor defined by the equation below:

$$SF = \left| \frac{dI_{FC}}{dD} \right| \quad (V.18)$$

Equation (V.17) shows that the proposed novel single sensor MPPT uses only the sensed PEM fuel cell current and the old generated PWM duty cycle to generate the new one to follow the MPP changes.

V.5.1 Results of Simulation

To assess the performance of the suggested single sensor MPPT (1S MPPT), the comparative study was conducted with two sensors IC MPPT (2S MPPT) under two tests: temperature and hydrogen pressure variations, the two system with 7 kW PEM fuel cell is implemented using Matlab/Simulink software:

In order to assess the effectiveness and capability tracking of the two algorithms in the two test scenarios under consideration, we utilize in the first step a quick stepped pattern that is regarded as a strained instance. The suggested 1S MPPT technique viability in actual operating circumstances is confirmed in the second phase when it is applied to a normal variation pattern.

V.5.1.1 Test Scenario N°1: Temperature Variation

In this part, we rapidly make changes in temperature over an extended period of time from 0 to 1.8s, where the temperature takes the values 353 K, 323 K and 343 K during the time interval from 0 and 0.6, 0.6 s to 1.2 and 1.2 s and 1.8 s respectively as illustrated in figure V.25, in order to assess the tracking effectiveness of the suggested 1S MPPT controller.

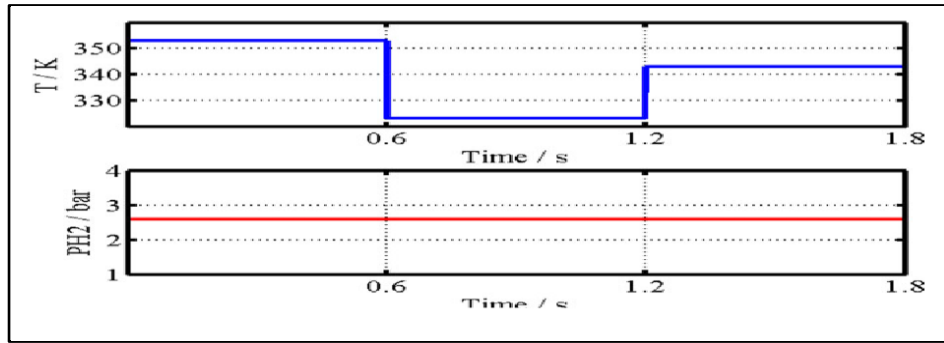


Figure V.25 Pattern test for test scenario N°1.

Figure V.26 displays the maximum output power when applied both 1S and 2S MPPTs under temperature variation, while figures V.27 to V.29 display the zoom-in of points 353-1, 323-1 and 343-1 respectively, which utilized to analyze and to assess dynamic performances of 1S-RT and 2S-RT based MPPT controllers; Meanwhile, the figures V.30 to V.32 display the zoom-in of points 353-2, 323-2 and 343-2 respectively, which utilized to analyze and to assess the static performances of 1S-SS-Osc and 2S-SS-Osc based MPPT controllers. From figure V.26, under test scenario of variation temperature, it can view clearly the temperature impact on the maximum power generated from PEMFC stack. On the other hand, the suggested 1S MPPT technique tracks accurately the maximum power by driving the PWM duty cycle using only one sensor for the PEMFC current.

Through figures V.27 to V.29, the 2S MPPT presents high dynamic performances compared to 1S MPPT, in which the response time for the 2S-RT are 56 ms, 70 ms and 32 ms instead of 160 ms, 190 ms and 63 ms for the 1S-RT corresponding to temperature values 353 K, 323 K and 343 K respectively. In contrast, regarding to the static performances, the suggested 1S MPPT controller is better than the 2S MPPT as displayed in figures V.30 to V.32, in which the oscillations reached for 1S-SS-Osc MPPT controller at 5W, 3 W and 3 W instead of 18 W, 16 W and 18 W for 2S-SS-Osc MPPT controller corresponding to temperature values 353 K, 323 K and 343 K respectively; It ameliorate the PEMFC efficiency and increasing its lifetime.

In this initial test carried out, The suggested single sensor MPPT technique shows its efficacy and tracking ability, which employed a quick temperature change that corresponded to a sudden or pulsed temperature change in order to assess the proposed algorithm's dynamic response.

To verify these results, we applied the temperature profile as displayed in Figure V.33, in order to test the suggested MPPT method (1s MPPT). Through figure V.33, it is obviously that the suggested 1S MPPT technique provides good performance to reach towards maximum power delivered by PEMFC with minimum overshoot or oscillations under normal temperature variation.

Finally, through figures V.27 until V.32, in the case of rapid or normal temperature variation, the suggested 1S MPPT provides good dynamic as well as static performances.

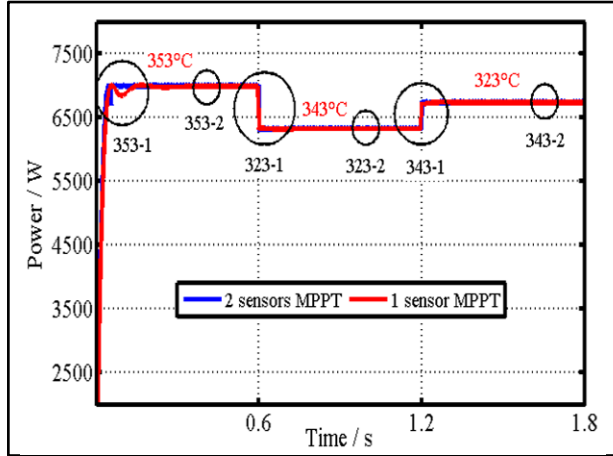


Figure V.26 PEMFC output power at temperature variation using 1 and 2 sensors based MPPT.

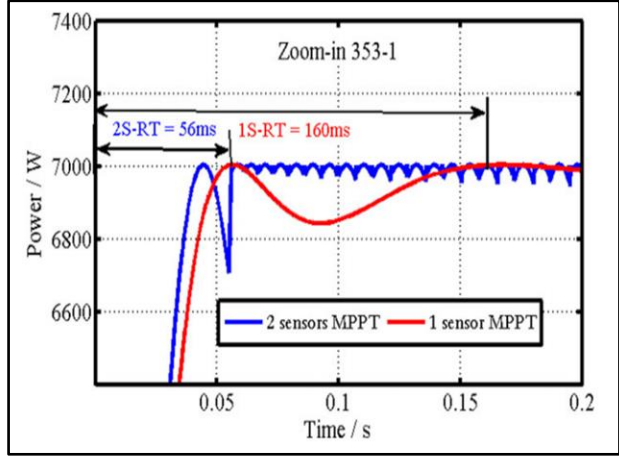


Figure V.27 Zoom-in of point 353-1.

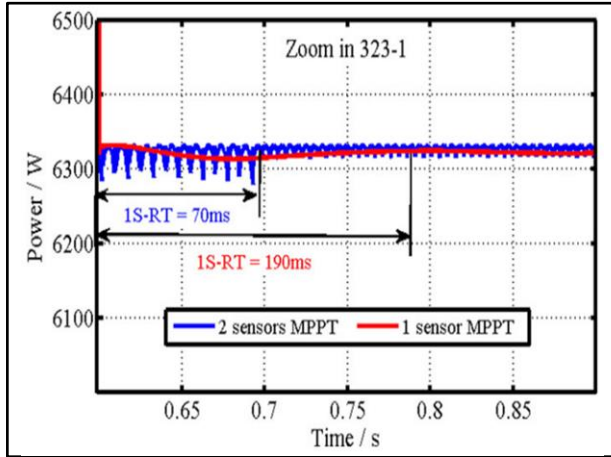


Figure V.28 Zoom-in of point 323-1.

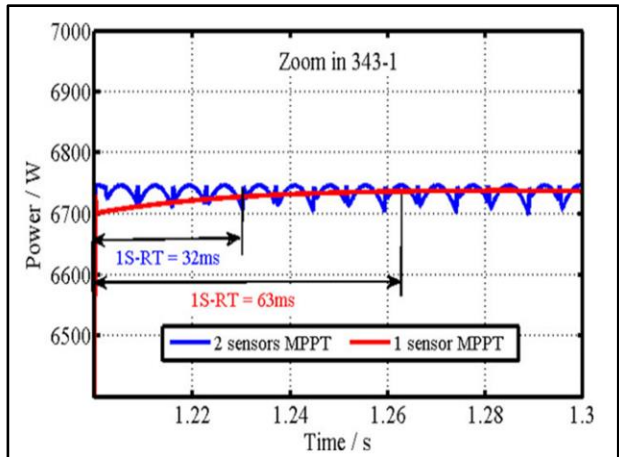


Figure V.29 Zoom-in of point 343-1.

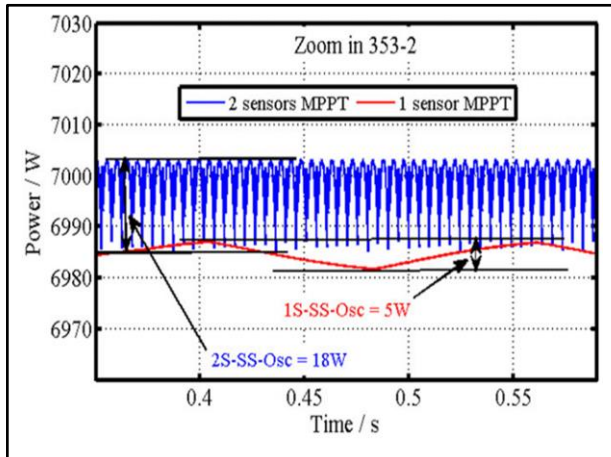


Figure V.30 Zoom-in of point 353-2.

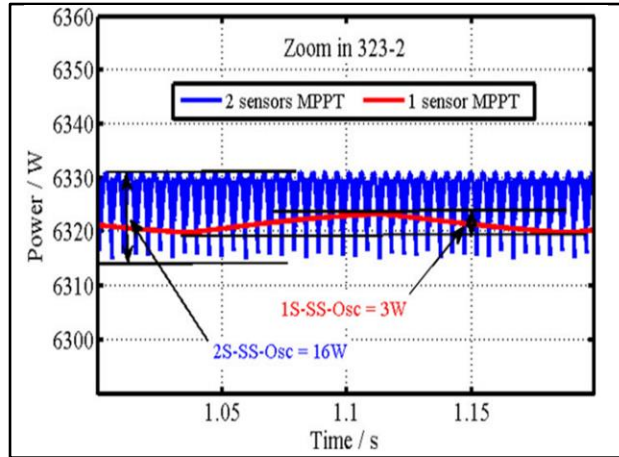


Figure V.31 Zoom-in of point 323-2.

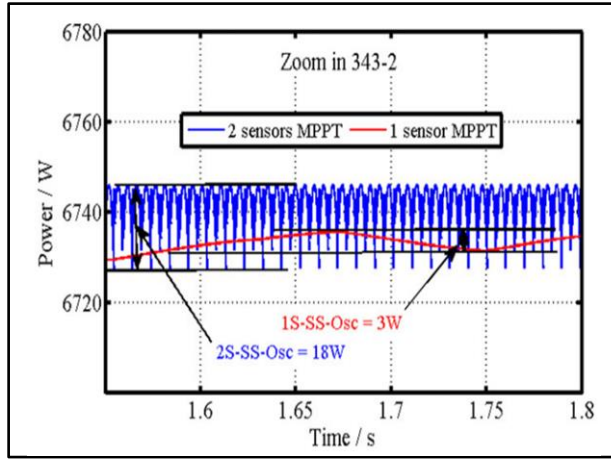


Figure V.32 Zoom-in of point 343-2.

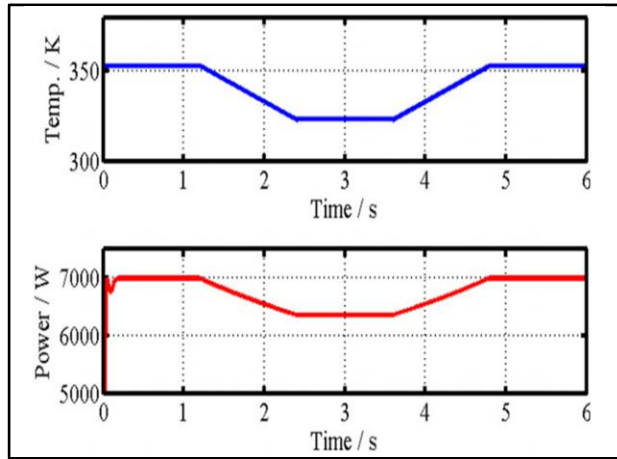


Figure V.33 PEMFC output power in case of normal temperature variation.

V.5.1.2 Test Scenario N°2: Hydrogen Pressure Variation

In this part, we rapidly make changes in pressure over an extended period of time from 0 to 1.8s, where the pressure takes the values 2.60 bar, 2.10 bar and 2.35 bar during the time interval from 0 and 0.6, 0.6 s to 1.2 and 1.2 s and 1.8 s respectively as illustrated in figure V.34, while temperature kept constant in order to assess the tracking effectiveness of the suggested 1S MPPT controller.

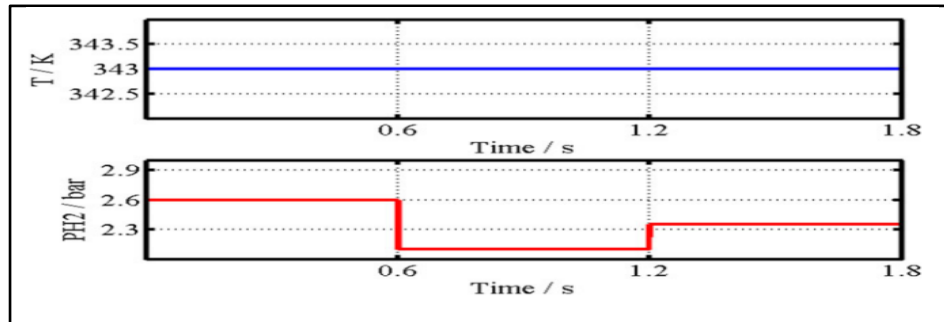


Figure 34 Pattern test for test scenario N°2.

Figure V.35 displays the maximum output power from PEMFC stack utilizing both 1S and 2S MPPTs, while figures V.36 to V.41 depict the zoom-in of points 2.60-1, 2.60-2, 2.10-1, 2.10-2, 2.35-1, and 2.35-2, respectively. As seen in Figure V.35, the suggested 1S MPPT method accurately tracks the MPP delivered by the PEMFC stack by controlling the PWM duty cycle utilizing just one sensor for the PEMFC current in the event of a change in hydrogen pressure.

Figures V.36 to V.38 demonstrate that, in terms of dynamic performances, the 2 S MPPT outperforms the 1S MPPT, in which the response time for the 2S-RT are 56 ms, 11 ms and 44 ms instead of 147 ms, 52 ms and 82 ms for the 1S-RT corresponding to pressure values 2.60 bar, 2.10 bar and 2.35 bar respectively. In contrast, when looking at the static performances, we find the suggested 1S MPPT outperforms the 2S MPPT, as seen in figures V.39 to V.41, in which the oscillations reached for 1S-SS-Osc MPPT controller at 5W, 5 W and 5 W instead of 18 W, 17 W and 16 W for 2S-SS-Osc MPPT controller corresponding to hydrogen pressure values 2.60 bar, 2.10 bar and 2.35 bar respectively.

As noticed in the premier exam scenario at quick temperature variation, using a quick change of the hydrogen pressure representing suddenly or a pulsed hydrogen pressure variation, the suggested 1S MPPT method exhibits good effectiveness and tracking capability even when put to the test in difficult circumstances. The suggested 1S MPPT method effectiveness in the presence of typical hydrogen pressure variation is confirmed by Figure V.42. Figures V.35 to V.42 show that the suggested 1S MPPT method achieves good overall performances when rapid or regular hydrogen pressure change is taken into account.

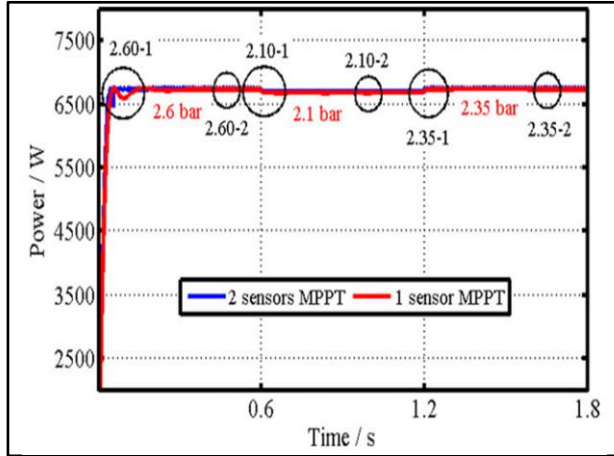


Figure V.35 PEMFC output power at pressure variation using 1 and 2 sensors based MPPT.

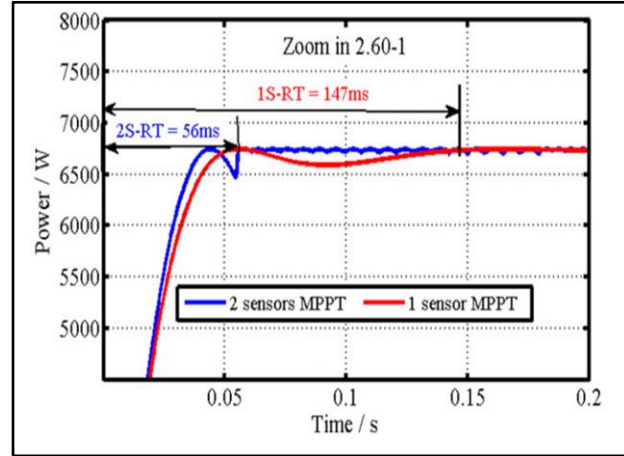


Figure V.36 Zoom-in of the point 2.60-1.

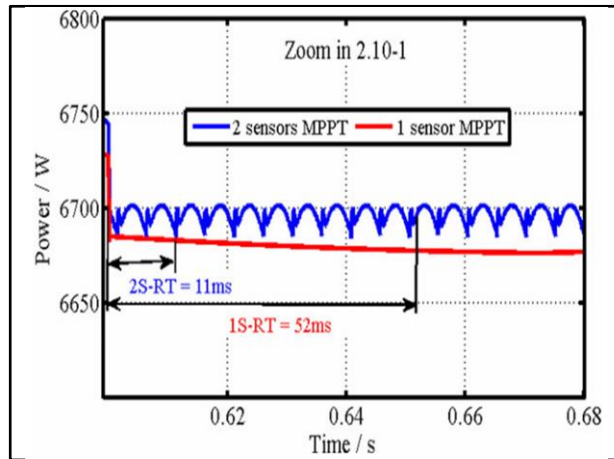


Figure V.37 Zoom-in of the point 2.10-1.

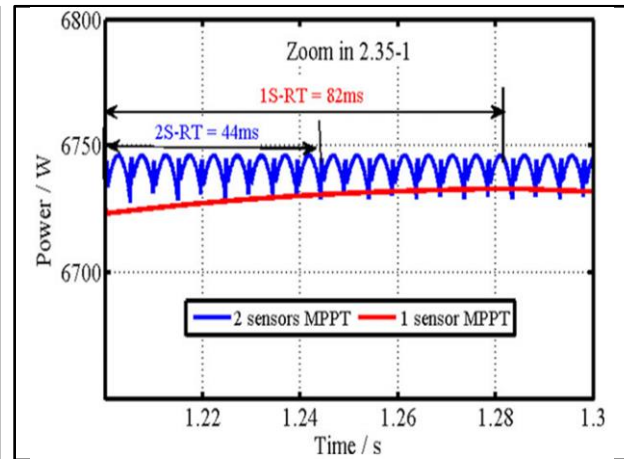


Figure V.38 Zoom-in of the point 2.35-1.

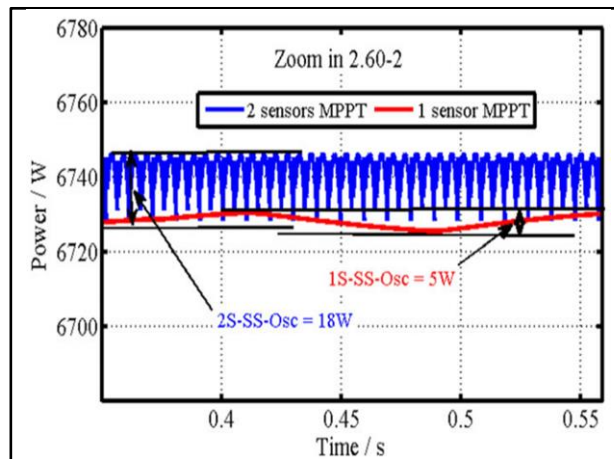


Figure V.39 Zoom-in of the point 2.60-2.

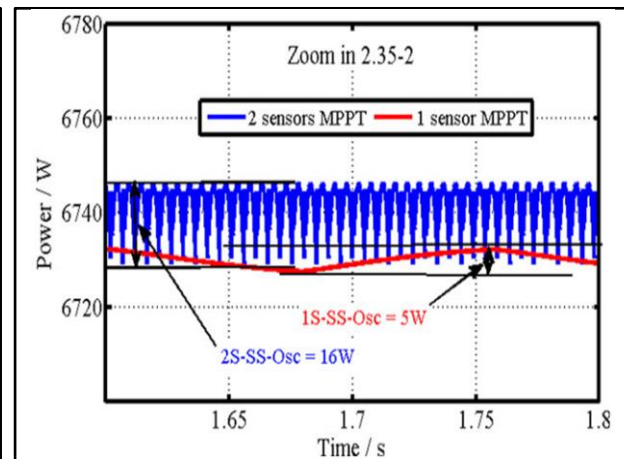


Figure V.40 Zoom-in of the point 2.10-2.

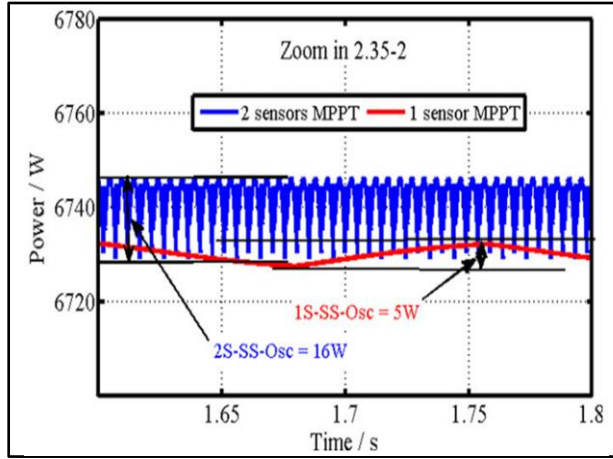


Figure V.41 Zoom-in of the point 2.35-2.

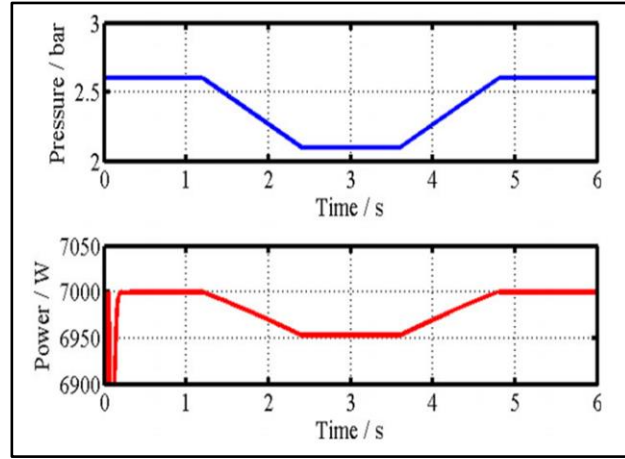


Figure V.42 PEMFC output power in case of normal hydrogen pressure variation.

Figure V.43 beneath displays the PEMFC current for both test scenarios. Through figure V.43, we can view that the suggested 1S MPPT method minimizes exceedingly the current ripple increasing by the way the PEMFC efficiency and lifetime, by reducing the frequent trip caused by over-current and even harmonics.

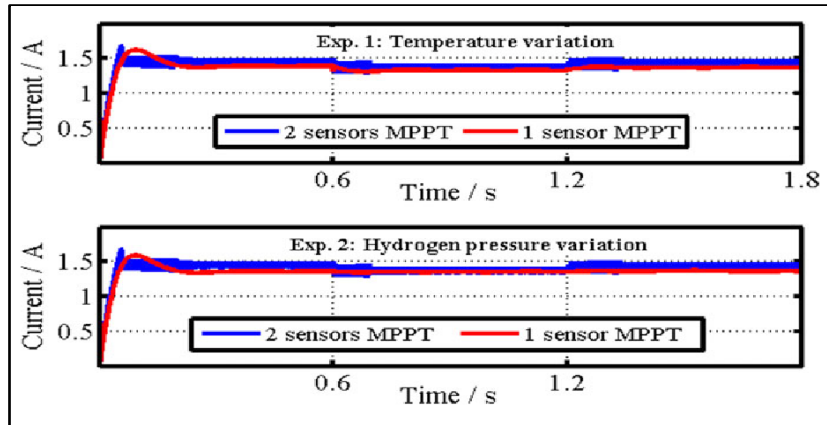


Figure V.43 PEMFC current using 1 and 2 sensors based MPPT.

V.5.1.3 Discussion Results of simulation

Under rapid and normal operating condition of temperature and pressure, the PEMFC system with the suggested 1S MPPT have been simulated. The results of simulations were presented through figures V.26 to V.33 and V.35 to V.42, where demonstrated the 1S MPPT method good performance in terms of static and dynamic. Table V.5 highlights the key findings.

It is evident from table V.5 that both MPPT techniques show high efficiency in the case of tracking the MPP of the PEMFC power stack, but in terms of dynamic and static performances, the MPPT gave different results. In terms of dynamic performances, using the 2S MPPT gave a better results, while the suggested 1S MPPT offers higher in the case of static performances, it gives several pros like raising the PEMFC efficiency and lengthening PEMFC lifetime by minimizing the frequent trip due to over-current and even harmonics. Additionally, the suggested 1S MPPT offers good dynamic and static performances utilizing just one sensor, which lowers the cost and

complexity of the PEMFC stack while still taking into account rapid or typical temperature or hydrogen pressure fluctuations.

Table V.5 Summarized results for 2S and 1S MPPTs.

Test scenario	Metric	Point	2S MPPT	1S MPPT
Temperature variation	Response time RT/ms	Point 353-1	56	160
		Point 323-1	70	190
		Point 343-1	32	63
	Steady state oscillation SS-Osc/W	Point 353-2	18	5
		Point 323-2	16	3
		Point 343-2	18	3
Pressure variation	Response time RT/ms	Point 2.60-1	56	147
		Point 2.10-1	11	52
		Point 2.35-1	44	82
	Steady state oscillation SS-Osc/W	Point 2.60-2	18	5
		Point 2.10-2	17	5
		Point 2.35-2	16	5

V.6 Golden Section Search based MPPT for PEMFC

Jack Carl Kiefer, a statistician, discovered the Golden Section Search (GSS) or Golden Ratio technique in 1953 [408]. By gradually reducing the range of values where the extremum is known to exist, this method seeks to locate the minimum or maximum of a unimodal function in its range of variation.

V.6.1 Golden section search based MPPT overview

The suggested of GSS for PV source to extract MPP has taken an significant part in the literature, below a review of some representative studies on GSS-based MPPT:

In Ref [409], authors compared three algorithms P&O, IC and PSO with GSS in terms of the value of the efficiency in two conditions sunny and cloudy day, quite simply the GSS provided the best efficiency. Another test to prove the accuracy and the rapidity of this technique concerning the convergence at the MPP by a minimum number of iterations, this test done in Ref. [410] under different atmospheric conditions, show that the results obtained using GSS requires a number of iterations less than P&O to reach MPP.

In Refs [411] and [412], authors used other boost converter topologies instead of classical boost converter (three level and dual output DC/DC converter), for the maximization of the power extraction by using MPPT algorithm based on GSS. Experimental results show that the best dynamic response with the faster convergence are obtained using GSS algorithm with efficiency between 90% and 94%.

In Ref [413] many tests have been applied to see the adequate quality of this technique under constant conditions, fast changing conditions and partial shading operations. The main advantage for the GSS is that under fast changing atmospheric conditions, the algorithm gives high dynamic efficiency with very low tracking error.

In Ref. [414], authors applied the GSS based MPPT for solar water pumping systems (SPWS) to improve the overall operating efficiency. In this study, the GSS based MPPT shows better performance considering time convergence time and the dynamic efficiency compared to P&O algorithm.

V.6.2 Principle of the GSS based MPPT

The GSS is a technique to search the maximum or minimum through specific interval for unimodal function by successively narrowing the interval of values inside in which extremum point known to exist. The GSS technique is employed to find the MPP in the PEMFC curve. The characteristic Power-Current of PEMFC is unimodal i.e. contains only one maximum on the interval $[I_a, I_b]$; if there are few points on the side $[I_a, I_1]$, then the function is increasing towards the maximum and decreasing on the side $[I_2, I_b]$. The proposed GSS method operates with the same principal of the bisection method: i) it begin with the definition of an interval with a single maximum inside; and ii) it divides the interval into three subintervals by inserting two internal points between the limit of the original interval as shown in figure V.44.

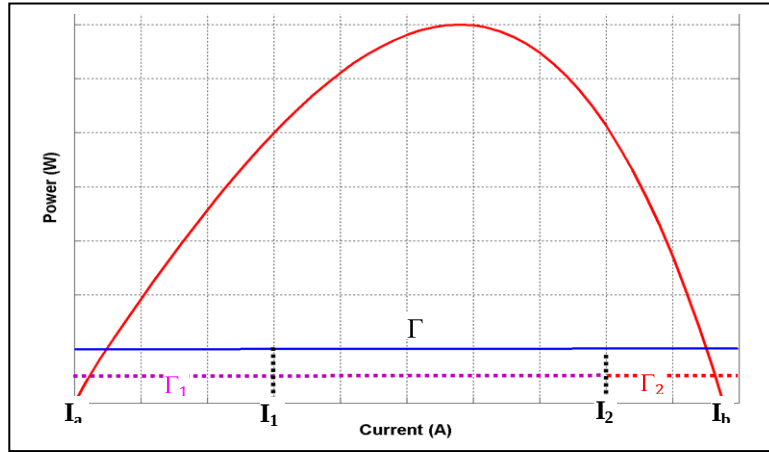


Figure V.44 Division of the original interval.

As shown in Figure V.44, the characteristic P-I start at point I_a and ends at point I_b . The function is then evaluated in the interval $[I_a, I_b]$. Two points I_1 and I_2 are computed inside the interval $[I_a, I_b]$ in such a way that each point subdivides the interval into two segments and length of whole line/length of larger sub-segment = length of larger sub-segment/length of smaller sub-segment. The relationship can be described in a mentioned in equation (V.19):

$$\frac{\Gamma}{\Gamma_1} = \frac{\Gamma_1}{\Gamma_2} \quad (\text{V.19})$$

Where:

Γ : is the length between the points (I_a, I_b) .

Γ_1 : is the length of the larger sub-segment.

Γ_2 : is the length of the smaller sub-segment.

The equation (V.19) can be rewritten as follow:

$$\frac{\Gamma_1 + \Gamma_2}{\Gamma_1} = \frac{\Gamma_1}{\Gamma_2} = \Phi \quad (\text{V.20})$$

Where Φ is the golden ratio that is the quotient of the larger sub-segment to the smaller sub-segment.

Equation (V.20) can be simplified as:

$$1 + \frac{\Gamma_2}{\Gamma_1} = \Phi \quad (\text{V.21})$$

Also from equation (V.20):

$$\frac{\Gamma_2}{\Gamma_1} = \frac{1}{\Phi} \quad (\text{V.22})$$

By substituting the expression of the equation (V.22) in the (V.21), we obtained the following expression:

$$1 + \frac{1}{\Phi} = \Phi \quad (\text{V.23})$$

We multiply both sides of the equation (V.23) by Φ and after simplification; the equation (V.23) can be expressed as:

$$\Phi^2 - \Phi - 1 = 0 \quad (\text{V.24})$$

The solution of this second-order equation (V.24) gives two (positive and negative), the positive solution is the only acceptable one expressed by:

$$\begin{cases} \Phi_1 = \frac{-(-1) - \sqrt{5}}{2} = -0.618 \\ \Phi_2 = \frac{-(-1) + \sqrt{5}}{2} = +1.618 \end{cases} \quad (\text{V.25})$$

Where Φ_2 is the golden ratio [413, 415].

The Golden Section is defined as the reciprocal of the Golden ratio, i.e. the ratio between the small sub-segment and the large sub-segment [413].

$$\phi = \frac{1}{\Phi} = \Phi - 1 = 0.618 \quad (\text{V.27})$$

Where: ϕ is the Golden Section.

This technique is known as Golden Section that uses the Golden Section to generate two points I_1 and I_2 from the search interval as follow [416]:

$$\begin{cases} I_1 = I_b - 0.618 \cdot (I_b - I_a) \\ I_2 = I_a + 0.618 \cdot (I_b - I_a) \end{cases} \quad (\text{V.28})$$

The GSS method searches for the interval in which the maximum point is located, the procedure operates by reducing the search interval of the left and right. Therefore, when the GSS is applied to extract the maximum power from PEMFC system, the reference current from GSS based MPPT is generated. The function is represented by P-I characteristic of the PEMFC wherein corresponds to power whose maximum value has to be tracked, and the searching interval

correspond to the range of operation $[I_a \ I_b]$ is from zero to short-circuit current $[0 \ I_{sc}]$. This latter is replaced by inner sub-intervals iteratively $[I_{aj} \ I_{bj}]$, $j=1, 2, 3, \dots$, of decreasing lengths, in which each sub-interval is likely to contain one local maximum of our unimodal function. As second step, the searching interval divides into three sub-intervals $[I_a \ I_1]$, $[I_1 \ I_2]$ and $[I_2 \ I_b]$, where I_1 and I_2 are computed as mentioned in equation (V.28). The algorithm then begins to narrow sub-interval either from the far right or far left toward the maximum power by comparing the value of $P(I_1)$ and $P(I_2)$ according to the following analysis [416].

- If $P(I_1) > P(I_2)$, this implies the MPP is located in the interval $[I_a \ I_2]$. The limit points of the search I_a and I_b change to another new narrow search section I_a and I_2 , in which considered as the interval taken in the next iteration with another set of three known points I_a , I_1 and I_2 .

$$\begin{cases} I_1^* = I_2 - 0.618 \cdot (I_2 - I_a) \\ I_2^* = I_a + 0.618 \cdot (I_2 - I_a) \end{cases} \quad (V.29)$$

- If $P(I_2) > P(I_1)$, this implies the MPP is located in the interval $[I_1 \ I_b]$. The limit points of the search I_a and I_b change to another new narrow search section I_1 and I_b , in which considered as the interval taken in the next iteration with another set of three known points I_1 , I_2 and I_b .

$$\begin{cases} I_1^* = I_b - 0.618 \cdot (I_b - I_1) \\ I_2^* = I_1 + 0.618 \cdot (I_b - I_1) \end{cases} \quad (V.30)$$

Consequently, based on the comparison result a decision is made to shrink the search interval from I_a or I_b . After several iterations, the GSS process will terminate when the absolute value of the difference between I_1 and I_2 becomes too small.

$$|I_1 - I_2| \leq \varepsilon \quad (V.31)$$

Where: ε is the current precision.

On the other hand, the maximum current is given as follow:

$$I_{mpp} = 0.5 \cdot (I_1 + I_2) \quad (V.32)$$

A flowchart of the GSS procedure is illustrated in figure V.45 [416].

V.6.3 Results and discussing

GSS based MPPT is designed, which can be employed to adjust the operating point of the PEMFC at every instant to the maximum power by tuning of boost converter duty cycle. The objective of the GSS based MPPT is to iteratively adjust the reference current and thus lead the operating point to the maximum of the power-current curve which matches to a maximum output power. The reference current that is generated from the GSS algorithm is compared with the output current measured. The error result from difference between the reference current and measured is treated through a PI controller which improves the steady state error and the resultant signal is used to set the duty ratio of the boost converter in such a way that the reference current is efficiently reflected at the output of the converter, which assures operation at MPP. Under two scenarios different of temperature and MWC variations, the GSS and Vss IC-based MPPTs are evaluated and compared between them in terms of: the response time and overshoot i.e dynamic performance as well as oscillation around MPP and ripple i.e static performance.

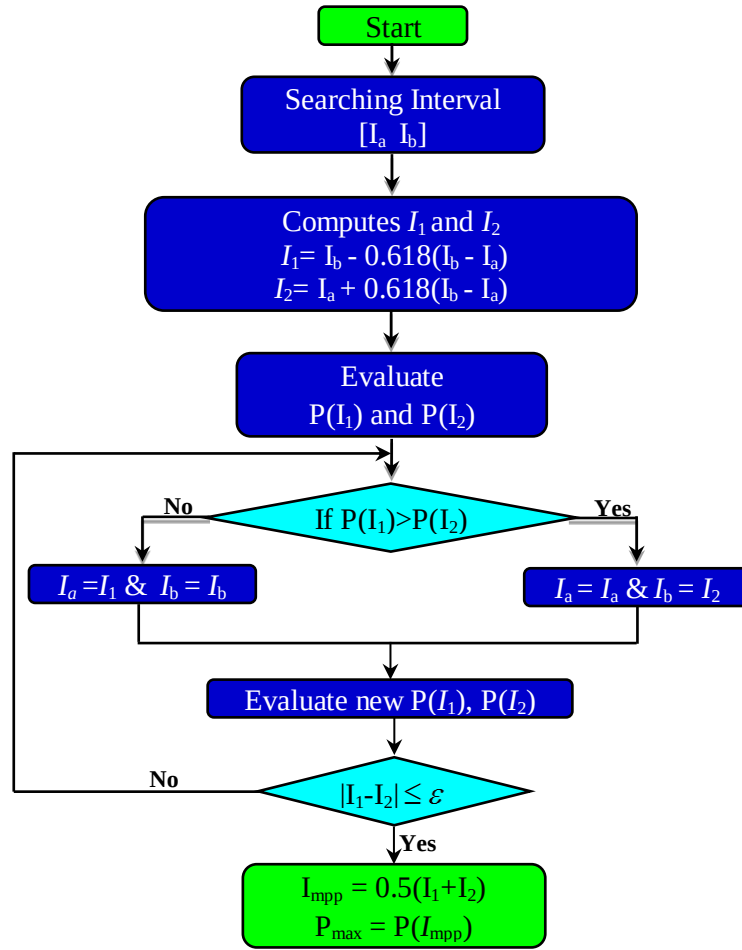


Figure V.45 Flowchart of GSS based MPPT algorithm.

V.6.3.1 Case of temperature change

In this test, we evaluate the tracking strength of the GSS MPPT controller in case of temperature changing with constant hydrogen pressure as illustrated in figure V.46.

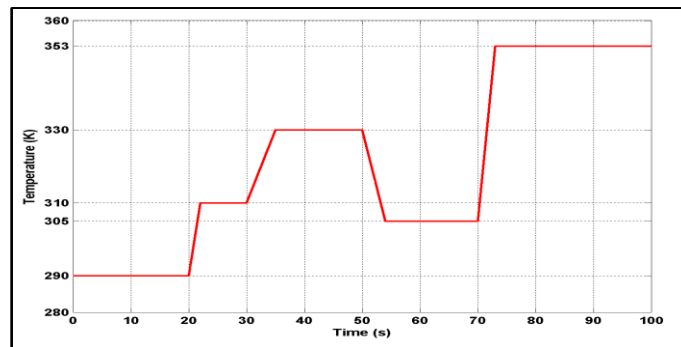


Figure V.46 Cell temperature variation.

The output power employing both the suggested GSS and the Vss IC MPPTs in the event of temperature change is shown in Figure V.47. It is obvious that the PEMFC performance was impacted by the operating temperature. Because of this, the PEMFC is sensitive to temperature change and performs better when the working temperature increases. On the other hand, we can observe that as the temperature changes, both MPPT controllers track the corresponding maximum output power in all cases.

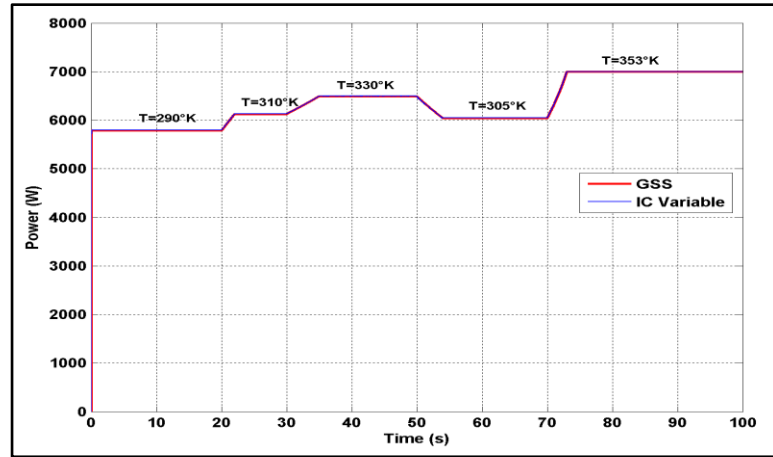
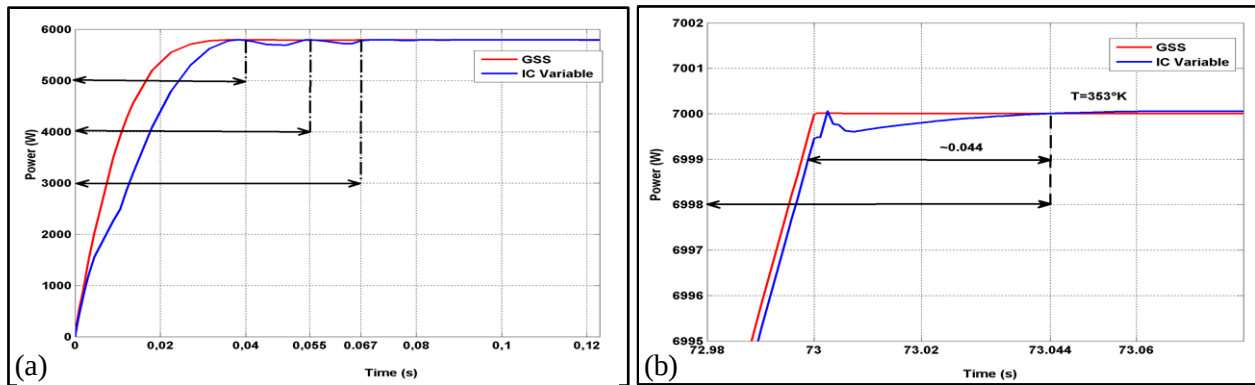


Figure V.47 PEMFC output power in case of cell temperature variation using GSS & Vss IC MPPT.

V.6.3.1.1 Dynamic performance in case of temperature change

Figures V.48 present the zoom-in of figure V.47 for the intervals 0-0.12s and 72-77s corresponding to $T=290\text{K}$ and $T=353\text{K}$ respectively.

Figure V.48 shows that the GSS MPPT performs better than the Vss IC MPPT in terms of convergence time to achieve the stabilization point, doing so in 44 ms as opposed to 67 ms for the Vss IC approach. Additionally, the suggested GSS MPPT algorithm also exhibits $\sim 0\text{W}$ overshoot, while the VSS IC method exhibits overshoot takes the values between 80-106W and 0.6W for $T=290\text{K}$ and $T=353\text{K}$ respectively, which significantly decreases the energy losses in dynamic situation.



Figures V.48 Response time and overshoot of PEMFC output power for the interval: a) 0-0.12s and b) 72-77s.

V.6.3.1.2 Static performance in case of temperature change

Figures V.49 present the zoom-in of figure V.47 for the intervals 49-55s and 75-87s to clarify the ripple for both utilized techniques. Figure V.49 confirms the superiority of the suggested GSS MPPT, it decreased the ripple until ~ 0 compared to the Vss IC-based MPPT that presents ripple reached at 0.05W and 0.54W.

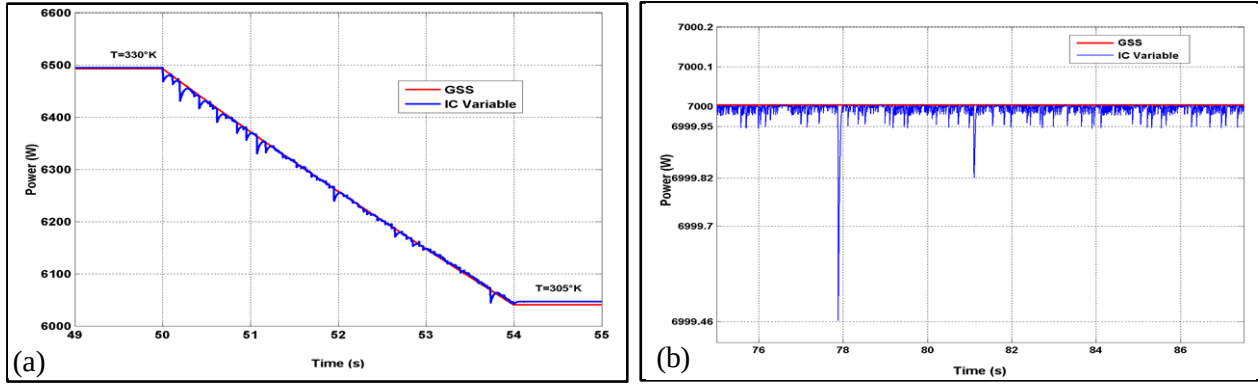
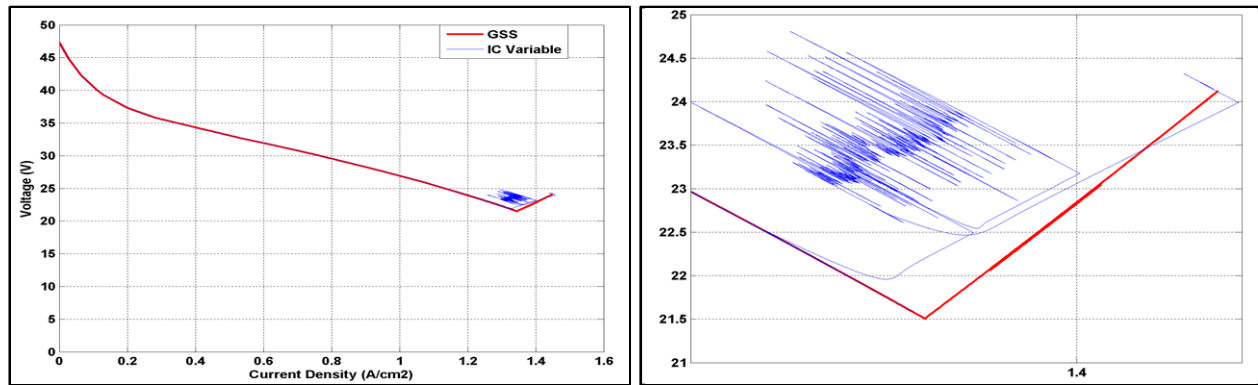
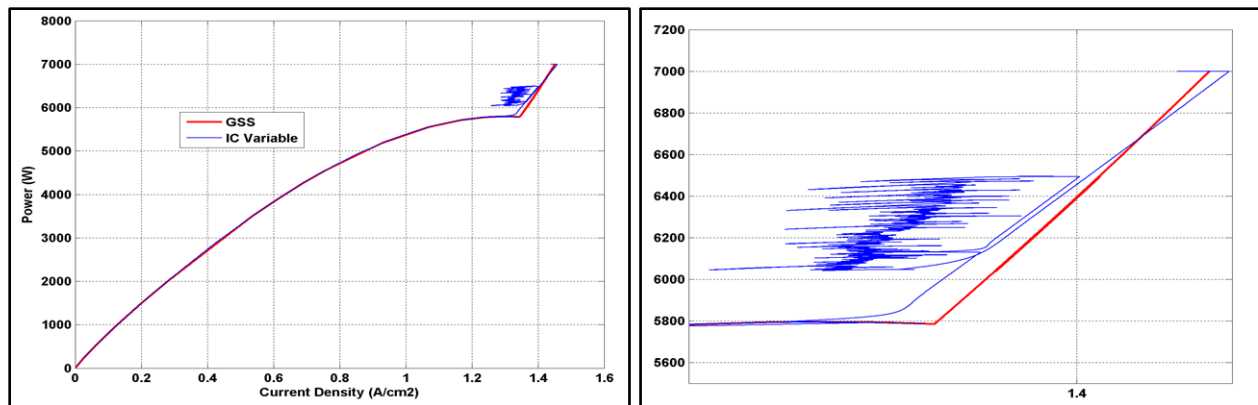


Figure V.49 The ripple of PEMFC output power for the interval: **a)** 49-55s and **b)** 75-87s.

Figures V.50 and V.51 exhibit the oscillations around the MPP utilizing both MPPT techniques by displaying the polarization curves of V_{FC} - I_{FC} and P_{FC} - I_{FC} , under temperature fluctuations that are shown in figure V.46. Figures V.50 and V.51 show that the suggested GSS MPPT does not oscillate around the MPP in contrast to the Vss IC MPPT.



Figures V.50 PEMFC U_{FC} - I_{FC} characteristic in case of cell temperature variation using GSS & Vss IC MPPT.



Figures V.51 PEMFC P_{FC} - I_{FC} characteristic in case cell temperature variation using GSS & Vss IC MPPT.

V.6.3.2 Case of the MWC change

In this scenario, as shown in figure V.52, we assess the tracking capabilities of the GSS MPPT technique in case of MWC change with constant temperature.

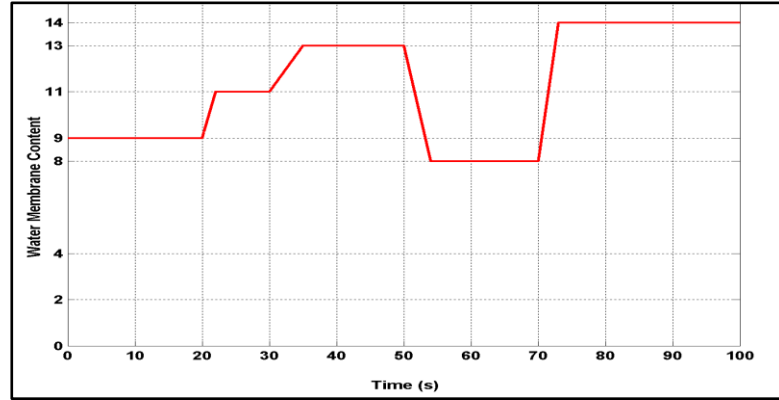


Figure V.52 Membrane water content variation.

In the event of MWC fluctuation, Figure V.53 displays the maximum output power utilizing both the suggested GSS and the Vss IC MPPTs. As anticipated, the MWC has a significant impact on how well the PEMFC performs. The maximum output power will increase with MWC's rise. When ($\phi = 09$), the maximum output power is 5389 W. The maximum output power of the PEMFC continues to increase, taking higher values of 6146 W, 6746 W, and 7 KW, along with increasing values of MWC ($\phi = 11$), ($\phi = 13$), and ($\phi = 14$), respectively. While dropping to 4936 watts at its lowest when the MWC equals ($\phi = 8$). On the other hand, figure V.53 shows that, both MPPT controllers follow the corresponding output power in the event of a changing MWC, as was shown in the case of a temperature shift.

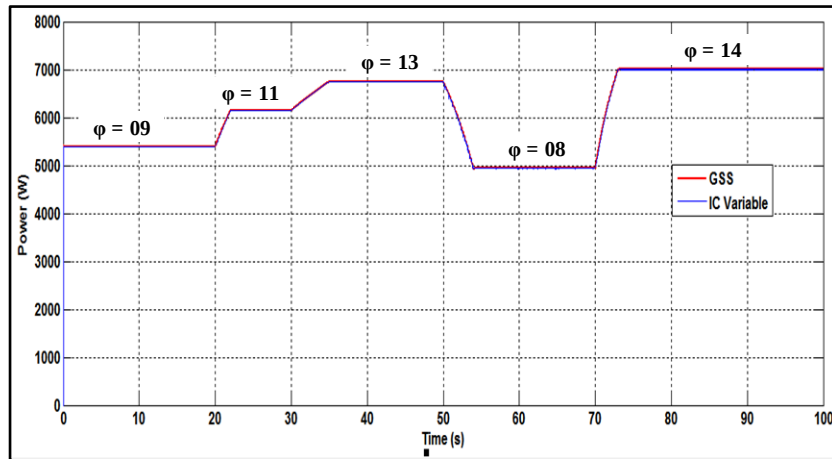


Figure V.53 PEMFC output power in case of MWC variations using GSS & Vss IC MPPT.

V.6.3.2.1 Dynamic performance in case of MWC change

Figures V.54 shows the zoom-in of figure V.53 for the intervals 0-0.12s and 21.5-22.5s corresponding to $\phi = 9$ and $\phi = 11$, respectively. It is evident that the GSS MPPT outperforms the Vss IC MPPT in terms of response time, it reached the MPP in just 36ms other than Vss IC MPPT that reached at MPP in 67 and 60ms. Another pros presented by the suggested method, it can be decrease the overshoot ~ 0 W as opposed to 130W-180W for $\phi = 9$ and 9.7W for $\phi = 11$ when utilizing the Vss IC method.

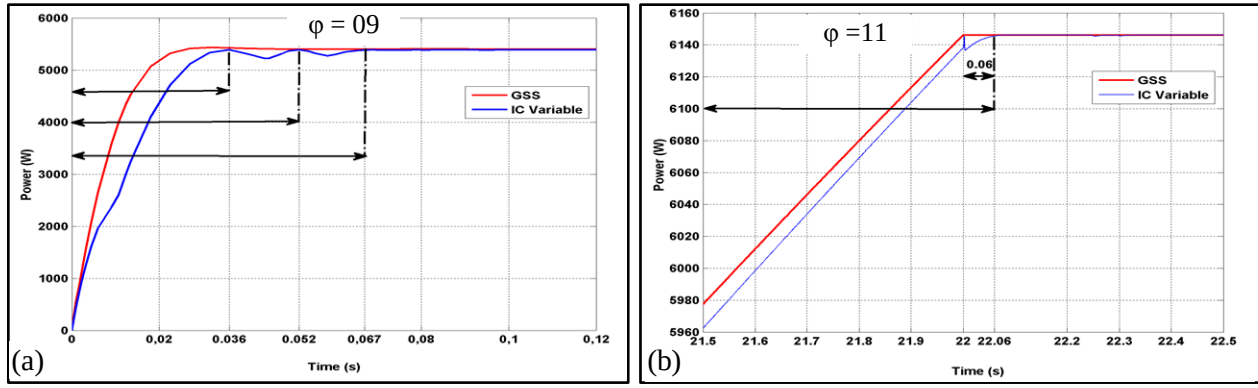


Figure V.54 Response time and overshoot of PEMFC output power for the interval: **a)** 0-0.12s and **b)** 21-22s.

V.6.3.2.2 Static performance of MWC change

Figures V.55 shows the zoom-in of figure V.53 corresponding to $\phi = 11$ and $\phi = 14$, respectively to illustrate the ripple using both algorithms. It shows that the GSS MPPT can remove the ripple in the event of a change in the MWC, in contrast to the Vss IC MPPT, which displays a ripple between 0.06W and 0.09W.

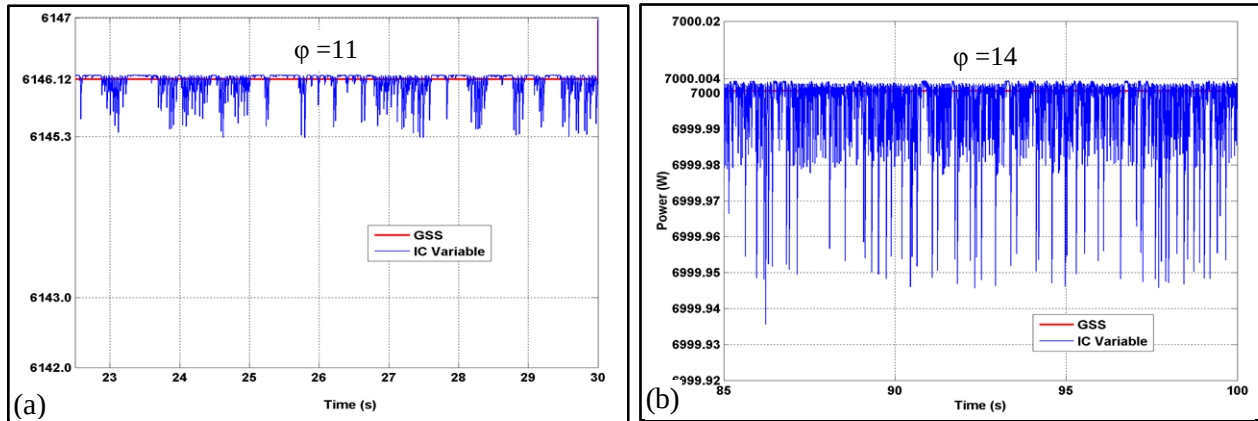


Figure V.55 The ripple of PEMFC output power for the interval: **a)** 22-30s and **b)** 85-100s.

As shown in figures V.56 and V.57, the suggested GSS MPPT exhibits less fluctuation near MPP than the Vss IC, which would increase the quantity of transmitted energy.

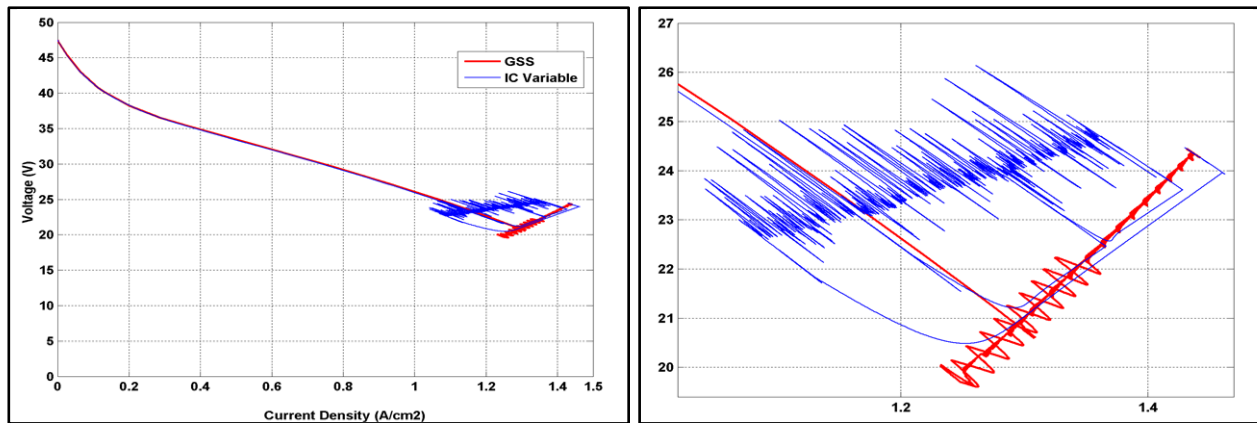


Figure V.56 PEMFC U_{FC} - I_{FC} characteristic in case of MWC variations using GSS & Vss IC MPPT.

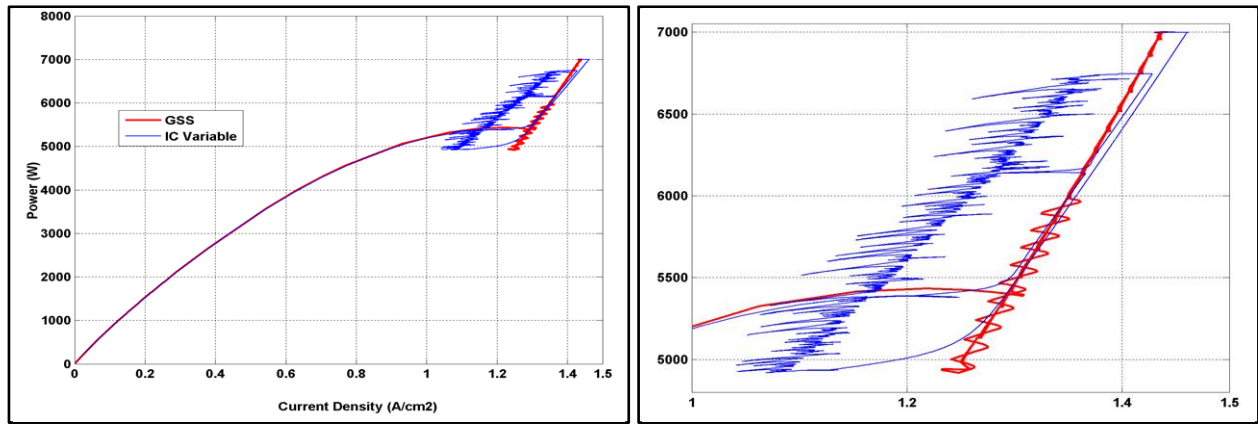


Figure V.57 PEMFC P_{FC} - I_{FC} characteristic in case MWC variations using GSS & Vss IC MPPT.

V.6.3.3 Discussion

Figures V.48 to V.49 and V.54 to V.55 illustrate how the suggested GSS MPPT algorithm performs well both dynamically and statically when temperature or MWC fluctuations are taken into account. Table V.6 presents a summary of the key findings for both methodologies. It shows that the recommended GSS MPPT approaches have the robust performance across all utilized measures, lowering response time by 34.33%, overshoot and ripple by around 100%, and neglecting oscillation around MPP while boosting PEMFC efficiency and enhancing the generated power.

Table V.6 Summarized results for GSS and Vss IC MPPT.

Test of:	Performance Measure		GSS MPPT		Vss IC MPPT		Average reduction ratio (%)
Temperature changes	Dynamic	Response time (ms)	44	44	67	67	34.33%
		Overshoot (W)	~0	~0	106	0.6	~100%
	Static	Oscillation around MPP	very weak	very weak	strong	strong	reduced
		Ripple (W)	~0	~0	0.54	0.05	~100%
MWC changes	Dynamic	Response time (ms)	<36	<36	67	60	40 to 46.27%
		Overshoot (W)	~0	~0	180	9.7	~100%
	Static	Oscillation around MPP	Weak	Weak	Strong	strong	reduced
		Ripple (W)	~0	~0	0.09	0.06	~100

V.7 Conclusion

This chapter deals the development of four MPPT algorithms to track the MPP, one for PV system and three for PEMFC system. The both systems have been successfully studied using a 150 W PV and 7 kW PEMFC fed by DC/DC boost converter derived using the proposed MPPTs controller. The results of simulation show that:

- The efficiency of the suggested Vss P&O technique is demonstrated by a comparative analysis of the results obtained for both the traditional Fss and the recommended Vss P&O-based MPPT to extract the MPP from PV source. The recommended method lowers power loss,

notably in the event of rapidly changing atmospheric circumstances, by reducing response time until 45.28% and the steady state oscillation between 83.33% and 100% in some cases .

- Neural network Vss IC-based MPPT controller for the PEMFC power system was proposed. The findings demonstrate that, in terms of convergence speed, overshoots, and steady state oscillations, the suggested MPPT performs better than both the traditional F_{ss} and the V_{ss} . The recommended MPPT method also significantly lowers voltage and current ripple. Knowing that a strong ripple current effect causes frequent trips due to overcurrent and even harmonics and may reduce the PEMFC lifetime, this property is crucial to increasing PEMFC efficiency and extending its lifespan.
- Single sensor MPPT controller was used to track the maximum power from PEMFC. According to simulation findings, the suggested 1S MPPT technique can successfully track the MPP utilizing just 1S for the PEMFC current. Results comparing the 1S MPPT to the 2S MPPTs demonstrate that the 2S MPPT performs better in terms of dynamic performances. However, the suggested 1S MPPT outperforms the 2S one when static performance is taken into account, enhancing PEMFC efficiency and extending PEMFC lifetime by minimizing frequent trips caused by over-current and even harmonics. Additionally, the suggested 1S MPPT exhibits strong dynamic and static performances utilizing only one sensor while accounting for rapid or typical temperature or hydrogen pressure fluctuations, which lowers the cost and complexity of the PEMFC power system.
- GSS-based MPPT is suggested method to oblige the PEMFC source to work at its MPP. The outcomes demonstrate that the suggested GSS MPPT has better advantages other than the Vss IC-based MPPT under the different scenarios of the operating conditions that applied, in terms of dynamic with static performances. As a result, the response time and the overshoot with ripple are reduced by 34.33% and by about 100% respectively, while the fluctuations around the MPP are neglected. Therefore, the PEMFC efficiency is boosted due to these characteristics. On the other hand, the advantage of the suggested approach is that it brackets the interval containing the local maximum in our case, and it continues to operate until the tolerance is greater than the resulting searched interval. This enables the proposed approach to track the MPP of the unimodal $P_{FC}(I_{FC})$ PEMFC characteristic more effectively than a linear algorithm with a very slow convergence rate. In addition, unlike certain linear methods, the suggested technique does not require any derivatives.

Chapter V

Optimization Sizing and Technical Economic Hybrid System PV/PEMFC

VI.1 Introduction

This chapter deals with the hybrid power generation system consisting of two generators PV/PEMFC connected to the load. Through this configuration, it is possible to provide power to many applications with high reliability and at affordable prices based on renewable energy sources PV/FC. HRES is constructed to be able to meet the pre-known electrical load consumptions, as the entire system consists of a mixture of photovoltaic arrays (PV), a FC stack, bank battery, an electrolyzer, and a hydrogen tank. This HRES supplying the cell tower located in the village of Ouanougha, country of Algeria.

In order to utilize HRES with high effectiveness in terms of technical and economical, the PV arrays number to be installed, the size of the PEMFC, battery bank, electrolyzer and hydrogen storage tank need to be calculated carefully considering all weather conditions. The optimum sizing process aids to ensure minimal investment with complete employ of the various components of HRES, so that the HRES can work at the best conditions in terms of economic feasibility and ensure continuity of power supply. Because over sizing the HRES components will raise the system cost while under sizing can lead to failure of power supply. Therefore, the optimization sizing of the HRES components is necessary through using HOMER software, in which combine between designing, planning and techno-economic analysis of HRES. The description of the HOMER software and HRES to be studied as well as the main results of simulation optimized are presented as follows:

VI.2 HOMER software description

In 1993, the National Renewable Energy Laboratory (NREL) USA has developed Hybrid Optimization Model for Electric Renewables (HOMER) software [73]. HOMER software is a powerful tool used by researchers in many countries, especially in remote and rural areas for optimal designing and planning of HRES [23]. It performs many simulations of the system, which may reach thousands in a period not exceeding one hour, in order to determine the optimal size of the system components based on economic technical analysis while ensuring the best possible compatibility between production and consumption [79]. HOMER has library includes several components to design the HRESs such as renewable and conventional energy resources (PV array, Wind, fuel cells, hydropower, biomass, Diesel generator, Electrical grid...etc), power electronic converter, battery, electrolyzer, hydrogen tank and other components. The loads can be found in the form of AC, DC, and/or hydrogen loads, as well as thermal loads. HOMER 2.68 beta software that used in this thesis is most widely used, its operation is simple and straightforward as well as freely available which developed in 2009, and its library is illustrated in figure VI.1.

In order to define the optimal sizes of the HRESs with high reliability and lowest cost, HOMER software needs three stages including simulation, optimization, and sensitivity analysis after the input data are fed into HOMER that includes some types such as: meteorological data, load profile, energy sources, equipment characteristics and economic data. Figure VI.2, present the principal methodology and the steps involved of the hybrid system modelling and analysis from the data input until the optimum system designing and sizing [417].

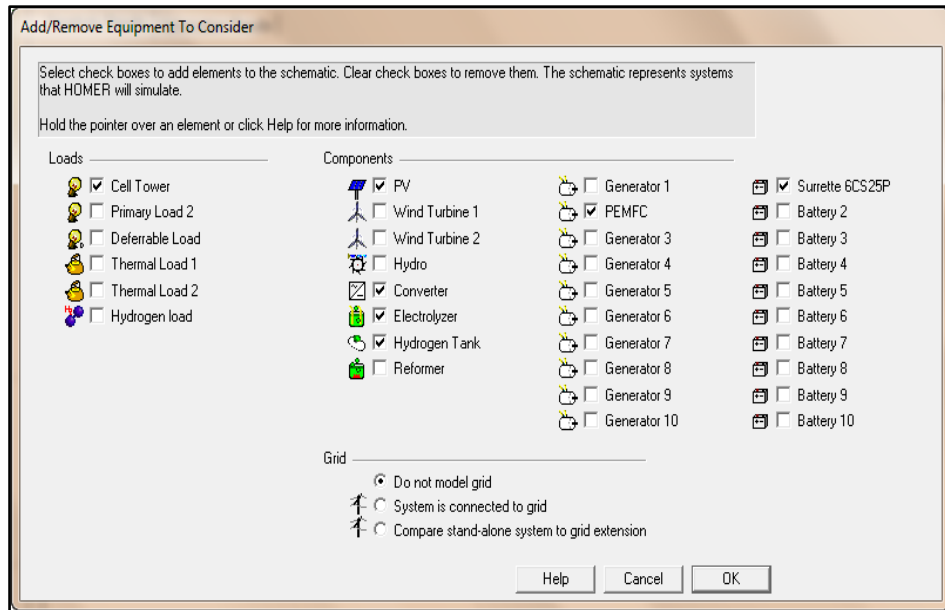


Figure VI.1 Library of HOMER software.

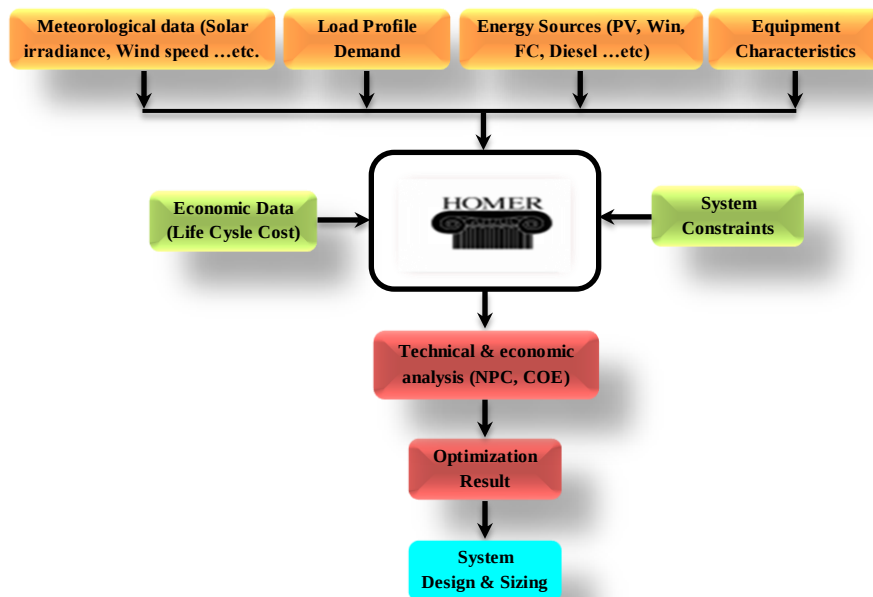


Figure VI.2 The Methodology of optimization and analysis procedure in HOMER.

VI.3 Inputs Data

VI.3.1 Climatic data

The climatic input data are sun radiation and temperature for PV array, wind speed for wind turbine and stream flow for hydropower. HOMER utilizes these inputs data to compute the power produced from these sources. HOMER software provides two methods for entering the meteorological data either manually or obtained from the NASA POWER (NASA Prediction of Worldwide Energy Resource) database, which makes it possible to obtain this data for each month simply by using the geographical coordinates (longitude and latitude), for the load location considered.

VI.3.2 Load profile

HOMER software provides two types of loads electric or thermal. The profile load or also named energy demand is the most important input data in the operating of HOMER for evaluating correctly the sources and optimizing. This information of the average consumption of load are fed into HOMER as daily profile and HOMER uses them to extract the average electricity consumption in kWh/day with the peak demand in kW as well as it is also used in power balance constraint. For the loads that have real load consumption data, it is easy to know the load consumption profile, but it is preferable to conduct a study to define the load profile in detail.

VI.3.3 Energy sources

HOMER software includes renewable/non-renewable energy resources such as: PV array, Wind turbine, Hydropower, diesel generator. Also, it provides the possibility of connected the HRES to the electrical network as another power source.

VI.3.4 Equipment characteristics

Equipment's in the HRES configuration based HOMER software are any system that generates, delivers, converts, or stores energy. According to the characteristics of each equipment in term of size, cost, fuel price and power, which is modeled in HOMER, efficient operation of it in HRES is determined.

VI.3.5 Economic data

In both steps of simulation and optimization, HOMER software needs the cost of all components involved in configuring HRES to searches for the optimal system configuration with the lowest total net present cost. Therefore, several costs data must be defined such as: initial construction, operation and maintenance, capital, and component replacements cost, fuel price, buying power from the grid, emissions penalty, system fixed capital cost as well as operation and maintenance cost and finally project lifetime are the different economic data that can be considered in HOMER.

VI.4 HOMER optimization procedure

After designing the HRES using the HOMER library and entering all the input data into HOMER for each component; the optimization sizing process is determined in three successive phases: simulation, optimization, and sensitivity analysis. It is only worth noting that the stage of simulation and the stage of optimization are done simultaneously. These stages are described as follows [121, 136, 418]:

VI.4.1 Simulation stage

Simulation stage is the first step in the he Homer software to build the rest of the required processes. In this stage, HOMER defines the various possible system configurations, number of components required, sizes, and dispatch power strategy. Therefore, simulation process can analyses the performance of HRES configuration to determine its technical feasibility and life-cycle cost, which is the mixing of both installing and operating cost. HOMER has a key feature which is

the ability to simulate for a long-time; it simulates the HRES based on the components selected by the user for 8760 hr in a year.

VI.4.2 Optimization stage

In this stage, among several varieties of system configurations that developed during simulation stage, the optimization process looks for the best system configuration that meets the required technical constraints at the lowest life-cycle cost. Therefore, the feasible configurations are arranged according to the lowest NPC and lowest COE. In addition, the objectives of this stage are to decide the optimal value of each component.

VI.4.3 Sensitivity stage

HOMER allows making certain assumptions that enable us to study the effect of certain variables on the system configuration. These assumptions are named sensitivity analysis. There are several variables that through it can be analysis the sensitivity of the HRES such as: fuel costs, irradiation, wind speed, interest rate, grid price...etc. The objective of the sensitivity analysis process is to know how the outputs results are affected by change in the inputs. HOMER software has the possibility to analyze several sensitive values at a time to search the best system configuration.

VI.5 Case Study

For any energy production system, the definition of load consumption is one of the key steps in order to determine the optimum size of the entire system components. Mostly, there are loads that always need continuity in the electrical power delivery service to avoid interruptions due to the importance of their services. Among these loads, we find that communication technology systems that operate continuously without stopping are considered a critical load, and that is why electrical energy must be provided constantly. Therefore, each electric load request continuous feeding without stopping, good quality and reliability of electrical power. In this work, an electrical load represented by a cell tower located in Ouanougha village was selected to test the feasibility of the HRES design.

Energy requirement of the cell tower is currently supplied by electrical network through transformer with a power of 160KVA. The electrical network connecting this transformer and the power source extends for a length of more than 100 km, which makes this region as a whole suffer from the problem of voltage drop, frequent interruptions as a result of the fall of electric columns or wires. On the other hand, this type of load is located at the up of the mountain, which makes it difficult to connect and maintain the electrical network.

The proposed case study aims to facilitate the definition of HRES for stand-alone mode that combining PV/PEMFC for supplying known electrical load requirements of cell tower, in addition to the possibility of exploiting available energy renewable sources and testing the feasibility of the designed HRES for the cell tower by using HOMER software.

VI.6 Input parameters description of HRES components

In this section, after the load profile is defined, as well as the data on solar radiation and temperature in the area of the cell tower site, we will talk about the characteristics of the component parts of this HRES presented in figure VI.3, which includes six principal components should be designed: PV source, bank battery, electrolyzer device, PEMFC stack which ensures feeding through hydrogen tank; DC/AC inverter to feed cell tower. To get realistic results with optimal configuration for the HRES component sizes, a few economic characteristics have to be given for each component as follows:

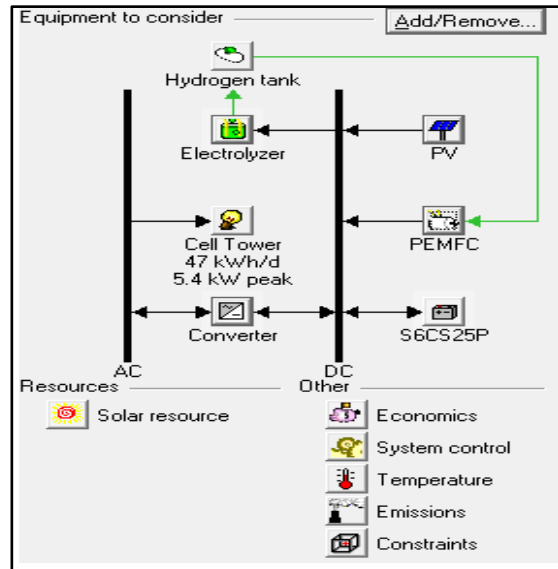


Figure VI.3 Schematic diagram of PV, Battery and PEMFC based system.

VI.6.1 Load profile

One of the most important parts in this type of studies is load profile modelling of evaluating the renewable energy sources correctly and determining the optimal sizing of the system components as a whole. Figure VI.4 exhibit the energy consumption profile of the load that studied, in which the consumptions of electricity in this load by the electrical appliances such as: power converters (DC/DC, DC/AC and AC/DC), Lamps, signalization lamp, air conditioning, electric fireplace and other devices.

In fact, these curves presented in figure VI.4 are obtained from the interface provided by Homer as illustrated in figure VI.5, through which the nature of the load is selected in addition to entering the data of the load consumption during the whole day for the different months of the year either manually or by calling a file containing this data. HOMER iterates this profile throughout the year unless you specify different load profiles for different months or day types. The interface also gives a table showing the total information of the proposed pregnancy, which includes the average electricity consumption 47.3 kWh/day and peak demand 5.37 kW.

Load profile can be showed from HOMER software by other possible types of graphics such as seasonal profile and Data Map (DMap) as presented in the figure VI.5 or by clicking on the icon of plot to show the load profile hourly during all year. The seasonal profile graphic is display by a box

and whisker, each box includes five data. The top and the minimum line of whisker represent the overall maximum and minimum monthly consumption. While the maximum and minimum line of the blue box corresponds to the average of the daily maximum and minimum consumptions on all days of the month. The middle line in the blue box is represents the overall average for the entire month. On the other hand, a data map (DMap) is a type of graph that has two axes, one representing the hours of the day and the other representing the days of the year. DMap showing the load consumption during one year of time series data, each time step of the year is represented by a rectangle which is colored according to the value of the power consumption.

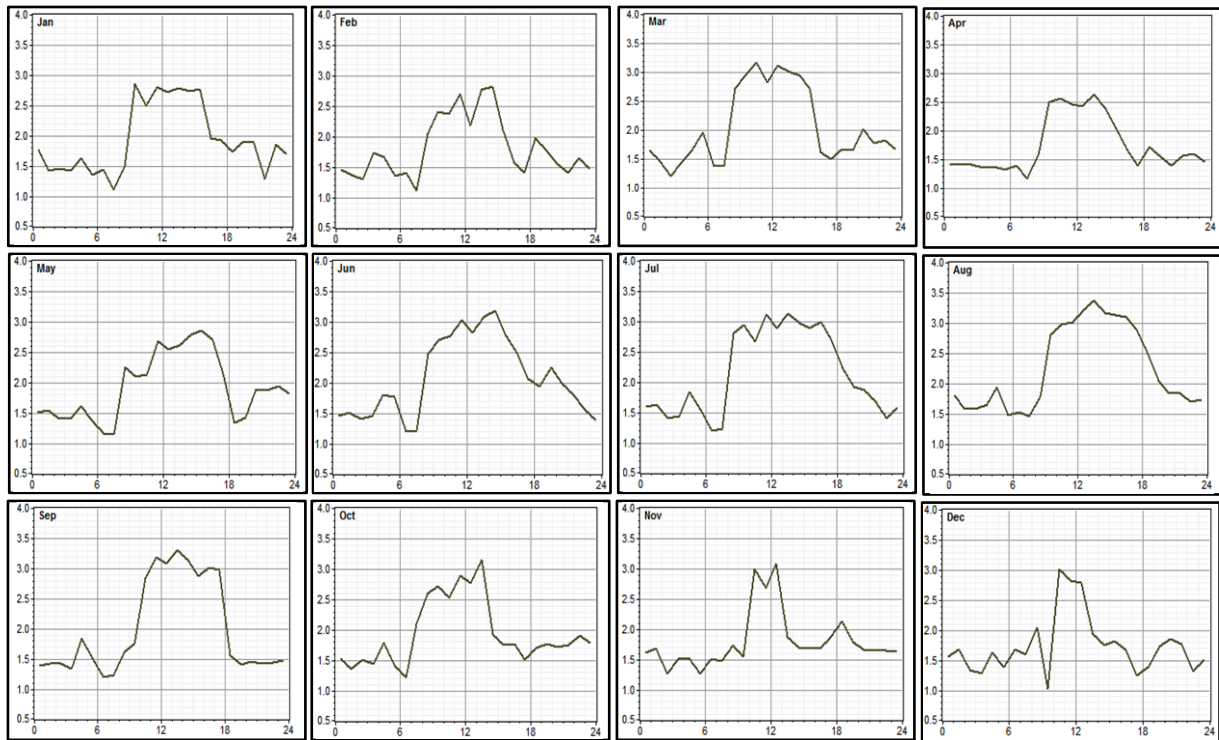


Figure VI.4 Profile of the average power demand per month.

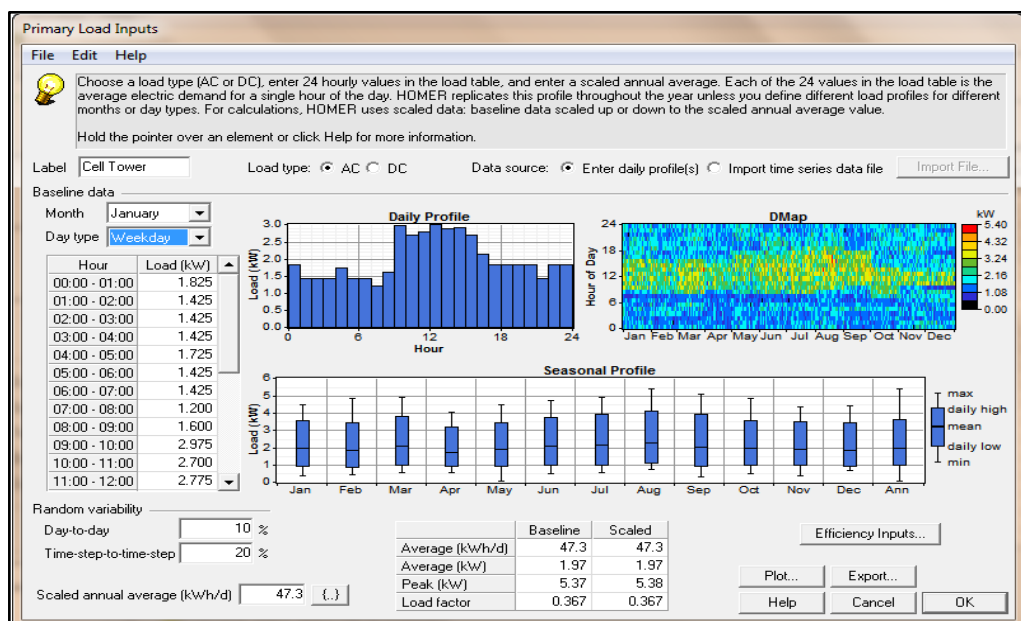


Figure VI.5 Interface HOMER software for load consumptions data.

VI.6.2 Solar radiation and temperature

Power generation from solar panels depends on climatic conditions, which vary according to the location and season. Therefore, an important requirement for solar energy harvesting is information on the amount of solar radiation and temperature received at the study site. HOMER provides a window to designate the coordinates (latitude and longitude) to generate the data for the photovoltaic array for each hour of the year. The geographic location of the cell tower is entered into the HOMER program using latitude and longitude of 35°98N, 4°21E respectively, for the purpose of entering sun radiation and temperature data's. Figure VI.6 exhibits the data's of sun radiation and temperature per month for the selected location. It is clear that the sun radiation and temperature vary according to the month of the year; it records a minimum and maximum value. For sun radiation, the minimum value is recorded in month of December 2,360 kWh/m²/day, while the maximum value recorded in month of June 7,710 kWh/m²/day; in which it rises during the summer and reduces during the winter. The same can be said for the average temperature, where the monthly average lower is 5°C and the upper is 25°C.

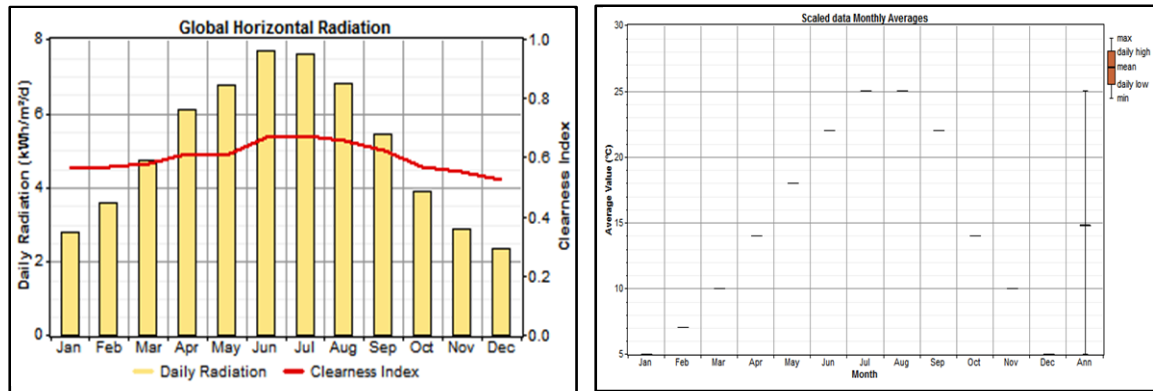


Figure VI.6 Monthly average of radiations and ambient temperatures.

VI.6.3 Components characteristic

VI.6.3.1 Solar PV panels

From the components of HOMER library, we choose the source of solar energy as the primary source to feed load. Homer software allows entering some parameters for PV panels divided into four sections: the panel costs section, the panel field sizes to be considered, the properties associated with the panels and advanced properties that can be completed. Regarding to the cost, it is linked to the rate of the energy generated as well as to the three costs known as installation, replacement and maintenance related to the tracking system. According to [151], the cost of PV panel to produce 1 kW is considered 1000\$. While the replacement and the operating and maintenance cost are considered 700\$ and 50\$/yr respectively. Then, it is necessary to indicate the power of solar panels in kW with which the HOMER software must make the simulations; the capacity range considered for this simulation is 5 kW to 15 kW assuming the cost curve is linear. In general, most manufacturers indicate on the data plate the life span of the PV panels, which is often 20 years. On the other hand, it should be noted that there are several factors that affect, either positively or negatively, the yield of the PV panel, including: the reflection of sun radiation from the earth estimated of 20%, and the derating factor that used to approximate the effect of

temperature variation, snow, wiring losses dust, shading, and aging [151]. Additionally, two factors must be mentioned are slope angle and azimuth range that taken the values of 36° and 0° and referring to the slope of the panels with the site and direction toward the south respectively. The last section contains the advanced properties includes two information's, one about the sun tracking system and the other about the effect of temperature on the arrays. For the system tracking system, we can choose that no tracking i.e. the PV arrays is mounted at a fixed slope, which is the simplest and most common case. To consider the effect of temperature on the efficiency of arrays, you need the following data: temperature coefficient of power ($\%/^\circ\text{C}$), nominal operating cell temperature ($^\circ\text{C}$) and the efficiency at the STC. Figure VI.7 shows the interface of HOMER for all parameters of PV array source.

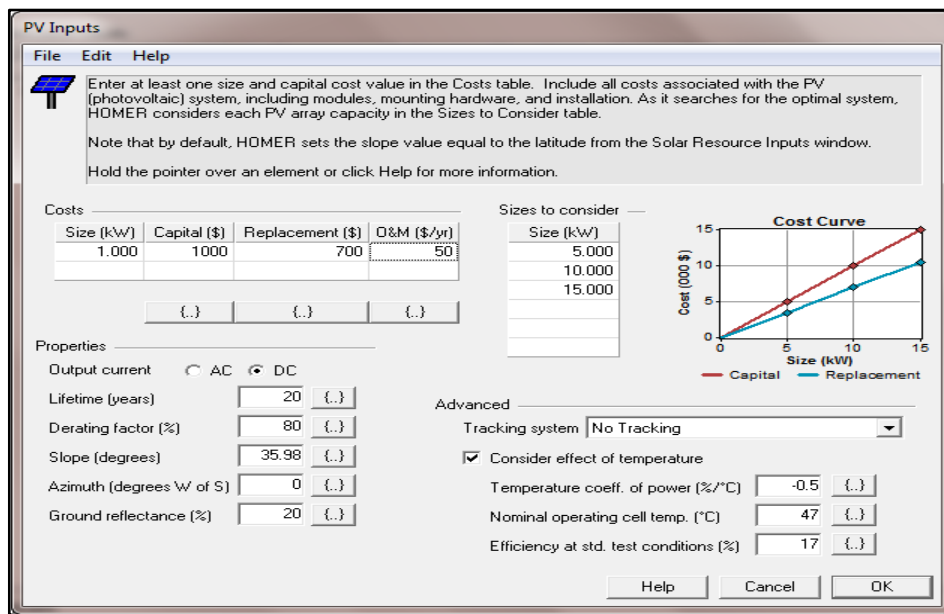


Figure VI.7 Parameters of PV panels.

VI.6.3.2 PEM Fuel Cell

As mentioned previously in chapter III, there are six sorts of FCs ready in the market. The choice of FC sort generally depends on the application to be accomplished. Despite this variety, there is no specific model available in HOMER software of FC can be simulated; therefore, the technical specifications and cost range of the PEMFC kind were considered. So, due to the use of this sort of FC in such applications, it has been adopted in this study. In this simulation, the capital cost varies between 3000\$-6000\$ as reference cost for PEMFC stack of 5 kW, as this total cost includes the PEMFC stack with auxiliary devices like compressor ...etc [419, 420]. While, the capital, replacement and O&M cost is estimated to be 3000 \$, 2500 \$ and 0.080 \$/h, respectively [1]. On the other hand, the PEMFC lifetime was assumed would last 40,000 hour and the minimum load ratio is 10% [1]. The sizes considered in this simulation range from 1 to 9 kW. Figure VI.8 shows the interface of HOMER for all parameters of PEMFC stack source.

The operating mode of PEMFC is different of PV arrays, only we click on the icon of Schedule to select its operating mode. The figure VI.9 present the operating mode of PEMFC, in which two steps must be completed to select the operating mode, the first contains three operating modes are:

forced on, forced off and optimized mode. PEMFC operates at night but the duration varies according to the months of the year, in which starts from 17:00 until 8:00 during the months of September, Octobre, November, December, January, February, March and April, while during the rest of the months operated from 18:00 until 7:00.. Whereas the remaining hours of days were chosen for the both modes optimized and forced off. The second step about the select time period that includes: All week, Weekdays and Weekends. All week time period has been selected in this simulation for the operating mode of PEMFC stack.

Generator Inputs

Choose a fuel, and enter at least one size, capital cost and operation and maintenance (O&M) value in the Costs table. Note that the capital cost includes installation costs, and that the O&M cost is expressed in dollars per operating hour. Enter a nonzero heat recovery ratio if heat will be recovered from this generator to serve thermal load. As it searches for the optimal system, HOMER will consider each generator size in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Cost | **Fuel** | **Schedule** | **Emissions**

Costs

Size (kW)	Capital (\$)	Replacement (\$)	O&M (\$/hr)
5.000	3000	2500	0.080
10.000	6000	5000	0.160
{..}	{..}	{..}	{..}

Sizes to consider

Size (kW)
1.000
2.000
3.000
4.000
5.000
6.000
7.000

Cost Curve

Cost (000 \$) vs Size (kW)

Legend: Capital (red line), Replacement (blue line)

Properties

Description: PEMFC Type: ☐ AC ☒ DC

Abbreviation: PEMFC

Lifetime (operating hours): 40000 {..}

Minimum load ratio (%): 10 {..}

Help Cancel OK

Figure VI.8 Parameters of PEMFC stack.

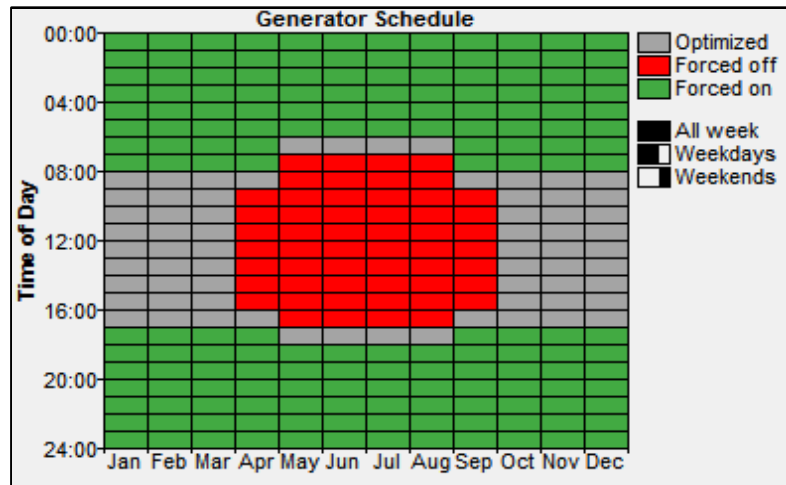


Figure VI.9 The operating mode of PEMFC stack.

VI.6.3.3 Battery storage bank

The battery bank is fundamental in a HRES in order to store the surplus energy which is later used to ensure a continuous power supply when any production shortfalls are recorded. For batteries, figure VI.10, you can choose a battery type from library of HOMER or enter new type that is not in the HOMER database. Once the type of batteries has been chosen, the properties will

be displayed automatically. Through many batteries available in library of HOMER, the Vision 6FM200D battery was chosen in this HRES. The specifications of this sort are terminal voltage 12V and capacity 200 Ah. On the other hand, it is necessary to enter cost data which includes capital, replacement and O&M cost. 600 \$ is the total capital cost of each battery and 110 \$ as replacement cost, while the O&M needs only 10 \$ [421]. Then, we indicate the quantities of batteries with which the software must make the simulations in the section of sizes to consider. Finally, in the advanced properties section, we can determine how many series batteries there are in each string that will be in parallel and we can also define a minimum battery life. This battery bank is composed of eight batteries connected in two strings in parallel, in which each string contains four batteries connected in series. Therefore the voltage of the DC bus is 48 V. During simulation, HOMER software does not take into account the impact of temperature variations on the operating of battery bank and thus the batteries maintain their lifetime of 3 years [421].

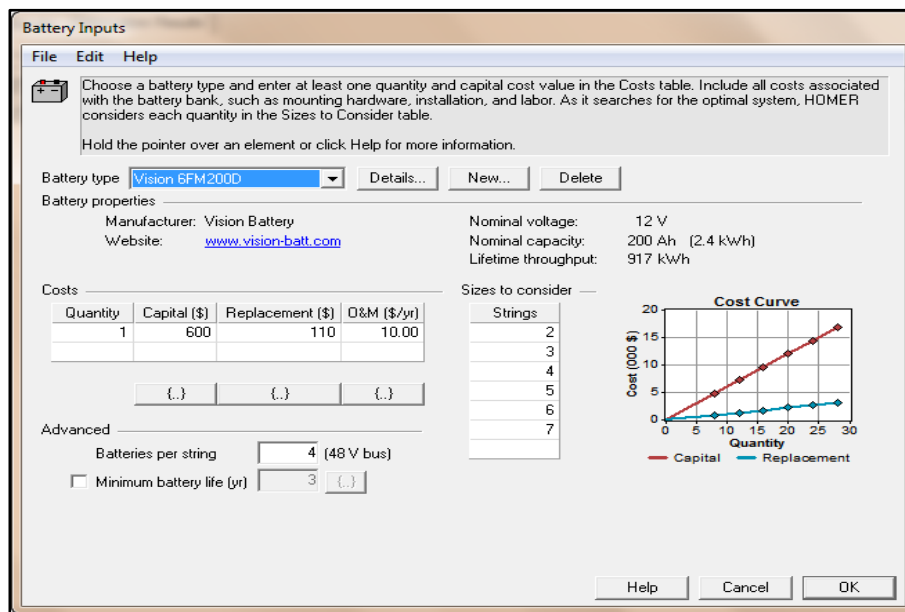


Figure VI.10 Parameters of Battery.

VI.6.3.4 Electrolyzer unit

Hydrogen is defined as a gaseous substance that consists of hydrogen atoms, which is the simplest element chemically on earth, as its atom contains a positive proton attached to only one negative electron, which gives it a light weight. In addition, it is considered the most abundant element, as it enters into the composition of more than 90% of the substances discovered [422]. It is easy to find hydrogen-rich substances in nature, such as water that contains two hydrogen atoms and one oxygen atom, but extracting it as an element alone is rather difficult and requires modern technology. Therefore, the technology of electrolyzer is employed to produce hydrogen through water electrolysis process [423]. It converts the DC electrical energy into chemical energy stored in hydrogen [424]. Indeed, the amount of hydrogen produced from the electrolyzer is directly proportional to the direct electrical current that supplied and the number of electrolyzer cells connected in series. On the other hand, the economic data regarding to the cost of the electrolyzer per kW is estimated between 1500\$-3000\$ [1], The installation, replacement and annual O&M costs are also considered, which are estimated at 1500\$/kW, 1000\$/kW and 5\$/yr respectively.

The lifetime and efficiency are considered 20 years and 80 % respectively. Figure VI.11 shows the interface of HOMER for all parameters of electrolyzer.

VI.6.3.5 Hydrogen tank

According to the operating mode of PEMFC stack and the suggested strategy to ensure the supply of cell tower, the PEMFC source needs significant amount of hydrogen that produced by the electrolyzer during day in order to generate the electrical power. Therefore, it must be stored the hydrogen in tanks to ensure continuous feeding for PEMFC and later the cell tower. In practice, there are two widespread technologies for storing hydrogen either as compressed gas in tanks or as metal hydride [425]. From paper [426], the price hydrogen gas linked to the volume of hydrogen tank, which is estimated to be 1500 \$ per 1.2 kg of hydrogen. Figure VI.12 shows the interface of HOMER for all parameters of hydrogen tank.

Electrolyzer Inputs

File Edit Help

An electrolyzer generates hydrogen from electricity. Enter at least one size and capital cost value in the Costs table. Include all costs associated with the electrolyzer such as installation, hardware, and labor. As it searches for the optimal system, HOMER will consider each electrolyzer size in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Size (kW)	Capital (\$)	Replacement (\$)	O&M (\$/yr)
1.200	1500	1000	5

Properties

Lifetime (years) 20 Type ☐ AC ☒ DC

Efficiency (%) 80

Minimum load ratio (%) 10

Sizes to consider

Size (kW)
0.500
1.000
2.000
3.000
4.000
5.000
6.000
7.000

Cost Curve

Cost (000 \$)

Size (kW)

— Capital — Replacement

Help Cancel OK

Figure VI.11 Parameters of Electrolyzer unit.

Hydrogen Tank Inputs

File Edit Help

The hydrogen tank stores hydrogen either for use in a generator or for serving a hydrogen load. Enter at least one tank size and capital cost value in the Costs table. HOMER will consider each tank size in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Size (kg)	Capital (\$)	Replacement (\$)	O&M (\$/yr)
1.200	1200	800	2

Properties

Lifetime (years) 25

Initial tank level

☒ Relative to tank size (%) 10

☐ Absolute amount (kg) 1

☐ Require year-end tank level to equal or exceed initial tank level

Sizes to consider

Size (kg)
0.500
0.700
1.000
2.000
4.000
5.000
6.000

Cost Curve

Cost (000 \$)

Size (kg)

— Capital — Replacement

Help Cancel OK

Figure VI.12 Parameters of Hydrogen Tank.

VI.6.3.6 Converter

The output power from the both sources that used in design HRES in addition to the battery bank are form of DC energy, while the cell tower is AC energy based. Thus, the introduction of DC/AC converter (inverter) between PV/PEMFC sources and cell tower is essential in order to convert the DC power to the AC power. During the simulation, the HOMER software determines the appropriate inverter size based the output power generated from HRES. The specification of the converter that used is characterized by its efficiency is 90% and lifetime is up to 15 years [124]. On the other hand, regarding to the economic data of inverter in terms of capital and replacement cost, it is given per kilowatt as follows: 800 \$ and 750 \$ respectively [151]. Meanwhile, O&M cost for converter DC/AC is 2 \$/yr. Figure VI.13 shows the interface of HOMER for all parameters of converter.

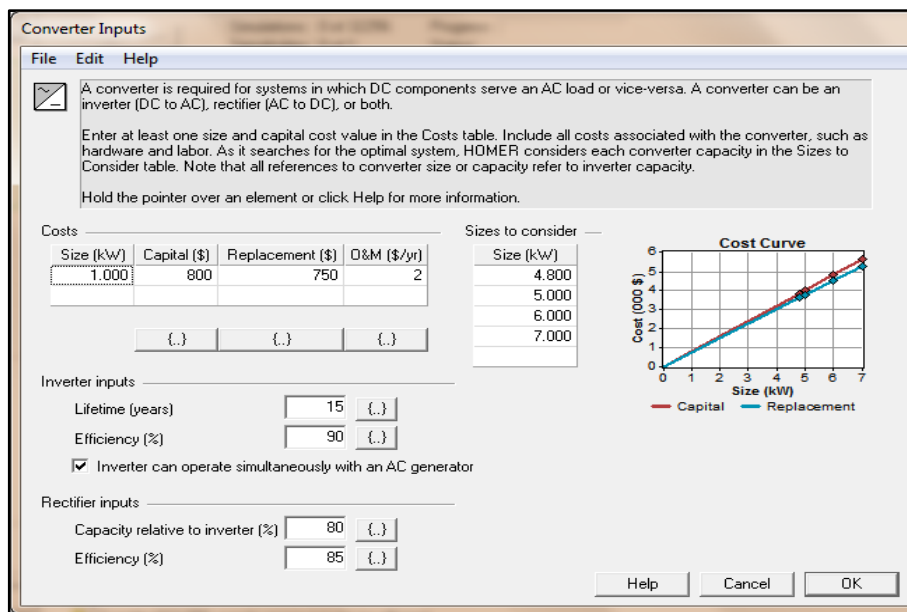


Figure VI.13 Parameters of Converter.

VI.7 Results of simulation

VI.7.1 Optimization results

According to the input parameters discussed previously such as: cell tower consumptions profile, meteorological data, green energy sources, technico-economic specifications of the HRES equipments, HOMER simulates all possible configurations that ensure the provision of cell tower requirements, and these configurations are displayed in list includes each them the components of the HRES, in ascending order from least to highest cost according to the NPC criteria. Figure V.14 shows the overall optimization results of HRES generated by HOMER software. The table of figure VI.14 is divided into rows and columns. Each row displays an applicable HRES configuration. While, there are 15 columns that can be grouped into three groups. The first four columns indicate the main components of the system which include: PV system, PEMFC, Batteries and power converter, the second group encloses six columns indicate the optimization sizing of components, and the rest five columns enclose the optimization criteria's i.e., the initial capital cost of the HRES, the operating cost, the total NPC, the levelized COE and capacity shortage.

	PV (kW)	PEMFC (kW)	Conv (kW)	Elec (kW)	H2 Tank (kg)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Capacity Shortage
1	12	7	3	7.0	5	35850	1974	64384	0.259	0.05
2	10	7	12	7.0	5	36250	1949	64419	0.259	0.05
3	12	7	8	7.0	5	36850	1967	65261	0.262	0.04
4	10	7	12	7.0	5	37250	1942	65324	0.263	0.04
5	12	7	8	8.0	5	36650	1984	65333	0.263	0.04
6	10	7	12	8.0	5	37050	1959	65368	0.263	0.05
7	10	7	16	6.0	5	36850	1989	65593	0.264	0.05
8	12	7	12	6.0	5	36450	2021	65668	0.264	0.04
9	10	7	16	6.0	5	37850	1962	66216	0.266	0.04
10	12	7	8	7.0	5	37850	1963	66228	0.266	0.04
11	12	7	8	8.0	5	37650	1977	66230	0.266	0.04
12	12	7	12	6.0	5	37450	1993	66257	0.266	0.03
13	10	7	12	8.0	5	38050	1953	66273	0.267	0.04
14	10	7	12	7.0	5	38250	1940	66293	0.267	0.04
15	10	7	16	7.0	5	37650	1999	66542	0.268	0.04
16	12	7	12	6.0	5	36450	2086	66607	0.268	0.04
17	12	7	12	7.0	5	37250	2032	66617	0.267	0.03
18	10	7	16	6.0	5	36850	2073	66811	0.269	0.05
19	12	7	8	7.0	6	38100	1994	66918	0.269	0.05
20	10	7	16	6.0	5	38850	1958	67153	0.270	0.04
21	12	7	12	6.0	5	38450	1986	67159	0.270	0.03
22	10	7	16	7.0	5	38650	1973	67165	0.270	0.03
23	12	7	8	8.0	5	38650	1974	67177	0.270	0.04
24	12	7	12	7.0	5	38250	2003	67206	0.270	0.02
25	12	7	12	6.0	5	37450	2060	67231	0.270	0.04
26	10	7	12	8.0	5	39050	1950	67242	0.271	0.04

Figure VI.14 Optimization results of PV/PEMFC hybrid configuration.

VI.7.2 Economic analysis

The first row in table of the figure VI.14 displays the optimal configuration for HRES, because it has lowest total NPC compared to the other configurations. The initial capital cost of this optimal system is 35850 \$ with yearly operating cost of 1974 \$/y, and TNPC of 64384 \$, and COE of 0.259 \$/kWh.

According to the definition presented in the chapter I about the NPC for the HRES, it sum of three cash flows that includes capital cost, replacement and O&M. Through the table VI.1, it can be noted that the capital cost is the highest followed by O&M and replacement cost. The PV system takes a large share of the capital cost, while other components of the HRES (PEMFC stack, battery, Electrolyzer and converter) take lower costs. For O&M, it also very expensive in the design of the HRES, in which the both sources PV and PEMFC stack take highest value. Meanwhile, PEMFC has highest for replacement cost. The figure VI.15 gives a graphical representation of component based NPC.

Table VI.1 Cost detail of the HRES components.

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
PV	12	3,32	8,67	0	-1,97	22,018
PEMFC	4,2	5,54	8,88	0	-627	17,994
Battery	4,8	1,51	1,16	0	-8	7,462
Converter	5,6	2,07	202	0	-1,23	6,643
Electrolyzer	6,25	1,65	301	0	-979	7,219
Hydrogen Tank	2	0	48	0	0	2,048
Other	1	0	0	0	0	1
HRES	35,850	14,1	19,26	0	-4,82	64,38

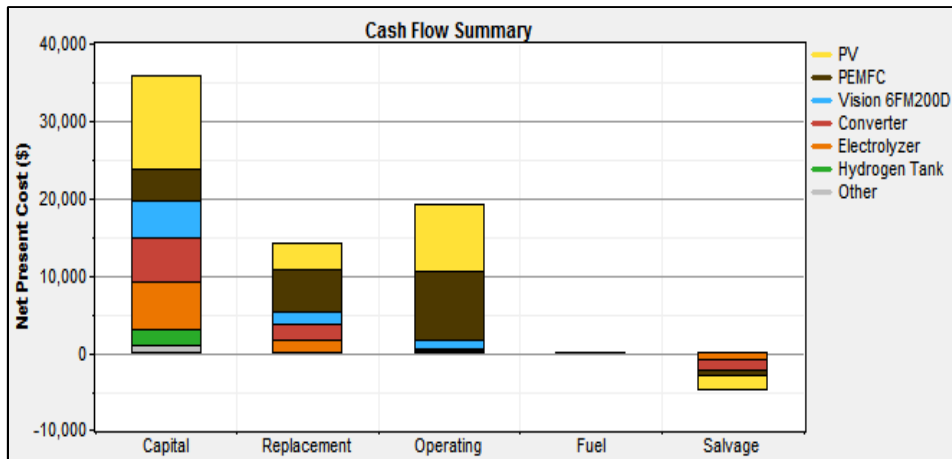


Figure VI.15 Cash flow summary of the optimized system by cost type.

Figure VI.16 shows the yearly cash flow over the life of the HRES which gives an overview of whether the project is financially attractive or not. The columns show the value of the total financial flow for each year by component type, where the negative value of the columns indicates the outflow (expenditures) due to replacement, or O&M of equipment's, While there are returns from all components at the end of the life of the system as a whole, where their value is indicated in the last column by a positive value. The first bar for year zero represents the estimated capital cost of the system at 35,850\$. Throughout the life of the project, it can be noted that during the 8th, 15th and 22th year, some expenses related to the operations of replacement, or operating and maintenance of the PEMFC system, as well as for the battery during the 7th, 13th and 19th year, as for the PV system, converter and electrolyzer, it will be in the 20th year. However, throughout the life of the project, all of the equipment replacement or operation and maintenance operations relate only to the fuel cell and photovoltaic system, but they are inexpensive.

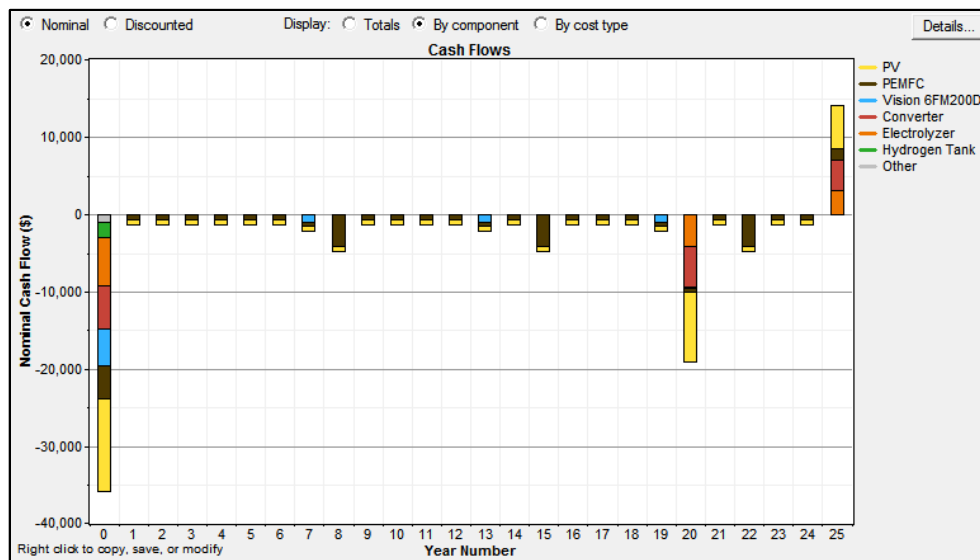


Figure VI.16 Cash flow information of the HRES.

VI.7.3 Technical analysis

In this part, details of electrical production and consumption rates generated by HOMER software for all sources and loads are presented in Table VI.2. The exploitation of this data shows

that the total energy production that was generated from the HRES was about 27,733 kWh/yr with The PV energy source contributes about 69% of the overall energy produced, or around 19,235 kWh/year, it considered the principal source in this HRES, while the PEMFC stack source comes second to contribute about 31% or 8,498 kWh/yr. This disparity in energy productivity between the two sources is due to the fact that the load consumes more energy during the day which requires more production, while PEMFC is used at night when load demands are less, in addition to the operating strategy that takes into account the price of energy generated by the hydrogen-based system. From HOMER software, the maximum output power from the solar PV array is 11.7 kW with monthly average energy production of just about 3 kW, as well as for PEMFC the maximum output power is 3.87 kW with monthly average energy production of just about 1 kW. Figure VI.17 shows the monthly average electric production from PV and PEMFC.

In fact, the electricity consumption produced is divided between the cell tower and the electrolyzer unit, in which the overall consumptions reached 23,431 kWh/yr. The highest amount consumed by the cell tower is 17,207 kWh/yr, which shows 73% of overall consumption, while the rest amount consumed by the electrolyzer unit is 6,225 kWh/yr, which represent only 27%. On the other hand, the whole system in terms of energy production shows an excess of energy of 7.71 % i.e. about 2,138 kWh/yr. Also, the unmet electric load is only 0.33 % with electricity shortage is 4.52 % which represent 57.8 kWh/yr and 781 kWh/yr respectively. Therefore, the HRES can supply almost the whole load demand.

Table VI.2 Total production and consumption of the HRES.

Production output (kWh/yr)				
PV array	PEMFC	Total Production		
	19,235	8,498	27,733	
69%	31%	100%		
System parameters (kWh/yr)				
Load consumption	Electrolyzer consumption	Excess Electricity	Unmet Electric Load	Capacity Shortage
	17,207	6,225	2,138	57.8
73 %	27 %	7.71 %	0.33 %	4.52 %

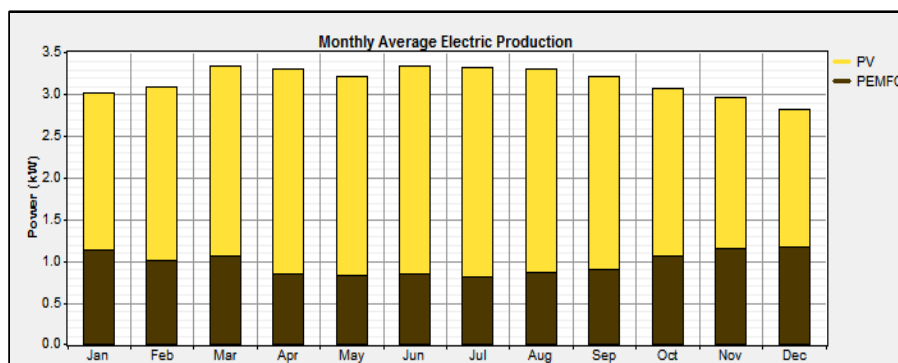


Figure VI.17 Monthly average electrical production results.

The optimization sizing of PV array obtained has a rated capacity of 12 kW. Mostly, the PV array of the HRES can produce the energy needed for every day of the year with some exceptions due to various weather conditions. From figure VI.18, which shows the output of the PV array

during the days of the year, the operation of the PV array generally starts generating power from 7 to 8 in the morning and stopped producing energy around 6 PM. The PV array was operated for about 4,387 hours per year, and the levelized cost of the energy produced was 0.0792\$/kWh. On the other hand, the color key on the right-hand side of figure VI.18 shows the output power produced from PV array is most during the middle of the days of the winter months. Further the production of PV array is affected during the summer months as a result of the angle slope and the high temperatures, which may reach 48°C, as the excess temperature acts as a parasitic load on the photovoltaic system, reducing its production. Therefore, HOMER software resort to increase the size of both the solar PV array and the PEMFC system to compensate for the loss of energy due to high temperatures.

For the PEMFC, electrolyzer and hydrogen tank, the optimization sizing architecture included a 7 kW PEMFC system along with a 5 kW electrolyzer and a 2 kg storage tank. PEMFC generate power to the cell tower during year for about 5485 hours, as it can be seen that it has more operating hours than PV due to the weather changes or other unknown factors. The PEMFC is primarily operated during the nighttime hours and optimized or forced off during day according to operating strategy chosen, and the highest demand for energy comes in the evening hours of the year as shown in figure VI.19.

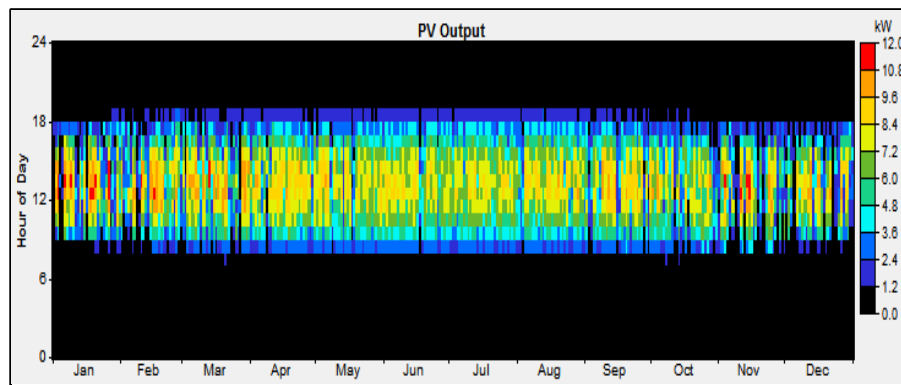


Figure VI.18 PV array output power results.

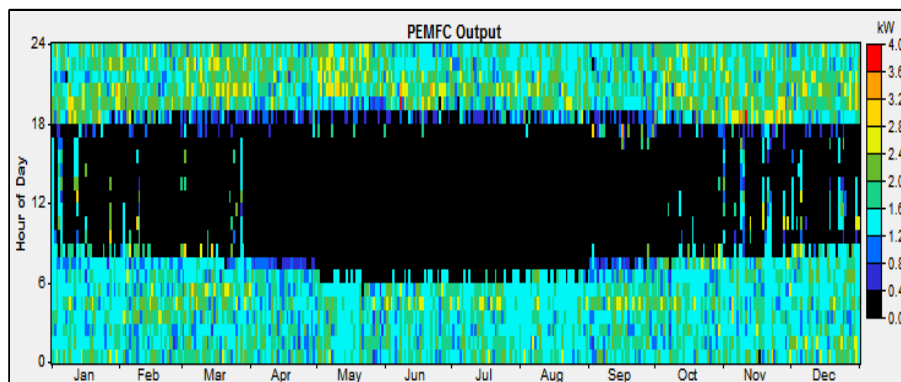


Figure VI.19 PEMFC array output power results.

The PEMFC source begins to generate the electrical power in the presence of the required amount of hydrogen that generated by the electrolyzer unit. The figure VI.20 displays the amount of hydrogen generated along a year. Total hydrogen production is 126 kg/year where the monthly

average hydrogen production fluctuates between 0.15 kg/day to 0.45 kg/day. This variance in the production rate is due to the availability of electrical energy from the PV panels to feed the electrolyzer unit. The generated hydrogen during day is stored in the hydrogen tank. The hydrogen storage level depends on the electrolyzer and PEMFC operation.

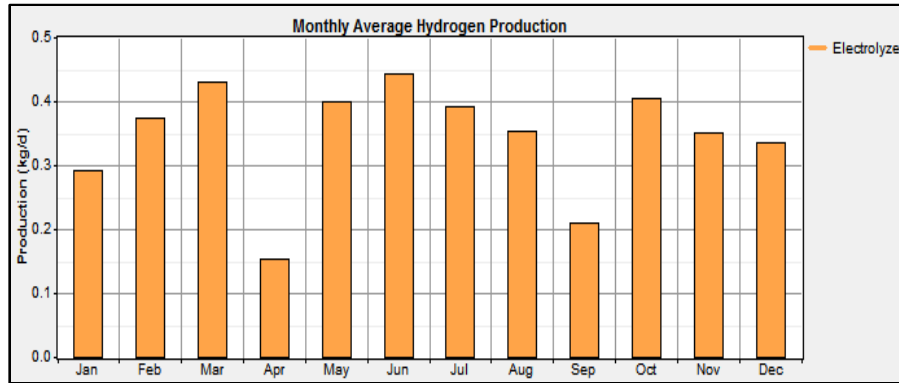


Figure VI.20 Monthly average Hydrogen production by the electrolyzer unit.

VI.7.4 Power output hourly data

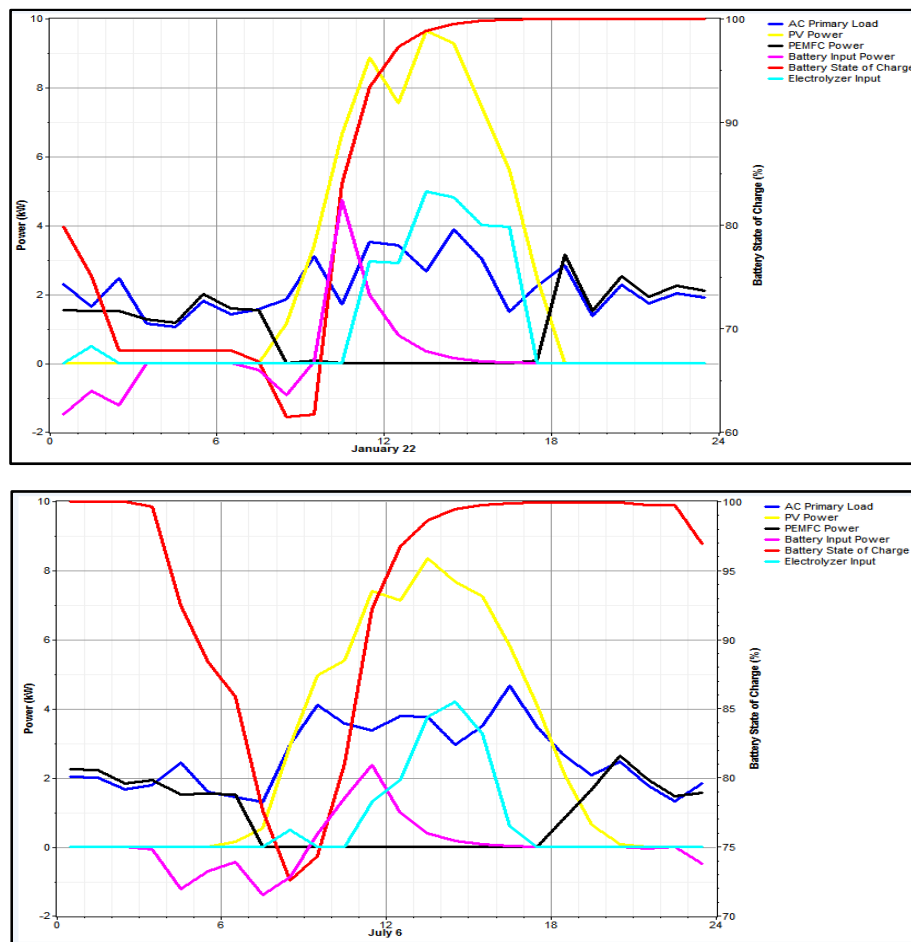
In the suggested HRES that combines two sources PV/PEMFC in addition to storage units in order to supply the cell tower. In this approach of HRES that integrates some sources, the main problem is to find a coherent strategy in energy management between sources in which a balance is ensured between many aspects such as: chosen of the optimum approach, less costs and longer components life. According to the requirements of the cell tower for electrical energy, the system defines a control strategy through which the orderly distribution of energy and the coordination between the sources is carried out effectively, i.e. which of the two sources operates first and the excess energy is exploited to charge batteries or to feed the electrolyzer unit. Therefore, the battery bank acts as a load in the case of charging, while acting as a source in the case of exporting the necessary energy. the state of charge (SOC) battery and power requested from load are important in the strategy of control, in which if the power generated by the PV system larger than the power needed by the load and the SOC of battery bank is 100%, the surplus energy generated by the PV system is employed to supply the electrolyzer unit, but in the case of SOC of battery bank is 50%, the excess energy is directed firstly to charge the battery bank then to feed the electrolyzer unit.

The HOMER software allows through the simulation results given every hour throughout the year according to the pre-set operating strategy of the system to give a detailed analysis of all the data. Figure VI.21, during 24 hours shows the curve of PV/PEMFC output power, electrolyzer unit input, battery bank input/SOC, and cell tower requirement profile.

In month of January, during the period corresponding to the decrease or absence of sun radiation i.e. from 17 in the evening until about 8 a.m., the requirements for cell tower are ensured by a PEMFC stack as well as a battery bank. As the morning starting, the rate of solar radiation begins to increase from 7:30 am, after which the PV system enters service and produces electrical energy, while the energy produced by the PEMFC begins to decrease until it stops working according to the specific strategy for its operation.; However, the power generated from PV source remained insufficient to ensure all the requirements of the cell tower during the first hours, so the

battery bank cover the shortfall in electrical energy to the cell tower as long as the SOC of battery bank is more than 40%. The PV system increases its output power in parallel with sun radiation increases to reach value over than 9.5 kW as maximum output power during the middle day; therefore, in this case the surplus power is exploited to charge the battery bank and to produce hydrogen using the electrolyzer unit. For the month of July as presented in figure VI.21, it can be observed the same strategy to feed the cell tower except a few variations related to the environmental conditions and the mode operating of the PEMFC stack.

In the Figure VI.21, month of November, it can be seen that during 7 a.m. until 12 p.m., the power needed by the cell tower more than the power generated by the PV source due to the reduction in the levels of solar radiation. Therefore, the control strategy obliges both the PEMFC stack and the battery bank to cover the cell tower requirements. After midday, the solar radiation levels return to take higher values, allowing the PV arrays to generate more power than the cell tower requirements, which also allows to use this excess energy to charge battery bank and to feed the electrolyzer until 18 p.m. During the night, the PEMFC stack ensures the electrical power needed by the cell tower without any insufficiency. In general, the unmet electric load criteria mentioned in Table VI.2 gives a view of the ability of the system as a whole to meet the load demands, its value is 57.8 kWh/yr, it considered is acceptable and very small.



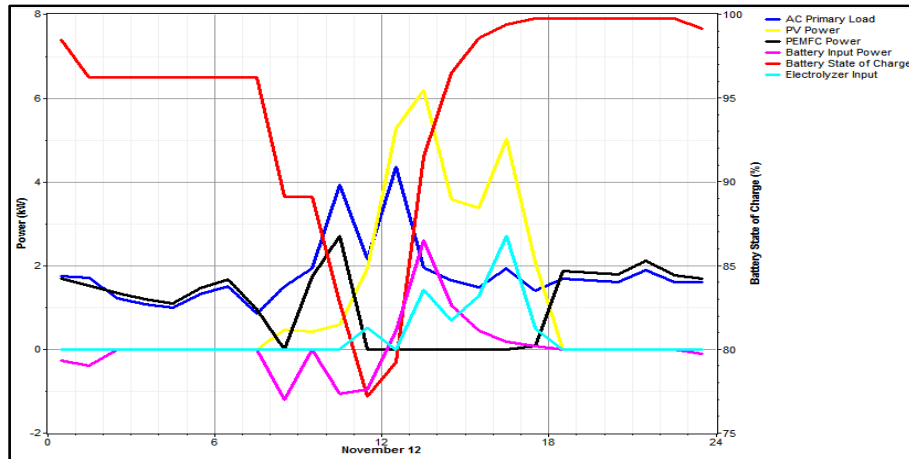


Figure VI.21 Power input, output and battery state of charge for HRES.

VI.7.5 Converter input and output power

The cell tower is fed through the converter. The figure VI.22 shows case of January of the input and output power from the converter, we can see the output power is lower than the input power comes from the PV array, PEMFC and battery bank due to value of the efficiency chosen during simulation that equal to 90%. From HOMER, the converter is operated about 8760 h/yr; the energy input is 19,119 kWh/yr; while the energy output from the converter to supply the load is 17,207 kWh/yr i.e. the total losses energy reaches at 1,912 kWh/yr.

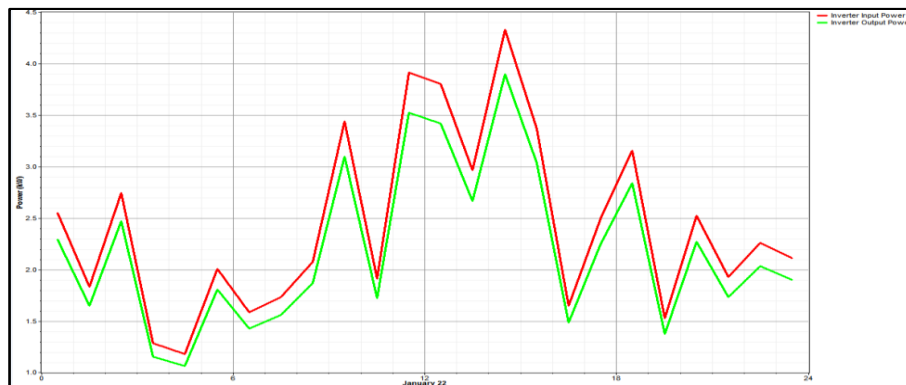


Figure VI.22 Input and output power from the converter.

VI.8 Sensitivity analysis of the HRES

As mentioned earlier, sensitivity analysis mainly aims to study the effect of changes in the inputs on the design and feasibility of the system. In fact, there are many scenarios for system sensitivity analysis. It is known that photovoltaic cells convert solar energy into electrical energy after receiving sufficient amount of solar radiation on their surface. Therefore, in order to obtain the highest capacity from the photovoltaic cells, it is necessary to ensure that the solar radiation falls perpendicular to the surface of the photovoltaic cells. In fact, it is difficult to achieve this because the sun cuts several angles from sunrise to sunset, meaning we find a certain period in which the sun's rays are perpendicular to the surface, while the rest of the periods will be diagonally, and this is what loses the photovoltaic cells from their production capacity. To solve this problem, the solar

panels are installed diagonally so that we gain the largest amount of solar radiation during the periods of the day. Thus, the angle of inclination of solar panels has an impact on the production capacity, and for this we often find two systems for installing solar panels, either with a fixed angle of inclination throughout the year or with a variable angle by using a system called the sun tracker. In this part, we will study the effect of the angle of inclination on the hybrid system, where we will take two values for the angle of inclination through which the solar panels are installed, while in the second part, the solar panels are installed at a variable angle using a solar tracker.

VI.8.1 Sensitivity analysis of the HRES with fixed angle slope

In this part, HRES sensitivity analysis is tested according to the angle at which the PV arrays are installed. In the first case, the PV arrays are mounted at an angle of 11° relative to horizontal, while in the second case they are mounted at an angle of 52° .

Figure VI.23 shows the optimal configuration of the HRES system for both cases. From figure VI.23, we can see that the difference in the configuration of the system lies only in the capacity of the hydrogen tank and the number of batteries. In the case of photovoltaic arrays with an angle of 11° , a larger hydrogen tank capacity is required due to the increase in the rate of hydrogen production, while the number of batteries increased to 12 in the case of the photovoltaic cells with an angle of 52° in order to store more energy.

From the economic side, we note a difference in the values of the NPC and COE of both systems according to the angle of installation of the solar panels, where the system installed with an angle of inclination of 11° appears the lowest cost (NPC = 64,290\$ and COE = 0.258\$/kWh) compared to the system installed with an angle of inclination of 52° (NPC = 66,127\$ and COE = 0.266\$/kWh).

Sensitivity Results Optimization Results												
Double click on a system below for simulation results.												
												
PV (kW)	PEMFC (kW)	6FM200D	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Capacity Shortage		
												
12	7	8	6.0	5	3	\$ 36,050	1,954	\$ 64,290	0.258	0.05		
												
12	7	8	7.0	5	2	\$ 35,850	1,970	\$ 64,324	0.259	0.04		
												
12	7	8	7.0	5	3	\$ 36,850	1,964	\$ 65,242	0.262	0.04		
												
12	7	8	6.0	5	4	\$ 37,050	1,951	\$ 65,253	0.262	0.05		
												
10	7	12	7.0	5	3	\$ 37,250	1,938	\$ 65,263	0.263	0.05		
												
12	7	8	8.0	5	2	\$ 36,650	1,980	\$ 65,273	0.262	0.04		
												
10	7	12	8.0	5	2	\$ 37,050	1,956	\$ 65,320	0.263	0.05		

(a)

Sensitivity Results Optimization Results												
Double click on a system below for simulation results.												
												
PV (kW)	PEMFC (kW)	6FM200D	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Capacity Shortage		
												
12	7	12	6.0	5	1	\$ 36,450	2,053	\$ 66,127	0.266	0.04		
												
12	7	12	6.0	5	2	\$ 37,450	2,024	\$ 66,710	0.268	0.04		
												
12	7	12	6.0	5	1	\$ 36,450	2,118	\$ 67,064	0.270	0.05		
												
12	7	12	7.0	5	1	\$ 37,250	2,063	\$ 67,076	0.270	0.03		
												
12	7	12	6.0	5	3	\$ 38,450	2,019	\$ 67,636	0.272	0.04		
												
12	7	12	7.0	5	2	\$ 38,250	2,035	\$ 67,659	0.272	0.03		
												
12	7	12	6.0	5	2	\$ 37,450	2,092	\$ 67,684	0.272	0.05		

(b)

Figure VI.23 Optimization results of PV/PEMFC hybrid configuration a) angle 11° and b) angle 52° .

Figure VI.24 shows the monthly average electric production of PV and PEMFC source. From figure VI.24, we can see the monthly average production of PV arrays are affected by the angle slope, in which the total production increases during the months of summer for PV arrays installed on angle 11° and decreases for the rest of the months. On the contrary, the total production increases during the months of winter for PV arrays installed on angle 52° and decreases for the rest of the months. In fact, these angles of 11° and 52° each correspond to the optimal angle for summer and winter, respectively.

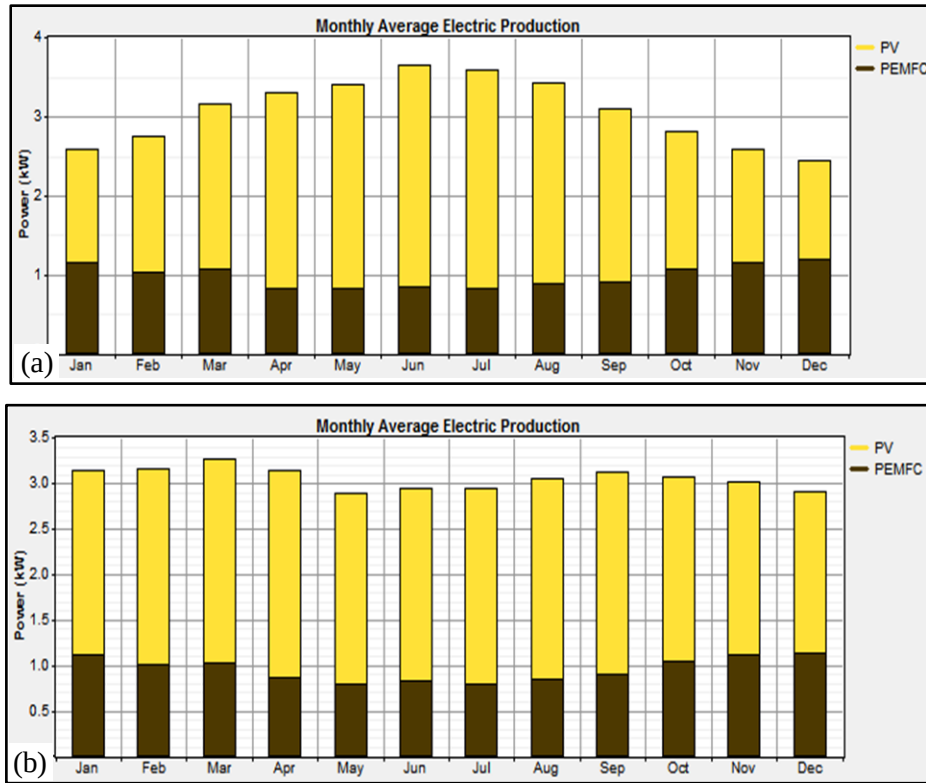


Figure VI.24 Monthly average electrical production results **a)** angle 11° and **b)** angle 52° .

VI.8.2 Sensitivity analysis of the HRES with PV tracking systems

Generally, the PV arrays are typically installed at fixed angle slope. However, other methods that can track the sun have been developed to maximize incoming solar radiation. PV tracking systems are classified according to the number of axes of rotation with which the adjustments are made. HOMER software can consider several tracking system such as: Horizontal Axis with monthly adjustment, Horizontal Axis with weekly adjustment, Horizontal Axis with daily adjustment, Horizontal Axis with continuous adjustment, Vertical Axis with continuous adjustment and finally two axes (horizontal and vertical).

In this part, the sensitivity analysis of the HRES is studied based on rotating the PV arrays around two axes (horizontal and vertical). It is only worth noting that some costs are added for sun tracker. The results obtained are shown in figure VI.25.

From figure VI.25, the optimum configuration of the HRES presented in the first line knew decrease in the PV arrays with increase in the number of batteries; it composed of 7 kW of PV arrays and 16 batteries. However, we note an increase in the initial cost, O&M, total NPC and COE,

so that it becomes 39,850\$, 2,852 \$/yr, 81,071 \$ and 0,372 \$/kWh respectively. Therefore, in the case of HRES having PV arrays installed with the sun tracker, the total system cost and COE are high which often leads to difficulty in achieving it.

Sensitivity Results

Optimization Results

Double click on a system below for simulation results.

  	PV (kW)	PEMFC (kW)	6FM200D	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Capacity Shortage
  	7	7	16	7.0	5	2	\$ 39,850	2,852	\$ 81,071	0.327	0.05
  	7	7	16	8.0	5	1	\$ 39,650	2,879	\$ 81,262	0.328	0.05
  	7	7	16	7.0	5	3	\$ 40,850	2,848	\$ 82,009	0.331	0.05
  	7	7	16	8.0	5	2	\$ 40,650	2,862	\$ 82,020	0.331	0.05
  	7	7	20	6.0	5	1	\$ 40,450	2,892	\$ 82,258	0.331	0.05
	8	7	12	7.0	5	2	\$ 39,050	2,993	\$ 82,312	0.332	0.05
	7	7	16	8.0	5	3	\$ 41,650	2,858	\$ 82,958	0.335	0.04

Figure VI.25 Optimization results of PV/PEMFC hybrid configuration with sun tracker.

Figure VI.26 shows the monthly average electric production of PV and PEMFC source. From figure VI.26, we can see the monthly average production of PV arrays reaches at 3 kW in the month of Jun although the capacity of PV arrays is reduced to 7 kW. The solar tracker rotates the PV arrays around both the horizontal and vertical axes so that the sun's rays are always perpendicular to the surface, allowing a large amount of solar radiation to be captured and thus increasing the energy production of the PV panels.

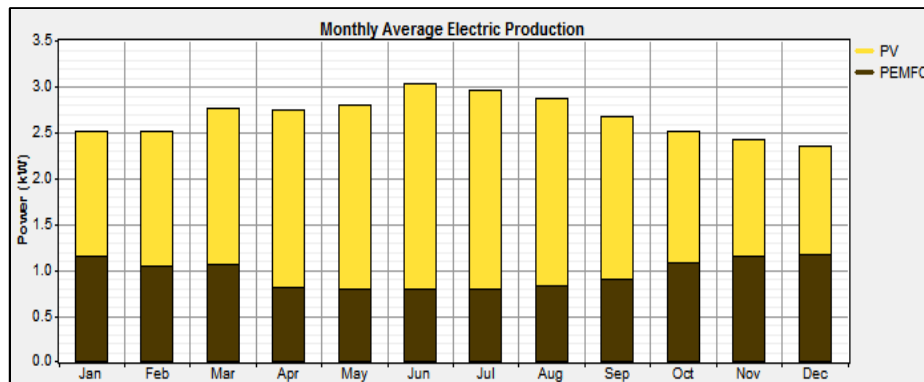


Figure VI.26 Monthly average electrical production results with sun tracker.

VI.9 Conclusion

HRESs have been widely used around the world as a sustainable source for future energy needs. Its optimization is a major factor in the assessment of the effectiveness of renewable energy systems. By using HOMER software, simulation, modeling and optimization of the HRES based on PV array, electrolyzer, and PEMFC stack technology, with battery and hydrogen energy storage capacity has been performed to meet the demands of cell tower in the village of Ouanougha. In the optimization sizing, operational strategy and techno-economic analysis of the HRES, the climatic data, cell tower profile, modeling of different components in the HRES, cost and reliability aspects have been processed as input data for HOMER software.

The outcomes got from the HOMER software provide diverse configurations achievable HRESs with various sizes of renewable sources which their decision is limited by changing the NPC of every setup. The prime criteria approved in this study are TNPC as well as COE. However, other costs like: initial, replacement, O&M costs are considered. According to these criteria's, the optimum configuration system obtaining from HOMER which refers to the less cost of TNPC. This latter, of the HRES has been found to be 66384 \$ and COE of 0.259 \$/kWh. Therefore, the optimization sizing of the configuration system corresponding to the lowest NPC includes 12 kW of PV array and 7 kW of PEMFC. However, the optimal sizing of the components is selected for an unmet electrical load of 57.8 kWh/yr, capacity shortage 781 kWh/yr and excess of electricity 2138 kWh/yr. So, the simulation results indicated the HRES comprising of PV/PEMFC will be able to meet the load requirements in all seasons with power interruption that hardly affect the operation of the system as a whole.

On the other hand, the proposed system shows a relatively high value for the COE compared to the national electricity tariff, but the new trends towards renewable energy both to support the energy shortage at the national level, renewable energy development, support the agricultural sector and expansion power generation it is a very commendable solution.

Lastly, the study shows that the HOMER software is powerful tool to achieve: optimal sizing with various design scenarios, technico-economic analysis, the capacity to simulate the real electricity system. Therefore, it requires high-precision input data, especially meteorological and economic data, in order to raise the reliability of the study for the hybrid system. As a result, we investigated HRES sensitivity analysis in terms of solar radiation changes by varying the angle of installation of the solar panels on the system configuration, as well as NPC and COE. The results obtained from the HOMER software in terms of financial and electrical performance help decision makers, energy planners and designers to achieve a sustainable energy system.

General Conclusion

General Conclusion

Many researchers have been carried out in the literature on renewable energy sources, as this science is becoming a center of gravity for government policies and research centers. In this study, the studied topic has many aspects that can be addressed. Initially, the problem of relying on non-renewable energy sources and ways to search solutions to reduce dependence on them and avoid the damage caused by them was suggested by resorting to the exploitation of renewable energy sources, including photovoltaic energy and fuel cells. Next, the topology of hybrid systems and the idea behind the integration of such systems rather than exploiting a single system to meet the load requirements were considered.

In order to make renewable energy sources more efficient and desirable to users, their performances are improved by extracting maximum energy from them. The problem of extracting maximum power has taken important part of the researches, as several methodologies and tracking algorithm were developed corresponding to the need to extract more power. In fact, each technique has different advantages both in terms of tracking methodology and methods of its application. In the literature, several common factors by which to judge whether an MPPT method can match the required application have been considered in order to be selected, which are the tracking performance, speed, accuracy, cost and the efficiency. Some other factors such as oscillation around MPP, and tracking under normal and partial conditions have also been added. Therefore, the principal function of MPP trackers is to ensure to find the MPP quickly with less converging time, less oscillation, high accuracy to optimize the energy generation.

For PV systems, it can be said that relatively all available algorithms that include three main categories have been applied conventional methods, soft Computing methods and hybrid methods. Whereas, for fuel cell systems the application of such algorithms are very little compared to PV systems. As result, we have applied some algorithms, including traditional and soft computing methods, to enrich the literature on such topics with ensure the main function of MPP.

We applied the variable step size IC MPPT, single sensor MPPT, ANN and GSS to extract the maximum power from the PEMFC. The results of simulation are shows the superiority of both technique ANN and GSS to reach the MPP quickly with less converging time, less oscillation around the MPP and high accuracy under variable operating conditions such as hydrogen pressure, temperature and water membrane content.

Hybrid systems are known as a feasible for supply option each for stand-alone or grid connected mode. Optimization methods must effectively search for an appropriate set of evaluation criteria that combines economic and reliability criteria. Analysis of some papers published in recent years for optimization of HRES especially in optimum sizing of components show the researcher uses several methods, among them software tools characterizes by simple to use, flexibility in simulation and don't need much time to present the best configuration of the HRES.

For second part that is studied, sizing optimization of HRES by using HOMER software, it used PV, PEMFC, Battery, Electrolyzer and Storage hydrogen as components of the HRES to feed the cell tower. The sizing optimization allows the using HRES with reliable performance and a competitive economic price. The criteria for optimization are based on energy continuity to meet load requirements and the NPC. The results obtained from HOMER software proves the HRES can effectively cover the energy consumption by the cell tower when optimized technically (using storage units such as battery bank and hydrogen storage), and economically (minimize investments cost or levelized cost of energy). The optimal sizing of HRES in order to feed the cell tower entails the both sources PV arrays of 12 kW and PEMFC of 7 kW. While the NPC of the HRES was estimated at 64384 \$ with COE at 0.259 \$/kWh.

Given the climatic characteristics such as solar radiation for the region that studied, it strongly stimulates the exploitation of solar energy applications in several fields with the possibility of introducing fuel cells as a new renewable energy system. In fact, the hybrid system can bring social and economic gains in rural areas where additional energy will be provided for setting up other activities and businesses.

Whether in a transport type or stationary application type, energy systems including PV, Wind, Fuel Cell or hybrid systems present a level of complexity. In addition, the use of a hybrid multi-source system will make it possible to meet the various constraints of load demand, sudden drop in production due to the intermittence of certain energies, etc. and to ensure the continuity and stability of the grid. In this spirit, as future works, we plan to extend our study to multi-sources micro-grids in in islanded and connected modes.

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ملخص

يتزايد القلق يوميًا بشأن مخاطر الاستخدام المفرط لموارد الطاقة التقليدية بالتزامن مع تفاقم ظاهرة الاحتباس الحراري. وبالتالي، أصبح من الضروري التحرك نحو استخدام مصادر الطاقة المتجددة والنظيفة، ولكن تطوير أنظمة الطاقة المتجددة بشكل أسرع كان ولا يزال تحديًا علميًا وتكنولوجيًا. من بين مصادر الطاقة المتجددة: يبدو أن الخلايا الكهروضوئية هي أكثر المصادر الواعدة. تتميز بأنها متاحة في كل مكان، صديقة للبيئة ويمكن صيانتها بسهولة. من ناحية أخرى، يمكن القول إن خلية الوقود هي الطريقة الأكثر ملاءمة للبيئة لتوليد الطاقة الكهربائية اليوم. في الواقع، بصرف النظر عن الكهرباء، فإن التفاعل بين الهيدروجين والأكسجين ينتج فقط بخار الماء. على هذا النحو، فإن العملية لا تطلق بأي حال من الأحوال أي غازات دفيئة. ومع ذلك، فإن العوائق الرئيسية لهذه المصادر هي التكلفة العالية والخصائص غير الخطية، وبالتالي عشوائية توافر الطاقة. لمواجهة هذه التحديات، يمكن أن يثبت تهجين المصادر وتحسينه أنه نهج مناسب لتصميم حلول طاقة فعالة. تتناول هذه الرسالة تهجين مصدرين من مصادر الطاقة المتجددة وتحسين أدائها. يتكون النظام الهجين من الألواح الشمسية الكهروضوئية وخلية الوقود، بالإضافة إلى البطارية، والمحول، والمحلل الكهربائي، وخزان الهيدروجين لتزويد برج الخلية. الهدف هو تطوير استراتيجيات تحكم جديدة لاستخراج الطاقة القصوى المتاحة من كلا المصدرين خلايا الوقود/الكهروضوئية وتحسين حجم مكونات النظام الهجين. نتيجة لذلك، تم تطوير بعض خوارزميات "تتبع أقصى نقطة للطاقة" التي أثبتت المتانة والأداء القوي في ظل ظروف التشغيل المتغيرة لاستخراج أقصى طاقة، بينما بالنسبة للهدف الثاني، تم إجراء التحجيم الأمثل لمكونات النظام الهجين باستخدام برنامج هومر.

Abstract

Concern is growing daily about the dangers of the excessive use of traditional energy resources in conjunction with the exacerbation of global warming. Thus, it has become necessary to move towards the use of renewable and clean energy sources, but the development of renewable energy systems faster has been and continues to be a scientific and technological challenge.

Among the renewable energy sources: Photovoltaic seems to be the most promising source. It has the advantage of being available everywhere, friendly to the environment and easily maintainable. On the other hand, the fuel cell is arguably the most environmentally friendly way to generate electrical energy today. Indeed, apart from electricity, the reaction between hydrogen and oxygen only produces water vapor. As such, the process does not in any case releases any greenhouse gas. However, the main drawbacks to these sources are the high manufacturing cost and non-linear characteristics, and thus the randomness of energy availability. To meet these challenges, sources hybridization and its optimization can demonstrate to be suitable approach for the design of efficient energy solutions.

This thesis deals with the hybridization of two renewable energy sources and improving their performance. The hybrid system comprises photovoltaic solar panels and a fuel cell, in addition to battery, converter, electrolyzer and hydrogen tank to supply cell tower. The objective is to develop new control strategies to extract the maximum power available from the both sources PV/PEMFC and optimize the size of the hybrid system components. As results, some MPPT algorithms have been developed that have proven durability and robust performance under variable operating conditions to extract maximum power, while for second objective, optimization sizing of the hybrid system components have been done using HOMER software.

Résumé

L'inquiétude grandit chaque jour sur les dangers de l'utilisation excessive des ressources énergétiques traditionnelles en conjonction avec l'exacerbation du réchauffement climatique. Ainsi, il est devenu nécessaire de s'orienter vers l'utilisation de sources d'énergie renouvelables et propres, mais le développement plus rapide de systèmes d'énergie renouvelable a été et continue d'être un défi scientifique et technologique.

Parmi les sources d'énergie renouvelables: le photovoltaïque semble être la source la plus prometteuse. Il a l'avantage d'être disponible partout, respectueux de l'environnement et facilement maintenable. D'autre part, la pile à combustible est sans doute le moyen le plus écologique de produire de l'énergie électrique aujourd'hui. En effet, en dehors de l'électricité, la réaction entre l'hydrogène et l'oxygène ne produit que de la vapeur d'eau. A ce titre, le procédé ne dégage en aucun cas de gaz à effet de serre. Cependant, les principaux inconvénients de ces sources sont le coût élevé et les caractéristiques non linéaires, et donc le caractère aléatoire de la disponibilité de l'énergie. Pour relever ces défis, l'hybridation des sources et son optimisation peuvent s'avérer être une approche appropriée pour la conception de solutions énergétiques efficaces.

Cette thèse porte sur l'hybridation de deux sources d'énergie renouvelables et l'amélioration de leurs performances. Le système hybride comprend des panneaux solaires photovoltaïques et une pile à combustible, en plus d'une batterie, d'un convertisseur, d'un électrolyseur et d'un réservoir d'hydrogène pour alimenter la tour cellulaire. L'objectif est de développer de nouvelles stratégies de contrôle pour extraire le maximum de puissance disponible des deux sources PV/PEMFC et optimiser la taille des composants du système hybride. En conséquence, certains algorithmes MPPT ont été développés qui ont prouvé leur durabilité et leurs performances robustes dans des conditions de fonctionnement variables pour extraire une puissance maximale, tandis que pour le deuxième objectif, le dimensionnement d'optimisation des composants du système hybride a été effectué à l'aide du logiciel HOMER.