



UNIVERSIDADE DE ÉVORA

MODELING PHOTOVOLTAIC PANELS UNDER VARIABLE INTERNAL AND ENVIRONMENTAL CONDITIONS WITH NON-CONSTANT LOAD

Masud Rana Rashel

Supervisors-

Doctor Mouhaydine Tlemçani

Doctor Mário Rui Melício da Conceição

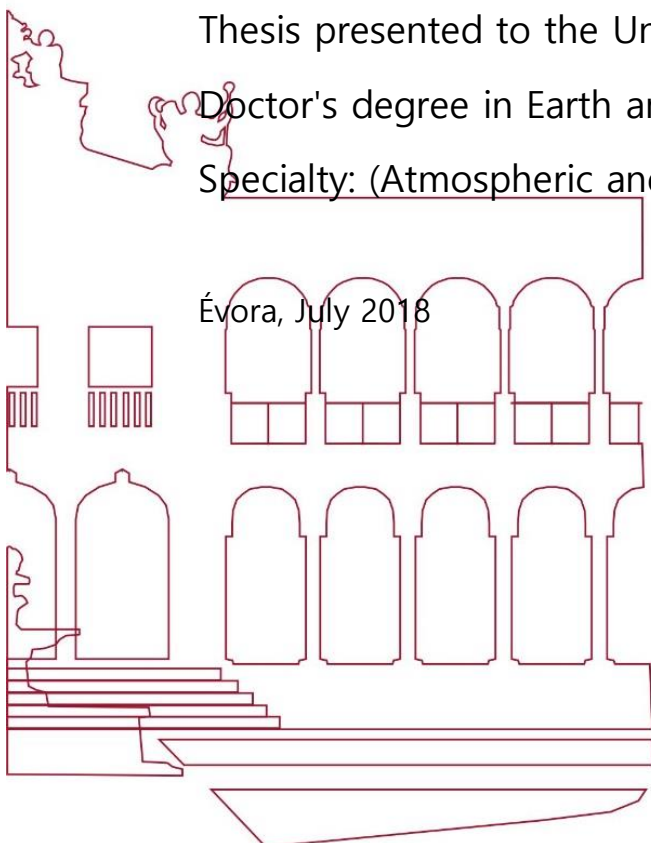
Doctor Teresa Cristina de Freitas Goncalves

Thesis presented to the University of Évora for obtaining the

Doctor's degree in Earth and Space Sciences

Specialty: (Atmospheric and Climate Physics)

Évora, July 2018





UNIVERSIDADE DE ÉVORA

MODELING PHOTOVOLTAIC PANELS UNDER VARIABLE INTERNAL AND ENVIRONMENTAL CONDITIONS WITH NON-CONSTANT LOAD

Masud Rana Rashel

Supervisors-

Doctor Mouhaydine Tlemçani

Doctor Mário Rui Melício da Conceição

Doctor Teresa Cristina de Freitas Gonçalves

Respectfully, Assistant professor

Department of Physics, School of Science and Technology

UNIVERSIDADE DE ÉVORA

Assistant Professor with Habilitation

Department of Physics, School of Science and Technology

UNIVERSIDADE DE ÉVORA

Assistant professor

Department of Informatics, School of Science and Technology

UNIVERSIDADE DE ÉVORA

Thesis presented to the University of Évora for obtaining the Doctor's degree
in Earth and Space Sciences

Specialty: (Atmospheric and Climate Physics)

Évora, July 2018

Abstract

This thesis focuses on the modeling and simulation of photovoltaic electric energy conversion systems, that considering different internal and environmental parameters, important for the forecast of the electric energy production. For the cell or panel modeling, the single diode five-parameter model is used. The internal parameters considered are the photocurrent, the cell temperature, the ideality factor, the series resistance, the shunt resistance and the saturation current; and on the other hand the external parameters considered are solar irradiance, ambient temperature and wind speed. New contributions are presented in the context of the modeling and simulation of the error function that identifies the more and less sensitive internal parameters of the cell model and the sensitivity of the external parameters. In the context of obtaining the experimental results, a monocrystalline silicon photovoltaic panel is used. And a signal generator, data acquisition device, an anemometer, a pyranometer and a sensor for measuring the ambient temperature are used. In the context of internal relation between external parameters, correlation studies are performed in order to show the relationships between them; and the obstacle concept is presented as a generalization of shadow types, namely dust and elements that reduce solar irradiance on the surface of the cell or panel.

Keywords

Photovoltaic Panel

Internal Parameters

Environmental Parameters

Error Function

Correlation

Modeling and Simulation

Shadow of Obstacles

Modelação de painéis fotovoltaicos sob condições internas e ambientais variáveis com carga não constante

Resumo

Esta tese incide sobre o tema da modelação e simulação de sistemas de conversão de energia eléctrica fotovoltaica considerando diferentes parâmetros internos e ambientais, importantes para a previsão da produção de energia eléctrica. Para a modelação da célula ou do painel é utilizado o modelo de cinco parâmetros de um díodo. Os parâmetros internos considerados são a corrente que atravessa o díodo, a temperatura interna da célula, o fator de idealidade, a resistência série da célula, a resistência paralela da célula e a corrente de saturação; os parâmetros externos considerados são a irradiância solar, a temperatura ambiente e a velocidade do vento. São apresentadas novas contribuições no contexto da modelação e simulação da função de erro que identifica os parâmetros internos mais e menos sensíveis do modelo da célula e a sensibilidade dos parâmetros externos. No contexto para a obtenção dos resultados experimentais foram utilizadas células e um painel fotovoltaico de silício monocristalino respetivamente, um gerador de sinais, dispositivos aquisição de dados, um anemómetro, um piranómetro e um sensor para medir a temperatura ambiente. Em ambos contextos, são realizados estudos de correlação entre os parâmetros externos no sentido de mostrar as relações entre eles; e é apresentado o conceito de obstáculo como uma generalização dos tipos de sombras, nomeadamente a poeira e elementos que reduzem a irradiância solar na superfície da célula ou do painel.

Palavras-chave

Painel Fotovoltaico

Parâmetros Internos

Parâmetros Ambientais

Função de Erro

Correlação

Modelação e Simulação

Sombra do Obstáculo

I like to dedicate this work
to
*my **Father** (1947 -2010)*

Acknowledgement

I like to give thanks to Professor Mouhaydine Tlemcani, Assistant Professor of Department of Physics, School of Sciences and Technology, University of Évora, who is primarily responsible for scientific guidance and as supervisor. I like to express my deepest thanks for his guides and ideas that he has given me and helps me to generate new research articles during the journey of my doctoral work. Also like to thanks him for availability and the good advices and also for giving me rigor imposed of transmit important knowledge and for understanding the difficulties that emerged during the doctoral work.

I like to give thanks to Professor Mário Rui Melício da Conceição, Assistant Professor with Habilitation of Department of Physics, School of Sciences and Technology, University of Évora, who is responsible as co-supervisor and like to express my deep appreciation, for the good advices, the guidelines, and for transmitting knowledge in consistency imposed during doctoral studies.

I like to give thanks to Professor Teresa Cristina de Freitas Gonçalves, Assistant Professor of Department of Informatics, School of Sciences and Technology, University of Évora, who is responsible as co-supervisor and like to expressed a deep gratitude for the assistance that has given during the doctoral work and specially for the guideline during writing period.

I like to thank the FUSION (Featured eUrope and South asIamObility Network) Erasmus Mundus project for funding the scholarship and to ICT of University of Évora for enabling this work. The work is also co-funded by the European Union through the European Regional Development Fund, included in the COMPETE 2020 (Operational Program Competitiveness and Internationalization) through the ICT project (UID /GEO/04683/2013) with the reference POCI-01-0145-FEDER-007690.

To the professors and colleagues, specially to Professor António Heitor Reis and Professor Maria João Costa of Department of Physics, University of Évora, I like to express my deep thankfulness for the vigorous conditions that has given and for the encouragement, that has given during the academic part of my 3rd cycle of studies in Higher Education, and in subsequent doctoral studies. Also like to give thanks to Professor Hasan Sawar and Professor Chowdhury Mofizur Rahman.

Special thanks to my supervisor's laboratory people, specially Andre Albino for helping me to start my research work smoothly and enlighten discussion about different problems and their possible solutions, and also like to thanks Md. Tofael Ahmed and Ana Catarina Foles for their fellowship and support.

Special thanks to my friends Md. Sajib Ahmed and his wife Sharmin Sultana Prite for their assistance during the journey of the thesis writing. They helped me to forget about cooking by providing various delicious food during this crucial time. Also my special thanks to Md. Mujahidul Islam, Sakin Sarwar and Sk Md Obaidullah for their assistance during writing. I also like to thanks my childhood friends Moni, Zamil, Sumon, Sabber, Rashel, Kamrul and Sabuj for continue giving the encouragement and appreciation. I also like to thanks my fellow friends Moinul Islam Robin, Prakash, Miguel, Ricardo, Fahad, Vanda and Sara.

To my father, Md. Abdur Rahim, who spent his life to help to build my dreams and who always had given courage during his life. I like to express my deep appreciation to my mother, Monwara Begum for her support and the strength that help me to continue my work. And I wish to express my gratitude to my sisters, Sultana Akter, Mukta Begum, Hasna Hena Hawya, Nargis Surayia Khushi, Nadia Parven and Nusrat Shahara Bithi.

To my wife Ishrat Jahan Reme and my son Ahmed Abdullah Ibn Masud whom I deprived of many hours of deserved attention, I express deep appreciation for the support and the strength they have given me.

To others that I did not mention for reasons of space, since there are many who contributed directly or indirectly to the elaboration of this doctoral work, I wish to express my gratitude.

And above all thanks to almighty to give me strength and help me to finish this journey.

Table of Contents

1	INTRODUCTION	1
1.1	PRELUDE	2
1.1.1	History of solar energy.....	6
1.1.2	The sun.....	8
1.2	MOTIVATION.....	11
1.3	OBJECTIVES.....	13
1.4	STATE OF THE ART	15
1.5	ORGANIZATION OF THE DISSERTATION	26
1.6	NOTATIONS	27
2	FUNDAMENTAL THEORY	28
2.1	INTRODUCTION.....	29
2.2	SOLAR RADIATION SPECTRUM	30
2.3	SEMICONDUCTOR	32
2.3.1	Intrinsic semiconductor.....	34
2.3.2	Extrinsic semiconductor.....	35
2.4	SEMICONDUCTOR DIODE.....	35
2.4.1	Real and ideal diode.....	36
2.4.2	Current-voltage characteristics of diode	37
2.5	PHOTOVOLTAICS	38
2.5.1	Working principle	39
2.5.2	Modeling of PV cell.....	41
2.5.3	Analytical approach of five parameter PV cell model.....	44

2.5.4	Datasheet values for a PV cell	45
2.6	SENSITIVITY ANALYSIS AND ERROR FUNCTION	48
2.7	INTERNAL PARAMETERS.....	51
2.7.1	Photocurrent.....	52
2.7.2	Internal cell temperature	53
2.7.3	Ideality factor	53
2.7.4	Saturation current.....	53
2.7.5	Series resistance	54
2.7.6	Shunt resistance	54
2.8	ENVIRONMENTAL PARAMETERS.....	54
2.8.1	Irradiance	54
2.8.2	Ambient temperature and effects on cell temperature	56
2.8.3	Wind speed.....	58
2.9	NON-CONSTANT LOAD	59
2.10	SHADOW OF OBSTACLE ON PV PANEL	60
2.10.1	Time-dependent obstacles.....	60
2.10.2	Time-independent obstacles.....	61
2.10.3	Evaluation of obstacles	62
2.11	EXPERIMENT AND SIMULATION.....	63
2.11.1	Instrumentation and measurement	63
2.11.2	MATLAB and Simulink modeling	70
2.12	SUMMARY	71
3	RESULTS AND DISCUSSION.....	72
3.1	INTRODUCTION.....	73

3.2	CASE STUDY 1: SENSITIVITY ANALYSIS FOR INTERNAL PARAMETERS	75
3.2.1	Photocurrent	76
3.2.2	Internal cell temperature	77
3.2.3	Diode ideality factor	78
3.2.4	Series resistance	79
3.2.5	Shunt resistance	80
3.2.6	Saturation current.....	81
3.2.7	Simplified PV model.....	82
3.3	CASE STUDY 2: SENSITIVITY ANALYSIS FOR ENVIRONMENTAL PARAMETERS	84
3.3.1	Irradiance	84
3.3.2	Ambient temperature	88
3.3.3	Wind speed.....	91
3.3.4	Changing irradiance and ambient temperature	94
3.3.5	Changing ambient temperature and wind speed	95
3.3.6	Changing irradiance and wind speed	97
3.3.7	Correlation between environmental parameters	98
3.4	CASE STUDY 3: NON-CONSTANT LOAD	101
3.4.1	Different resistances as non-constant load.....	101
3.5	CASE STUDY 4: SHADOW OF OBSTACLE ON PV PANEL	107
3.5.1	PV cells under obstacle.....	107
3.5.1.1	Cells in series connection	107
3.5.1.2	Cells with parallel connection	108
3.5.2	PV panel under obstacle.....	109
3.5.2.1	Time-dependent obstacle.....	111

3.5.2.2	Time-independent obstacle.....	122
3.5.3	Different type obstacles on a PV panel.....	128
3.6	SUMMARY.....	130
4	CONCLUSION.....	131
4.1	CONTRIBUTIONS.....	132
4.2	PUBLICATIONS.....	134
4.3	FUTURE RESEARCH DIRECTION.....	136
	REFERENCES.....	137
5	APPENDIX.....	153
	APPENDIX – I.....	153
	APPENDIX – II.....	155

List of Figures

Figure 1.1 Future state of the world CO ₂ emission.....	2
Figure 1.2 Decreasing price of PV module cost.	4
Figure 1.3 PV in remote area for improving life standard.....	5
Figure 1.4 Increasing efficiency of different PV technologies in different time period.....	6
Figure 1.5 PV installation growth around the world.....	8
Figure 1.6 The burning Sun.	9
Figure 1.7 World map of insolation.....	10
Figure 1.8 World energy consumption.	11
Figure 1.9 World energy consumption by energy source prediction till 2040.	12
Figure 2.1 Spectral irradiance of the solar radiation with different wavelengths.....	31
Figure 2.2 Standard spectral irradiance with wavelengths.	32
Figure 2.3 Diagrams of different energy bands for conventional materials. (a)Insulator (b)conductor (c)semiconductor.....	33
Figure 2.4 Different types of Silicon.	34
Figure 2.5 <i>p-n</i> junction diode.....	36
Figure 2.6 Symbol for diode.....	36
Figure 2.7 Voltage-current curve of real diode.....	36
Figure 2.8 Voltage-current curve of ideal diode.....	37
Figure 2.9 Different regions of a diode.....	37
Figure 2.10 Different types of PV technologies.	39
Figure 2.11 Photovoltaic device working process.....	40
Figure 2.12 Simple single diode PV model.....	41

Figure 2.13 Four-parameter of PV cell model.	42
Figure 2.14 Single diode five parameters PV cell model.	43
Figure 2.15 Typical structure of a c-Si PV cell.	46
Figure 2.16 Voltage-current curve for single diode five parameters PV cell model.	46
Figure 2.17 Voltage-current curve for single diode five parameters PV cell model.	47
Figure 2.18 Flow chart of sensitivity analysis.	48
Figure 2.19 Parameter with error function for identify sensitiveness.	49
Figure 2.20 Flowchart describing the model to get sensitive parameters for internal model.	52
Figure 2.21 Sequential daily average irradiance of year 2017.	55
Figure 2.22 Pyranometer.	56
Figure 2.23 Sequential daily average temperature of year 2017.	57
Figure 2.24 Vaisala weather station with temperature sensor.	57
Figure 2.25 Sequential daily average wind speed of year 2017.	58
Figure 2.26 Anemometer.	59
Figure 2.27 Cloud shadow on PV panels as time-dependent obstacle.	61
Figure 2.28 Shadow of birds as time-dependent obstacle.	61
Figure 2.29 Dust on PV as time-independent obstacles.	62
Figure 2.30 Physical damage as time-independent obstacles.	62
Figure 2.31 Instrumentation interface with computer for controlling.	64
Figure 2.32 Data Acquisition interface with computer.	64
Figure 2.33 NI USB-6009 DAQ.	65
Figure 2.34 Signal description for NI USB-6009.	66
Figure 2.35 AFG 320 function generator.	66
Figure 2.36 GPIB-USB-HS interface.	67

Figure 2.37 Monocrystalline silicon PV panel.	67
Figure 2.38 DAQ and signal generator connect to computer.	68
Figure 2.39 Circuit diagram for PV for measurement.	69
Figure 3.1 Smart Grid System.	74
Figure 3.2 Predict PV output to integrate with SG system.	75
Figure 3.3 Change of error function with different photocurrent.	76
Figure 3.4 Change of error function with different cell temperature.	78
Figure 3.5 Change of error function with different diode ideality factor.	79
Figure 3.6 Change of error function with different series resistance.	80
Figure 3.7 Change of error function with different shunt resistance.	81
Figure 3.8 Change of error function with different saturation current.	82
Figure 3.9 I-V curve for simple and single diode five parameters PV cell model.	83
Figure 3.10 P-V curve for simple and single diode five parameter PV cell model.	83
Figure 3.11 Irradiance with error function.	85
Figure 3.12 I-V curve under different irradiance.	86
Figure 3.13 P-V curve under different irradiance.	87
Figure 3.14 Maximum power points with increasing irradiance.	87
Figure 3.15 Ambient temperature with Error function to identify sensitivity.	88
Figure 3.16 Voltage-current curve under different ambient temperature.	89
Figure 3.17 Voltage-power curve under different ambient temperature.	90
Figure 3.18 Maximum power points with increasing ambient temperature.	91
Figure 3.19 Wind speed with error function.	92
Figure 3.20 Voltage-current curve under different wind speed.	92
Figure 3.21 Power-voltage curve under different wind speed.	93

Figure 3.22 Maximum power point with increasing wind speed.....	94
Figure 3.23 Power with changing irradiance and ambient temperature.	95
Figure 3.24 Power with changing ambient temperature and wind speed.	96
Figure 3.25 Power with changing wind speed and irradiance.	97
Figure 3.26 Correlation matrix of irradiance and temperature.	98
Figure 3.27 Correlation matrix between irradiance and wind speed.	99
Figure 3.28 Correlation matrix between wind speed and temperature.	100
Figure 3.29 I-V curve with resistance load value of 100 Ω	101
Figure 3.30 P-V curve with resistance load value of 100 Ω	102
Figure 3.31 I-V curve with resistance as load value of 220 Ω	102
Figure 3.32 P-V curve with resistance load value of 220 Ω	103
Figure 3.33 I-V curve with resistance as the load value of 560 Ω	103
Figure 3.34 P-V curve with resistance as the load value of 560 Ω	104
Figure 3.35 I-V curve with resistance as load value of 1500 Ω	104
Figure 3.36 P-V curve with resistance as load value of 1500 Ω	105
Figure 3.37 I-V curve with resistance as load value of 4.7 k Ω	105
Figure 3.38 P-V curve with resistance as load value of 4.7 k Ω	106
Figure 3.39 P-V curves of two cells in series connection and one of them is under different level of obstacle.	108
Figure 3.40 P-V curves of two cells in parallel connection and one cell is under different level of obstacle.	109
Figure 3.41 I-V curve without obstacle and constant irradiance source.....	110
Figure 3.42 P-V curve without obstacle and constant irradiance source.....	110
Figure 3.43 I-V curve with time under dynamic obstacle.	112
Figure 3.44 P-V curve with time under time-dependent obstacle.	112

Figure 3.45 I-V curve with time under rapid changing obstacles.....	113
Figure 3.46 P-V curve with time under rapid changing obstacles.....	113
Figure 3.47 I-V curve with time, 48 cells get constant irradiance, and 24 cells are under obstacles and without diode between cells.....	114
Figure 3.48 I-V curve with time, 48 cells get constant irradiance, and 24 cells are under obstacles and diode between the cells.....	115
Figure 3.49 P-V curve with time and without diode between cell, 48 cells having constant irradiance, and 24 cells get varying irradiance.....	115
Figure 3.50 P-V curve with time, cells are connected with diode, and 48 cells get constant irradiance, and 24 cells get varying irradiance.....	116
Figure 3.51 I-V curve with time, 36 cells having constant irradiance, and 36 cells get varying irradiance and no diode between cells.....	117
Figure 3.52 I-V curve with time with connected diode cells, 36 cells having constant irradiance and 36 cells get varying irradiance.....	117
Figure 3.53 P-V curve with time and cells are connected in series without diode, 36 cells get constant radiance, and 36 cells get varying irradiance.....	118
Figure 3.54 P-V curve with time, 36 cells get irradiance, and 36 cells get varying irradiance with diode connection.....	118
Figure 3.55 I-V curve with time without diode, 24 cells get irradiance, and 48 cells get various irradiance.....	119
Figure 3.56 I-V curve with time, 24 cells having irradiance, and 48 cells get varying irradiance with diode connection.....	120
Figure 3.57 P-V curve with time, 24 cells get irradiance, and 48 cells get varying irradiance and without diode between cells.....	120
Figure 3.58 P-V curve with time, connected with diode, 24 cells having irradiance, and 48 cells having varying irradiance.....	121
Figure 3.59 I-V curve under thin layer with uniform thickness dust on the surface of a PV panel.....	122
Figure 3.60 P-V curve under thin layer with uniform thickness dust on the surface of a PV panel.....	123

Figure 3.61 I-V curve for 54 cells of a 72 cells' panel is under time-independent obstacle.	124
Figure 3.62 P-V curve for 54 cells of a 72 cells' panel is under time-independent obstacle.	124
Figure 3.63 I-V curve when 4 cells is fully damaged of a PV panel.	125
Figure 3.64 P-V curve when 4 cells is fully damaged of a PV panel.	125
Figure 3.65 I-V curve having 54 cells under time-independent obstacle.	126
Figure 3.66 P-V curve with 54 cells under time-independent obstacle condition.	127
Figure 3.67 I-V curve with 18 cells under static obstacle condition and rest in healthy condition.	127
Figure 3.68 P-V curve with 18 cells under time-independent obstacle.	128
Figure 3.69 I-V curve with constant irradiance, time-independent obstacle, and time-dependent obstacle.	129
Figure 3.70 P-V curve with constant standard irradiance, time-independent obstacle, and time- dependent obstacle.	129

List of Tables

Table 1.1 Power generation from different renewable sources	4
Table 1.2 Population without electricity and with electrification rate.....	5
Table 2.1 Data for the c-Si PV cell at STC.....	45
Table 2.2 Physical properties of a c-Si PV Cell.....	45
Table 3.1 Changing irradiance and ambient temperature with their maximum power point	95
Table 3.2 Changing wind speed and ambient temperature with their maximum power	96
Table 3.3 Changing wind speed and irradiance with their maximum power	97
Table 3.4 Different additive load resistance with respective maximum power.....	106

List of Acronyms

AC	Alternating Current
AFG	Arbitrary Function Generator
AM	Air Mass
c-Si	Crystalline Silicon
DHI	Direct Horizontal Irradiance
DNI	Direct Normal Irradiance
DC	Direct Current
DAQ	Data Acquisition
ECMWF	European Centre for Medium-Range Weather Forecasts
FF	Fill Factor
GaAs	Gallium arsenide
GHI	Global Horizontal Irradiance
GPIB	General Purpose Interface Bus
GW	Giga Watt
HS	High Speed
MPPT	Maximum Power Point Tracking
MPP	Maximum Power Point
NREL	National Renewable Energy Laboratory

NI National Instruments

OECD Organization for Economic Co-operation and Development

PV Photovoltaic

STC Standard Test Condition

SG Smart Grid

USB Universal Serial Bus

List of Nomenclatures

CO_2	Carbon dioxide
C	Speed of light
E_v	Valence band
E_c	Conduction band
E_g	Energy band gap
E_p	Photon energy
e	Euler's constant
eV	Electron Volt
G	Irradiance
G_n	Irradiance at standard condition
h	Planck's constant
I	Current
I_0	Saturation current
I_{on}	Internal diode current
I_L	Photocurrent
I_{sc}	Short circuit current
I_{mp}	Current at maximum point
I_p	Intensity of light

I_D	Current at diode
N_A	Acceptor atoms
N_D	Donor atoms
n_i	Intrinsic semiconductor
n_p	Number of photon
k	Boltzmann constant
K_l	Temperature coefficient
L	Length
L_o	Zenith path span at sea level
m_h	Effective mass of a hole
m_e	Effective mass of an electron
N_c	Effective density at conduction band
N_v	Effective density at valance band
n	Diode ideality factor
p_i	Hole density
q	Electron charge
R_s	Series Resistance
R_{sh}	Shunt Resistance
T	Internal cell temperature

T_{cell} Cell temperature with ambient condition

T_{air} Ambient temperature

V Voltage

V_{oc} Open circuit voltage

V_{mp} Voltage at maximum point

V_T Thermal voltage

V_D Voltage at diode

ν Frequency

Z Zenith angle

λ Wavelength

CHAPTER

1

Introduction

In this chapter, the discussion is about the work's fundamental aspects. It starts with an introduction about the chapter and describes the motivations of the proposed work. After that, the dissertation's objectives and motivations are discussed to give an idea about the ground of the work. State of the art is included with all the related literature research done. Then, the proposed approach is briefly described and the main idea of this work is discussed in short to provide an idea about the findings. At the end of this chapter, the organization of the dissertation is given.

1.1 Prelude

The use of electricity is increasing all over the world with the increase of electronic equipment. All electronic devices run on this electrical energy. People use such devices in their daily life. To fulfil the power requirement from the consumers, enough sources of power are needed. Existing power plants cannot give enough electricity power, and the most part of the sources of energy is fossil fuel. Fossil fuel power plant generates massive amount of CO₂ and lots of other gases which are not suitable for the environment [COP2115]. This a major reason for global warming. It causes an increase in the temperature of the environment [IEA13, UNFCC15, UN16].

Figure 1.1 shows the future of the world for different scenarios where CO₂ increases in different ways [IEA15]. If the emission of CO₂ and other harmful gases are controlled, then it will be possible to reduce the temperature of the world. Observing the surrounding environment, it is possible to observe the effect of global warming. The icebergs are melting and causing an increase in the water level [IEA11, IEA14a, IEA14b]. This is an alarming situation for several countries those have the low height relative to sea level.

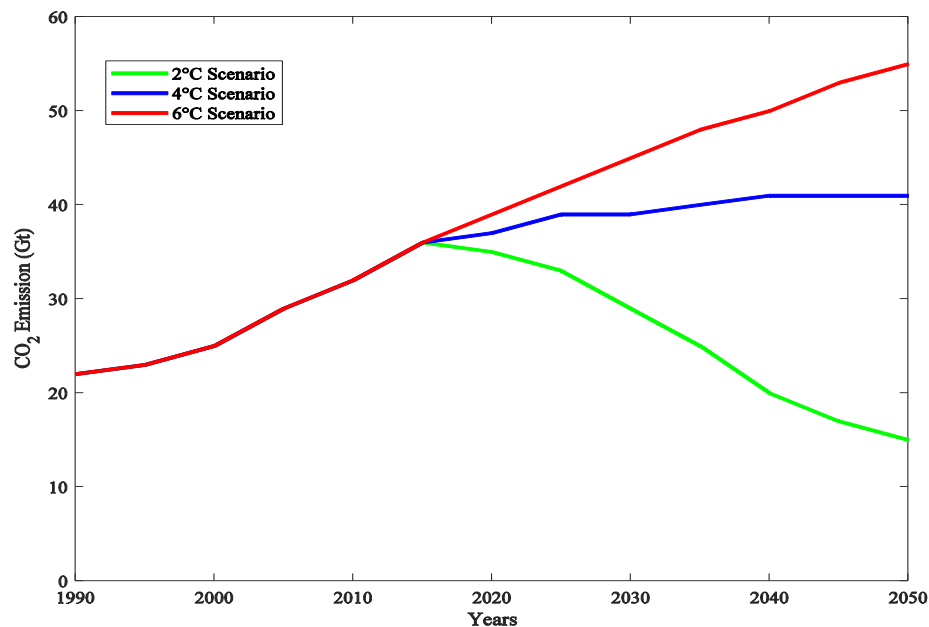


Figure 1.1 Future state of the world CO₂ emission.

Figure 1.1 shows three predicted scenarios using different strategy of energy sources and their power conversion system. The first one, 6°C scenario, is the process what is going on now if there is no control over the situation of carbon emission. This will cause huge damage of atmosphere and increase the global temperature, thus melting the ice of the poles and increasing the water level. Many land will go under the water. The temperature of the earth will increase on average by 5.5°C in long period of time. The second scenario (4°C) is the process, which will happen if emission is controlled and efficiency of energy system is improved; it will cause an increase in temperature of 4°C temperature in the long term. In the third scenario (2°C) reports an ambitious strategy that needs huge effort to control the emission; this strategy will keep the atmospheric temperature within increase of 2°C. This should be aspiration for all the world policies [IEA15].

Renewable energy has a big role to play in the control CO₂ emission. It is the energy source that already got attention from scientists, businessmen and policymakers. This is a sustainable solution to protect the atmosphere by reducing the greenhouse effect and control the rising temperature. There are different kinds of renewable energy sources. They are wind, solar, hydro, biomass etc. Among these, solar is the most significant.

There are two types of system in solar energy: solar thermal and photovoltaic. Solar thermal had more economical efficiency than PV system, but for the last few years, the cost of PV panel has been kept to the minimum and on the other hand, the performance is increasing. Among these two types of technology, Photovoltaic is growing faster due to easy establishment. It is portable and very flexible to use. For the last few decades the cost of PV reduced dramatically. This cost reduction [Solarcellcentral11, Weforum15] is shown in Figure 1.2.

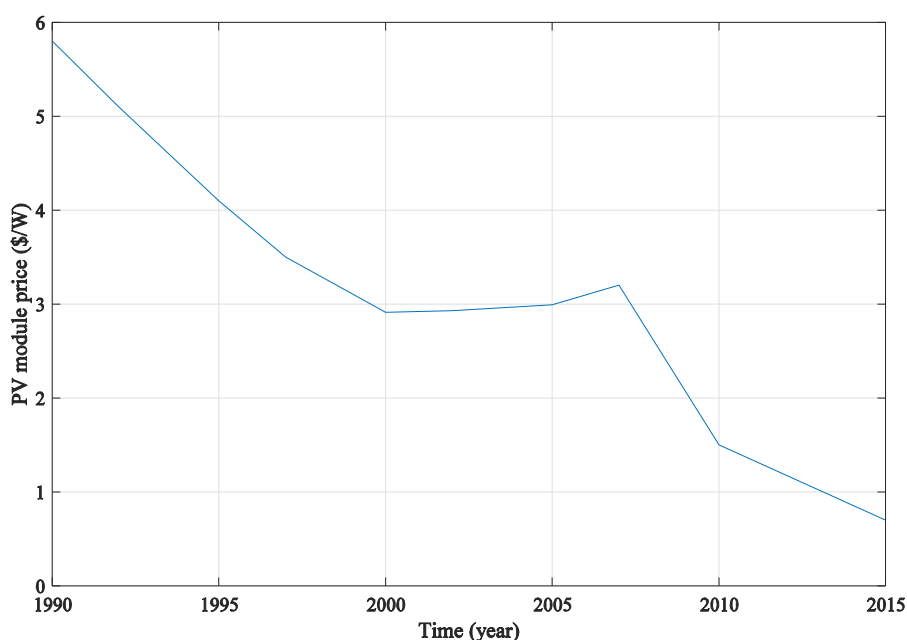


Figure 1.2 Decreasing price of PV module cost.

From Figure 1.2 it can be seen that the cost of PV module is decreasing in high rate in last few years (2010-2015), making it affordable to general people. During the year 2007 and 2008, due to shortage of polysilicon, PV module price was increased. Later on the price of the PV was decreased again and the trend is still remaining same. To establish a large power plant using PV module has now become cost effective than before [Graichen15, GTM17]. Moreover, maintenance cost is low for a PV plants. In the case of solar thermal, it is very expensive and lot of financial resources are needed to maintenance the plant.

The increasing usability and power generation from Photovoltaics and other renewable energy sources are shown in the Table 1.1 [REN16].

Table 1.1 Power generation from different renewable sources

Different Technology	2014	2015
Photovoltaics	177 GW	227 GW
Concentrating Solar Power	4.3 GW	4.8 GW
Wind Power	370 GW	433 GW
Bio Power	101 GW	106 GW
Geothermal power	12.9 GW	13.2 GW
Hydro Power	1036 GW	1064 GW

Table 1.2 presents different regions population all over the world without electricity and the electrification rate [IEA15].

Table 1.2 Population without electricity and with electrification rate

Region	Population without Electricity(Millions)	Rate of Electrification	Rate of Urban Electrification	Rate of Rural Electrification
Developing Asia	526	86%	96%	78%
Sub-Sahara Africa	634	32%	59%	17%
Latin America	22	95%	98%	84%
Middle East	17	92%	98%	78%
World	1201	83%	95%	70%

PV panel now reaches rural and remote areas to make life over there more comfortable. The education system also gets pace due to portable PV systems; in villages, schools and houses are using them to get electricity. Electricity helps those people to improve their life quality. Figure 1.3 shows a PV in a remote area for improving life standard [Solar98].



Figure 1.3 PV in remote area for improving life standard.

PV is a kind of energy conversion system that uses solar power to produce electrical directly. The working principle is very simple and this process of energy conversion does not produce any harmful gases. This makes it suitable to play a vital role to develop the sustainable future. Scientists all over the world are trying to increase the efficiency by using different types of materials with different kind of technologies. Figure 1.4 represents the present state of the research on

Photovoltaics and how much efficiency different technologies have achieved in different time period [NREL15].

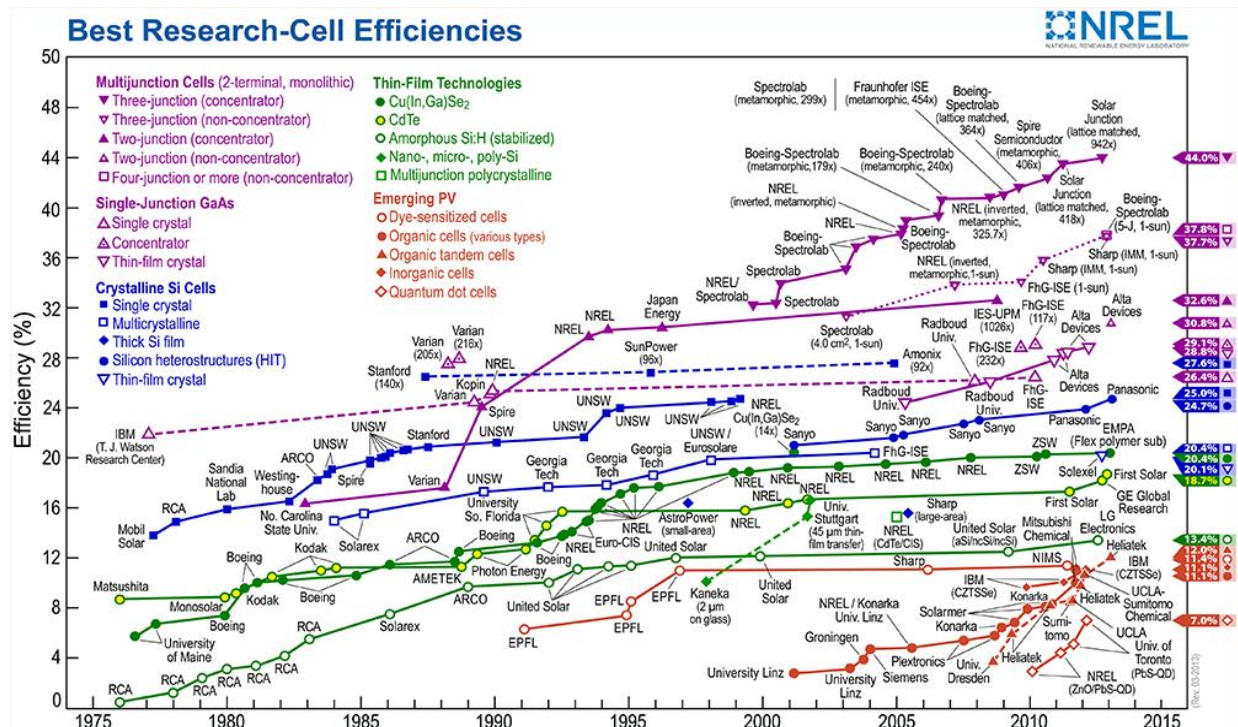


Figure 1.4 Increasing efficiency of different PV technologies in different time period.

Mainly five different technologies are shown; among them, multi-junction cells are in the leading position for the efficiency and has reached 44.4% efficiency in laboratory environment. After them the single-junction cells are in second position and reports 29.1% efficiency; then crystalline silicon technology has achieved 27.6% efficiency, thin-film technology comes at fourth position with 23.3% efficiency (cost is lower than other efficient technologies). At the bottom line the emerging PV technologies have less efficiency; among them Perovskite cell has 16.2% efficiency and are progressing very fast and promising.

1.1.1 History of solar energy

People from the early ages have been utilizing solar energy; from the beginning of mankind history, human and the sun have had a *good relation*. The sun is always the symbol of hope, after the darkness of night, the sun comes out as a symbol of hope. The sunlight is abundantly distributed all over the world. Depending on the geographical location the solar resource percentage varies.

Solar radiation itself is a primary resource for Photovoltaics system; it converts solar radiation into electricity following the law of photoelectric effect.

The History of using the solar energy is as old as the history of mankind. Human started to use the solar energy in different ways. In the early time, around 7th-century B.C. people have used magnifying glasses to concentrate the sun rays to make fire; in the 3rd century that Romans and Greeks used mirrors to light the torches. After that, Archimedes used reflection properties of light to fire wooden ships of the Roman Empire. At 20 A.D. Chinese people also used mirror to light up the torches. From the 1st to 4th century A.D., the Romans had south-facing windows to warm the bathhouses and in the 6th century A.D. Justinian people used sunrooms on houses. In 1767 the Solar collector was created by the Swiss scientist Horace de Saussure and in 1839 the French scientist Edmond Becquerel first saw the photovoltaic effect when he was doing experiments with two metal electrodes in a solution. In 1860 the French mathematician first come up with an idea to build a solar-powered steam engine. Willoughby Smith discovered the Selenium as photoconductivity in 1873 [Eere17].

In 1905 Albert Einstein described the photovoltaic effect in his paper [Einstein1905]. In 1916 Robert Millikan proved the photovoltaic effect and in the year of 1918 the Polish scientist Jan Czochralski built a way to grow single-crystal silicon. In 1932 Audobert and Stora identified the photovoltaic effect in Cadmium sulfide and in 1954 Daryl Chapin, Calvin Fuller and Gerald Pearson developed the first silicon photovoltaic cell at Bell labs which could convert sunlight to electricity; at first its efficiency was 4% which raised to 11% later on. After that, Western Electronic started to sell commercial licenses for silicon photovoltaic technologies in 1955. In 1959, PV was first used in satellite and in 1963, the Japanese built a lighthouse with array of photovoltaic which generated power value equivalent to 242 W. In 1970s Dr. Elliot Berman successfully designed a low cost solar cell and in 1976 David Carlon and Christopher Wronski prepared the first amorphous silicon PV cell. The first thin film solar cell was built at the University of Delaware in 1980 [Eere17].

Later on, the PV technologies spread worldwide and it has come from industry level to household standalone systems. Different companies all around the world are producing PV panels; different

countries come forward to investigate more about these technologies, implemented them and connected them to a central grid. From 2001 to 2017 the investment on PV systems has grown very rapidly. This rapid growth of PV is shown in Figure 1.5 [Greentechmedia16].

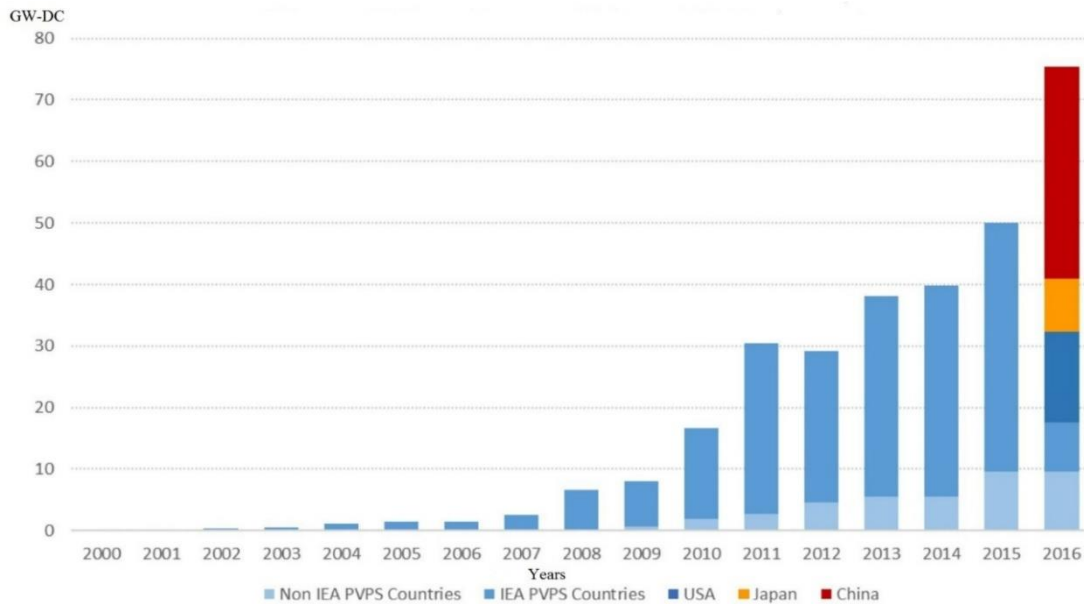


Figure 1.5 PV installation growth around the world.

There has been an enormous amount of PV installations done in the last 10 years. Their energy production was linked with central electrical grid and distributed. This energy source is clean and sustainable.

1.1.2 The sun

Our solar system is built up with only with one star named Sun, the ultimate energy source. This source of energy is the main reason for life on this planet Earth. It is important to know about the sun and its internal energy to comprehend the precise knowledge of solar energy.

The mass of the Sun is 1.99×10^{30} kg, and its radius is 6.96×10^8 m. Until now, it is not possible to access its internal information directly. Based on the theoretical information and analysis of the solar surface it is assumed that the interior temperature is about 15 million kelvins. Every moment it is producing energy by burning different elements it contains. It consists of hydrogen (~73%), helium (~25%) and rest of the part is oxygen, carbon, neon, and iron. The birth of the Sun is thought to be about 4.5 billion years ago, and it has a vast amount of fuel which can be used for

another 5 billion years. The source of its fuel is hydrogen and helium gases [Chen11]. In the core, two isotopes, named Tritium and Deuterium, collide with each other under a massive amount of heat. In this process, a new molecule is formed, named Helium, and an enormous amount of energy is released in the form of heat and light. It travels from the core to the sun surface which is called photosphere. After the photosphere, there exists the Sun's atmosphere, called chromosphere. This layer absorbs a few colors of the radiation emitted from the photosphere [Wieder92, Chen11].

The energy is produced and release every single moment. Because of relatively transparent nature of chromosphere, its effect is being ignored to calculate solar radiation. The spectrum of solar radiation is counting by the thermal and optical properties of the solar surface. Typically, it is considered that the Sun behaves like a black body whose temperature is consistent at around 6000 K [Wieder92, Chen11].

Solar energy comes to the Earth being the primary source of life of all living elements. Thermal energy keeps the planet warm and helps the plants to do photosynthesis. There is lots of fossil fuel because of the photosynthesis, where plants convert the solar energy to chemical energy. The flow of wind and water depends on the thermal energy of it. In the ecosystem, solar radiation is an essential part to continue the process. The burning Sun is shown in the Figure 1.6 [Sunnymorgan16, ESA17].

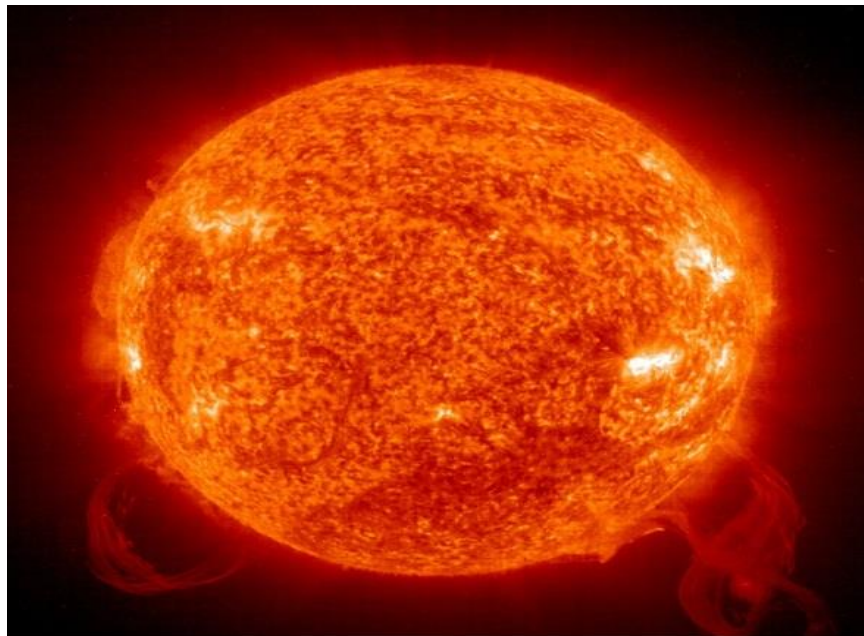


Figure 1.6 The burning Sun.

The radiation from the Sun travels to the Earth as electromagnetic waves without any medium. The power density of average solar radiation outside the atmosphere is 1366W/m^2 . The annual solar energy the Earth gets is around $5.46 \times 10^{24}\text{J}$ [Chen11].

Among the total solar radiation which comes to the Earth, 30% is reflected and back to space, 20% is absorbed by the clouds and air molecules and rest reaches the Earth's surface. However, a majority part of the Earth consists of water, where only 10% radiation is utilizable. Even though only 0.1% percent of it is enough to supply the energy to entire world [Chen11], so a huge amount of solar resource is available all over the world.

On the Earth's land, the solar radiation is not equally distributed. Someplace have a vast amount of solar power, and others have very less. Figure 1.7 presents the average distribution insolation of solar radiation through the Earth [Altestore17].

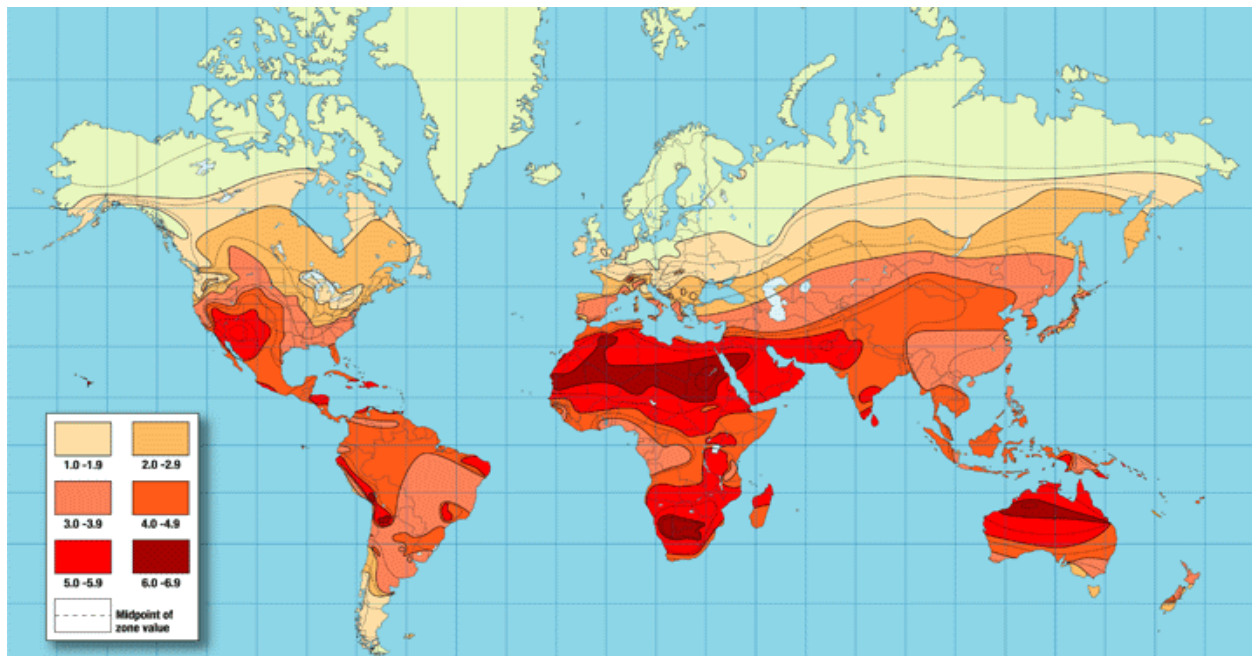


Figure 1.7 World map of insolation.

It is observed that Earth has been divided into six zones depending on the average amount of solar radiation over a year on a surface of 1 m^2 (in kilojoules) [Chen11]. From the world map, there are some places which can generate a tremendous amount of energy from solar irradiation; in Europe, Portugal is one of the places which gets more solar irradiance. The condition in Portugal is perfect

for producing an enormous amount of energy from irradiation for its geographical position; it does not have very high temperatures but has sufficient amount of sun light. This situation makes Portugal a splendid place for utilizing solar energy.

1.2 Motivation

Imagining our life without energy is becoming quite impossible due to the reliance on technologies. Future development of technology and civilization is depending on the development of energy. This civilization is based on electrical and electronics equipment and without energy these components are useless. World energy consumption is shown in the Figure 1.8 [EIA17] It depicts the present state and future prediction till 2040 of energy. The red part represents the non-OECD (non-Organization for Economic Co-operation and Development) member countries and grey part represents OECD (Organization for Economic Co-operation and Development) member countries.

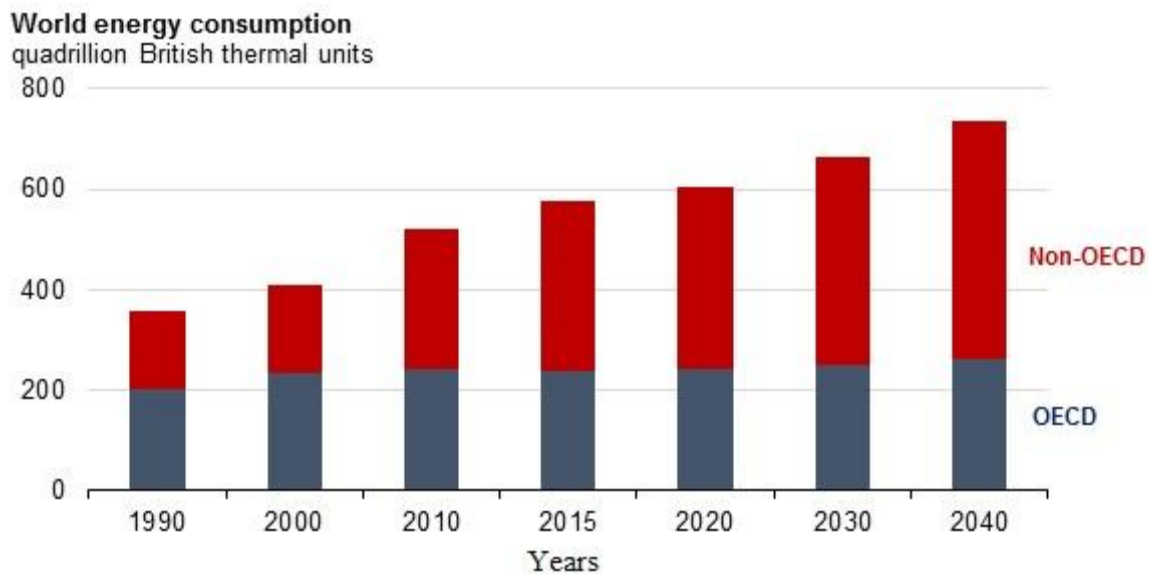


Figure 1.8 World energy consumption.

From the Figure 1.8, it is viewed that the non-OECD countries need more energy than OECD countries. Non-OECD countries include China and India; these two countries are using massive amounts of energy to grow their industries and its productions. All over the world the energy

demand is growing and, on the other side, people are trying to decrease the use of fossil fuel. Fossil fuel in power conversion systems is identified as a threat to the world atmosphere [EIA17, UN16].

Figure 1.9 presents the consumption prediction increase until 2040 for different energy sources. Energy sources like gas, oil, coal etc. will finish due to their limited quantity. On the other hand, renewable energy sources like wind, solar and hydro energy are abundant [EIA14a, EIA14b, EIA17].

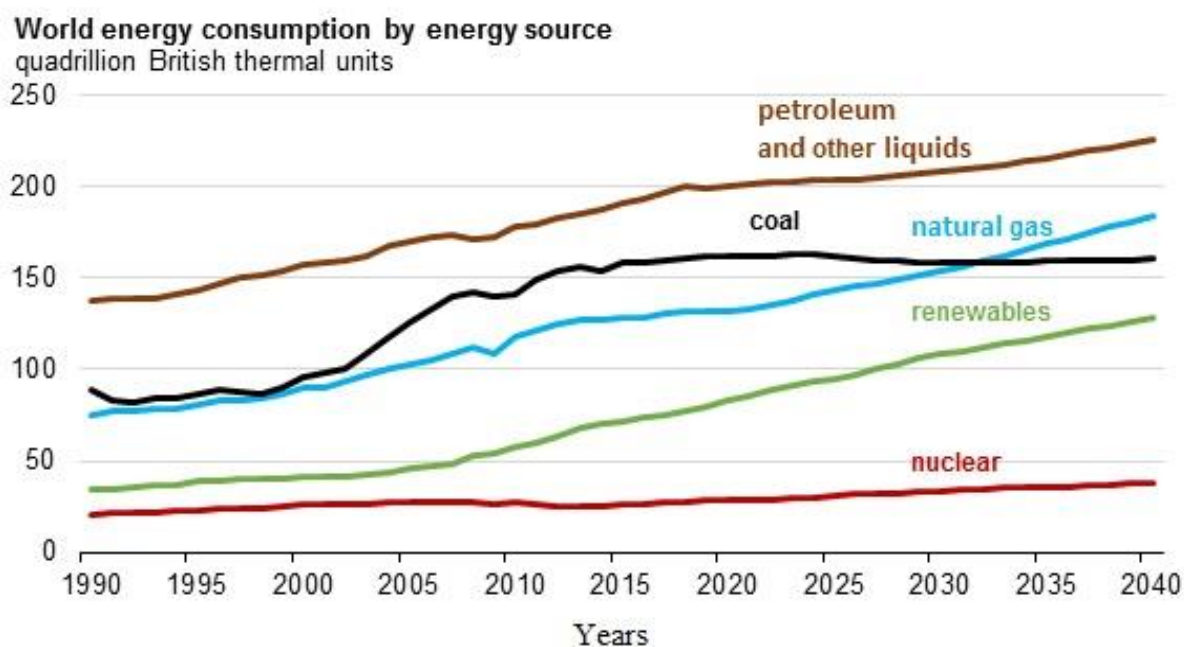


Figure 1.9 World energy consumption by energy source prediction till 2040.

Fossil fuels have more consumption than any other sources. But it has critical impacts on atmosphere and generates CO₂ and other harmful components. These gases have negative impact and cause global warming. People are willing to leave the sources of energy that have negative impacts. All are trying to develop sustainable energy.

Renewable sources are sustainable and helpful for developing sustainable system. According to working principle, PV is one of the technologies that utilize the solar energy and have not generated any damaging elements during lifetime working period. It is now cheap in production and maintaining cost is low.

For increasing energy conversion efficiency, the key areas are:

1. Explore materials for improving of PV cell efficiency (Different kind of semiconductors and other materials);
2. Power conditioner technologies (DC/AC and DC/DC converters, MPPT Devices);
3. Healthy surrounding conditions for the system (Dust, human-created shadow).

Focusing on the increasing efficiency, researchers all over the world are working on these three vital areas. All kinds of photovoltaics technologies are operating with solar energy and have the same working principle. Due to lack of system knowledge, poor maintenance and environmental effect, the performance of a PV panel decreases a lot. If the system is not maintained properly, then the output quality will decline gradually.

Analysis through the present PV power conversion system, it is identified that due to lack of maintenance its performance declines [Rashel18b]. Also surrounding parameters have a noteworthy effect on it. Maintaining surrounding conditions improves the performance [Rashel18a]. Shadow of obstacles on PV surface like dust and shadow are two significant detrimental elements that decrease its efficiency. Classification and identification of the obstacles type and magnitude is important to identify the problem that occurs to PV panel and also acquire information about the fault in real-time.

Prediction of photovoltaics power conversion system's output has full dependency on environmental parameters. Identification of the behavior under different environmental conditions assist to predict future production and that's helpful to enrich knowledge of smart grid (SG) system.

These are the motivation for the dissertation, to get appropriately the maximum output from the PV system, predict system's output in advance and also to identify the fault. This identified knowledge will enrich the SG to design a load balancing system that would more efficient than existing system.

1.3 Objectives

Important tasks of this work is to understand the single diode five parameters PV cell model, namely their sensitivity of internal and environmental parameters. Also environmental effects on

the PV power conversion rate. Another objective is to classify the obstacles of PV panel in real-time aiming to identify different types of fault. Precise modeling of the PV conversion system could give rise to prediction model with more accurate results. PV is nonlinear in nature with dependency on environmental parameters which shows complex behavior. These effects are observed and identified by computational simulation and experimental work. Also work has done to get results for non-constant load effect on it. Objectives of this work is given below:

The work's first objective is to create an error function that analyses the sensitivity of different internal parameters. By constructing the error function, a computational model is created for understanding different internal parameters and simulated their behaviors. This model is observed under varying parameter values that simulate different conditions of the model. This is done to understand internal parameters' sensitivity.

Secondly, the error function is used to identify the sensitivity of environmental parameters and a model can be built for the same PV model under different environmental conditions. Correlation between environmental parameters must also be analyzed to understand the affiliation between them.

Thirdly, to understand the non-constant load effect on PV power conversion, PV panels are put under different load experimentally. A signal generator is used to generate the desire signal (RAMP signal) and the Matlab environment is used to collect the data from the real-time system. This data is used to analyze voltage and current behavior that is acquire from the PV panel with other instrumentations (DAQ and GPIB).

At the end, the obstacles are classified and its influence on PV panels is analyzed. Obstacles are something that interrupt the sunlight to reach its surface; a simulation model is used to categorize and recognize different types of shadow of obstacles. This simulation gives valuable information about faults on the surface that reduce the panels' performance. Identifying the problem enriches and helps to solve fault of the system and improve the productivity.

All these computational simulation and physical models are created to analyze PV under different conditions and its power conversion efficiency under different situations. This bottom-up approach

will give hints to create better PV models under distinctive situations that integrate with smart grid (SG).

1.4 State of the Art

Energy, renewable energy and climate

In December 2015, 195 countries gathered together in the Paris climate conference [COP2115] agreed to set a goal to limit the global warming below 2⁰C. Almost all governments from all over the world were united in the decision to keep the temperature level low, reduce the emissions of harmful gases and help each other to reach the common goals using the available science and technology. Developing countries will get continuous support from the EU and other developed countries for tackling the climate change effects. It was a historical agreement for the world to save the environment and develop a sustainable climate. Renewable energy sources have a huge role to reach this goal [UN16].

Bozkurt et al. [Bozkurt10] states that there is no energy resource that is risk free. For choosing a source of energy, it is important to keep in mind environmental effects and cost issues. Renewable energies are the solution and can help reverse the global warming.

In [Omer11, Mitoula11] discuss renewable energy and sustainable development environmental issues from the perspectives of past, present and future. Different renewable energies like solar, biomass, wind, geothermal etc. are discussed from the economic and environmental point of view. At the end of this work concern is shown about temperature rising caused by different greenhouse gases.

The works of [Dresner08, Dincer12, Heshmati15] introduce the concept of sustainable engineering, a new type of engineering branch that designs, develops and encourages sustainable energy production systems. They discuss about different sources of energy like solar energy, geothermal energy, biomass, natural gases, petroleum, coal, nuclear energy etc. and briefly discuss the effect of energy efficiency.

Demirel et al. [Demirel16] divided the sources of energy between primary and secondary energy sources. Primary sources are available in environment and are fulfilled from the nature; secondary sources are derived from primary sources. This deriving processes generate harmful components, or the process itself could be harmful. It also briefly gives evidence of various implication of the energy effects on the environment.

In [Kverndokk94, Nada14, BP17], the details of the energy consumption are shown with latest status about oil, natural gas, coal, nuclear energy, hydroelectricity, renewable energy, electricity, carbon dioxide. The report shows world's and regions carbon emission rate.

In [Shell97, Zeman14] the scenario for diversification of energy source is given for the 21st century and gives brief status of the electricity generation and consumption at different levels.

[IEA14a, IEA14b] report a brief overview of the present state of the energy and the total production from different sources of energy and the consumption; graphical and numerical data are availed on the reports.

[WEC16] reports details about technologies, economics and markets, socio-economics and environmental impacts about energy sources (coal, oil, natural gas, uranium and nuclear, hydropower, bioengineering, waste to energy, solar, geothermal, wind and marine). It also discusses carbon capture and storage, e-storage giving detailed status about different countries and their production related to different energy sources. The report shows the importance of solar energy: its growth, the cost-benefit analysis and the impact over the environment.

The future of renewable energy and their statistical analysis is given in [REN16] and the production of CO₂ from fossil fuel and the importance of renewable energy to make sustainable world is also discussed in [Isoaho16].

Smart grid and PV system

In [Phuangpornpitaka13] a description of how renewable energy could connect with smart grid and an indication about the work that should have been done to make a stable smart grid connecting with renewable energy is presented. PV power conversion is nonlinear and to connect with SG an

improvement of computational tools and other hardware component like huge power storage is needed.

[Gomes16] describes how wind and PV system can integrate with central grid system. showing the reduction of risk factor when the two systems work together to supply electricity to SG. It also discusses about electricity marketplace.

Viegas et al. [Viegas15] tries to predict the electricity load profile mainly for residential areas. The outcome from this work helps market policy makers to get estimation about the total load of the consumers assisting to design load balance model integration of renewable energy power with central grid.

[Net110, Gharavi11] describe how the society and world can benefit from the smart grid. This is important to make a balance between demand and supply; it also helps to reduce the price of the electricity and is one of the solutions to integrate all sources of electricity and make a good plan for an efficient supply and distribution process.

[Kaur15, Benabdallah17] give details about the challenges to integrate PV systems with SG. One important part is to make the prediction of PV power generation more precise; though lots of work is going on related to this, more work needs to be done to predict the PV power generation. They also suggest to improve and establish integrated energy storage system to efficient connection between PV plants and SG.

[Mekkaoui17, Shafiullah13] describe the model and simulation for integrating smart grid with solar plant and wind farm. The model is built with Simulink. Gives idea about smart house system. It shows the PV modeling and importance of a good modeling to predict the PV power for future.

Prakesh et al. [Prakesh17] describe different methods for forecasting PV power in the ground for grid system. It gives details about why prediction of PV is needed for the SG for optimize the load and balancing system. Introduce prediction algorithm like; artificial neural network, hybrid models.

Saleem et al. [Saleem17] in one of the recent work, describes the SG integrate with internet of things (IoT) to make communication with energy sources and with energy consumer for efficient

energy distribution. IoT is combination of sensors that collect information from different end and then central SG system analyses the total scenario based on the information it gives.

Rauf et al. [Rauf17] gives detail method about PV generation integrates with SG introducing the DC-AC hybrid grid system and also describe battery storage system.

In [Meena14, Wan15] show the integrated system between the rooftop PV and SG. This system generates electricity in efficient way and it possible to financially benefited as a house owner. They also developed a forecasting system that predict solar power generation.

In [Kempener13, Elzinga15] is described the SG as solution for the future electric system. When renewable sources and distribute electricity is connected with central system and can efficiently do the load balancing. Forecasting is important for this system. In [IEA11] report describes the details about the deployment and structure of SG with renewable energies.

In [Fialho14a, Fialho14e, Fialho15a, Fialho15b, Fialho15c, Fialho15d] describe different methods for connecting PV with smart grid system and also about control method. These works describe method to integrate SG with PV plat through DC-DC boost converter and two-level converter. Also describe three level inverter. Fialho et al. [Fialho15c] shows the way to connect the Poly-Si PV system with the central grid. It introduces the fuzzy controller to control the converter and connected with SG in efficient way.

Batista et al. [Batista14] describe an architecture in secure and reliable method to connect with smart grid. It also introduces ZigBee technology for communication between renewable generation with SG in secure way.

Different technologies of PV

Gangopadhyay et al. [Gangopadhyay13] give the detail description about different existing technologies of PV materials. It shows that the price decreased very rapidly because of finding usability of using different cheap materials.

Zeman et al. [Zeman10] describe the thin film technology based on silicon materials. It includes description about the structure and characteristics of amorphous and crystalline silicon thin film and also the photon management inside cell to increase the performance.

Tamirat et al. [Tamirat17] describe the nanotechnology with semiconductor solar cells. The existing technology with nanotechnology, together they are improving the performance by using more solar radiation.

Parida et al. [Parida11] describe different PV technologies, named amorphous silicon, crystalline silicon, cadmium telluride, organic cell, polymer cell, hybrid cell, thin film PV cells.

Kalkman et al. [Kalkman18] state three promising technologies of PV named perovskite, quantum-dots and concentrated photovoltaics. It mentions that crystalline silicon PV is the dominant technology in the market, and it has high efficiency than maximum available technologies.

In [Hudedmani17, Sharma15] describe different type of materials that are using to do research to find future materials for manufacturing efficient PV with low cost.

Rwenyagila et al. [Rwenyagila17] discuss about organics PV cell, their structure and working process. In [Chu11, Smets16] describe review for different type of solar energy technologies and their cons and pros.

Candelise et al. [Candelise11] describes the new type of PV technologies like; Cadmium Telluride, Copper Indium Gallium Selenide TF technologies. Mainly these materials are exploring because of low cost and availability.

Modeling of PV cell

Kalogirou et al. [Kalogirou09] discuss about the importance of solar energy at the introduction chapter. The book has total overview about the solar energy and its different technologies. It describes detail modeling and characteristics of PV cell and panel.

In [Vergura16] states a way to model a PV cell that only depend on manufacturer datasheet values. It describes two PV models; one is with five parameters in a standard one and another one is a simplified model that has not include the shunt resistance. Ahmed et al. [Ahmed16] describe

different parameters and their variation effect on PV model, that is important to get vital information about the parameters sensitivity.

Tayyan [Tayyan11, Tayyan13] describes to get I-V and P-V characteristics from five parameters single diode PV model based on the datasheet values. This work gets five parameters value after solving five equations and using datasheet. Different test condition is described under changing irradiation and temperature.

Aoun et al. [Aoun14] show a model using five parameters named; photocurrent, dark saturation current, series resistance, shunt resistance and diode ideality factor. This model also created based on datasheet parameters like [Tayyan13]. This model is tested under real environmental conditions and under simulation. Simulation value has very good accuracy with real scenarios.

Lineykin et al. [Lineykin12] describe a PV cell model building from single diode with seven parameters values, named; the photocurrent, the reverse bias saturation current, the ideality factor, the series resistance, the shunt resistance, the bandgap energy, and the temperature coefficient of the photo-generating current.

Chatterjee et al. [Chatterjee11] describe the PV model for a cell, string model, array model using the datasheet values provided by manufacturer. Matlab is used for simulation of different scenarios model.

Fialho et al. [Fialho14d, Fialho15d, Fialho15e] describes method of the five parameters of PV cell model. In [Fialho15d] describes the parameters extraction procedure using a heuristic method. It gives detail method that connects PV system with grid system. Its included the partial shading condition in the simulation model. In [Fialho15e] describes model that is built on the basis of monocrystalline PV cell's characteristics.

Bikaneria et al. [Bikaneria13] describe one-diode model and simulate that using different values of different parameters of the model. Saraiva et al. [Saraiva12] describes monocrystalline PV cell model for equivalent circuit model. It introduces iteration process to find values of series resistance, shunt resistance and diode ideality factor.

Bonkougou et al. [Bonkougou13] find parameters value of a single diode five parameter model using Newton Raphson's method. The values that they get from the iterative method is validated by the values provided from manufacturer datasheet.

Cubas et al. [Cubas13] describe an analytical method to get parameters' value of five parameters circuit model. Pereira et al. [Pereira14] focus on five parameters PV model, consisting on a current controlled generator. They derive details PV Simulink model that is approximate model for the real seniors one.

Sera et al. [Sera07] describes a model, it is constructed from the given manufacturer datasheet values. This model includes the series and shunt resistance in the cell model. It is tested under different irradiance and temperature conditions.

Rodrigues et al. [Rodrigues11] derive the single diode PV cell model and has done simulation with temperature, solar irradiance, series resistance and ideality factor. It compares ideal diode model with their constructed model.

Masmoudi et al. [Masmoudi16] describe single diode and double diode models for mono-crystalline PV cell. Proposed model's derived values are compared with datasheet values of the real PV cell. The simulation is created using Matlab environment. Ghani et al. [Ghani14] give a numerical process for calculating the values for single diode PV cell model.

Chenni et al. [Chenni07] describe details method for PV cell modeling and include irradiance, series resistance and temperature variation to see their effect on the model. Datasheet values are used to evaluated the model under changing irradiance and temperature. Also shows effect of parallel and series connections of cells.

Environmental effects on PV power conversion

In [Wieder92, Zeman10, Kalogirou09] give clear idea about the sun and its behavior with changing the Sun's position and time. Position of the Sun is always changed with the seasons around the year. The irradiation varies region to region based on their geographical. In their text, they describe annual motion of the earth around the Sun.

Gokmen et al. [Gokmen16] show the wind speed effect on PV panels. It examines the relationship between wind speed and tilt angles to get maximum output. Wind speed cool the PV modules and increase the performance. The tilt angle is not similar during the whole year; it changes time to time to get better performance.

Dubey et al. [Dubey13] show that operating temperature is a key parameter of PV that is important to get maximum from the PV power conversion. They find temperature has linear relation with PV power conversion rate.

Arjyadhara et al. [Arjyadhara13] state a detail analysis about the PV cell performance under changing irradiance and temperature. They conclude that with increasing temperature the photon generation rate increases and reverse saturation current also increases fast that reduce the band gap. Katz et al. [Katz01] describe temperature and irradiance effect on polymer solar cell. They state temperature as a negative factor for the PV performance.

Salim et al. [Salim13] shows a practical simulation for irradiance effect to the PV performance. In their work, they test performance of Solara-130 PV module with different irradiance using solar model tester.

Bhattacharya et al. [Bhattacharya14] describe the effects of wind speed and ambient temperature on the performance of monocrystalline PV. They collect information from real environment and analysis them to get the effects from those factors.

Islam et al. [Islam14] show that different internal parameters of PV changes with changing value of irradiance. They show how series and shunt resistance change with changing irradiation.

Singla et al. [Singla16] state that PV performance is not only dependent on the internal parameter of PV, it is also strongly connected with environmental variables. Shadow have great impact on PV and it decrease the performance of PV power generation.

Darwish et al. [Darwish13] describes about different environmental parameters named; humidity, irradiation, air population with dust in the ground of PV panel performance. The paper gives clear evidence that dust have significant effect on PV power conversion and decreases its performance.

In [Homadi16] show that the elevation has effect on PV performance with other environmental parameters named; irradiance and temperature. Huld et al. [Huld15] describe PV module performance under changing irradiance, air temperature and wind speed. This paper gives clear idea that PV power conversion dependent on these environmental factors.

Schwingshackla et al. [Schwingshackla13] show how wind effect the PV module's cell temperature. It states different techniques to estimate the PV performance based on wind speed prediction. They use ECMWF for weather parameters prediction and get better performance in prediction than standard approach.

Nordmann et al. [Nordmann03] give data analysis for different PV plants and shows temperature is a significant factor for PV module performance. To make airflow through modules that decrease temperature of it and increase the performance.

Fesharak et al. [Fesharaki11] state temperature effects on the PV efficiency and it shows that the PV power generation efficiency and temperature has linear relationship. Lay-Ekuakille et al. [Lay-Ekuakille13] describe CdTe and CIS PV modules performance with different environmental parameters. It states the performance curve with temperature, ambient temperature, humidity and irradiance.

Load analysis with PV

Kuai et al. [Kuai05] state the load analysis for PV. Describes a method to quick scanning the load of a PV in field condition to get maximum power. It describes PV output as nonlinear nature and is needed for PV to scan the load fast to maximize the power conversion.

In [Hategekimana17] describes the load as an important factor for PV power management. In standalone system, during less load condition and high production of PV, has power loss. On the other hand, in the reverse situation the system needs power but PV has less generation. PV connected with grid is a balance system that is the way to reduce the power loss and also connected with battery storage could reduce the loss of the system.

Bataineh et al. [Bataineh12] describe a stand-alone PV system with converter and battery for a remote area in Jordan. It states that load analysis is important to design the PV system with controller and battery.

Zerhouni et al. [Zerhouni10] describe the optimized system for PV at processing state under changing weather situation. In changing weather condition load is changing depending on the environmental condition. In hot or cold weather people use air conditioner to control the air temperature and it increase the load. They state load as an important factor that needed to make an optimized system.

Shadow of obstacle effect on PV power conversion

In this work, different types of shadow effects, dust effect is given a generalized name obstacle. In this section, different obstacles reviews are given.

Mohamed et al. [Mohamed12] state PV performance under different types of dust in Libya. It gives details performance overview of PV under clean and dust environment. The dust on PV surface decreases performance a lot. Piazza et al. [Piazza10] design a simulator under partial and dynamic shadow condition, that simulates the shading effect of PV.

In [Saluos15] describe different types of shadow in form of dust. There are different types of dust in the environment and those are not clearly identified. Dust reduces the PV performance in rustically.

Wang et al. [Wang12] give details about shadow and partial shadowing condition and proposed an architecture for get better efficiency under these conditions. Develop a hybrid method to get better performance in such condition.

Wang et al. [Wang17] describe dust effect on PV modules. They got a relation between dust deposition on PV and the sunlight transmit in that condition. They also include the incident radiation with tilt angle.

Nguyen et al. [Nguyen08] propose an architecture for adaptive reconfiguration scheme in the ground of reducing shadow effect on the PV. The new architecture is a switching technique due to shadow to improve performance.

Zaihidee et al. [Zaihidee16] show the deposition density of dust is related with PV power conversion rate. Low dense dust has low effect and high dense dust have high effect on the PV performance, it reduces more solar radiation to reach to the surface. For dust the PV module gets more temperature.

Haoyuan et al. [Haoyuan15] state the dynamic shadow simulation in Matlab environment. In lab it performs experiment for validate the model.

Casanova et al. [Casanova11] give details about the dust that became an obstacle on the PV surface that reduce the radiation and change the incident angle of the Sun ray. It shows due to dust on the module it loss 4.4% of energy in daily basis.

Fialho et al. [Fialho14b, Fialho14c] state the shadow effect on a series solar modules of monocrystalline silicon PV modules. In simulation it shows that this effect makes the performance low and gives several peaks in the voltage-power curves and in this way misguide the maximum power point tracking (MPPT) system to get the global maxima. Fialho et al. [Fialho14d] simulate partial shading with five parameters single diode PV model. They validate the simulation result with real-time data.

Anjos et al. [Anjos17] simulate the hot-spot using crystalline silicon PV module and it is under shadow on the module. It describes the conditions under fully shaded or some cells under shaded condition. They simulate hot-spot condition when the cells are without bypass diode. Ibrahim et al. [Ibrahim11] describe indoor measurement system for making experiment to understand the dust effect. They use silicon solar cells for the experiment.

In [Francisco15] state the solar PV cell's performance under shadow effect. It describes that PV power conversion is strongly related with weather and ambient parameters and has strong relation with seasonal environment. Also states that shadow makes the PV output more uncertain to predict the power conversion rate.

Mani et al. [Mani10] describe the review about the dust impact on PV system. Regular cleaning of the PV is a way to improve the performance and it is the way to keep the efficiency high.

Alam et al. [Alam12] analyze the dynamic shadow effect for both diffuse and direct radiation. They observe the shadow from the aspect of city area and analyzes different kind of shadow on PV. 3D city model is used to analyze different type of properties that causes the shadow. Romano et al. [Romano13] discuss about shadow effect and introduced a switching matrix technique to make the system more efficient under shadowing condition.

Gao et al. [Gao09] discuss about portable PV power system and include the rapid change environmental condition, that includes the shadow condition also. Parallel connection of cells give better performance in rapidly changing condition for PV power conversion.

Nguyen et al. [Nguyen12] discuss potential of Photovoltaics in urban area and states the losses due to shading effect. They used GRASS and Scilab software for modeling the scenarios.

Menoufi [Menoufi17] give details about the dust accumulation on the surface of the PV and introduce photovoltaic soiling index, that states the health condition of PV under different type of situation. Storey et al. [Storey13] show the relation between number of cell of PV under shadow effect. They used Matlab for making simulation of the behavior.

1.5 Organization of the Dissertation

This dissertation is completed with four chapters, including this one. This section gives the organization of each chapter.

Chapter 1 describes the introductory literature with other important point ideas to make the dissertation. It contains motivations, objectives, state of the art and at the end, this section that gives the organization of the dissertation.

Chapter 2 introduces the fundamental theory and the mathematical formulation of PV model. It starts by describing the solar radiation spectrum that is the primary source of PV energy. Next, the photovoltaics (PV) working mechanism is introduced. It gives brief details about semiconductor and diode, then it describes the working principle of PV and the characterization of the PV using the single diode five parameters PV cell model and also its mathematical formulation is given. The error function is introduced with a mathematical formulation that identifies the sensitivity of

different internal and environmental parameters; the basic of the non-constant load are described. Measurement and instrumentation system is introduced. Finally, obstacles theory is introduced to understand different types of shadow or dust on PV and methods and simulation techniques are described at the end part of the chapter.

Chapter 3 presents the results of this work and includes different case studies. Each case study has a particular identification on behalf of PV modeling. These results are significant for increasing the efficiency of the PV conversion system; this is also important for smart grid systems. The first case study is about internal parameters behavior and sensitivity; the second case study is about environmental parameters sensitivity; then environmental effects to PV output are also analyzed and correlation between environmental parameters also included. The third case study is about non-constant load where significant behavior of the non-constant load is analyzed using laboratory experiments. The last case study is about the shadow of obstacles on PV; in this part different simulation model are constructed to identify the behavior.

Chapter 4 depicts the conclusions of this work. It describes the contributions and includes the list of the publication related to this dissertation. At the end, it gives the guideline principle for the future work.

1.6 Notations

Every chapter of this thesis uses the most common notation. Mathematical expressions, tables and figures are given with their right reference. They are presented and numbered sequentially with respected chapter. Numbering is restarted for each new chapter. Mathematical expressions are identified using curved parentheses, (). The identification of references are done using brackets, [].

CHAPTER

2

Fundamental Theory

In this chapter, it presents the theoretical foundations followed by the modeling of the photovoltaic panel with other required theories to understand the work. It describes the theoretical concepts that are used in this work. Starting from the knowledge about solar radiation which is the fundamental element and source to generate electric energy from PV and heat from concentrated solar system, the theory of ideal diode and its characteristics are briefly described. The single diode five parameter PV cell model is introduced and its analytical solution is derived. The error function is fully described in next section to understand the internal parameters of PV model. Environmental parameters are discussed and different sensors used to collect these parameters are introduced. Concepts for load and non-constant load are given to understand their effect on PV. Then, the obstacle theory on behalf of PV is discussed it is developed to understand different types of fault in PV panel in real-time. Methods for this work are described in detail for Matlab and Simulink. Details of different measurements and instrumentation systems are recited.

2.1 Introduction

The rapid advancement in technologies creates vast demands for energy. There is a significant relation between energy consumption and economic growth. Energy creates the opportunities to produce different kinds of new businesses; that keeps further growth of the economy. In the year 1973, the growing energy crisis made people think about new kinds of energy sources. This is vital to ensure securing power supply and an obligation to protect the environment in the process of energy production.

Last one hundred years, because of consuming huge energy considered necessary for advancement in technology, creates momentous amount of damage of climate. To mitigate the effect of climate change, it is essential to produce clean and green energy. There are harmful gases that are generated at the time of producing power. Earlier; the main sources of energy were from fossil fuel. It becomes very urgent to reduce the consumption of fossil fuel, this emerge search for new sources that is available and clean. The resurgence of renewable energies has motivated many countries to research and development in this sustainable future.

Solar energy is a source of renewable energy that is available all over the world. In advanced research of solar energy, there are two types of technologies, named solar thermal and solar electricity. Solar thermal energy is the system for generating thermal energy for industry and household works. Solar electricity production has two sections, named concentrated solar power (CSP) and Photovoltaics (PV). CSP uses the sunlight to generate high temperature and, from that it generates electricity and heat. Photovoltaics is a simple device based on the photo effect [Einstein1905], it directly generates electricity from sunlight. Last few years, due to large amount of research work, PV becomes one of the cheap renewable sources. Its efficiency also has improved a lot. For standalone system, this is an ideal source of energy due to portability.

At present, PV power conversion system has improved a lot. Its price also becomes less that is affordable by masses. It has changed quality of rural people's life. PV is eradicating poverty through supplying electricity. Among all other renewable sources of energy, because of portability

it gets more attention in remote areas. It is easy to establish a standalone system for a house or a school. There are rural and remote areas without electricity, they need it to grow their economy.

PV panel shows increasing high efficiency at laboratory standard test conditions. In real-time environmental condition, power conversion rate is decreased a lot and not stable. It varies with environmental parameters variation. PV plants are connected with central grid. The grid system becomes smart grid with different kind of intelligent programs and smart sensors. This smart grid handles the load balancing in efficient way, that helps to build sustainable energy production system.

It is needed to understand PV power conversion system profoundly to predict future power production. It is also needed to understand model of PV internal configuration. It is necessary to get internal acquaintance about relation between environment and PV. Nonlinear behavior of environmental factors makes it nonlinear and it becomes default to predict the future power generation from it. Forecasting environmental parameters early helps to predict the PV output.

Modeling of PV panel is a continuing research process to make an improved indulgent to get enhanced approximate of it power generation. It becomes imperative to predict PV output with better model.

2.2 Solar Radiation Spectrum

The sun is the source of primary energy for the planet earth. This energy comes in the form of electromagnetic waves of a broad spectrum. In the spectrum, shorter wavelength has more energy than longer wavelength once. The sunlight passes through the atmosphere and interacts with different elements of the atmosphere, some part of them are absorbed, and some are scattered. The higher the thickness of the atmosphere, the more is the attenuation of the light. In the solar energy and PV field, the air mass expresses as AM. The air mass is the path distance for the light from the solar ray source to pass through the atmosphere. Outside of the atmosphere where the free space exists is named an air mass zero (AM0). Air mass coefficient is calculated as [Würfel05].

$$AM = \frac{L}{L_0} = \frac{1}{\cos z} \quad (2.1)$$

where L is the total path span through the atmosphere, L_0 is the zenith path span at the sea level, and z is the zenith angle (measured at degree) [Würfel05].

Spectral irradiance of the solar radiation with different wavelengths is shown in Figure 2.1 [Pvlighthouse17].

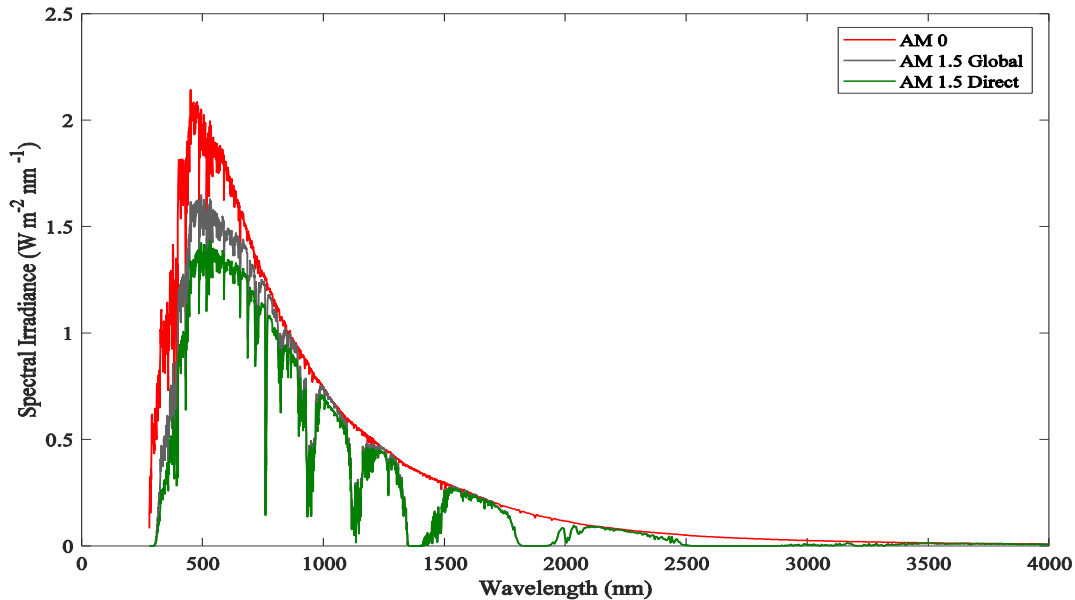


Figure 2.1 Spectral irradiance of the solar radiation with different wavelengths.

In Figure 2.1 spectral irradiance is given with different wavelength to view their spectral analysis. The drawn figure is getting from the data under different air mass at standard value ASTM G173-03 Reference Spectra Derived from SMARTS v. 2.9.2. AM0 is on the outer surface of the atmosphere where there are no elements to collision with, and the spectrum irradiance has the highest level of radiation in every wavelength. AM1.5 global tilted spectral irradiance, and AM1.5 direct is direct normal irradiance. Standard spectral irradiance with wavelengths is shown in Figure 2.2 [Pvlighthouse17].

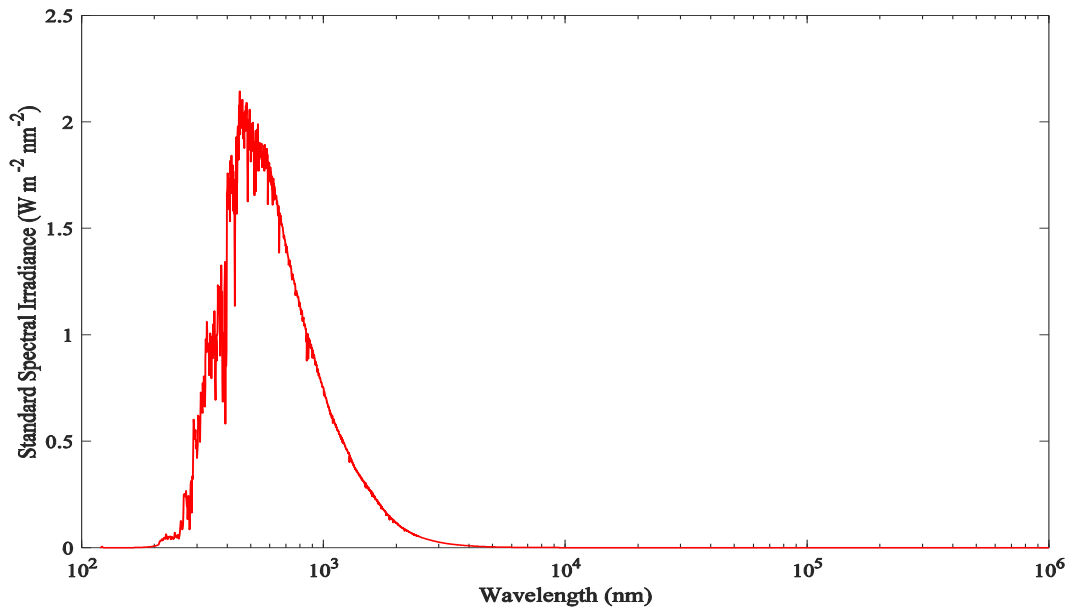


Figure 2.2 Standard spectral irradiance with wavelengths.

In Figure 2.2 standard spectral irradiance is drawn with a different wavelength. This data got through the ASTM E-490 AM0 Standard Spectra.

2.3 Semiconductor

Usually PV panels are made of semiconductors. Hence it is necessary to know about the semiconductors and their properties. Molecules are composed of atoms. Inside an atom, there is a nucleus that has protons and neutrons and, outside of nucleus there are electrons. The number of this elements are based on the material properties. In isolation atom, electrons could have only specific quantized or discrete energy level.

In molecules, electrons are organized in orbitals. Innermost orbital electron needs more energy to make free than outer orbitals once. Electrons of the outer shell are mainly responsible for interaction with other atoms. Outer most shell electrons are called valence electron and the band associated with them is called valance band. These are loosely attached to the nuclei of the atoms. If energy is given from outside, valance band's electrons acquire energy. If the energy is sufficient, the electrons jump from valence to the higher band named conduction band. The electrons of the conduction band are responsible for generation of heat and electricity. In conduction band

electrons are free to move. The energy difference of an electron at valence band and at the conduction band's innermost shell is called band gap.

There are three types of materials named insulator, conductor, and semiconductor. Insulator has wider band gap than any other type of materials. The band gap in materials is more than 3eV . In conductor materials, there is no band gap, valence and conduction band overlap with each other. Diagrams of different energy bands for conventional materials [Kalogirou09, Zeman10, Zeman14, Hu09] is shown in Figure 2.3.

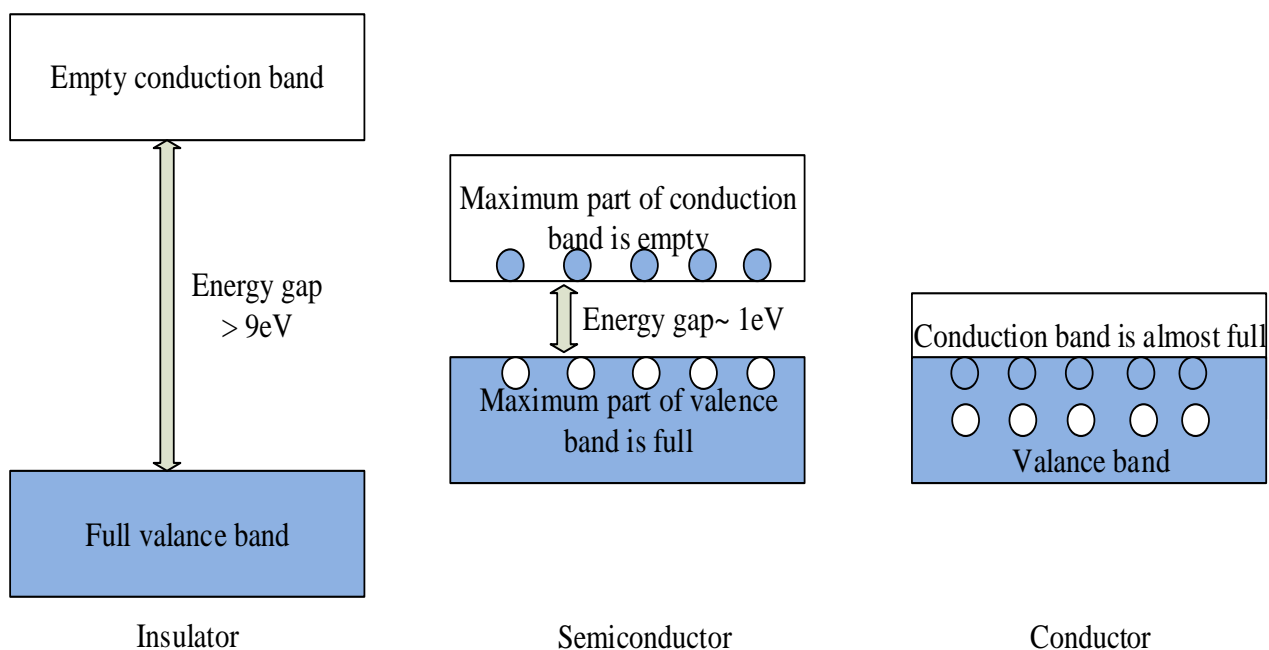


Figure 2.3 Diagrams of different energy bands for conventional materials. (a)Insulator (b)conductor (c)semiconductor.

Semiconductors have less band gap than 3eV . Semiconductor associations have few properties like metals and few characteristics from insulators. This recombination of different essential properties from metal and insulator, makes the semiconductor a particular kind of material.

There are two types of semiconductors; named as:

- Intrinsic semiconductor.
- Extrinsic semiconductor.

2.3.1 Intrinsic semiconductor

Intrinsic semiconductors have no impurity. This is a pure form of semiconductors, and they are chemically pure and undoped. The number of excited electrons is equal with the number of holes in it. Pure silicon and germanium are an example of an intrinsic semiconductor. These types of materials' band gap are minimal, and electrons can gain sufficient energy and jump from valence band to conduction band in the room temperature condition. The known symbol for intrinsic semiconductor is n_i ; it refers as the intrinsic carrier density. Different types of Silicon [Warwick10, Answers10, Hu09] is shown in Figure 2.4.

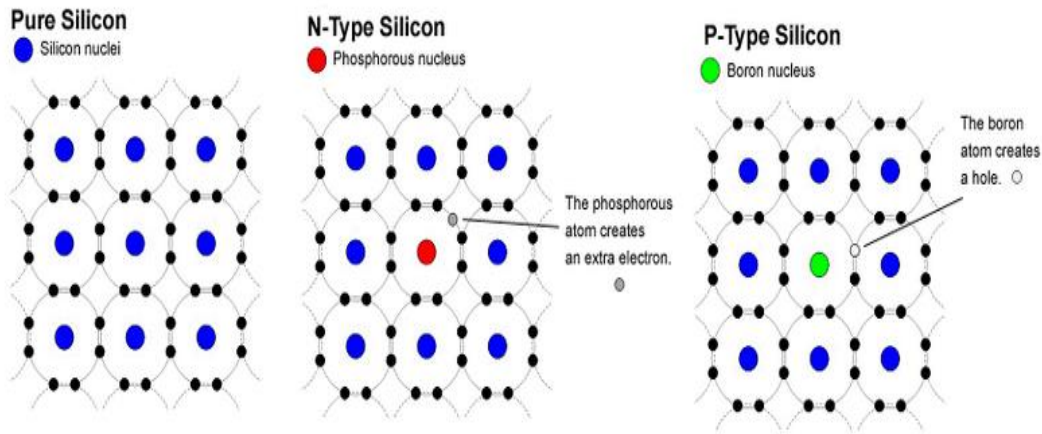


Figure 2.4 Different types of Silicon.

In Figure 2.4, it shows the pure silicon that is included in intrinsic semiconductor and the n -type and p -type silicon that counts in the extrinsic semiconductor.

Temperature has an influence on intrinsic carrier density. The density of charge carrier in intrinsic semiconductor [Kalogirou09] is given by:

$$n_i = N_c \left[\exp\left(\frac{E_f - E_c}{kT}\right) \right] \quad (2.2)$$

$$\text{where, } N_c = 2 \left(\frac{2\pi m_e kT}{h^2} \right)^{\frac{3}{2}}$$

$$p_i = N_v \left[\exp\left(\frac{E_v - E_f}{kT}\right) \right] \quad (2.3)$$

$$\text{where, } N_v = 2 \left(\frac{2\pi m_h kT}{h^2} \right)^{\frac{3}{2}}$$

where, n_i is the carrier density, p_i is hole density, N_c is the effective density when states is the conduction band, N_v is the effective density when states in the valance band, value of k is

$1.38 \times 10^{-23} \text{JK}^{-1}$ is the Boltzmann constant, E_f is Fermi energy, E_v is energy level of valence band, E_c is energy level of conduction band, T is temperature, h is Plank constant and its value is $6.624 \times 10^{-34} \text{ Js}$, m_e is effective mass of the electron and m_h is effective mass of the hole.

2.3.2 Extrinsic semiconductor

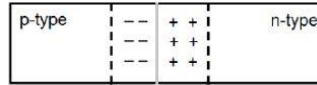
An extrinsic semiconductor is an impure one that is created by doping. It has excess electrons or holes. Electricity conductivity is high for this type of materials. Depending on the doping process, there are two types of extrinsic semiconductors. They are an n -type and p -type.

If the semiconductor is doped by materials which have more electrons in the valence band, it is called n -type. In n -type, there are more electrons. And if it is doped by the materials which have fewer electrons in the valence band are called p -type that has positive particles named holes. In p -type, there are more holes.

In both of the types electrons and holes could move freely. These both types together make the p - n junction. In the junction, from n -type electrons try to go to p -type to fill the holes and the holes from p -type spread to the n -type side. After occurring this, the negative charge of the p side restricts the movement of extra electrons from n side. There are positive charges at the junction of n side that ease the movement of negative charges from p side. In this way this p - n junction works as a diode. The n -type semiconductor is known as a donor because it gives extra electrons in work to fill the hole and p -type semiconductor is known as an acceptor because it gets electrons to fill its holes [Kalogirou09, Hu09].

2.4 Semiconductor Diode

Diodes are consisting of p -type and n -type semiconductors. When a semiconductor is made of n materials region and a p material region. This n - p together make a p - n junction, in the n region there are many electrons, and the p region has many holes. In the combination of p - n , there is a significant number of positive and negative ions created near the p - n junction and created the depletion region. p - n junction diode is shown in Figure 2.5 [Kalogirou09, Eon12].

Figure 2.5 p - n junction diode.

2.4.1 Real and ideal diode

Real diode and ideal diode both have two terminals named anode and cathode. Anode is the positive and cathode is the negative terminal as shown in Figure 2.6 [Kalogirou09, Eon12].

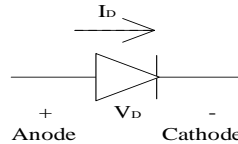


Figure 2.6 Symbol for diode.

where V_D is voltage over the diode and I_D is the current flows from anode to cathode. It is in forward biased when the positive polarity is applied at the anode, and negative is at the cathode. In this time, it is in conducting process. In the other direction when the positive polarity applied at the cathode and negative polarity applied at anode then the diode is at reverse bias. In this time, it is not conducting process.

A diode works like a switch, in the time of forward biasing it acts like a switch is on and when the reversed bias is given, then it acts like an open switch. For understanding the diode, it is vital to know the current-voltage behaviors of it. Real voltage and current is shown in Figure 2.7 [Electronicsdesignhq18].

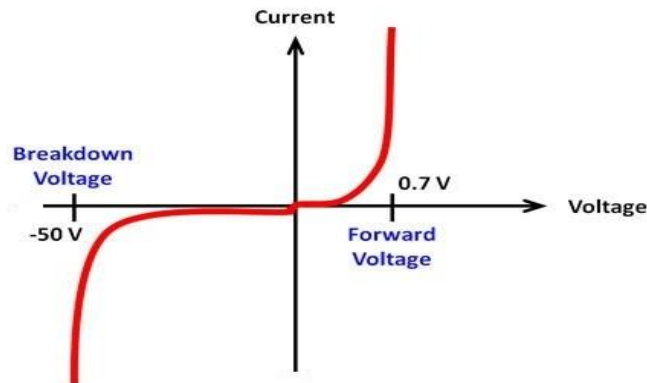


Figure 2.7 Voltage-current curve of real diode.

Voltage and current curve for ideal diode is shown in Figure 2.8 [Electronicsdesignhq18].

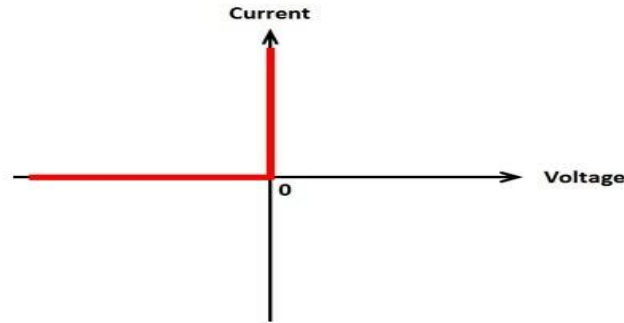


Figure 2.8 Voltage-current curve of ideal diode.

2.4.2 Current-voltage characteristics of diode

It is considered that diode is a device that has a little resistance in one direction called forward bias and very high resistance in other called reverse bias. The diode law named as Shockley diode is given by:

$$I = I_0 \left(e^{\frac{V_D}{nV_T}} - 1 \right) \quad (2.4)$$

where, I is the diode current, I_0 is the reverse bias saturation current, V_D is the voltage across the diode, V_T is the thermal voltage, n is the diode ideality factor.

In the ideal diode case, the value for the n is 1. The thermal voltage is given by:

$$V_T = \frac{kT}{q} \quad (2.5)$$

where, k is the Boltzmann constant, T is the absolute internal temperature of the $p-n$ junction, q is the electron charge. Different regions of a diode are shown in Figure 2.9 [Lu17, ElectronicsTutorials17].

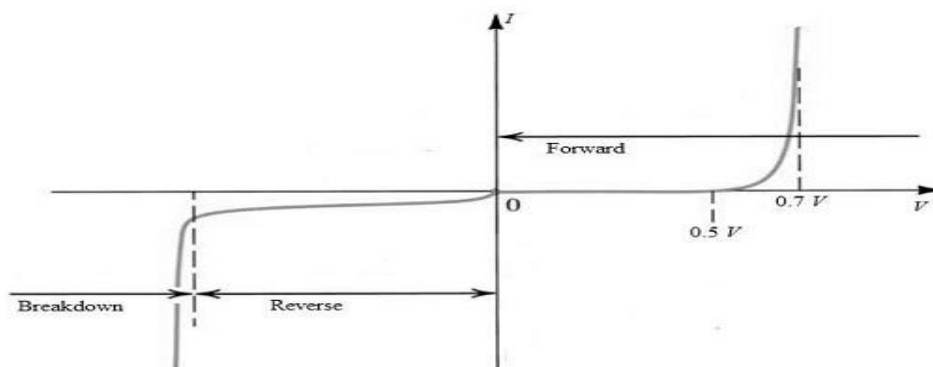


Figure 2.9 Different regions of a diode.

Figure 2.9 shows different regions of a diode, right part of the graph gives the forward region, and cut-in voltage value is 0.5 V. The diode is fully conduction at voltage value 0.7 V. Diode has dependency on the temperature. For a given current, voltage decreases in increasing temperature. For a given voltage, current increases when the temperature increases.

In the situation, when the voltage is greater than zero ($V > 0$) then it is in forwarding bias region. The resistance that linked with the diode is near to zero. In the ideal diode curve, the slope of forwarding bias is infinite.

In the condition when a voltage is less than zero ($V < 0$) the diode works in the reverse bias region and the resistance linked with the diode is an infinite state. The reverse biased slope is zero for ideal diode curve.

In reverse biased condition there is a voltage point where the diode performs appreciably in reverse. This voltage point is called Zener voltage.

2.5 Photovoltaics

Photovoltaic (PV) is known as the source of renewable energy that converts solar energy to electrical energy. Usually it is a semiconductor device, and simple in its working principle. Utilizing the photovoltaic effect, it converts sunlight to electricity. The source of the power for it is free and abundant. For sustainable development it has got importance. There are different types of PV cells exist, and new types of research are improving the performance by converting most of the solar radiation to power. Different types of PV technologies are shown in Figure 2.10 [Ahmed17, Foles17].

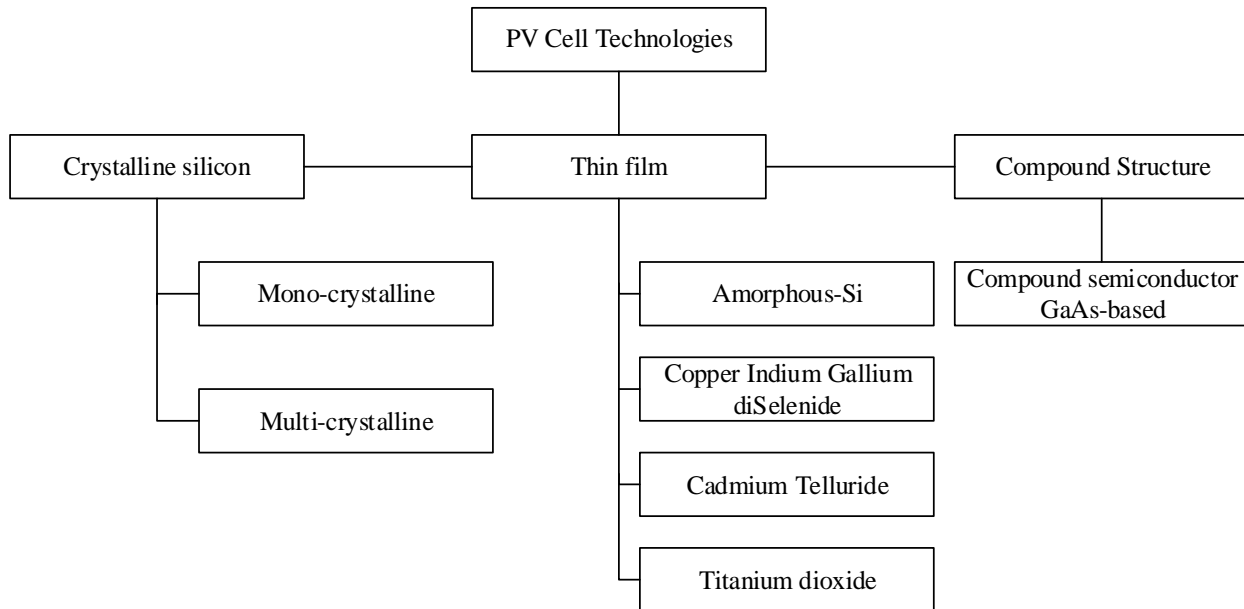


Figure 2.10 Different types of PV technologies.

Most of the PV cells are from different semiconductors and combination of them. Most of them are different kinds of composition of silicon components. Thin film is a kind of technology that decreases the size and also makes the panel cheap. This technology has used Amorphous Silicon, Cadmium Telluride, Titanium Dioxide etc. There is also compound structure, that have more than two junctions and they show good performance. There is organic solar cell technology, that makes it very cheap and flexible. But in the performance, it hasn't shown good efficiency.

2.5.1 Working principle

The sunlight come to the earth as electromagnetic wave and hit on the PV panel surface. The light reaches the PV materials; it consists of packets of energy named as photons. After light hit on the PV surface different events are happened; a. It can reflect, b. It can absorb and c. It can transmit. If the photon is absorbed by the valence electrons of the atoms of PV materials, i.e. when the photon energy is sufficient enough then it help the electron to jumps from the conduction band and travelled freely. In semiconductor with $p-n$ junction when there is electric field is applied across the front and back of the materials and external load is connected, then electron flows throw the load to complete the circuit. If the photon has less energy that needs to generate to flow electron, then this photon energy is absorbed by electron. It increases kinetic energy that causes increase of heat in the device.

Photovoltaic device working process is shown in Figure 2.11 [Kalogirou09].

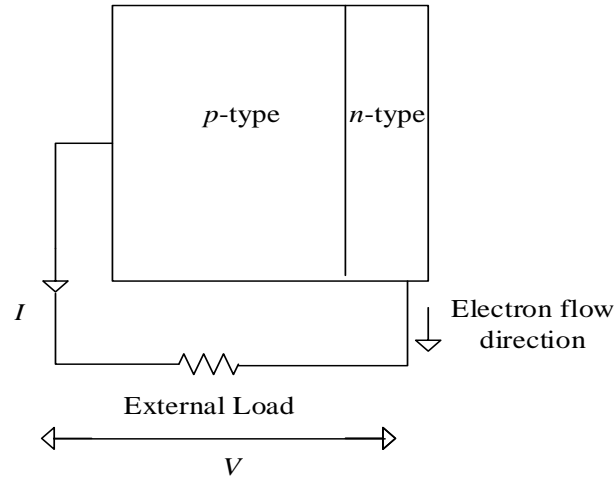


Figure 2.11 Photovoltaic device working process.

Figure 2.11 shows a photovoltaics cell arrangement having p - n junction, I shows current flow, V shows voltage across the load. When photon having more energy than band gap hit on the surface of a PV cell, it frees electrons with sufficient energy. Electron and hole pairs are created and when they are enough near to p - n junction then the electric field make them split. Hole goes to p -type side and electron goes to n -type side. In this condition when system is connected by wire with an external load the current start to flow through the wire. As long the sunlight is there the current continues to flow.

It is possible to calculate the number of photons from the intensity of light. The light is the electromagnetic radiation, and it maintains the law of energy. The photon energy is given by:

$$E_p = h\nu \quad (2.6)$$

where, h is the Planks constant is 6.625×10^{-34} Js, ν is frequency (s^{-1}) and is expressed as $\nu = \frac{c}{\lambda}$

Then it becomes,

$$E_p = \frac{hc}{\lambda} \quad (2.7)$$

where, C is the speed of light, λ is wavelength. The number of photons (n_p) could calculate the intensity of light and the wavelength given by:

$$n_p = \frac{I_p}{E_p} \quad (2.8)$$

where, I_p is the intensity of light.

2.5.2 Modeling of PV cell

Single PV cell is a small building block that made up the big PV power conversion system for generating power. When the negative and positive lead is connected to a load, makes an electrical circuit, there electrons flow completing the circuit.

The generated current in PV is named photocurrent (I_L). In a simple single diode model of PV is constructed with photocurrent source that is connected with a diode in parallel. The electrical behavior of this part works like a p - n junction. The current generated from irradiance (G) is proportional to the solar radiation that direct fall on the surface. Simple PV model has not counted the series and shunt resistance. This simple model is possible to describe with Shockley diode theory. PV is not a constant source of current. Simple single diode PV model [Sera07, Rashel17a] is shown in Figure 2.12.

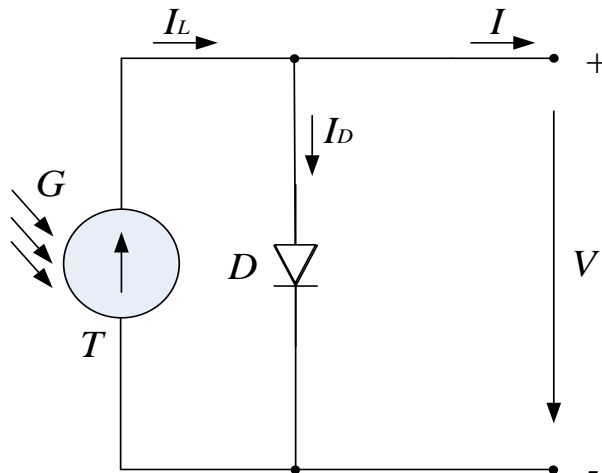


Figure 2.12 Simple single diode PV model.

Figure 2.12 shows simple single diode PV model that has no series and shunt resistance. This model is represented based on Shockley diode equation [Shockley61]. In Figure 2.12 G is the irradiance. The diode current is given by:

$$I_D = I_0 \left[\exp\left(\frac{qV}{nkT}\right) - 1 \right] \quad (2.9)$$

According to the Kirchoff's current law, total incoming current and the outgoing current summation are always zero. From Kirchoff's current law, the current generated from PV is given by:

$$I = I_L - I_D \quad (2.10)$$

The total current is the photocurrent minus the diode current is given by:

$$I = I_L - I_D = I_L - I_0 \left[\exp \left(\frac{qV}{nkt} \right) - 1 \right] \quad (2.11)$$

In (2.10), I_L is photocurrent, I_D is diode current, and I_0 is dark saturation current, n is diode ideality factor, q is electron charge, k is Boltzmann's constant, T is the cell temperature of the junction.

For characterization of PV cell, short-circuit (I_{sc}) current and open-circuit (V_{oc}) voltage have considerable influence. When a voltage is zero then, I_{sc} is equal to photocurrent (I_L).

Therefore, $I_{sc} = I = I_L$.

The simple model gives the value for PV output. A series resistance is added with simple PV model. Four-parameter model of PV cell is shown in Figure 2.13 [Ahmed17].

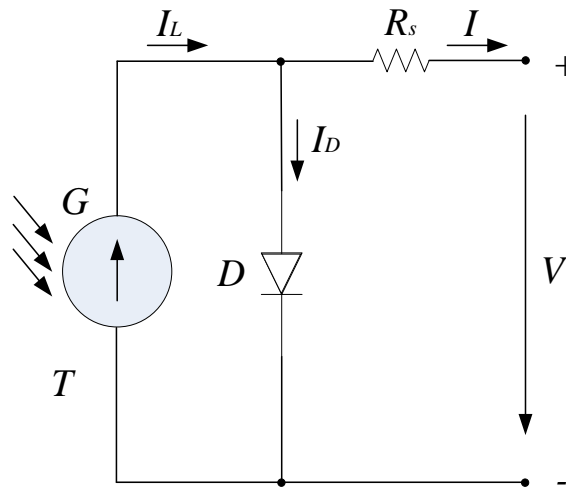


Figure 2.13 Four-parameter of PV cell model.

The four-parameter mathematical model gives the current-voltage characteristics of PV cell. The total current is given by:

$$I = I_L - I_D = I_L - I_0 \left[\exp \left(\frac{qV + qR_s I}{nkt} \right) - 1 \right] \quad (2.12)$$

In (2.11), R_s is the internal series resistance in the PV equivalent circuit. For making more approximate to get the output from it, needs a more sophisticated model that includes series and shunt resistance. Five parameters single diode PV model is well known and most used to simulate the PV cell. This model is the electrical equivalent of PV cell. It shows approximate behavior like solar cells in a PV panel. Series resistance and shunt resistance is included in the parallel in the PV

equivalent circuit and it becomes five parameters model of the PV cell. Five parameters model of PV cell is shown in Figure 2.14 [Rashel17a].

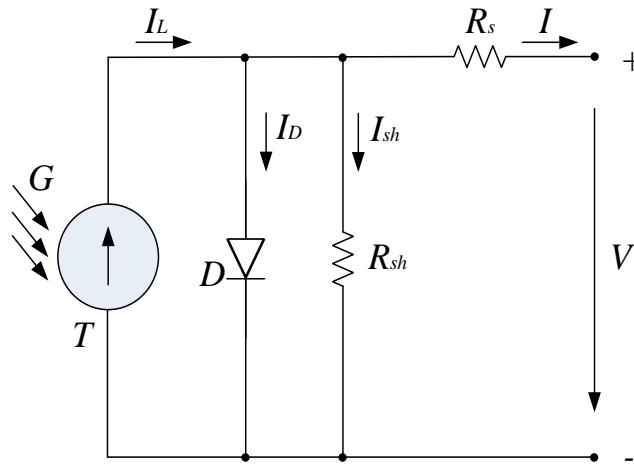


Figure 2.14 Single diode five parameters PV cell model.

In Figure 2.14, I_L Photocurrent which is the current source for the circuit, single diode D which have I_D current across it, a series resistance R_s which represents the resistance in the cell, shunt resistance R_{sh} is in parallel.

The current across the shunt resistance (I_{sh}) is given by:

$$I_{sh} = \frac{V+IR_s}{R_{sh}} \quad (2.13)$$

For Figure 2.15, applying the Kirchoff's current law, the total incoming current and the outgoing current summation are always zero. From Kirchoff's current law, the current generated from PV is given by:

$$I = I_L - I_D - I_{sh} \quad (2.14)$$

After putting all the values, the total current is given by:

$$I = I_L - I_D - I_{sh} = I_L - I_0 \left\{ \exp \left[\left(\frac{q(V+IR_s)}{nkT} \right) \right] - 1 \right\} - \left(\frac{V+IR_s}{R_{sh}} \right) \quad (2.15)$$

In (2.15), the series resistance and shunt resistance is included. It is used for the different simulations.

If the shunt resistance is much more significant than the load resistance, and series resistance is much smaller than the load resistance, then it is possible to ignore their loss in the cell. When the loss is ignored, then the series resistance and shunt resistance also could be ignored from the model.

Then the total current is the difference between photocurrent and diode current and the equation becomes like as same as (2.11). It is the ideal PV model without series and shunt resistance.

The current and voltage has different significant characteristics for PV model. The open circuit voltage (V_{oc}) is the voltage when the current is zero. The power output is also zero. The short-circuit current (I_{sc}) is the condition when the voltage is zero and power production is zero. Current at maximum power (I_{mp}) is the current when the PV gives the maximum power output, depending on internal and environmental conditions. The voltage at maximum power (V_{mp}) is the voltage when the PV gives the maximum power. Maximum power point (*MPP*) is important when the PV gives the best output. This point depends on the different value that is related to internal and environmental parameters.

2.5.3 Analytical approach of five parameter PV cell model

An analytical approach is carried on to solve the (2.15) to get the parameters values.

The (2.15) is re-writes as [Ahmed17]:

$$I = I_L - I_0 \left[\exp\left(\frac{qV + qIR_s}{nkT}\right) - 1 \right] - \frac{V}{R_{sh}} - \frac{IR_s}{R_{sh}} \quad (2.16)$$

From (2.16), it is possible to write as below:

$$I + \frac{IR_s}{R_{sh}} + I_0 \left[\exp\left(\frac{qV + qIR_s}{nkT}\right) \right] = I_0 - \frac{V}{R_{sh}} + I_L \quad (2.17)$$

After going through different calculation and divided both sides of (2.17) with I_0 is written as:

$$\left(\frac{R_s + R_{sh}}{IR_{sh}}\right) I + \left(\exp\left(\frac{qV + qIR_s}{nkT}\right)\right) = 1 - \frac{V}{R_s I_s} + \frac{I_L}{I_0} \quad (2.18)$$

From (2.18), left side part have I the current, that makes the equation impossible to solve analytically. It is possible to solve the equation in another way by making the series resistance R_s to zero makes the term zero that has contained the R_s . The (2.18) then becomes as:

$$I = \frac{1 - \frac{V}{I_0 R_{sh}} - \left(\exp\left(\frac{qV}{nkT}\right)\right) + \frac{I_L}{I_0}}{\left(\frac{R_{sh}}{IR_{sh}}\right)} \quad (2.19)$$

This is the analytical solution for the output current from five parameters PV cell model. It is difficult to find an analytical solution for PV model[Ahmed17].

2.5.4 Datasheet values for a PV cell

In this work, the datasheet values are used to build a computational model to characterize the PV cell behavior. This characterization is done under standard condition. Then it included variable internal parameters value and environmental parameters value.

The five parameters single diode cell model is used for getting simulation result, and it gives an excellent result that is close to the real scenario under standard condition. This model is used for sensitivity analysis of internal and environmental parameters. In this work, crystalline silicon solar cell is used, the values of different parameters are obtained from the datasheet. The values for a c-Si cell under STC condition is given in Table 2.1.

Table 2.1 Data for the c-Si PV cell at STC.

Technology	V_m	I_m	V_{oc}	I_{sc}	∞_{sc}
c-Si	0.55 V	1.98 A	0.64 V	2.1 A	1.7 mA/°C

Table 2.1 values used for doing the simulation under different internal and environmental conditions. I_{sc} is the value for short circuit current, V_{oc} is the open circuit voltage, and V_{mp} is maximum voltage, I_{mp} is the current when there is maximum power output from the PV cell.

Below Table 2.2 gives the typical physical properties of a c-Si PV cell. The specific area is given in millimeter unit. Thickness is in micrometer unit. Different layers doping type are also specified. Physical properties of a c-Si PV Cell is given in Table 2.2 [Ahmed17].

Table 2.2 Physical properties of a c-Si PV Cell

Name	Description	Unit
Doping Type	p-type	N/A
Thickness	300	[μm]
Area	100 × 100 or 120.5 × 120.5	[mm^2]
Top side doping	n ⁺ type	N/A
Backside doping	p ⁺ type	N/A
Reduced thickness	250	[μm]
Reduced Area	200 × 200	[mm^2]

After manufacturing the PV device, industry tests different values for the PV and it releases the datasheet. These values from datasheet are useful to understand the behaviors of PV cell under different condition and choose the perfect condition to get maximum power. Typical structure of a c-Si solar cell is shown in Figure 2.15 [Zeman14].

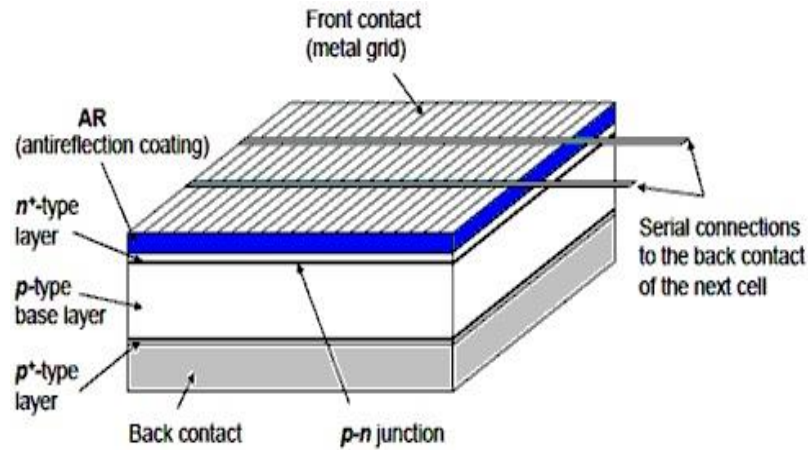


Figure 2.15 Typical structure of a c-Si PV cell.

Using (2.15) and the values from Table.2.1, making simulation under STC condition and get the Figure 2.16 of voltage-current, and get the Figure 2.17 of voltage-power. Voltage and current curve for single diode five parameters PV cell is shown in Figure 2.16 [Rashel17a, Rashel16b].

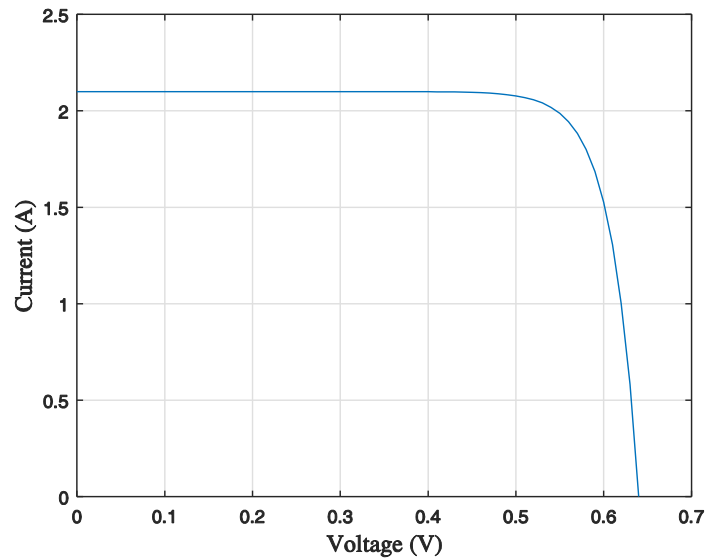


Figure 2.16 Voltage-current curve for single diode five parameters PV cell model.

Figure 2.16 shows the ideal behavior of PV cell, the short circuit current (I_{sc}) value is 2.1 A, there the voltage is zero. The open circuit voltage (V_{oc}) value is 0.64 V, there the current is zero. Voltage and power curve for single diode five parameters PV cell voltage-power behavior is shown in Figure 2.17 [Rashel17c].

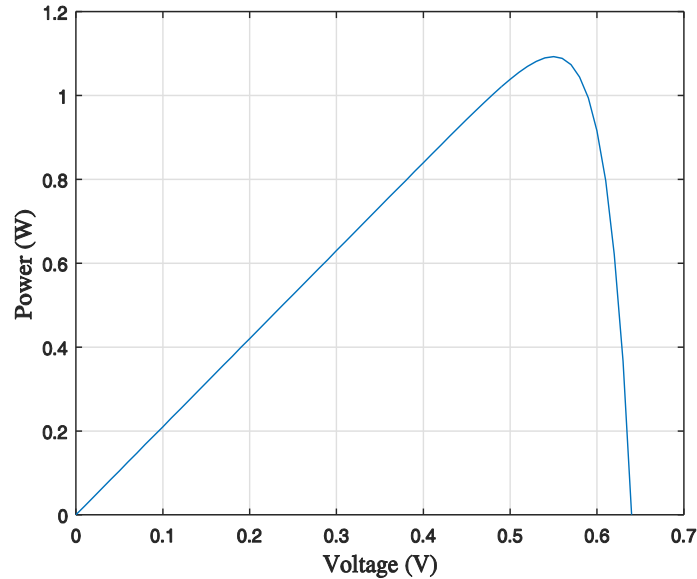


Figure 2.17 Voltage-current curve for single diode five parameters PV cell model.

Figure 2.17 has the total power graph including the maximum power point where the PV reaches the peak point of the power. The maximum power (P_{max}) value is 1.1 W and the voltage at maximum power (V_{mp}) value is 0.56 V.

The P_{max} is the point where the load resistance is at the most favorable point. At P_{max} the power output through the PV to the resistive load is maximum and is given by:

$$P_{max} = I_{mp} \times V_{mp} \quad (2.20)$$

where, I_{mp} is the current at P_{max} and V_{mp} is the voltage at P_{max} .

This maximum point also given by:

$$P_{max} = I_{sc} V_{oc} FF \quad (2.21)$$

where, FF is the fill factor:

$$FF = \frac{P_{max}}{I_{sc} V_{oc}} = \frac{I_{mp} V_{mp}}{I_{sc} V_{oc}} \quad (2.22)$$

The fill factor gives the real measurement of voltage and current characteristics. If the quality of the PV is fair enough, then it should be greater than value 0.7 V [Kalogirou09]. Depending on the environmental condition its values decrease.

2.6 Sensitivity Analysis and Error Function

In all measurement systems, there is always the presence of uncertainties. All of them, sensitivity analysis is the study to identify the uncertainty of inputs for a particular model's (mathematical model and computational model) output value. It determines the impact of different values of an independent parameter to a dependent variable under specific circumstances. Sensitivity analysis gives critical information about independent parameters. The boundary values for an independent parameter takes from the real-time scenario or a valid source for the particular system. Inside a system when one parameter is varying to implement different circumstance, effects imposed on the output. In the real-time system, between entire workflow there are many events occurred. The changes that take place because of changing the values of the parameters values. Flow chart for Sensitivity Analysis is shown in Figure.2.18.

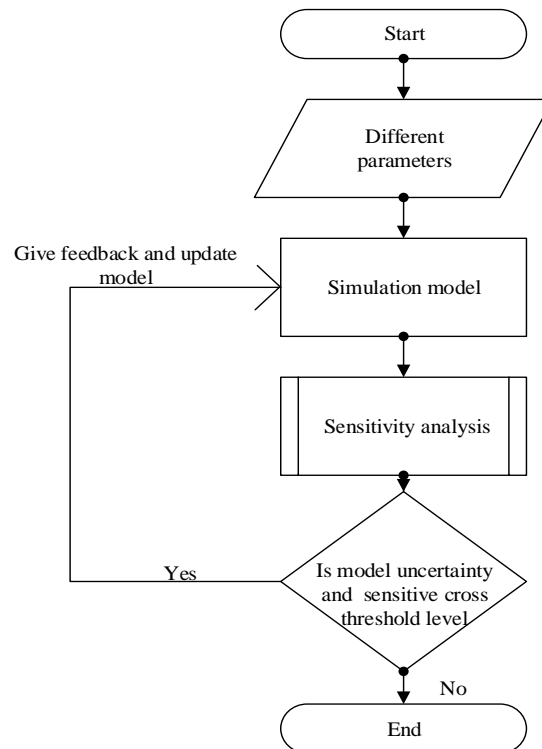


Figure 2.18 Flow chart of sensitivity analysis.

This flow chart shows the sensitivity analysis of different parameters that are included in the model. There are valid purpose and importance to go through sensitivity analysis that recalculated the outcomes with alternative assumptions determining the impact of a parameter. Sensitivity analysis helps to improve a model that includes:

- a. Increase the understanding between input and output parameters of a model;
- b. Reduce the complexity of a model by identifying the critical parameters;
- c. Identify the error in the model through observing the unexpected relations between input and output parameters;
- d. Reduction of the uncertainty of the model, giving more attention on the parameters that make a significant change to output;
- e. In a high dimension of inputs space, identify an area that optimized the model to give the best output for a model;
- f. Analyze the strength of the results of a model under uncertainty;
- g. Identify valuable parameters in a model.

In this work, to understanding parameter effects to the system is identified using the sensitivity test, through error function. Error function of a parameter gives the precise value how an output value is sensitive to that parameter. The figure describes a sample graph of a single parameter with an error function, gives the idea about the certainty of output in that value position. Parameter with sensitivity function is shown in Figure 2.19 [Rashel17a, Rashel17c].

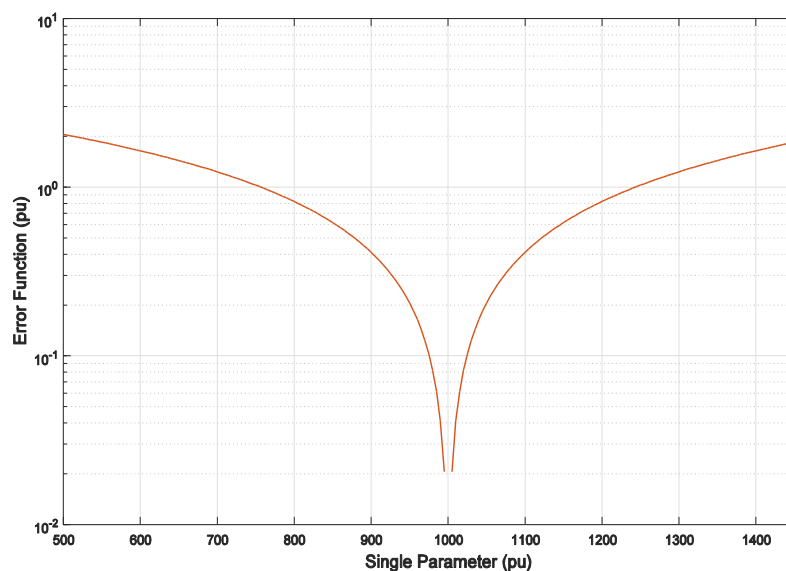


Figure 2.19 Parameter with error function for identify sensitiveness.

The main idea is to identify the effect of the parameters for the PV system through the sensitivity identification. The sensitivity is tested through the error function $E(I)$, it is a function of output of PV, that gives the difference of output from standard condition to the different variable conditions where the parameters values are changed. Below the equation is described for error function. This helps to identify sensitivity for a particular parameter of a model given by:

$P = \text{Vector of paramters.}$

$$P = \begin{bmatrix} I_L \\ R_s \\ R_{sh} \\ T_{cell} \\ a \\ I_s \end{bmatrix}$$

$I_{iP} = \text{The model estimated current with optimal values.}$

$I_{iM} = \text{Measure value (varying the value of a particuler parameter in simulation).}$

For a specific parameter the error function is calculated as below:

$$E(P)_1 = \left(\frac{1}{n} \sqrt{\sum_{i=1}^n (I_{iP} - I_{iM})^2} \right)$$

$$E(P)_2 = \left(\frac{1}{n} \sqrt{\sum_{i=1}^n (I_{iP} - I_{iM})^2} \right)$$

For n^{th} parameter, it is express as:

$$E(P)_n = \left(\frac{1}{n} \sqrt{\sum_{i=1}^n (I_{iP} - I_{iM})^2} \right)$$

In general, it is expressed as:

$$E(P)_{1\dots n} = \frac{1}{n} \sqrt{\sum_{i=1}^n (I_{iP} - I_{iM})^2} \tag{2.23}$$

where I_{std} is the output under standard condition.

Calculation of the sensitivity of different parameters through error function is given by:

Step 1: Input, $P_1 = \text{Analyzed Parameter}$

Step 2: Input, $O_1, \dots, O_n = \text{Other Parameters}$

Step 3: Calculating, $I_{iP} = \text{output value calculation from standard value of parameter}$

Step 4: for $i = 1$ to n

$I_{iM, 1\dots n} = \text{output value calculation from variable } P_{1,1\dots n}$

end

$$\text{Step 5: Output, } E(P)_{1,\dots,n} = \frac{1}{n} \sqrt{\sum_{i=1}^n (I_{iP} - I_{iM})^2}$$

Sensitivity analysis is done for internal parameters and environmental parameters, those are related with the model of PV cell and effect its performance. This is used to identify the valuable, sensitive variable in the system. After identifying the valuable parameters, it is possible to give more concern to improve the quality of model and invent system to improve the situation for getting more power from the PV system.

2.7 Internal Parameters

Five parameters PV cell model is represented by (2.15) that is equivalent representation of Figure 2.14 that is consists of different parameters. Photocurrent (I_L), internal cell temperature (T), diode ideality factor (n), Series resistance (R_S), shunt resistance (R_{Sh}) and saturation current (I_0) are internal parameters. Variation of these parameters have impact on PV system performance. Using sensitivity analysis, these parameters sensitivity to the system is identified. For identifying less sensitive parameters in work, all the parameters I_L , T , n , R_S , R_{Sh} and I_0 are tested through the $E(I)$. It gives clear idea about the sensitiveness of parameters of PV model. Flowchart gives clear picture to get sensitive internal parameters is shown in Figure 2.20 [Rashel17a].

Figure 2.20 shows flow chart to identify sensitive parameters from five parameters PV model and get a simplified model of PV. This is simulated in Matlab. All the internal parameters are going through the error function to see their sensitivity. After analyzing the sensitivity of each parameter, creates a new simplified model.

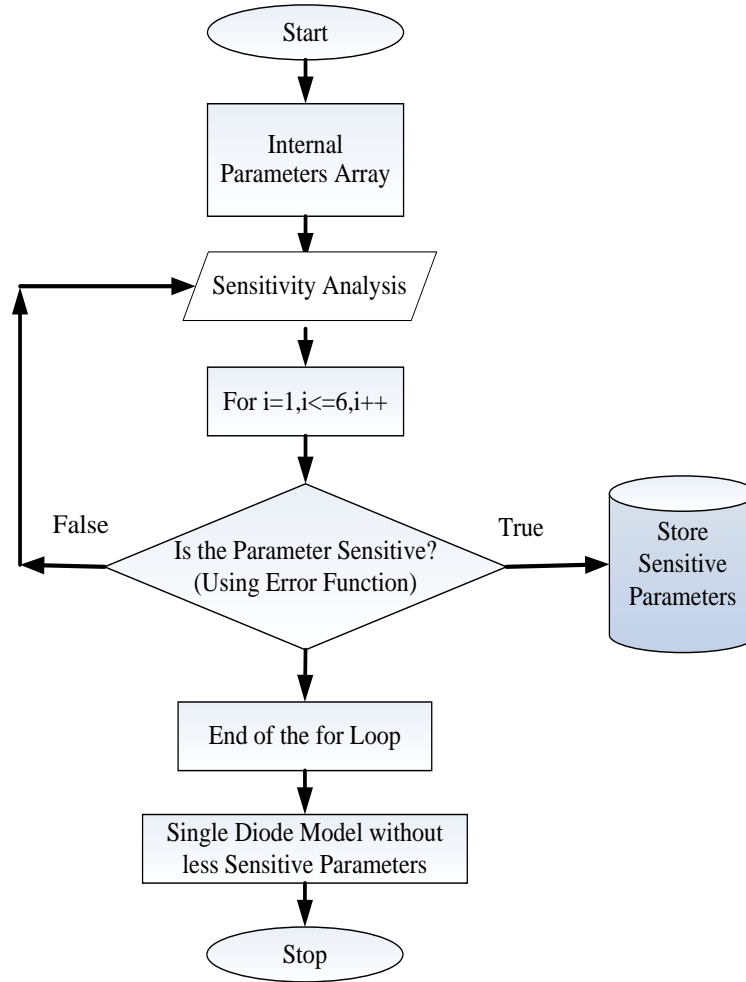


Figure 2.20 Flowchart describing the model to get sensitive parameters for internal model.

2.7.1 Photocurrent

The photocurrent is produced in PV device from the sunlight when the light strikes on the PV surface with enough quantity of energy. This current is get from the negative terminal of the PV cell. But according to the circuit model, there is also diode current and current across the shunt resistance, those are minus from the photocurrent (I_L), that gives the final current output from a PV. Photocurrent mainly depends on irradiance (G) and temperature and it is given by:

$$I_L = \left(\frac{G}{G_n}\right)[I_{sc} + K_l(T - T_n)] \quad (2.24)$$

where, G is irradiance, G_n is irradiance at standard test condition (STC), K_l is temperature current coefficient, T is working internal temperature of cell and T_n is internal cell temperature at STC and I_{sc} is short circuit current. The photocurrent is the primary current that produces from the PV cell and keeps the wheel moving for the system.

2.7.2 Internal cell temperature

A typical PV panel efficiency is 15%. Rest of the irradiance convert to heat. This heat has a reverse effect on the performance of PV. Cell temperature is a critical part; its fluctuation shaves a significant impact on PV output. In (2.9) and (2.15) both model have this parameter and it has significant importance on the performance of PV cell. This is also analyzed through the error function to understand the sensitivity with the model.

2.7.3 Ideality factor

Diode ideality factor (n) is used in (2.14) and change of this value makes change in the value of diode current (I_D). It is the measurement of a diode how it is close to ideal diode. There are many moving carriers over the p - n junction of PV. The value of this parameter varies in accordance with its diode behavior. PV model does not follow the ideal diode behavior so ideality factor is introduced to describe its deviation from the ideal characteristics. Usually the value of diode ideality factor varies in the range between 1 to 2. It is important because changing of the value of the parameter, changes the value of PV output.

2.7.4 Saturation current

Following (2.15), Saturation current (I_0) has a high impact on the PV power conversion. I_0 variation effects the output of PV. The value of I_0 is given by:

$$I_0 = I_{0n} \left(\frac{T}{T_n} \right)^3 \exp \left[\frac{e \times E_g}{n \times k} \left(\frac{1}{T_n} - \frac{1}{T} \right) \right] \quad (2.25)$$

where, T is working internal temperature of cell, T_n is internal cell temperature at STC, E_g is band gap, n is diode ideality factor, k is Boltzmann constant, e is the value of electron charge and I_{0n} is internal diode current is calculated using (2.28). I_{0n} is express as:

$$I_{0n} = \frac{I_{sc}}{\exp \left(\frac{V_{oc}}{n \times V_T} \right)} \quad (2.26)$$

where, I_{sc} short circuit current, V_{oc} is open circuit voltage and V_T is thermal voltage that calculated using (2.5).

2.7.5 Series resistance

Series resistance (R_s) is a part of the single diode five parameters PV cell model. Changing of the value makes changes in the value of the output but it is not significant amount. The series resistance has less dependency on irradiance and temperature [Soto06]. When the load resistance is bigger enough then the effect of series resistance is not significant at all [Kalogirou09].

2.7.6 Shunt resistance

Shunt resistance (R_{sh}) is situated at the parallel to the diode and it is included in the single diode five parameters PV cell model. It is enormous in quantity, then the load resistance. The effect to the total output also becomes less significant. This parameter's sensitivity test is done through error function.

2.8 Environmental Parameters

Irradiance, ambient temperature, wind speed, cloud, humidity, and perspiration are different environmental parameters that have an impact on PV power conversion. In this work, irradiance, ambient temperature, and wind speed are analyzed through error function to identify their sensitivity to PV power conversion. Other parameters of the environment were not analyzed. Work with other parameters is an ongoing process of the work but were not included in the thesis. For real-time data, the weather station at University of Évora's data has been used.

2.8.1 Irradiance

Irradiance is the power per unit received by a solar power conversion system. This power is received in the form of electromagnetic radiation. It is measured on the Earth surface and, is the environmental factor that is the primary energy for producing electricity. With sufficient power solar rays strike on the PV surface and generate electricity. In (2.24), photocurrent is depending on the irradiance. More the sunlight more the electricity will be produced. Name of measurement instrument of irradiation is by radiometry device. On average a PV cell can convert 15% of irradiance to be utilized. The generated heat in the PV cell becomes the obstacle for the performance of the system. It is vital to understand the irradiance with other environmental parameters. Total irradiance is the measurement of all wavelengths per area that fall on the upper

atmosphere of Earth. This gives the total solar power. But for the PV system, global horizon irradiance is counted. It is the total irradiance that comes from the sun on a horizontal surface on Earth. It is given by:

$$GHI = DHI + DNI \times \cos(z) \quad (2.27)$$

where, GHI is global horizontal irradiance, DHI is diffuse horizontal irradiance and DNI is direct normal irradiance.

The SI unit for irradiance is watt per square meter, and it is expressed as W/m^2 . Yearly (31st December 2016 to 30th December 2017) irradiance data from University of Évora Weather station is shown in Figure 2.21 [Clima18].

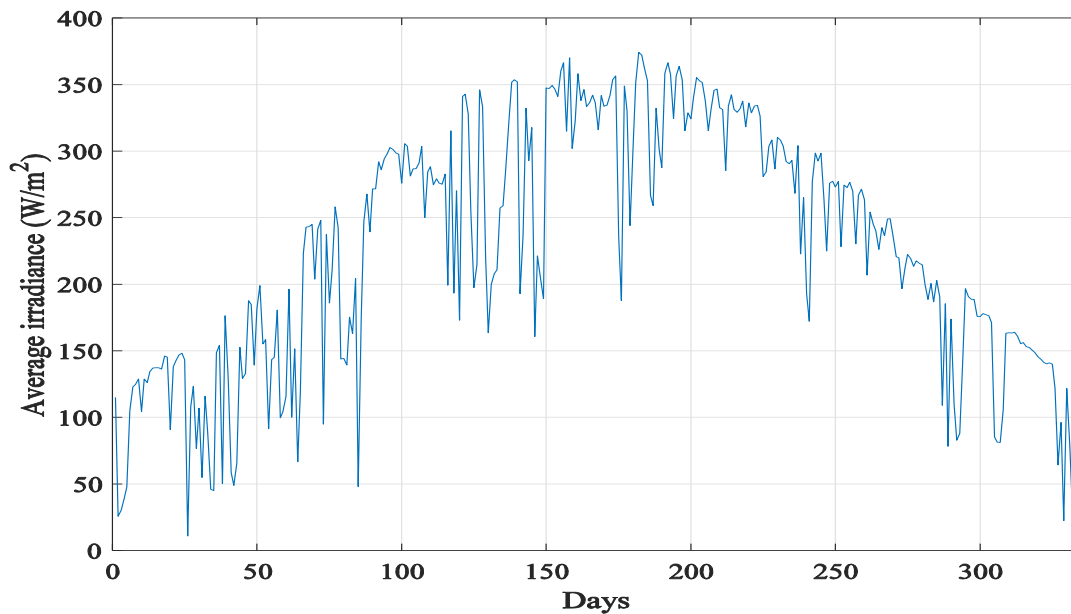


Figure 2.21 Sequential daily average irradiance of year 2017.

Figure 2.21 shows the total irradiance all over the year for a specific area. Middle of the year the irradiance is more than any other time of the year, but in the same time, the temperature also gets very high. Pyranometer is shown in Figure 2.22 [Clima18].



Figure 2.22 Pyranometer.

2.8.2 Ambient temperature and effects on cell temperature

Ambient temperature is a significant factor for PV performance. This parameter is easily measured by a thermometer. In the equation, it is possible to calculate the value of cell temperature knowing the ambient temperature. The increase of ambient temperature increases the cell temperature. There is a propositional relationship between ambient temperature with cell temperature is given by [Rashel18b].

$$T_{cell} \propto \frac{T_{air}}{v_{wind}} \quad (2.28)$$

where T_{cell} is cell temperature with ambient condition, T_{air} is air temperature of surrounding and v_{wind} is wind speed. The (2.28) shows that cell temperature with ambient temperature is propositional to ambient temperature and inverse proportional to wind speed. It is one of the important parts of PV conversion system. T_{cell} value depends on irradiance, ambient temperature, and wind speed. Other environmental factors is not take in account for this model and simulation. Using these parameter values the cell temperature with ambient condition value is calculated and given by:

$$T_{cell} = T_{air} + 0.035 \times G \quad (2.29)$$

Where, T_{cell} is cell temperature with ambient condition, T_{air} is ambient temperature and G is the irradiance.

T_{cell} is calculated with wind speed is given by:

$$T_{cell} = T_{air} + \left(\frac{0.32}{8.91 + (2 \times v_{wind})} \right) \times G \quad (2.30)$$

Where G is the irradiance and v_{wind} is wind speed. It is observed that cell temperature rises with irradiance and ambient temperature. [Migan13]. In (2.30), it is clear that T_{cell} is directly related to v_{wind} . T_{cell} has directly relation with the PV power conversion system.

Getting knowledge about ambient temperature is essential to create an improvement in the model of PV and is vital to predicting the PV power conversion more precisely. Yearly (From 31st December 2016 to 30th December 2017) temperature data from University of Évora Weather station is shown in Figure 2.23 [Clima18].

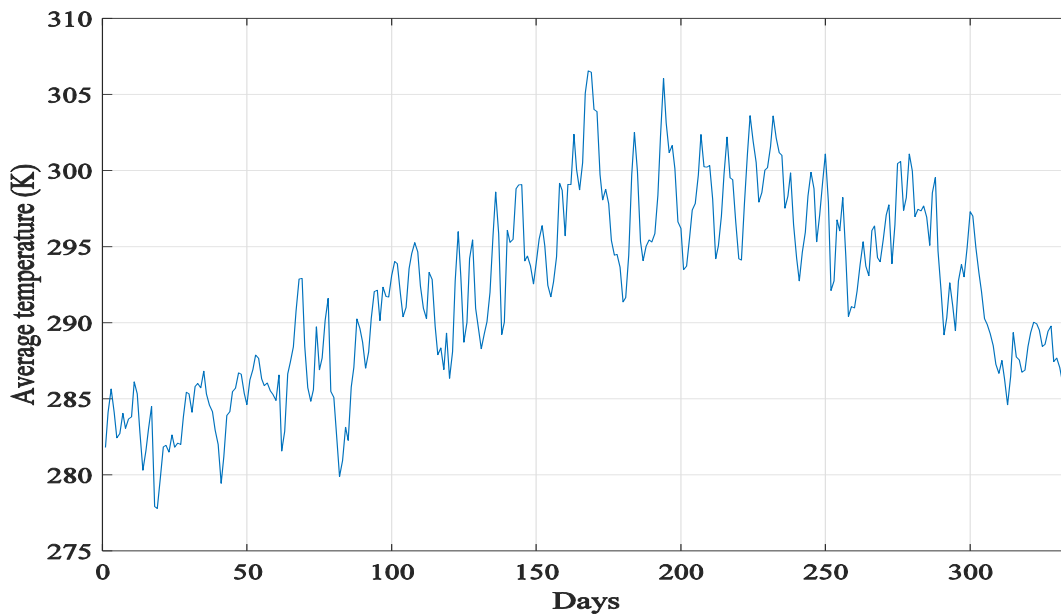


Figure 2.23 Sequential daily average temperature of year 2017.

Figure 2.23 shows one-year temperature of a specific area, and it has very close behavior like irradiance. There is a different unit that uses as SI unit for temperature, from the most used is Celsius (C) and Kelvin (K). 0-degree Celsius is equal to 273.15 Kelvin. Vaisala weather station with temperature sensor is shown in Figure.2.24 [Clima18].



Figure 2.24 Vaisala weather station with temperature sensor.

Figure 2.24 is a portable weather station that is light and flexible and also has a USB port to connect with computer. Its software directly gives the values of different environmental parameters with temperature value.

2.8.3 Wind speed

Wind speed is the flow velocity of the wind. It is one of the fundamental quantity of atmosphere. The behavior of air is its flows from high pressure to low pressure, and it caused wind speed. Wind speed is measured by an anemometer. It is already identified that Wind speed has effect on the PV and in (2.30) wind speed is needed to calculate the cell temperature with ambient condition. T_{cell} is directly related to wind temperature, and it is inverse proportional to wind speed. For improving the performance of PV, this parameter plays a vital role. Wind speed is a natural process, it is possible to predict the wind speed and that helps to predict the PV power conversion more accurately. Yearly (From 31st, 2016 to 30th Dec 2017) wind speed data from University of Évora Weather station is shown in Figure 2.25 [Clima18].

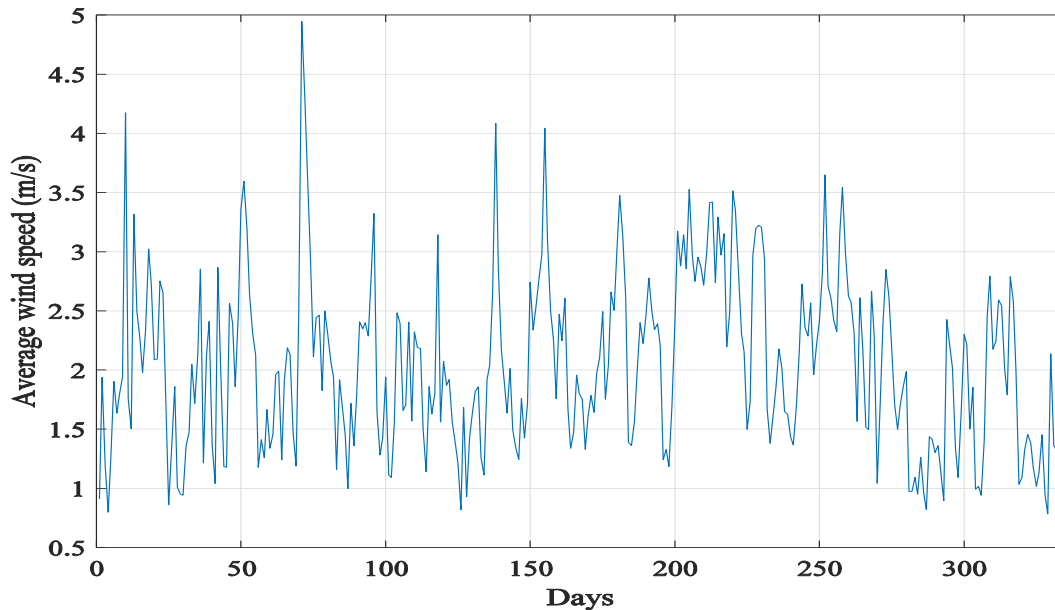


Figure 2.25 Sequential daily average wind speed of year 2017.

Figure 2.25 shows the yearly wind speed. It does not follow any defined pattern, and it is very random. Wind speed is measured in meter per second (m/s). Anemometer is shown in Figure 2.26 [Clima18].



Figure 2.26 Anemometer.

Figure 2.26 shows Anemometer, it is the device that measures the wind speed. This device is connected to central system to collect data in real-time.

2.9 Non-constant Load

An electrical load is the part of an electrical circuit which consumes the electric power of the electric system. If PV is not connected to the battery and direct connection is to the load. In this time if the load is varied with the use of power then it becomes a variable load for PV system and become the non-constant load. The non-constant load has an effect on the maximum power point of the PV Panel. Generally, with a controller, this non-constant load's effect is minimized to get MPP. But in the stand-alone system, if PV has a direct connect with the load then the MPP varies with the load behavior. It is important to understand the relationship between maximum power point and non-constant load.

This work is done using a PV panel in the laboratory. The PV panel is connected with different resistances having different values. It connects with a breadboard that connects with DAQ. The DAQ measures the open-circuit voltage. Based on the open-circuit voltage Matlab sends request to signal generator for generating signal to measure the voltage-current under specific load over different point. This same work is continuing with different resistances and store the data for analysis.

2.10 Shadow of Obstacle on PV Panel

Shadow of obstacle on the PV surface makes the performance of the PV cell deficient, and in some time it becomes zero. There could be different types of obstacles around the PV; these obstacles could be shadows or dust or physical damage of cells. All of these factors decrease efficiency and performance of PV dramatically. In this work all the things those create barrier to reach the irradiance to PV conducting surface are named as obstacles. Identification of different types of obstacles is critical for remotely control a big PV plant. This helps to identify the fault in PV panels.

Few obstacles are temporary, and few of them are permanent. Temporary obstacles are environmental obstacles, like clouds, flying birds, etc. There are permanent obstacles also exist, those are not removable without human interaction, like dust, damage of cells.

Obstacles are divided with dependency of time variable,

- a. Time-dependent obstacles;
- b. Time-independent obstacles.

2.10.1 Time-dependent obstacles

Time-dependent obstacles are depending on the time change the obstacles behavior. With time this type of obstacles moves away or stay, like a cloud, flying object shadow, etc. These type of obstacles are expressed with the variation of time given by:

$$PV_o \propto O_{bs}(t) \quad (2.31)$$

In (2.31), in the situation of time-dependent obstacles the power generation from a PV panel is proportional to the shadow of obstacles with time function. Shadow on PV panels as time-dependent obstacle is shown in Figure 2.27 [Pixabay17].



Figure 2.27 Cloud shadow on PV panels as time-dependent obstacle.

Shadow of bird as time-dependent obstacle is shown in Figure 2.28 [Blog17].



Figure 2.28 Shadow of birds as time-dependent obstacle.

2.10.2 Time-independent obstacles

This type of obstacles is not change their characteristics with the time. This type of fault of PV panel should solve manually. Example of this type of faults is: thick layer of dust, physical damage of a cell in a panel. Dust on PV as time-independent obstacles is shown in Figure 2.29 [Solarglassshield17].



Figure 2.29 Dust on PV as time-independent obstacles.

Physical damage as time-independent obstacles is shown in Figure 2.30 [Homepower11].



Figure 2.30 Physical damage as time-independent obstacles.

2.10.3 Evaluation of obstacles

These two types of obstacles are classified and identified in this work with simulation. This work is important to detect fault of a PV panel. In result part the details identification of obstacles is given. The obstacles effect that create shadow on PV is simulated from two cells to a PV panel. PV cells are analyzed through two cells connected in series and parallel condition. This model is built under SIMULINK model. A PV panel consist of 72 cells is constructed to get significant behavior using SIMULINK model.

2.11 Experiment and Simulation

In this section, a detailed method is described for this work. Matlab, Simulink, measurement and instrumentation system are used for the whole work. MATLAB code is generated for computational modeling of PV cell. In Matlab error function modeling is created and the both models are used to identify the sensitiveness of internal parameters. This PV model with environmental parameters through error function the sensitiveness is analyzed. Correlation between different parameters of the environment is demonstrated in Matlab. Also, the correlation coefficient is calculated using person correlation function of this software.

For non-constant load analysis, the instrumentation and measurement system is used to get the real-time data from PV panel. In this process different resistances are used to simulate non-constant load. These data are analyzed in Matlab software to identify their significant.

Smart grid (SG) system needs information from different parts of PV plants that makes it more efficient. More knowledge about the system helps to build efficient central system of SG. Modeling of the system is vital to enrich the knowledge of SG that help to create intelligent workable system.

2.11.1 Instrumentation and measurement

This part explains about the measurement and instrumentation process from the aspect of PV measurement. Doing experiment with PV panel in a real environment and get the information with more accuracy is important to identify the underlying behavior of the panel. There are many different processes to do the work. Data acquisition (DAQ) and single generator are using in this work to get the valid information from the real-time system. This information later on used for identifying different characteristics.

In an instrumentation control system which included instrumentation, hardware for a connection established between computer program and instrument, a computer that has the programmable software. Mainly instrumentation control is a system to connect instruments with programmable software using different hardware that makes connectivity and measures automatically from a

third-party device. Instrumentation is essential in the field of automatic control and analyses sensors and devices. Recent colossal development of instrumentation helps to understand different system easily. It also helps to observe the devices remotely, and all the information that is occurring in a system is automatically logged in a workstation. Later this information is used to understand the behavior of environment both the internal and external of the system. Instrumentation interface with computer for controlling is shown in Figure 2.31 [Autosofttech18].

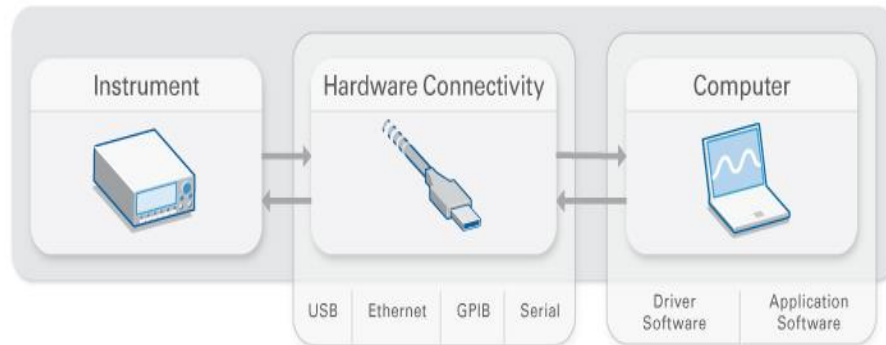


Figure 2.31 Instrumentation interface with computer for controlling.

In this diagram, it shows that instruments connect with computer with different types of ports. These ports could be easily readable by a computer that has drivers and application software to read the data. Universal serial bus (USB) is a standard interface for enabling the communication between instruments and the controller such as computer [Techopedia18]. It replaces a wide range of interfaces in communication with the control system. Hot swapping makes USB more usable that helps to control device continuing the work without a system reboot. Another important thing about USB is it uses direct current (DC). In the experiments, the devices use USB port for connecting with the computer. Data Acquisition interface with computer is shown in Figure 2.32 [Autosofttech18].

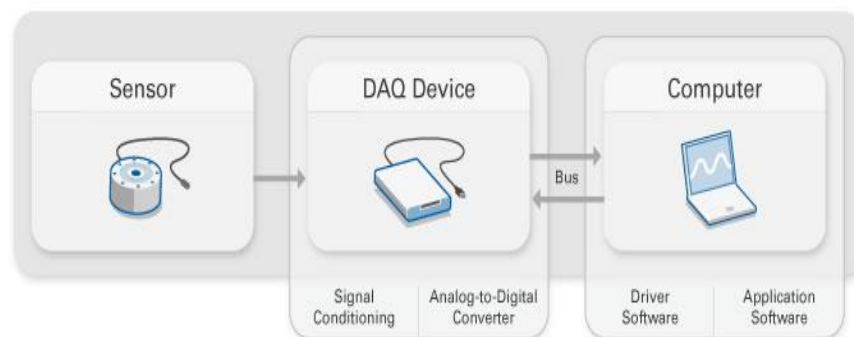


Figure 2.32 Data Acquisition interface with computer.

This is a diagram for a pathway from sensor or device that needs to measure is connected with DAQ that is connected with the workstation. It is smart enough to convert the Analog signal to digital signal. Then the digital signal is recognized by computer using driver and application software.

In this part of the work, MATLAB 2017a is used as programmable software that establishes a connection with instrumentation. PC could be connected with USB, Ethernet, GPIB, serial ports. GPIB port to USB is used for connection of this work. Drivers for different hardware had been installed in the computer. Windows 7 environment is used for the work.

Data acquisition (DAQ) device plays an important role as a middleware that connects with sensors and on the other hand connects with a computer which has its driver. The computer can understand the signal from DAQ because it has the driver and the application software. Using application software, the computer can decode the signal from DAQ and also sends the signal to instrumentation part. NI USB-6009 DAQ is shown in Figure 2.33 [NI16].



Figure 2.33 NI USB-6009 DAQ.

Figure.2.33 is the NI USB-6009 data acquisition; it is very efficient and low-cost device with multifunction that communicates with the computer. It connects with a computer with USB. Signal description for NI USB-6009 is shown in Figure 2.34 [NI16].

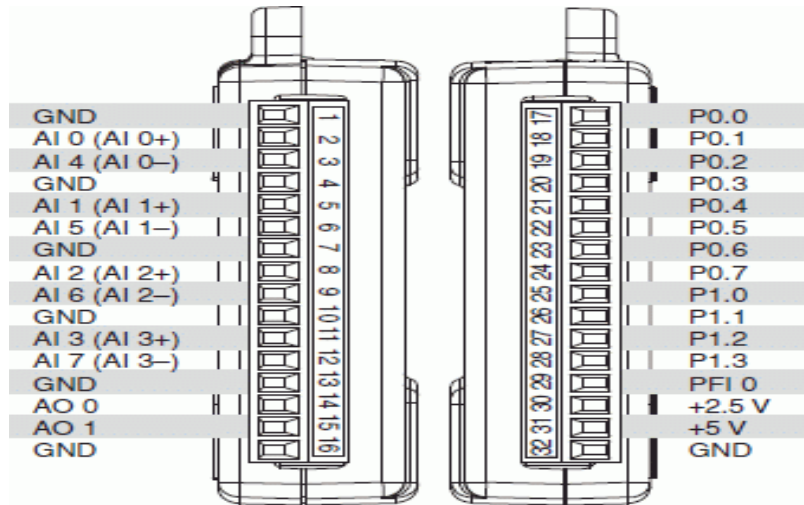


Figure 2.34 Signal description for NI USB-6009.

Figure 2.34 shows the signal description of the NI-6009 that is used for the work. It has 8 Analog inputs at 12 or 14 bit and up to 48 KS/s and 2 Analog output at 12 bits. It has one 32 bit, 5 MHz counter. Digital input-output lines 12 bit and 32-bit counter. The triggering technique is digital. It is normally used for environmental data logging in a faster way. For lab experiment, it is an ideal device.

AFG 320 is an arbitrary function generator. It has two independent channels. It loads waveforms from Oscilloscopes using GPIB interface. From computer software interface using GPIB, different waveforms are possible to generate as per requirement. AFG 320 function generator is shown in Figure.2.35 [Tektronix16].



Figure 2.35 AFG 320 function generator.

Figure 2.35 shows the AFG 320 function generator in operating mode and is connected with a computer to generate required waveform. Matlab code is used to give command to the signal generator for expected signal type, frequency and amplitude.

GPIB-USB-HS is an IEEE 488 controller device which is namely an instrument control device that is possible to connect with computer with USB. In this work, this one is used to control function generator instrument to generate a different kind of wave functions to measure different point of PV panel. GPIB-USB-HS interface is shown in Figure 2.36 [NI16].



Figure 2.36 GPIB-USB-HS interface.

A low power PV panel is used for the experiment, and it is a monocrystalline silicon PV panel. This output is suitable for the DAQ, if it is more power conversion one then the DAQ, that is used would not work because it works in low voltage and low current situation. Monocrystalline silicon PV panel is shown in Figure 2.37 [Rashel16a].



Figure 2.37 Monocrystalline silicon PV panel.

Figure 2.37 shows a PV panel that is used for the experiment. It is used for different design scenario of non-constant load. The PV is connected in a breadboard, and through the breadboard, it connects with DAQ and function generator.

The computer had the driver software installed and the application software. The interface of Matlab helps to do the work in a simple way. Matlab code is powerful enough to communicate with both DAQ and GPIB. DAQ and signal generator connect to computer is shown in Figure 2.38 [Autosofttech18].

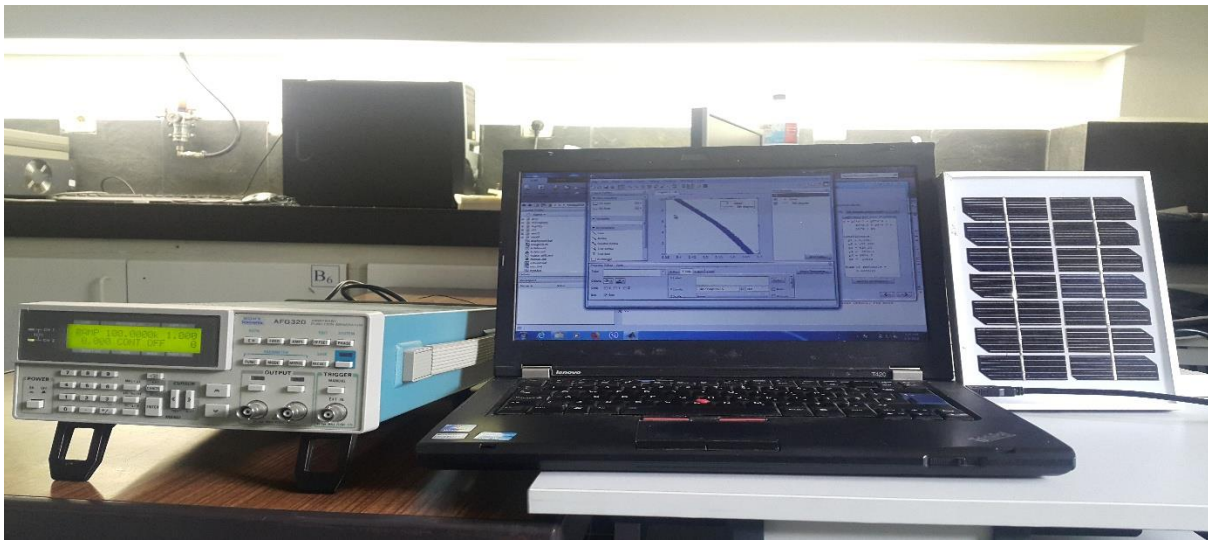


Figure 2.38 DAQ and signal generator connect to computer.

Figure 2.38 shows the working setup for the experiment's different phenomenon. The computer has drivers for all devices of National Instrumentation. Matlab is installed in the computer to do the total work and gives the command to the function generator. DAQ is connected with the computer and gives the information of the PV output to the computer, and it is translated through Matlab. The resistance that is used for the experiments is inputted through the Matlab code.

The PV panel is connected with a breadboard. PV panel's voltage measure to get the open circuit voltage point and then it connects with a series resistance that works as a load resistance and the voltage is measured for the load resistance. The function generator is connected with PV panel in parallel and connected with resistance, and it generates a function to get the different point of the I-V and P-V curve. This curve is for a specific scenario that is created in a lab to identify the

importance of the situation. This setup is used for non-constant load and also for the obstacle observe section.

The equivalent circuit diagram is drawn for the work. In the circuit diagram, the set up for the PV panel is given. Circuit diagram for PV for measurement is shown in Figure 2.39 [Ahmed17].

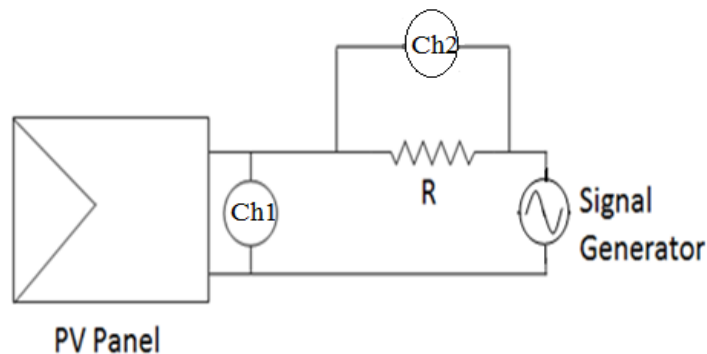


Figure 2.39 Circuit diagram for PV for measurement.

Figure 2.39 shows the circuit diagram of the PV panel with instruments to measure the current and voltage with non-constant load.

Both channel 1 (Ch_1) and channel 2 (Ch_2) of DAQ is connected with measurement system and also with workstation by USB cable. Signal generator is connected with workstation with GPIB cable. For measurement process, at first the signal generator is disabled from the system to measure the open circuit voltage using, Ch_1 (Channel 1). Then the value passes to the workstation. Using the value computer calculate the amplitude and offset for the RAMP signal. Then workstation send the value to the signal generator to start the measurement process. Signal generator generates RAMP signal with specific value that comes from workstation. Then Ch_2 (Channel 2) measures the voltage. Using the value of additive resistance (R) and the value of voltage, workstation calculate the current. In this process the frequency of the signal is 10 Hz. All the values are stored in the workstation. These values are used to analyze and generated the I-V and P-V curves.

Measurement gives numerical value or point of an object or an event [Pedhazur91, VIM08]. This numerical value must follow a standard unit system and in this way compare with any other same type of event that happened in the world. In every field of research, engineering and daily day life measurement is an essential part. Measurement has an international system of units. All over the

world people try to maintain a standard way to make the numerical value in a specific way that is recognizable by all.

In the experiment, measurement is done for all the instrument and devices that are related to the experimental work. The instruments are connected with a computer with USB device and the driver software are installed in the user computer and Matlab software is used as application software. All data is collected through the Matlab interface. The values for measurement is given to the Matlab output space. The data are collected and used for different analysis. These data are used for making a different graph.

2.11.2 MATLAB and Simulink modeling

This work is done under windows 7 of the 64-bit version. For simulation of this thesis, Matlab and Simulink are used. Matlab is one of the pioneer software for solving the mathematical equation and for solving model in mathematical approach. It is a good software and support the massive amount of facility to solve the diversified problem in the real-time system.

Simulink is block based simulation software that was developed by MathWorks. It is a block diagram based modeling environment that simulates and analyses multi domain dynamic and model-based system. [Mathworks15]. It has an enormous standard library that has built in a model of different of real-time components. These small pieces of the model are used to create a big system that is used to simulate real scenarios. The information of the Simulink system is transferred to Matlab and analysis with different functions.

2.12 Summary

This chapter describes essential theories in brief to make the work understandable to all. It also narrates important formulation that is needed. Instrumentation and measurement systems are described related to the experiment of the work. Detail simulation and modeling techniques are described. Experimental setup and the theory includes in this chapter. Good and approximate simulation and modeling of a system helps to get valuable information and gives estimated result that is close to real-time value. Next chapter gives detail results and discussion of the work and that is the continuation of the theory work.

CHAPTER

3

Results and Discussion

This chapter describes the outcomes of the work. In this journey, several results have been found. These results are important to enrich knowledge about the PV power conversion system aiming to improve the modeling and predicting power generation. The information about power generation capacity of energy resources connected with Smart Grid is important. Among them, PV is significant because of its nonlinear behavior; different types of internal and external behaviors are simulated and experimented to better model a PV system. At the beginning of this chapter, the work to identify the sensitive parameters of PV five parameters single diode model is introduced; using the understand ability of sensitiveness, the simplified model is created and compared with the standard one; later, three environmental parameters are analyzed to understand their effect on the system and correlation between them is analyzed. Non-constant load is analyzed for different circumstances using variable resistances. Finally, different types of obstacles are classified and the behaviors are identified using Simulink models.

3.1 Introduction

Improvement of the PV power conversion system's performance and efficiency has vital part that is modeling of the PV system under different internal and environmental conditions. Presently, in the operation phase, the efficiency of the system is not up to the mark, but a huge amount of plants has established already generated and contributed with a significant amount of electricity. This contribution to the energy sector enables a sustainable development grow. Green energy and sustainable development is the ultimate solution to reach the Paris agreement goal [COP2115].

After a colossal research work, the efficiency of PV has reached 46% in the laboratory (NREL) [NREL15]; in commercial places the efficiency reaches 22.5% under standard testing condition (STC). The efficiency variation depends on technologies and surrounding environmental factor. The power generation from the PV is entirely dependent on the environmental and ambient conditions. There are different kinds of studies going on to improve the performance: a group of researchers is working on new types of materials able to use the sunlight more efficiently increasing the efficiency of PV cells and a group of people is trying to enhance conditions to generate more power; due to the environmental deprived behaviors and poor performance of electrical equipment under rapid changing condition, the power conversion rate decreased significantly; sometimes become less than 5%, but this research aims to get optimized environmental conditions and surroundings able to generate a maximum power equal to standard conditions.

This work aims to identify the system's internal strength, making the way to increase the performance of PV, protect it from the external noise that decreases the performance dramatically. Here, noise are those components that decrease the performance of the system; they can be internal or external. There are internal parameters and environmental parameters directly related to the power conversion. Among all these parameters, some of them have a positive effect, and others have an adverse effect. There are different crucial issues where the system needs more focus to improve the performance.

For establishing a PV plant that integrates with smart grid, it is essential to take care of all the factors that have even a little influence on PV power generation. Smart grid system overview is shown in Figure 3.1 [Tranverter18, Rashel17a].

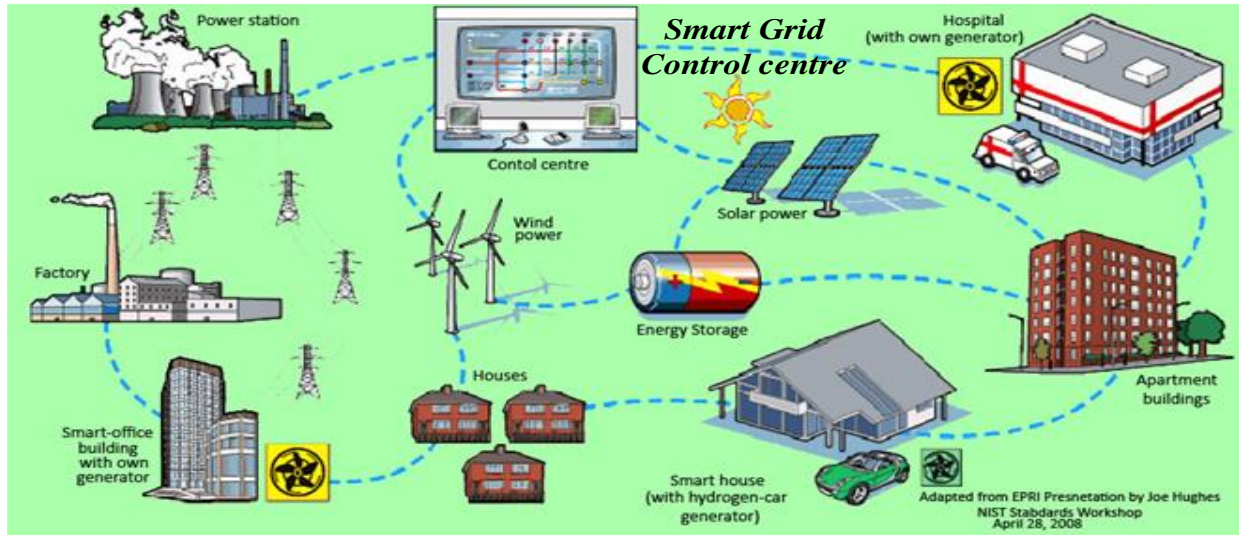


Figure 3.1 Smart Grid System.

SG is a control center that is connected with PV and also with other renewable energy sources in bidirectional way utilizing all the possible procedure to improve the performance. Renewable energy and SG is the right combination for a sustainable energy in the future. This work contributes to understanding the PV and its surrounding environment, to identify the sensitive features and faults.

Smart Grid system integrates with future predictable PV power conversion system is shown in Figure 3.2 [Rashel16b, Rashel17a]. In the flow chart the process is as, first it collects the forecasted data from the meteorological station on that day. This values are used with the single diode five parameter model to estimate the PV power generation from the system. Get the value of PV power generation from historical data. Analysis both data and find their absolute difference with each other. If absolute value of the difference is less than five percent, then go to the next step otherwise run the first simulation with present meteorological data and also analyze the historical data with present meteorological data to check their variation. After getting difference less than five percent, calculate the mean value from both predicted and historical data. Give this value to smart grid to calculate the rest of the power needed from the other kind of power generation. This system helps

to reduce the fossil fuel power generation using renewable energy and among them PV plays an important role.

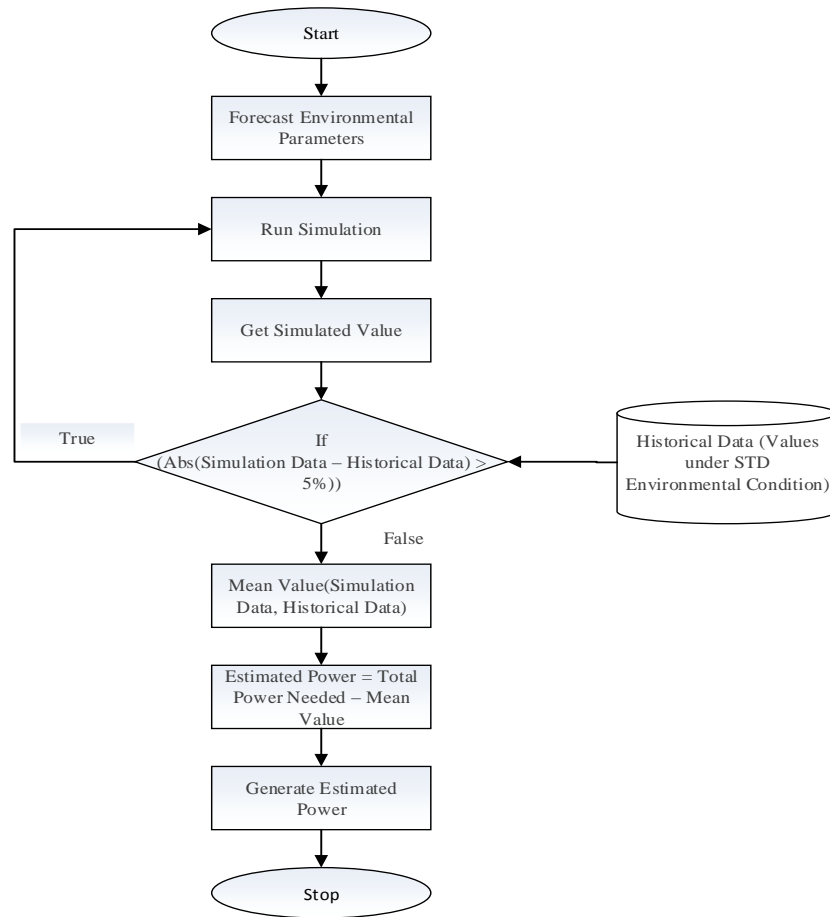


Figure 3.2 Predict PV output to integrate with SG system.

3.2 Case Study 1: Sensitivity Analysis for Internal Parameters

This section describes the result and discusses the details of the outcome from the simulation to identify the sensitiveness of the internal parameters of the five parameters single diode model. Semiconductor photovoltaic cells that is simple in the mechanism that use irradiance to generate power. According to Figure 2.14 the five internal parameters are: photocurrent, cell temperature, diode ideality factor, series resistance, shunt resistance and diode saturation current. In this work,

cell temperature also includes to see the sensitivity. All these parameters are observed through the sensitivity test using error function. The error function introduces the optimal value for each parameter by minimizing the error.

3.2.1 Photocurrent

In the electrical equivalent circuit (Figure 2.14) of PV modelled in Section 2.5.2, the photocurrent is the source of electricity. Depending on irradiation, its conversion rate varies: less irradiation generates less output and high irradiation generates much electricity. The irradiance with enough power gives strength to electrons to jump out and help to travel on the surface of the semiconductor, thus generating electricity.

The simulation assists checking the behavior of power generation with changing values of photocurrent. In this simulation, the current value varies from 0 A to 4.2577 A and this is done changing the irradiation value in (2.24) and get the value of photocurrent (I_L). The current (I) output is generated using (2.15). After doing several calculations by using (2.23), the error function is calculated. These values are used to generate the graph that shows the sensitivity of the parameter. Changes of the error function with different photocurrent values is shown in Figure 3.3 [Rashel17a, Rashel17c, Rashel16b].

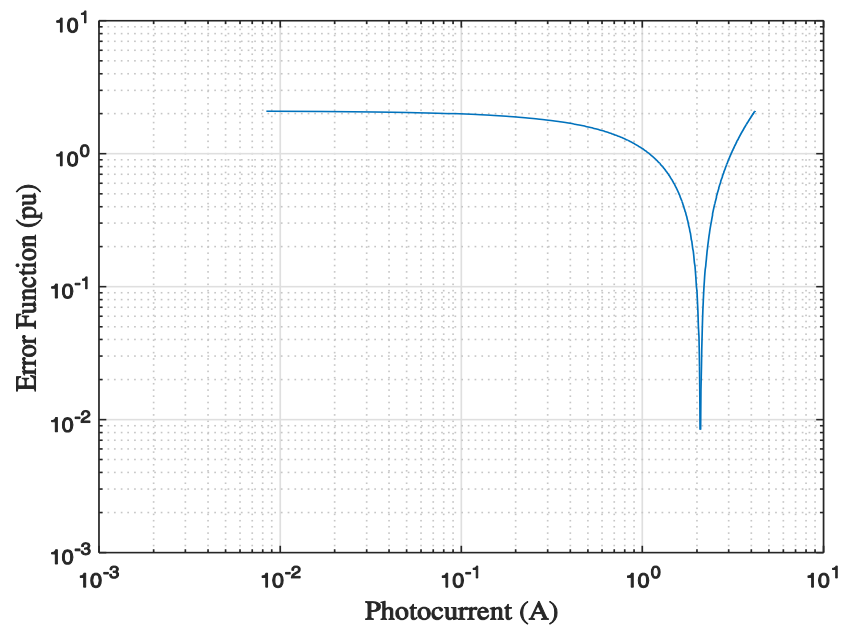


Figure 3.3 Change of error function with different photocurrent.

The curve behavior is significant enough to understand the sensitivity. The curve is drawn in logarithmic scale to view the full region of both x and y axis. The I_L values are changing and, at the same time, the curve behavior is changing. The curve has two part, one left before the optimal value and another one is the right side in that. The right side of the curve is more convergence to the optimal value. So, to get optimal value for this parameter, it is important to overestimate the value to get the optimal value quickly. The value of the parameter is changing in a small range, and the effect is significant for PV power generation, the photocurrent is one of the most critical parts and plays a vital role. Concluding, the error function analysis identified the sensitiveness of this parameter and its behavior is one of the most significant among all other internal parameters (as it will be seen in the following sub-sections).

3.2.2 Internal cell temperature

Internal cell temperature (T) has direct impact on (2.15), and it has a significant impact on the performance of PV power conversion. Changing the value of this factor, changes the power conversion rate. This parameter has shown significant influence on the productivity [Rashel17a].

The error function is used to get the information about the sensitivity of cell temperature. It is calculated through (2.23). In the sensitivity analysis, the value of T is start from 273K and is gradually increases till 353K. It is done to identify the sensitivity of this parameter. Calculated values are used to create the graph presented on Figure 3.4 and it can be seen that the parameter presents a vital behavior [Rashel17a, Rashel17c, Rashel16b].

The shape of the curve demonstrates a considerable change in the error function when changing the value of T . The line is sensing the small change, and it is counted as sensitiveness of the parameter. For y-axis, the logarithmic scale is used to observe the total behavior of the curve in a frame. The result is significant to identify it as a sensitive parameter. Due to its variation the output of the PV changes in a significant range.

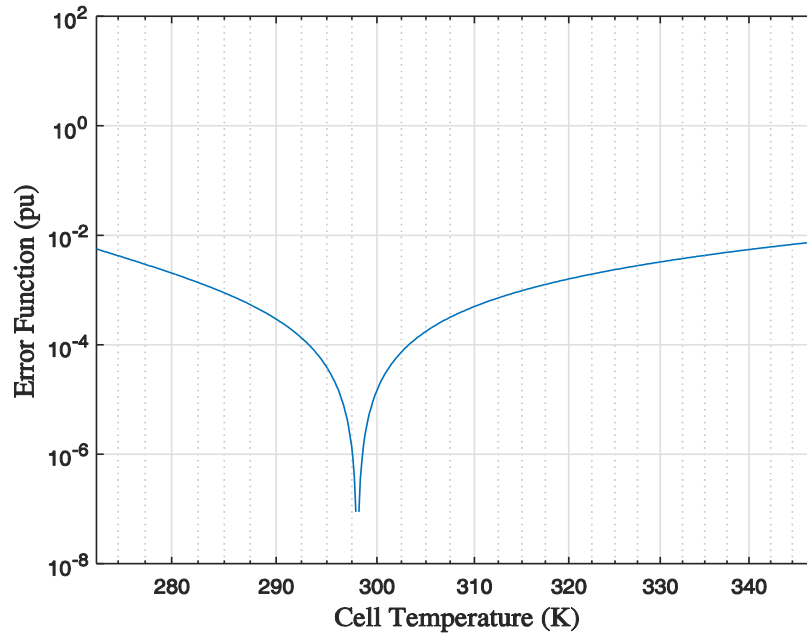


Figure 3.4 Change of error function with different cell temperature.

In the Figure 3.4, the curve has two part, one left before the optimal value and another one is the right side of it. The left side of the curve is more convergence to the optimal value. So, to get optimal value for this parameter, it is important to underestimate the value to get it quickly.

3.2.3 Diode ideality factor

Diode ideality factor changes the PV power conversion rate. During operation, changing parameter's values produces a change in the output value.

For understanding diode ideality factor's (n) sensitiveness, the error function is calculated using (2.23) changing the value of n and the output is obtained using (2.15). In the simulation, the value of the parameter is kept in the range between zero to two. One is the ideal diode ideality factor. The results of this simulation are presented in Figure 3.5 (y-axis uses a logarithmic scale to get the full picture in the box of the graph) [Rashel17a, Rashel17c, Rashel16b].

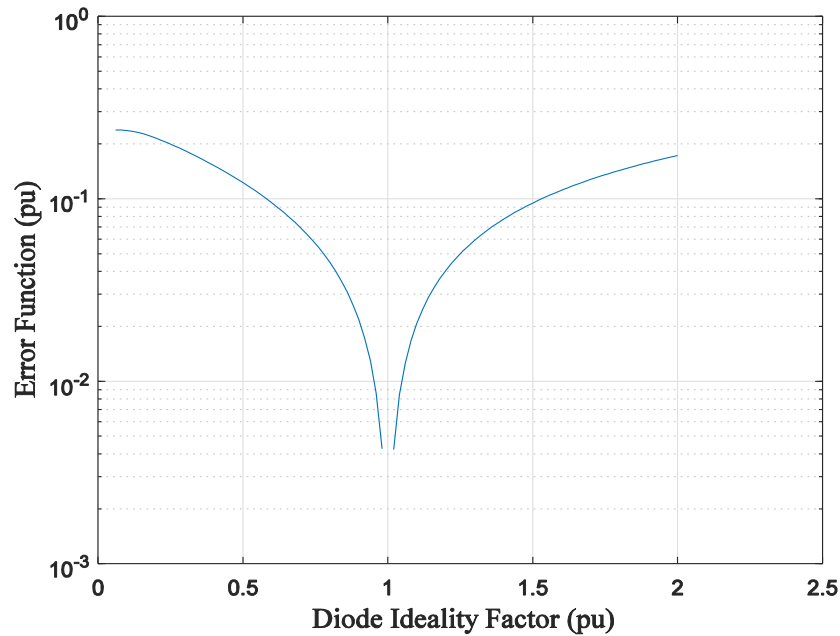


Figure 3.5 Change of error function with different diode ideality factor.

From the curve variation, a definite idea about the behavior of n with error function is observed. It shows sensitiveness and has a significant behavior. The curve has two part, one left before the optimal value and another one is the right side of it. The left side of the curve is more quickly convergence to the optimal value. So, to get optimal value for this parameter, it is important to underestimate the value to get the it quickly.

3.2.4 Series resistance

Series resistance(R_s) is included in (2.15) and changes in this parameter are used to calculate the error function. Range of series resistance is from 0Ω to 0.02Ω . Changes along the error function are significant and the simulation gives Figure 3.6, giving the idea that it has sensitivity (y-axis is taken in logarithmic scale for keeping them in a single frame).

In Figure 3.6, the graph shows sensitiveness through changing error function. It also shows identical behavior. In the simple ideal diode model of PV (Figure 2.12), the series resistance is not included; When Series resistance's value is 0Ω then it supports the simple diode model of PV. Concluding, when R_s value is 0 then it gives the maximum output and behave like ideal cell model.

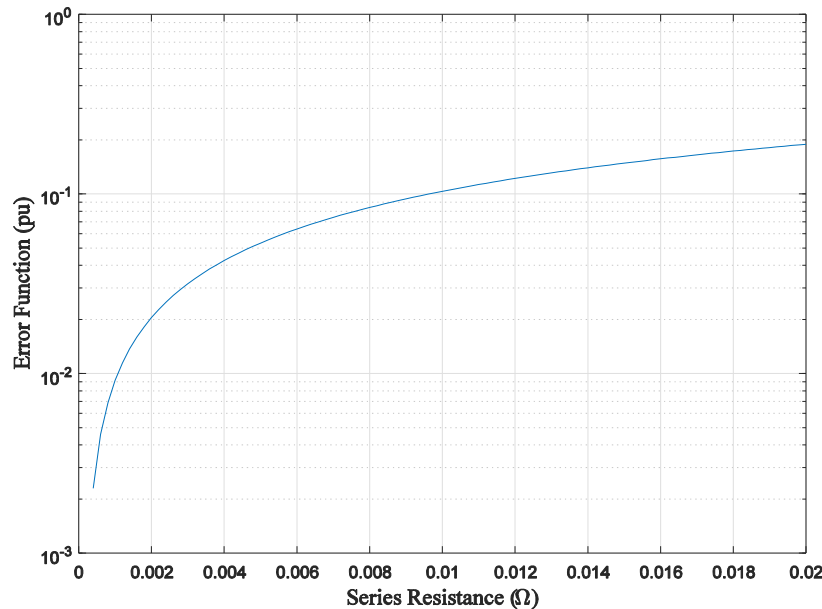


Figure 3.6 Change of error function with different series resistance.

The curve has only one part, zero is the optimal value for this parameter. After going right from the optimal value, the right side is showing convergence toward optimal value. It is better to overestimate this parameter.

3.2.5 Shunt resistance

Shunt resistance (R_{sh}) is included in (2.15) it is also considered in the simulation model to verify its sensitivity. (2.23) is used to calculate the error function with changing values from 50 Ω to 2.5 kΩ.

Figure 3.7 shows the simulation results (both axis of the curve is drawn under logarithmic scale) and it can be concluded that, in this range, the error function is sensitive to changes on the shunt resistance [Rashel17a, Rashel17c, Rashel16b]. The curve has two part, one left before the optimal value and another one is the right side of it. The left side of the curve is more quickly convergence to the optimal value. So, to get optimal value for this parameter, it is important to underestimate the starting value of this parameter to get optimal value quickly. To get the total picture in a single window, the x-axis and y-axis are converted to logarithmic scale.

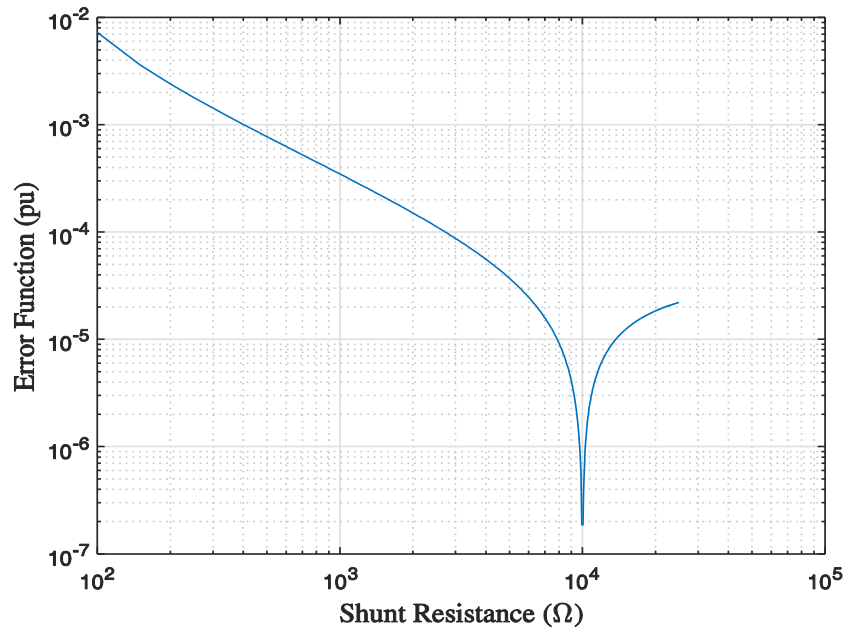


Figure 3.7 Change of error function with different shunt resistance.

In the Figure 3.7, the curve has the fluctuation that is evidently observed. A significant change in the value of the parameter gives a small change in the curve of the graph, giving the idea that it is not as significant as the other parameters and that it could be excluded from the single diode five parameters PV model that shows in Figure 2.12.

3.2.6 Saturation current

The single diode five parameters model contains another essential parameter called diode saturation current (I_0) and it includes in (2.15).

The error function is calculated from (2.23) and changes of error function with different diode saturation current is shown in Figure 3.8 (both axes are taken in logarithmic scale for keeping them in a single frame) [Rashel17a, Rashel17c, Rashel16b].

This graph gives a clear idea of the behavior of the parameter; when a small change happens a noticeable variation in the error function is shown. This concludes that it is a sensitive parameter.

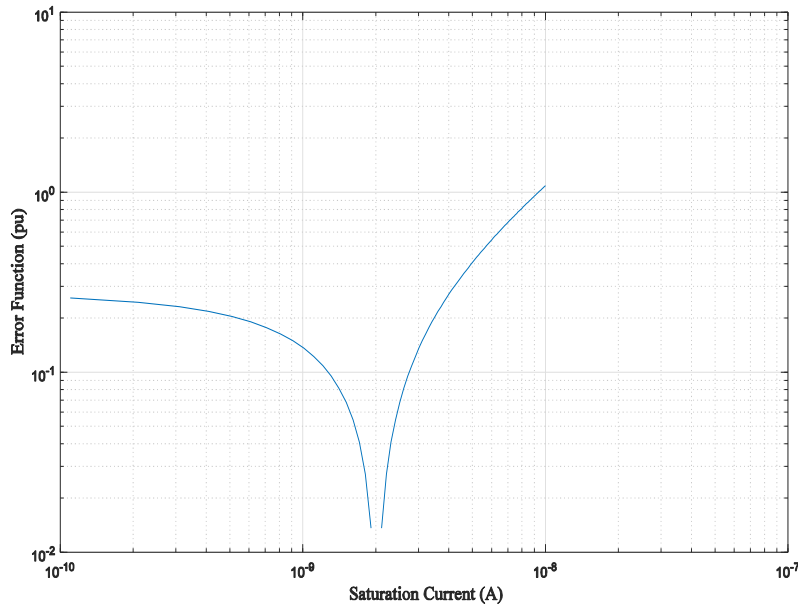


Figure 3.8 Change of error function with different saturation current.

In Figure 3.8, the curve has two part, one left before the optimal value and another one is the right side of it. The right side of the curve is more quickly convergence to the optimal value. So, to get optimal value for this parameter, it is important to overestimate the value to get the it quickly.

All of these curve shows minimum point, where the optimal values are occurred by minimizing the error between optimal and measure values (here measured values are getting through simulating a specific parameter's variation at a time).

3.2.7 Simplified PV model

The sensitivity analysis made shows different significant indications for different internal parameters. The simplified model, presented in (2.11), is an ideal single diode PV equation and takes these results into account as it does not include series and shunt resistance.

It is identified that the majority of the internal parameters have a vital importance to create simplified model, namely the photocurrent, internal cell temperature, saturation current and diode ideality factor and series resistance. They show significant sensitiveness when compared

to shunt resistance. When series resistance become zero and shunt resistance value is larger than load resistance then as ideal case (2.15) become (2.11)

Figure 3.9 shows voltage vs. current curve for the simplified and the five parameter model, using (2.11) and (2.15). It is clearly observed that the difference is not noticeable [Rashel17a, Rashel16d].

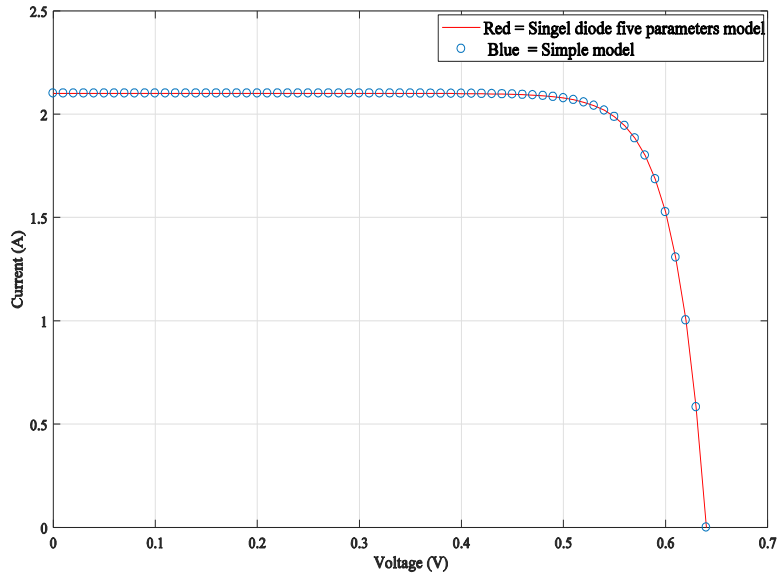


Figure 3.9 I-V curve for simple and single diode five parameters PV cell model.

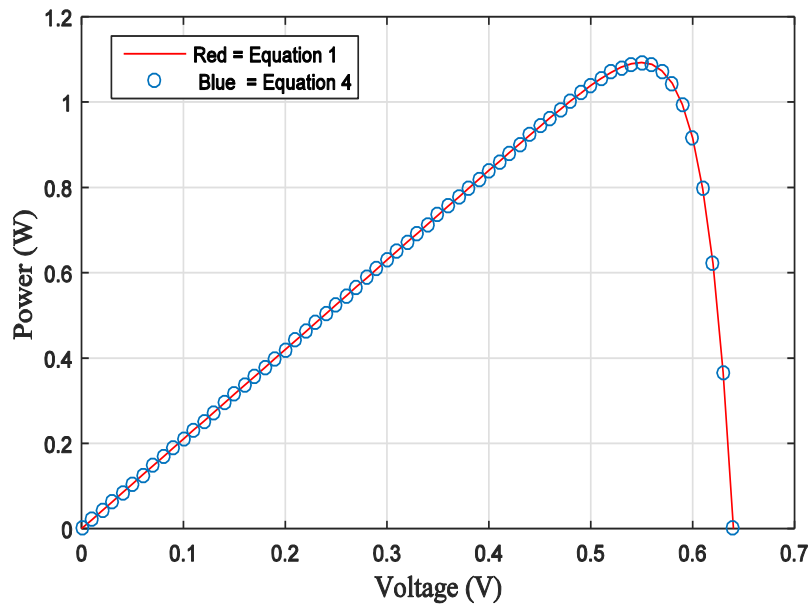


Figure 3.10 P-V curve for simple and single diode five parameter PV cell model.

Figure 3.10 presents the voltage vs. power curve for the simple and the five parameter model using both (2.11) and (2.15). Like the voltage-current curve differences are not noticeable in this figure also [Rashel17a, Rashel16d].

In conclusion, the sensitivity tests done and the simple model and five parameter model is compare in Figure 3.9 and Figure 3.10. The five parameters single diode model and the simple model for PV has close result.

3.3 Case Study 2: Sensitivity Analysis for Environmental Parameters

PV has direct relation with environmental parameters. This work shows that it has dependency on irradiation, ambient temperature, and wind speed [Rashel16c, Rashel17b, Rashel18a]. Sensitivity analysis is done to understand the sensitiveness of environmental parameters. Using (2.15) and (2.23) is used in Matlab to create the simulation model for error function. Sensitiveness is identified using sensitivity analysis through error function.

In the first three sub-section, error function is build and identify the sensitiveness of each environmental parameters. Voltage-current and voltage-power curves for changing value of these parameters is observed.

After that in next few sub-sections, two parameters values have changed in the same time to get output behavior of PV in that scenarios. These simulations give the information to understand the PV power conversion under rapidly changing environmental conditions. Later on other sub-sections, correlation test on environmental parameters to get the internal relationship of them. It is known that atmosphere itself is very sophisticated in nature, and many more variables are related to each other.

■ Irradiance

Irradiance is one of the essential environmental parameter that is the primary energy to generate electricity from PV. Irradiance sensitivity is analysis through error function. The simulation is build using Matlab to visualize the sensitiveness. The irradiance value varies

from 0 W/m^2 to 2000 W/m^2 . 1000 W/m^2 is count as STC condition for PV power conversion. Using (2.15), with changing irradiance value to get output. Using (2.23) the error function is calculated. Using these values, the graph is constructed. Irradiance with error function is shown in Figure 3.11 [Rashel18, Rashel17b, Rashel16c].

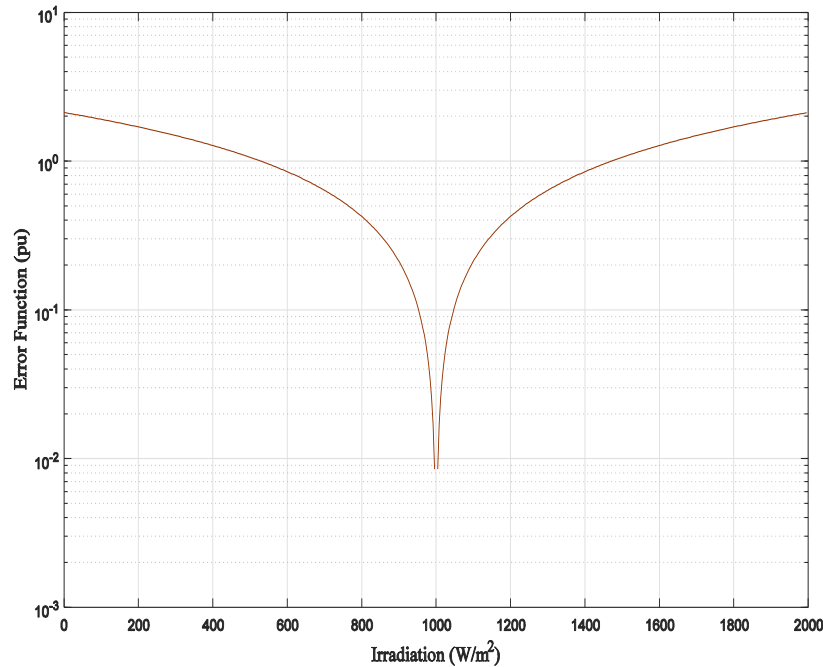


Figure 3.11 Irradiance with error function.

This graph shows the clear picture for irradiance sensitiveness with PV output. Y-axis is kept in logarithmic scale to see the total view in a window. With the change of values, the error function slope is changing. A small change of the value gives a significant response to the error function and it defines as a sensitive one to PV.

The output of (2.15) is observed with different irradiance value. It shows that with varying irradiance, voltage, current and power are also changing. This fluctuating makes change on maximum power. Increasing of irradiance also quick increases I_{sc} and increase V_{oc} . Voltage and current curve under different irradiance is shown in Figure 3.12 [Rashel18a, Rashel17b, Rashel16c].

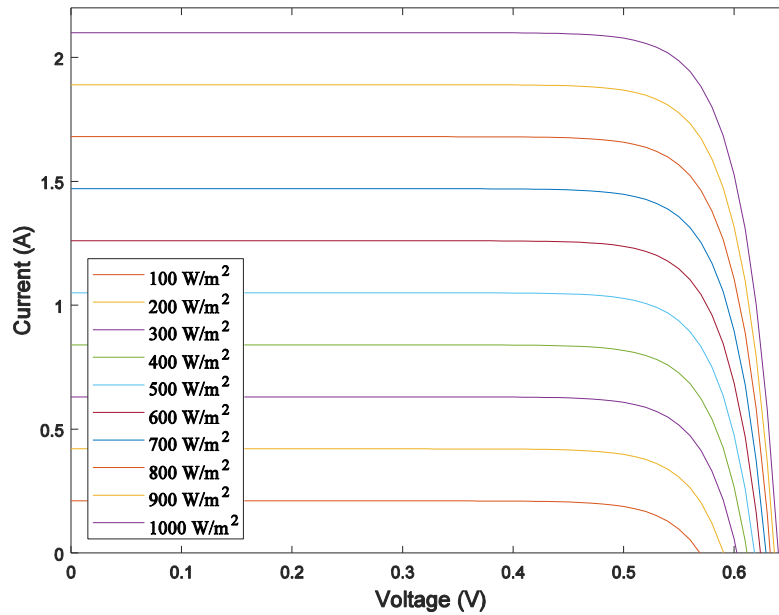


Figure 3.12 I-V curve under different irradiance.

It shows voltage and current curve under variable irradiance condition where I_{sc} and V_{oc} also changing.

With varying irradiance, the maximum power point (MPP) also vary. When irradiance is low, the maximum power point is also low. Increasing irradiance, increases the MPP and increases the output.

Voltage and power curve under different irradiance is shown in Figure 3.13 [Rashel18a, Rashel17b, Rashel16c].

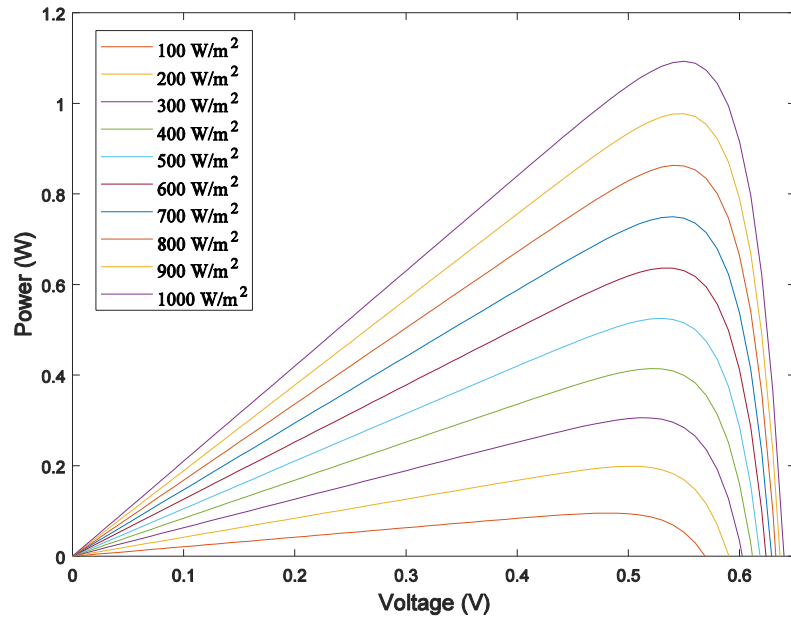


Figure 3.13 P-V curve under different irradiance.

This graph shows the voltage power curve under variable irradiance condition with varying MPP. The power is increasing with increasing irradiance. MPP is with changing irradiance is shown below Figure 3.14.

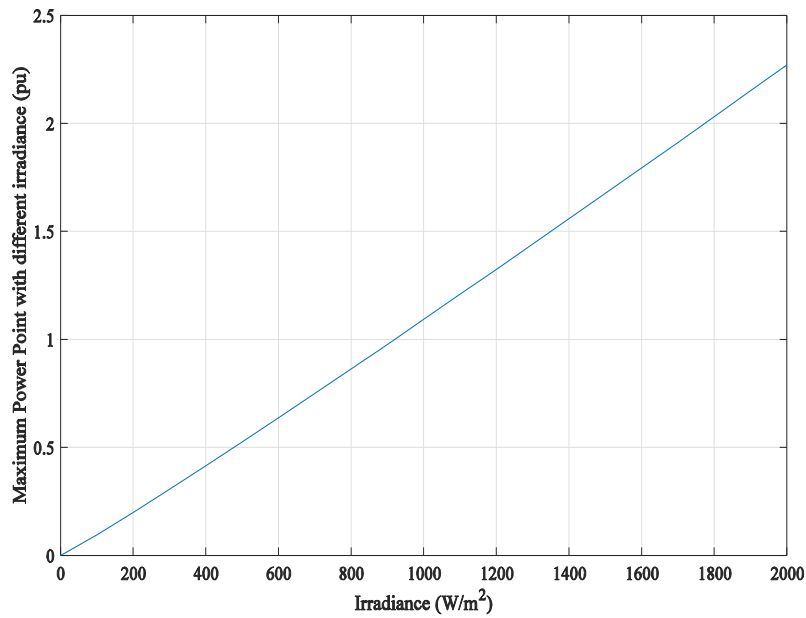


Figure 3.14 Maximum power points with increasing irradiance.

This graph shows that the irradiance changing increasing the MPP and it helps to get more power.

■ Ambient temperature

Ambient temperature has a significant role in PV power conversion system. It is observed that increases temperature decreases the performance dramatically [Rashel18a]. To identify and understand the role of this parameter the simulation is done using (2.15). Error function is used to identify sensitiveness. Using (2.29) cell temperature with ambient condition (T_{cell}) is possible to calculate from ambient temperature (T_{air}) without wind speed, and using (2.30) T_{cell} is possible to calculated with ambient temperature and wind speed.

From (2.23) the sensitiveness of the parameter is got through error function. The graph gives precise information about the consequences. T_{air} with error function to identify sensitivity is shown in Figure 3.15 [Rashel18a, Rashel17b, Rashel16c].

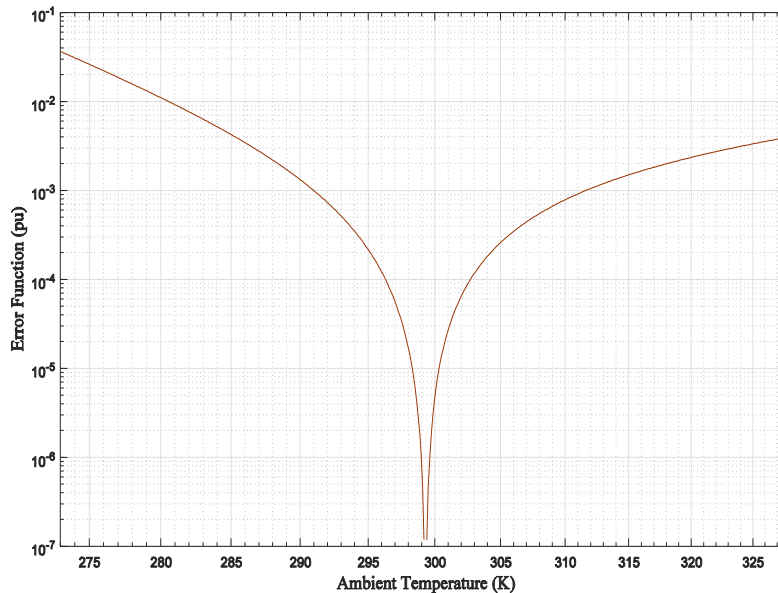


Figure 3.15 Ambient temperature with Error function to identify sensitivity.

This graph shows significant sensitiveness with changing the value of ambient temperature that changes the value of error function. Y-axis is kept in the logarithmic scale to get the full

picture in a single window. Small change of ambient temperature makes a momentous conversion in error function.

Using different ambient temperature, the voltage and current curve is drawn. Increasing ambient temperature decrease the open circuit voltage (V_{oc}) and increase short-circuit current (I_{sc}). Voltage and current curve under different ambient temperature is shown in Figure 3.16 [Rashel18a, Rashel17b, Rashel16c].

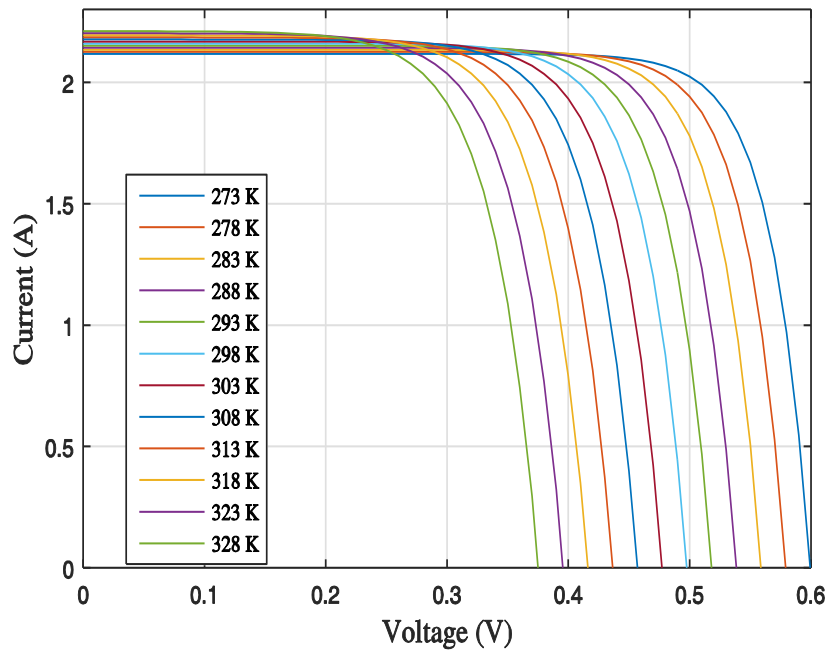


Figure 3.16 Voltage-current curve under different ambient temperature.

It shows the specific behavior of PV current and voltage under different ambient temperature. Ambient temperature has a direct relation with cell temperature; this relation is got through (2.29) and (2.30). When ambient temperature increases, it assists to increase the cell temperature also. Because of increasing ambient temperature cell could not reduce its temperature by convection or radiation with its surrounding area. On the other hand, reduces ambient temperature assists to decrease cell temperature.

Voltage and power curve is important for understanding the maximum power and ambient temperature relation. Voltage and power curve under different ambient temperature is shown in Figure 3.17 [Rashel18a, Rashel17b, Rashel16c].

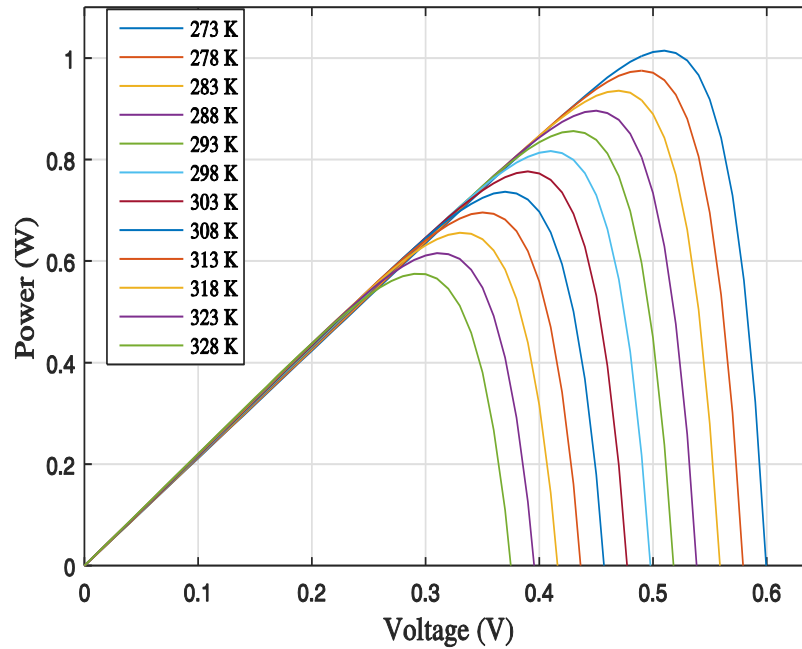


Figure 3.17 Voltage-power curve under different ambient temperature.

This graph shows clear view of the maximum power point (MPP) properties. It is decreasing with changing ambient temperature. The power generation is decreased when the ambient temperature is increased.

Both I-V and P-V curves include the ambient temperature effect and due to the T_{air} effect the V_{max} decrease to 0.6V. To see MPP behavior with the different ambient temperature a graph is created. MPP with increasing ambient temperature is shown in Figure 3.18 [Rashel18a, Rashel17b, Rashel16c].

This graph gives the clear visualization of ambient temperature and MPP that states that during low ambient temperature is a helpful condition for PV. During operation time, PV starts to generate power and the same time it produces heat. In maximum PV technologies, on average 15% of irradiance converted to electricity and rest of them converted to heat. This generated heat, increases PV cell temperature and also by the process of radiation it goes to surrounding areas and assists to rise ambient temperature. And due to hot ambient temperature, the PV cells could not release heat to surrounding environment. In this way, it makes adverse effect on PV performance. This result is supported by [Katz01, Dubey13].

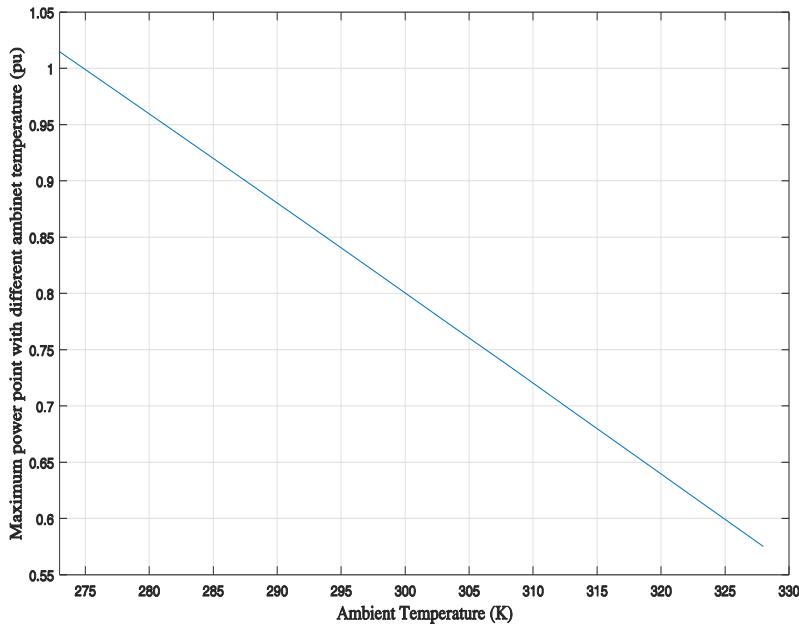


Figure 3.18 Maximum power points with increasing ambient temperature.

Wind speed

This is another environmental parameter that has a decent role on the performance of PV system. This parameter is helped to reduce the ambient temperature of the PV cell. Ambient temperature and PV have a negative correlation with each other. Increasing ambient temperature always decreases the performance of PV. Wind speed (v_{wind}) aids to take out ambient heated air, that helps to reduce cell temperature by forced convection and radiation process.

The sensitivity of v_{wind} to the PV model is understood through error function. It has a direct relation to ambient temperature, and (2.30) calculates cell temperature with wind speed. Using (2.23) is used to get the error function. v_{wind} with error function is shown in Figure 3.19 [Rashel18a, Rashel17b, Rashel16c].

This graph shows changes in wind speed assist to change in error function. A small change of v_{wind} changes error function and show sensitiveness.

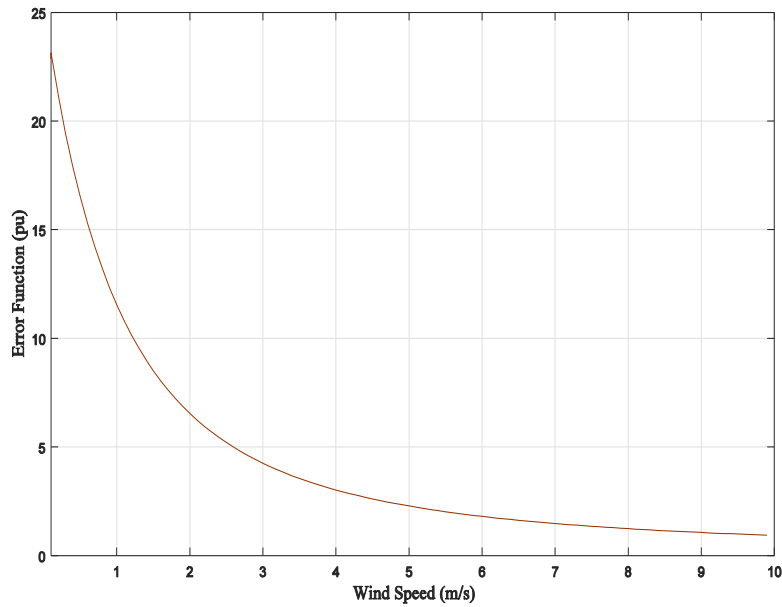


Figure 3.19 Wind speed with error function.

Voltage and current is an informative curve that gives knowledge about the output of PV on the basis of changing v_{wind} . v_{wind} is linked to cell temperature. Voltage and current curve under different wind speed is shown in Figure 3.20 [Rashel18a, Rashel17b, Rashel16c].

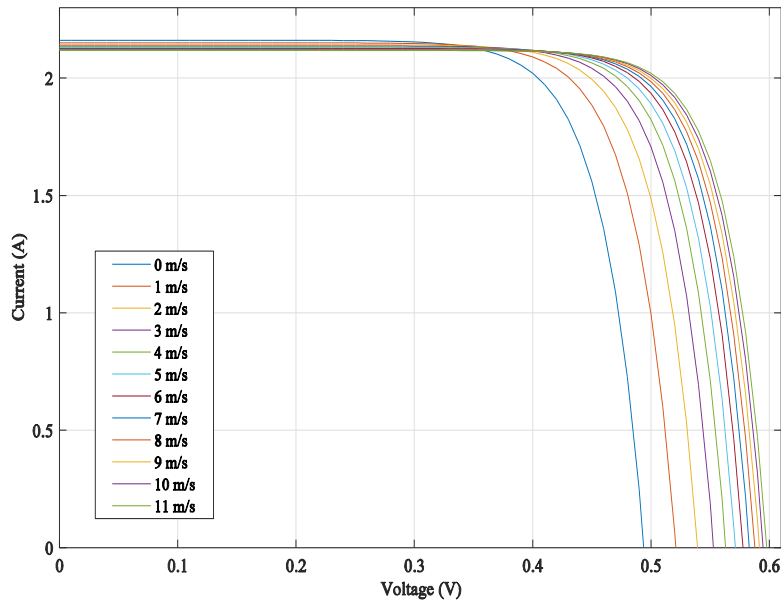


Figure 3.20 Voltage-current curve under different wind speed.

This graph shows that variation of v_{wind} changes the voltage and current value. The increasing speed of the wind makes a positive impact on the PV output. Mainly the wind flew away from the heated ambient air that surrounding around PV panel. It makes force convection; when heated air goes away, it carries the heat from PV. It helps PV to radiate the temperature from panel to surrounding area. PV releases temperature to surrounding area by using heat transfer process: convection and radiation. Wind flow helps to continue heat transfer process. Voltage and power curve under different v_{wind} is shown in Figure 3.21 [Rashel17b].

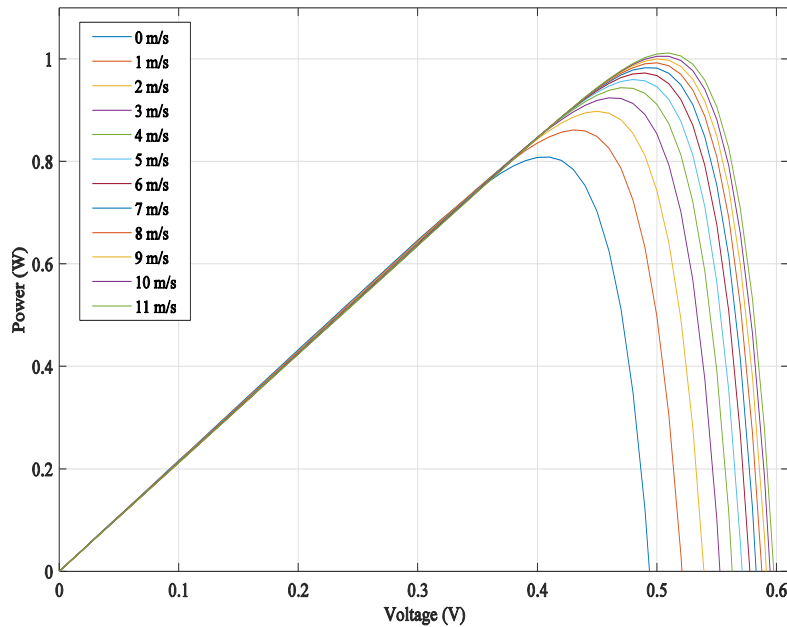


Figure 3.21 Power-voltage curve under different wind speed.

This graph shows the voltage and power curve for changing v_{wind} . Increasing v_{wind} , increasing the maximum power point and it is because of reducing the cell temperature. Maximum power point with increasing v_{wind} is shown in Figure 3.22 [Rashel17b].

Both I-V and P-V curves include the ambient temperature effect and due to the T_{air} with v_{wind} the V_{max} decrease to 0.6V. This graph gives the graph of v_{wind} with maximum power point. It shows that the increasing speed of wind makes increasing the maximum power point. The increase rate of maximum power point is not linear with v_{wind} . The increment of maximum power point with increasing v_{wind} follows the logarithmic function, as $P_{max} = In x$.

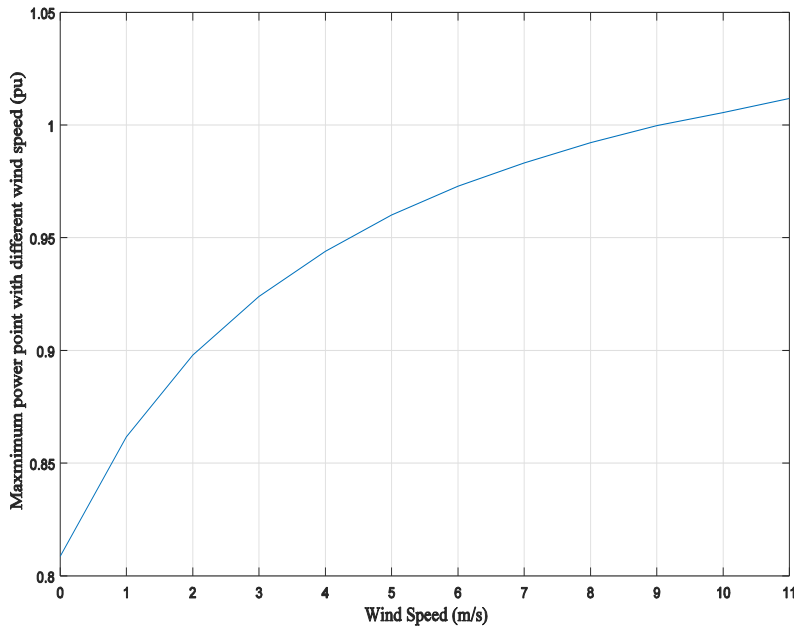


Figure 3.22 Maximum power point with increasing wind speed.

Changing irradiance and ambient temperature

In this sub-section, two parameters' values have changed at the same time; irradiance and ambient temperature values. This work is done to simulate the dynamic behavior of the atmosphere. In real time environmental parameters are always changing and the change randomly. Simulation of the environment is complicated enough. PV power with changing irradiance and ambient temperature is shown in Figure 3.23 [Rashel18a, Rashel17b, Rashel16c].

This graph shows that in the condition of increasing irradiance and low ambient temperature give the maximum power. And decreasing of irradiance with increased ambient temperature give the minimum power output.

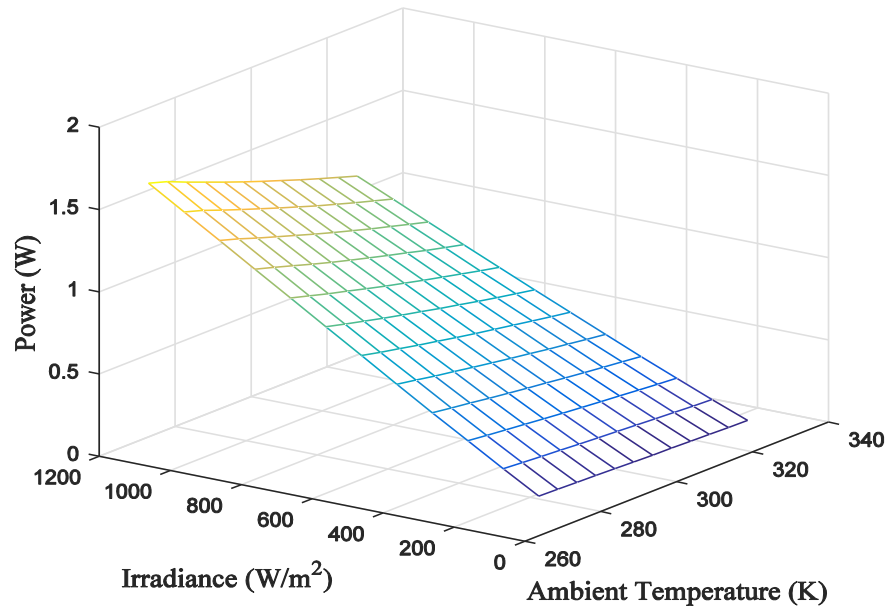


Figure 3.23 Power with changing irradiance and ambient temperature.

Table 3.1 Changing irradiance and ambient temperature with their maximum power point

Irradiance (W/m ²)	Ambient Temperature (K)	P_{max} (W)
100	273	1.5431
200	278	1.5068
300	283	1.4585
400	288	1.4122
500	293	1.3674
600	298	1.3237
700	303	1.2816
800	308	1.2411
900	313	1.2014
1000	318	1.1622
1100	323	1.1241
1200	328	1.0880

Changing ambient temperature and wind speed

This sub-section is simulated varying ambient temperature and wind speed against PV power conversion. Ambient temperature has shown that it has a negative impact on PV performance. Wind speed has a positive impact on PV power conversion [Rashel17]. PV power with changing ambient temperature and wind speed is shown in Figure 3.24 [Rashel18a, Rashel17b, Rashel16c].

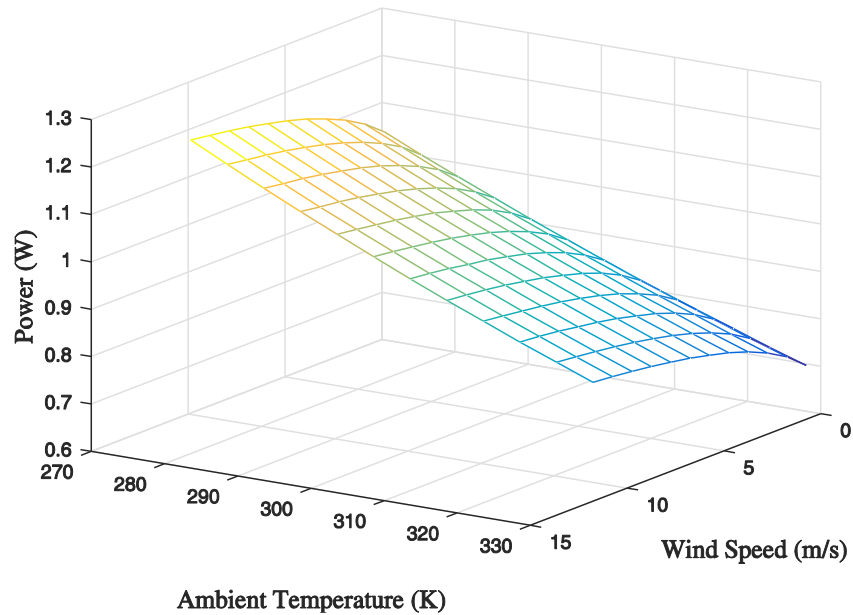


Figure 3.24 Power with changing ambient temperature and wind speed.

This graph states that changing ambient temperature and changing wind speed made change in PV power output. At the point where wind speed is zero, and the ambient temperature is high, there occurred lowest power. At the point where the power rises to the highest point, there wind speed is at the highest point, and ambient temperature is at the lowest point. In low ambient temperature, the cell temperature is increasing because PV cell itself generate heat in the working process.

Table 3.2 Changing wind speed and ambient temperature with their maximum power

Wind Speed (m/s)	Ambient Temperature (K)	P_{max} (W)
0	273	1.0170
1	278	1.0618
2	283	1.0942
3	288	1.1179
4	293	1.1366
5	298	1.1519
6	303	1.1640
7	308	1.1739
8	313	1.1828
9	318	1.1901
10	323	1.1960
11	328	1.2022

Changing irradiance and wind speed

In this sub-section, changing irradiance and changing wind speed is observed at same time. PV power with changing wind speed and irradiance is shown in Figure 3.25 [Rashel18a, Rashel17b, Rashel16c].

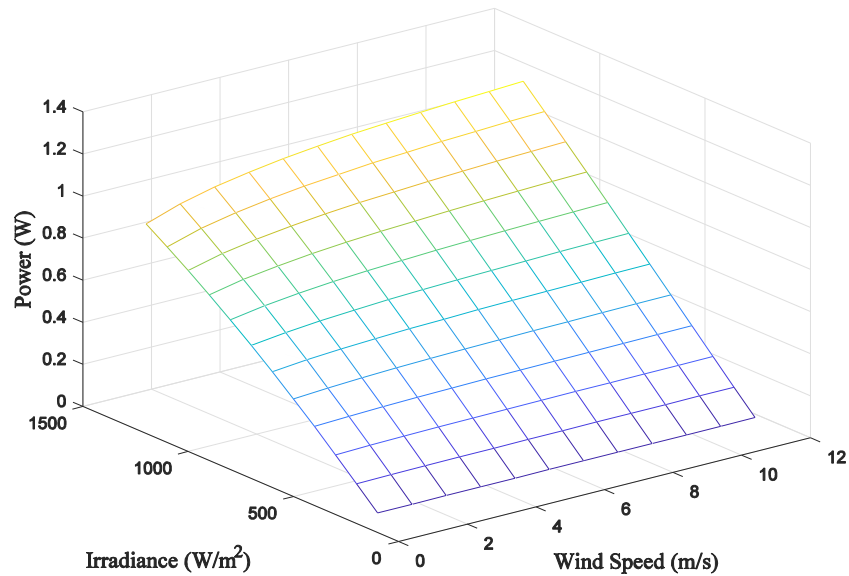


Figure 3.25 Power with changing wind speed and irradiance.

This graph shows the highest power output is occurred where irradiance is high and the wind speed also high, and lowest power point is consisting of low irradiance and low wind speed.

Table 3.3 Changing wind speed and irradiance with their maximum power

Wind Speed (m/s)	Irradiance (W/m ²)	P_{max} (W)
0	100	0.9961
1	200	1.0500
2	300	1.0898
3	400	1.1185
4	500	1.1413
5	600	1.1600
6	700	1.1750
7	800	1.1869
8	900	1.1980
9	1000	1.2068
10	1100	1.2142
11	1200	1.2218

From this sub-section, it is clear that both of the irradiance and wind speed have positive effect on PV power conversion and ambient temperature has a negative impact on it.

Correlation between environmental parameters

Irradiance, ambient temperature and wind speed data are logged in the weather station of the University of Évora. This weather station has many other environmental data, and it is collecting data in real time and log them in the database. These stored data are used for correlation analysis. The correlation between irradiance, ambient temperature, and wind speed is analysis using person correlation test. This test helps to visualize the parameters' correlation between each other. These correlation coefficient plots are created with last four years' data of Évora, weather station. Only linear correlation is analyzed using this data [Clima18].

Correlation relation between irradiance and temperature is shown in Figure 3.26.

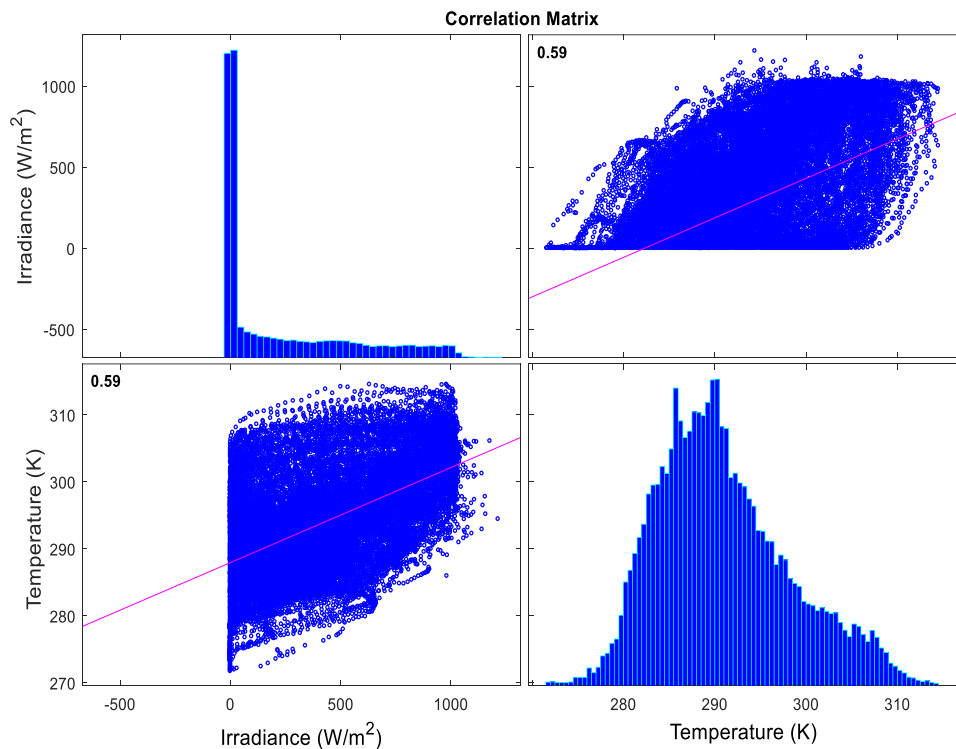


Figure 3.26 Correlation matrix of irradiance and temperature.

First correlation test is done between irradiance and temperature. The correlation coefficient value is equal to 0.59, and it is positive. It describes that they have a positive relationship between them. It tells that one variable increases and the other also increases. This fact makes the complicated situation for PV power conversion. Irradiance has a positive effect to PV, and on the other hand, ambient temperature has an adverse effect. Due to irradiance the ambient temperature also

increases in the environment. The positive value of correlation means when the irradiance increase then temperature also increases and with decreasing irradiance, temperature also decreases.

Another person correlation test is done with irradiance and wind speed, and they have a very low linear correlation, the value is equal to positive 0.10. Correlation relation matrix between irradiance and wind speed is shown in Figure 3.27.

Figure 3.27 Correlation matrix between irradiance and wind speed.

This graph gives the correlation relation between irradiance and wind speed that has a positive correlation and is not significant enough. Irradiance and wind speed are linearly correlated with each other, but their relationship is shallow in a linear manner.

Correlation relation matrix between wind speed and temperature is shown in Figure 3.28.

Figure 3.28 Correlation matrix between wind speed and temperature.

This graph shows correlation matrix between wind speed and temperature. The test correlation coefficient value is negative, and its value is equal to 0.05. Changing of wind speed has small negative effect on temperature. It is like, when wind speed increases then temperature decreases. This is an important observation that due to wind blowing the ambient temperature is decreasing that is important for PV power generation.

These correlation tests are done to see the internal correlation behavior of three imperative environmental parameters and their effect on each other. Irradiance, temperature and wind speed have direct impact on PV performance. From this correlation, it is identified that irradiance has positive correlation with temperature, where irradiance has positive effect on PV, and on the other hand, temperature has negative effect on PV and wind speed has positive impact on PV output performance by decreasing the temperature. That makes a complex scenario for the improvement of PV performance.

3.4 Case study 3: Non-constant Load

The load is a significant part of any kind of electrical source component. PV is a semiconductor component that generates electricity using solar energy. Changing of load make a significant impact on maximum power point of PV. Maximum PV system has batteries to store electrical energy. Some PV system has a direct connection to the grid system. The PV system that direct connection with a load needs a better understanding of load effect. In this section, with different resistances as a load is observed in real-time lab experiment. This work helps to identify behavior of PV with the non-constant load.

■ Different resistances as non-constant load

Different resistances are used for understanding the variable loads against PV. Using GPIB and DAQ the computer gets the value from the real-time system. It gives different voltage and current values that keep in the computer system to calculate the power for different resistances. The curves are fitted by fifth degree polynomial function.

Start with the resistance of $100\ \Omega$ as an additive load with the PV panel. Here the open circuit voltage (V_{oc}) is $5.0909\ \text{V}$, and short circuit (I_{sc}) current is $0.0055\ \text{A}$. Voltage and current with resistance load value of $100\ \Omega$ is shown in Figure 3.29.

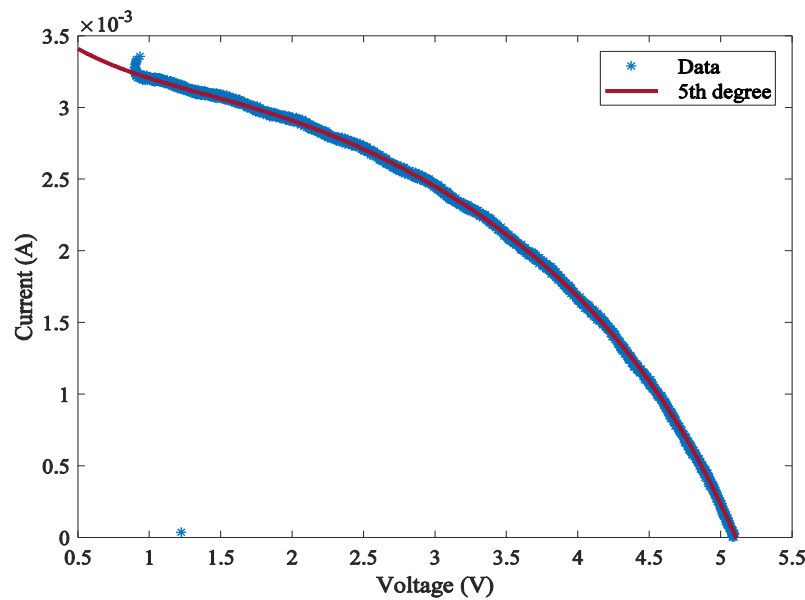


Figure 3.29 I-V curve with resistance load value of $100\ \Omega$.

For the given resistance the maximum power is 0.0281 W. For given load resistance value 100 Ω, the voltage and power is shown in Figure 3.30.

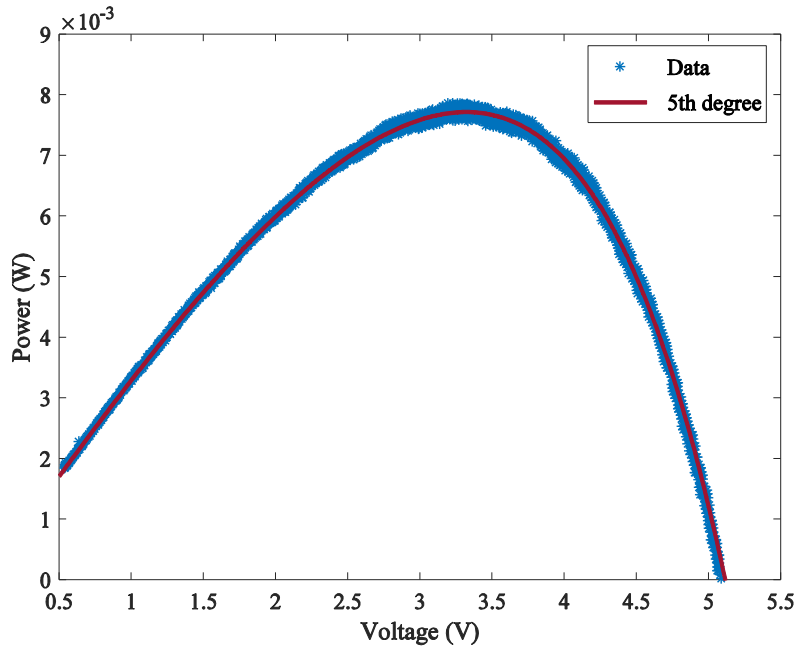


Figure 3.30 P-V curve with resistance load value of 100 Ω.

For the resistance 220 Ω, the V_{oc} value is 5.0959 V, and I_{sc} value is .0057 A. Voltage and current with resistance load value of 220 Ω is shown in Figure 3.31.

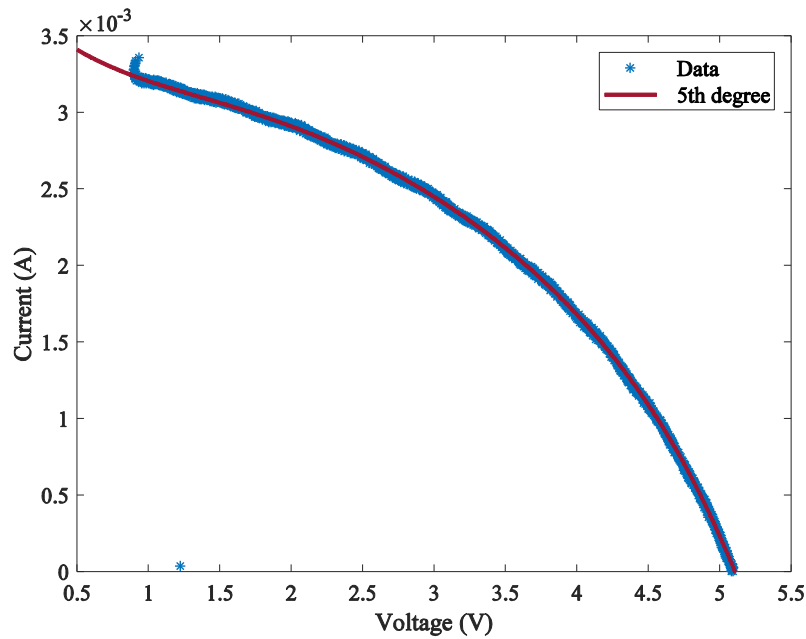


Figure 3.31 I-V curve with resistance as load value of 220 Ω.

For the given resistance the maximum power value is 0.0275 W. Voltage and power with resistance load value of 220 Ω is shown in Figure 3.32.

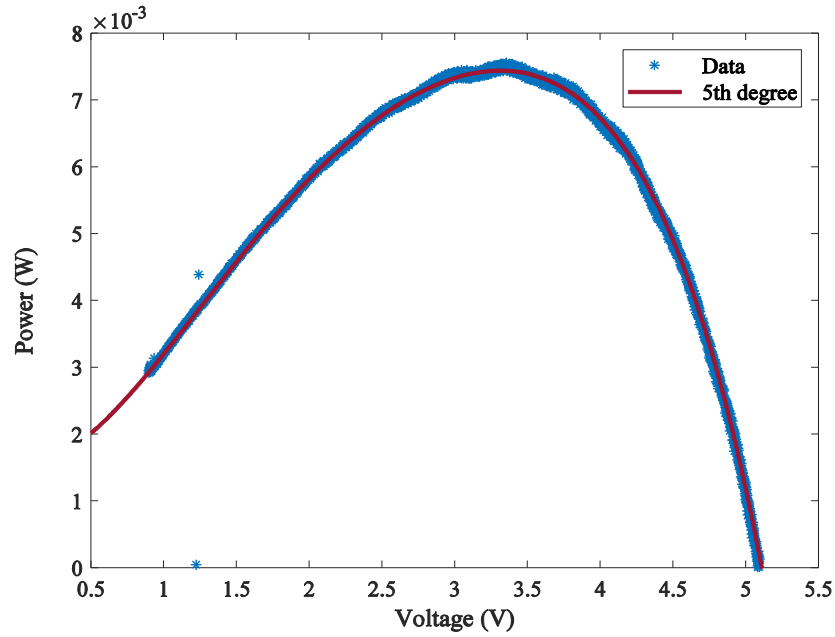


Figure 3.32 P-V curve with resistance load value of 220 Ω.

For the resistance 560 Ω, the V_{oc} value is 5.1214 V, and I_{sc} value is .0046 A. Voltage and current with resistance load value of 560 Ω is shown in Figure 3.33.

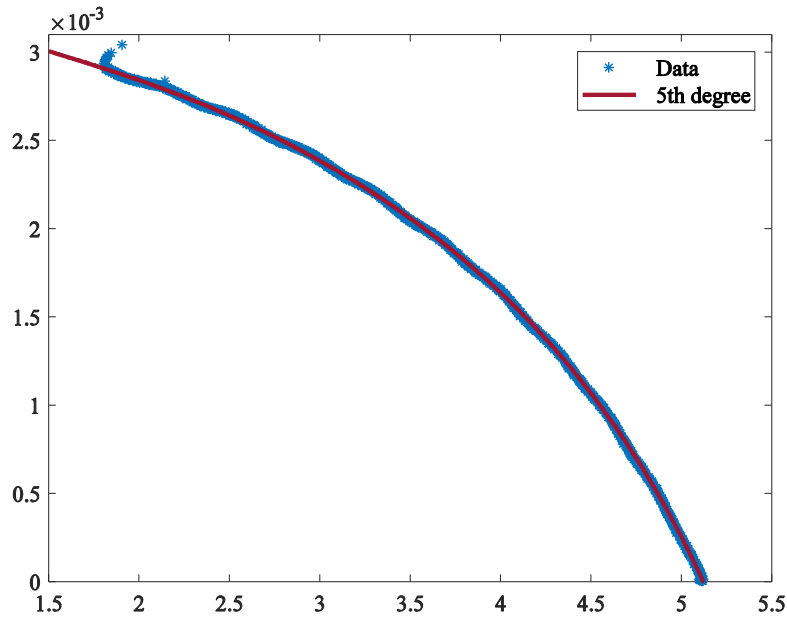


Figure 3.33 I-V curve with resistance as the load value of 560 Ω.

For given resistance the maximum power value is 0.0204 W. Voltage and power with resistance load value of 560 Ω is shown in Figure 3.34.

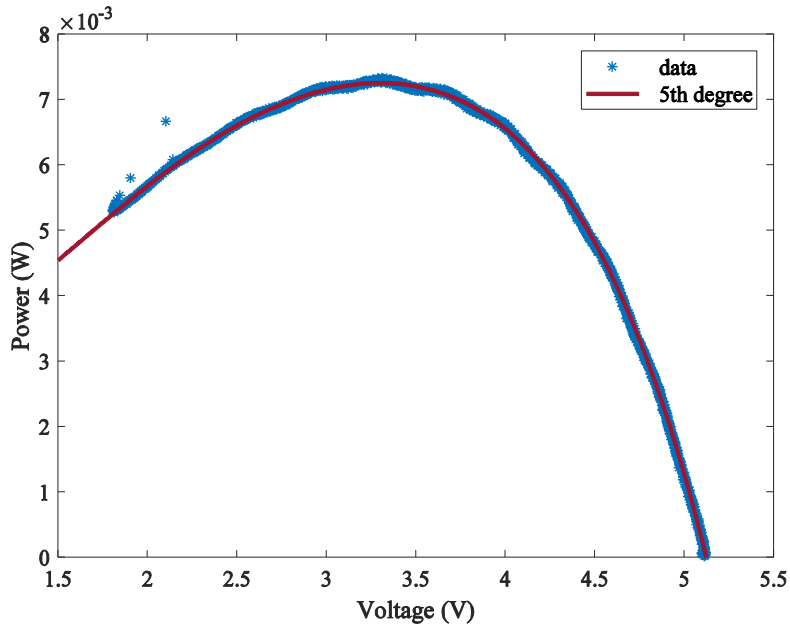


Figure 3.34 P-V curve with resistance as the load value of 560 Ω.

For the resistance 1500 Ω, the V_{oc} value is 5.1048 V, and I_{sc} value is 0.0029A. Voltage and current with resistance load value of 1500 Ω is shown in Figure 3.35.

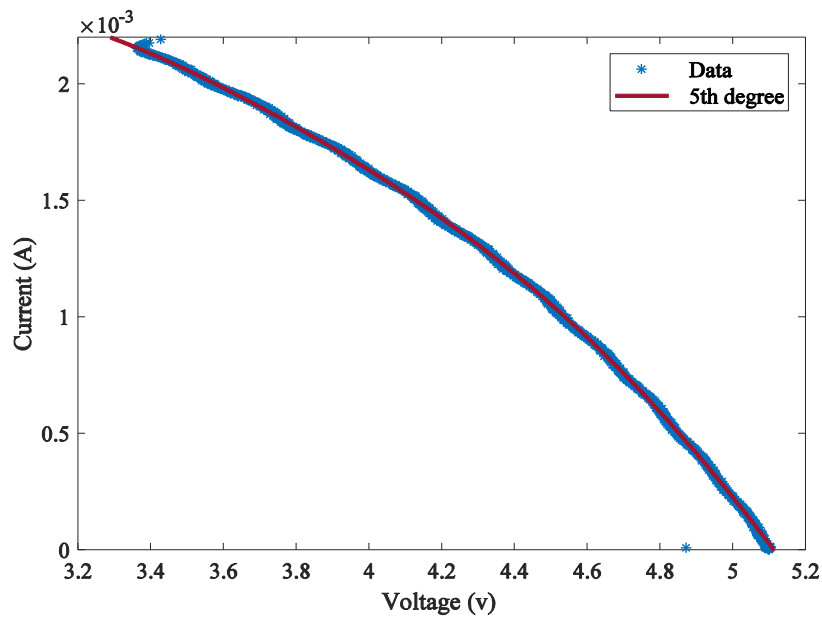


Figure 3.35 I-V curve with resistance as load value of 1500 Ω.

For given value the maximum power value is 0.0149 W. Voltage and power with resistance load value of $1500\ \Omega$ is shown in Figure 3.36.

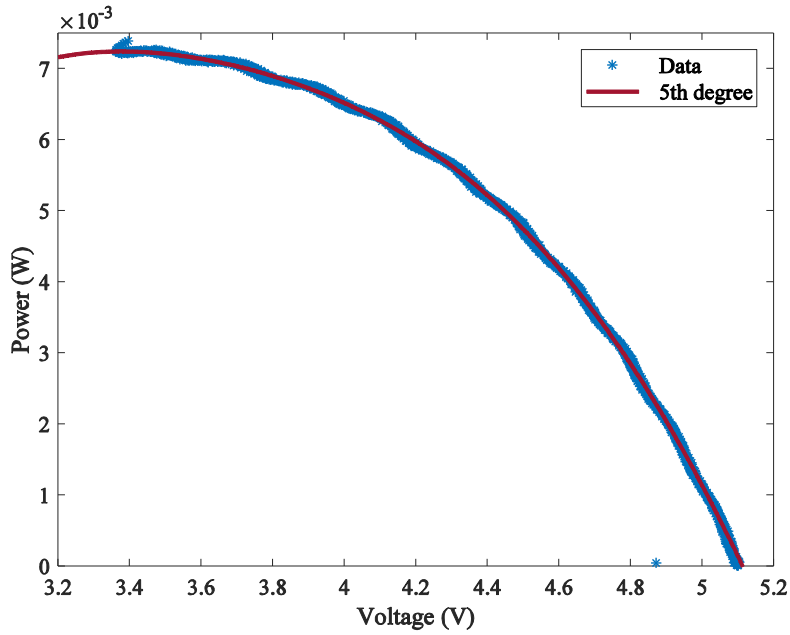


Figure 3.36 P-V curve with resistance as load value of $1500\ \Omega$.

For the resistance $4.7\ \text{k}\Omega$, the V_{oc} value is 5.1188 V, and I_{sc} value is 0.0010 A. Voltage and current with resistance load value of $4.7\ \text{k}\Omega$ is shown in Figure 3.37.

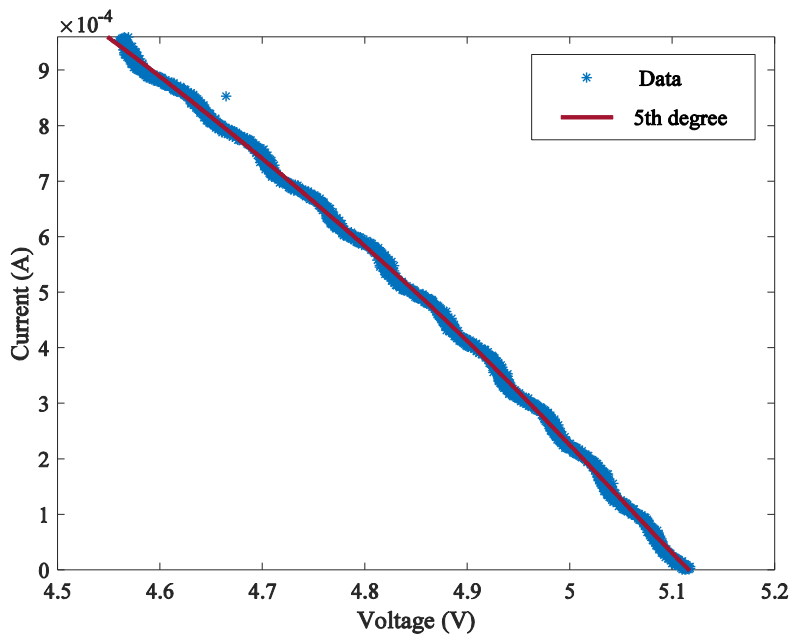


Figure 3.37 I-V curve with resistance as load value of $4.7\ \text{k}\Omega$.

For given resistance the maximum power value is 0.0053 W. Voltage and power with resistance load value of 4.7 k Ω is shown in Figure 3.38.

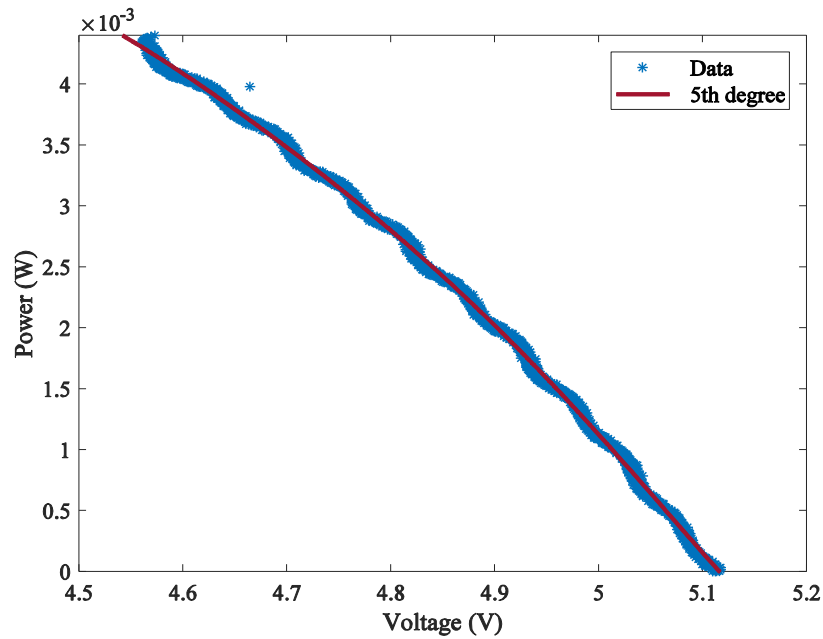


Figure 3.38 P-V curve with resistance as load value of 4.7 k Ω .

The different additive load resistance with respective maximum power is shown in Table 3.4.

Table 3.4 Different additive load resistance with respective maximum power

Resistance	V_{oc}	I_{sc}	P_{max}
100 Ω	5.0909 V	0.0055 A	0.0281 W
220 Ω	5.0959 V	0.0057 A	0.0275 W
560 Ω	5.1214 V	0.0046 A	0.0204 W
1.5 k Ω	5.1048 V	0.0029 A	0.0149 W
4.7 k Ω	5.1188 V	0.0010 A	0.0053 W

Table 3.4 shows increasing load values decrease the maximum power point of particular PV panel. Identify an optimal load for a PV panel is important. It is identified that the current at maximum power (I_{mp}) and voltage at maximum power (V_{mp}) is changing and change the MPP with the value of the load. Using five different resistances, get a different result with same PV panel under real environmental condition. Variation of load makes PV power and behavior unpredictable.

3.5 Case Study 4: Shadow of Obstacle on PV Panel

There are different kind of things that become obstacles for irradiance to reach PV panel working surface. Because of obstacles; like shadow, dust etc. maximum power point (MPP) get multiple picks meaning multiple local maxima in power curve. In this condition, it becomes difficult to get the global maxima.

In the section, the obstacles are divided into two categories, time-dependent obstacles, and time-independent obstacles. Like cloud in the sky is time-dependent obstacle; it is not a permanent one. Physical damage of cells is count as time-independent obstacles because of not changing with time. These two types of obstacles are analyzed in this section.

At the beginning the analysis is done for PV cells; for series and parallel connected two cells and they are investigated under different irradiance level. After that, a PV panel with 72 cells is used to do simulation for time-dependent obstacles, and time-independent obstacles. Simulations are done in Simulink. Results are discussed in details for different types of scenarios.

■ PV cells under obstacle

Two PV cells connected with series and parallel is observed under different irradiance level. It gives the vital identification about the obstacles behavior when they are connected in different way [Rashel16a, Rashel18b].

3.5.1.1 Cells in series connection

Here, two PV cells are connected in series for making a simulation with Simulink. One of them is under a different level of irradiance. Different level of irradiance simulates the obstacles on a cell. Voltage and power curves with two cells in series connection is shown in Figure 3.39 [Rashel16a].

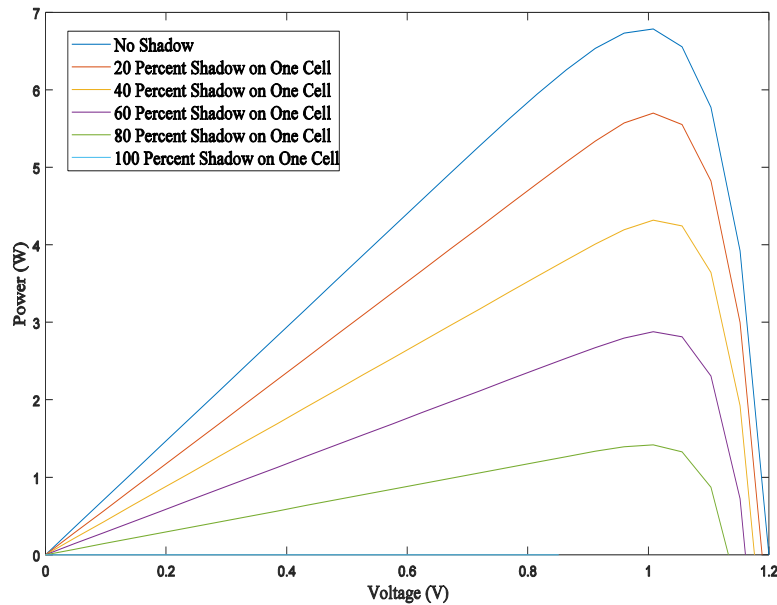


Figure 3.39 P-V curves of two cells in series connection and one of them is under different level of obstacle.

This graph shows the behavior between two connected series cells. Among them one cell is without shadow, and another cell is under shadow of obstacles that reduce the sunlight to reach this cell surface. Irradiance value is decreasing to simulate the intensity of the shadow of obstacle over PV panel is increasing and don't let the light reach to the panel's surface. Values obtained from the simulation are recorded and drawn. Shadow of obstacle changes the worth of PV maximum power. The entire shape of the curve of the graphs is changing with the changing proportion shadow of obstacle.

3.5.1.2 Cells with parallel connection

Here two cells in parallel connected and the obstacle's percentage is increasing. Get the value and recorded. From the values, the P-V curve is drawn. Voltage and power curves with two cells in parallel connection and one cell is under different level of obstacle is shown in Figure 3.40 [Rashed16a]. This graph shows two parallel cells' power graph and one of them gradually getting shadow of obstacle. In this condition, the power also decreases when the obstacle is increasing.

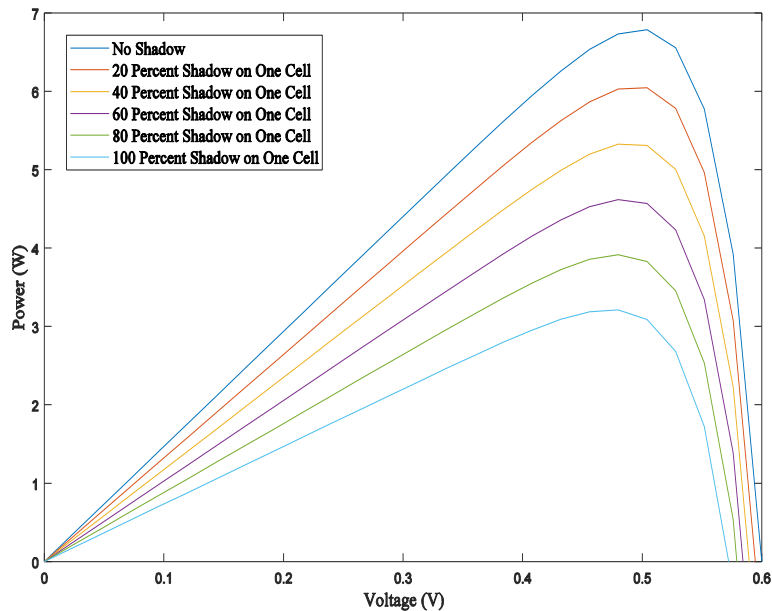


Figure 3.40 P-V curves of two cells in parallel connection and one cell is under different level of obstacle.

In case of changing the intensity of the shadow of obstacle over a single PV cell, series connected cells' power decreases more than the parallel connection one and on the other hand, in parallel connected cells', the power decreases less than the series connected cells.

■ PV panel under obstacle

A PV panel with 72 cells is used to simulate different types of obstacles. A full part of the PV is operating in a healthy condition without obstacles. Irradiance is used in this part is 1000 W/m^2 as STC condition. Voltage and current curve without obstacle and constant irradiance source is shown in Figure 3.41. This graph shows voltage and current curve follows the ideal behavior without obstacle condition, and the irradiance is used as a constant source.

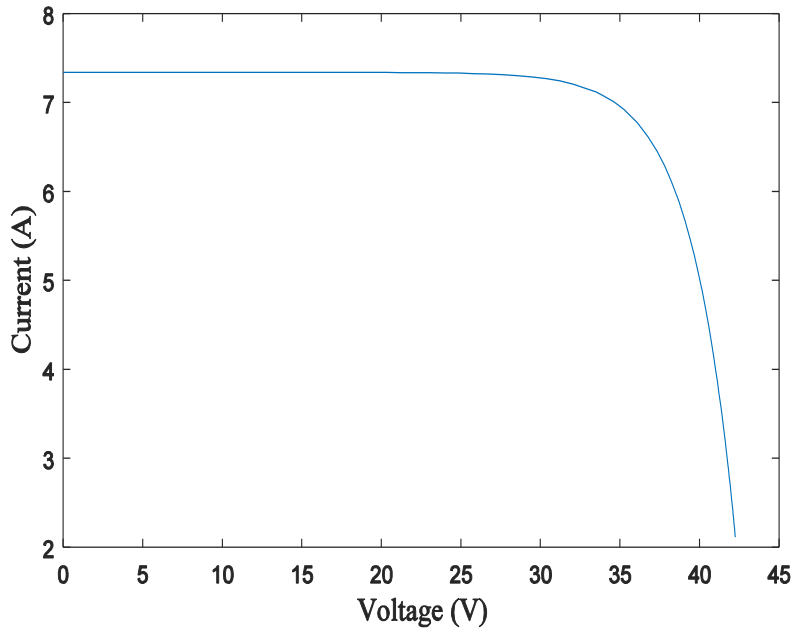


Figure 3.41 I-V curve without obstacle and constant irradiance source.

Voltage and power curve without obstacle and constant irradiance source is shown in Figure 3.42.

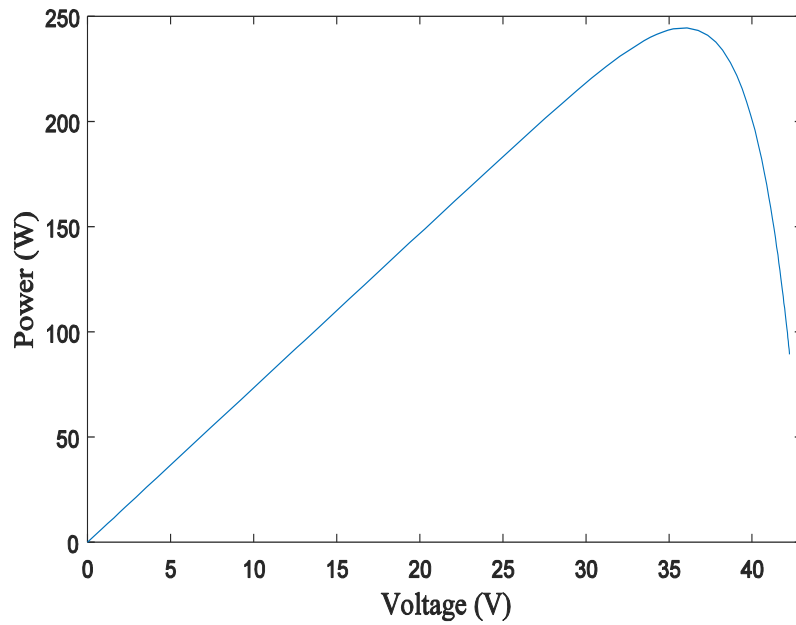


Figure 3.42 P-V curve without obstacle and constant irradiance source.

This graph shows voltage and power curve follows the ideal behavior without obstacle condition.

In these conditions, there is only one peak, no local maxima.

3.5.2.1 Time-dependent obstacle

This type of obstacle's shape is changing with time. The effect of the obstacles is not permanent on PV. The obstacle makes change to the value of irradiance and variation of irradiance value varies the output of a PV panel. Obstacles like a sudden cloud, a flying bird over the PV, etc. that causes an interrupt of irradiance to reach the PV surface, and the count as time-dependent obstacle. These time-dependent obstacle comes over the panel and go away from the site of PV panel with time [Rashel18b].

This section is going to describe the different condition of a PV panel under various of shape and different magnitude of obstacle. Various shape means; like small cloud or big cloud the panel whole at a time or small part of it. The different magnitude of obstacle means; some can have shaded like dark cloud or some can have shaded like clear sky with white cloud. In this section, simulate both the scenarios on a PV panel and analysis the result with voltage-current curve and voltage –power curve. The shape of the curve is important to identify their behavior.

In this simulation, without bypass diode and with bypass diode both scenarios are observed. In PV panel normally bypass diodes are used to get away from the hotspot condition. If bypass diode is not used in the real time PV panel, then the total panel could be damage due to heat increase in the panel. The work, analyze to see the output behavior in both conditions.

Scenario 1:

First scenario is, a big cloud goes through over a PV panel. Voltage and current with time under dynamic obstacle on a PV panel is shown in Figure 3.43 [Rashel18b]. This graph shows the voltage and current graph with different time period of time-dependent obstacle, where the obstacle decrease irradiance over the full panel and its vary. Simulation is done duration of 10 second (s).

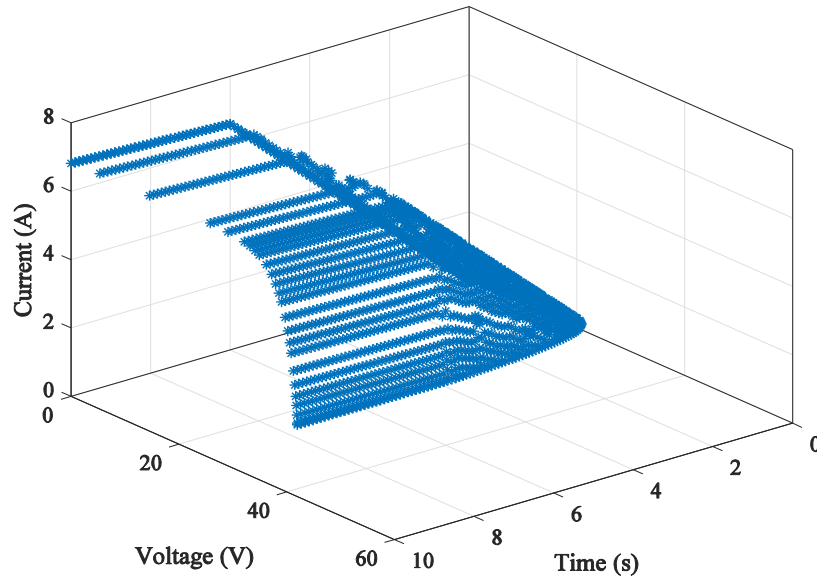


Figure 3.43 I-V curve with time under dynamic obstacle.

Voltage and power performance with time under time-dependent obstacles on a PV panel is shown in Figure 3.44. This graph shows the voltage and power with variable time when obstacle is moving over the PV panel, irradiance value is changing rapidly.

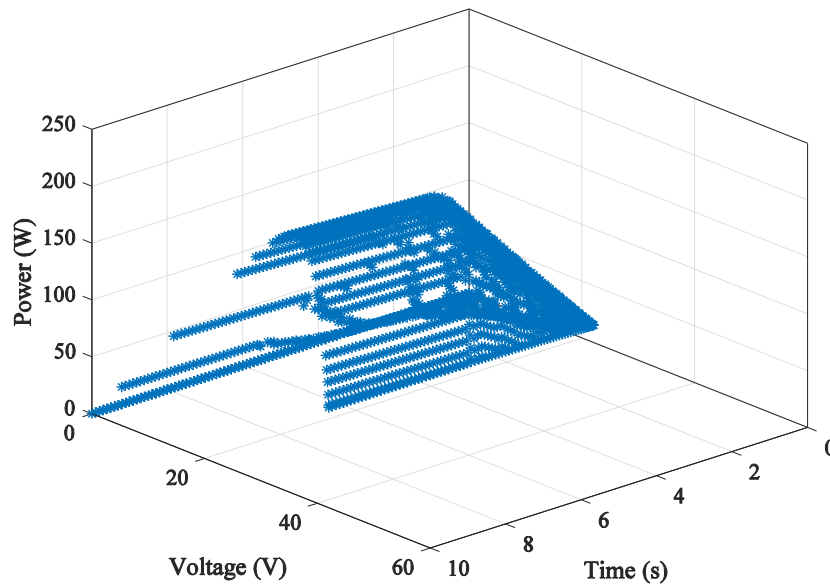


Figure 3.44 P-V curve with time under time-dependent obstacle.

In this scenario; small cloud come then go away and then another cloud come that make another obstacle over the PV panel. For this simulation, voltage and current behavior with time under changing of time-dependent obstacles is shown in Figure 3.45.

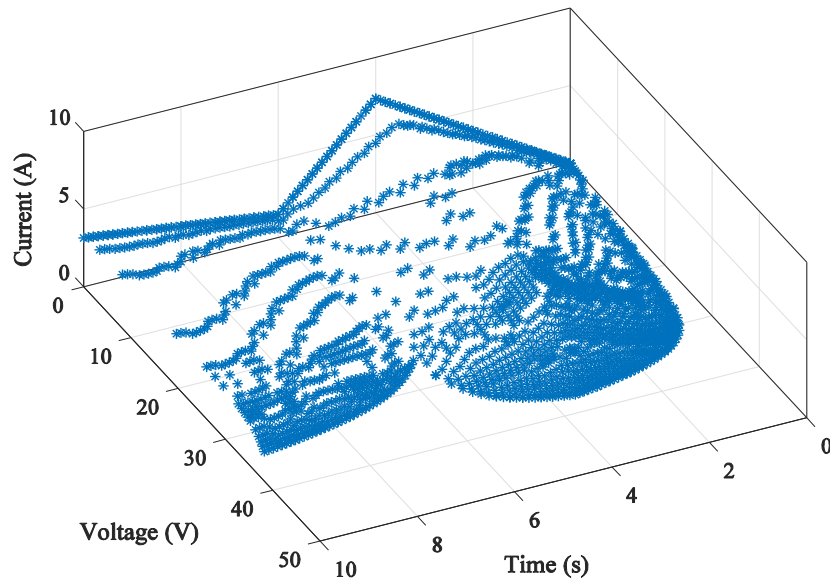


Figure 3.45 I-V curve with time under rapid changing obstacles.

This graph shows the voltage and current with varying time with a rapid environmental condition that already explained. The variation of the irradiance is very high with time.

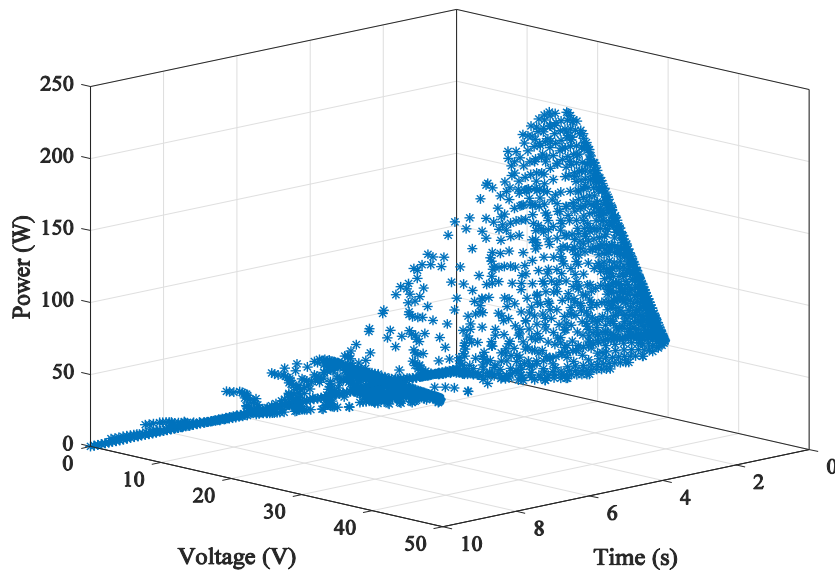


Figure 3.46 P-V curve with time under rapid changing obstacles.

For the same scenario, voltage and power with time under rapid changing obstacles is shown in Figure 3.46. This graph shows the voltage and power with time when the pattern of the obstacles is very random that described. This curve shows several peaks in very short time. The pattern of curve is changing with the pattern of obstacles.

Scenario 2:

In this scenario, 48 cells out of 72 cells of a panel have constant irradiance because of no obstacle on them. On the other hand, 24 cells are under obstacles. Two type of arrangement take in account; cells are connected with and without diode. For this conditions, voltage-current and voltage-power curve with time is simulation result is given below. Simulation is done duration of 20 second (s).

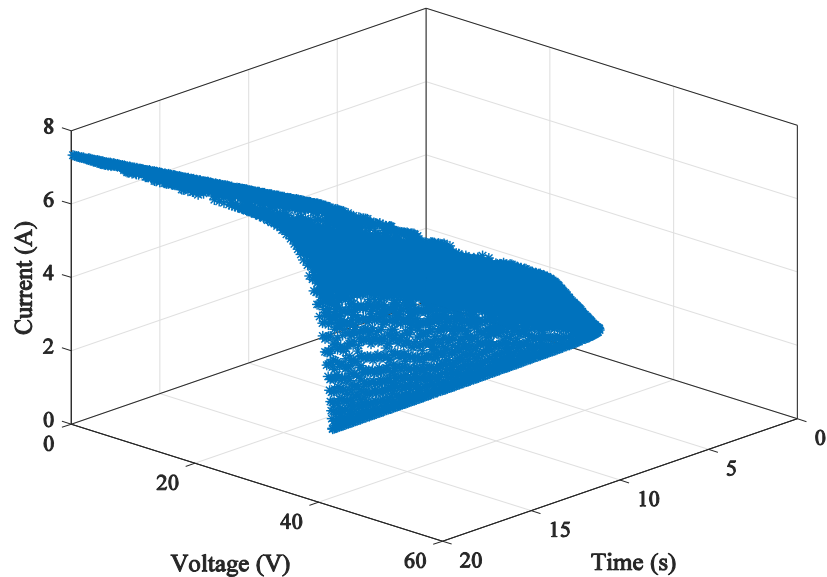


Figure 3.47 I-V curve with time, 48 cells get constant irradiance, and 24 cells are under obstacles and without diode between cells.

This graph shows voltage and current curve with time where curve pattern is changing with the pattern of obstacle over time.

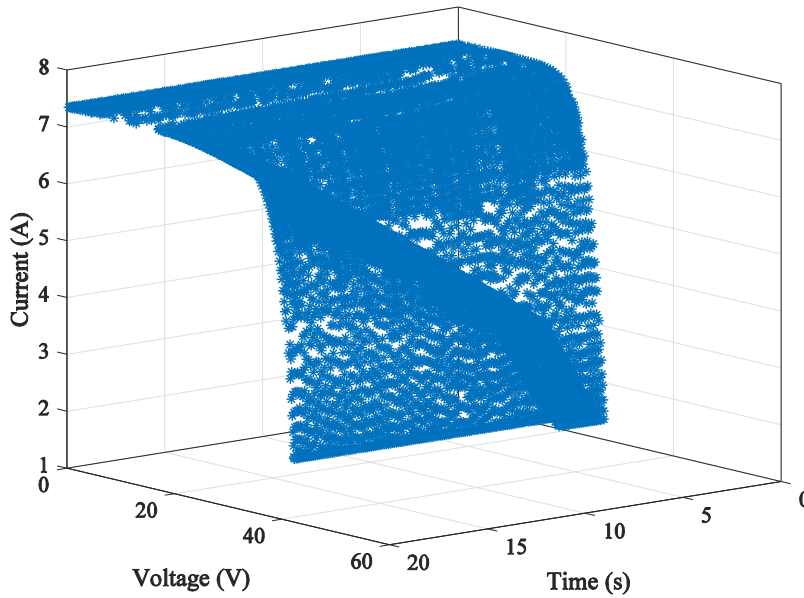


Figure 3.48 I-V curve with time, 48 cells get constant irradiance, and 24 cells are under obstacles and diode between the cells.

This graph shows a phenomenon, same like the before voltage and current curve but in this time, cells are connected with diodes the different irradiance means having a dynamic obstacle and have diode between cells.

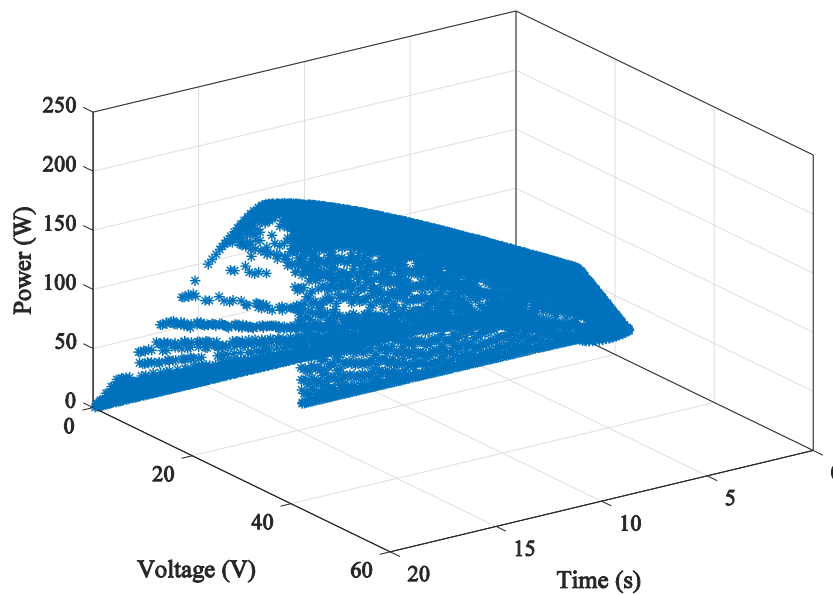


Figure 3.49 P-V curve with time and without diode between cell, 48 cells having constant irradiance, and 24 cells get varying irradiance.

This graph shows voltage and power curve with time and under the same scenario that describe above. The panel's cells are not connected with diode and all of them are in series connected. There is no additional peak in the power curve, no local maxima are showed.

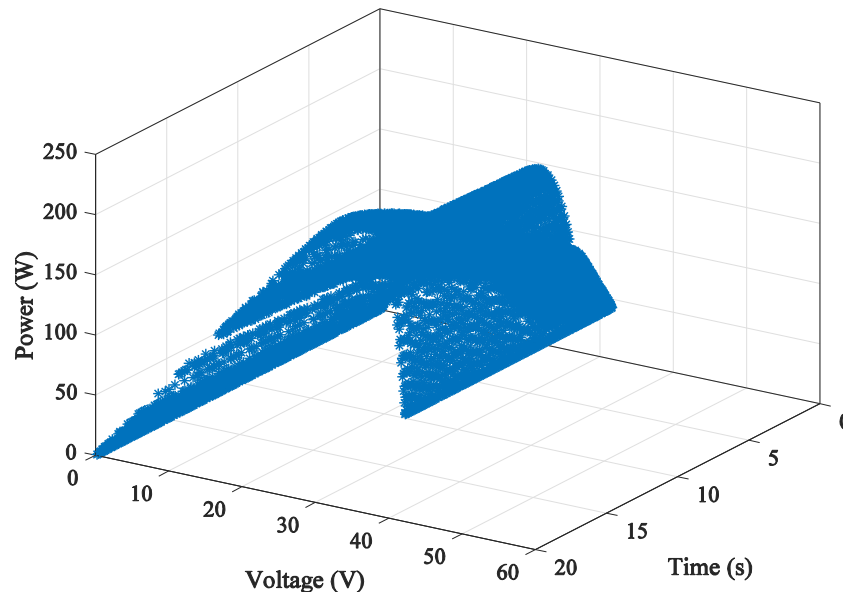


Figure 3.50 P-V curve with time, cells are connected with diode, and 48 cells get constant irradiance, and 24 cells get varying irradiance.

This graph shows the voltage and power curve with time, in the same scenario like above. The cells are connected with diode. In the curve there are several peaks. The peaks introduce local maxima and misguide maximum power point tracker.

Scenario 3:

This is another scenario, where 36 cells get constant irradiance, and 36 cells get varying irradiance due to time-dependent obstacle. In PV panel, one scenario there is no diode and another has diode connection between cells. Simulation is done duration of 20 second (s).

This graph shows the voltage and current curve with time for the condition when the half part is under time-dependent obstacle and half part is under constant irradiance. Between the cells there is no diode.

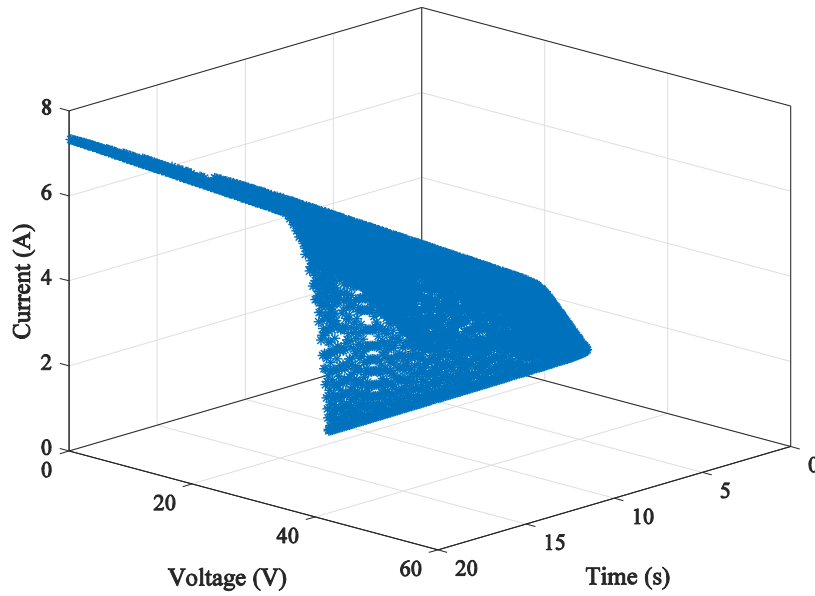


Figure 3.51 I-V curve with time, 36 cells having constant irradiance, and 36 cells get varying irradiance and no diode between cells.

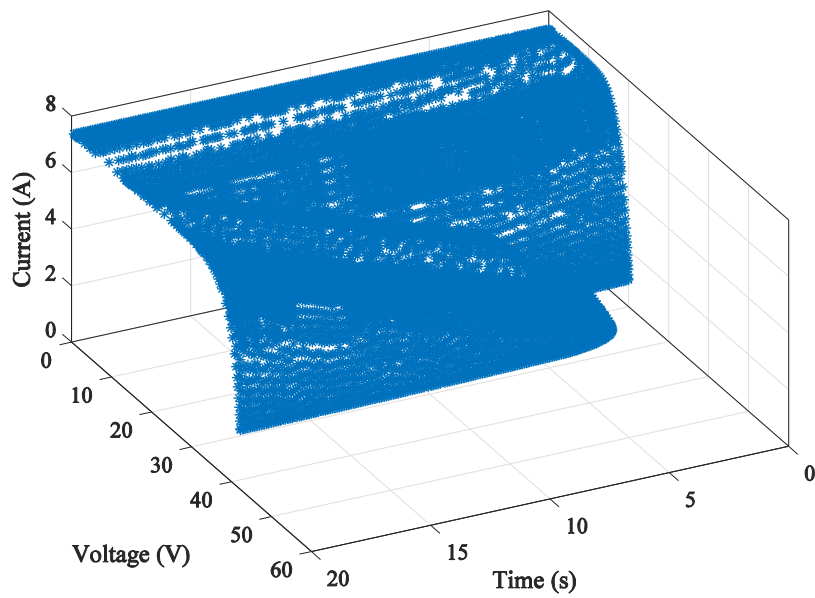


Figure 3.52 I-V curve with time with connected diode cells, 36 cells having constant irradiance and 36 cells get varying irradiance.

In Figure 3.52, under the same scenario, voltage and current curve with time when there is diode between cells is shown. This graph shows the curve when there is diode connection between cells. The curve has peaks in single fraction of time.

Voltage and power curve with time for the same scenario without diode is shown in Figure 3.53.

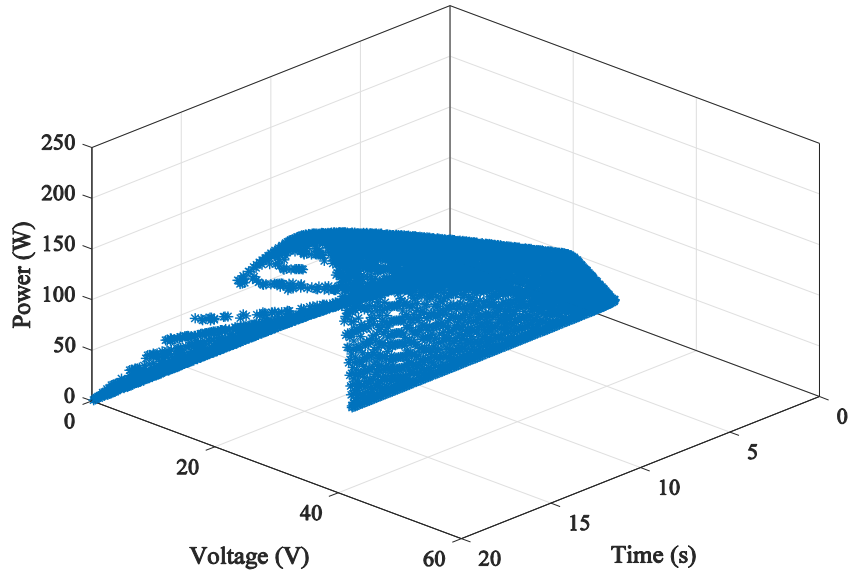


Figure 3.53 P-V curve with time and cells are connected in series without diode, 36 cells get constant radiance, and 36 cells get varying irradiance.

This graph shows voltage and power curve with time where the cells are connected without diode and all are in series connection. The curve has no extra peak and no local maxima.

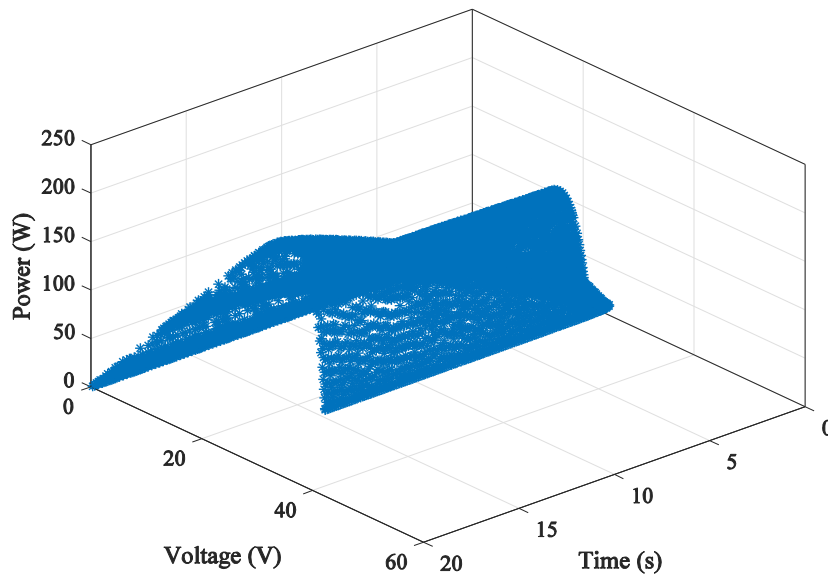


Figure 3.54 P-V curve with time, 36 cells get irradiance, and 36 cells get varying irradiance with diode connection.

In the same scenario, voltage and power curve with time, having diode between them is shown in Figure 3.54. This graph shows voltage and power curve with time for the scenario that cells are connected by diodes. The curve is having extra peaks. Half of the cells are under constant irradiance and half of them is having variable irradiance due to time-dependent obstacle.

Scenario 4:

In this scenario, in a PV panel among 72 cells, 24 cells having constant irradiance, and 48 cells having various irradiance due to time-dependent obstacles. One part of the simulation is done with diode connected cells and another part is done under without diode. Simulation is done duration of 20 second (s).

Under the scenario, voltage and current curve with time, without diode between them is shown in Figure 3.55. This graph shows the curve with time for the present scenario and cells are connected without the diode. When the time-dependent obstacle is moving away the shape of the curve is also changing.

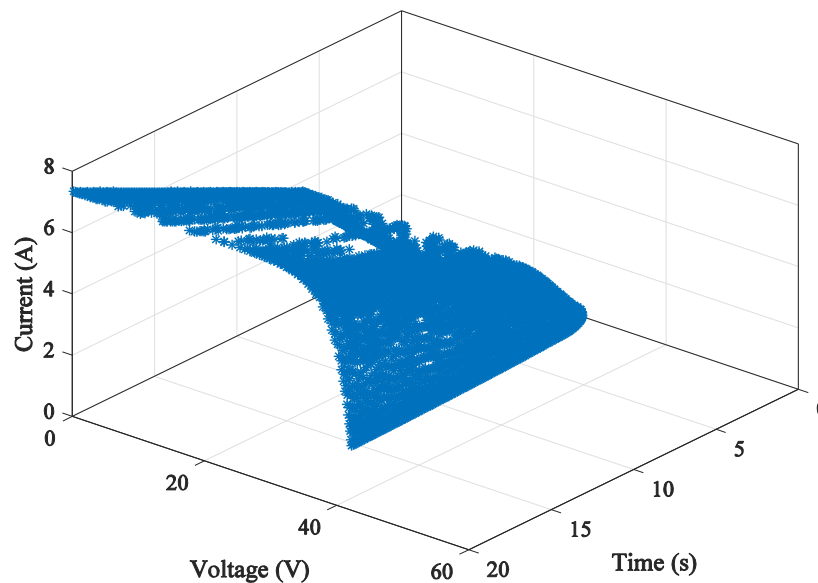


Figure 3.55 I-V curve with time without diode, 24 cells get irradiance, and 48 cells get various irradiance.

In the same situation when cells are connected with diode is shown in Figure 3.56.

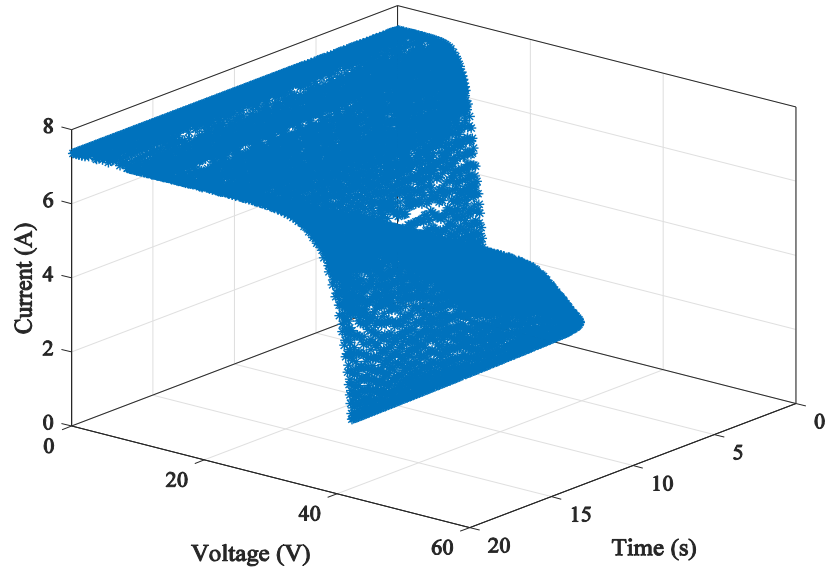


Figure 3.56 I-V curve with time, 24 cells having irradiance, and 48 cells get varying irradiance with diode connection.

When $t = 0$, one part of the panel has full STD irradiance and other part have zero irradiance; graph shows I-V curve having peaks due this scenario and also for the connection of cells by bypass diode. When time-dependent obstacle is moving over the panel, shape of the curve is changing.

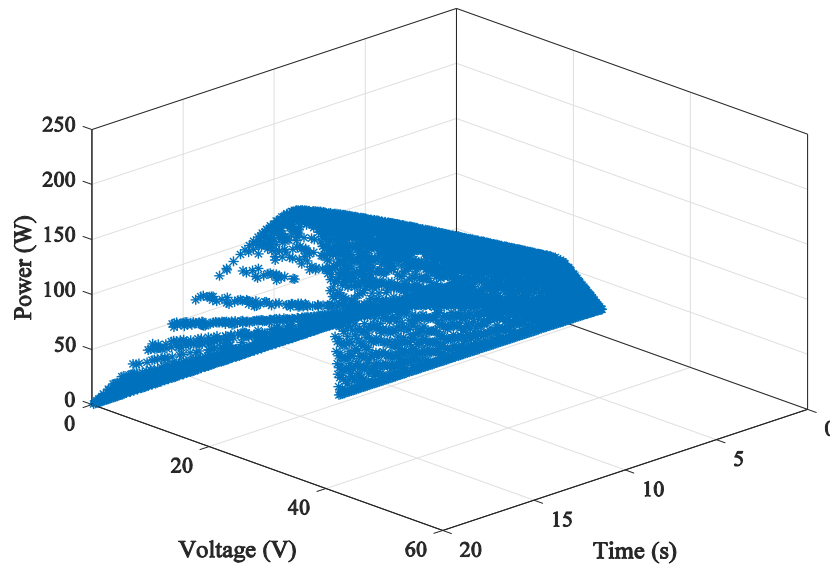


Figure 3.57 P-V curve with time, 24 cells get irradiance, and 48 cells get varying irradiance and without diode between cells.

This graph shows P-V curve with time for the same scenario and having no extra peak due to absent of bypass diode between cells. At the starting when maximum part of the panel is under obstacle the output is very low. With the time when the obstacle is move away, the power is also start to increase.

With diode connection in the same scenario, voltage and power curve is shown in Figure 3.58.

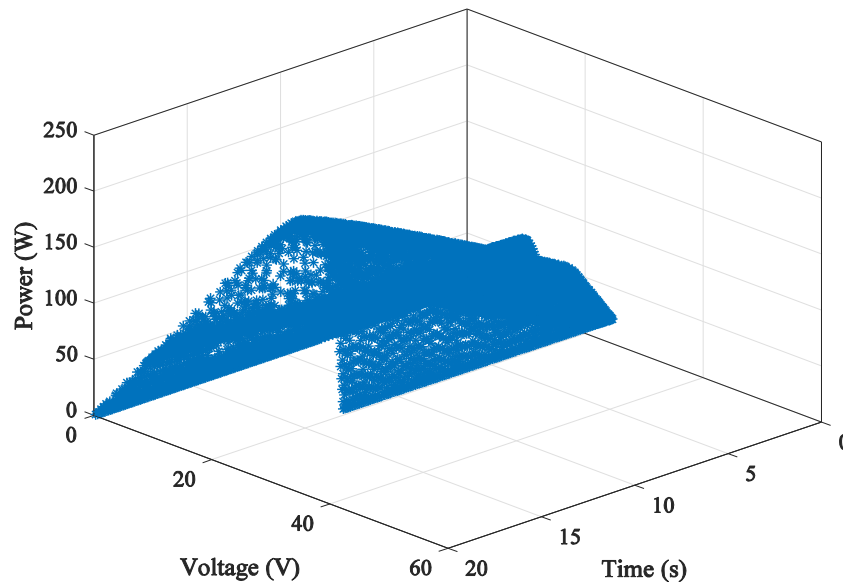


Figure 3.58 P-V curve with time, connected with diode, 24 cells having irradiance, and 48 cells having varying irradiance.

This graph shows peaks in the curve because of the time-dependent obstacle. The behavior of obstacle is identified using curve structure.

After seeing all these results from the simulations, it is identified that due to diode there is the extra peaks are generated and in the other hand when there is no diode in PV panel cell could damage and had hotspot. For safety the bypass diode is needed. Using diode also increase the performance of the panel. Understanding curve structure, it is possible to identify the obstacle characteristics and the percentage of effected area. For identifying exact problem this need future process of the signal that getting from the panels. This is one of our future work to continue.

3.5.2.2 Time-independent obstacle

This type of obstacle is permanent damage to PV panel or have to fix manually. These obstacles are like few cells of PV panel may damage, or something fall on the panel like layer of dust, bird droppings etc. that should be clean manually.

For different time independent situation, Simulink simulation is designed and get the I-V and P-V curves. This section is to see the structure of the curve with changing patterns of obstacle on changing number of cell. Time-independent obstacles have not change with time and the pattern are fixed, so time has not taken in account to see the curves pattern.

Scenario 1:

In this scenario, PV panel has uniform thin layer of dust on the surface. This type of scenario is occurred in desert due to the sand and also city area for air pollution. Dust reduce the percentage of irradiance to reach the PV operating part that convert light to electricity. Simulation gives the underlying characteristics.

For this scenario, in Figure 3.59 voltage and current curve is shown.

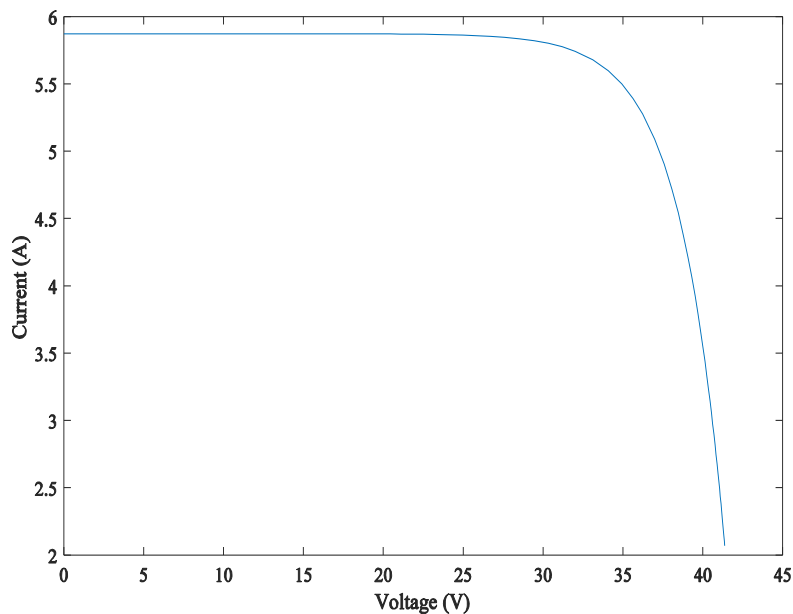


Figure 3.59 I-V curve under thin layer with uniform thickness dust on the surface of a PV panel.

For the same scenario, in Figure 3.60 voltage and power curve is shown.

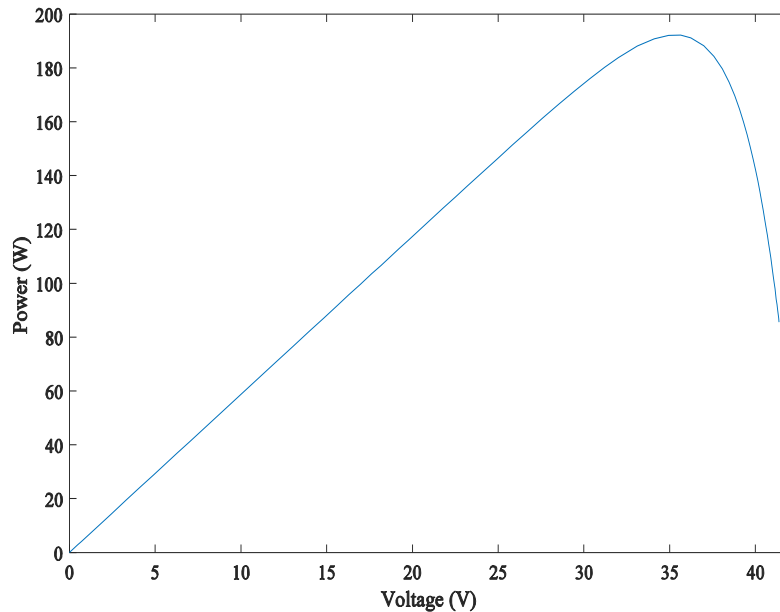


Figure 3.60 P-V curve under thin layer with uniform thickness dust on the surface of a PV panel. Due to thin uniform layer of dust accumulated over the surface, the power is reduced than the normal standard condition. There is no peak is shown in the curve. In state of the art, it is observed that due to the dust the power is reduced.

Scenario 2:

In this scenario, 54 cells among 72 cells of a PV panel is under time-independent shadow of obstacles. Usually the pattern of the shadow of obstacle is not changing with time. And it is considered that the cells are not connected with bypass diode. Normally in real scenario in panel, PV cells are connected with diode to reduce the thermal effect. The simulation is observed in describe condition and identify and recode PV panel's behavior under this conditions.

With this condition, in Figure 3.61 voltage and current curve is shown using collected data from the simulation.

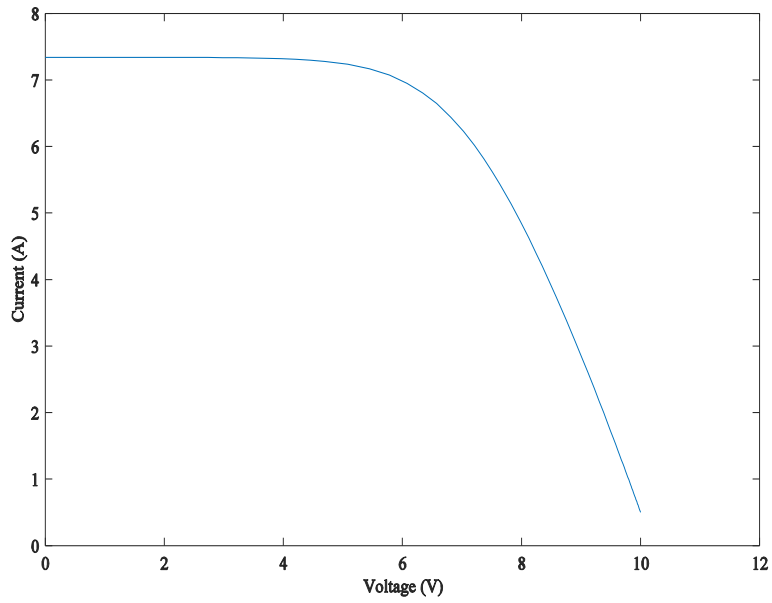


Figure 3.61 I-V curve for 54 cells of a 72 cells' panel is under time-independent obstacle.

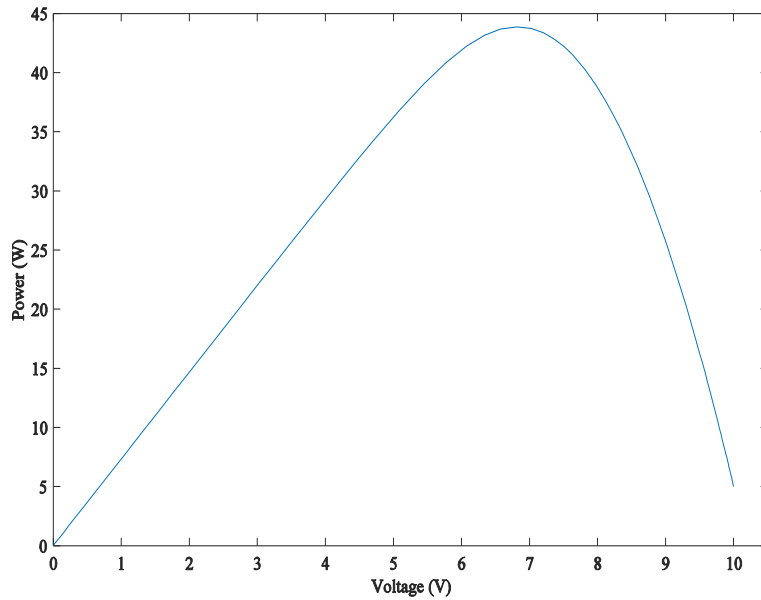


Figure 3.62 P-V curve for 54 cells of a 72 cells' panel is under time-independent obstacle.

This graph shows voltage and power curve that having less power than a standard PV panel output. Due to time-independent obstacle the performance of PV panel has decreased.

Scenario 3:

This scenario, among 72 cells of a PV panel 4 cells are totally damaged and they don't have diode to connect them. In this condition, in Figure 3.63 voltage and current curve is shown.

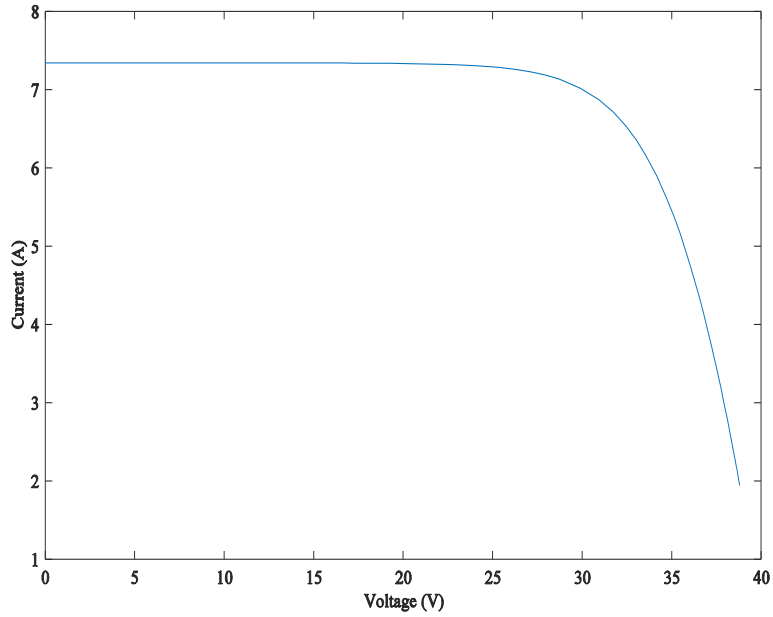


Figure 3.63 I-V curve when 4 cells is fully damaged of a PV panel.

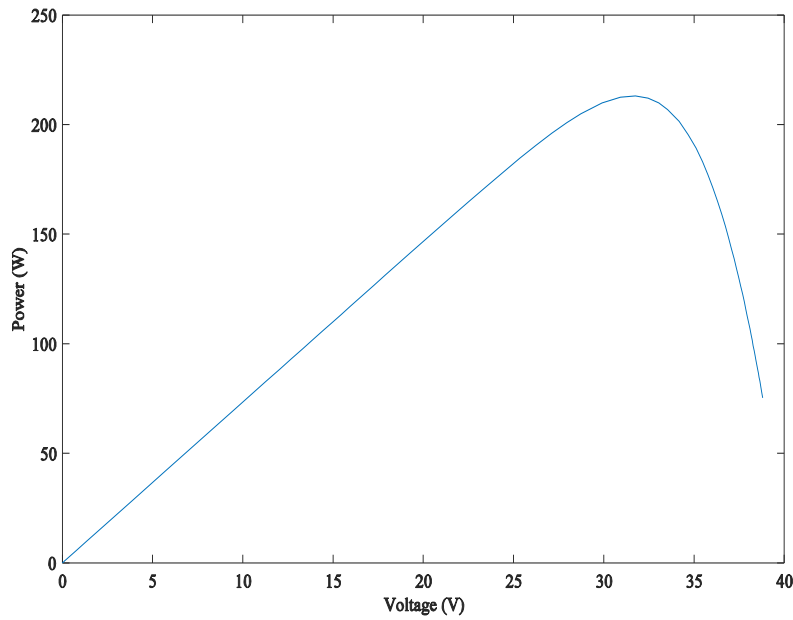


Figure 3.64 P-V curve when 4 cells is fully damaged of a PV panel.

In same condition, in Figure 3.64 voltage and power curve is shown. This graph shows voltage and power curves that power has reduced than a standard healthy PV panel. There is no other peak in the curve. Small damage of a PV reduces the power that reduces the performance of PV.

Scenario 4:

In this scenario, among 72 cells, 54 cells are under time-independent obstacle condition and other part is having standard irradiance. The cells are connected with bypass diode. For this condition, in Figure 3.65 voltage and current curve is shown.

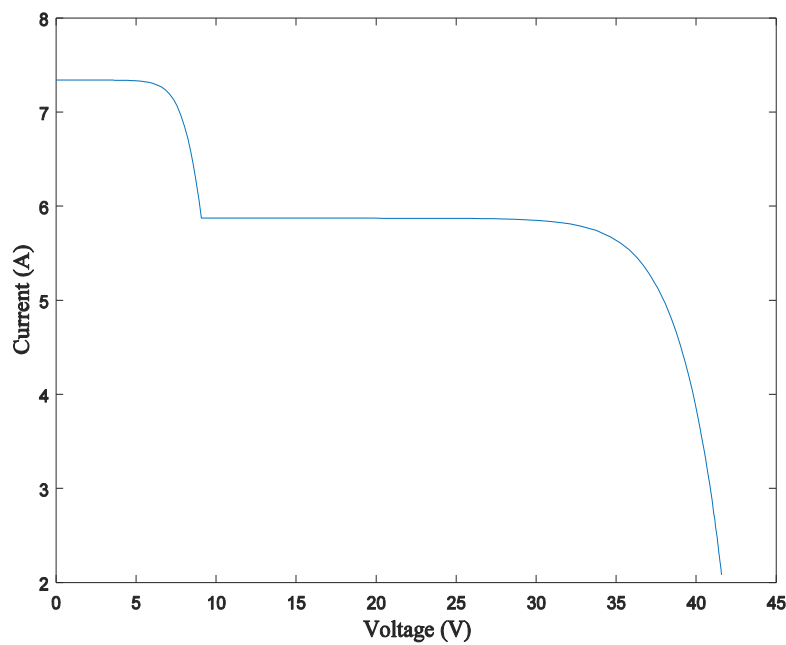


Figure 3.65 I-V curve having 54 cells under time-independent obstacle.

This I-V curve is different from the condition where the bypass diode is not used. Due to bypass diode the extra peaks is observed.

Under the same condition, Figure 3.66 is drawn with collected data from the simulation. Due to the bypass diode, the curve has extra peak. It introduces the local maxima that could misguide MPP tracker to get maximum power. Below the Figure 3.66 shows voltage and power curve with bypass diode with extra peak.

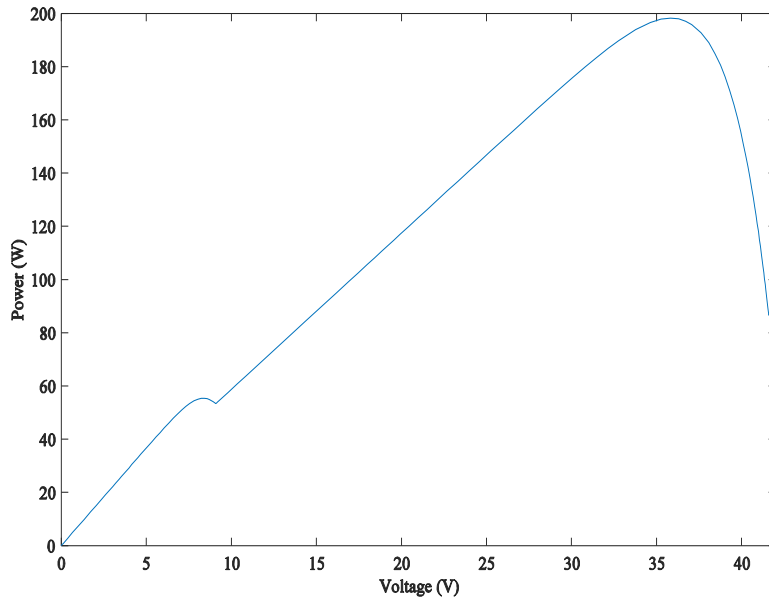


Figure 3.66 P-V curve with 54 cells under time-independent obstacle condition.

Scenario 5:

In this scenario, among 72 cells of a PV panel, 18 cells are under time-independent obstacle condition and rest of them is under standard irradiance. The cells of the panel are connected with diode. In this condition, in Figure 3.67 voltage and current curve is shown.

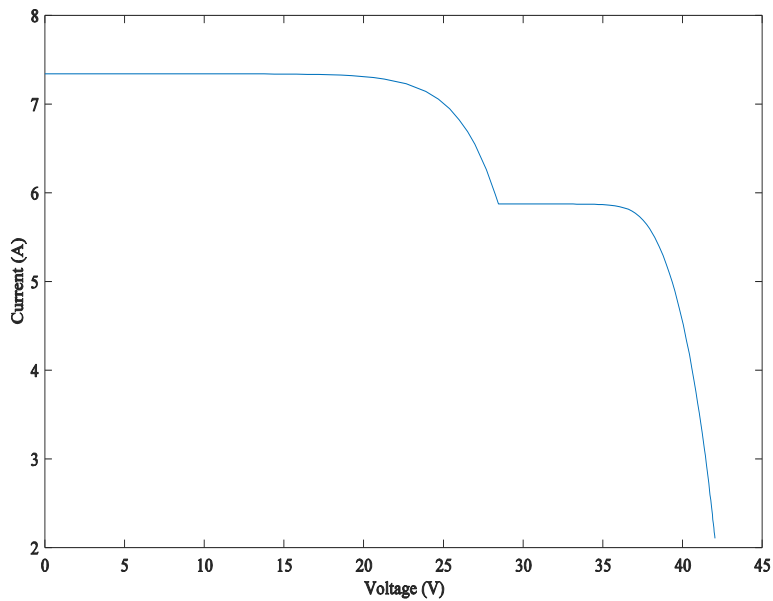


Figure 3.67 I-V curve with 18 cells under static obstacle condition and rest in healthy condition.

In Figure 3.68 voltage and power curve is shown.

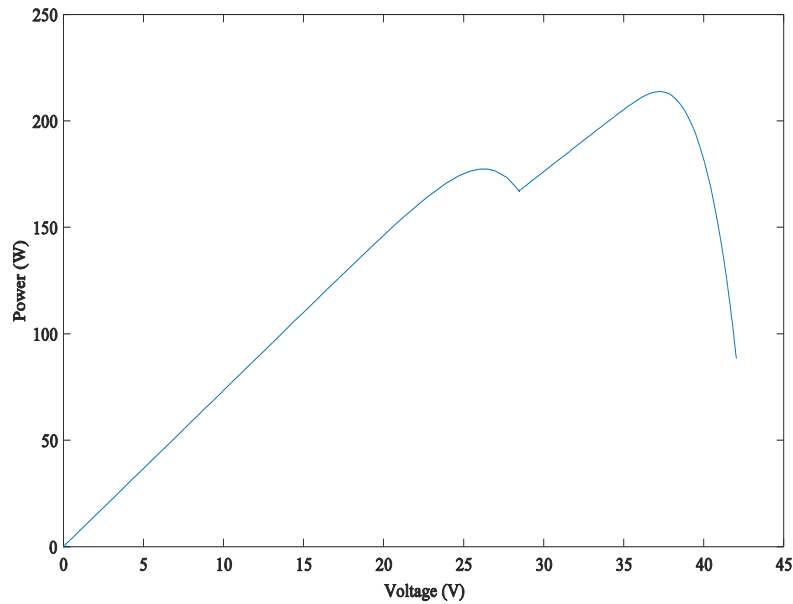


Figure 3.68 P-V curve with 18 cells under time-independent obstacle.

In Figure 3.67 shows voltage and current curve and Figure.3.68 shows voltage and power curve both of them have extra peak. In curves, this extra peaks introduces local maxima.

All these scenarios have different pattern and they show different characteristic. Due to bypass diode in the curve, it introduces extra peaks. All of them are separable from each other. Base on the characteristics of curves, it is the fact that will help to identify and classify the shadow of obstacles effect on PV panel. This could guide the remote PV system checking to identify the fault's rate and type.

3.5.3 Different type obstacles on a PV panel

In this scenario, three different types of condition are applied on a PV panel that consist of 72 cells. On the PV surface, it is simulated that it has constant irradiance, statistical obstacle, and dynamic obstacle. Cells are connected with diode and time is considered due to time-dependent obstacle.

In this scenario, in Figure 3.69 voltage and current curve is shown. This graph shows voltage and current curve is under three different condition. The pattern of the curve is different than before observed curves. Simulation is done duration of 20 second (s).

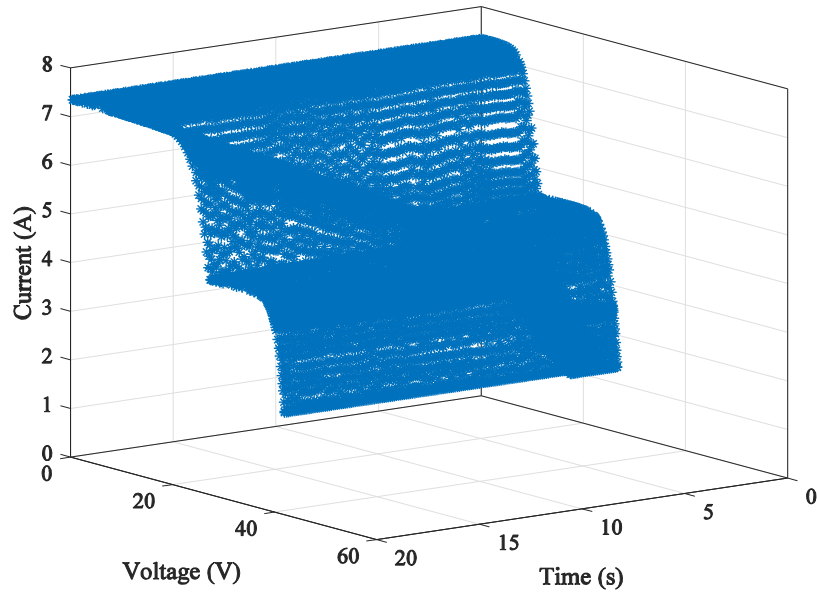


Figure 3.69 I-V curve with constant irradiance, time-independent obstacle, and time-dependent obstacle.

In the same scenario, in Figure 3.70 voltage and power is shown.

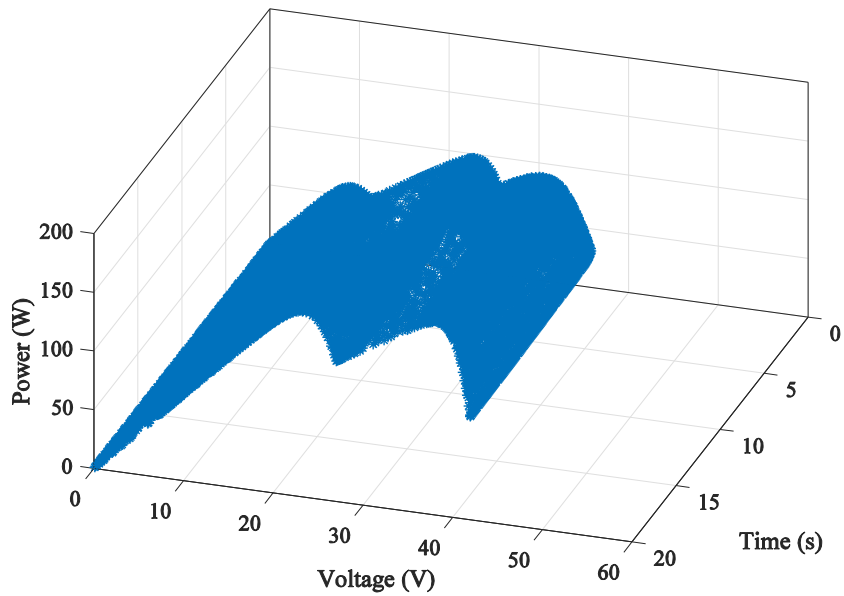


Figure 3.70 P-V curve with constant standard irradiance, time-independent obstacle, and time-dependent obstacle.

This graph shows voltage and power curve under three different condition. The curves have several peaks. It introduces local maxima and it is become difficult to get the maximum power point using MPP tracker.

All these Figures are important to analysis the fault characteristics of a PV panel in the working ground. These figures' shapes are unusual than a standard one. The results are vital to keep track of the faulty/damage PV and to identify the type of fault.

3.6 Summary

PV is fast growing renewable resource. Plant and small PV system are connected with smart grid. Deep understanding about PV's nonlinear behavior is important. Due to directly relation with environment factors and changing characteristics with environment make it more complex system. Better modeling of PV system under diverse condition is essential to get maximum from it.

Sensitiveness of internal parameters of five parameters PV model is made using error function. Series resistance is identified as a less sensitive parameter. Shunt resistance shows less sensitivity after series resistance. Rest of the internal parameters show significant behavior.

Three environmental parameters, named irradiance, ambient temperature and wind speed show significant sensitivity to PV power conversion efficiency. Ambient temperature has negative effect with PV output and Wind speed has positive effect.

Non-constant loads show momentous behavior with PV power conversion system. Changing the load effects the power conversion rate.

Obstacle on a PV panel have shown significant behavior. Different types of arrangement on a PV panel surface are modelled in the Simulink to observe their behaviors. These models are key to identify the fault on a PV in real-time. When cells are connected with diode then it shows extra peak due to obstacles and introduce local maxima that misguide to get maximum power point.

Next chapter gives the conclusion of the work with main contributions, publications and the future direction this research work.

CHAPTER

4

4 Conclusion

In this chapter, we present the original contributions of this thesis on the subject of PV modeling under variable internal and environmental conditions with the non-constant load. It further discusses the contribution of different types of obstacles on PV surface that decrease performance. Next, the scientific publications that were carried out during the work done for this thesis aiming its dissemination to the scientific community are enumerated. Finally, guidelines are given for future research work.

4.1 Contributions

For sustainable development, it is needed to concern about the environment safety that headed to the Paris Agreement and the decision is made to limit the emission of greenhouse gases (GHG). To cooperate with this decision, it is important to develop energy sources that are clean in nature. Figure 1.1 shows three different scenarios of world's temperature prediction following different way of energy production. Renewable energy is an area identified as an important factor to reduce greenhouse gases and help control the temperature [IEA15].

The integration of renewable energy sources assists to decrease the usage of fossil power plants in the energy generating sector. This combination is important to pursuit the objective of limiting GHG emissions to the atmosphere, aiming to comply with the Paris Agreement and subsequent decisions.

PV gets attention from scientists, businessman and policy makers due to its increasing performance with decreasing price and clean energy generation in production life. It is abundant all over the world. Ongoing research on PV system has global importance for the suitability and quality of the forthcoming society.

This research work was carried out on modeling of Photovoltaics under different environmental conditions. This thesis leading to the explanation of the work that is structured as:

- T1 The simulation is done using the error function to identify sensitiveness effects of internal and environmental parameters;
- T2 The effect of different environmental parameters on PV power conversion is simulated to get their impact on PV's performance;
- T3 Experimental work is done with different resistances with a fixed PV panel to identify the effect of non-constant load;
- T4 Simulink model is created to implement the different kind of obstacles effect on PV power conversion and classify obstacles.

The original contributions of this thesis are:

- C1 The identification of the sensitivity of internal and environmental parameters through error function using simulation [Rashel17a, Rashel17b, Rashel17c]
- C2 The identification of the environmental parameters variation effect on PV power conversion [Rashel16c, Rashel18a]
- C3 The experimental identification of non-constant load effect on the PV using different resistances as variable load.
- C4 Classification and identification of different types of obstacles in PV cells and introduction of different fault types in PV panel [Rashel18b, Rashel16a].

These are the identification from the computational simulation and experiment, that assist to model the PV system more accurate with internal and external environment. All of these contributions improve the prediction accuracy of PV aiming to integration with the smart grid. The following points are important for integration:

Five parameter single diode PV model includes series resistance (R_s) and shunt resistance (R_{sh}). All the parameters of the model have analyzed through error function. R_{sh} are find as less sensitive to the model and other have significant sensitivity;

Simple model and single diode five parameters model is compared and identified as close output from them;

Among environmental parameters, temperature has negative linear relation with PV output generation. Wind speed has positive relation with it;

Load is important to get the maximum output from the system, helping to maximize power generation;

Shadow of obstacles classification is important to fault identification of a PV panel and this helps to improve the performance of the system and control remotely.

4.2 Publications

The topic of this thesis was chosen to do research in the area of sustainable energy development and, at the same time, get work for pursuing the academic degree. To complete the task, different computational simulations with laboratory experiments were done. Important results have come out and the work was published periodically helping to enrich the dissertation with comments from scientific committee.

For contributing in the branch of energy, especially in photovoltaics power conversion system, the thesis contributions were prepared and submitted to scientific community. The list of published works is presented next.

Scientific publications in journals

- 1 Rashel, M.R., Rifath, J., Gonçalves, T., Tlemçani, M., Melicio, R., “Sensitivity analysis through error function of Crystalline-Si photovoltaic cell model integrated in a smart grid”, *International Journal of Renewable Energy Research*. Vol. 7(4), December 2017.
- 2 Rashel, M.R., Ahmed, T., Goncalves, T., Tlemceni, M., Melicio, R., “Analysis of Environmental Parameters Sensitivity to Improve Modeling of a c-Si Panel” *Sensor Letters*, Vol.16, pp. 1-6, March 2018.

Scientific publications in conferences and workshops

- 1 Rashel, M.R., Ahmed, T., Goncalves, T., Tlemceni, M., Melicio, R., “Analysis of different types of obstacles for PV panel”, Poster paper in *Eradication Poverty through Energy Innovation Workshop*, Arizona State University, United State of America, 2018.
- 2 Rashel, M. R., Gonçalves, T., Tlemçani, M., Melicio, R., “Photovoltaic cell performance analysis under different ambient temperature and wind speed for sustainable energy”, *proc. Of Workshop on Sustainability and Green Technology*, 2017.
- 3 Rashel, M. R., Albino, A., Gonçalves, T., Tlemçani, M., “Sensitivity Analysis of Environmental and Internal Parameters of a Photovoltaic cell”, *3rd Energy for*

- Sustainability International Conference, Designing Cities & Communities for the Future, Portugal, 2017.
- 4 Rashel, M. R., Albino, A., Gonçalves, T., Tlemçani, M., “Error Function Analysis of Five-Parameter Model of Photovoltaic Cell”, 5th Anniversary of ANSOLE, International Conference on Renewable Energy, Egypt, 2016.
 - 5 Rashel, M.R., Albino, A., Gonçalves, T., Veiga, A., Ahmed, T., Tlemçani, M., “Comparison of Photovoltaic panel’s standard and simplified models”, The International Conference for Students on Applied Engineering, Newcastle, United Kingdom, 2016 (IEEE xplorer, Scopus)
 - 6 Rashel, M.R., Albino, A., Gonçalves, T., Tlemçani, M., “MATLAB Simulink modeling of Photovoltaic Cells for understanding shadow effect”, International Conference on Renewable Energy Research and Applications, Birmingham, United Kingdom, 2016 (IEEE xplorer, Scopus)
 - 7 Rashel, M.R., Albino, A., Gonçalves, T., Tlemçani, M., “Sensitivity analysis of parameters of a photovoltaic cell under different condition”, 10th International Conference on Software, Knowledge, Information Management & Applications, China, 2016 (IEEE xplorer, Scopus)
 - 8 Rashel, M.R., Albino, A., Gonçalves, T., Tlemçani, M., “Analyzing Ambient Temperature and Wind Speed Effect on the Photovoltaic Cell”, Workshop on Earth Sciences, Portugal, 2016.
 - 9 Ahmed, T., Gonçalves, T., Albino, A., Rashel, M.R., Veiga, A., Tlemçani, M., “Different parameters variation analysis of a PV cell”, The International Conference for Students on Applied Engineering, Newcastle, United Kingdom, 2016 (IEEE xplorer, Scopus)

4.3 Future Research Direction

This section, gives the future direction of the research. They are not the objectives of this thesis but deserve consideration for the continuation of the studies of the application of precise modeling of PV power conversion to build efficient PV plants and to integrate with the smart grid system.

Thus, the research direction for future development are enunciated as:

- D1 Experimental workout in laboratory with PV panel under real environmental conditions for getting valuable information aiming at modeling more accurate PV system enabling the integration with SG.
- D2 Database development on the base of different types of obstacles on PV aiming to identify faults and improve the system's performance.
- D3 Faster maximum power point tracker development for rapid changing dynamic time-dependent, and also for time-independent obstacles conditions.

References

- [Autosofttech18] URL: <http://www.autosofttech.net/resources/>(Accessed:12.09.2017)
- [Anjos17] Anjos, R.S., Melício, R., Mendes, V.M.F., Pousinho, H.M.I., “Crystalline silicon PV module under effect of shading simulation of the hot-spot condition”, in *Technological Innovation for Smart Systems*, SPRINGER, pp. 479-487, May 2017.
- [Ahmed17] Ahmed, M,T, “*Modelization and Characterization of Photovoltaic-Panels*”, Master’s Thesis, University of Évora, January 2017.
- [Altestore17] URL: <https://www.altestore.com/howto/solar-insolation-map-world-a43/> (Accessed:07.09.2017)
- [Ahmed16] Ahmed, T., Gonçalves, T., Albino, A., Rashed, M.R., Veiga, A., Tlemçani, M., “Different parameters variation analysis of a PV cell”, in Proc. Of *International Conference for Students on Applied Engineering*, Newcastle, United Kingdom, October 2016.
- [Aoun14] Aoun, N., Chenni, R., Nahman, B., Bouchouicha, K., “Evaluation and validation of equivalent five-Parameter model performance for photovoltaic panels using only reference data”, *Energy and Power Engineering*, Vol. 06, No. 9, pp. 235-245, September 2014.
- [Arjyadhara13] Arjyadhara1, P., Ali S.M., Chitralkha, J., “Analysis of solar PV cell performance with changing irradiance and temperature”, *International Journal of Engineering and Computer Science*, Vol. 2, No. 1, pp. 214-220, January 2013.
- [Alam12] Alam, N., Coors, V., Zlatanova, S., Oosterom, P.J.M., “Shadow effect on photovoltaic potentiality analysis using 3d city models”, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XXXIX-B8, Melbourne, Australia, September 2012.
- [Answers10] URL: <http://www.answers.com/topic/n-type-silicon-technology> (Accessed:07.01.2018)

- [Benabdallah17] Benabdallah, I., Oun, A., Cherif, A., “Grid Connected PV plant based on smart grid control and monitoring”, *International Journal of Advanced Computer Science and Applications*, Vol. 8, No. 6, 2017.
- [Blog17] URL:<https://blogs.thomsonreuters.com/answeron/christiana-figueres-addressing-climate-change-is-our-task/> (Accessed:03.01.2018)
- [BP17] BP Statistical Review of World Energy, 2017.
- [Batista14] Batista, N.C., Melício, R., Mendes, V.M.F., “Layered smart grid architecture approach and field tests by ZigBee technology”, *Energy Conversion and Management*, Vol. 88, pp. 49-59, December 2014.
- [Bonkougou13] Bonkougou, D., Koalaga, Z., Njomo, D., “Modelling and simulation of photovoltaic module considering single diode equivalent circuit model in MATLAB”, *International Journal of Emerging Technology and Advanced Engineering*, Vol. 3, pp. 593–502, March 2013.
- [Bikaneria13] Bikaneria, J., Joshi, S. P., Joshi, A. R., “Modeling and simulation of PV cell using one-diode model”, *International Journal of Scientific and Research Publications*, Vol. 3, No. 10, October 2013.
- [Bozkurt10] Bozkurt, I., “Energy resources and their effects on environment”, *WSEAS Transactions on Environment and Development*, Vol. 6, No. 5, May 2010.
- [Bhattacharya14] Bhattacharya, T., Chakraborty, A.K., Pal, K., “Effects of ambient temperature and wind speed on performance of monocrystalline solar photovoltaic module in Tripura, India”, *Hindawi Publishing Corporation Journal of Solar Energy*, Vol. 2014, September 2014.
- [Bataineh12] Bataineh, K., Dalalah, D., “Optimal configuration for design of stand-alone pv system”, *Smart Grid and Renewable Energy*, Vol. 3, pp. 139-147, May 2012.
- [Clima18] URL: <http://www.clima.ict.uevora.pt/> (Accessed:01.02.2018)
- [COP2115] Paris Climate Change Conference, (FCCC/CP/2015/L.9/Rev.1), The global standard of globalization is not limited to the limitations of the system, XXI 2°C, 2015.
- [Cubas13] Cubas, J., Pindado, S., Farrahi, A., “New method for analytical photovoltaic parameter extraction”, in Proc. Of *International Conference*

- on Renewable Energy Research and Applications*, pp. 873–877, Madrid, Spain, October 2013.
- [Chatterjee11] Chatterjee, A., Keyhani, A., Kapoor, D., “Identification of Photovoltaic source models”, *IEEE Transactions on Energy Conversion*, Vol. 26, pp. 883–889, September 2011.
- [Candelise11] Candelise, C., Spiers, J., Gross, R., “Materials availability for thin film (TF) PV technologies development: a real concern?”, *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 9, December 2011.
- [Chu11] Chu, Y., Meisen, P., “Review and comparison of different solar energy technologies”, *Global Energy Network Institute*, August 2011.
- [Casanova11] Casanova, J.Z., Piliouline, M., Carretero, J., Bernaola, P., Carpena, P., Lopez, L.M., Cardona, M.S., “Analysis of dust losses in photovoltaic modules”, In Proc. Of *World Renewable Energy Congress*, Linkoping, Sweden, May 2011.
- [Chen11] Chen, C.J., *Physics of Solar Energy*, John Wiley & Sons, Inc, August 2011.
- [Chenni07] Chenni, R., Makhlof, M., Kerbache, T., Bouzid, A., “A detailed modeling method for photovoltaic cells”, *Energy*, Vol. 32, No. 9, pp. 724–730, September 2007.
- [Demirel16] Demirel, Y., *Energy: production, conversion, storage, conservation and coupling*, Springer, Springer International Publisher, 2016.
- [Dubey13] Dubey, S., Sarvaiya, J.N., Seshadri, B., “Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world A Review”, *Energy Procedia*, Vol. 33, pp. 311 – 321, June 2013.
- [Darwish13] Darwish, Z.A., Kazem, H.A, Sopian, K., Alghoul, M.A., Chaichan, M.T., “Impact of some environmental variables with dust on solar photovoltaic (PV) performance: review and research status”, *International Journal of Energy and Environment*, Vol. 7, No. 4, 2013.
- [Dincer12] Dincer, I., Zamfirescu, C., *Sustainable energy systems and application*, Springer, Springer US, 2012.
- [Dresner08] Dresner, S., *The Principles of sustainability*, 2nd Edition, Earthscan, UK and USA, 2008.

- [Electronicsdesignhq18] URL: <https://www.electronicsdesignhq.com/diodes/> (Accessed: 06.04.2018)
- [EIA17] International Energy Outlook, 2017.
- [ESA17] NASA & European Space Agency (ESA)
- [ElectronicsTutorials17] URL: <https://www.electronics-tutorials.ws.> (Accessed:07.10.2017).
- [Eere17] URL: https://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf (Accessed:01.11.2017)
- [Elzinga15] Elzinga, D., “Electricity system development: a focus on - Smart Grids Overview of activities and players in Smart Grids”, *United Nations Economic Commission for Europe*, 2015.
- [EIA14a] U.S. Energy Information Administration, "International Energy Statistics", URL:<http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=2&aid=2&cid=regions&syid=1982&eyid=2012&unit=BKWH>, (Accessed:07.10.2016).
- [EIA14b] U.S. Energy Information Administration, International Energy Outlook 2014.
- [Eon12] URL: http://eon.sdsu.edu/~johnston/ME204/Lecture_Notes/ (Accessed:07.02.2016).
- [Einstein1905] Einstein, A., “On a heuristic point of view concerning the Production and Transformation of Light,” *Annalen der Physik*, Vol. 17, pp. 132-148, Bern, March 1905.
- [Fialho14a] Fialho, L., Melício, R., Mendes, V.M.F, Viana, S, Rodrigues, C., Estanqueiro, A., "A simulation of integrated photovoltaic conversion into electric grid", *Solar Energy*, Vol. 110, pp. 578–594, December 2014.
- [Fialho14b] Fialho, L., Melício, R., Mendes, V.M.F., Figueiredo, J., Collares-Pereira, M., “Amorphous solar modules simulation and experimental results: effect of shading”, *in: Technological Innovation for Collective Awareness Systems*, Springer, pp. 315–323, April 2014.
- [Foles17] Foles, A.C.N., “MPPT study from a solar photovoltaic panel- according to perturbations induced by shadows”, *Masters’s Thesis*, University of Évora, 2017.

- [Francisco15] Francisco, C.S.J., “Shadowing effect on the performance in solar PV cells”, *Master’s Thesis, University of Gavle*, June 2015.
- [Fialho15a] Fialho, L., Melicio, R., Mendes, V.M.F., Pereira, M. C., “Simulation of a-Si PV system linked to the grid by DC boost and three-level inverter under cloud scope”, *Technological Innovation for Cloud-Based Engineering Systems, Springer*, pp. 423-430, April 2015.
- [Fialho15b] Fialho, L., Melicio, R., Mendes, V.M.F., Estanqueiro, A., “Simulation of a-Si PV system grid connected by boost and inverter”, *International Journal of Renewable Energy Research*, Vol. 5, No. 2, pp. 443-451, 2015.
- [Fialho15c] Fialho, L., Melicio, R., Mendes, V.M.F., “Poly-Si PV system grid connected and fuzzy controlled”, *Proceedings of the 16th IEEE International Conference on Computer as a Tool*, pp. 1–6, Salamanca, Spain, 08–11 September 2015.
- [Fialho15d] Fialho, L., Melicio, R., Mendes, V.M.F., Estanqueiro, A., Collares-Pereira, M., “PV systems linked to the grid: parameter identification with a heuristic procedure”, *Sustainable Energy Technologies and Assessments*, Vol. 10, pp. 29-39, June 2015.
- [Fialho15e] Fialho, L., Melicio, R., Mendes, V.M.F., “Simulation and experimental results for a m-Si PV by five parameters”, *Atas das 5as Jornadas de Informática da Universidade de Évora-JIUE 2015*, pp. 1–7, Évora, Portugal, 26–27 fevereiro 2015.
- [Fialho14c] Fialho, L., Melicio, R., Mendes, V.M.F., Figueiredo, J., Collares-Pereira, M., “Effect of shading on series solar modules: simulation and experimental results”, *Procedia Technology*, Vol. 17, pp. 295-302, December 2014.
- [Fialho14d] Fialho, L., Melicio, R., Mendes, V.M.F., “PV system modeling by five parameters and in situ test”, *Proceedings of the International Symposium on Power Electronics, Electrical Drives and Motion*, pp. 573–578, Ischia, Italy, June 2014.
- [Fialho14e] Fialho, L., Melicio, R., Mendes, V.M.F., Rodrigues, L., Viana, S., Estanqueiro, A., “Simulation of a-Si PV system linked to the grid by DC-

- DC boost and two-level converter”, *Proceedings of the 16th International Power Electronics and Motion Control Conference and Exposition* pp. 934–938, Antalya, Turkey, September 2014.
- [Fesharaki11] Fesharaki, V.J., Dehghani, M., Fesharaki, J.J., “The effect of -temperature on photovoltaic cell efficiency”, in Proc of *the 1st International Conference on Emerging Trends in Energy Conservation, Iran*, November 2011.
- [GTM17] IEA: Global Installed PV Capacity Leaps to 303 Gigawatts, 2017.
- [Greentechmedia16] URL:<https://www.greentechmedia.com/articles/read/iea-global-installed-pv-capacity-leaps-to-303-gw#gs.v6tqMGI> (Accessed:01.09.2016).
- [Gomes16] Gomes, I.L.R., Pousinho, H.M.I., Melício, R., Mendes, V.M.F.-, “-Bidding and optimization strategies for Wind-PV systems in electricity markets assisted by CPS”, *Energy Procedia*, Vol. 106, pp. 111–121, December 2016.
- [Gokmen16] Gokmen, N., Hu, W., Hou, P., Chen, Z., Sera, D., Spataru, S., “Investigation of wind speed cooling effect on PV panels in windy locations” *Renewable Energy*, Vol. 90, pp. 283-290, May 2016.
- [Graichen15] Graichen, P., “Current and future cost of photovoltaics”, *Fraunhofer-institute for solar energy systems*, February 2015.
- [Ghani14] Ghani, F., Rosengarten, G., Duke, M., Carson, J. K., “The numerical calculation of single-diode solar-cell modelling parameters”, *Renewable Energy*, Vol. 72, pp. 105–112, December 2014.
- [Gharavi11] Gharavi, H., Ghafurian, R., “Smart grid: the electric energy system of the future” in Proc of *the IEEE*, Vol. 99, No. 6, May 2011.
- [Gao09] Gao, L., Dougal, R.A., Liu, S., Iotova, A.P., “Parallel-connected solar PV system to address partial and rapidly fluctuating shadow conditions”, *IEEE Transactions on Industrial Electronics*, Vol. 56, No. 5, pp. 1548-1556, May 2009.
- [Hudedmani17] Hudedmani, M.G., Soppimath, V., Jambotkar, C., “A study of materials for solar pv technology and challenges”, *Scholars Research Library European Journal of Applied Engineering and Scientific Research*, Vol. 5, No. 1, pp. 1-13, 2017.

- [Hategekimana17] Hategekimana, P., “Analysis of electrical loads and strategies for increasing self-consumption with BIPV Case study Skarpnes zero energy House”, *Master’s Thesis, University of Agder, Grimstad, Norway*, 2017.
- [Homadi16] Homadi, A.M., “Effect of elevation and wind direction on silicon solar panel efficiency”, *World Academy of Science, Engineering and Technology International Journal of Energy and Power Engineering*, Vol. 10, No. 9, 2016.
- [Huld15] Huld, T., Amillo, A.M.G., “Estimating PV module performance over large geographical regions: the role of irradiance, air temperature, wind speed and solar spectrum”, *Energies*, Vol. 8, pp. 5159-5181, June 2015.
- [Haoyuan15] Haoyuan, Y., Shuo, Y., Tan, S.C., Hui, S.Y.R., “Dynamic modeling of partial shading on photovoltaic arrays”, *IEEE Energy Conversion Congress and Exposition*, September 2015.
- [Heshmati15] Heshmati, A., Abolhosseini, S., altmann, J., “The Energy and environment relationship”, *The development of renewable energy sources and its significance for the environment, Springer*, 2015.
- [Gangopadhyay13] Gangopadhyay, U., Jana, S., Das, S., “State of art of solar photovoltaic technology”, *Hindawi Publishing Corporation Conference Papers in Energy*, Vol. 2013, April 2013.
- [Homepower11] URL: <https://www.homepower.com/articles/solar-electricity/design-installation/potential-pv-problems> (Accessed:05.10.2016).
- [Hu09] Hu, C., “Electrons and holes in semiconductors”, URL:https://people.eecs.berkeley.edu/~hu/Chenming-Hu_ch1.pdf, (Accessed:06.01.2016).
- [IEA15] International Energy Agency, Energy and Climate Change, 2015.
- [IEA14a] International Energy Agency, Key World Energy Statistics Report, 2014.
- [IEA14b] International Energy Agency, Energy, climate change and environment Executive summary, 2014.
- [IEA13] International Energy Agency, World Energy Outlook, 2013.
- [IEA11] Technology Roadmap Smart Grids, 2011.

- [Isoaho16] Isoaho, K., Goritz, A., Schulz, N., “Governing clean energy transitions in China and India”, *The Political Economy of Clean Energy Transitions*, Oxford Scholarship, May 2017.
- [Smets16] Smets, A., Jäger, K., Isabella, O., Swaaij, V.R., Zeman, M., “Solar Energy, The physics and engineering of photovoltaic conversion, technologies and systems”, *UIT Cambridge Ltd*, England, 2016.
- [Islam14] Islam, M.N., Rahman, M.Z., Mominuzzaman, S.M., “The effect of irradiation on different parameters of monocrystalline photovoltaic solar cell”, in *Proc of 3rd International Conference on the Developments in Renewable Energy Technology*, Dhaka, Bangladesh, May 2014.
- [Kalkman18] Kalkman, J., Merhaba, A., Bose, S., Bradely, H., “Emerging technologies in Solar PV: identifying and cultivating potential winners, Traversing the PV lab-to-fab valleys of death”, 2015. URL: <http://www.adlittle.com/sites/default/files/viewpoints/ADL-Renewable-Energy-Emerging-PV-Technology.pdf>, (Accessed:05.02.2018).
- [Kaur15] Kaur, T., “Solar PV Integration in smart grid issues and challenges”, *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, Vol. 4, No. 7, July 2015.
- [Kempener13] Ruud Kempener, R., Komor, P., Hoke, A., “Smart grids and renewables: a guide for effective deployment”, *International Renewable Energy Agency*, November 2013.
- [Kalogirou09] Kalogirou, S., “Solar energy engineering: processes and systems”, *2nd Edition, Elsevier, Burlington, USA*, 2009.
- [Kuai05] Kuai, Y., Yuvarajan, S., “An electronic load for testing photovoltaic panels”, *Journal of Power Sources*, Vol. 54, No. 1, pp. 308–313, March 2006.
- [Katz01] Katz. E.A., Faimana, D., Cohena, Y., Padingerc, F., Brabec, C., Sariciftci.N.S., “Temperature and irradiance effect on the photovoltaic parameters of a fullerene/conjugated-polymer solar cell” in *Proc of the SPIE--The International Society for Optical Engineering*, Vol. 4108, pp. 117-124, February 2001.

- [Kverndokk94] Kverndokk, S., “Depletion of fossil fuels and the impacts of global warming”, *Resource and Energy Economics*, Vol. 18, No. 2, pp. 115-136, June 1994.
- [Lu17] Lu, L., “Diodes in NTUEE Electronics”, URL: <http://resources.stkfupm.com/download/dXBsb2Fkcy9FRS9FRTIwMy9Ob3RlcyUyMCUyNiUyMFNsaWRlcy9FRTIwM19fTm90ZXMtU2xpZGVzX19MaWFuZy1ldW5nLUx1X19DaDMucGRm/h/86ad311876f99dfb0edbab5241a0af6> (Accessed:06.05.2017).
- [Lay-Ekuakille13] Lay-Ekuakille, A., Vergallo, P., Arnesano, A., Morello, R., Capua, C., “Effects of environmental conditions on photovoltaic module measurements”, in Proc of *Seventh International Conference on Sensing Technology*, Wellington, New Zealand, December 2013.
- [Lineykin12] Lineykin, S., Averbukh, M., Kuperman, A., “Five-parameter model of photovoltaic cell based on STC data and dimensionless”, in Proc. Of *Electrical & Electronics Engineers in Israel*, pp. 1–5, November 2012.
- [Mekkaoui17] Mekkaoui, A., Laouer, M., Mimoun, Y., “Modeling and simulation for smart grid integration of solar/wind energy”, *Leonardo Journal of Sciences*, Vol. 30, pp. 31-46, June 2017.
- [Menoufi17] Menoufi, K., “Dust accumulation on the surface of photovoltaic panels: introducing the photovoltaic soiling index (PVSI)”, *Sustainability-Open Access Journal*, MDPI, June 2017.
- [Masmoudi16] Masmoudi, F., Salem, F.B., Derbel, N., “Single and double diode models for conventional mono-crystalline solar cell with extraction of internal parameters”, in Proc of *International Multi-Conference on Systems, Signals and Devices*, Leipzig, Germany, March 2016.
- [Mathworks15] URL: <https://www.mathworks.com/> (Accessed: 05.03.2015)
- [Meena14] Meena, M.R.S., Rathore, J.S., Johri, S., “Grid connected roof top solar power generation: A Review”, *International Journal of Engineering Development and Research*, Vol. 3, No.1, 2014.
- [Migan13] Migan, G.A., “Study of the operating temperature of a PV module”,

- Project Report 2013 MVK160 Heat and Mass Transfer*, Lund, Sweden, May 2013.
- [Mohamed12] Mohamed, A.O., Hasan, A., “Effect of dust accumulation on performance of photovoltaic solar modules in Sahara environment” *Journal of Basic and Applied Scientific Research*, Vol. 2, No. 11, pp. 11030-11036, 2012.
- [Mitoula11] Mitoula, R., Abeliotis, K., Vamvakari, M., Gratsani, A., “Sustainable regional development through the use of photovoltaic (PV) systems. The case of the Thessaly region”, in *Proc. of World renewable energy congress*, Linkoping, Sweden, May 2011.
- [Mani10] Mani, M., Pillai, R., “Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations”, *Renewable and Sustainable Energy Reviews*, Vol. 14, pp. 3124–3131, December 2010.
- [NI16] URL: <http://www.ni.com/en-gb.html>(Accessed:03.10.2016).
- [NREL15] Photovoltaic Research, NREL, 2015.
- [Nada14] Nada, Kh, Alrikabi, M.A., “Renewable Energy Types”, *Journal of Clean Energy Technologies*, Vol.2, No. 1, pp. 61-64, January 2014.
- [Nguyen12] Nguyen, H., Pearce, J., “Incorporating shading losses in solar photovoltaic potential assessment at the municipal scale.” *Solar Energy*, Vol. 86, No. 5, pp. 1245-1260, April 2012.
- [Net110] National Energy Technology Laboratory, U.S. Department of Energy, *Understanding the Benefits of the Smart Grid*, June 2010.
- [Nguyen08] Nguyen, D., Lehman, B., “a reconfigurable solar photovoltaic array under shadow conditions”, *Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition*, Austin, USA, May 2008.
- [Nordmann03] Nordmann, T., Clavadebacher, L., “Understanding temperature effects on PV system performance”, In *Proc of 3rd World Conference on Photovoltaic Energy Conversion*, Osaka, Japan, May 2003.
- [Omer11] Omer, A.M., “Energy and environment: applications and sustainable development”, *British Journal of Environment & Climate Change*, Vol. 1, No. 4, pp. 118-158, October-December 2011.

- [Pixabay17] URL: <https://pixabay.com/en/photovoltaic-system-solar-2742308/>(Accessed:01.01.18).
- [Pedhazur91] Pedhazur, Elazar J.; Schmelkin, Liora Pedhazur, “Measurement, design, and analysis: an integrated approach”, NJ: Lawrence Erlbaum Associates, pp. 15–29, Taylor & Francis, New York, USA, 1991.
- [VIM08] International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM) (3rd ed.). *International Bureau of Weights and Measures*. 2008.
- [Prakesh17] Prakesh, S., Sherine, S., “Forecasting Methodologies Of Solar Resource And PV Power For Smart Grid Energy Management”, *International Journal of Pure and Applied Mathematics*, Vol. 116, No. 18, pp. 313-318, 2017.
- [Pvlighthouse17] PV Lighthouse is a website of online resources for photovoltaic (PV) engineers and scientists,
URL:<http://pvlighthouse.com.au>(Accessed:07.10.2017).
- [Pereira14] Pereira, R.J., Melicio, R., Mendes, V.M.F., Joyce, A., “PV System with maximum power point tracking: modeling, simulation and experimental results”, *Procedia Technology*, Vol. 17, pp. 495 – 501, 2014.
- [Phuangpornpitaka13] Phuangpornpitaka, N., Tia, S., “Opportunities and challenges of integrating renewable energy in smart grid system”, *10th Eco-Energy and Materials Science and Engineering Symposium, Energy Procedia*, Vol. 34, pp. 282-290, 2013.
- [Parida11] Parida, B., Iniyar, S., Goic, R., “A review of solar photovoltaic technologies”, *Renewable and Sustainable Energy Reviews*, Vol. 15, pp. 1625-1636, 2011.
- [Piazza10] Piazza, M.C.D., Vitale, G., “Photovoltaic field emulation including dynamic and partial shadow conditions”, *Applied Energy*, Vol. 87, pp. 814–823, March 2010.
- [Rashel18a] Rashel, M.R., Ahmed, T., Goncalves, T., Tlemcani, M., Melicio, R., “Analysis of environmental parameters sensitivity to improve modeling of a c-Si panel”, *Sensor Letters*, Vol.16, N° 3, pp. 176-181, March 2018.

- [Rashel18b] Rashel, M.R., Ahmed, T., Goncalves, T., Tlemçani, M., Melicio, R., “Analysis of different types of obstacles for PV panel”, Poster paper in *Eradication Poverty through Energy Innovation Workshop*, Arizona State University, poster, Tempe, Arizona, USA, 12–14 February 2018.
- [Rashel17a] Rashel, M.R., Rifath, J., Gonçalves, T., Tlemçani, M., Melício, R., “Sensitivity analysis through error function of crystalline-Si photovoltaic cell model integrated in a smart grid”, *International Journal of Renewable Energy Research*, Vol. 7, No.º 4, pp. 1926–1933, December 2017.
- [Rashel17b] Rashel, M. R., Gonçalves, T., Tlemçani, M., Melicio, R., “Photovoltaic cell performance analysis under different ambient temperature and wind speed for sustainable energy”, *Vietnam Journal of Science*, Vol. 3, No.º 1, pp. 1–16, 22 August 2017.
- [Rashel17c] Rashel, M.R., Albino, A., Gonçalves, T., Tlemçani, M. “Sensitivity analysis of environmental and internal parameters of a photovoltaic cell”, in Proc. of *Energy for Sustainability International Conference - Designing Cities & Communities for the Future*, Madeira, Portugal, February 2017.
- [Rauf17] Rauf, S., Khan, N., “Application of DC-AC hybrid grid and solar photovoltaic generation with battery storage using smart grid”, *Hindawi International Journal of Photoenergy*, Vol. 2017, 2017.
- [Rwenyagila17] Rwenyagila, E.R., “A review of organic photovoltaic energy source and its technological designs”, *Hindawi International Journal of Photoenergy*, Vol. 2017, 2017.
- [Rashel16a] Rashel, M.R., Albino, A., Gonçalves, T., Tlemçani, M., “MATLAB Simulink modeling of photovoltaic cells for understanding shadow effect”, in Proc. Of *International Conference on Renewable Energy Research and Applications*, Birmingham, UK, November 2016.
- [Rashel16b] Rashel, M.R., A. Albino, Gonçalves, T., Tlemçani, M., “Sensitivity analysis of parameters of a photovoltaic cell under different condition”, in Proc. of *International Conference on Software, Knowledge, Information Management & Applications*, Chengdu, China, December 2016.

- [Rashel16c] Rashel, M.R., Albino, A., Gonçalves, T., Tlemçani, M., “Analyzing ambient temperature and wind speed effect on the photovoltaic cell”, *Workshop on Earth Sciences, University of Évora, Portugal*, December 2016.
- [Rashel16d] Rashel, M.R., Albino, A., Gonçalves, T., Veiga, A., Ahmed, T., Tlemçani, M., “Comparison of Photovoltaic panel’s standard and simplified models”, in Proc. of *International Conference for Students on Applied Engineering*, UK, October 2016.
- [REN16] REN21, *Renewables 2016, Global Status report*, 2016
- [Romano13] Romano, P., Candela, R., Cardinale, M., Vigni, V.L., Musso, D., Sanseverino, R., “Optimization of photovoltaic energy production through an efficient switching matrix”, *Journal of Sustainable Development of Energy, Water and Environment Systems*, Vol. 1, No. 3, pp. 227-236, 2013.
- [Rodrigues11] Rodrigues, E.M.G., Melício, R., Mendes, V.M.F., Catalão, J.P.S., “Simulation of a solar cell considering single-diode equivalent circuit model”, in Proc. of *International Conference on Renewable Energies and Power Quality*, pp. 1–5, Las Palmas de Gran Canaria, Spain, 13–15 April 2011.
- [Saleem17] Saleem, Y., Rehmani, M.H., “Internet of things-aided smart grid: technologies, Architectures, Applications, Prototypes, and Future Research Directions”, *ArXiv*, April 2017.
- [Solarglassshield17] URL:<https://www.solarglassshield.com/construction-mining-dust> (Accessed:10.11.2017).
- [Singla16] Singla, A., Singh, K., Yadav, V.K., “Environmental effects on performance of solar photovoltaic module”, *Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy*, Bangalore, India, January 2016.
- [Sunnymorgan16] URL: <http://sunnymorgan.co.za/>(Accessed:10.11.2017)
- [Sharma15] Sarma, S., Jain, K.K., Sharma, A., “Solar cells: in research and applications—A Review”, *Scientific Research Publishing, Materials Sciences and Applications*, Vol. 6, pp. 1145-1155, December 2015.

- [Saluos15] Saluos, W.A., “Dust effect on photovoltaic electric systems”, *International Journal of Emerging Engineering Research and Technology*, Vol. 3, No. 10, pp. 4-9, October 2015.
- [Shafiullah13] Shafiullah, G.M., Amanullah, M. T.O., Ali, A.B.M.S., Wolfs, P., “Smart Grid for a Sustainable Future”, *Scientific Research open access*, February 2013.
- [Salim13] Salim, M.S., Najim. J.M., Salih, S.M., “Practical evaluation of solar irradiance effect on PV performance”, *CSCanada Energy Science and Technology*, Vol. 6, No. 2, pp. 36-40, November 2013.
- [Schwingshackla13] C. Schwingshackla, C., Petittaa, M., Wagnera, J.E., G. Belluardoc, G., Moserc, D., Castellia, M., Zebischa, M., Tetzlaff, A., “Wind effect on PV module temperature: analysis of different techniques for an accurate estimation”, *European Geosciences Union General Assembly, Energy Procedia*, Vol. 40, pp. 77-86, 2013.
- [Storey13] Storey, J.P., Wilson, P.R., “Improved optimization strategy for irradiance equalization in dynamic photovoltaic arrays”, *IEEE Transactions On Power Electronics*, Vol. 28, No. 6, June 2013.
- [Saraiva12] Saraiva, S., Melicio, R., Matias, J.C.O., Cabrita, C.M.P., Catalao, J.P.S., “Simulation and experimental results for a photovoltaic system formed by monocrystalline solar modules”, *Technological Innovation for Value Creation, Springer*, pp. 329–336, February 2012.
- [Solarcellcentral11] URL:http://solarcellcentral.com/markets_page.html (Accessed:10.11.2016).
- [Sera07] Sera, D., Teodorescu, R., Rodriguez, P., “PV panel model based on datasheet values”, in Proc. of *IEEE International Symposium on Industrial Electronics*, pp. 2392-2396, Vigo, Spain, June 2007.
- [Soto06] Soto, W. D., Klein, S. A., Beckman, W. A., “Improvement and validation of a model for photovoltaic array performance”, *Solar Energy*, Vol. 80, pp. 78-88, January 2006.
- [Solar98] URL: <http://www.solar.coppe.ufrj.br/pr03.html> (Accessed:10.01.2016).

- [Shell97] Veer, J.V., Dawson, J., Shell International Renewables. Web page: <http://www.shell.com>, 1997, Transcript of a Press conference in London,1997, (Accessed:10.11.2016).
- [Shockley61] Shockley, W., Queisser. H., "Detailed balance limit of efficiency of p-n junction solar cells", *Journal of Applied Physics*, Vol. 32, No. 3, March 1961.
- [Tranverter18] URL: <http://www.transverter.com/smart.html> (Accessed: 13.03.2017).
- [Techopedia18] URL:<https://www.techopedia.com/definition/2320/universal-serial-bus-usb> (Accessed:10.12.2018).
- [Tamirat17] Tamirat, Y., "The Role of nanotechnology in semiconductor industry: Review Article", *Journal of Materials Science & Nanotechnology*, Vol. 5, No. 2, September 2017.
- [Tektronix16] URL:<https://www.tek.com/datasheet/afg310-afg320> (Accessed:10.01.2017).
- [Tayyan13] Tayyan, A. A. E., "A simple method to extract the parameters of the single-diode model of a PV system", *Turkish Journal of Physics*, Vol. 37, pp. 121–131, March 2013.
- [Tayyan11] Tayyan, A. A. E., "PV system behavior based on datasheet", *Journal of Electron Devices*, Vol. 9, pp. 335–341, 2011.
- [UN16] Paris Agreement. Paris: United Nations, pp.1-27, 2016.
- [UNFCCC15] United Nations Framework Convention on Climate Change, 2015.
- [Vergura16] Vergura, S., "A Complete and simplified datasheet-based model of PV cells in variable environmental conditions for circuit simulation" energies, April 2016.
- [Viegas15] Viegas, J.L., Susana, M., Melicio, R., Mendes, V.M.F., "Electricity demand profile prediction based on household characteristics", in Proc of *12th International Conference on the European Energy Market*, Lisbon, Portugal, May 2015.
- [Wang17] Wang, J., Gong, H., Zou, Z., "Modeling of dust deposition affecting transmittance of PV modules" *Journal of Clean Energy Technologies*, Vol. 5, No. 3, May 2017.

- [WEC16] World Energy Council, World Energy Resources 2016.
- [Weforum15] URL: <https://www.weforum.org/> (Accessed:17.05.2016)
- [Wan15] Wan, C., Zhao, J., Song, Y., Xu, Z., Lin, J., Hu, Z., “Photovoltaic and solar power forecasting for smart grid energy management” *CSEE Journal of Power and Energy Systems*, Vol. 1, No. 4, December 2015.
- [Wang12] Wang, Y., Lin, X., Kim, Y., Chang, N., Pedram, M., “Enhancing efficiency and robustness of a photovoltaic power system under partial shading”, in Proc of *13th International Symposium on Quality Electronic Design*, Santa Clara, USA, March 2012.
- [Warwick10] URL: <https://warwick.ac.uk/fac/sci/physics/current/postgraduate/regs/mpagswarwick/ex5/bandstructure/> (Accessed:12.01.2018).
- [Würfel05] Würfel, P., The physics of solar cells: from principles to new concepts, 1st Edition, Wiley-VCH, Germany, 2005.
- [Wieder92] Wider, S., An introduction to solar energy for scientist and engineers, 1st Edition, John Wiley & Sons, Inc. Florida, USA, 1992.
- [Zaihidee16] Zaihidee, F.M., Mekhilef, S., Seyedmahmoudian, M., Horan. B., “Dust as an unalterable deteriorative factor affecting PV panel's efficiency: Why and how”, *Renewable and Sustainable Energy Reviews*, Vol. 65, pp. 1267-1278, November 2016.
- [Zeman14] Zeman, M., Solar cells, *Open Education Consortium, Delft University of Technology*, Netherland, 2014.
- [Zeman10] Zeman, M., “Thin-Film Silicon PV technology”, *Journal of Electrical Engineering*, Vol. 61, No. 5, pp.271–276, 2010.
- [Zerhouni10] Zerhouni, Z.F., Zerhouni, M.H., Zegrar, M., Benmessaoud, M.T., Stambouli, A.B., Midoun, A., “Proposed methods to increase the output efficiency of a photovoltaic (PV) system”, *Acta Polytechnica Hungarica*, Vol. 7, No. 2, July 2010.

5 Appendix

Appendix I

Matlab Code for communicating the DAQ with workstation.

```
daqread = daq.createSession('ni');

% add channel
%daqread.addAnalogInputChannel('Dev2', 'ai0', 'Voltage'); % channel 0
%daqread.addAnalogInputChannel('Dev2', 'ai1', 'Voltage'); % channel 1

ai0 = addAnalogInputChannel(daqread,'Dev2', 'ai0', 'Voltage');
ai0.Range=[-10,10];

ai1 = addAnalogInputChannel(daqread,'Dev2', 'ai1', 'Voltage');
ai1.Range=[-10,10];
```

Part of Matlab code for identify the temperature effect.

```
Vt = Ns*(K*Tn)/q;
Ion = Isc /(exp(Voc/(N*Vt))-1);
Iphn = Isc;

T_STD = [273 278 283 288 293 298 303 303 313 318 323 328]';

for r = 1:1:12
    i = 1;
    I_STD(i,r) = 0;

    Iph = (Ir_STD/Irn)*(Iphn + (Ki*(T_STD(r,1) - Tn)));
    Io = ((Ion*((T_STD(r,1)/Tn)^3))*(exp((q*Eg)/(N*K)*((1/Tn)-(1/T_STD(r,1))))));

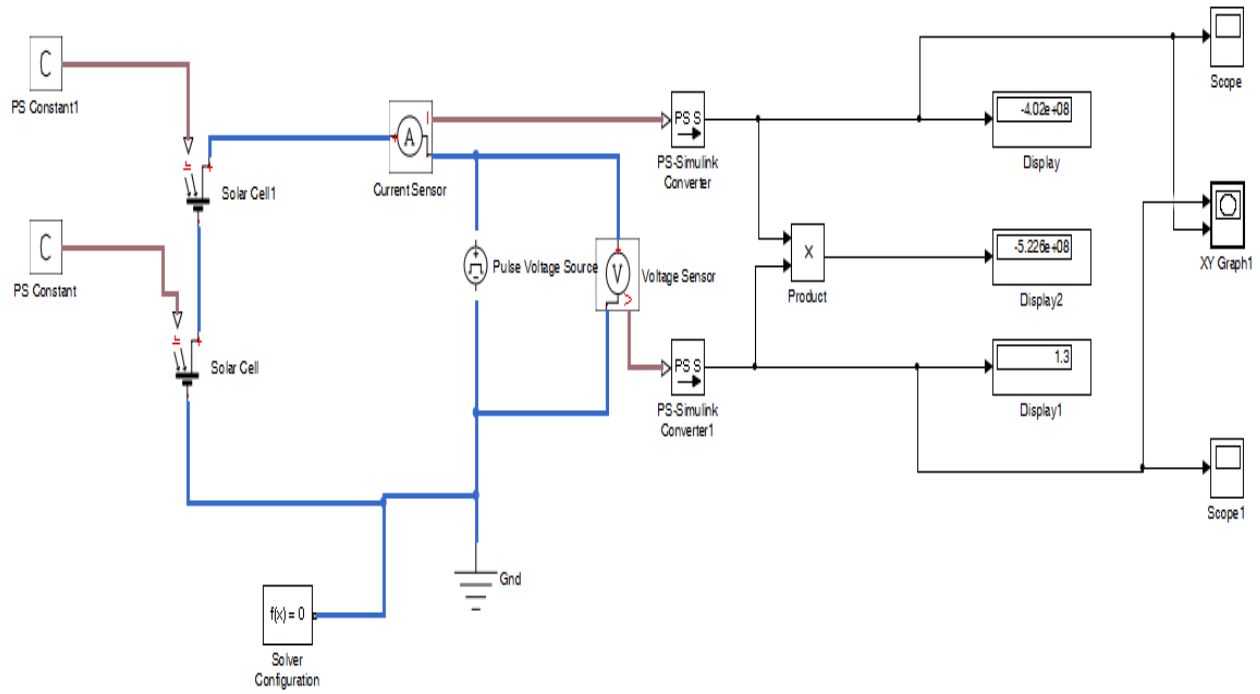
    for V = 0.0:0.01:.64;

        value1 = (V+(I_STD(i,r)*Rs))/(N*Vt);
```

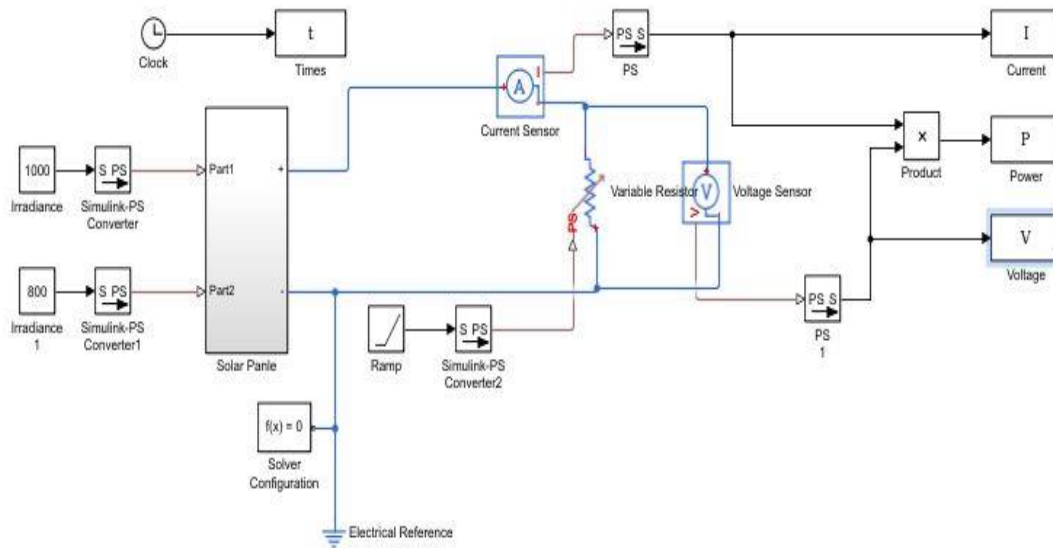
```
value2 = (V+(I_STD(i,r)*Rs))/Rsh;  
I_temp = (Io*(exp(value1)))-(value2);  
  
I_STD(i,r) = Iph - I_temp;  
  
% V1(i,1) = V; % Voltage value store in a 2D array  
P_STD(i,r) = V * I_STD (i,r);  
  
i = i + 1;  
  
end  
end
```

Appendix II

Simulink model for identify cells behavior in Serial connection.



Simulink model for identify the shadow of obstacles on PV panel.





UNIVERSIDADE DE ÉVORA
INSTITUTO DE INVESTIGAÇÃO
E FORMAÇÃO AVANÇADA

Contactos:

Universidade de Évora

Instituto de Investigação e Formação Avançada - IIFA

Palácio do Vimioso | Largo Marquês de Marialva, Apart. 94

7002-554 Évora | Portugal

Tel: (+351) 266 706 581