ANALYSIS ON MICRO GRID USING SOLAR CELL / PHOTOVOLTAIC & FUEL CELL FOR ENERGY SUPPLY IN REMOTE AREAS

A thesis submitted

In partial fulfillment of the requirements

For the Degree of

MASTER OF TECHNOLOGY

In POWER SYSTEM & CONTROL

(Electrical Engineering)

By

Miss ITISHA SINGH

1170450002

Under the Guidance of

Prof. V.K. MAURYA

BABU BANARASI DAS UNIVERSITY, LUCKNOW

To the

School of Engineering

BABU BANARASI DAS UNIVERSITY

LUCKNOW

MAY 2019

Candidate's Declaration

I hereby declare that the work, which is being presented in the thesis entitled in partial fulfillment for the award of degree of "**Master of Technology**" in Department of Electrical Engineering with Specialization in **Power System & Control** "**ANALYSIS OF MICRO-GRID USING SOLAR CELL /PHOTOVOLTAIC FUEL CELL FOR ENERGY SUPPLY IN REMOTE AREAS"** and submitted to the **Department of Electrical Engineering, Babu Banarasi Das University** is a record of my own investigations under the guidance of **Prof. V.K.Maurya , Associate Professor & Head Department of Electrical Engineering, Babu Banarasi Das University, Lucknow.**

I have not submitted the matter presented in this dissertation anywhere for the award of any other degree.

(Itisha Singh)
M..Tech Scholar (Power System & Control)
Roll No. : **1170450002**
Department of Electrical Engineering
School of Engineering
Babu Banarasi Das University, Lucknow.

CERTIFICATE

This is to certify that the work contained in this thesis, titled **"Analysis on Micro-Grid using Solar Cell/Photovoltaic Fuel Cell for Energy supply in remote areas**" has been successfully carried out by the **Itisha Singh** (Roll No. : **1170450002**), from Babu Banarasi Das University, Lucknow has been carried out under my/our supervision and this work has not been submitted elsewhere for a degree.

Place:

Date:

Signature

V.K. MAURYA

Associate Professor & Head

Department of Electrical Engineering

School of Engineering

Babu Banarasi Das University, Lucknow.

May 2018-19

ABSTRACT

In this thesis a new approach is projected for Analysis on Micro Grid using Solar Cell / Photovoltaic-Fuel Cell Simultaneous operation of PV & FV Hybrid system. This technique offers continuous supply without any pollution and failure.

In the discussed model we are studying the Simultaneous operation of Hybrid System. Energy is obtained at grid by Photovoltaic cell with parallel operation of Fuel cells.

The technology of photovoltaic's (PV) is essentially concerned with the conversion of this energy into usable electrical form. The basic element of a PV system is the solar cell. Solar cells can convert the energy of sunlight directly into electricity. On the other hand PEM fuel cell, H_2 and O_2 are the fuel and oxidant respectively. The product is pure water H_2O and electricity. The operation is based according to the Look up table.

In this operation some other devices are also used, like dc-dc converter, DC bus, Inverter (An Inverter is a device which converts DC into AC), Electrical Load (Three phase).

Energy at grid is used to provide services such as lighting, water pumping, refrigeration, telecommunications, and electrification at remote areas.

The proposed method topology & its operation with analysis explained and analyzed in details.

The proposed topology has been implemented and investigated in the MATLAB/Simulink and the various results are provided to verify the proposed concepts.

ACKNOWLEDGEMENT

It gives me immense pleasure to express my sincere gratitude toward my supervisor **Prof. V.K Maurya**, Associate Professor & Head Department of Electrical Engineering, School of Engineering, Babu Banarasi Das University, Lucknow for his scholarly guidance. It would have never been possible for me to take this thesis to completion without his innovative ideas and his relentless support and encouragement. I consider myself extremely fortunate to have had a chance to work under his supervision. In spite of his hectic schedule he was always approachable and spared his time to attend my problems. I am also thankful to **Mr. Akash Varshney,** Assistant Professor, Department of Electrical Engineering, School of Engineering, Babu Banarasi Das University, Lucknow.

I would like to express my special thanks to Head Electrical Engineering, School of Engineering, Babu Banarasi Das University, Lucknow for their kind support.

I also express my gratitude to all the respected faculty member of Electrical Engineering, School of Engineering, Babu Banarasi Das University, Lucknow for their kind support who have helped me directly or indirectly in completion of this thesis.

I am really thankful to ***Department of Electrical Engineering***, School of Engineering, Babu Banarasi Das University, Lucknow for all the technical facilities both infrastructural and rich faculty due to which my dream of achieving M. Tech. could prove true.

Finally, yet importantly, I would like to express my heartfelt thanks to my **Parents** to give invaluable support in all the circumstances that exhibited a high degree of patience and kept my moral always high.

ITISHA SINGH

CONTENTS

TITLE	PAGE NO.
CANDIDATE'S DECLARATION	ii
CERTIFICATE	iii
ABSTRACT	iv
ACKNOWLEDGEMENT	v
CONTENTS	vi
LIST OF FIGURES	x
LIST OF TABLES	xiii
LIST OF ABBREVIATIONS	xiv
LIST OF SYMBOLS	xvi
1. INTRODUCTION	1
1.1 Motivation	3
1.2 Objective of the Study	3
1.3 This thesis aims towards the following	3
1.4 Outline of the thesis	4
2. LITERATURE SURVEY	5
2.1 Solar Energy	6
2.1.1 Units of solar power and solar energy	6
2.1.2 Necessary subsystems in a solar energy plant	6
2.1.3 Energy transport medium	7
2.1.4 Energy storage	7
2.1.5 Energy conversion plant	7
2.1.6 Power conditioning, control and protection system	7
2.1.7 Alternative or standby power supply	7
2.1.8 Energy from the sun	7
2.1.9 Solar constant	7
2.1.10 Clarity index	8
2.1.11 Solar radiation data for India	8
2.1.12 Solar radiation	8

2.2 Photovoltaic Unit 9
2.2.1 Semiconductor (n and p type) Material 9
2.2.2 Absorption and Conduction 10
2.2.3 I-V Characteristics of a Photovoltaic Module 12
2.2.4 Maximum Power Point Tracker (MPPT) 14
2.2.5 Advantages of the photovoltaic power 15
2.2.6 Sources of Losses in a Photovoltaic Generator 16
2.2.7 Solar panel 17
2.2.8 Working of solar cell 19
2.3 Fuel Cell Unit 20
2.3.1 Cell Components 20
2.3.2 Fuel cell 21
2.3.3 Working of fuel cells 23
2.3.4 Cost of the fuel cell 24
2.3.5 Drawback of fuel cell for its business 25
2.3.6 Historical development of fuel cell technology 25
2.3.7 Fuel cell's application 26
2.3.8 Advantages and disadvantages of fuel cells 27
2.3.9 Modular Hybrid Power System Technology 28
2.4 Topologies of Hybrid Power Systems 32
2.4.1 DC Coupled System Topology 33
2.4.2 AC Coupled System Topology 33
3. WORKING OF PHOTOVOLTAIC & FUEL CELL HYBRID SYSTEM 35
3.1 Introduction of Hybrid system 35
3.2 Elements of Proposed Hybrid System 36
3.2.1 PV Cell 38
3.2.2 Fuel cells 39
3.2.3 FC Power Control Unit (look up Table) 41
3.2.4 DC-DC Converter 42
3.2.5 DC Bus 46
3.2.6 Inverter Unit 47

3.2.6.1 Three-Phase Inverter 47
3.2.6.2 Space Vector PWM Technique 47
3.2.7 Electrical Load (Three phase) 52
4. MODELING OF THE INDIVIDUAL COMPONENTS OF HYBRID SYSTEM 54
4.1 Modeling of Hybrid System (Photovoltaic & Fuel Cell Module) 54
4.1.1 Modeling of Photovoltaic Module 55
4.1.2 Modeling of Fuel Cell Module 67
4.1.3 Modeling of FC Power Control Unit 68
4.1.4 Modeling of DC to DC converter (Type-Boost) 68
4.1.5 Modeling of Inverter Unit 70
4.1.6 Modeling of Electrical Load 71
5. RESULT 73
5.1 Simultaneous PV and FC result 73
5.2 Radiation 1000 W/m^2 and 50 kW load 74
5.3 Radiation 750 W/m^2 and 50 kW load 75
5.4. Radiation 500 W/m^2 and 50 kW load 75
5.5 Radiation 250 W/m^2 and 50 kW load 76
6. CONCLUSION AND SCOPE FOR FUTURE WORK 77
6.1 Conclusion 77
6.2 Scope for future work 77
7. LITERATURE REFERENCES 78
7.1 References 78
PLAGIARISM REPORT 83
LIST OF PUBLICATION 84
CERTIFICATE OF FINAL THESIS SUBMISSION 85
CURRICULUM VITAE 86

LIST OF FIGURES

FIGURE NO.	DESCRIPTION OF FIGURE	PAGE NO.
CHAPTER - 2		
2.1.	Solar Constant	8
2.2.	Solar Radiation Geometry	9
2.3.	Semiconductor materials (n & p-types)	10
2.4. (a) & (b)	The I-V Curve and Maximum Power Point	13 - 14
2.5.	Simulated I-V Curve of PV Module	14
2.6.	Solar panel	18
2.7.	P & N layers of PV Cell	18
2.8.	PV Cell, PV Module, PV Panel and PV Array	18
2.9.	Unit of PV Array	18
2.10.	Solar Cell	19
2.11.	Schematic of PEFC	21
2.12.	Single Cell Structure of PEFC	21
2.13.	PEM unit cell structure	22
2.14.	Characteristic curves of a typical PEM fuel	23
2.15.	A typical PEM fuel cell	23
2.16.	A typical circuit of PEM Fuel cell	23
2.17.	Block diagram of the DC coupled hybrid power system	28
2.18.	General modular hybrid System.	28
CHAPTER - 3		
3.1.	PVFC hybrid system	37
3.2.	Flow chart of PV & FC hybrid system	37
3.3.	Circuit diagram of PV Cell	38
3.4.	Circuit of Solar Panel	38
3.5.	The natural energy hydrogen cycle	39
3.6.	Internal working of a Typical FC	39
3.7.	Boost converter	42
3.8.	Circuit Diagram of converter	43

3.9.	Characteristics of boost converter	45
3.10.	DC Bus System	46
3.11.	Typical Waveform of Inverter Unit	47
3.12.	Two level voltage source inverter	48
3.13	Phasor diagram of voltages	51
3.14.	Typical VSI switching waveform	52
3.15.	Water Pump	52
CHAPTER -4		
4.1.	Modeling of Hybrid System	54
4.2.	Picture Of BPSX 50S PV Module	55
4.3.	Equivalent circuit model of solar cell	55
4.4.	Modeling of Photovoltaic Module.	56
4.5.	Characteristics of PV cell connected in series	57
4.6.	Modeling of PV array	57
4.7.	I-V and P-V characteristics (1000 W/m^2)	58
4.8.	I-V and P-V characteristics (800 W/m^2)	59
4.9.	I-V and P-V characteristics (600 W/m^2)	60
4.10.	I-V and P-V characteristics	61
4.11.	More Accurate Equivalent Circuit of PV cell	63
4.12.	Equivalent Circuit diagram PV cell	64
4.13.	Modeling of fuel cell module	68
4.14.	Modeling of FC Power Control Unit	68
4.15.	Modeling of DC to DC Boost converter	69
4.16.	Square wave of DC-DC converter	70
4.17.	Inverter	70
4.18.	Modeling of Inverter Unit	70
4.19.	Sinusoidal pulse-with modulation for three-phase inverter	71
4.20.	50 kW Load	71
4.21.	Modeling of Electrical Load	72

CHAPTER -5

5.1.	Three phase output of Inverter at (1000 W/m^2)	74
5.2.	Output waveform of Vdc, Vab_inv, Vab_load and m at (1000 W/m^2)	74
5.3.	Three phase output of Inverter at (750 W/m^2)	75
5.4.	Output waveform of Vdc, Vab_inv, Vab_load and m at (750 W/m^2)	75
5.5.	Three phase output of Inverter at (500 W/m^2)	75
5.6.	Output waveform of Vdc, Vab_inv, Vab_load and m at (500 W/m^2)	76
5.7.	Three phase output of Inverter at (250 W/m^2)	76
5.8.	Output waveform of Vdc, Vab_inv, Vab_load and m at (250 W/m^2)	76

TABLES

TABLE NO.	DESCRIPTION OF TABLE	PAGE NO.
CHAPTER – 2		
2.1	Band and gap, maximum current density, and theoretical efficiency of some different Semiconductor technologies	12
2.2	Fuel cell technologies	26
2.3	Overview of the fuel cell application	27
CHAPTER -3		
3.1	Look-up Table	41
3.2	Possible switching vectors, phase voltage, phase voltage and Output line voltage	50
CHAPTER -4		
4.1	Electrical Characteristics PV modules	55
4.2	V, P, & I Output (1000 W/m^2)	58
4.3	V, P, & I Output (800 W/m^2)	59
4.4	V, P, & I Output (600 W/m^2)	60
4.5	Output at different radiation levels	62
CHAPTER -5		
5.1	Output at 50 kW Load	73
5.2	Output at 60 kW Load	73
5.3	Output at 70 kW Load	74

LIST OF ABBREVIATIONS

ABBREVIATIONS	DESCRIPTION
AC	Alternating Current
AFC	Alkaline Fuel Cell
ACI	Atmospheric Clarity Index
CCM	Continuous Conduction Mode
CHP	Combined Heat and Power Generation
D	Diode
DC	Direct Current
DCM	Discontinuous Conduction Mode
EL	Electric Load
EEF	Efficiency Enhancement Factor
FC	Fuel Cell
GT	Grid Terminal
MA	Modulation index
MEAs	Membrane Electrode Assemblies
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
NOCT	Nominal Operating Cell Temperature
PF	Power factor
PL	Passive Load
PAFC	Phosphoric Acid Fuel Cells

PCUs	Power Conditioning Units
PEFC	Polymer Electrolyte Fuel Cells
PEMFC	Proton Exchange Membrane Fuel Cells
PNGV	Partnership for a New Generation Vehicles
PVS	Photovoltaic System
PVA	Photovoltaic array
PWM	Pulse width modulation
RMS	Root mean square
SOFC	Solid Oxide Fuel Cells
SVPWM	Space Vector Pulse Width Modulation
WC	Wind Converter

LIST OF SYMBOLS

SYMBOL	DISCRIPTION
$\overline{H_t}$	Solar radiation
λ_p	Miscellaneous PV array losses
λ_c	Other power conditioning losses
β_p	Temperature coefficient for module efficiency (% / °C)
η	Efficiency
η_{inv}	Inverter efficiency
η_p	Array average efficiency
η_r	PV module efficiency at reference temperature (Tr = 25 °C)
Φ	Angle of latitude of the location. By convention φ is considered positive in northern hemi sphere.
ω	Hour angle. It is the angle made by sun in 1 hour with reference to 12 noon and is equivalent to 1.5^0 per hour.
δ	Angle of declination. It is the angle between line joining centers of the sun and the earth and the equatorial plane.
A	Area of the array
a & b	Constants for various cities of the world (Constant and expressed in $kJ/m^2/day$)
D_m	Duty cycle of the switch at maximum converter input power
E_g	Band gap energy
E_{dlvd}	Energy delivered to load
E_{grid}	Energy available to the grid
E_A	Energy available to the load
E_p	Energy delivered by the PV array
f_s	Switching frequency
G_a	Irradiance from the sunlight (W/m^2)
H_o	Daily extra-terrestrial radiation, (mean value for the month). It is calculated from solar energy.
H_g	Daily Global Radiation for a flat surface at the location for the particular month kJ/m^2/ Day

I_R	Load current (A)
I_d	Diode current (A)
I_{ph}	Current by Photon (A)
I_{sc}	Short-circuit current (A)
I	Output current of the PV (A)
I_{scc}	Nominal short-circuits current (A)
I_S	Cell saturation of dark current (A)
I_0	Reverse saturation current of diode (A)
I_{mp}	Current at maximum power at STC (A)
I_{pv}	Currents generated by the solar cells (A)
I_{om}	Output current at maximum output power (A)
$\Delta I_{Lripple}$	Ripple current of the inductor
J_{cell}	Current density
J_{ph}	Induced photocurrent density
J_{d1}	Dark current density due to the carries diffusion
J_{d2}	Dark current density due to the carries recombination
K_p	Voltage temperature constant
K_i	Current temperature coefficient
k	(1.38×10^{-23} J/K) is a Boltzmann's constant
L_m	Longest day of the month hours
L_h	Length of day (average for the month) (in hours)
N_s	Number of cells in series
N_{pp}	Number modules in parallel
N_{ss}	Number of modules in series
P_{mp}	Power at maximum power point
R_{sh}	Shunt resistance (Ω)
R_s	Resistance series (Ω)
R_p	Resistance parallel (Ω)
S	Solar constant in terms of kJ/m^2/hr = S x 3600 =1.353 x 3600 = 4871
S_1 - S_6	Power Switches
$T_1 - T_2$	Time Duration
T_c	Cell temperatures (^{o}C)

T_a (°C)	Ambient temperature
Tc	Surrounding Temperature
Tr	Reference Temperature (25 °C)
V_d	Diode voltage
V_{cell}	Voltage of cell
V_{oc}	Open circuit voltage (V)
V	Output voltage of the PV (V)
V_{mp}	Voltage at maximum power point
V_{load}	Output voltage of the boost converter
V_{tria}	Peak amplitude of the triangular carrier
$V_{ref: peak}$	Amplitude of the sinusoidal reference signal
V_{pv_nmpp}	PV output voltage at maximum power point
V_{om}	Maximum of the dc component of the output voltage
ΔV_{load}	Output ripple voltage

CHAPTER -1

INTRODUCTION

1.1 Motivation:

The Petroleum, Natural gas, and Coal which meet most of the world's energy demand today are known as conventional fossil fuel and are being depleted very rapidly. Also, their combustion products are causing Global problems such as the greenhouse effect and pollution which are posing great danger for our environment and eventually for the entire life on our planet, So Solar, Wind, Tidal, Geothermal etc. RES (Renewable Energy Sources) are attracting more attention in the field of energy as an alternative Source. Among the renewable energy sources, the photovoltaic (PV) energy has been widely utilized in low power applications [1]. It is also the most promising candidate for research and development for large scale users as the fabrication of low cost PV devices becomes a reality. Photovoltaic generators are those which directly convert solar energy in to electricity.

It has a lot of significant advantages such as:

- Pollution free.
- Inexhaustible.
- Silent in operation.
- With no rotating parts.
- Low running cost.
- Size-independent electric conversion efficiency.

Due to harmless environmental effect and good reliability of PV generators, they are replacing electricity generated by other polluting ways and even more popular for electricity generator where none was available before. With increasing penetration of solar photovoltaic devices, various anti-pollution apparatus can be operated by solar PV power; for example, water purification by electrochemical processing or stopping desert expansion by PV water pumping with tree implantation. From an operational point of view, a PV power generation experiences large variations in its output power due to intermittent weather conditions. Those phenomena may cause operational problems at the power station, such as excessive frequency deviations. In many regions of the world, the fluctuating nature of solar radiation means that purely PV power generators for off-grid applications must be large and thus expensive. One method to overcome this problem is to integrate the photovoltaic plant with other power sources such as diesel, fuel cell (FC), or battery back-up. The diesel back-up generator for PV power is able to ensure a continuous 24-hour & 7 days. However, it has a number of significant disadvantages such as noise and exhaust gases pollution [2]. In addition, reasonably reliable diesel back-up generators are available only for the power range above about 50kW, which is too much high for a large number of applications. In the middle and small power range this technology cannot be used in an effective way successfully.

Now, the fuel cell beak-up power supply is become a very attractive option to be used with an intermittent power generation source like PV power because the fuel cell power system is characterized with many attractive features such as efficiency, fast load-response, modular production and fuel flexibility. Its feasibility in co-ordination with a PV system has been successfully realized for both grid-connected and stand-alone power applications. Due to the fast responding capability of the fuel cell power system, a photovoltaic-fuel cell (PVFC) hybrid system may be able to solve the photovoltaic's inherent problem of intermittent power generation. Unlike a storage battery, which also represents an attractive back-up option, such as fast response, modular construction and flexibility, the fuel cell power can produce electricity for unlimited time to support the PV power generator. Therefore, a continuous supply of high quality power generated from the PVFC hybrid system is possible day and night (technically) (7X 24).

The Fuel Cell power generation has small environmental impacts as compared to other fossil fuel power sources. Since chemical reactions inside the fuel cell stack are accomplished by catalysts, it requires a low Sulfur-content fuel. Low-emission characteristics of the fuel cell power system may allow some utilities to offset the costs of installing additional emission control equipment. Moreover, their high efficiency results in low fossil fuel CO_2 emissions, which will help in reducing the rate of global warming.

Therefore, the fuel cell power system has a great potential to play the role as a co-ordinate part with the PV generator to provide smooth output without fluctuations in the photovoltaic power.

1.2 Objective of the Study:

It has been well-proven that a photovoltaic power source should be integrated with other power sources, whether used in either a stand-alone (as a back up or simultaneously mode) or grid-connected mode (as a back up or simultaneously mode). Grid connected power systems are very popular, especially in remote areas. The system under study in this dissertation is a simultaneously mode of grid connected PVFC hybrid power system, System is constituted of a photovoltaic generator, A proton exchange membrane (PEM) fuel cell, DC / DC converter, FC power controller, DC Bus, Inverter and 3-Phase Load. This system is intended to be a future competitor of hybrid PV/Diesel systems, especially from an environmental point of view (low noise, zero emission and operational costs). Two refilling tanks (Hydrogen & Oxygen) are used as an input to Fuel Cell to produce electricity. The development of appropriate simulation tools will help in dealing with modeling, simulation, and design and energy management of the system under study. A simulation software program known as MATLAB has been used to simulate the system performance. The system design and performance analysis could thus be achieved through computer modeling and simulation prior to practical realization.

1.3 This dissertation aims towards the following:

- Proper data collecting and/or data synthesizing that describe the system operation and the load profile. Visualizing and analyzing the system dynamic behavior using power flow trace over long-term duration, for example, one year. Creating an accurate simulation system model to predict the real performance of the hydrogen / Oxygen PVFC hybrid system.
- Undertaking detailed analysis of the effect of changes in the system configurations, power conditioning units, and sites to choose an optimal system design.

The objective of the study is to reach a design that optimizes the operation of a hydrogen/oxygen PVFC hybrid system. All components of this system have been selected for an optimal operation of the complete system. The data of the component models was taken from real projects or manufacturer's data sheet. The methodology selected is to simulate a number of different system topologies based on the type of coupling DC or AC between the components system. A library of the system models is produced under the designation.

Library used over here is Simulink library. Models of this library are developed and under continuous enhancement by new models. The component models of the system are verified with component's experimental data to assure the accuracy of these models before being implemented into the system simulation study.

1.4 Outline of the Dissertation:

Chapter 1 [NTRODUCTION] gives an introduction to the concept of photovoltaic hybrid system and the objectives of study.

Chapter 2 [LITERATURE SURVEY] gives a description on different components of hybrid power systems configurations, and includes notes about the hybrid power system topologies, modularization, and standardization

Chapter 3 [WORKING OF PHOTOVOLTAIC & FUEL CELL HYBRID SYSTEM] gives the working of PV & FC hybrid system covers the background information about all components used in the system study, such as photovoltaic (Solar) cell, Fuel cell, PV Cell, FC Power Control Unit, DC to DC converter (Type-Boost), DC Bus, Inverter Unit, Electrical Load (3-Phase load).

Chapter 4 [MODELLING OF THE INDIVIDUAL COMPONENTS OF HYBRID SYSTEM] deals with the models of the all components used for the hydrogen PVFC hybrid system. The described models here are used to study the long-term energy performance of the system.

Chapter 5 [RESULT] Explanation of various waveforms of different components of hybrid system simulates the overall system that uses solar radiation as the primary energy input and Fuel Cell as energy storage device. Also a comparison between different topologies such as DC/AC coupled systems at different load on the basis of energy point of view is studied.

Chapter 6 [CONCLUSIONS AND FUTURE SCOPE] comparative study and concludes the thesis, and proposes recommendations for future work.

Chapter 7 [LITERATURE REFERENCES] Name of References are given in this chapter and then **APPENDIX**.

CHAPTER -2

LITERATURE SURVEY

Hristiyan Kanchev *et al.*[1], Georg Hille *et al.*[2], OKA Heinrich Wilk *et al.*[3] and R. Messenger *et al.*[4] discussed the basic ideas of Photovoltaic cell and develop a Micro grid for different applications.

Chapin *et al.* [5] presented the role of semi conductor materials in the renewable energy.

Hohm, *et al.* [6], Hussein *et al.* [7], Koutroulis *et al.* [8], Eftichios Koutroulis *et al*. [9], M. Veerachary *et al.* [10] and I. S. Kim *et al.* [11] have investigated and proposed various method for the operation of PV cell. A PV module can produce the power at a point, called an operating point, anywhere on the I-V curve. The coordinates of the operating point are the operating voltage and current. There is a unique point near the knee of the I-V curve, called a maximum power point (MPP), at which the module operates with the maximum efficiency and produces the maximum output power.

J. A. Gow *et al*. [12], I. H. Altas *et al.* [13] and I. S. Kim *et al*. [14] discussed different method to develop photovoltaic array.

Mohamed A. H. El-Sayed *et al.* [15] presented the working of solar cell and array.

E. Santi *et al.* [16], D. Franzoni *et al.* [17], Adel M. Sharaf *et al.* [18] and M. Tanrioven *et al.*[19] presented the stand alone working of fuel cell at different loads.

Y. M. Chen *et al.*[20] have presented the working of hybrid system.

J.J. Brey *et al.*[21] , B. Ozpineci *et al.*[22] And O. Wasynczuk *et al*. [23] have presented the role of look-up table in the field of renewable energy.

K.Wang *et al.*[24], S. Jang *et al.*[25], H. Matsuo *et al.*[26], H. Matsuo *et al.*[27], F. Caricchi, *et al.*[28] and M. Marchesoni *et al.*[29] worked on a circuit technique that reduces the boost-converter losses. Here, unregulated DC input into a controlled DC output at a desired voltage level.

Y. Song *et al.*[30], A. M. Tuckey *et al.*[31], L. Solero *et al.*[32], G. K. Andersen *et al.*[33] and H. Ertl *et al.*[34] presented the working of inverter with MOSFET technology.

A. Kotsopoulos, *et al* [35], N. Ashari *et al.*[36] and C. V. Nayar *et al.*[37] Ziyad M. Salameh *et al.*[38] and J. Larminie *et al.*[39] have made a comparison of the three phase load connected with renewable sources.

2.1 Solar Energy:

Solar energy is an important, clean, cheap and abundantly available renewable energy. It is received on Earth in cyclic, intermittent and dilute form with very low power density 0 to 1 kW/m^2 [1]. Solar energy received on the ground level is affected by atmospheric clarity, degree of latitude, etc. For design purpose, the variation of available solar power, the optimum tilt angle of solar flat plate collectors, the location and orientation of the heliostats should be calculated.

2.1.1 Units of solar power and solar energy:

In SI units, energy is expressed in Joule. Other units are Langley and Calorie where:

$$1 \text{ Langley} = 1 \text{ calories} / cm^2 / \text{day}$$

$$1 \text{ Calorie} = 4.186 \text{ J}$$

For solar energy calculations, the energy is measured as an hourly or monthly or yearly average and is expressed in terms of $kJ/m^2/day$ or $kJ/m^2/hour$. Solar power is expressed in terms of W/m^2 or kW/m^2.

2.1.2 Necessary subsystems in a solar energy plant:

Solar collector or concentrator receives solar rays and collects the energy. It may be of following types:

- Flat plate type without focusing
- Parabolic trough type with line focusing
- Parabolic dish with central focusing
- Fresnel lens with centre focusing
- Heliostats with centre receiver focusing

2.1.3 Energy transport medium:

Substances such as water/ steam, liquid metal or gas are used to transport the thermal energy from the collector to the heat exchanger or thermal storage. In solar PV systems energy transport occurs in electrical form.

2.1.4 Energy storage:

Solar energy is not available continuously. So we need an energy storage medium for maintaining power supply during nights or cloudy periods. There are three major types of energy.

2.1.5 Energy conversion plant:

Thermal energy collected by solar collectors is used for producing steam, hot water, etc. Solar energy converted to thermal energy is fed to steam-thermal or gas-thermal power plant.

2.1.6 Power conditioning, control and protection system:

Load requirements of electrical energy vary with time. The energy supply has certain specifications like voltage, current, frequency, power etc. The power conditioning unit performs several functions such as control, regulation, conditioning, protection, automation, etc.

2.1.7 Alternative or standby power supply:

The backup may be obtained as power from electrical network or standby diesel generator.

2.1.8 Energy from the sun:

The sun radiates about 3.8×10^{26} W of power in all the directions. Out of this about 1.7×10^{17} W is received by earth [2]. The average solar radiation outside the earth's atmosphere is 1.353 kW/m^2 varying from 1.43 kW/m^2 (in January) to 1.33 kW/m^2 (in July).

2.1.9 Solar constant (S):

Solar constant is the solar radiation received per unit area normal to the sun's rays in a space outside the earth's atmosphere. In SI units the value of S is 1353 W/m^2. As shown in fig. 2.1.

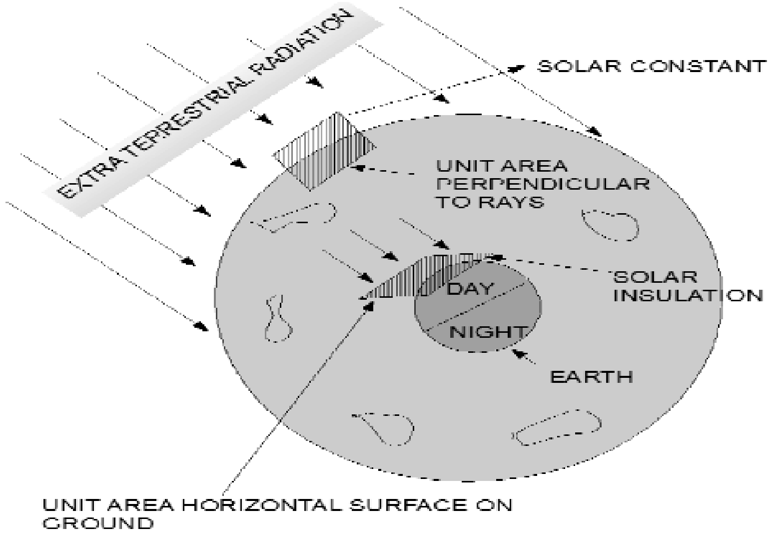


Fig.2.1.Solar Constant

2.1.10 Clarity index:

While passing through the atmosphere, the beam radiation from the sun is partly absorbed and partly scattered by the atmospheric dust, gases, cloud, moisture etc. On a moderate cloudy day, reduction is 10-50%. During dark and cloudy day, radiation reduces to 1%. Flat plate collectors are better suited than focusing collectors for diffused sunlight (cloudy atmosphere). The effect of atmospheric conditions on the beam radiation is expressed by Atmospheric Clarity Index (ACI) given by:

ACI = It is the ratio of solar radiation (W/m^2) to solar constant (W/m^2)

2.1.11 Solar radiation data for India:

India is situated in the Northern hemisphere of earth within latitudes 7^ON and 37.5^ON. The average solar radiation values for India are between 12.5 and 22.7 MJ/m^2.day [3]. Peak radiation is received in some parts of Rajasthan and Gujarat. Radiation falls by 60% during monsoon.

2.1.12 Solar radiation:

Solar radiation is shown in fig. 2.2. It is the solar radiation received on a flat, horizontal surface at a particular location on earth at a particular instant of time [4]. It depends on the following parameters:

- Daily variation (Hour angle).
- Seasonal variation and geographic location of the particular surface.
- Atmospheric clarity.
- Shadows of trees, tall structures, adjacent solar panels, etc.
- Degree of latitude of the location.
- Area of exposed surface, m^2
- Angle of tilt of solar panel.

Modified Angstrom equation for Average Daily Global Radiation is used to determine the radiation at different places on earth. It is given as:

$$\frac{Hg}{Ho} = a + b\frac{Lh}{Lm} \tag{2.1}$$

We have:

$$H_0 = \frac{H01 + H02 + H03 + \cdots \ldots \ldots \ldots \ldots \ldots \ldots \ldots H030}{30} \tag{2.2}$$

and individual values of $H_{01}, H_{02}, H_{03}, \ldots\ldots\ldots H_{030}$ are calculated from

$$H_0 = \frac{24}{\pi} \, Isc\{\, 1+0.033.Cos(360n/365)\,\}\int [(Sin\varphi.\,Sin\delta) + (Cos\varphi.\,Cos\delta.\,Cos\omega)]\, dt \tag{2.3}$$

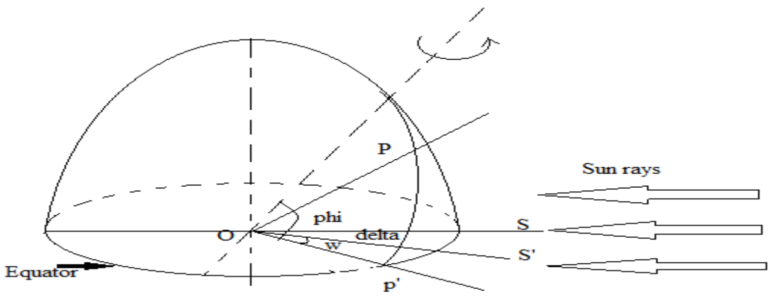


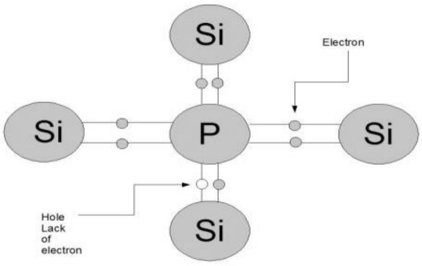
Fig. 2.2. Solar Radiation Geometry

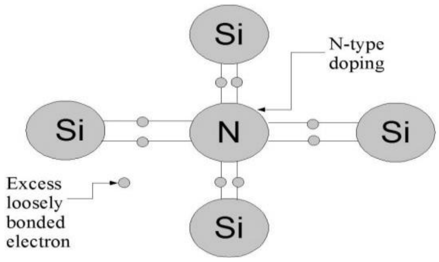
2.2 Photovoltaic Unit:

Photovoltaic unit is made of semiconductor, which converts solar energy into electrical energy. It is explained as below:

2.2.1 Semiconductor (n and p type) Material:

The most common way of making p-type or n-type silicon material is to add an element that has an extra electron or is lacking an electron [5]. In silicon, we use a process called "doping." We'll use silicon as an example because crystalline silicon was the semiconductor material used in the earliest successful PV devices, it's still the most widely used PV material. Fig. 2.3. Shows the bond structure of semiconductor materials.





p-type semiconductor *n-type semiconductor*

(Silicon Crystal doped with p-type impurity) (Silicon Crystal doped with n-type impurity)

Fig. 2.3. Semiconductor materials (n & p-types)

2.2.2 Absorption and Conduction:

In a PV cell, photons are absorbed in the p layer. It's very important to "tune" this layer to the properties of the incoming photons to absorb as many as possible and thereby free as many electrons as possible. Another challenge is to keep the electrons from meeting up with holes and "recombining" with them before they can escape the cell. To do this, we design the material so that the electrons are freed as close to the junction as possible, so that the electric field can help send them through the "conduction" layer and out into the electric circuit. By maximizing all these characteristics, we improve the conversion efficiency of the PV cell. To make an efficient solar cell, we try to maximize absorption, minimize reflection and recombination, and there by maximize conduction.

The conversion efficiency of a PV cell is the proportion of sunlight energy that the cell converts to electrical energy. This is very important when discussing PV devices, because improving this efficiency is vital to making PV energy competitive with more traditional sources of energy (e.g., fossil fuels). Naturally, if one efficient solar panel can provide as much energy as two less-efficient panels, then the cost of that energy (not to mention the space required) will be reduced. For comparison, the earliest PV devices converted about 1%-2% of sunlight energy into electric energy. Today's PV devices convert 7%-17% of light energy into electric energy. Of course, other side of the equation is the money it costs to manufacture the PV devices. This has been improved over the years as well. In fact, today's PV systems produce electricity at a fraction of the cost of early PV systems. General Description of a Photovoltaic cell, Photovoltaic cells convert solar radiation directly into DC electrical energy. The basic material for almost all the photovoltaic cells existing in the market, which is high purified silicon (Si), is obtained from sand or quartz. Basically three types of technology are used in the production of photovoltaic cells: mono crystalline; polycrystalline; and amorphous silicon. The crystalline-Si technology is commonly used as a reference, or baseline, for the solar power generation technology. In general, the status of a photovoltaic cell technology depends on the cell efficiency, and manufacturing cost. The focus of R&D is on improving its efficiency and cost, where the optimal solution is based on a trade-off between the two. The efficiency of a photovoltaic cell is determined by the material's ability to absorb photon energy over a wide range, and on the band gap of the material. Approximate values of the band gap, maximum currents, and maximum theoretical efficiencies at room temperature of some used materials are given in Table 2.1. Crystalline and polycrystalline silicon are the materials most commonly used in photovoltaic cells. The advantage of silicon cells is primarily the abundance of silicon on earth.

The photovoltaic cell consists of several layers of semiconductor materials with different electronic properties. In a typical polycrystalline cell, the bulk of the material is silicon, doped with a small quantity of boron to give it a positive or *p*-type character. A thin layer on the front of the cell is doped with phosphorous to give it a negative or *n*-type character. The interface between these two layers produces an electric field and forms the so called a "cell junction".

When the cell is exposed to sunlight, a certain percentage of the incoming photons are absorbed in the region of the junction, freeing electrons in the silicon crystal.

If the photons have enough energy, the electrons will be able to overcome the electric field at the junction and are free to move through the silicon and into an external circuit. The direction of the electrical current is opposite to its direction if the device operates as a diode.

TABLE 2.1

BAND GAP, MAXIMUM CURRENT DENSITY, AND THEORETICAL EFFICIENCY OF SOME DIFFERENT SEMICONDUCTOR TECHNOLOGIES

Material	**Band gap (eV)**	**Max. Current density (mA/cm^2)**	**Max. Efficiency (%)**
Silicon (Si)	1.12	43.4	28
Gallium arsenide GaAs	1.4	31.8	30
Cadmium telluride CdTe	1.5	28.5	29
Amorphous silicon A-Si	1.65	21.7	27

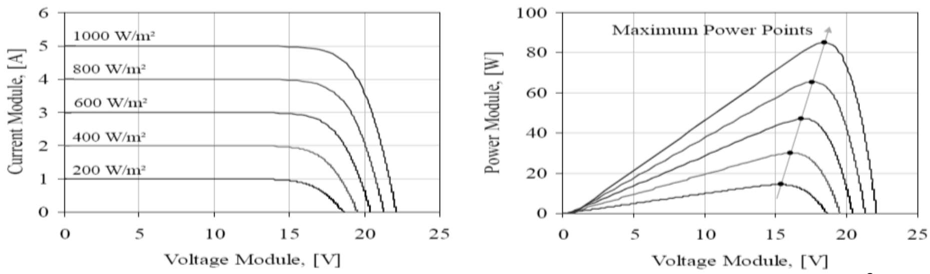
A photovoltaic generator consists of a number of modules, formed by the interconnection of photovoltaic cells, connected together in series and parallel to provide the required voltage and current. Therefore, the performance of the PV generator depends on the modules that comprise the generator and the cells that comprise the modules [5]. The operating point of the generator is defined by the intersection of its I-V characteristics with the load line of the load connected to it.

2.2.3 I-V Characteristics of a Photovoltaic Module:

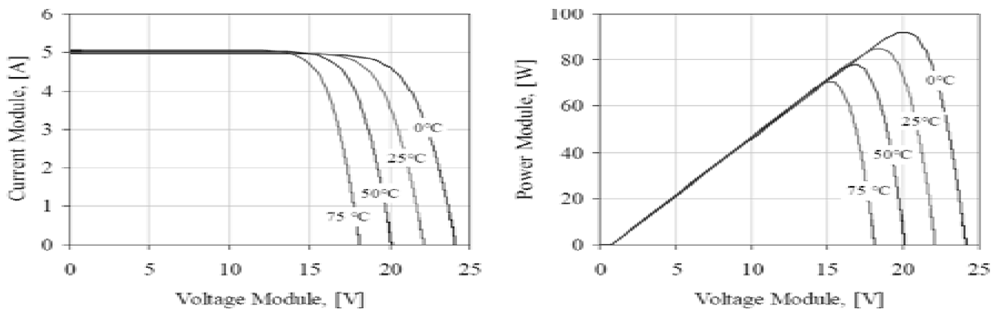
The performance characteristics of a photovoltaic module depend on its basic materials, manufacturing technology and operating conditions. Fig. 2.4. shows typical current-voltage I-V and power-voltage P-V curves of a *BP 585 High-Efficiency Mono crystalline Photovoltaic Module* according to the variation of solar radiation level and cell temperature. Three points in these curves are of particular interest:

- *Short circuit point*, where the voltage over the module is zero and the current is at its maximum (*short circuit current Isc*).
- *Maximum power point or MPP*, where the product of current and voltage has its maximum (defined by $I_{mpp} \times V_{mpp}$).
- *Open circuit point*, where the current is zero and the voltage has its maximum (*open circuit voltage Voc*).

The measurements taken for obtaining an I-V curve depend on controlling the load current. At open circuit, when no load current is generated, a first characteristic value can be measured; the *open circuit voltage Voc*. Decreasing the load fed by the photovoltaic module leads to a decreasing voltage *V* with an increasing current *I*. In other words, by increasing the load current from zero to its maximum value, the operating point moves from the open circuit voltage at zero current to the short circuit current *Isc* at zero voltage. The series of all measured pairs (*V, I*) yields the characteristic I-V curve of the module. From the characteristic curves of the module, it is clear that the open circuit voltage of the photovoltaic module, the point of intersection of the curve with the horizontal axis, varies little with solar radiation changes. It is inversely proportional to temperature, i.e., a rise in temperature produces a decrease in voltage. Short circuit current, the point of intersection of the curve with the vertical axis, is directly proportional to solar radiation and is relatively steady with temperature variations. Actually, the photovoltaic module acts like a constant current source for most parts of its I-V curve. If there is increase in solar radiation causes the output current to increase and the horizontal part of the curve moves upward. An increase in cell temperature causes the voltage to move leftward, while decreasing temperature produces the opposite effect. Thus, the I-V curves display how a photovoltaic module responds to all possible loads under different solar radiation and cell temperature conditions. An operating point of a photovoltaic module will move by varying solar radiation, cell temperature, and load values. For a given solar radiation and operating temperature, the output power depends on the value of the load. As the load increases, the operating point moves along the curve towards the right. So, only one load value produces a P-V maximum power. The maximum power points line, which is positioned at the knees of the I-V curves, has a nearly constant output voltage at varying solar radiation conditions. When the temperature varies, the maximum power points are generated in such a manner that the output current stays approximately constant.



(a) Influence of solar radiation (cell temperature $T_f = 25^0$



(b) Influence of cell temperature (solar radiation $E_o = 1kW/m^2$)

Fig. 2.4. (a) & (b) The I-V Curve and Maximum Power Point

2.2.4 Maximum Power Point Tracker (MPPT):

Fig. 2.4. Shows the I-V curve of the PV module simulated with the MATLAB model. A PV module can produce the power at a point, called an operating point, anywhere on the I-V curve. The coordinates of the operating point are the operating voltage and current [6]. There is a unique point near the knee of the I-V curve, called a maximum power point (MPP), at which the module operates with the maximum efficiency and produces the maximum output power [7]. It is possible to visualize the location of the by fitting the largest possible rectangle inside of the I-V curve, and its area equal to the output power which is a product of voltage and current .

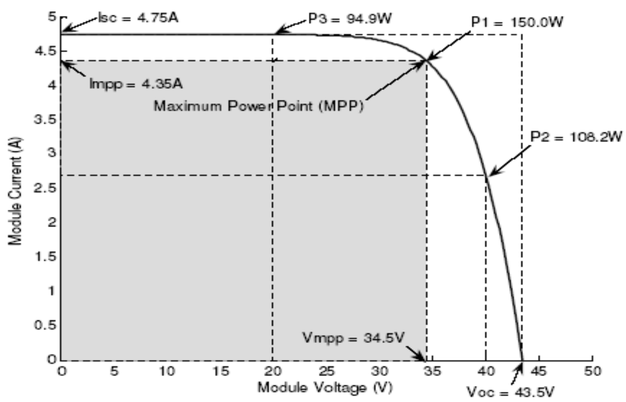


Fig. 2.5. Simulated I-V Curve of PV Module

It reveals that the amount of power produced by the PV module varies greatly depending on its operating condition.

It is important to operate the system at the MPP of PV module in order to exploit the maximum power from the module.

The position of the maximum power points on the PV generator characteristic depends strongly on the solar radiation and the cells temperature, as shown in Fig. 2.5. It is used to adjust the actual operating voltage and current of the PV generator so that the actual power approaches the optimum value as closely as possible [8]. Operation of the PV generator at its MPP involves matching the impedance of the load to that of the generator. For this purpose, an electronic device, normally a power conditioning unit, capable of performing the function of a MPPT has to be connected between PV generator and the load. Therefore, a tracking of the MPP is only meaningful, if components for processing are available and the tracking of the working point does not bring additional energy losses and at small additional costs [9]. Many different techniques have been developed to provide maximum power tracking of PV generators. These techniques can be classified as either direct or indirect methods. The direct methods are based on a searching algorithm to determine the maximum of the power curve without interruption of the normal operation of the PV generator [10]. For a certain working point, the corresponding voltage is changed around by a certain increment. Consequently, if the output power becomes larger than the last value calculated, then the search direction is maintained for the next step. Otherwise, it will be shifted in the opposite direction. The indirect methods use an outside signal to estimate the MPP. Such outside signals may be given by measuring the solar radiation, the module temperature, the short circuit current, or the open circuit voltage of a reference PV cell [11]. A set of physical parameters has to be given, and the MPP set point is derived from the monitored signal. In this dissertation, the direct method is used and a MPPT model is available in the PV generator model.

2.2.5 Advantages of the photovoltaic power:

Major advantages of the photovoltaic power are as follows:

- Short lead time to design, install, and start up a new plant.
- Highly modular, hence, the plant economy is not a strong function of size.
- Power output matches very well with peak load demands.
- Static structure, no moving parts, hence, no noise.
- High power capability per unit of weight.

- Longer life with little maintenance because of no moving parts.
- Highly mobile and portable because of light weight.

The *fill factor (FF)* of a photovoltaic generator is defined as the ratio of output power at MPP to the power computed by multiplying *Voc* by *Isc*. It determines the shape of the photovoltaic generator characteristics. The factors which affect the fill factor are the series and shunt resistances of the photovoltaic generator. A good fill factor is between 0.6-0.8. As the photovoltaic generator degrades with age, its series resistance tends to increase resulting in a lower fill factor.

2.2.6 Sources of Losses in a Photovoltaic Generator:

The losses occurring in the field operation of a PV generator have to be considered in order to calculate precisely its real electric power output. The following losses have to be taken into account.

- **Reflection Losses:** when the incidence angle of the solar radiation differs from the perpendicular direction on the surface of a PV generator, reflection losses occur which will cause an overestimation of the PV yield under field conditions. These losses are reduced by coating the surface with antireflection layer.

- **Spectral Losses:** the solar radiation is characterized by a wide spectral distribution because the Air Mass (AM) value changes during the day. The solar radiation contains photons with extremely different energies. Photons with smaller energy than the band gap energy are not absorbed and thus are unused. In case of photons with larger energy than the band gap energy, only an amount of energy equals to the band gap energy is useful, regardless of the value of a photon’s energy. The excess energy is simply dissipated as heat into the crystal lattice.

- **Mismatch Losses:** the I-V characteristic of PV modules from the same type and the same manufacturer can vary from one module to another. According to the information of the suppliers, the MPP of a module under STC can deviate up to 10% from the data sheet characteristics. By series and parallel connection of the modules in a PV generator, the different I-V characteristics will produce power losses which are called mismatch losses. As example, for quantifying the mismatch losses, measurements were performed in which the PV generator was made up of 36 identical modules and then compared with calculations in which the manufacturer's parameters of the individual 36 modules were used, and the results showed mismatch losses of about 3%.

- **Shadowing Losses:** the characteristics of the PV generators are affected by the presence of the partial shadowing especially the value of maximum output power, the fill factor, and the efficiency of PV generator. Therefore, it is very important to choose the suitable site for the PV generator to prevent partial shadowing during the operation of the PV system.

- **External losses:** In a real system, the PV generator output power is not exactly equal to the input power to the connected power conditioning unit. In order to calculate this input power, the losses caused by the voltage drop due to cable resistances and the blocking diodes have to be considered. The losses caused by resistance of the connecting cables (ohmic losses) form the PV generator have to be calculated based on cables length and diameter. This resistance is considered as a series resistance of the PV model. In each string that forms the PV generator, blocking diodes are connected in series with these strings. If a short circuit occurs in one or more of these strings, the blocking diodes will prevent the currents to flow from the perfect strings to the faulty strings. During operation there is a voltage drop through each diode of approximately 0.7V. This value has to be subtracted from the output voltage of the PV generator.

2.2.7 Solar panel:

The diagram of solar panel n is shown here in fig. 2.6 & fig. 2.8. Modern solar Cells make use of semiconductor materials usually based on single-crystal silicon. When doped with phosphorus, arsenic or antimony the silicon becomes an n-type semiconductor, and when doped with boron, Aluminum, Indium, or Gallium, it forms a p-type semiconductor [12]. If a p-type semiconductor is brought into intimate contact with one of the n-type, they form a p-n (or n-p) junction. if the two semiconductor materials are derived from the same element (or compound), such as silicon, the system is referred to as a homo-Jn. It is also possible for a p-n Jn. [13]. To be formed from two different semiconductor materials, such as CdS and Cu_2S. This is known as a hetero Jn.

The Schottky Jn. Consisting of a semiconductor at the metal. This Jn. is formed by depositing a thin layer of a metallic conductor on to a p or n type semiconductor Schottky Jn. photovoltaic cells made with the so called amorphous Silicon are more efficient than homo Jn. p-n cells of the same materials. Cost of it, is also less [14].

The MIS (metal insulator semiconductor) Solar cell is similar to the Schottky type except that a very thin layer (about 0.1 to 0.3 micro meter) of an insulator is deposited between the semiconductors or and the metallic conductor a conversion efficiency of more than 17% has been reported for an MIS solar cell made with single crystal silicon. PV cell is a light sensitive two-terminal N-P junction made of semiconducting material such as silicon. P type and N-type semiconductor and a solar cell are shown in fig. 2.6 and 2.7 respectively.

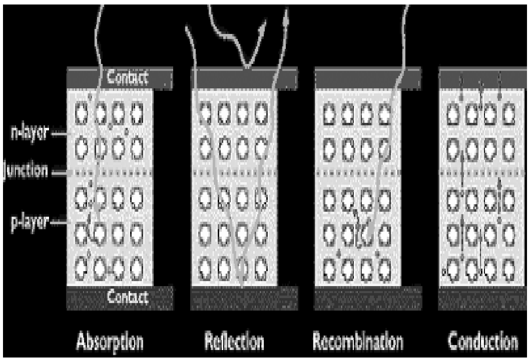


Fig. 2.6. Solar panel

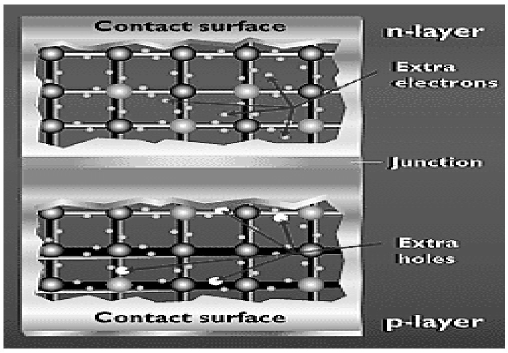


Fig. 2.7. P & N layers of PV Cell

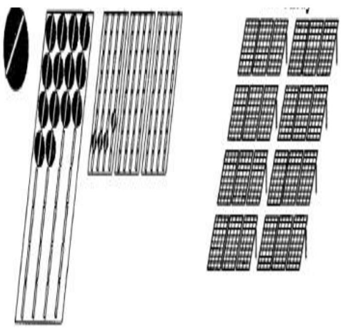


Fig. 2.8. PV Cell, PV Module, PV Panel and PV Array

Fig. 2.9. Unit of PV Array

Pictures of PV cell, PV module, PV panel and PV array are shown here in fig. 2.8. and 2.9. These are made of Semiconductor materials.

2.2.8 Working of solar cell:

A solar cell (also called a photovoltaic cell as shown in fig. 2.10.) is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect. It is a form of photoelectric cell (in that its electrical characteristics e.g. current, voltage, or resistances vary when light is incident upon it) which, when exposed to light, can generate and support an electric current without being attached to any external voltage source [15]. The term "photovoltaic" comes from the Greek word (*phōs*) meaning "light", and from "Volt", the unit of electro-motive force, the volt, which in turn comes from the last name of the Italian physicist Alessandro Volta, inventor of the battery (electrochemical cell). The term "photo-voltaic" has been in use in English since 1849. *Photovoltaics* is the field of technology and research related to the practical application of photovoltaic cells in producing electricity from light, though it is often used specifically to refer to the generation of electricity from sunlight. Cells can be described as *photovoltaic* even when the light source is not necessarily sunlight (lamplight, artificial light, etc.) [16].The operation of a photovoltaic (PV) cell requires 3 basic attributes:

- The absorption of light, generating either electron-hole pairs.
- The separation of charge carriers of opposite types.
- The separate extraction of those carriers to an external circuit.

In contrast, a solar thermal collector collects heat by absorbing sunlight, for the purpose of either direct heating or indirect electrical power generation.

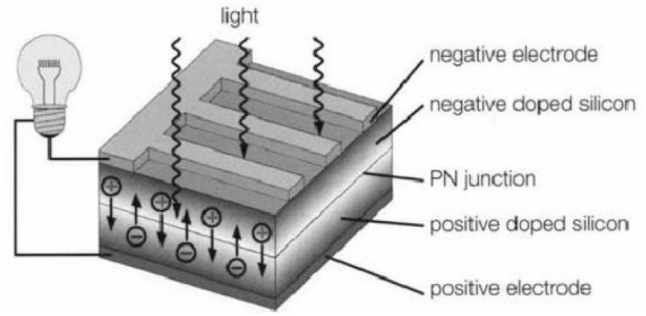


Fig. 2.10. Solar Cell

"Photo electrolytic cell" (photo electrochemical cell), on the other hand, refers either a type of photovoltaic cell (like that developed by A.E. Becquerel and modern dye-sensitized solar cells) or a device that splits water directly into hydrogen and oxygen using only solar illumination.

2.3 Fuel Cell Unit:

Introduction: The conversion of hydrogen into electricity can be achieved by different methods such as fuel cell and combustion reactions. The advantage of the fuel cell reaction is its higher overall conversion efficiencies. Therefore, the fuel cell will be the topic of interest in this dissertation.

2.3.1 Cell Components:

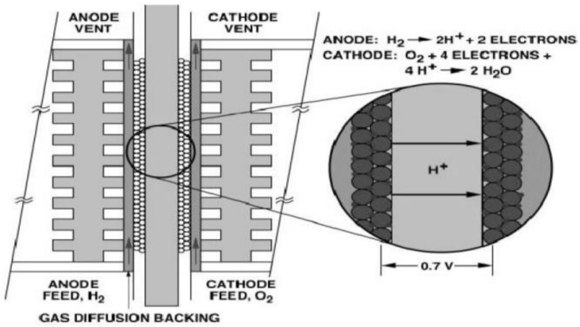
Typical cell components within a PEFC stack include:

- The ion exchange membrane
- An electrically conductive porous backing electro-catalyst (the electrodes) at the interface between the backing layer and the membrane Cell interconnects and flow-plates that deliver the fuel and oxidant to reactive sites via flow channels and electrically connect the cells (Fig. 2.11.).

PEFC stacks are almost universally of the planar bipolar type. Typically, the electrodes are cast as thin films that are either transferred to the membrane or applied directly to the membrane. Alternatively, the catalyst-electrode layer may be deposited onto the backing layer, then bonded to the membrane. Organic-based cat-ion exchange membranes in fuel cells were originally conceived by William T. Grubb (2) in 1959 [19]. The function of the ion exchange membrane is to provide a conductive path, while at the same time separating the reactant gases. The material is an electrical insulator. As a result, ion conduction takes place via ionic groups within the polymer structure.

An accelerated interest in polymer electrolyte fuel cells has led to improvements in both cost and performance. Development has reached the point where both motive and stationary power applications are nearing an acceptable cost for commercial markets [20]. Operation of PEFC membrane electrode assemblies (MEAs) and single cells under laboratory conditions similar to transportation or stationary applications have operated for over 20,000 hrs continuously with degradation rates of 4 to 6 _V/hr (or about 0.67 to 1.0 percent per 1000 hrs), which approaches the degradation rates needed for stationary applications (about 0.1

percent per 1000 hrs is used as a rule of thumb) [21]. Complete fuel cell systems have been demonstrated for a number of transportation applications including public transit buses and passenger automobiles. For stationary applications, a number of demonstration systems have been developed and numerous systems have been installed, mostly in the 2 to 10 kW range.



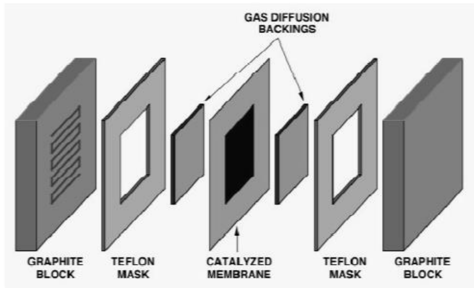


Fig. 2.11. Schematic of PEFC

Fig. 2.12. Single Cell Structure of PEFC

However, Although these systems have collectively logged millions of kW.hrs, developers have not yet demonstrated system or stack life of more than 8,000 hours with realistic catalyst loadings and realistic operating conditions, and then with degradation rates of several percent per 1000 hrs. Consequently, PEFC developers and researchers are focused on achieving critical improvements in this field.

2.3.2 Fuel cell:

A fuel cell is a device that generates electricity by a chemical reaction. Structure of cell is shown in fig. 2.13. Every fuel cell has two electrodes, one positive and one negative, called, respectively, the anode and cathode. The reactions that produce electricity take place at the electrodes. Every fuel cell also has an electrolyte, which carries electrically charged particles from one electrode to the other, and a catalyst, which speeds the reactions at the electrodes. Hydrogen is the basic fuel, but fuel cells also require oxygen. One great appeal of fuel cells is that they generate electricity with very little pollution–much of the hydrogen and oxygen used in generating electricity ultimately combines to form a harmless byproduct, namely water. One detail of terminology: a single fuel cell generates a tiny amount of direct current (DC) electricity. In the same way many fuel cells are formed, with principle.

In a PEM fuel cell, the gas diffusion backings provide electrical contact between the electrodes and the bipolar plates, and distribute reactants to the electrodes. Also, they allow the reaction product water to exit the electrode's surface and permit passage of water between the electrodes and the flow channels. These layers are made of a porous, electrically conductive material, usually carbon paper. In a fuel cell stack, bipolar plates or separator plates separate the reactant gases of adjacent cells, connect the cells electrically, and act as a support structure.

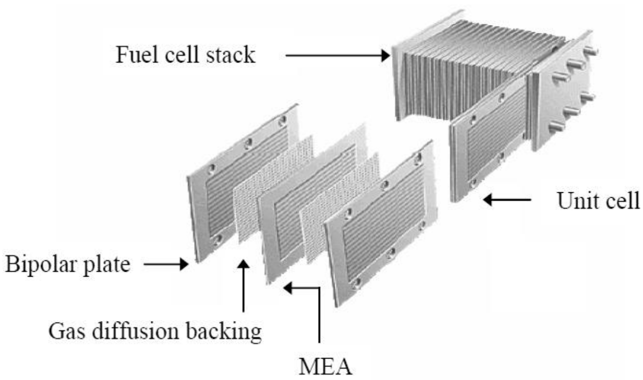
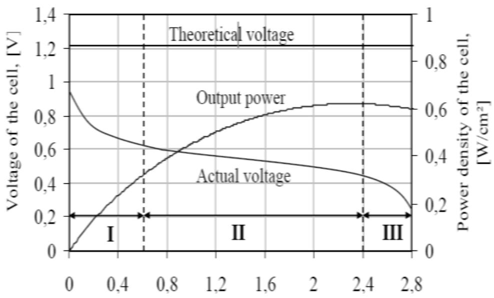


Fig. 2.13. PEM unit cell structure

Bipolar plate materials must have high conductivity and be impermeable to gases. The I-V and I-P characteristics of a PEM fuel cell are presented in fig. 2.14. They can be divided into three regions, which are governed by different over-voltages. Activation over-voltage dominates at low current densities in region I. Region II is governed by the ohmic losses and in region III bending down of the polarization curves due to the concentration over-voltage. Some fuel cells are not operated at high enough currents to ever see the effects of losses in region III. Hydrogen and oxygen pressures in a H_2/O_2 PEM fuel cell during operation are kept fairly constant. A fan is usually used to force atmospheric air across the cathode side. The overall performance of the PEM fuel cell can be improved by increasing one or all of the following conditions:

- Temperature of the PEM fuel cell (20-80°C).
- Hydrogen and/or oxygen pressure (1-5 Bar)
- Flow rates of hydrogen and oxygen Current density of the cell (A/cm^2)



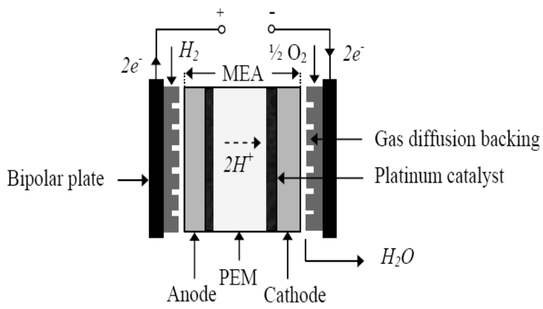


Fig. 2.14. Characteristic curves of a typical PEM fuel. Fig. 2.15. A typical PEM fuel cell.

2.3.3 Working of Fuel Cells:

Polymer Electrolyte Membrane (PEM) fuel cells used in automobiles—also called Proton Exchange Membrane fuel cells use hydrogen fuel and oxygen from the air to produce electricity. Step 1 : Hydrogen fuel is channeled through field flow plate to the anode on one side of the fuel cell, while oxygen from the air is channeled to the cathode on the other side of the cell. Step 2 : At the anode a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons. Step 3: The polymer Electrolyte Membrane (PEM) allows only the positively charged ions to pass through it to the cathode. The negatively charged electrons must travel along an external circuit to the cathode, creating an electrical current. Step 4: At the cathode, the electrons and positively charged hydroen ions combine with oxygen to form water, which flows out of the cell.

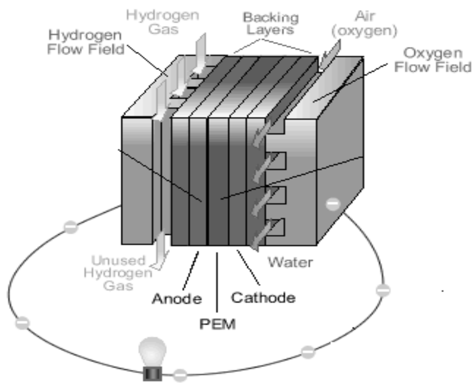


Fig. 2.16. A typical circuit of PEM Fuel cell.

The diagram to the right shows how a PEM fuel cell works. Fuel Cell Stacks, Most fuel cells designed for use in vehicles produce less than 1.16 volts of electricity—far from enough to power a vehicle. Therefore, multiple cells must be assembled into a fuel cell stack. The potential power generated by a fuel cell stack depends on the number and size of the individual fuel cells that comprise the stack and the surface area of the PEM.

Fuel cells are based on a controlled reaction between H and O-atoms which generates electric power and heat. In the process, the fuel enters the reformer where it is transformed into hydrogen and at the anode, hydrogen splits into a proton and a negative part (electron). The membrane of a fuel cell is permeable for protons, but not for the electrons, thus the electron flow through the external circuit including a power consumer such as a motor and then return to the cathode of the fuel cell. At the cathode, the oxygen gas absorbs electrodes and protons forming water. Hence, water acts as the main emission from the fuel cell. Now, in order to increase the power of the fuel cell, many separate membrane electrode assemblies are combined together to form a fuel cell stack.

2.3.4 Cost of the fuel cell:

The cost is a barrier for all types of fuel cells across all applications. The cost of fuel cells is determined by the market segment, by costs of the competing technologies and by the energy economic developments (energy taxation). Due to the higher efficiency of fuel cell systems, the fuel and the maintenance costs are lower compared to other systems such as gas turbines. The following factors can influence the operational costs of fuel cell systems:

- The cost of natural gas.
- The operation mode (heat conducted, electricity conducted, or combinations).
- The lifetime of the system (costs for stack replacement).
- To reduced the investment costs of fuel cell systems.
- Improving power density of fuel cell and using lower cost materials.

Minimizing temperature constraints (e.g. lowering SOFC operating temperature to use lower cost materials).

The cost of fuel cells varies widely depending on size, power electronics requirements, and reformer requirements. Two autonomous remote renewable energy systems, a small 356W radio repeater station and a 148kW village power system are analyzed in detail in [20]. The capital cost of a PEMFC is 5000$/kW for the radio repeater station because of its small size. This cost was reduced to 3000$/kW for the other system to account for its large size. The cost issues facing portable and standby power applications are less acute than the challenges facing transportation and stationary applications.

2.3.5 Drawback of fuel cell for its business:

The basic workings of a fuel cell may not be difficult to illustrate. But building inexpensive, efficient, reliable fuel cells is a far more complicated business. Scientists and inventors have designed many different types and sizes of fuel cells in the search for greater efficiency, and the technical details of each kind vary. Many of the choices facing fuel cell developers are constrained by the choice of electrolyte. The design of electrodes, for example, and the materials used to make them depend on the electrolyte. Today, the main electrolyte types are alkali, molten carbonate, phosphoric acid, proton exchange membrane (PEM) and solid oxide. The first three are liquid electrolytes; the last two are solids. The type of fuel also depends on the electrolyte. Some cells need pure hydrogen, and therefore demand extra equipment such as a "reformer" to purify the fuel. Other cells can tolerate some impurities, but might need higher temperatures to run efficiently. Liquid electrolytes circulate in some cells, which require pumps. The type of electrolyte also dictates a cell's operating temperature–"molten" carbonate cells run hot.

2.3.6 Historical development of fuel cell technology:

The fuel cell principle was discovered by the Englishman William Robert Grove in 1839 [19]. The technical development of fuel cells started shortly after World War II when Francis T. Bacon of Cambridge, England, successfully developed a high pressure fuel cell. Subsequently alkaline fuel cells (AFC) and proton exchange membrane fuel cells (PEMFC) were developed for space programs (Gemini, Apollo, Space-lab). In the early 1970s, the development of phosphoric acid fuel cells (PAFC), high temperature molten carbonate (MCFC), and solid oxide fuel cells (SOFC) started [19]. PEMFC was not investigated with significant efforts before the late 1970s. These intensified activities, mainly by Ballard, Siemens, H Power, International Fuel Cells and several US universities and research centers, resulted in significantly improved Membrane Electrode Assemblies (MEA). Therefore, weight and cost of the PEMFC could be reduced drastically and their performance increased dramatically. The first commercial power plant for the PEMFC began operation in 1992 with the 200kW PC25TM. With the formation of the Partnership for a New Generation of

Vehicles (PNGV) by Chrysler, Ford, General Motors and the US Government in 1993, a new focus was set on transportation applications of fuel cells.

2.3.7 Fuel cell's application:

Fuel cells are classified as power generators because they can operate continuously, or for as long as fuel and oxidant are supplied. The application of fuel cells largely depends on the operation conditions such as the values of the typical operation temperature and efficiency. Fuel cell types are listed in Table 2.2. [18, 19].

TABLE 2.2

FUEL CELL TECHNOLOGIES [18, 19]

Fuel cell type	**Electrolyte**	**Temperature (^{0}C)**	**Electrical Efficiency (%)**
PEMFC	Polymer	~80	60-65
AFC	KOH	~100	60-70
PAFC	H_3PO_4	~200	40-45
MCFC	Li_2CO_3	~650	53-57
SOFC	ZrO_2	~1000	55-65

SOFC and MCFC operate at high temperatures, and are therefore most suitable for large power plants. PAFC is today commercially available and can be used over a large power range, from a few kW to several MW.

TABLE 2.3

OVERVIEW OF THE FUEL CELL APPLICATION [19]

FC Type	**Fields of Application**	**Availability**
PEMFC	Stationary application for domestic power and heat production Stationary application for dedicated power heat production Mobile application for buses, service vehicles Mobile application for railroad system	2000 / 2001, 2002 / 2003, 2001-2003 / 2003
AFC	Space and special military applications	Today
PAFC	Stationary applications for dedicated power and heat production Mobile applications	1998 > 2000

MCFC	Stationary application for combined power and vapor production Stationary application for unility use	2001 > 2005
SIFC	Stationary applications for domestic heat and power production Stationary applications for commerical heat and powerproduction Stationary applications for utility	2001- 2003 > 2005

However, it operates at medium high temperatures and is typically most suitable for co-generation (Combined Heat and Power generation, CHP). The two low temperature fuel cells AFC and PEMFC are attractive options for stand-alone power systems due to their low operation temperatures.

2.3.8 Advantages and disadvantages of fuel cells:

The fuel cell is important for terrestrial applications of the hydrogen technology, because it combines a relatively high efficiency with a very low environmental emission. In addition, it operates at a constant temperature, and the heat from the electrochemical reaction is available for co-generation applications. Fuel cell power plants can be configured to use a wide variety of fuels and produce a wide range of electrical outputs. Also, these plants by operating on hydrogen and oxygen offer high energy density [16] and [17]. Therefore, large energy outputs can be produced from a system with a relatively small weight and volume. Thus, a fuel cell is a preferred power generator in remote applications where system weight and volume are important parameters.

Advantages:

Advantages of fuel cells and fuel cell plants are:

- Direct conversion of chemical to electrical energy.
- Excellent characteristics, even with partial loading.
- High availability of lower temperature units.
- Fuel flexibility.
- Zero or very low noise except for occasional vibrations.

Disadvantages:

- Relatively high costs compared to conventional power sources.
- Life time limitations (no confirmed knowledge about real life time).
- Decreasing electrical efficiency as function of the operating life time.
- Special treatment of fuel (H_2) is necessary.
- Noble materials are needed for membranes and electrodes, e.g., platinum is one of the most effective catalysts.

2.3.9 Modular Hybrid Power System Technology:

Recent developments allow coupling all components of a PV hybrid system on the AC side in a standardized way.

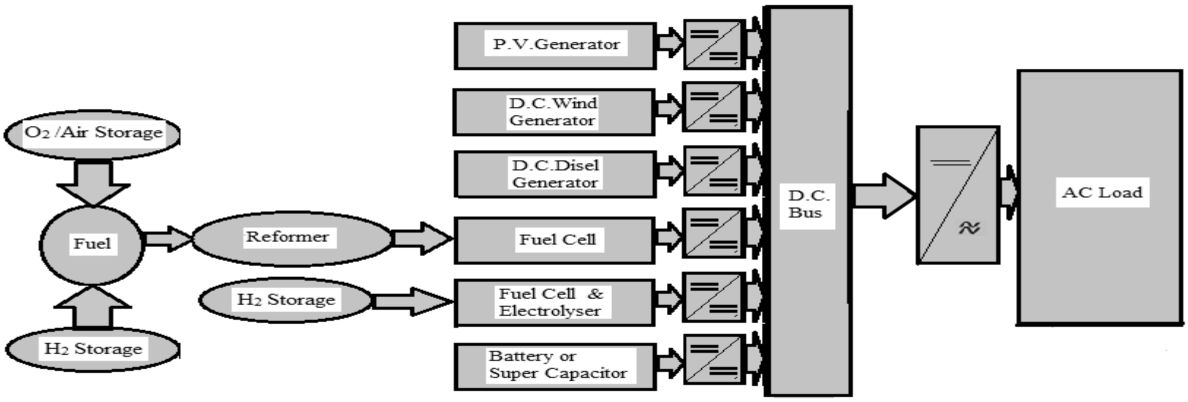


Fig. 2.17. Block diagram of the DC coupled hybrid power system.

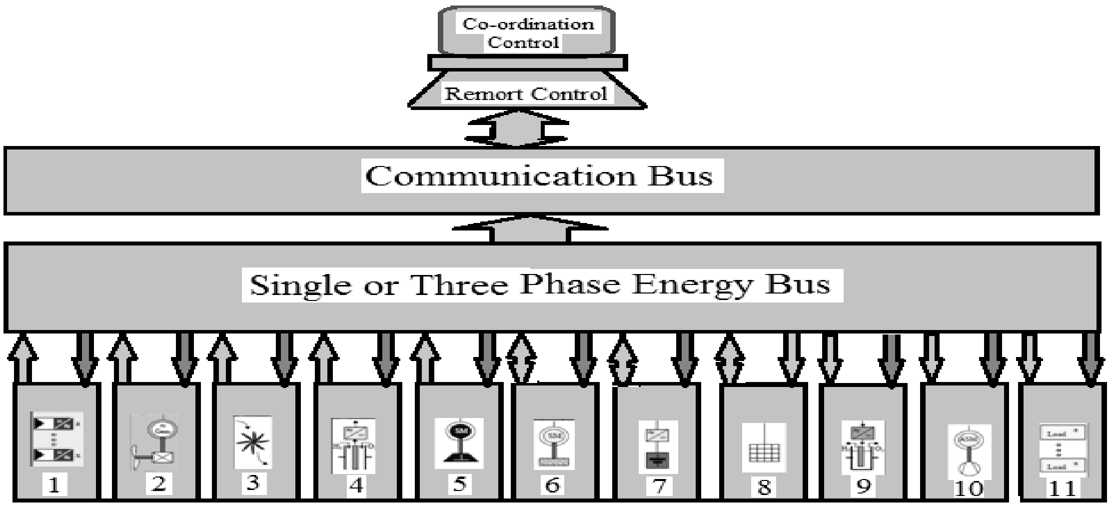


Fig. 2.18. General modular hybrid System. .

Main features of this way are system expandability, general adaptability, utility-grid compatibility, cost reduction, and simple system design and installation. The overall system control needs not to be changed with any change in the size of the system components [20]. Block diagram of hybrid power system with different sources & load is shown here.

Where:

1 to 4: Energy availability, 5 to 7: Power-demand, 8 to 11: Energy used (Load)

Different types of sources & loads are represented from 1 to 11.

Where:

1: P.V. with Inverter

2: Wind Converter

3: Water Turbine

4: Fuel Cell

5: Combustion Aggregate

6: Transient Storage

7: Battery Storage

8: Grid Terminal

9: Electrolyser

10: Mechanical Load

11: Passive Load

In hybrid system following blocks are given such as Coordinate control unit, Remote Control, Communication bus, Single or Three phase and energy bus and different generating sources & load. Based on the standardization of system design, the construction of hybrid power systems, especially power conditioning units, has the potential to strongly reduce the cost [20]. Using a small set of inverter types with a global-market-oriented degree of modularization, such as PV string inverters or PV module integrated ones; the whole PV application spectrum for supplying power can be covered. "The advantages of modularization of power supply units appear mainly in the kilowatt-range and can be extended up to the MW power scale" [20]. Fig. 2.18. Shows a general modular system technology for reliable hybrid power systems [20]. This structure contains two connection buses which are called the energy and communication buses. The energy bus couples the system's components among each other and with the user load. All components are considered to be connected on the AC side as recommended in the modular system concept. The communication bus connects all system components and the user load with the supervisory controller. The task of this bus, in practice, is to transfer signals, which describe the status of the subsystem components for monitoring and control purposes of the hybrid system. Upon this information and based on the predefined settings, the supervisory energy dispatch decisions which are signaled back via the same communication line to the corresponding component's controller or actuator. For the modular AC coupled power generation and storage units, the well established standard 230V/50Hz or 110V/60Hz is most suitable with the energy bus. Defined units are integrated with a standard interface, hence one unit being compatible with another [20]. This approach has worked on modularization and standardization at the component level which is a more satisfactory solution than standardization at the system level. Consequently, serial production is achievable, which in itself leads to cost reduction and improves the supply reliability. The modular low power hybrid systems in single and three phase technology which are based on PV generator and battery storage components are being developed and tested at ISET together with partners from industry and research. Hybridization through combining different energy sources in one supply system offers the best possibility to use locally available renewable energies. The nature of hybridization is mainly based on the special features and economic potential of various energy conversion processes and on the power range. Hybrid system technology mainly covers stand-alone systems as well as isolated grids of small and medium power ranges. The modular hybrid power system coupling all generators, storage media and user loads on the AC side come out with numerous advantages, such as simplicity in system design, high reliability, and expandability. Moreover, the AC side structure provides standardization, quality assurance and serial production which also results in a considerable potential of cost reduction. Due to the features of modular expandability and general adaptability a family of hybrid systems in megawatt-range is initiated in order to cover a multitude of different stand-alone applications.

The utilization of intermittent natural energy resources such as solar, wind, and hydro energy requires some form of energy storage. The concept of utilizing hydrogen as a substance for storage of energy is shown in fig. 2.15. In this work, a hybrid system based on hydrogen technology is considered which needs a hydrogen producing unit, a hydrogen storing unit (Tanks), and a hydrogen utilizing unit (PEM Fuel Cell). However, the system based on intermittent energy sources and is likely to experience large minutely, hourly, and daily fluctuations in energy input. Thus, it should be emphasized that the main purpose of the hydrogen storage system is to store energy over short and long periods of time, i.e., hour to hour and season to season. Other small short-term energy storage such as a secondary battery or super capacitor must also be included for the safe operation of the fuel cell component and also to supply power during transient load conditions. In addition, a control system is required to monitor and guide the operation of the components of the system. Utility interactive inverters not only condition the power output of the photovoltaic arrays but ensure that the PV system output is fully synchronized with the utility power. These systems can be battery-less or with battery backup. Systems with battery storage (or a flywheel) provide additional power-supply reliability. The grid connection of photovoltaic systems is gathering momentum because of various rebate and incentive schemes. This system allows the consumer to feed its own load utilizing the available solar energy, and the surplus energy can be injected into the grid under the energy buy-back scheme to reduce the payback period. Grid-connected PV systems can become a part of the utility system. The contribution of solar power depends on the size of system and the load curve of the house. When the PV system is integrated with the utility grid, a two-way power flow is established. The utility grid will absorb excess PV power and will feed the house at night and at instants when the PV power is inadequate. The utility companies are encouraging this scheme in many parts of the world. The grid-connected system can be classified as follows:

- Rooftop application of grid-connected PV system
- Utility-scale large system

For small household PV applications, a roof-mounted PV array can be the best option. Solar cells provide an environmentally clean way of producing electricity, and rooftops have always been the ideal place to put them. With a PV array on the rooftop, the solar-generated power can supply residential load. The rooftop PV systems can help in reducing the peak summer load to the benefit of utility companies by feeding the household lighting, cooling, and other domestic loads. The battery storage can further improve the reliability of the system at times of low radiation level, at night or on cloudy days. But the battery storage has some inherent problems, such as maintenance and higher cost. For roof-integrated applications, the solar arrays can be either mounted on the roof or directly integrated into the roof. If the roof integration does not allow for an air channel behind the PV modules for ventilation purposes, then it can increase the cell temperature during the operation, consequently leading to some energy losses. The disadvantage of the rooftop application is that the PV array orientation is dictated by the roof. In cases, where the roof orientation differs from the optimal orientation required for the cells, the efficiency of the entire system would be suboptimal. Utility interest in PV has centered on the large grid connected PV systems. In Germany, the United States, Spain, and several other parts of the world, some large PV-scale plants have been installed.

The utilities are more inclined toward large-scale, centralized power supplies. The PV systems can be centralized or distributed systems. Grid-connected PV systems must observe the islanding situation, when the utility supply fails. In case of islanding, the PV generators should be disconnected from mains. PV generators can continue to meet only the local load, if the PV output matches the load. If the grid is reconnected during islanding, transient over-currents can flow through the PV system inverters, and protective equipment such as circuit breakers may be damaged. Islanding control can be achieved through inverters or via the distribution network. Inverter controls can be designed on the basis of detection of grid voltage or measurement of impedance, frequency variation, or increase in harmonics. Protection must be designed for islanding, short circuits, over under voltages/currents, grounding and lightning etc. The importance of the power generated by the PV system depends on the time of the day, especially when the utility is experiencing peak load. The PV plants are well suited to summer peaking, but it depends upon the climatic condition of the site. PV systems being investigated for use as peaking stations would be competitive for load management. The PV users can defer their load by adopting load management to get the maximum benefit out of the grid-connected PV plants and feeding more power into the grid at the time of peak load. The assigned capacity credit is based on the statistical probability that the grid can meet peak demand. The capacity factor during peaks is very similar to that of conventional plants, and similar capacity credit can be given for PV generation, except at times when the PV plants are generating very much less power, unless adequate storage is provided. With the installation of PV plants, the need for extra transmission lines and transformers can be delayed or avoided. The distributed PV plants can also contribute in providing reactive power support to the grid and reduce the burden on VAR compensators.

2.4 Topologies of Hybrid Power Systems:

From the application's point of view, hybrid power systems which combine conventional and renewable power conversion systems can be classified as DC or AC coupled topologies [20]. A DC coupled hybrid power system is a system whose different power sources are connected to a main DC bus-bar and through this bus they are connected to the AC grid or AC user load.

An AC coupled hybrid power system is a system whose different power sources are connected to the AC grid or AC user load without an intermediate DC bus-bar connecting them.

2.4.1 DC Coupled System Topology:

In this topology, all generator and storage units are tied to the DC bus-bar. The output of all AC power sources, if available, is converted into DC, then added to the output of all DC power sources to a main DC bus-bar, which is connected to the AC user load through a main DC/AC inverter [22]. This inverter converts the generated DC power from different generators and storages to AC of the desired voltage and frequency to satisfy the AC user load demand. This inverter should be adequate to cover the peak load demands, while the back-up generator capacity (diesel or fuel cell generator) should be able to meet the peak load and charge the short term storage units simultaneously. It can be seen that each power source is connected to the DC bus-bar through its own DC/DC converter. The DC/DC converters which connect the battery or hydrogen fuel cell system to the DC bus-bar differs from the others by being bi-directional, instead of unidirectional, in order to allow charge and discharge of battery as well as hydrogen storage by electrolyser and fuel cell. These converters are used in order to produce a constant DC voltage on their outputs regardless of the voltage variations on their inputs [23]. The advantage of this topology is that the load demand is satisfied without interruption even when the generators charge the short-term storage units. The design principles of this topology are rather easy to implement. Its serious disadvantages are low overall conversion efficiency, and limited control by the diesel generator in case of being incorporated in the system. Furthermore, expanding the system by increasing a component capacities or adding further generators is very complicated due to the limited nominal capacity of the DC/AC inverter [24].

2.4.2 AC Coupled System Topology:

All system components in this topology are connected to the AC user load via the AC bus-bar. The AC coupled system topology has a superior performance compared to the DC coupled configuration since each inverter can be synchronized to its generator so that it can supply the load independently and simultaneously with other inverters [25].

This offers some flexibility for the energy sources to meet the user load demand. In case of low load demand, all the inverters of the generators and storages are in standby mode operation without one inverter, for example the PV generator inverter, to cover the load demand [26]. However, during high load demands or peak times, some generators and storage units or all are operated in parallel to cover the user load demand. Because of this parallel operation capability, the capacities of the power conditioning units (PCUs) and the generators are reduced [27, 28]. This topology has several advantages compared to the DC coupled topology such as higher overall efficiency, smaller sizes of the PCUs while keeping a high level of energy availability, and optimal operation of the diesel generator due to reducing its operating time and consequently its maintenance cost. The operation and control of this topology are sophisticated due to the synchronization process required between the components. The development of an advanced PCU simplifies the control and the load dispatch problem. Therefore, advanced control algorithms which build and stabilize the isolated grid and allow parallel operation of different renewable and conventional generators as well as the integration of storage media have been developed [29]. Moreover, due to continuous developing of power conditioning units, such complicated control tasks become reliable in their applications. In this way, the expansion or modification of the hybrid system configurations can easily be carried out in order to cover the demand growth or change in demand behavior.

CHAPTER -3

WORKING OF PHOTOVOLTAIC & FUEL CELL HYBRID SYSTEM

3.1 Introduction of Hybrid system:

A number of power generators and storage components are combined to meet the energy demand of remote or rural area, or even a whole community. In addition to PV generators, diesel generators, wind generators, small hydro plants, and others sources of electrical energy can be added as needed to meet the energy demand in a way that fits the local geography and other specifics. Before developing a hybrid electric system for a specific site, it is essential to know the particular energy demand and the resources available at that site. Therefore, energy planners must study the solar energy, wind, and other potential resources at the site, in addition to the energy demand. This will allow them to design the kind of hybrid power system that meets the demands of the facility at best. In this chapter, a brief technical description of some different hybrid power system configurations is considered. It also includes notes about hybrid power system topologies, modularization, and standardization.

The utility grid extension to remote and inaccessible areas is not a cost effective option and sometimes technically not feasible, and the need for stand-alone power systems is essential. The first solution to provide electricity to these areas is achieved by using diesel generators which have low investment costs but high running costs, particularly for the smaller units. Their power generation costs increase when meeting short period peak loads, especially encountered in small communities with low consumer diversity and similar social habits. Therefore, systems are often over-dimensioned by installing multiple diesel units in order to compensate the peak periods, causing low efficiency and higher maintenance costs. The first hybridization step is taken by adding a PV generator or a wind turbine generator to such conventional power generation systems, which increases the operational problems. As the power has to be supplied continuously, these generators must run continuously to meet any instantaneous deficit caused by load increase or renewable resource fluctuations. In such a hybrid system, the renewable energy generators serve as fuel saving units. None the less, renewably generated power serves to decrease further the average loading ratio of the diesel plant, and consequently the increased maintenance costs may outweigh fuel savings. The addition of some kind of energy storage partially solves the problem of the diesel by shutting down the conventional power generator when the generated renewable energy plus the stored energy is higher than the user load demand [20]. Moreover, integration of a storage medium enhances the renewable energy usability. Different stand-alone hybrid systems based mainly on a PV generator combined with a battery as a storage medium and an auxiliary diesel generator have been installed and operated in different climates and applications for several years [20].

The diesel generator in this system is replaced by a fuel cell system. When the batteries reach the minimum allowable charging level and the load exceeds the power produced by the PV generator. The advantages of this system are in general the same as for a Photovoltaic-Battery-Diesel hybrid system with regard to the PV generator size and batteries availability. Some principle differences exist between a diesel generator and a fuel cell which affect the design, sizing and the operating strategy of such a hybrid system. For example, a diesel generator will provide the rated power to the load in a few seconds after start up, but a fuel cell system needs more time to provide the rated power and the output should only be increased slowly after start up.

A significant advantage of the fuel cell as a back-up generator over the diesel or petrol generator is the high conversion efficiency of the fuel cell. Whereas a 1 kW diesel generator achieves total efficiencies between 8-15% [20], a similar fuel cell system can achieve up to 50% efficiency when operated with H_2 and O_2. Diesel generators need high maintenance costs and they are noisy and emit exhaust gases continuously. In contrast, the fuel cells have very good technical properties which make them interesting for stand-alone power systems, such as low noise level and clean exhaust gases, especially when pure hydrogen is used as a fuel. Due to their very low maintenance cost, the fuel cells are expected to generate electricity at lower cost than conventional diesel generators in spite of their higher initial investment cost.

Lower investment cost and higher life time of fuel cell systems are expected in the future, when mass production and technical improvements are realized.

3.2 Elements of Proposed Hybrid System:

Here in this dissertation we are studying the Simultaneous operation of PV & FV Hybrid System.

Diagram of Simultaneous operation of PV & FV Hybrid System is given below:

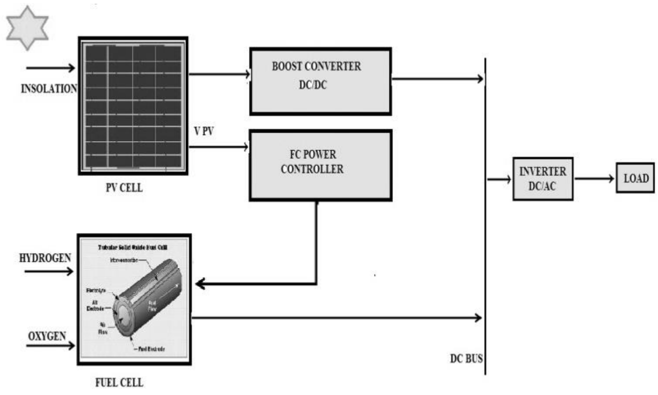


Fig. 3.1. PVFC hybrid system

Main parts of this hybrid system are given below:

- PV Cell.
- Fuel Cell (Hydrogen and Oxygen)
- FC Power Control Unit (Look up Table)
- DC to DC converter (Type-Boost)
- Inverter Unit
- Electrical Load

The flow chart of proposed PV & FC hybrid system is shown below:

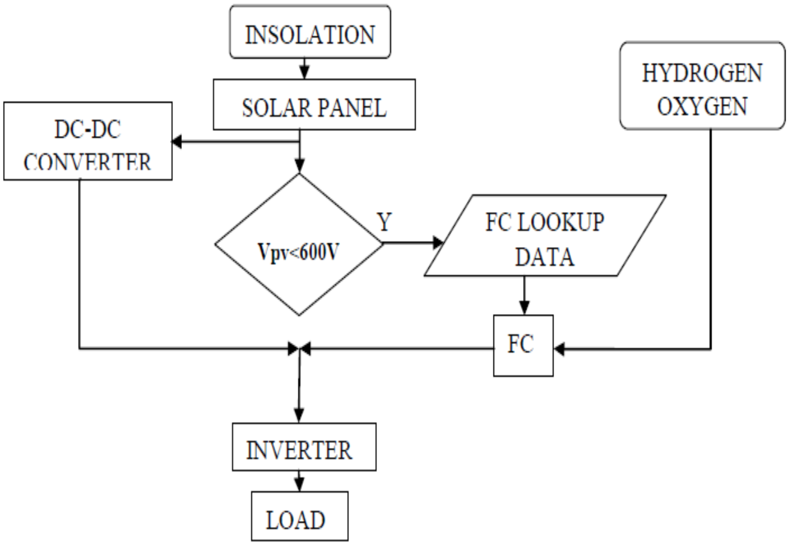


Fig. 3.2. Flow chart of PV & FC hybrid system

3.2.1 PV Cell:

The density of power radiated from the sun (referred to as the ‘‘solar energy constant’’) at the outer atmosphere is 1.373 kW/m^2. Part of this energy is absorbed and scattered by the earth’s atmosphere. The final incident sunlight on earth’s surface has a peak density of 1 kW/m^2 at noon in the tropics. The technology of photovoltaic’s (PV) is essentially concerned with the conversion of this energy into usable electrical form. The basic element of a PV system is the solar cell. Solar cells can convert the energy of sunlight directly into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunications, and television can be run from photovoltaic electricity. Solar cells rely on a quantum-mechanical process known as the ‘‘photovoltaic effect’’ to produce electricity. A typical solar cell consists of a p n junction formed in a semiconductor material similar to a diode.

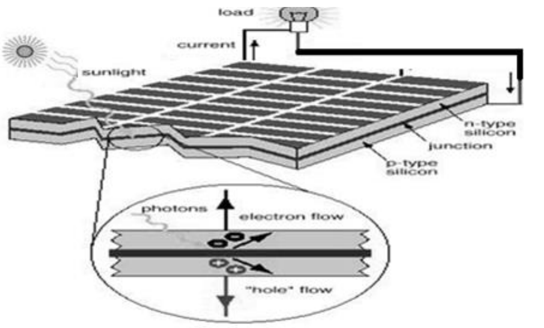


Fig. 3.3. Circuit diagram of PV Cell

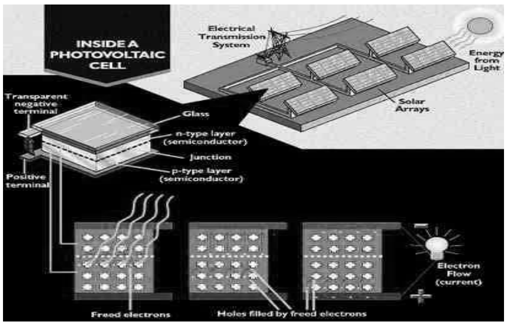


Fig. 3.4. Circuit of Solar Panel

Fig. 3.3 shows a schematic diagram of the cross section through a crystalline solar cell. It consists of a 0.2–0.3 mm thick mono-crystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by ‘‘doping’’ it with other impurities (e.g., boron and phosphorus). An electric field is established at the junction between the negatively doped (using phosphorus atoms) and the positively doped (using boron atoms) silicon layers. If light is incident on the solar cell, the energy from the light (photons) creates free charge carriers, which are separated by the electrical field.

An electrical voltage is generated at the external contacts, so that current can flow when a load is connected. The photocurrent (Iph), which is internally generated in the solar cell, is proportional to the radiation intensity.

In the early 1980's, the photovoltaic industries attracted the interest of large energy companies and government agencies. With their capital investment, a tremendous acceleration in PV modules' development took place. Today whole product lines are available with PV modules designed to withstand environmental wear for decades. As automation, better designs and improved manufacturing techniques have been applied to PV technology; its price has dropped significantly.

3.2.2 Fuel cells:

In the case of a H_2/ O_2 PEM fuel cell, H2 and O2 are the fuel and oxidant respectively. The product is pure water H_2O and electricity. The cell reactions are:

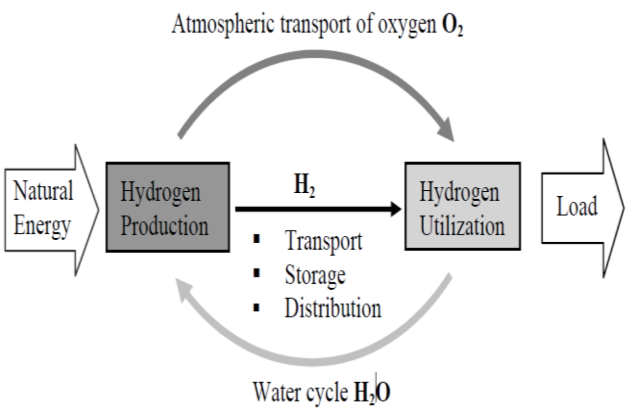
Hydrogen/Oxygen PEM fuel cell operation

Anode half reaction: $H_2 \rightarrow 2H+ + 2e-$ (3.1)

Cathode half reaction: $½\ O_2 + 2H++2e- \rightarrow H_20$ (3.2)

The overall reaction: $H_2+ ½\ O_2 \rightarrow H_20$ (3.3)

Hydrogen is oxidized on the anode and oxygen is reduced on the cathode. Protons are transported from the anode to the cathode through a PEM and electrons are carried to the cathode over an external circuit. On the cathode, oxygen reacts with protons and electrons forming water and producing heat.



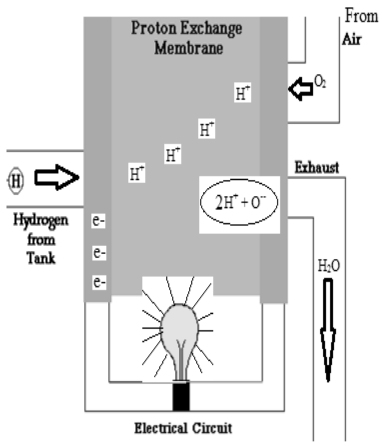


Fig. 3.5. The natural energy hydrogen cycle

Fig. 3.6. Internal working of a Typical FC.

Both the anode and the cathode contain a catalyst to speed up the electrochemical processes. Basic description of a PEM fuel cell operation is shown in fig. 3.5 In the case of a H_2/O_2 PEM fuel cell H_2 and O_2 are the fuel and oxidant respectively. The product is pure water H_2O and electricity.

The purpose of a fuel cell is to produce an electrical current that can be directed outside the cell to do work, such as powering an electric motor or illuminating a light bulb or a city. Because of the way electricity behaves, this current returns to the fuel cell, completing an electrical circuit. (To learn more about electricity and electric power, visit "Throw The Switch" on the Smithsonian website Powering a Generation of Change.) The chemical reactions that produce this current are the key to how a fuel cell works. There are several kinds of fuel cells, and each operates a bit differently. But in general terms, hydrogen atoms enter a fuel cell at the anode where a chemical reaction strips them of their electrons. The hydrogen atoms are now "ionized," and carry a positive electrical charge. The negatively charged electrons provide the current through wires to do work. If alternating current (AC) is needed, the DC output of the fuel cell must be routed through a conversion device called an inverter.

Oxygen enters the fuel cell at the cathode and, in some cell types (like the one illustrated above), it there combines with electrons returning from the electrical circuit and hydrogen ions that have traveled through the electrolyte from the anode. In other cell types the oxygen picks up electrons and then travels through the electrolyte to the anode, where it combines with hydrogen ions. The electrolyte plays a key role. It must permit only the appropriate ions to pass between the anode and cathode. If free electrons or other substances could travel through the electrolyte, whether they combine at anode or cathode, together hydrogen and oxygen form water, which drains from the cell. As long as a fuel cell is supplied with hydrogen and oxygen, it will generate electricity. Even better, since fuel cells create electricity chemically, rather than by combustion.

A single fuel cell produces a limited voltage, usually less than 1V. In order to produce a useful voltage for practical applications, several cells are connected in series to form a fuel cell stack. The output voltage depends on the number of the cells in the stack. A view of a PEM fuel cell structure and a PEMFC stack are presented in Fig. 3.6. The main part of a single cell is the Membrane Electrode Assembly (MEA) which consists of an anode, electrolyte membrane (PEM), and cathode. These components are pressed between two gas diffusion backings and two bipolar current collector plates. The Anode (fuel electrode) must provide a common interface for the fuel and electrolyte, catalyze the fuel oxidation reaction, and conduct electrons from the reaction site to the external circuit. The Cathode (oxygen electrode) must provide a common interface for the oxygen and the electrolyte, catalyze the oxygen reduction reaction, and conduct electrons from the external circuit to the oxygen electrode reaction site. The Electrolyte Membrane (PEM) must transport one of the ionic species involved in the fuel and oxygen electrode reactions, while preventing the conduction of electrons.

3.2.3 FC Power Control Unit (look up Table):

There is fluctuation in the output voltage due to the following reasons:

- Change in load
- Low radiation level of Sun (Due to bad weather conditions)

The power control unit plays the most important role in the proper simultaneous functioning of All the above are monitored by the following look up table.

TABLE 3.1

LOOK-UP TABLE

S.N.	Vector of input values	Look up data	S.N.	Vector of input values	Look up data	Sample time
1	5	0	9	80	30	1
2	10	3	10	90	40	
3	20	5	11	95	50	
4	30	8	12	100	60	
5	40	10	13	105	75	
6	50	12	14	110	80	
7	60	15	15	115	85	
8	70	20	16	120	90	

3.2.4 DC-DC Converter:

Choppers (DC –DC converter) are widely Used in regulated switch mode DC power supplies and in DC motor drive and other applications. often, the input of these converters is an unregulated DC voltage, (Here it is obtained by the Photovoltaic array and Fuel cell unit at DC bus bar.) It will fluctuate due to change of solar radiation. Switch mode DC to DC converters are used to convert the unregulated DC input into a controlled DC output at a desired voltage level.

Different types of DC to DC converters:

- Buck converter
- Boost converter
- Buck-Boost converter
- Cuk converter

Out of these four converters, only the step down and step-up are the basic converter technologies. Buck –Boost and Cuk converters are the combination of these technologies. Here, we are using Boost converter to convert the unregulated DC input into a controlled DC output at a desired voltage level. Circuit diagram of Boost converter using a power MOSFET is shown in fig. 3.7.

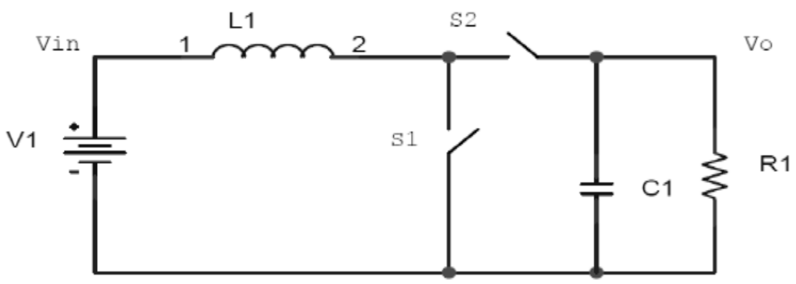


Fig. 3.7. Boost converter

Several methods exist to achieve DC-DC voltage conversion. Each of these methods has its specific benefits and disadvantages, depending on a number of operating conditions and specifications. Examples of such specifications are the voltage conversion ratio range, the maximal output power, power conversion efficiency, number of components, power density, galvanic separation of in- and output, etc. When designing fully-integrated DC-DC converters these specifications generally remain relevant, nevertheless some of them will gain weight, as more restrictions emerge [28]. For instance the used IC technology, the IC technology options and the available chip area will be dominant for the production cost, limiting the value and quality factor of the passive components. These limited values will in-turn have a significant impact upon the choice of the conversion method. In order for the designer to obtain a clear view of the DC-DC voltage conversion methods and their individual advantages and disadvantages, with respect to monolithic integration, the three fundamental methods are discussed in this chapter. The first and oldest method of performing DC-DC voltage conversion is by means of linear voltage converter. The second method, which also has an interesting potential for the purpose of monolithic voltage conversion, is by means of capacitor charge-pumps, Power conversion efficiency is in most cases a primary specification for any given energy converter [29]. a formal method for the fair comparison of DC-DC converters, in terms of power conversion efficiency. This method is referred to as the Efficiency Enhancement Factor (EEF).

Circuit diagram of Boost converter using a power MOSFET is shown in fig. 3.7. This is a converter whose output voltage is larger than the input voltage and output current is smaller than the input current. In this Boost Converter MATLAB model two IGBTs are used. Duty cycle for switching is calculated on the basis of output function and reference value. When the power device is ON, the inductor L is connected to the supply E_{dc} and inductor stores energy during on-period, Ton. Hence, diode D_F is reverses biased and isolated the output stage. When the power devices is OFF, the output stage reverse energy form the inductor as well as from the input. The current which was flowing through the transistor would now flow through L, D_F, C and load. The associated voltage & current waveforms are shown in fig. 3.9.

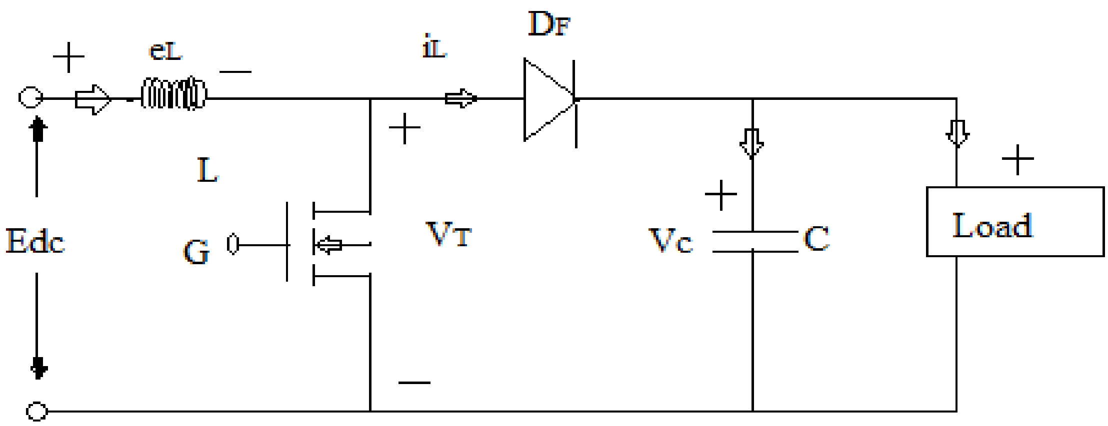


Fig. 3.8. Circuit Diagram of converter

During T_{ON}, by assuming that the inductor current rises linearly from I_1 to I_2, we can write.

$$E_{dc} = L\frac{I2 - I1}{Ton} = L\frac{\Delta I}{Ton} \quad (3.4)$$

$$Ton = L\frac{\Delta I}{Edc} \quad (3.5)$$

During time T_{off}, the inductor current falls linearly from I_2 to I_1, therefore, we can write,

$$E_{dc} - E_0 = -L\frac{\Delta I}{Toff} \quad (3.6)$$

$$T_{off} = L\frac{\Delta I}{Eo - Edc} \quad (3.7)$$

The peak to peak ripple current of inductor L can be written as,

$$\Delta I = \frac{Edc.Ton}{L} = \frac{(E0 - Edc)Toff}{L} \quad (3.8)$$

$T_{on} = \alpha T$ and $T_{off} = (1-\alpha)T$, yields the average output voltage,

$$E_0 = E_{dc}.\frac{T}{Toff} = \frac{Edc}{(1-\alpha)} \quad (3.9)$$

Assuming a lossless circuit,

$P_i = P_o$

$$E_{dc}.I_s = E_o.I_o = E_{dc}.\frac{Io}{(1-\alpha)} \quad (3.10)$$

Therefore, the average input current becomes

$$I_s = \frac{Io}{(1-\alpha)} \quad (3.11)$$

Now, the switching period T can be obtained as

$$T = 1/f = T_{on} + T_{off} \quad (3.12)$$

$$T = L\frac{\Delta I}{Edc} + L\frac{\Delta I}{Eo - Edc} = LEo\frac{\Delta I}{Edc(Eo - Edc)} \quad (3.13)$$

Form above equation , the peak –to peak ripple current becomes

$$\Delta I = \frac{Edc.(E0 - Edc)}{f.L.(E0)} \quad (3.14)$$

$$\Delta I = \frac{Edc.\alpha}{f.L.} \quad (3.15)$$

When the device is ON, the capacitor supplies the load current for $t = T_{on}$ period. During time T_{on}, the average capacitor current is Ic = Io and peak to peak ripple voltage of the capacitor is

$$\Delta Vc = Vc - Vc\,(t=0) = \frac{1}{C}\int_0^{Ton} Ic\,dt = \frac{1}{C}\int_0^{Ton} Io\,dt = \frac{Io\,Ton}{C} \quad (3.16)$$

$$T_{on} = \frac{Eo - Edc}{Edc}\; T_{off} \quad (3.17)$$

$$E_{dc} = \frac{Eo}{T}\; T_{off} \quad (3.18)$$

$$E_{dc} = E_o T_{off} f \quad (3.19)$$

$$T_{on} = \frac{Eo - Edc}{Eo\,.\,\mathbf{Toff}\,.\,f}\; T_{off} = \frac{Eo - Edc}{Eo\,.\mathbf{f}} \quad (3.20)$$

$$\Delta vc = I_o\,(E_o - E_{dc}) / E_o\,.f.C \quad (3.21)$$

$$\Delta V_C = \frac{\mathbf{Io.\,\alpha}}{f.\,\mathbf{C}} \quad (3.22)$$

Now, it is clear that a duty cycle α in the range $0 < \alpha < 1$, the output voltage E_o will vary in the range $E_{dc} < E_o < \infty$. Hence, the boost converter can step-up the output voltage without a transformer. Again, it has a high efficiency due to single power device.

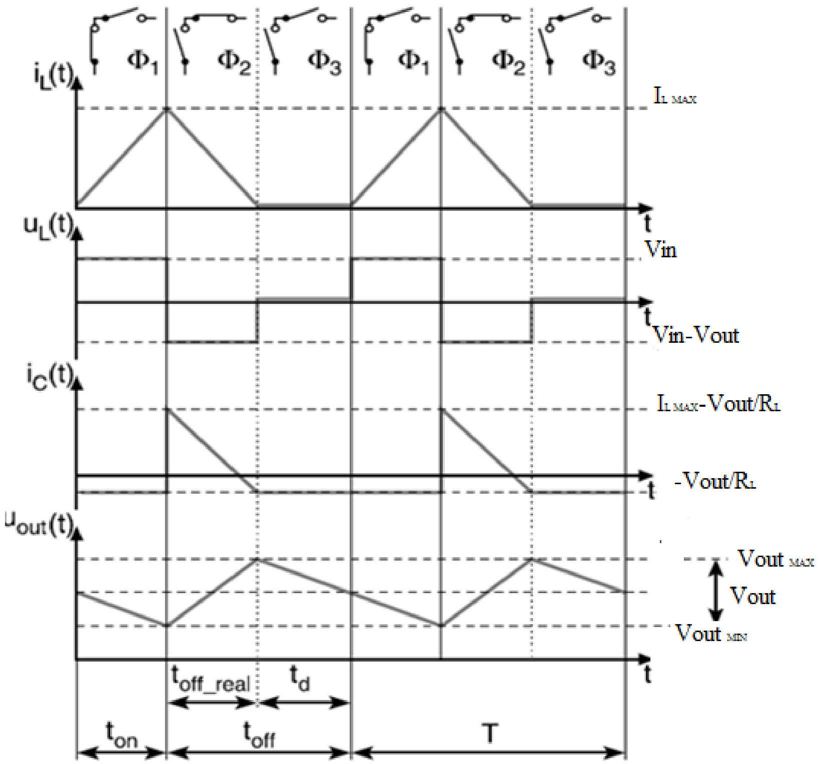


Fig. 3.9. Characteristics of boost converter

In the boost converter, the input current is continuous. However, a high peak current has to flow through the power device. Since, the output voltage is very sensitive to change in duty-cycle α, therefore, it might be difficult to stabilize the regulator. It is noted that the average output current is less than the average inductor current by a factor of (1- α), and a much higher RMS current would flow through the filter capacitor, resulting in the use of a larger filter capacitor and a larger inductor than those of a buck converter. The main application of a boost converter is in regulated DC power supplies and the regenerative breaking of DC motors.

3.2.5 DC Bus:

An increasing number of drive systems in a wide range of industrial applications and power ranges are being configured today in a common DC bus configuration. This drive system configuration provides users with significant advantages such as; design flexibility, higher efficiency, and cost savings. A common rectifier can supply power to the DC bus for all the DC-AC inverters instead of individual rectifiers in the stand-alone AC drives. The power sharing on the DC bus is possible for applications where some inverters may be motoring while others in the same process may be simultaneously generating power.

The power generating inverters feed power through the DC bus to the motoring inverters. This results in less power usage from the rectifier unit. Cost savings are realized through the use of application rated system components such as reactors, braking units, contactors, etc. This reduces the number of parts used on the drive system as well as assembly, wiring, wiring costs, number of failures and spare parts. Power Flex Common Bus products provide a wide range of modular solutions for the common DC bus application. In other world bus is nothing but a wide area of common voltage.

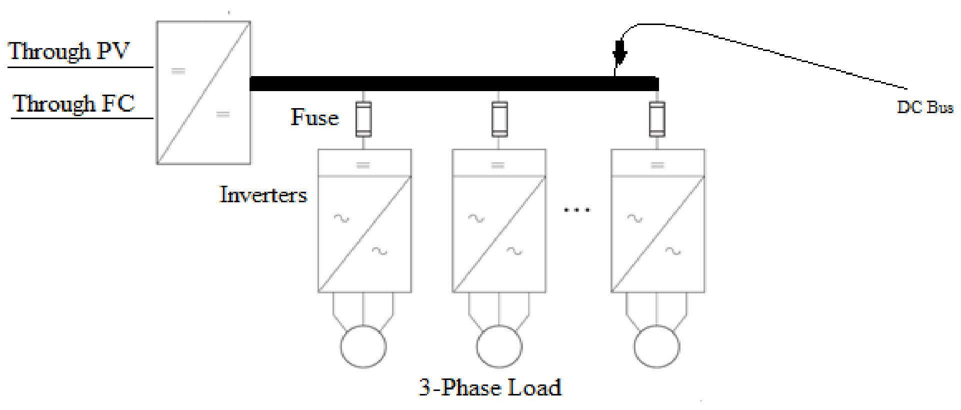


Fig. 3.10. DC Bus System

3.2.6 Inverter Unit:

An Inverter is a device which converts DC into AC Here we receive the energy at DC bus bar and then it is converted into AC with the help of inverter by using Space Vector Pulse Width Modulation Technique. Converted AC is used to run a three phase load [30]. (Here it is 50kW 3 phase load).

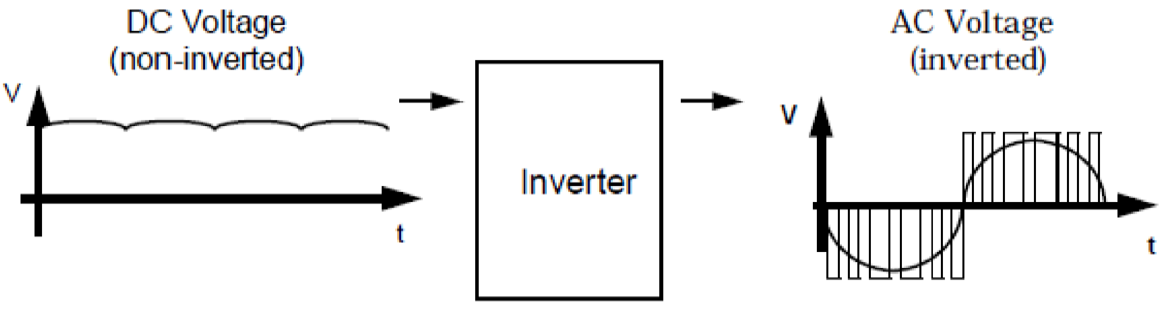


Fig. 3.11. Typical Waveform of Inverter Unit

3.2.6.1 Three-Phase Inverter:

The major purpose of the PWM inverter is to generate variable-voltage variable-frequency (VVVF) three-phase voltage from a DC voltage.

3.2.6.2 Space Vector PWM Technique:

Voltage source inverter (VSI) synthesizes AC voltage and frequency from a constant DC voltage using PWM techniques. Nowadays, VSI is used in large applications such as variable speed drives (VSDs), uninterruptible power supplies (UPS's), frequency converters, and active filters.PWM techniques have been studied extensively during the last few decades.

➢ **Pulse Width Modulation Technique:**

Variation of duty cycle in the PWM signal to provide a DC voltage across the load in a specific pattern will appear to the load as an AC signal.

The reference signal is sinusoidal and at the frequency of the desired output signal, while the carrier signal is often either a saw tooth or triangular wave at a frequency significantly greater than the reference.

SVPWM is a different approach from PWM modulation, based on space vector representation of the voltages in the α-β plane. Space Vector PWM (SVPWM) refers to a special switching sequence of the upper three IGBT of a three-phase power inverter [31].

It has been shown to generate less harmonic distortion in the output voltages and/or currents applied to the phases of a load and to provide more efficient use of dc input voltage.

- **Space Vector Concept:**

The space vector concept, which is derived from the rotating field of induction motor, is used for modulating the inverter output voltage. In this modulation technique the three phase quantities can be transformed to their equivalent two-phase quantity either in synchronously rotating frame (or) stationary frame [32]. From these two-phase components, the reference vector magnitude can be found and used for modulating the inverter output.

Two-level VSI consists of six power semiconductor switches with anti parallel diodes. In the widely used pulse width modulation (PWM) methods, the inverter output voltage approximates the reference value through high frequency switching for the six power semiconductor switches [33]. The circuit model of a typical two-level inverter is as shown in Fig. 3.12. S_1–S_6 are the six power switches that shape the output, these are controlled by the signal to terminals a, a', b, `b, c, and `c.

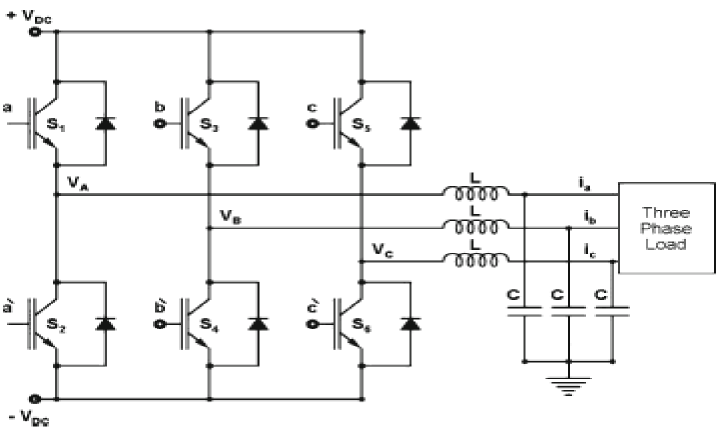


Fig. 3.12. Two-level voltage source inverter

It is assumed that S_1 and S_2, S_3, and S_4 as well as S_5 and S_6 are switched in a complementary way. There are only eight possible switching vectors. Six out of these eight vectors produce a non-zero voltage and are known as non-zero switching states the remaining two vectors produce zero output voltage and known as zero switching states. The output voltages of the inverter are composed by these eight switch states. The six active vectors divide the space vector plane into six equal sized sectors of 60◦ with equal magnitude which forms an origin centered hexagon, and two zero space vectors found at the origin as shown in Fig. 3.12. The hexagon is the maximum boundary of the space vector, and the circle is the trajectory of the regular sinusoidal outputs in linear modulation. Table 3.3 lists all of the possible switching vectors and the respective line to line/line to neutral voltages [34]. To obtain a sinusoidal waveform from the VSI, a voltage reference *V*ref is provided in terms of a revolving space vector. The magnitude and the frequency of the fundamental component are specified by the magnitude and frequency, respectively, of the reference vector. The reference vector is sampled once in every sub-cycle. The inverter is maintained in different states for appropriate durations such that an average voltage vector equal to the sampled reference vector is generated over a given sub-cycle.

A large variety of methods, differing in concept and performance, have been developed to achieve one or more of the following objectives: wide linear modulation range, fewer switching losses, less total harmonic distortion (THD), easy implementation and less computation time Several modulation strategies differing in concept and performance have been developed. With the development of microprocessors, space vector modulation has become one of the most important PWM methods for three-phase converters. It uses the space vector concept to compute the duty cycle of the switches [35]. It is simply the digital implementation of PWM modulators. An aptitude for easy digital implementation and wide linear modulation range for line to line voltages are the noticeable features of space vector modulation. Many methods have been developed to implement the space vector pulse width modulation (SVPWM) for driving VSI's. Generally, the SVPWM implementation involves sector identification, switching time calculation, switching vector determination, and optimum-switching-sequence selection for the inverter voltage vectors. The lookup tables can be used for determining the switching vectors in best switching sequence as introduced in calculating the duration of the switching vectors can be simplified by mapping the sector of the multilevel inverter to a corresponding sector of the two-level inverter as introduced in the objective of this paper is to introduce a simplified SVPWM technique in which the inverter leg switching times are directly obtained from the instantaneous sampled reference phase voltages, and the inverter switching vectors are generated automatically. This method is much simpler and more executable than conventional means without lookup tables or complex logical judgments. In addition, an objective of this is to introduce a practical SVPWM inverter design based on a low cost microcontroller [36]. The practical design is modeled using the MATLAB SIMULINK software package, and experimentally implemented on the low cost microchip PIC microcontroller 18F4431 platform.

TABLE 3.2

POSSIBLE SWITCHING VECTORS, PHASE VOLTAGE, PHASE VOLTAGE AND OUTPUT LINE TO LINE VOLTAGE

Voltage vectors	**Switching vector**			**Pole voltage**			**Line voltage**		
	a	**B**	**C**	**Vao**	**Vbo**	**Vco**	**Vab**	**Vbc**	**Vca**
V_o	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	1	0	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

All the respective voltage is given by following equation and the inverter is in active state 1 for a period T_1 and in active state 2 for a period T_2.

$$\bar{V}_{ref} = \frac{T1}{Ts} x \square + \frac{T2}{Ts} x \ \bar{V}\, 2 + \frac{\frac{T0}{7}}{Ts} x \ \bar{V}_{0/7} \qquad (3.23)$$

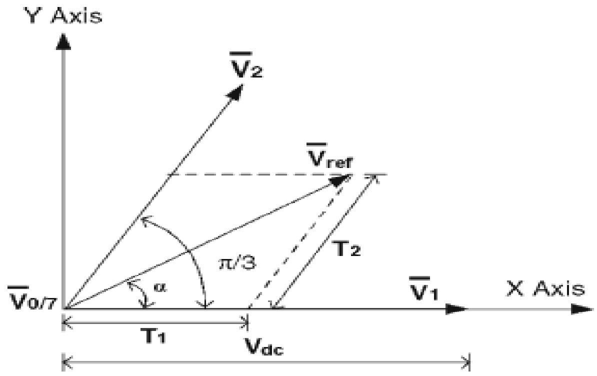


Fig. 3.13. Phasor diagram of voltages

For the remaining time of the sampling interval period *T*s there is no voltage applied. This can be achieved by applying inactive state 0 or 7 for the remaining time T_0 or T_7.

To generate this vector in an average sense, the durations for which the active state 1, the active state 2, and the two zero states together must be applied which are given by T_1, T_2 and T_Z, respectively, obtained as:

$$T_1 = \bar{V}_{ref}.\mathrm{Sin}(600\text{-}\alpha) \quad (3.24)$$

$$T_2 = \bar{V}_{ref}.\mathrm{Sin}(\alpha) / \mathrm{Sin}\ 60^0 \quad (3.25)$$

$$T = T_s\text{-}T_1\text{-}T_2 \quad (3.26)$$

Where α is the angle of rotating vector $\bar{V}_{ref}$. The division of the duration T_Z between the two zero vectors T_0 and T_7 is a degree of freedom in the space vector approach [37]. This division of T_Z in a sub-cycle is equivalent to adding a common mode component to the three-phase average pole voltages. The typical VSI switching waveforms in sector 1, as defined in Eq. 3.26 are as given in fig. 3.13. Realization of conventional SVPWM involves the following steps:

- Coordinate transformation for the reference vector $\bar{V}_{ref}$ from rotating reference frame to stationary reference frame.
- Determine time durations T_1, T_2, and T_0. Determine the switching time of each transistor (S_1–S_6).

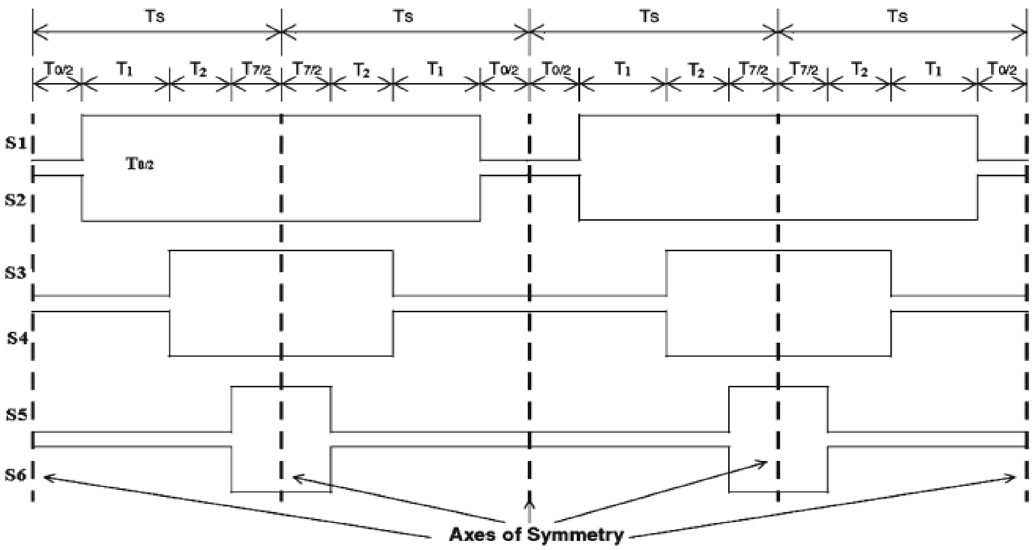


Fig. 3.14. Typical VSI switching waveform

3.2.7 Electrical Load (Three phase):

Here we use a three phase load of 50kW i.e. a water pump. It runs with the grid developed by a hybrid system energy [38].

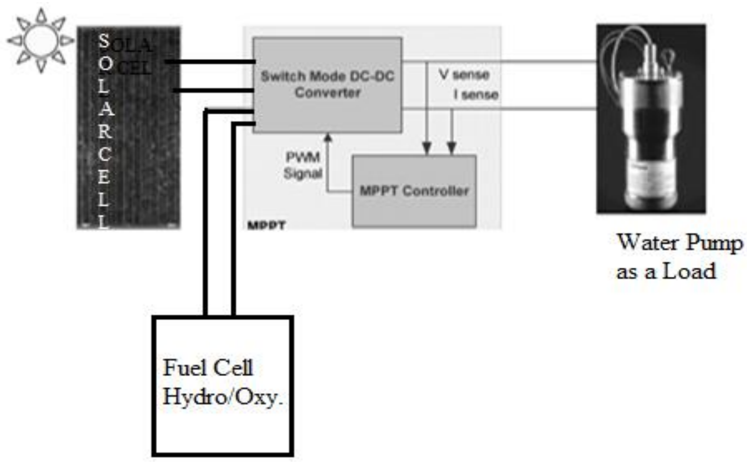


Fig. 3.15. Water Pump

A photovoltaic-fuel cell (PVFC) hybrid system may be able to solve the photovoltaic's inherent problem of intermittent power generation [39]. Unlike a storage battery, which also represents an attractive back-up option, such as fast response, modular construction and flexibility, the fuel cell power can produce electricity for unlimited time to support the PV power generator. Therefore, a continuous supply of high quality power generated from the PVFC hybrid system is possible day and night (technically) (7 X 24).

Varies type of three phase electrical load of different sites are given below:

- Three phase motor.
- Water Pumping sets for micro irrigation.
- Drinking water supply.
- Small Industry.
- In Hospital (As a backup in Operation Theater).
- Radio beacons for ship navigation at ports.
- Railways signaling equipment.
- Electrification in small remote area (Small Island).
- Cathode protection of oil pipe lines.
- Weather monitoring.

CHAPTER -4

MODELING OF THE INDIVIDUAL COMPONENTS OF HYBRID SYSTEM

4.1 Modeling of Hybrid System (Photovoltaic & Fuel Cell Module):

Model of PVFC Hybrid system is shown here for modeling. It contains following main parts.

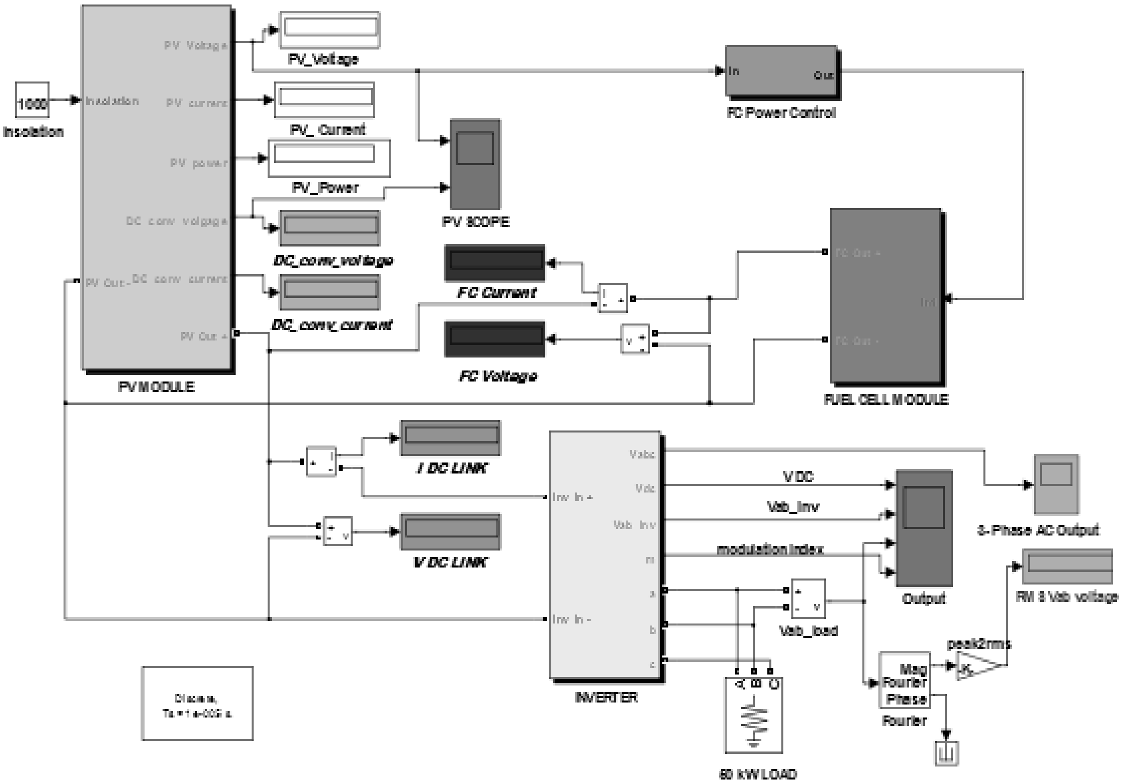
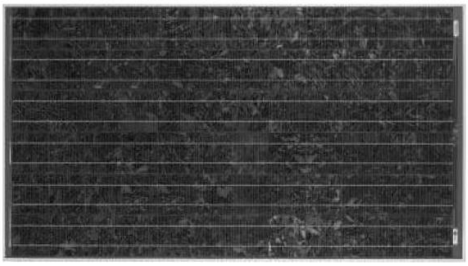


Fig. 4.1. Modeling of Hybrid System

- Modeling of Photovoltaic Module
- Modeling of Fuel Cell Module
- Modeling of FC Power Control Unit
- Modeling of DC to DC converter (Type-Boost)
- Modeling of Inverter Unit
- Modeling of Electrical Load

4.1.1 Modeling of Photovoltaic Module:

Solar PV module, pictured in fig. 4.1, the module is made of 72 multi-crystalline silicon solar cells in series and provides 50W of nominal maximum power. Table 4.1 shows its electrical specification.



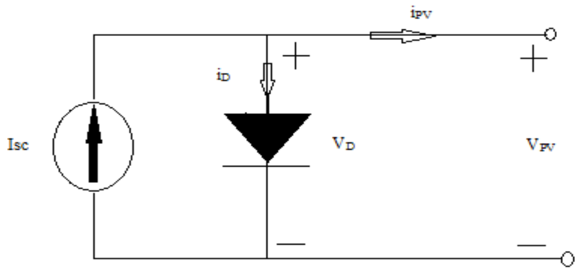


Fig. 4.2. Picture Of BPSX 50S PV Module   Fig. 4.3. Equivalent circuit model of solar cell

TABLE 4.1

ELECTRICAL CHARACTERISTICS PV MODULE

Electrical Characteristics	Rating
Maximum Power (P_{max})	150 W
Voltage at P_{max} (V_{mp})	34.5V
Current at P_{max} (I_{mp})	4.35A
Open-circuit Voltage (V_{oc})	43.5 V
Short-circuit Current (I_{sc})	4.75A
Temperature coefficient of I_{sc}	0.065 ± 0.015% /^{0}C
Temperature coefficient of V_{oc}	-160 ± 20 mV/^{0}C
Temperature coefficient of power	-0.5 ± 0.05%/^{0}C
NOCT	47 ± 2^{0}C

- The strategy of modeling a PV module is no different from modeling a PV cell. It uses the same PV cell model.
- The parameters are the all same, but only a voltage parameter (such as the open-circuit voltage) is different and must be divided by the number of cells. In the modeling of photovoltaic module, first of all we convert solar cell in to the equivalent circuit.

Equivalent circuit of solar cell contains short circuit current (Isc) parallel with diode as shown in fig.4.3. Equations for the above model are:

$i_D = Io.(e^{VD/VT}-1)$ (4.1)

Input equation: $V_D = V_{PV}$ (4.2)

Output equation: $i_{PV} = I_{SC} - i_D$ (4.3)

A single PV cell produces an output voltage less than 1V, about 0.6V for crystalline silicon (Si) cells, thus a number of PV cells are connected in series to archive a desired output voltage. When series-connected cells are placed in a frame, it is called as a module. Most of commercially available PV modules with crystalline-Si cells have either 36 or 72 series-connected cells. A 36-cell module provides a voltage suitable for charging a 12V battery, and similarly a 72-cell module is appropriate for a 24V battery.

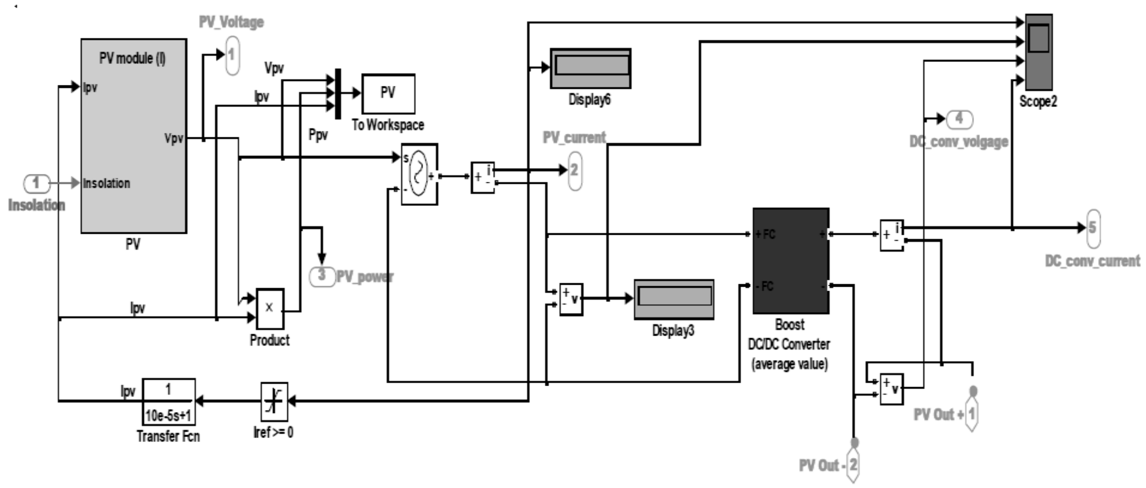


Fig. 4.4. Modeling of Photovoltaic Module.

This is because most of PV systems used to have backup batteries, however today many PV systems do not use batteries; for example, grid-tied systems. Furthermore, the advent of high efficiency DC-DC converters has alleviated the need for modules with specific voltages.

When the PV cells are wired together in series, the current output is the same as the single cell, but the voltage output is the sum of each cell voltage, as shown in Fig. 4.5 Also, multiple modules can be wired together in series or parallel to deliver the voltage and current level needed. The group of modules is called an array.

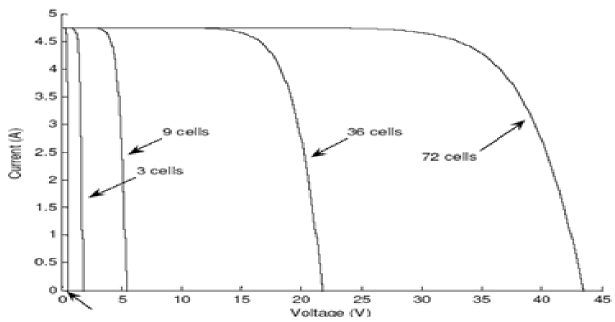


Fig. 4.5. Characteristics of PV cell connected in series

Fig 4.4. Shows the circuit model of photovoltaic cell. In the equation at the input side is voltage which is V_{pv} and the o/p is the current which is $I_{pv.}$ Now modeling the circuit and we get the characteristics of solar cell. When the radiation is high, more current draw in the circuit. The radiation is change with the atmosphere. Condition at the early morning the radiation is about 600W/m^2, then nearer to noon its 800W/m^2 and at the noon it is max about 1000 W/m^2.

Now, fig 4.6. Shows the modeling block diagram of PV array.

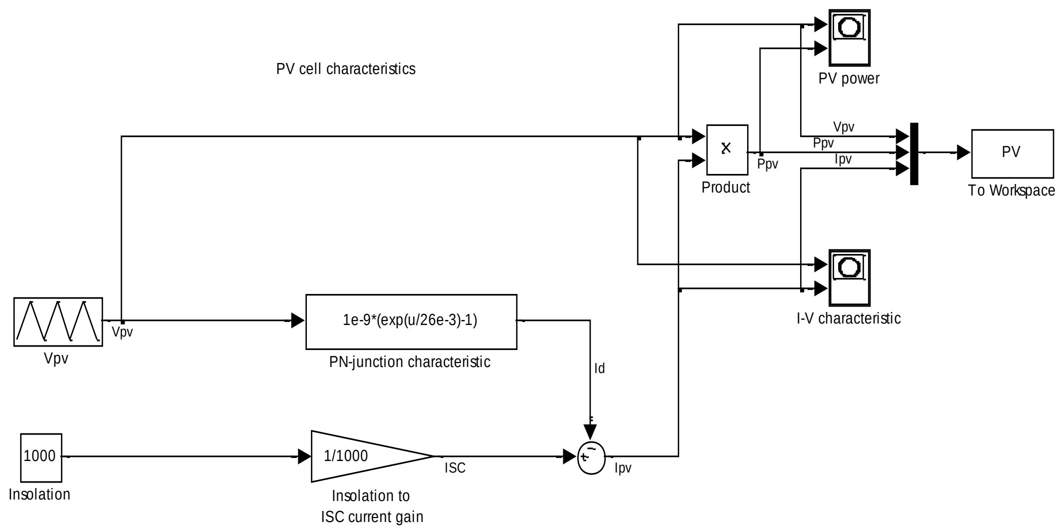
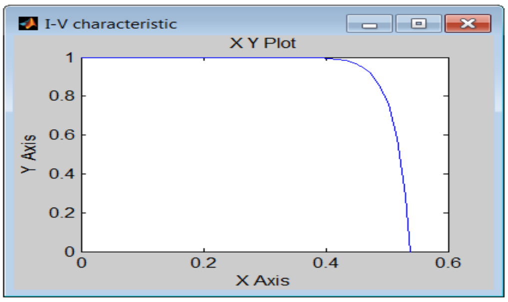


Fig. 4.6. Modeling of PV array

Different characteristics I-V and P-V at the different radiation level. (As 1000W/m^2, 800W/m^2, 600 W/m^2):

1000W/m^2:



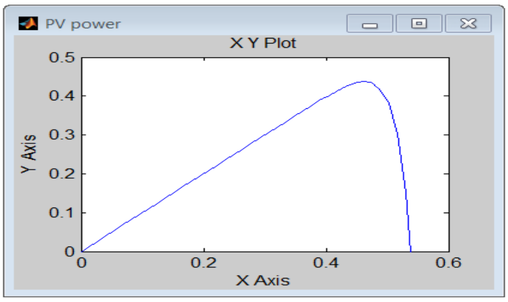


Fig. 4.7. I-V and P-V characteristics (1000 W/m^2)

TABLE 4.2

V, P, & I OUTPUT (1000 W/m^2)

Voltage	Power	Current
0.012	0.012	1
0.026	0.026	1
0.04	0.04	1
0.054	0.054	1
0.068	0.068	1
0.18	0.18	0.999999
0.194	0.194	0.999998
0.208	0.207999	0.999997
0.222	0.221999	0.999995
0.236	0.235998	0.999991
0.474	0.434799	0.917297
0.488	0.41885	0.858299
0.502	0.380121	0.757214
0.516	0.301353	0.584017
0.53	0.152252	0.287268

Solar Radiation		1000W/m^2
MPP Power	**MPP Voltage**	**MPP Current**
0.2550	0.4460	0.5718

800W/m^2:

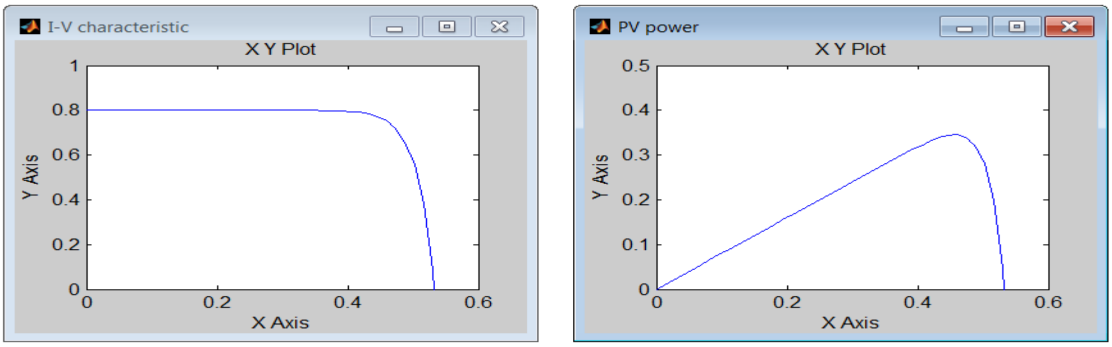


Fig. 4.8. I-V and P-V characteristics (800 W/m^2)

TABLE 4.3

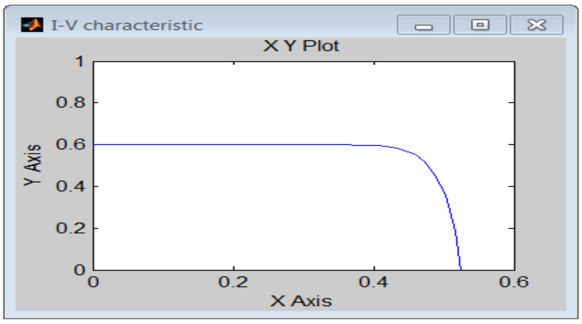
V, P, & I OUTPUT (800 W/m^2)

Voltage	Power	Current
0.012	0.0096	0.8
0.026	0.0208	0.8
0.04	0.032	0.8
0.054	0.0432	0.8
0.068	0.0544	0.8
0.082	0.0656	0.8
0.18	0.144	0.799999
0.194	0.1552	0.799998
0.208	0.166399	0.799997
0.222	0.177599	0.799995
0.236	0.188798	0.799991

0.46	0.345796	0.751731
0.474	0.339999	0.717297
0.488	0.32125	0.658299
0.502	0.279721	0.557214

Solar Radiation		**800W/m^2**
MPP Power	**MPP Voltage**	**MPP Current**
0.3458	0.4400	0.7517

600W/m^2:



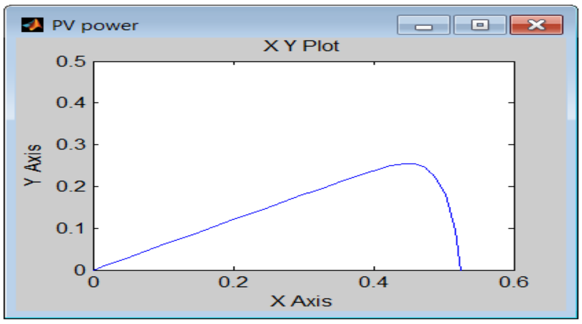


Fig. 4.9. I-V and P-V characteristics (600 W/m^2)

TABLE 4.4

V, P, & I OUTPUT (600 W/m^2)

Voltage	Power	Current
0.012	0.0072	0.6
0.026	0.0156	0.6
0.04	0.024	0.6
0.054	0.0324	0.6
0.068	0.0408	0.6
0.082	0.0492	0.6

0.18	0.108	0.599999
0.194	0.1164	0.599998
0.208	0.124799	0.599997
0.222	0.133199	0.599995
0.236	0.141598	0.599991
0.46	0.253796	0.551731
0.474	0.245199	0.517297
0.488	0.22365	0.458299
0.502	0.179321	0.357214

Solar Radiation		**600W/m^2**
MPP Power	**MPP Voltage**	**MPP Current**
0.4600	0.2537	0.5517

To get more and more voltage. It is necessary to connect solar cells in series, Then it becomes a PV array. PV array for the output of 50kW is shown here.

PV ARRAY 50 KW OUTPUT

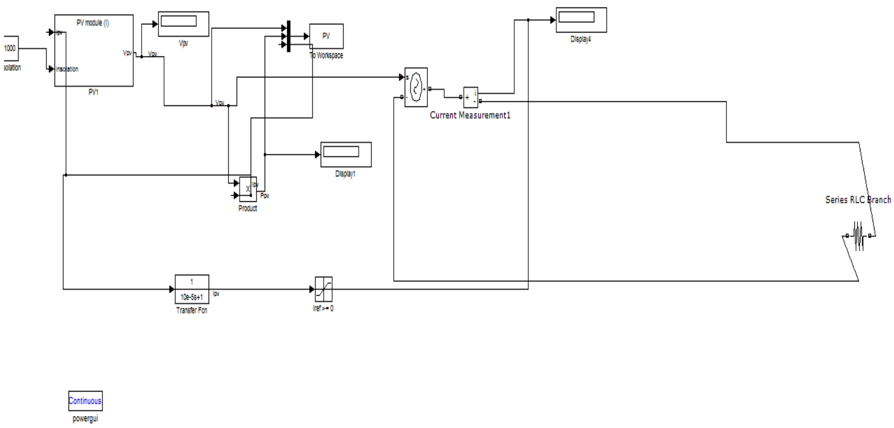


Fig.4.10. I-V and P-V characteristics

I_{sc} = 87.2, Voc = 888, I_{max} = 79.2, V_{max} = 704,

V= I*R, 888 = 87.2 R, so R = 10.18 Ω

TABLE 4.5

OUTPUT AT DIFFERENT RADIATION LEVELS

1000W/m²			**PV array 50 kW**
R	**V**	**P**	**I**
10	737.7	54.49	73.77
800W/m²			**PV array 50 kW**
R	**V**	**P**	**I**
10	655.7	43.08	65.57
600W/m²			**PV array 50 kW**
R	**V**	**P**	**I**
10	500.6	24.99	50.06
200W/m²			**PV array 50 kW**
R	**V**	**P**	**I**
10	166.1	2765 w	16.61

- **The More Accurate Model:**

There are a few things that have not been taken into account in the simple model and that will affect the performance of a PV cell in practice.

- **Series Resistance**

In a practical PV cell, there is a series of resistance in a current path through the semiconductor material, the metal grid, contacts, and current collecting bus. These resistive losses are lumped together as a series resister (*Rs*). Its effect becomes very conspicuous in a PV module that consists of many series-connected cells, and the value of resistance is multiplied by the number of cells.

➢ **Parallel Resistance**

This is also called shunt resistance. It is a loss associated with a small leakage of current through a resistive path in parallel with the intrinsic device . This can be represented by a parallel resister (*Rp*). Its effect is much less conspicuous in a PV module compared to the series resistance, and it will only become noticeable when a number of PV modules are connected in parallel for a larger system.

➢ **Recombination**

Recombination in the depletion region of PV cells provides non-ohmic current paths in parallel with the intrinsic PV cell. This can be represented by the second diode (*D2*) in the equivalent circuit.

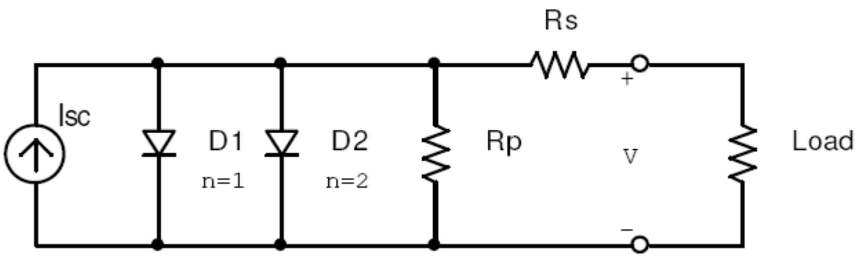


Fig. 4.11. More Accurate Equivalent Circuit of PV Cell

Summarizing these effects, the current-voltage relationship of PV cell is written as:

$$I = I_{sc} - I_{01}\left[e^{q\left(\frac{V+I.R_S}{kT}\right)} - 1 \right] - I_{02}\left[e^{q\left(\frac{V+I.R_S}{kT}\right)} - 1 \right] - \left(\frac{V+R_s}{R_p}\right) \qquad (4.4)$$

It is possible to combine the first diode (*D1*) and the second diode (*D2*) and rewrite

the equation (4.2) in the following form.

$$I = I_{sc} - I_0\left[e^{q\left(\frac{V+I.R_S}{kT}\right)} - 1 \right] - \left(\frac{V+R_s}{R_p}\right) \qquad (4.5)$$

where: *n* is known as the "ideality factor" ("*n*" is sometimes denoted as "*A*") and takes the value between one and two. Here we use the electric model with moderate complexity, shown in Fig. 4.11, and provides fairly accurate results. The model consists of a current source (Isc), a diode (D), and a series resistance (Rs).

The effect of parallel resistance (Rp) is very small in a single module, thus the model does not include it. To make a better model, it also includes temperature effects on the short-circuit current (Isc) and the reverse saturation current of diode (Io). It uses a single diode with the diode ideality factor (n) set to achieve the best I-V curve match.

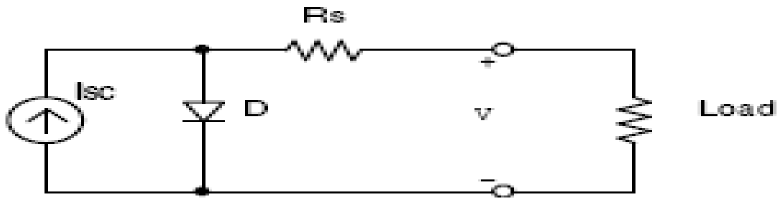


Fig. 4.12. Equivalent Circuit diagram PV cell

Since it does not include the effect of parallel resistance (Rp), letting Rp = infinite in equation (4.3) gives the equation(4.6) that describes the current-voltage relationship of the PV cell, and it is shown below.

$$I = I_{sc} - I_0 \left[[e]^{q\left(\frac{V+I.R_S}{kT}\right)} - 1 \right] \qquad (4.6)$$

Where:

I is the cell current (the same as the module current),

V is the cell voltage = {module voltage} ÷ {no of cells in series},

T is the cell temperature in Kelvin (K).

First, calculate the short-circuit current (Isc) at a given cell temperature (T):

$$I_{sc}\, I_T = I_{sc}\, I_{Tref} \cdot [1 + a(T - T_{ref})] \qquad (4.7)$$

Where:

Isc at T_{ref} is given in the datasheet (measured under irradiance of $1000W/m^2$),

T_{ref} is the reference temperature of PV cell in Kelvin (K), usually 298K (25^oC),

a is the temperature coefficient of Isc in percent change per degree temperature also given in the datasheet.

The short-circuit current (Isc) is proportional to the intensity of irradiance, thus Isc at a given irradiance (G) is:

$$I_{sc} I_G = \left(\frac{G}{G_0}\right) I_{sc} I_{Go} \qquad (4.8)$$

where: G_o is the nominal value of irradiance, which is normally 1 kW/m^2.

The reverse saturation current of diode (Io) at the reference temperature (T_{ref}) is given by the equation (4.8) with the diode ideality factor added.

$$I_0 = \frac{I_{sc}}{\left(e^{\frac{qv}{kt}} - 1\right)} \qquad (4.9)$$

The reverse saturation current (Io) is temperature dependant and the Io at a given temperature (T) is calculated by the following equation.

$$I_0 I_T = I_0 \cdot \left(\frac{T}{T_{ref}}\right)^{\frac{3}{n}} \cdot e^{\frac{-qEg}{n.k}\left(\frac{1}{T} - \frac{1}{Tref}\right)} \qquad (4.10)$$

The diode ideality factor (n) is unknown and must be estimated. It takes a value between one and two; the value of n=1 (for the ideal diode) is, however, used until the more accurate value is estimated later by curve fitting.

The series resistance (R_s) of the PV module has a large impact on the slope of the I-V curve near the open-circuit voltage (Voc), as shown in Fig. 4.12., hence the value of Rs is calculated by evaluating the slope of the I-V curve at the Voc.

The equation for R_s is derived by differentiating the equation (4.10) and then rearranging it in terms of R_s.

$$I = I_{sc} - I_0 \left[[e]^{q\left(\frac{V + I.R_S}{kT}\right)} - 1\right] \qquad (4.11)$$

$$dI = 0 - I_0 \cdot q \left(\frac{dV + R_s \cdot dI}{nkT}\right) \cdot e^{q} \left(\frac{V + I.R_s}{nkT}\right) \qquad (4.12)$$

$$R_s = -\frac{dI}{dV} - \frac{\frac{nkT}{q}}{I_{0} \cdot e^{q\left(\frac{V + I.Rg}{nkT}\right)}} \qquad (4.13)$$

Then, evaluate the equation (4.13) at the open circuit voltage that is $V=V_{oc}$ (also let I=0).

$$R_s = -\frac{dI}{dV}\bigg| V_{oc} - \frac{\frac{nkT}{q}}{I_{0} \cdot e^{\left(\frac{qVoc}{nkT}\right)}} \qquad (4.14)$$

where:

$\frac{dI}{dV}\Big|V_{oc}$ is the slope of the I-V curve at the V_{oc} (use the I-V curve in the datasheet then divide it by the number of cells in series), Voc is the open-circuit voltage of cell (found by dividing Voc in the datasheet by the number of cells in series).

Finally, it is possible to solve the equation of I-V characteristics.

It is, however, complex because the solution of current is recursive by inclusion of a series resistance in the model.

Although it may be possible to find the answer by simple iterations, the Newton's method is chosen for rapid convergence of the answer.

The Newton's method is described as:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{4.15}$$

Where: $f'(x)$ is the derivative of the function, $f(x) = 0$, x_n is a present value, and x_{n+1} is a next value.

Rewriting the equation (4.15) gives the following function:

$$f(I) = I_{sc} - I - I_0\left[e^{q\left(\frac{V+I.R_s}{nkT}\right)} - 1\right] \tag{4.16}$$

Plugging this into the equation (4.16) gives a following recursive equation, and the output current (I) is computed iteratively.

$$I_{n+1} = I_n - \frac{I_{sc} - I_n - I_0\left[e^{q\left(\frac{V+I.R_s}{nkT}\right)} - 1\right]}{-1 - I_0\left(\frac{q.R_s}{nkT}\right)e^{q\left(\frac{V+I.R_s}{nkT}\right)}} \tag{4.17}$$

The testing result has shown that the value of In usually converges within three iterations and never more than four interactions.

4.1.2 Modeling of Fuel Cell Module:

Fuel cell may be defined as an *electro chemical device* for the continuous conversion of the portion of the free energy change in a chemical reaction to electrical energy. It is distinguished from a battery in that it operates with continuous replenishment of the fuel and the oxidant at active electrode area and does not require recharging.

Main components of a cell are:

- A fuel electrode,
- An oxidant or air electrode,
- An electrolyte.

Hydrogen as a fuel has so far given the most promising results, though cells consuming coal, oil or natural gas would be economically much more useful for large scale application. Some of the fuel cells are hydrogen, oxygen (H_2, O2), Hydrazine (N_2H_4, O_2), carbon/coal (C, O_2) methane (CH_4, O_2) etc.

Hydrogen oxygen fuel cells are efficient and the most highly developed cell. A low pressure Hydrogen oxygen cell is illustrated in the diagram. Two porous carbon or nickel electrodes are immersed in an electrolyte. Catalyst is embedded in nickel electrodes. The electrolyte is typically 30% KOH because of its high electrical conductivity and it is less corrosive than acids.

H_2 is fed to one electrode and is absorbed gives free electrons and also reacts with hydroxyl ions of the electrolyte to form water. The free electrons travel towards oxygen electrode through the external circuit. The two electrons arriving by the external circuit and one molecule of water to form 2 OH^- ions. These OH^- ions migrate towards to H_2 electrode and are consumed there. The electrolyte remains in variant. It is prime requirement that the composition of electrolyte should not change as the cell operates. The cell operates at or slightly above atmospheric pressure and at a temperature about 90^0C. These type of cell are called low temperature cells in high pressure cells pressure is up to about 45 atmospheric and temperature up to 300^0C. A single hydrogen oxygen cell can produce an emf of 1.23 volts at atmospheric pressure and 25^0C. By connecting a no. of cells, it is possible to create useful potential of 100 to 1000 volts and power levels of 1 kW to nearly 100 MW.

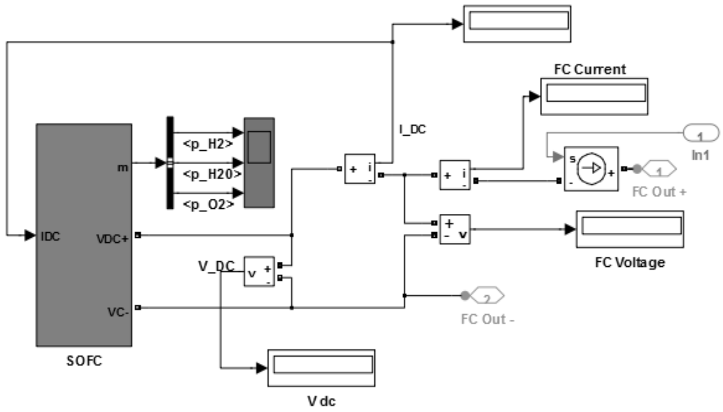


Fig. 4.13. Modeling of Fuel Cell Module

In the modeling of fuel cell the levels of H_2 and O_2.

4.1.3 Modeling of FC Power Control Unit:

Monitoring is the main work of this unit. This is known as FC power control unit, It run on the basis of LOOK-UP DATA. LOOK-UP DATA is a table, which decides the operation of FC power control unit. Fuel cell unit come in action according to the low values of radiation of photovoltaic array. Scope-1 is used for the Output wave form of FC power control unit.

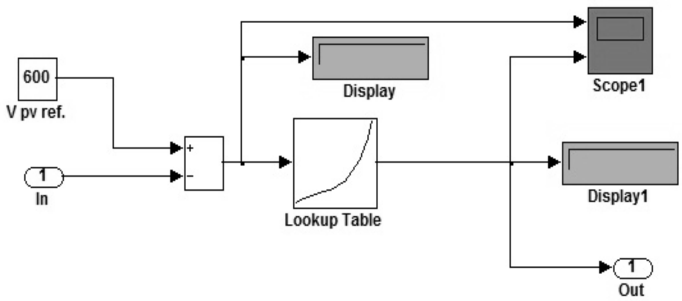


Fig. 4.14. Modeling of FC Power Control Unit

4.1.4 Modeling of DC to DC converter (Type-Boost):

Electronic switch-mode DC to DC converters convert one DC voltage level to another, by storing the input energy temporarily and then releasing that energy to the output at a different voltage. The storage may be in either magnetic field storage components (inductors, transformers) or electric field storage components (capacitors). This conversion method is more power efficient (often 75% to 98%) than linear voltage regulation (which dissipates unwanted power as heat). This efficiency is beneficial to increasing the running time of battery operated devices. The efficiency has increased since the late 1980s due to the use of power *FETs*, which are able to switch at high frequency more efficiently than power *bipolar transistors*, which incur more switching losses and require a more complicated drive circuit. Another important innovation in DC-DC converters is the use of *synchronous rectification* replacing the flywheel diode with a power FET with low "on resistance", thereby reducing switching losses. Before the wide availability of power semiconductors, low power DC to DC converters of this family consisted of an electro-mechanical *vibrator* followed by a voltage step-up transformer and a vacuum tube or semiconductor rectifier or synchronous rectifier contacts on the vibrator.

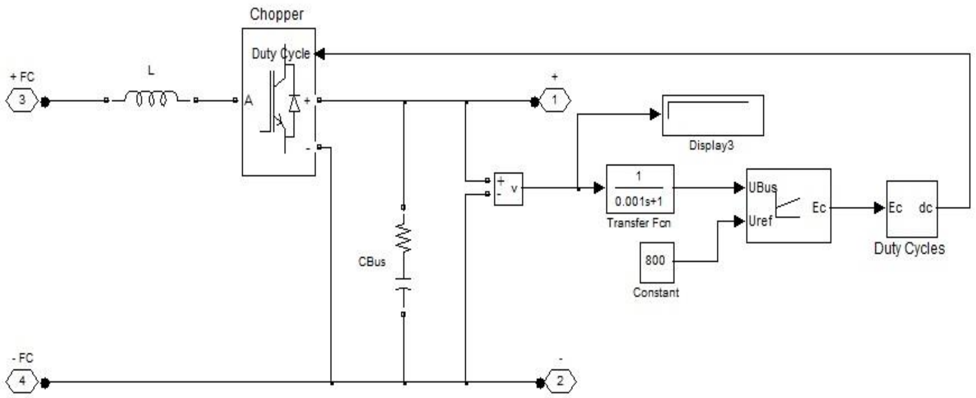


Fig. 4.15. Modeling of DC to DC Boost converter

Most AC-to-DC converters are designed to move power in only one direction, from the input to the output. However, all switching regulator topologies can be made bi-directional by replacing all diodes with independently controlled active rectification. A bi-directional converter can move power in either direction, which is useful in applications requiring regenerative braking. Drawbacks of switching converters include complexity, electronic noise (EMI / RFI) and to some extent cost, although this has come down with advances in chip design.

DC-to-DC converters are now available as integrated circuits needing minimal additional components. They are also available as a complete hybrid circuit component, ready for use within an electronic assembly.

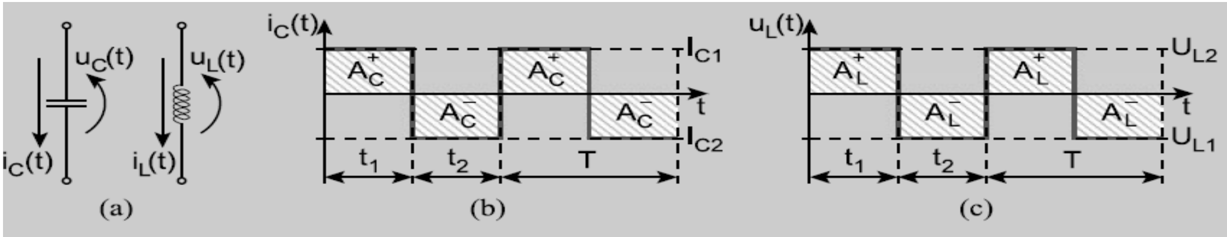


Fig. 4.16. Square wave of DC-DC converter

4.1.5 Modeling of Inverter Unit:

This is the unit which is run by diode and switchs. Three phase inverter may be considered as three single –phase inverters and the output of each single phase inverter is shifted by 120^0. The voltage control techniquies is applied in three phase inverter.

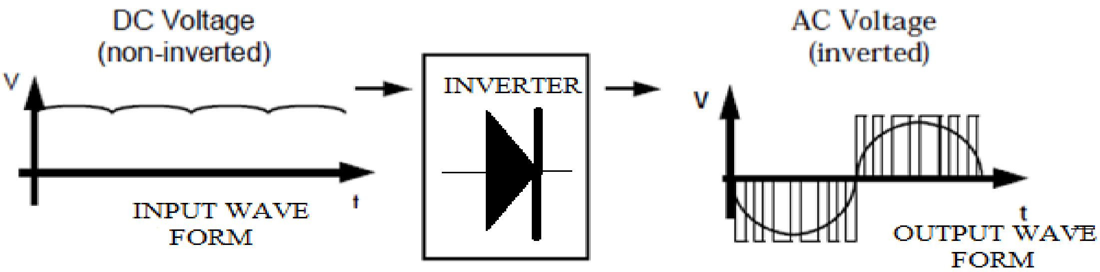


Fig.4.17. Inverter

There are three-sinusoidal reference waves, each shifted by 120^0. Acarrier wave is compared with the reference signal corresponding to a phase to generate the gating signals for that phase. The output voltage, as shown in fig.4.19. It is generated by eliminating the condition that two switching devices in the same arm can not conduct at the same time

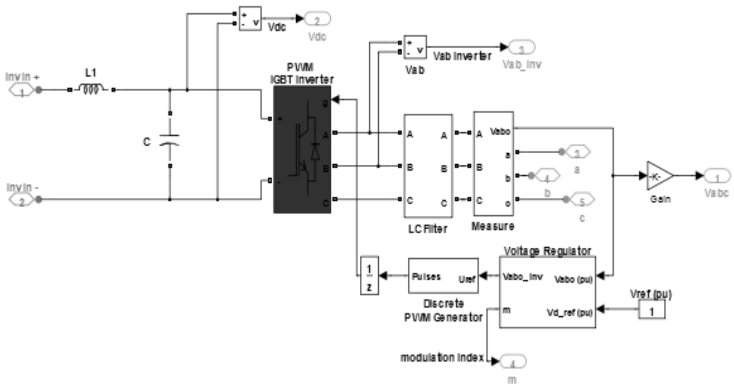


Fig. 4.18. Modeling of Inverter Unit

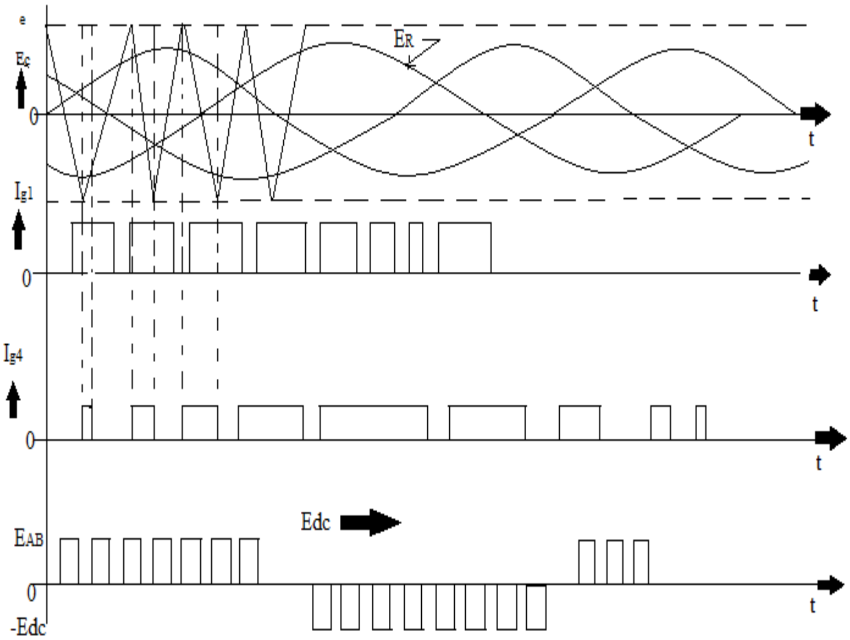


Fig. 4.19. Sinusoidal pulse-with modulation for three-phase inverter

Gate-commutated power devices, like BJT, MOSFET, IGBTs etc., are used for low-and medium-power applications. For high power applications, it is necessory to connect them in series and / or parrel combinations, which increase the circuit complexxity. Therefore, for high power applications, fast-switching thyristers (inverter-grade) which are available in high voltage and current ratings are more suitable.

4.1.6 Modeling of Electrical Load:

Output voltage may varry only by two reasons, one is change in radiation (Radiation) level of solar and other one is change in load. The output load may varry from microwatts up to mega watts by connecting more and more arrays of units in series. Here modeling is done for the three phase AC load of value 50kW. A constant voltage of 415 volts is made at the output(rms value). While there is change in the output load stil we get a constant output voltage, it is obtained by the simultanious operation of PV and FC hybrid system.

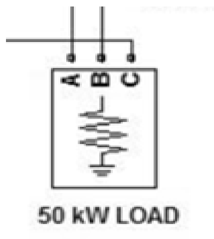


Fig. 4.20. 50kW Load

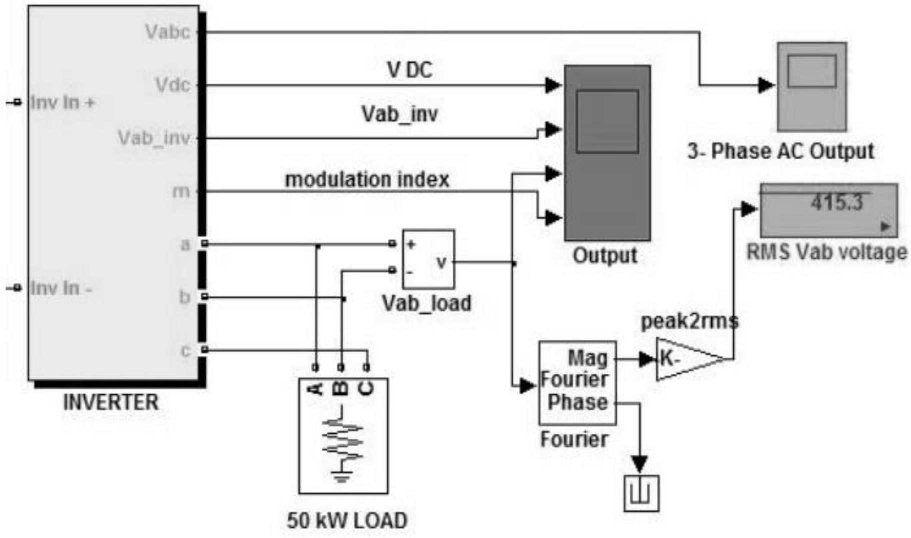


Fig. 4.21. Modeling of Electrical Load

CHAPTER -5

RESULT

5.1 Simultaneous PV and FC result:

Various inputs have been given to the prescribed model and for different Radiation Levels and loads the following results have been obtained:

TABLE 5.1

OUTPUT AT 50 kW LOAD

Radiation	**Load**	**AC voltage**	**PV Cell**				**Fuel Cell**		**DC Bus**	
			Cell	**Converter**			**I**	**P**	**V**	**I**
W/m^2	**kW**	**V(rms)**	**V**	**V**	**I**	**P**				
			(V)	**(V)**	**(A)**	**(kW)**	**(A)**	**(kW)**	**(V)**	**(A)**
1000	50	415.3	961.3	986	51.1	50384.6	0	0	986	51.1
750	50	415.3	803.8	824.4	59.79	49290.876	0	0	824.4	59.79
500	50	415.1	510.3	798.8	32.51	25968.988	30	23943	798.1	62.51
250	50	415.1	500.5	800.1	12.18	9745.218	50	40005	800.1	62.18

TABLE 5.2

OUTPUT AT 60 kW LOAD

Radiation	**Load**	**AC voltage**	**PV Cell**				**Fuel Cell**		**DC Bus**	
			Cell	**Converter**			**I**	**P**	**V**	**I**
W/m^2	**kW**	**V(rms)**	**V**	**V**	**I**	**P**				
			(V)	**(V)**	**(A)**	**(kW)**	**(A)**	**(kW)**	**(V)**	**(A)**
1000	60	415	925.4	949.2	63.91	60663.372	0	0	949.2	63.91
750	60	415.4	509.1	801	35.22	28211.22	40	32040	801	75.22

TABLE 5.3

OUTPUT AT 70 kW LOAD

Radiation	Load	AC voltage	PV Cell				Fuel Cell		DC Bus	
			Cell	Converter			I	P	V	I
W/m^2	kW	V(rms)	V	V	I	P				
			(V)	(V)	(A)	(kW)	(A)	(kW)	(V)	(A)
1000	70	415.3	867.7	889.8	80.82	71913.636	0	0	889.8	75.22
750	70	415.4	505.3	798.6	46.95	37494.27	40	31944	798.6	86.95

5.2 Radiation 1000W/m^2 and 50 kW load :

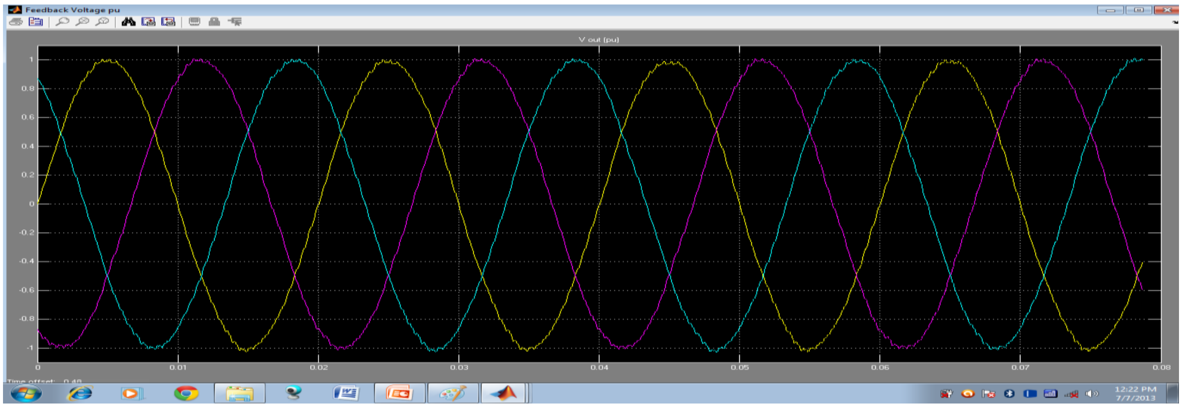


Fig. 5.1 Three phase output of Inverter at (1000W/m^2)

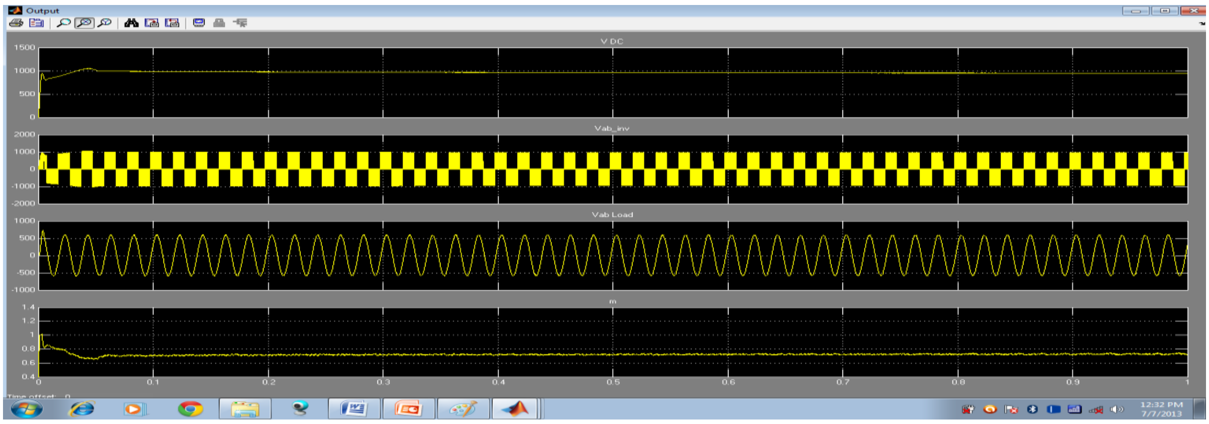


Fig. 5.2 Output waveform of V_{dc}, V_{ab_inv}, V_{ab_load} and m at (1000W/m^2)

5.3 Radiation 750W/m^2 and 50 kW load:

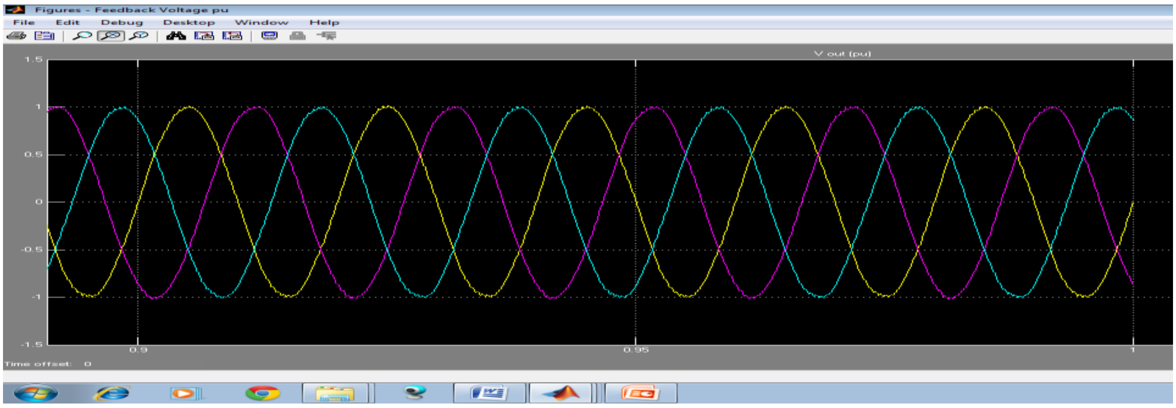


Fig. 5.3. Three phase output of Inverter at (750W/m^2)

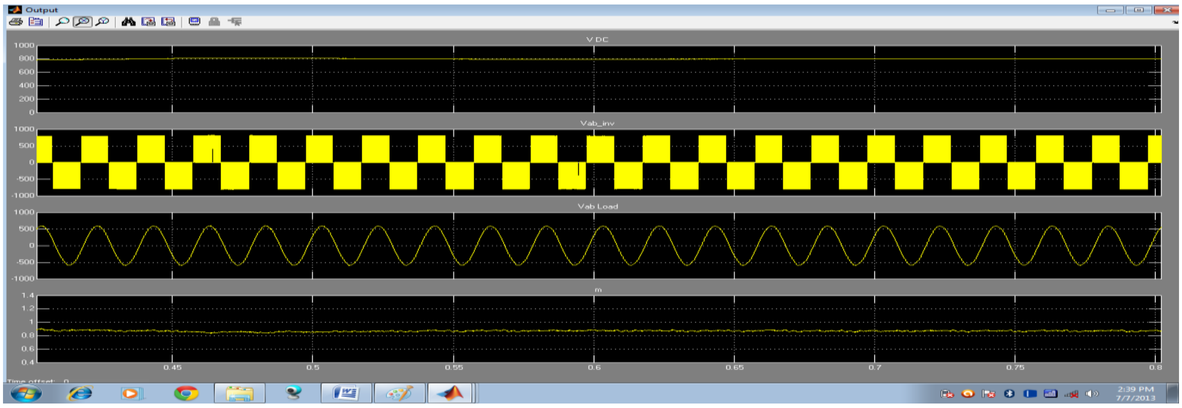


Fig. 5.4. Output waveform of V_{dc}, V_{ab_inv}, V_{ab_load} and m at (750W/m^2)

5.4. Radiation 500W/m^2 and 50 kW load:

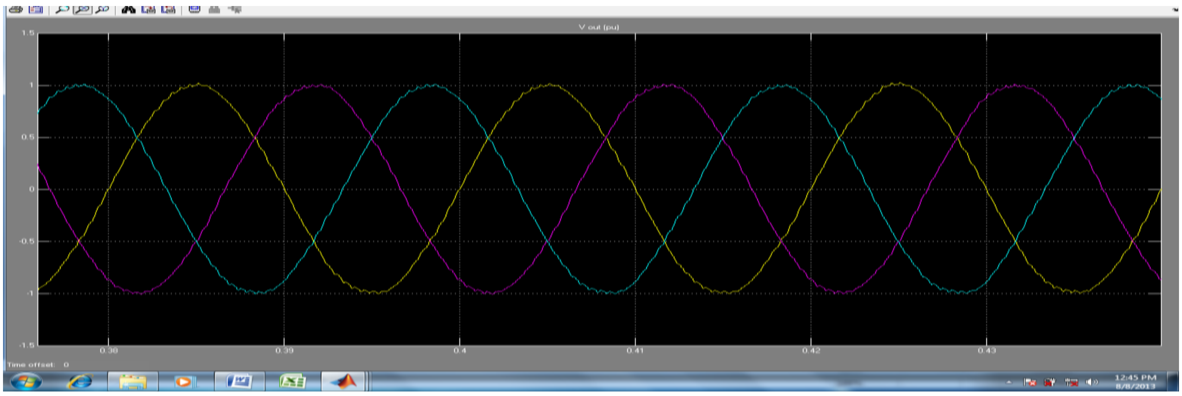


Fig. 5.5. Three phase output of Inverter at (500W/m^2)

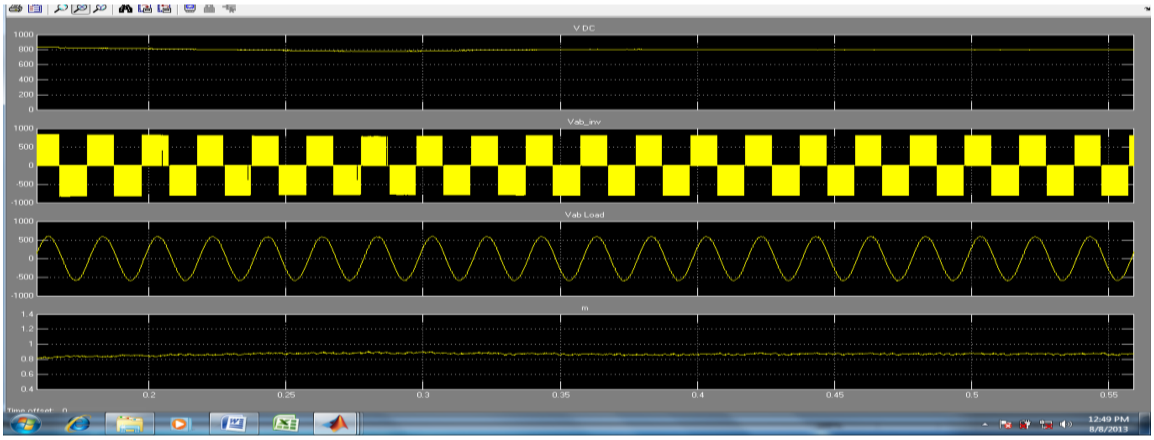


Fig.5.6. Output waveform of V_{dc}, V_{ab_inv}, V_{ab_load} and m at (500W/m^2)

5.5 Radiation 250W/m^2 and 50 kW load :

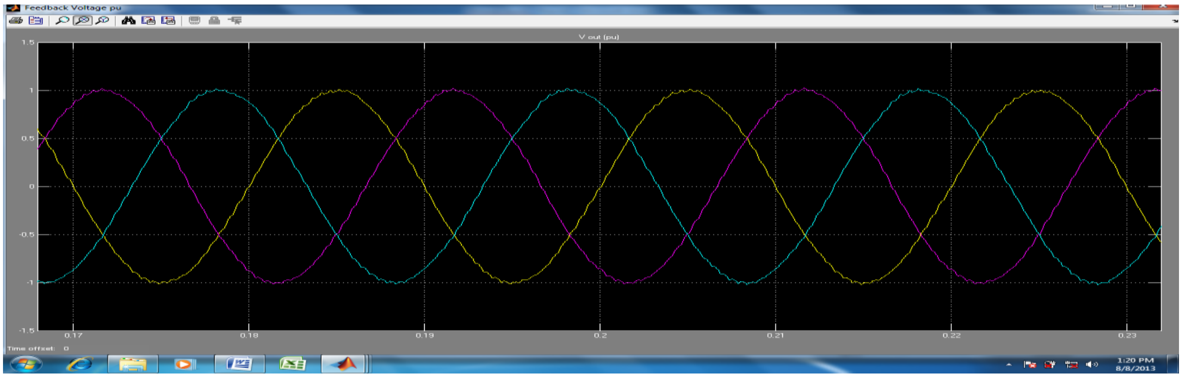


Fig.5.7. Three phase output of Inverter at (250W/m^2)

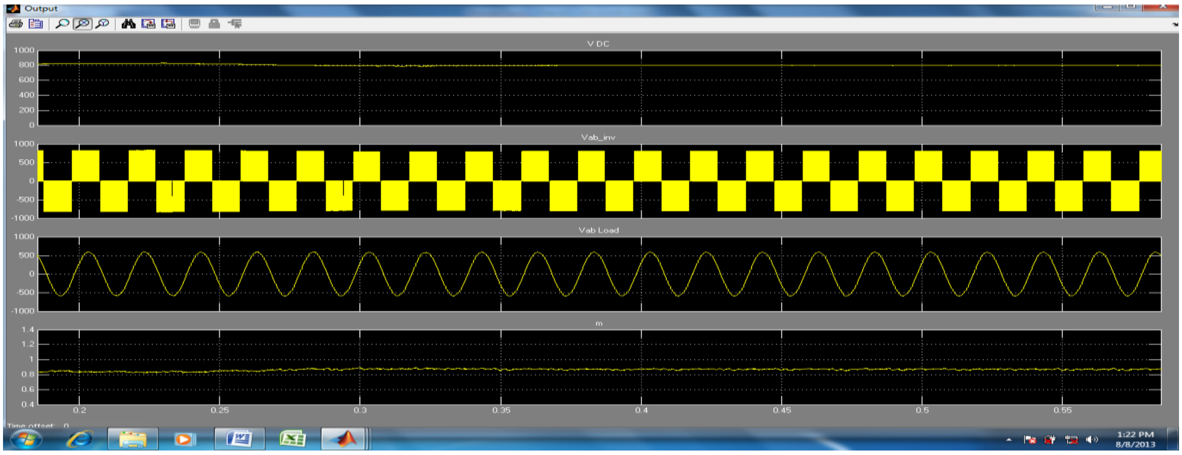


Fig. 5.8. Output waveform of V_{dc}, V_{ab_inv}, V_{ab_load} and m at (250W/m^2)

CHAPTER -6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusion:

Various results of the dissertation in the form of voltage, current, power, and waveforms are discussed with the old work and following conclusions have been made from the comparative study of table no. 5.1, 5.2 and 5.3:

‘It has been seen that unlike the Micro grid PV Based System, here in the PVFC Hybrid System the Fuel Cell Unit is operated in parallel with the Photo Voltaic Unit and hence the voltage remains constant at output.’

‘Also it has been observed from the comparative study from the table that the R.M.S. value of output voltage is 415 V (Approx.) and it remains constant in spite of the fluctuation in load and radiation.’

6.5 Scope for future work:

- Operates PV array at max power point.
- Connect battery to DC Bus and store surplus solar power in it. In case of less radiation first uses battery power then FC power.
- Connect grid to this Hybrid Generation model & set logic for optimum use of solar.
- Hybrid Generation can be extended for wind/solar/fuel cell.

CHAPTER -7

LITERATURE REFERENCES

7.1 References:

[1]. Hristiyan Kanchev, Di Lu, Frederic Colas, *Member, IEEE*, Vladimir Lazarov, and Bruno Francois, *Senior Member, IEEE* “Energy Management and Operational Planning of a Microgrid With a PV-Based Active Generator for Smart Grid Applications” vol. 58, no. 10, pp. 4583 - 4592 October 2011.

[2]. Georg Hille, Werner Roth, and Heribert Schmidt, ‘‘Photovoltaic systems,’’ Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany, pp. 25 – 28, March 1995.

[3]. OKA Heinrich Wilk, ‘‘Utility connected photovoltaic systems,’’ contribution to design handbook, Expert meeting Montreux, pp.19–21, October 1992, International Energy Agency (IEA).

[4]. R. Messenger and J. Ventre, “Photovoltaic Systems Engineering”. London, UK: CRC Press, pp. 25- 28, 2004.

[5]. Chapin, D. M., C. S. Fuller, & G. L. Pearson, Bell Telephone Laboratories, Inc., Murray Hill, New Jersey “A New Silicon p-n Junction Photocell for Converting Solar Radiation into Electrical Power” Journal of Applied Physics, Volume 25, Issue 5, pp. 676-677 May 1954.

[6]. Hohm, D. P. & M. E. Ropp “Comparative Study of Maximum Power Point Tracking Algorithms” Progress in Photovoltaics: Research and Applications, page 47-62, November 2002

[7]. Hussein, K. H., I. Muta, T. Hoshino, & M. Osakada “Maximum Photovoltaic Power Tracking: an Algorithm for Rapidly Changing Atmospheric Conditions” IEE Proceedings – Generation, Transmission and Distribution – v. 142 January 1995, page 59-64

[8]. Koutroulis, Efichios, Kostas Kalaitzakis, Nicholas C. Voulgaris "Development of a Microcontroller-Based, Photovoltaic Maximum Power Point Tracking Control System" IEEE Transactions on Power Electronics, Vol. 16, No. 1, January 2001, page 46-54

[9]. Eftichios Koutroulis, Kostas Kalaitzaiis and Nicholas C. Voulgaris, Development of a microcontroller-based, photovoltaic maximum power point tracking control system, *IEEE Transactions on Power Electronics,* Vol. 16, No.1, Jan., 2001, pp. 46-54.

[10]. M. Veerachary, T. Senjyu, and K. Uezato, "Voltage-based maximum power point tracking control of PV system," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 38, no. 1, 2002, pp. 262-270.

[11]. I. S. Kim, M. B. Kim, and M. J. Youn, "New maximum power point tracker using sliding-mode observer for estimation of solar array current in the grid-connected photovoltaic system," *IEEE Transaction on Industrial Electronics*, vol. 53, no. 4, 2006, pp. 1027-1035.

[12]. J. A. Gow and C. D. Manning, "Development of a photovoltaic array model for use in power-electronics simulation studies," *IEE Proceedings- Electric Power Applications*, vol. 146, no. 2, pp. 193-199, 1999.

[13]. I. H. Altas, A. M. Sharaf, " A photo-voltaic array simulation model for Matlab-Simulink GUI Environment", International Conference on Clean Electrical Power, pp 256-258, ICCEP'07, May 21-23 Capri, Itelay, 2007.

[14]. I. S. Kim and M. J. Youn, "Variable-structure observer for solar array current estimation in a photovoltaic power-generation system," *IEE Proceedings-Electric Power Applications*, vol. 152, no. 4, 2005, pp. 953-959.

[15]. Mohamed A. H. El-Sayed, Adel M. Sharaf, "An Efficient Hybrid Wave/Photovoltaic Scheme for Energy Supply in Remote Areas", accepted for publication in international journal of Renewable Energy Technology, vol. 25, no. 2, 2008, pp. 531-532.

[16]. E. Santi, D. Franzoni, A. Monti, D. Patterson, F. Ponci, and N. Barry, "A fuel cell based domestic uninterruptible power supply," in Proc. IEEE Applied Power

Electronics Conference and Exposition (APEC’02), Dallas, TX, USA, Mar. 2002, pp. 605–613.

[17]. D. Franzoni, E. Santi, A. Monti, F. Ponci, D. Patterson, and N. Barry, “An active filter for fuel cell applications,” in Proc. IEEE Power Electronics Specialists Conference (PESC’05), Recife, Brazil, Jun. 2005, pp. 1607–1613.

[18]. Adel M. Sharaf, Mohamed A. H. El-Sayed,” Dynamic Control of Fuel Cell Powered Water Pumping Station”, Accepted for presentation at International Conf. on Renewable Energies and Power Quality (ICREPQ) Valencia, page no. 42-45, Spain 15-17 April 2009.

[19]. M. Tanrioven and M. S. Alam, “Modeling, control and power quality evaluation of a PEM fuel cell based power supply system for residential use,” in Proc. The 39th IEEE Industry Application Society Conference and Annual Meeting (IAS’04), Seatle, USA, Oct. 2004, pp. 2808–2814.

[20]. Y. M. Chen and Y. C. LIV, “Development of multi-port converters for hybrid wind-photovoltaic power system,” in Proc. IEEE Region 10 International Conference on Electrical and Electronic Technology, Aug. 2001, pp. 804–808.

[21]. J.J. Brey, A. Castro, E. Moreno and C. Garcia, "Integration of Renewable Energy Sources as an Optimized Solution for Distributed Generation," 28th Annual Conference of the Industrial Electronics Society 2002, vol. 4, pp. 251 – 253, 5-8 Nov. 2002,

[22]. B. Ozpineci, L. M. Tolbert, G. J. Su, and Z. Du, “Optimum fuel cell utilization with multilevel DC-DC converters,” in Proc. IEEE Applied Power Electronics Conference and Exposition (APEC’04), Anaheim, California, Feb. 2004, pp. 1572–1576.

[23]. O. Wasynczuk, “Dynamic behavior of a class of photovoltaic power systems,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-102, no. 9, 1983, pp. 3031-3037. [5] S. Chandrasekaran and L. Gokdere, “Integrated magnetics for interleaved DC-DC boost converter for fuel cell powered vehicles,” in Proc. IEEE Power Electronics Specialists Conference (PESC’04), Aachen, Germany, Jun. 2004, pp. 356–361.

[24] . K.Wang, C. Lin, L. Zhu, D. Qu, F. Lee, and J. Lai, "Bi-directional DC to DC converters for fuel cell systems," in Proc. IEEE workshop Power Electronics in Transportation, Dearborn, MI, USA, Oct. 1998, pp. 47–51.

[25] . S. Jang, T. Lee, W. Lee, and C. Won, "Bi-directional DC-DC converter for fuel cell generation system," in Proc. IEEE Power Electronics Specialists Conference (PESC'04), Aachen, Germany, Jun. 2004, pp. 4722–4728.

[26]. H. Matsuo, K. Kobayashi, Y. Sekine, M. Asano, and L. Wenzhong, "Novel solar cell power supply system using the multiple-input DC-DC converter," in Proc. IEEE Telecommunications Energy Conference (INTELEC'98), San Francisco, CA, USA, Nov. 1998, pp. 797–802.

[27]. H. Matsuo, W. Lin, F. Kurokawa, T. Shigemizu, and N.Watanabe, "Characteristic of the multiple-input DC-DC converter," IEEE Trans. Ind. Electron., vol. 51, no. 3, pp. 625–631, Jun. 2004.

[28]. F. Caricchi, F. Crescimbini, A. D. Napoli, O. Honorati, and E. Santini, "Testing of a new DC-DC converter topology for integrated wind-photovoltaic generating systems," in Proc. 5th European Conference on Power Electronics and Applications, Brighton, UK, Sep. 1993, pp. 83–88.

[29]. M. Marchesoni and C. Vacca, "New DC-DC converter for energy storage system interfacing in fuel cell hybrid electric vehicles," IEEE Trans. Power Electron., vol. 22, no. 1, pp. 301–308, Jan. 2007.

[30]. Y. Song and P. Enjeti, "A high frequency link direct DC-AC converter for residential fuel cell power systems," in Proc. IEEE Power Electronics Specialists Conference (PESC'04), Aachen, Germany, Jun. 2004, pp. 4755–4761.

[31]. A. M. Tuckey and J. N. Krase, "A low-cost inverter for domestic fuel cell applications," in Proc. IEEE Power Electronics Specialists Conference (PESC'02), Cairns, Jun. 2002, pp. 339–346.

[32]. L. Solero, F. Caricchi, F. Crescimbini, O. Honorati, and F. Mezzetti, "Performance of a 10 kW power electronic interface for combined wind/PV isolated generating

systems," in Proc. IEEE Power Electronics Specialists Conference (PESC'96), Jun. 1996, pp. 1027–1032.

[33]. G. K. Andersen, C. Klumpner, S. B. Kjaer, and F. Blaabjerg, "A new green power inverter for fuel cells," in Proc. IEEE Power Electronics Specialists Conference (PESC'02), Cairns, Jun. 2002, pp. 727–733.

[34]. H. Ertl, J. W. Kolar, and F. C. Zach, "A novel multicell DC-AC converter for applications in renewable energy systems," IEEE Trans. Ind. Electron., vol. 49, no. 5, pp. 1048–1057, Oct. 2002.

[35]. A. Kotsopoulos, J. L. Duarte, and M. A. M. Hendrix, "A converter to interface ultra-capacitor energy storage to a fuel cell system," in Proc. IEEE International SymposIVm on Industrial Electronics, Corsica, May 2004, pp. 827–832.

[36]. N. Ashari, W. W. L. Keerthipala, and C. V. Nayar, ''A single phase parallel connected Uninterruptible power supply/Demand side management system,'' pp. 92 - 95, PE-275-EC (08-99), IEEE Transactions on Energy Conversion, August 1999.

[37]. C. V. Nayar, J. Perahia, S. J. Philips, S. Sadler, and U. Duetchler, ''Optimized power electronic device for a solar powered centrifugal pump,'' Journal of the Solar Energy Society of India, SESI Journal 3(2), pp. 87–98 (1993).

[38]. Ziyad M. Salameh, and Fouad Dagher, ''The effect of electrical array reconfiguration on the performance of a PV-powered volumetric water pump,'' IEEE Transactions on Energy Conversion 5, pp.653–658 (1990).

[39]. J. Larminie and A. Dicks, Fuel Cell Systems Explained. Chichester, England: John Wiley & Sons, pp. 162-165, 2000.

Babu Banarasi Das University

Plagiarism Report

Student Name - Itisha Singh

Roll no - 1160450002

Thesis title -Analysis on Micro Grid using Solar Cell / Photovoltaic Cell- Fuel Cell for Energy supply in remote areas

Guide- Associate Professor & Head Mr. V.K. Maurya

Plagiarism Report Details

- 70.2 % Unique Content
- 29.8 % Plagiarism report

LIST OF PUBLICATION

- Phovoltaic and fuel cell application in remote areas

Vol. 6, Issue 04, April 2019

Scientific Journal of impact factor: 5.71

- Results at grid of photovoltaic and fuel cell matlab model for remore areas

Vol 6, issue 04, April 2019

Scientific Journal of impact factor: 6.200

BABU BANARASI DAS UNIVERSITY, LUCKNOW

CERTIFICATE OF FINAL THESIS SUBMISSION

1. Name: Itisha Singh
2. Roll No: 1160450002
3. Thesis Title: Analysis on Micro Grid using Solar Cell / Photovoltaic- Fuel Cell for Energy supply in Remote Areas.
4. Degree for which thesis is submitted: Master of Technology (Power System & Control)
5. School (of the University to which the thesis is submitted)

School of Engineering

6. Thesis Preparation Guide was referred to for preparing the thesis. YES ☐ NO ☐
7. Specification regarding thesis format have been closely followed. YES ☐ NO ☐
8. The content of the thesis have been organized based on Guidelines YES ☐ NO ☐
9. The thesis has been prepared without resorting to plagiarism. YES ☐ NO ☐
10. All sources used have been cited appropriately. YES ☐ NO ☐
11. The thesis has not been submitted elsewhere for a degree. YES ☐ NO ☐
12. All the corrections have been incorporated YES ☐ NO ☐
13. Submitted 4 hard bound copies plus one CD. YES ☐ NO ☐

(Signature of the Supervisor)

Name: Mr V.K. Maurya

(Signature of the candidate)

Name : Itisha Singh

Roll No: 1160450002

CURRICULUM VITAE