

Study on Design and Performance Characterization of Stand-alone Solar Photovoltaic System

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ABSTRACT

The depletion of fossil fuel resources on a worldwide basis has necessitated an urgent search for alternative energy sources to meet up the present day demands. Solar photovoltaic (SPV) is growing at a rapid pace since the last decade, and has attracted considerable attention as one of the most promising low carbon emitting renewable energy alternatives. The Photovoltaic's performance depends mainly on the incident irradiation, ambient temperature and thermal characteristic of the PV technology. Solar energy is clean, inexhaustible and environment-friendly, making it a potential resource among renewable energy options. The main aim of this project is to analyze the performance characteristics of PV system for different conditions of a solar cell, module and array by developing an appropriate model using Matlab and also analyze the performance characteristics by proper interface among solar photovoltaic system, load, battery and other electronic devices

Keywords: Photovoltaic system, Matlab, Simulink, Renewable energy, Island mode operation.

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Chapter 1
INTRODUCTION

1.1 Introduction

Energy of various forms is of great importance in world civilization from start of it to modern era and will play a deterministic role in shaping the future human civilization. There are different types of energy sources available and the efficient conversion of different types of energy resources to electrical energy is an important aspect of research work to be carried out extensively. Electrical energy is most important form amongst various types of energy and the use of electrical energy is noticed in everywhere, such as home, industry, agriculture, transported.

The rapid growth in population and economic growth has led to an enormous energy demand all over the globe. Fossil fuels being the most reliable and primary source of energy, fossil fuels reserve has been decreasing rapidly due to over use of it to fulfil the huge energy demand. Moreover, the combustion of the fossil fuels leads to the release of huge amount of toxic emissions (greenhouse gases) resulting in the phenomenon of global warming. So on one hand, the rapid extinction of the worldwide fossil fuels reserves looking imminent and on the other hand the adverse impact of fossil fuels combustions on the surrounding environment is looming large. This has necessitated an urgent search for an alternative source of energy.

It is great concern for a country like India which is heavily dependent on coal and imported oil to meet the growing energy demand. But for sustainable development, India has shifted its focus to power generation from renewable energy sources due to high oil & coal import bill, greenhouse gas (GHG) emission from thermal plants and air pollution. Considering the socio-economic aspects and environmental issues in the long term and for enhanced energy security, renewable energy is getting top strategic priority in the country. On the contrary, intermittent and stochastic nature of these resources and dependence on the topography conditions of the specific sites and different meteorological conditions make it difficult to design the renewable energy systems in a reliable and robust way [1, 2].

As of now, the share of coal for power production is quite large compared to other fuels in India though the shifting towards green energy is evident from discussion presented in next section.

1.2 Energy scenario of India

For rapid economic growth, increase in population and industrialisation all over the world, the energy requirement has increased manifold.

The International Energy Agency (IEA) has anticipated that world primary energy demand in 2030 would be 16,800 million tonnes of oil equivalent (Mtoe) which is 40% more than the present day energy demand of 12,000 (Mtoe) with 1.5% increase per year. Developing Asian countries especially India and China are the main drivers of this growth, followed by Middle East [3].

India is the world's one of the fastest growing economy market and is the second largest country in the world in terms of population after China (1.34 billion). The population of India as per Census 2011 is 1.21 billion which is more than five times of the population of the year 1901 (about 238.4 million). The growth rate of population for India in the last decade was 17.64% [4]. Rapid population growth and fast growing economic have accelerated the energy demand. To keep pace with the demand, India is producing huge electricity and is 3rd in electricity generation (1208 TWh) in the world at the end of year 2014[5].

The table presented below shows the actual electricity supply position in terms of energy requirement vis-à-vis energy availability of various states/systems of India during the year 2014-2015. It may be seen that almost all the states and Union Territories had the deficit power supply during the year 2014-2015. The maximum deficit was in Andaman & Nicobar Island with 25% deficit followed by Jammu & Kashmir with a deficit of 19.1%. The average deficit in India during the mentioned year was 3.6% and this deficit energy against the actual requirement poses a great threat to the energy security of the country [6]. Therefore search for alternative energy resources is imminent for sustainable & inclusive development of India.

Table1.Actual power supply position in terms of Energy Requirement vis-à-vis Energy Availability of various States/ Systems during the year 2014-15 [6]

State / Region	ENERGY			
	Requirement	Availability	Surplus(+)/ Deficit (-)	
	(MU)	(MU)	(MU)	(%)
Chandigarh	1,616	1,616	0	0.0
Delhi	29,231	29,106	-125	-0.4
Haryana	46,615	46,432	-183	-0.4
Himachal Pradesh	8,807	8,728	-79	-0.9
Jammu & Kashmir	16,214	13,119	-3,095	-19.1
Punjab	48,629	48,144	-485	-1.0
Rajasthan	65,717	65,310	-407	-0.6
Uttar Pradesh	103,179	87,062	-16,117	-15.6
Uttarakhand	12,445	12,072	-373	-3.0
Chhattisgarh	21,499	21,230	-269	-1.3
Gujarat	96,235	96,211	-24	0.0
Madhya Pradesh	53,374	53,082	-292	-0.5
Maharashtra	134,897	133,078	-1,819	-1.3
Daman & Diu	2,086	2,086	0	0.0
D.N. Haveli	5,307	5,304	-3	-0.1
Goa	3,969	3,932	-37	-0.9
Andhra Pradesh	59,198	56,313	-2,885	-4.9
Karnataka	62,643	59,926	-2,717	-4.3
Kerala	22,459	22,127	-332	-1.5
Tamil Nadu	95,758	92,750	-3,008	-3.1
Telemngana	43,337	40,644	-2,693	-6.2
Puducherry	2,402	2,376	-26	-1.1
Lakshadweep	48	48	0	0.0
Bihar	19,294	18,759	-535	-2.8
Damodar Valley Corporation	18,222	17,728	-494	-2.7
Jharkhand	7,599	7,390	-209	-2.8
Odisha	26,482	26,052	-430	-1.6
West Bengal	47,086	46,827	-259	-0.6
Sikkim	399	399	0	0.0
Andaman & Nicobar	240	180	-60	-25.0
Arunachal Pradesh	677	610	-67	-9.9
Assam	8,527	7,926	-601	-7.0
Manipur	705	678	-27	-3.8
Meghalaya	1,930	1,634	-296	-15.3
Mizoram	455	425	-30	-6.6
Nagaland	688	661	-27	-3.9
Tripura	1,242	1,048	-194	-15.6
All India	1,068,923	1,030,785	-38,138	-3.6

The fossil fuels are predominant compared to other sources of energy to meet the above energy requirement of the country. The fuel wise installed capacity of power stations in India is shown in below Fig. 1.1

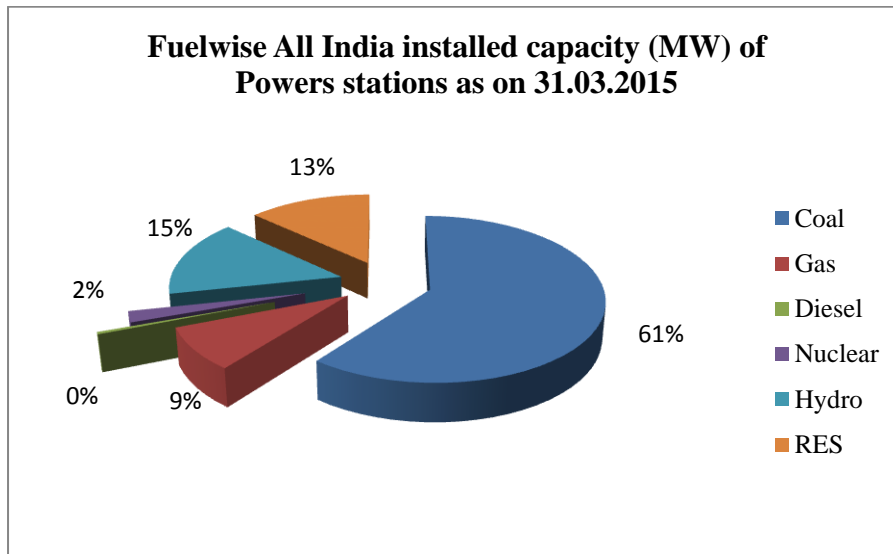


Fig.1.1 Fuel wise installed capacity of Power stations in India as on 31.03.2015 [7]

The Renewable energy sources (RES) include Small hydro power (SHP), Wind power, Biomass Power (BP), Urban and Industrial power (U&I) and Solar power. The detailed share of various Renewable sources is given in Fig.1.2

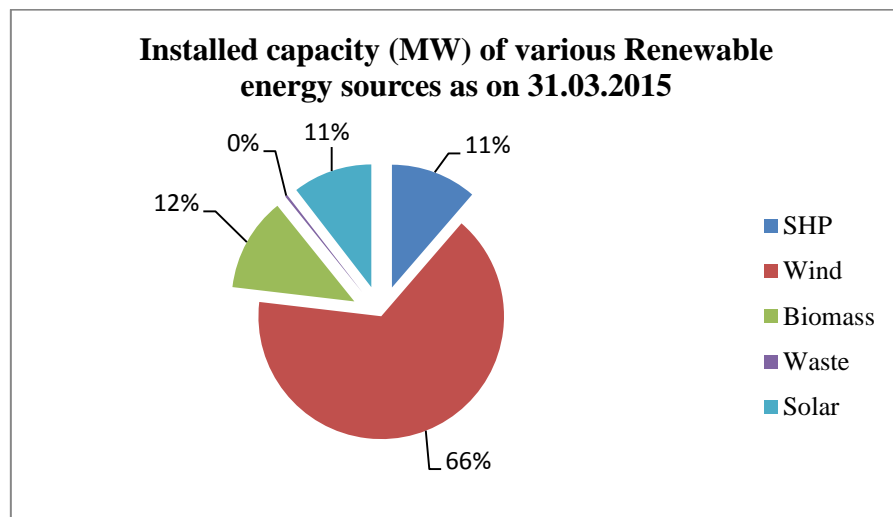


Fig.1.2 Installed capacity of various Renewable energy sources in India as on 31.03.2015 [7]

It is evident from Fig.1 and Fig.2 that the major and primary fuel for power generation is coal and accounts almost 61% of the India’s total installed capacity. Large hydro power comes second in the list with a share of 15%. Renewable energy sources (RES) which include

various renewable energy like solar and wind energy are another important energy sources and its share is 13% of the total installed capacity as of 31st March, 2015. If breakup of RES is considered, then the share of wind power is 66% which is six times of solar power (11%). Small hydro power and Biomass have almost same share of installed capacity of 11% and 12% respectively [7]. It can also be observed that the total installed capacity of RES in the year 2014-2015 is 35776.96MW which is 30% higher than the installed capacity of 27541.71 MW in the year 2012-2013. But with the increased demand, the total thermal installed capacity in the year 2014-2015 has registered a growth of 24% from the year 2012-2013 [7, 8]. Thus it may be said that the shifting towards the renewable energy resources has already been started and more and more emphasis is given to the power production from these sources and it is obvious that thermal energy sources will be saturated or may foresee a decline within next few decades.

So for sustainable socio-economic development and to keep pace with economic growth rate, energy generation is unavoidable keeping in mind the environmental issues and since India is a developing country it can be anticipated that India's share on energy requirement will be quite higher than many other nations.

1.3 Aim and Objective

As of now, India is mostly dependent on the thermal power stations for required electricity production using fossil fuels which is associated with detrimental environmental effects. Therefore, increased energy demand & rapid depletion of fossil fuels on one side and socio-economic aspects and environmental issues on other side make people to think for green energy sources. For sustainable development, India has shifted its focus to power generation from renewable energy sources due to high oil & coal import bill, GHG emission from thermal plants and air pollution for enhanced energy security. Hence renewable energy resources like solar photovoltaic (PV) and wind play an important role for sustainable socio-economic growth of the country. But the intermittent and stochastic nature of these resources and dependence on the topography conditions of the specific sites and different meteorological conditions make these resources most unreliable sources of energy. Therefore, extensive research works are to be carried out for proper characterization, modelling, analysis and system design of these resources to make the renewable energy systems a reliable, economic and environment friendly energy system.

India has great potential of solar energy and in future solar will play the deterministic role in India's energy security. Solar energy is abundant, readily available and almost free source of energy. But the conversion from solar energy to electric energy is a major issue in capturing the abundant solar energy and on this aspect, lot of research works is going on to increase the efficiency of the PV modules. On the other hand, the electrical performance characterization of PV is also an important aspect to work under maximum power condition in stand-alone system or in integrated system. Therefore, lot of effort has been made to model, design and analysis of PV modules as well as PV arrays for optimized performance in terms of voltage, current and power output.

Here the focus of research work is to develop a renewable energy system namely solar PV system. Before developing any prototype of the system, a soft computing analysis is carried out in this work. Here the modelling of solar cell, module and array are presented and their electrical characteristic are analysed under different conditions and then a complete solar photovoltaic system with battery and load is designed in MATLAB SIMULINK and its performance is reported. In this dissertation, software simulations of solar PV cells, modules and arrays are developed using standard equations available in relevant literature. Also, standard toolboxes already available in Matlab have been used to develop a similar model. Results from the simulation of these models are then analysed graphically as well as in tabular form.

1.4 Outline of the thesis

The main aim of this thesis to publicize renewable energy technology which is most efficient, reliable to small scale or large scale power generation and less harmful to the environment for the upcoming future. Nowadays traditional energy sources are used for household and commercial purpose. Though this type energy sources have several types of advantages such as limited quantity, environmental pollution and also consuming more time to installation. So, power generation from renewable energy sources will be more advantages over conventional sources and it should be beneficial to our society.

This thesis work is mainly focused on solar photovoltaic system. In this work solar module and array are developed based on their numerical equation. The whole system is developed on MATLAB platform. Through the mathematical modelling of these system with the help of MATLAB/SIMULINK, the performance characteristics are observed. By developing a

solar photovoltaic system with a battery and a load, the voltage, current and power characteristics are observed. During the thesis work the some topics like introduction, energy scenario of India, aim & objective are discuss in chapter 1. The literature survey regarding the thesis is discussed in chapter 2. The thesis work focused on the performance of solar photovoltaic module, array and system. Before developed the thesis work it is necessary to study on solar photovoltaic technology. A brief discussion on solar photovoltaic technology is covered in chapter 3. After the discussion on solar PV system, the mathematical modelling is developed using PV equivalent circuit and a PV system including a battery and resistive load discussed in chapter 4. By using MATLAB/SIMULINK the model are simulated and the simulation result are discussed in chapter 5. At the end of the result & discussion of conclusion of this work and future scope are discussed briefly in chapter6.

Chapter-2

LITERATURE SURVEY

2.1 Introduction

In 1839, a French physicist Alexandre Edmond Becquerel first discovered the light to electricity phenomena on solid state physics[49]. In 1883 Charles Frittscha described the first solar cell selenium wafers[49]. In 1954 bell's lab first discovered high power silicon PV cells. In 1958 first PV array radios was introduced to US Vanguard-I[49]. Since from the inception, solar photovoltaic cell technology was modified by different ways. Nowadays the solar photovoltaic technology is focused in different way.

2.2 Solar photovoltaic cell

A photovoltaic system is able to convert light energy form sun to electricity. The main component of the photovoltaic (PV) system is PV cell. PV cell is nothing but a two dissimilar semiconductor device which is coupled in junction diode [9, 10]. Based on different type of manufacturing process PV cells are made of different type of semiconductor. From the commercial point of view two types of PV cells are observed, such as mono-crystalline and polycrystalline [9,11]. For silicon based PV cells one side of Si layer is doped to form the p-n junction. When light energy incidences on the cell, the charge carrier create a potential barrier between the junction, i.e. electricity generated and the output collect at the terminals of the cell. The output of the PV cell is depending on wavelength of incidence light [9, 10, 12]. The output photocurrent is directly proportional to the solar irradiation [10, 12].

2.3 Available circuit model

Generally two types of models are used to represent the undergoing research work regarding photovoltaic module, such as single diode model and double diode model. The two types of model differ from each other due to the existing numberof diodes which denotes the saturation current.

2.3.1 Single diode model

A PV cell is a solid state semiconductor device which has a junction between the two dissimilar semiconductor materials. The value of ideality factor is varies in between 1 and 2 which is determined from the fabrication process. When the incident light interface with the PV cell, photocurrent generated.

2.3.2 Double diode Model

The generated photocurrent of a PV cell is not only effect of a single diode. It can be generated by the overall effect of more diodes existing in circuit. The photocurrent through all the diodes, as a result the voltage is dropped.

2.4 Extraction of parameters for PV model

2.4.1 Five parameter model

According to the conventional method, the photocurrent, load current (I_L) depend on the solar irradiance where as the diode current depend on the temperature. A typical solar cell depends on five parameter, such as load current (I_L), diode saturation current (I_0), diode ideality factor (n), series resistance (R_s) and shunt resistance (R_{sh}). For the evocation process of that parameter either single diode or double diode model is used.

Valeria *et al.* [13] proposed a new model, consists of five parameters which is capable to describe the I-V characteristics by analytically of a PV module, in a specific condition of operating temperature and solar irradiation. The evaluation of the parameters of solar cells is based on single diode model. The parameters are evaluated from the equivalent circuit's equations by using datasheet provided by the manufacturers (R_s , R_{sh} , n , I_L , I_0) [14]. In this method any change in external condition (temperature & irradiation) is considered to find out those values. The result of this method is accurate approximation of current generated in PV panel.

In paper [15] Celik, *et al.* presents a model of derivation of five parameters (R_s , R_{sh} , n , I_L and I_0) which are operating in a certain solar irradiation and temperature level from the limiting conditions of V_{oc} , I_{sc} , V_{mp} , I_{mp} and using the reciprocal slope of the open circuit point and short circuit point. The proposed model is based on single diode model. The model is applied to calculate the I_{sc} & V_{oc} based on their reference values, and also adjusting the simultaneously change in environmental condition. The reciprocal gradient value for five parameter model is not provided by the manufactures and it is difficult to determine their exact value [14, 15]. The effect of these values is minor to the proposed model.

In paper [16] Merbah *et al.* proposed another method for extracting the five parameter's values of the solar cell. For the evaluation of those parameters, here double diode model is considered. Here the parameters are R_s , G_{sh} , n_1 , n_2 , I_L , I_{01} and I_{02} . Under the illuminated condition of solar cell a gradient of V_{oc}/I_{sc} divided the I-V characteristics in two sections.

First section is close to short circuit current zone and another section which is close to open circuit voltage zone. The I-V characteristics are function of current and voltage [14, 16]. The first region is fitted near to the short circuit current to determine the I_{sc} and G_{sh} . Similarly the second region is fitted to open circuit region to obtain the V_{oc} and R_s . To determine all the parameter the system must be solved with the non-linear equations respective to the parameters. From this procedure, the I-V curve under the illumination is developed to determine the solar cell parameters. In this way current measurement error and voltage measurement error are observed [16].

2.4.2 Four parameter model

In paper [15] Celiket *al.* proposed a single diode four parameter model with the assumption that R_s equals to infinite. In [17] Tivanovet *al.* an algorithm is used to determine the solar cell parameter like series and parallel resistance, diode coefficient, reverse current density from the I-V characteristics at a constant intensity of solar irradiation. The mathematical equation of single diode model with the assumption of the photocurrent (I_{ph}) is almost equal to the short circuit current (I_{sc}). With the analysis of the I-V curve characteristics under a constant irradiation the parameters can be calculated [14, 17].

In paper [18], Khan *et al.* proposed a single diode model, to determine the parameters of a c-Si solar cell with the prediction of illumination level. Here analytical method is used to obtain the shunt resistance (R_{sh}), series resistance (R_s), diode ideality factor (n), reverse saturation current (I_0) by using the values of I_{sc} , V_{oc} , R_{sc} , R_{oc} , V_{mpp} , I_{mpp} . The values of I_{mpp} increase linearly with the increment of solar irradiation.

In Kaminski *et al.* [19] evaluate the solar cell parameters such as I_{od} , I_{or} , n_d , n_r , R_s , R_{sh} by using a single diode model in dark condition. To analyze the I-V characteristics of solar cell in dark condition, it is focused in two regions. First region is higher due to the importance of series resistance and diffusion mechanism. Similarly second region is lower due to the importance of shunt resistance and recombination mechanism. The parameter I_{od} , n_d , R_s are obtained in first section by linear regression. Similarly the parameters I_{or} , n_r , R_{sh} can be obtained by least square method.

2.4.3 Three parameter model

In paper [20] Zhang *et al.* proposed a model based on single diode to determine the parameters of solar cell using I-V characteristics at fixed level illumination of solar irradiance

and Lambert W function. In this method the three parameters (n , R_s , R_{sh}) is obtained by using numerical fit method. The initial value of shunt resistance (R_{sh}) is found out by the appropriate equation which is linearly dependent on dV/dI . On the other side the series resistance (R_s) and diode ideality factor (n) are obtained from the intercept and gradient.

In paper [21] Arcipiani proposed the generalized area method for determine the parameter of non-ideal solar cell. Through this method the series resistance (R_s), shunt resistance (R_{sh}), ideality factor (n) are determined by the calculation of the area between V and I with their respective axes in the I-V characteristics of solar cell.

In paper [22] GarridoAlzar devised a model of solar cell based on double diode. To determine the parameters of the solar cell the method used the equation system at four points like $I_{(1)}$, $I_{(2)}$, $I_{(3)}$, $I_{(4)}$ from the I-V characteristics. Here also in zero order hold approximation for n and R_s is considered.

2.5 Equation based solar PV modelling methods

Sam Koochi-Kamali *et al.* in their paper [23] have extensively presented dynamic modelling methods for smart grid applications for photovoltaic electricity generator. A new classification on existing PV cell /module/array modelling methods has been presented here. The authors have categorized modelling techniques into two main classes, circuitry based methods and equation based methods. Under equation based methods, two subsections have been presented: numerical analysis techniques and analytical techniques.

Equation based modelling methods can be used to model non linear PV cell characteristics analytically or numerically [23]. Non linear equations pertaining to mathematical modelling are studied and analysed in this form of modelling and then iterative solving methods are used to solve the derived nonlinear equations. By changing the diode voltage over a range, I-V characteristics of PV cell have been obtained by Bishop [24]. Partial shading effect has been considered in this work and such a method does not need to solve non-linear equations. Bishop went ahead to develop a software tool named PV Sim for PV system simulation [25]. Bishop's work was extended further by Abete *et al* [26] and rules for analyzing shading effects on PV module mismatch were proposed.

2.5.1 Analytical Methods

Analytical methods for PV cell modeling have been taken up by various researchers. In such methods, nonlinear equations are analyzed with the help of physical properties of the cell. PV cell circuits can be extended to 2-diode or 3-diode configurations for more efficient modeling. Such modeling involves optimization techniques and iterative algorithms. But using such schemes might increase the computation complexity due to the slow convergence of such methods. Therefore a balance has to be established in this regard. Hence a usual practice is to use experimental measurement methods along with numerical methods that involve optimization techniques. Such an approach can ensure better accuracy.

Chan[27] *et al.* have taken up three methods of analytical 5 point method, curve fitting method, and iterative 5 point method and compared them to obtain the parameters of single diode lumped circuit model of PV cell.

Ishaque *et al.* [28,29] have taken up PV modeling with two diodes. In their approach they have added partial shading effects in [29] and have validated the model using Matlab /Simulink. Such a model is useful if need arises to use PV modeling with MPPT algorithms. For low irradiance, such a method provides better results and therefore is better suited for partial shading.

Ishaque *et al.* in their paper [30] have taken their work ahead with the use of Differential Evolution (DE) algorithm in PV modeling. This scheme makes possible simultaneous computation of all the parameters at various temperature and irradiation levels.

2.5.2 Numerical methods

In order to solve the nonlinear equations of PV cells, iterative numerical equation solvers are to be used. Phang in [31] used experimental data to derive analytical expressions in order to obtain parameters of solar cell single-diode model. Newton-Raphson method has been used in this work.

Chan *et al.* [32] have carried out similar work in the fields of analytical modeling by developing a solar cell double diode model.

Sera *et al.* [33] have used analytical methods to extract five parameters of single diode PV panel model and have embedded temperature and irradiation dependency in the formulation of PV panel model.

2.6 Standard performance characteristics of PV system

2.6.1 Standard P-V characteristics of PV module

From the standard P-V characteristics curve we can observe the relation between power and voltage. From this graphical feature exact point where the power is maximum can also be observed. In short circuit condition the value of current is high but voltage is zero. Similarly in open circuit condition voltage is high but current is zero. In between two conditions the power is maximum [34, 35]

2.6.2 Standard I-V characteristics of PV module

In short circuit condition the amount of current is maximum and voltage will be zero due to zero resistance. On the other side in open circuit, voltage level is high and current will be zero due to infinite resistance. By the plotting I_{sc} and V_{oc} in a graph, we can observe the graphical characteristics of current (I) vs voltage (V).

By developing a mathematical model of solar cell or module or array based on equivalent equation the performance parameters characteristics can be evaluated. The performance of a solar module or array can be evaluated by the I-V and P-V characteristics. To compare this performance of solar photovoltaic system to the practical hardware model, the manufacturers provided datasheet are used [36,37].

In the paper [34], a simple overview concept of solar photovoltaic technologies is described. These technologies are used to design the model of solar cell and the efficiency and their performance are evaluated & also lifetime is highlighted. In this paper, the whole performance of PV cell, module and array can be observed by the single diode equivalent model of solar cell which is known as four parameter model. In this paper work is implemented by Matlab Simulink. The performance characteristics are compared with Kyocera KC85T high efficiency datasheet. Here it is also configured a PV array with six modules connected in series to evaluate the performance.

In the paper [35, 38,39,40], authors proposed a single diode mathematical model of solar module which is consisted of solar cell using Matlab software. The implementation of this model is to obtain the accurate I-V and P-V characteristics. The model parameters are taken from manufactures datasheet. The purpose of simulation of the experimental model is to determine the effect of the different factors which are affecting the solar photovoltaic module

characteristics. The factors are temperature, irradiation, shunt resistance, series resistance and diode ideality factor which is based on solar cell material. Through this experiment it is illustrated the relationship between different parameters which are considered for solar module.

In the paper [41], the author proposed a novel simplified two diode model of solar photovoltaic module. The main objective of this paper is to represent the two diode model to reduce computational time. Here also the effect of series resistance and shunt resistance are neglected. The simulation result of the proposed model using Matlab is validated with the datasheet of the commercial PV module provided by the manufactures. Different type of PV technologies of the solar like multi-crystalline and mono-crystalline are considered. In this simulation Kyocera KC200GT and BP solar MSX-60 datasheet for Multi-crystalline and Renesola JC260S datasheet for Mono-crystalline are considered as references. This model is greatly simplified by omitting series and shunt resistances, and at the same time, comparable accuracy is achieved with less computational burden. This simplified model is free from arbitrary assumption and all the parameters are calculated analytically.

2.7 Effective factors of PV system performance

To evaluate the performance of PV system, There are several factors considered which are responsible for variation in PV system characteristics.

2.7.1 Temperature effect

Temperature has a dominant effect on open circuit voltage. From the I-V characteristics, it can be seen that with the increasing temperature the magnitude of open circuit voltage is decreased keeping the irradiance level constant. For silicon solar cell, for every 1⁰C increase in temperature voltage drops about $0.002/0.55 \approx 0.4\%$ from its room temperature value.

Change of short circuit current with temperature is negligible with constant irradiance level. Practically, there is a very small increase of short circuit current with temperature.

Output power is the product of voltage and current. So the output power is also affected by the temperature variation [42, 43].

2.7.2 Irradiance effect

Open circuit voltage changes logarithmically with irradiance at constant temperature. Short circuit current is linearly dependent on irradiance at constant temperature. Due to the variation of open circuit voltage and short circuit current, the output power also changes with the temperature variation[10, 42,44,].

2.7.3 Combined effect of Temperature and Irradiance

Throughout a day with the rise of irradiance, the cell temperature also rises. Due to the variation in temperature and irradiance, the open circuit voltage and short circuit current simultaneously changes. Short circuit current rises with irradiance and open circuit voltage falls with temperature. As a result the open circuit voltage falls with the rise of irradiance due to temperature effect. The open circuit voltage changes with increasing temperature but the short circuit current steeply changes with the increasing temperature. The open circuit voltage increases logarithmically with irradiance and decreases with increasing temperature. The decreasing effect of open circuit voltage is more than the increasing characteristics of open circuit voltage. So as a result, open circuit voltage is decreased. Due to dependency on open circuit voltage and short circuit current the output power is also varied [42,43].

In paper [44,45], the performance of a photovoltaic (PV) array is affected by temperature, solar irradiation as well as affected by shading. Sometimes the PV arrays get shadowed, completely or partially, by the passing clouds, neighbouring buildings and towers, trees, and utility. Under this condition the PV module or array is working in non-uniform solar irradiance. Sudden, largeChange in PV power because of irradiance variation, caused by shading, may lead to instability. Under this condition multiple peaks are shown in P-V curve. If the likely shading pattern on the PV array is known, the simulation model is appropriate to design the most optimum configuration of the PV array to extract the maximum power.

2.8 Contribution of different software

It is clear from the literatures that before going to implement a practical visualized model, a software based computing model should be developed to observe all features and characteristics. For any experiment on PV module, it was modelled through software such as, Matlab/Simulink[9,10,12,13, 34, 37, 46] PSCAD, SPICE[47], SABER[47], HOMER[55] etc.

Chapter3

SOLAR PHOTOVOLTAIC SYSTEM

3. Introduction

Solar cells or Photovoltaic (PV) cells (silicon wafer cells) convert solar energy to electrical energy and the energy conversion process is carried out with the help of appropriate solid state semiconductor device. When photon energy from the Sun is incident on a solar cell, a small fraction of the incident photon energy is converted to electricity and this process of electric power generation is referred to as photovoltaic (PV) technology. Power generated from solar photovoltaic is cheap & clean and hence it has emerged as a lucrative, effective and efficient technology. In today's world, it is not an alternative to fossil fuels but an essential source of power for sustainable development by strengthening the energy security of any country.

The drastic growth in installed capacity of solar PV has been observed all over the world and replacing the thermal power stations, it is becoming a primary source of energy. This chapter focuses on the solar PV technologies & theory, materials used in solar cell, electrical characteristic and various solar PV systems.

3.1 Growth in Solar Photovoltaic

The importance of the renewable energy is evident and India is potentially rich in renewable resources. Apart from solar PV, wind and small hydro are also feasible options for power generation. But there are some limitations on the power generation from wind, hydro and other sources of energy due to geographical conditions and a host of other factors, making them either unreliable or lack environment friendly application whereas abundant solar potential makes power generation from solar PV an environment friendly and reliable one. Solar power has seen a rapid growth throughout the world as its demand has increased manifold. The figure below presents a prediction of power generation through the use of photovoltaic cell for the future years and indicates a huge increase in such demand [48].



Fig.3.1 Global annual and cumulative installation for years 2014-2020(GW) [48].

3.2 Solar Photovoltaic technology

The photovoltaic effect is generation of voltage and current in any material upon exposure to the light and can be observed in various materials in nature, but since electricity generation requires additional inherent characteristics of the material, semiconductor materials are best suited for electric generation. A solar cell is a solid state semiconductor device and it converts a smaller fraction of the incident photon energy into dc electrical energy.



Fig.3.2A simple solar cell.

Solar radiation to electrical energy conversion process takes place due to existence of a barrier layer at the junction between the two dissimilar semiconductor materials forming the cell. In solar cell, usually there are two types of semiconductor, p-type semiconductor and n-type semiconductor.

- When p-type and n-type semiconductor are connected by a junction, a potential energy gap (E_g) is created in the junction.
- When photon energy of the sunlight incidents on the semiconductor material, then pairs of electron (-) & proton (+) are generated. Figure below shows the basic structure formation and working principle of solar cell.

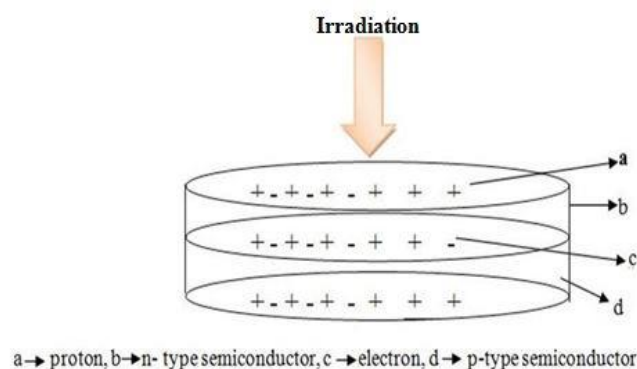


Fig. 3.3 Working principle of photovoltaic cell.

- After the generation of electrons in p-region and holes in n-region, some of them combine with the oppositely charged particles and do not contribute to the energy conversion process. Rest of the electrons and holes reach the junction layer and form

Chapter 3: Solar Photovoltaic System

two opposite charge layers. The electrons are collected in the n-region and holes are collected in p-region. Thus an open circuit voltage is developed across the external terminals. P region becomes the positive terminal and n region becomes the negative terminal. Fig. 3.4 shows the different parts of a solar cell.

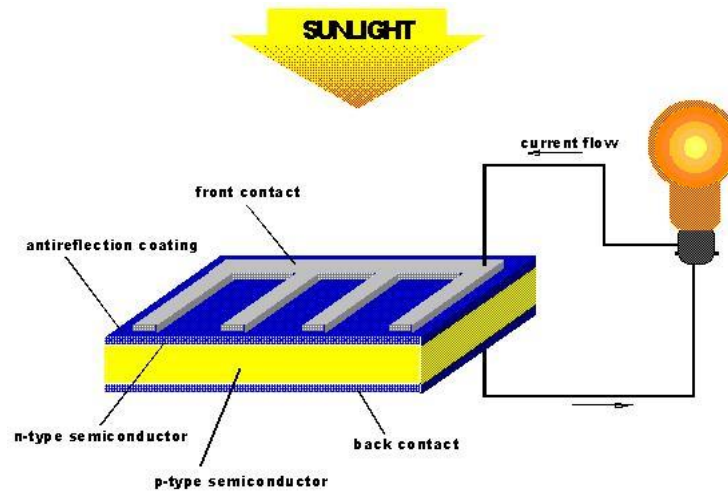


Fig.3.4 Configuration of photovoltaic cell.

3.2.1 Photovoltaic cell materials & technologies

Various types of material and technologies are used to develop the modern photovoltaic cells. Crystalline silicon cells are very common material in solar photovoltaic system. For specific application specific material with unique strength & characteristic is used in solar cell. The classification of different types of solar cell materials based on their crystallinity, band gap, absorption, and manufacturing complexity [34,49]. The various technologies that are used for photovoltaic cell development may be classified into three generations:

- i) First generation Photovoltaic System (PVS)
- ii) Second generation photovoltaic system and
- iii) Third generation photovoltaic system.

In the first generations of photovoltaic system, crystalline silicon cells are used which are divided into two groups

1. Single-crystalline silicon (sc-Si) cell
2. Multi-crystalline silicon (mc-Si) cell

The efficiency range of sc-Si is 15%-19% and for mc-Si the range is 13%-15% [34]. The figure below shows two types of silicon cells.

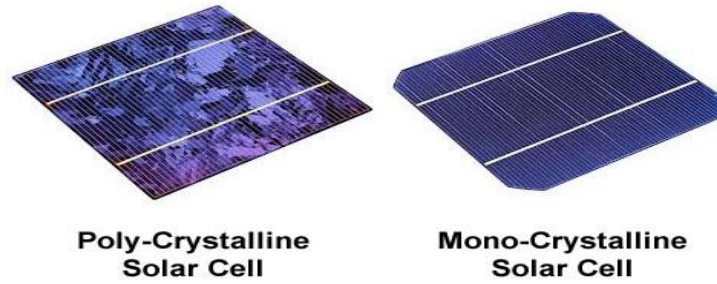


Fig.3.5 Image of Ploy-crystalline and mono-crystalline solar cell.

Second generation PVS are focused on thin film PV cells which are categorized to be of three types.

1. Amorphous silicon (a-Si) and micro morph silicon(a-Si/ μ c-Si) with the efficiency rage of 6%-9% [34].
2. Copper-Indium-Gallium-Diselenide (CIGS) and Copper-Indium-Selenide (CIS) with the efficiency range of 9%-12% [34].
3. Cadmium Telluride (CdTe) with the efficiency range of 8%-14% [34].

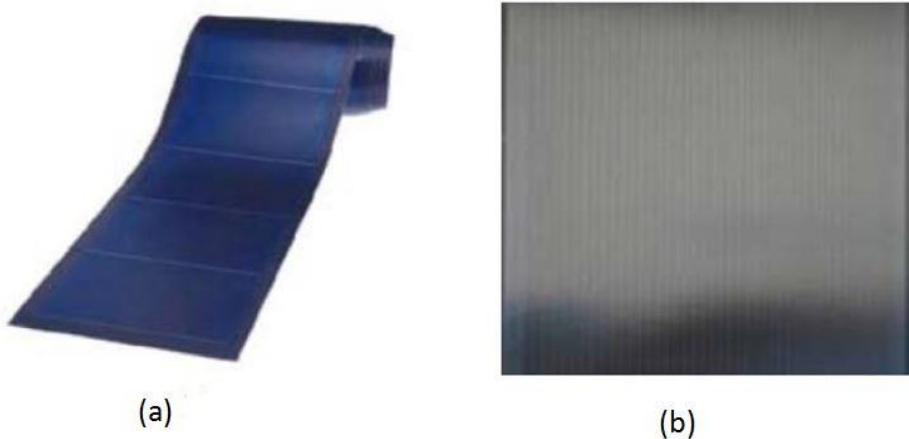


Fig. 3.6 Image of (a) flexible amorphous thin film and (b) CIGS thin film module.

The above two figures represents the amorphous thin film and CIGS thin film module. CdTe has band gap energy of 1.5eV at room temperature and thus, it is more efficient as a solar cell material in comparison to silicon which has band gap energy of 1.12eV[34]. But in practice, silicon is the most dominant semiconductor used in solar cell for followings reasons [49]:

Chapter 3: Solar Photovoltaic System

- Silicon is the second most available element in nature after oxygen and 26% of earth crust contains silica or silicates
- Silicon is a safe material to handle
- Silicon possesses a high degree of chemical stability

3.2.2 Construction of solar cell

There are six essential steps in the processing technology for crystalline solar cell manufacturing. The flow chart of those processes is given below [49]

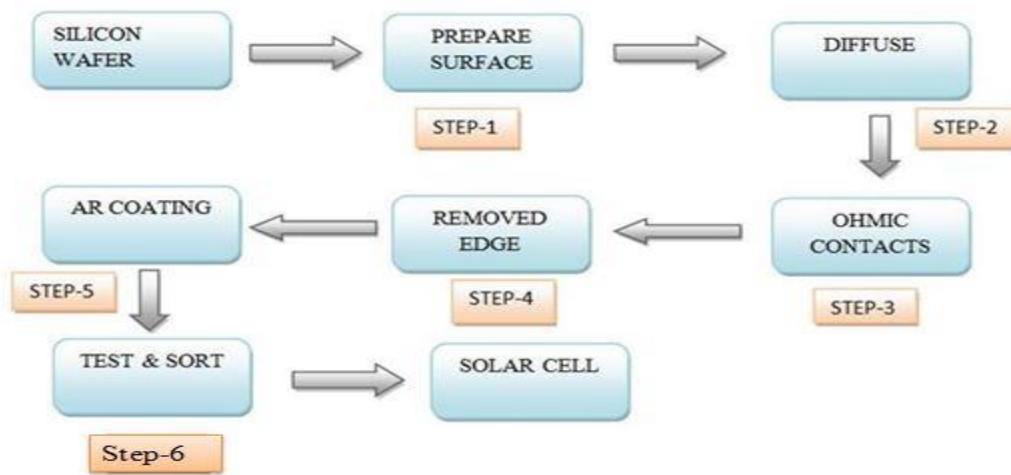


Fig. 3.7 Simple flow chart diagram of solar cell construction[49].

3.2.3 Specific terminology of solar photovoltaic system

- ❖ **Open circuit voltage (V_{oc}):** The open circuit voltage is the maximum voltage produced by a solar cell at no load and in full sunlight (i.e. at 1000 W/sq.m). In this condition there is no current flow.
- ❖ **Short Circuit Current (I_{sc}):** Short circuit current is the maximum current drawn from the solar cell or array when the two terminals of the cell or array are shorted at full sunlight (i.e. at 1000 W/sq.m). At this condition, voltage across the terminal is zero.
- ❖ **Maximum power (P_{max}):** Maximum amount of power delivered by the solar cell or array is known as maximum power. The maximum power point is a balance of current and voltage to produce the maximum amount of power achievable from the solar panel [49].

- ❖ **Voltage at maximum power (V_{mp} or V_{max}):** The voltage obtained across the two terminals of the cell when it provides maximum power is called voltage at maximum power.
- ❖ **Current at maximum power (I_{mp} or I_{max}):** It is the maximum current that is obtained at operating condition of maximum power drawn from the solar cell or array.
- ❖ **Maximum power point tracking (MPPT):** In case of open circuit, voltage across the terminals is high but current becomes zero and so the amount of power drawn is also zero. During short circuit, the amount of current is high but voltage is zero, so the power is also zero. By the use of advanced controllers, solar panel or array can draw maximum power with the desired value of current and voltage [49]. The maximum power point tracker controls the voltage and current to get maximum power.

3.3 Photovoltaic module

A single solar cell or a suitable interconnected matrix form of solar cells, when hermetically sealed with a transparent cover and a back cover constitutes a module. To increase the voltage level, PV cells are connected in series and to increase the current level, PV cells are connected in parallel. To achieve the required level of power, PV cells are connected in series and parallel. This combination of cells is referred to as a 'module'. Combination of several modules in series and parallel is referred to as a PV array [49, 50]. The figure below shows the transformation of PV cell to a complete PV system.

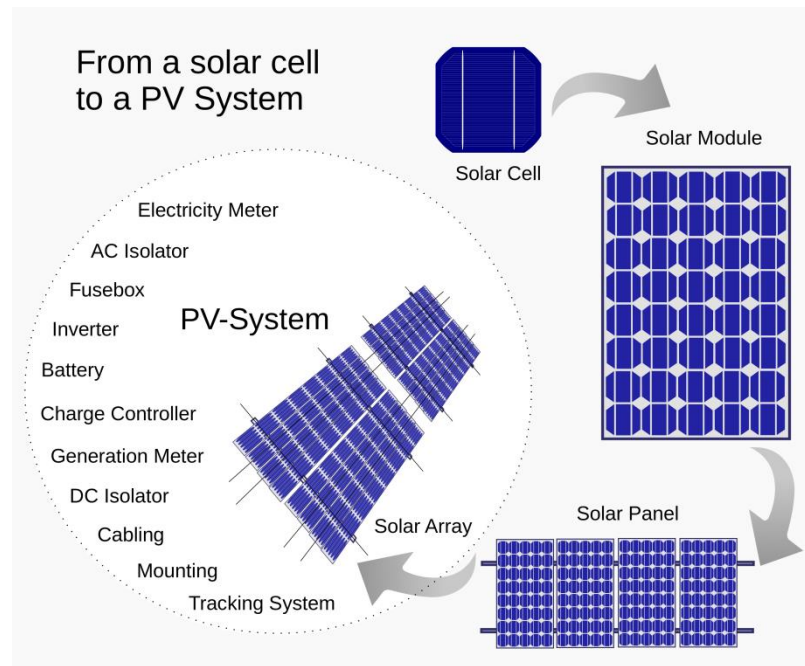


Fig. 3.8 Typical diagram of solar cell to solar system [51].

3.4 Standard Characteristics of PV system

There are unique characteristics of each PV cell, module or array. These characteristics characterize the PV system and the application of these systems is governed mainly by these characteristics.

3.4.1 The standard I-V characteristic curve of Photovoltaic module

In short circuit condition, the current is maximum (I_{sc}) and voltage is zero due to zero resistance while in open circuit, voltage level is maximum (V_{oc}) and current is zero due to infinite resistance. When a graph is plotted between current and voltage, I-V characteristic is obtained [49, 51]. Voltage parameter is taken in X-axis and current is taken in Y-axis and curve is shown in Fig. 3.9.

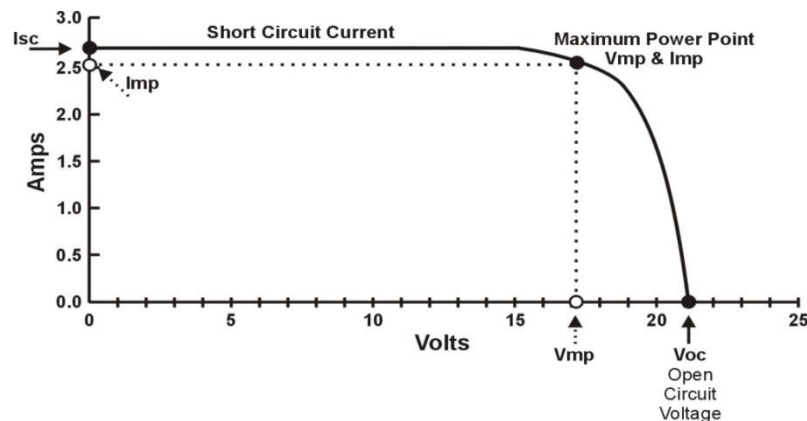


Fig. 3.9 Standard I-V characteristics of solar module [51].

3.4.2 The standard P-V characteristic curve of Photovoltaic module

PV output voltage versus power plot gives the P-V characteristic of PV module. From the Fig.3.10, we can see that during short circuit and open circuit, the power is zero. For all intermediate circuit operating conditions, with a suitable value of resistance the maximum power from a solar module can be obtained [49,51].

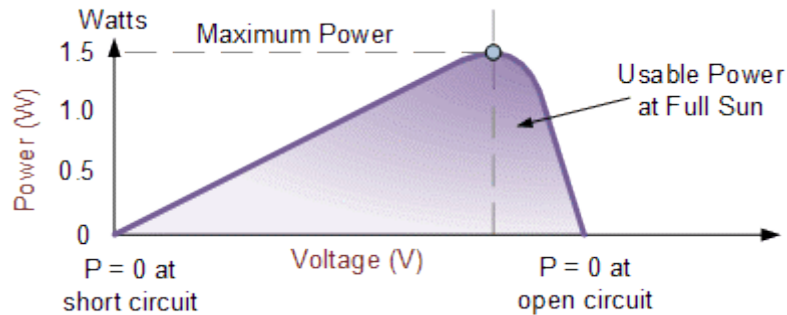


Fig.3.10 Standard P-V characteristics of solar module [51].

3.5 Equivalent Circuit of solar photovoltaic module

The equivalent circuit model of solar photovoltaic module can be analysed in several ways, like [46]

1. Ideal single diode model
2. Practical model with series resistance
3. Practical model with series and shunt resistance.

3.5.1 Ideal single diode model

It is the simplest representation of a PV module. In figure below, the internal losses of current is neglected. A diode is connected in anti-parallel with the generated current from solar radiation. According to Kirchhoff's law the output current I is [34, 46,53]

$$I = I_{ph} - I_d \quad (3.1)$$

Where

I_{ph} is the photocurrent

I_d is the diode current and can be expressed as [46]

$$I_d = I_0 \left[\exp\left(\frac{V}{A N_S V_t}\right) - 1 \right] \quad (3.2)$$

Where

V is the voltage imposed on the diode

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$$V_t = \frac{kT_c}{q} \quad (3.3)$$

$$\text{The modified ideality factor } a = \frac{N_s A k T_c}{q} = N_s A V_t \quad (3.4)$$

I_0 =Reverse saturation current.

T_c =Actual cell temperature (K)

K =Boltzmann constant (1.381×10^{-23} J/K)

q = Charge of electron (1.602×10^{-19} C)

V_t =Terminal voltage

A =Diode ideality factor

N_s =Number of cell in series

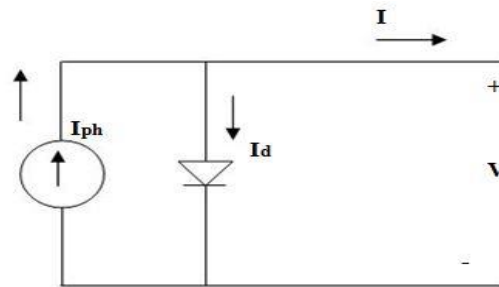


Fig. 3.11Equivalent circuit of ideal single diode model [46, 53].

3.5.2 Practical model with series resistance (R_s)

The figure below represents the single diode four parameter model. In practice, the value of series resistance R_s cannot be neglected and therefore included in this model [34, 46]. Due to computational efficiency and simplicity this model is widely used for PV module simulation. The value of current is obtained from Equation (3.2) and is given below:

$$I = I_{ph} - I_0 \left[\exp \left(\frac{V + IR_s}{AN_s V_t} \right) - 1 \right] \quad (3.5)$$

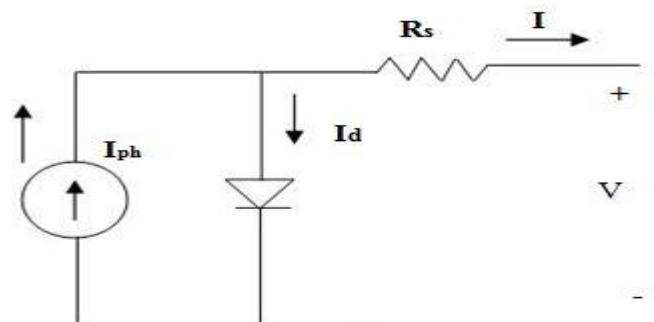


Fig. 3.12Equivalent circuit of practical model with series resistance [34,46].

3.5.3 Practical model with series resistance (R_s) and parallel resistance (R_p)

The equivalent circuit of photovoltaic cell should consider the value of both series resistance (R_s) and parallel resistance (R_p) for calculating the leakage current to the ground. Here I_p is the current flow through the parallel resistance R_p . So by applying Kirchhoff's law, output current is obtained as[34, 46]

$$I = I_{ph} - I_d - I_p \tag{3.6}$$

or

$$I = I_{ph} - I_0 \left[\exp\left(\frac{V+IR_s}{a}\right) - 1 \right] - \frac{V+R_s I}{R_p} \tag{3.7}$$

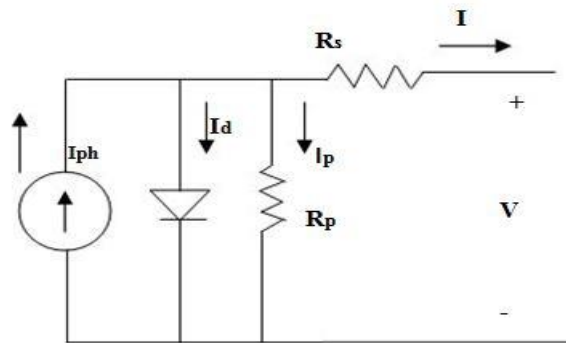


Fig. 3.13Equivalent circuit of practical model with series and parallel resistance [34,46].

3.5.4 Two diode model

The single diode model is implemented on the basis of assuming the recombination loss in the depletion region to be negligible. For accurate calculation the next version model is used and is known as two diode model as shown below [46, 53]

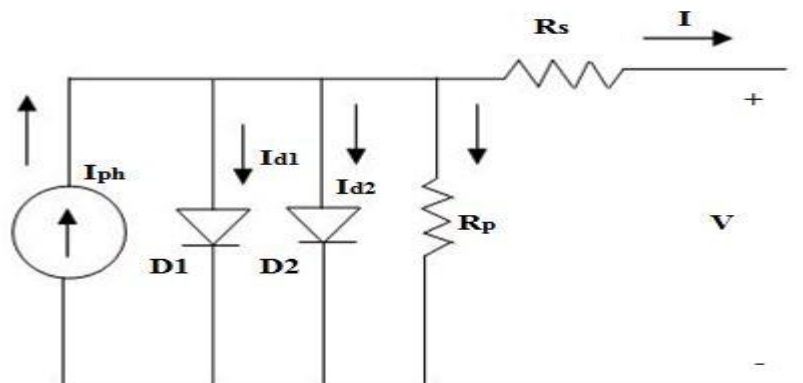


Fig. 3.14 Equivalent circuit of two diode model[46,53]

The output current for two diode model can be expressed as [46, 53]:

$$I_{ph} - I_{d1} \left[\exp\left(\frac{V+IR_s}{a}\right) - 1 \right] - I_{d2} \left[\exp\left(\frac{V+IR_s}{a}\right) \right] - \frac{V+R_s I}{R_p} \quad (3.8)$$

3.6 Different types of Photovoltaic systems

Solar PV system can be used in centralized mode as well as in decentralized and distribution mode for the generation of electricity.

Solar photovoltaic system can be classified into several groups depending on their operations and shown in Fig. 3.15 [49].

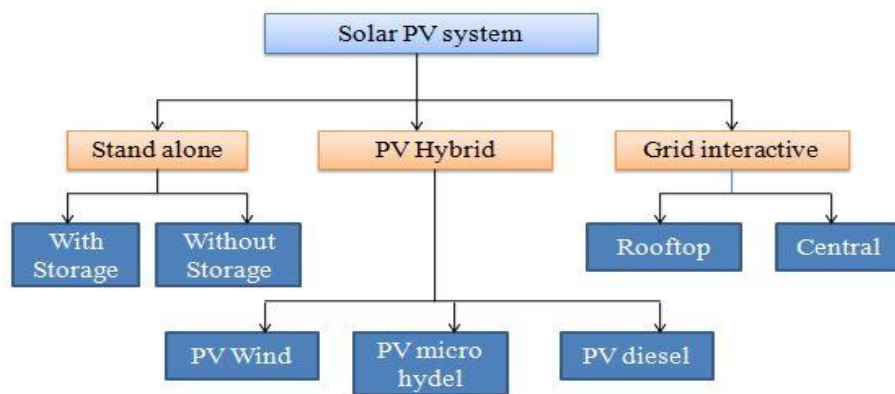


Fig. 3.15 Different type of Solar Photovoltaic system [49].

3.6.1 Stand-alone PV system

The stand-alone system is designed to meet the load requirement by its own power generation abilities without any backup energy resources. Stand-alone PV systems may or may not consist of electrical storage subsystem [49].

❖ Stand-alone system without Storage

In this mode of operation, a PV module can be made to supply energy to an electrical load by connecting it directly to the load without an intermediate energy storage medium as presented in figure below [49]. The module or array generates variable dc output during the day and delivers it to the dc load. The amount of energy delivered to the load depends on the incident solar radiation, ambient temperature and also on the current-voltage characteristics of the module [49].

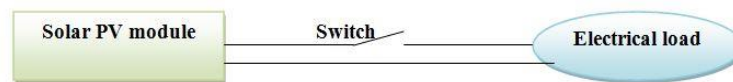


Fig. 3.16 Stand-alone system without storage [49].

❖ Stand-alone system with Storage

Electrochemical batteries are the only commercially available practical energy storage devices that can be used for the purpose of power storage though Fuel Cell (FC) with hydrogen and Superconducting Magnetic Energy Storage system (SMES) are explored for the storage purpose with great enthusiasm [49]. With the help of energy storage systems, a PV system becomes capable of providing energy during any time of the day. Moreover energy storage provides stable load voltage and power. During non-sunshine hours, in order to prevent a reverse flow of current from the battery to the PV module, a blocking diode is used with energy storage as shown in figure below [49]

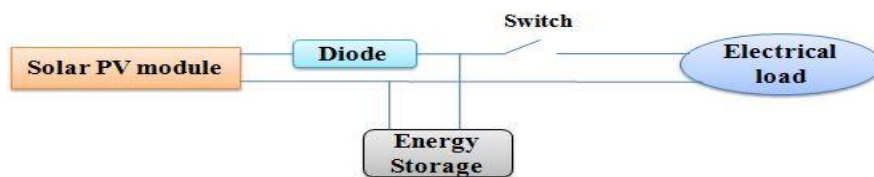


Fig. 3.17A Stand-alone system with storage [49].

3.6.2 PV hybrid system

A PV hybrid system is an appropriate combination of stand-alone PV system and either a conventional energy source (petrol, diesel or dual fuel generator) or another renewable energy source like wind, solar thermal or biomass generator [49,52]. In this system both PV source and non PV sources together meet the load demand. PV hybrid system is useful in all those scenarios where the solar radiation changes randomly or the cost of solar photovoltaic system is too high [49]. The typical PV hybrid system is shown in Fig. 3.18.

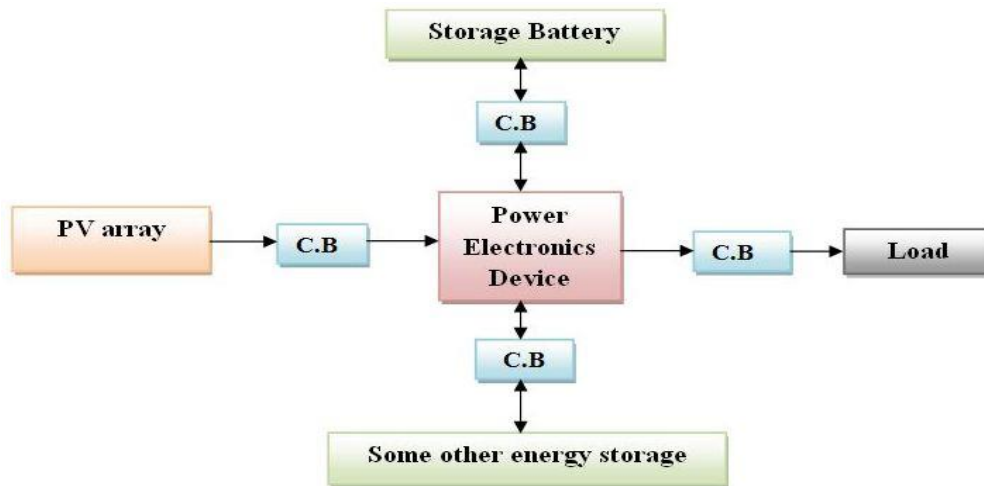


Fig. 3.18 PV hybrid system [49].

3.6.3 Grid Interactive system

A grid interactive PV system is connected to and synchronized with the existing utility grid, whose major supply sources are the conventional centralized power plants. In this mode of operation solar PV acts as a supplementary peak load sharing electrical energy source, whose load become the utility grid itself as shown in figure below [49].

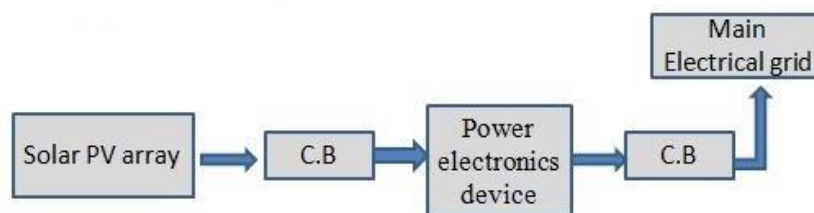


Fig.3.19 Grid Interactive system [49].

3.7 Conclusion

The solar PV system is very promising technology and lot of research works are carried out for proper characterization of the PV systems. The chapter gives an overview about solar photovoltaic technology, materials details and different types of equivalent circuit model which are used to implement a PV model. Before application of the PV system, inherent characteristics and various technical parameters need to be studied very well. In next chapter the mathematical modelling of a PV module and array is discussed in brief.

CHAPTER 4

MATHEMATICAL MODELLING OF SOLAR PHOTOVOLTAIC

4. Mathematical model of photovoltaic system

Characterization of the PV system in terms of voltage, current and power under different conditions is done by developing mathematical models of PV cell and subsequently mathematical models of PV module, Array and PV systems are developed using Matlab Simulink. In this work, two systems have been considered. In Test System-I, different sub systems are developed to represent the various parameters associated with PV cell. The subsystems and system are developed using basic equations of various parameters in Matlab Simulink. Then P-V, I-V characteristics of the system under different conditions are determined and reported in next chapter. Here the characterization of PV system is done without considering the load or storage connected to the system. But in Test System-II, the resistive load and battery storage are integrated and the subsystems and composite system are modelled using Simpower toolbox block in Matlab/Simulink and various characteristics are observed.

4.1 Test System-I

For proper understanding and performance analysis, various parameters associated with PV cell and their representations by various mathematical equations have to be studied first. An ideal solar cell is usually modelled with a combination of ideal current source and a diode. The diode is placed in anti-parallel with the current source. The equivalent circuit model of solar cell is shown in Fig. 4.1 [34].

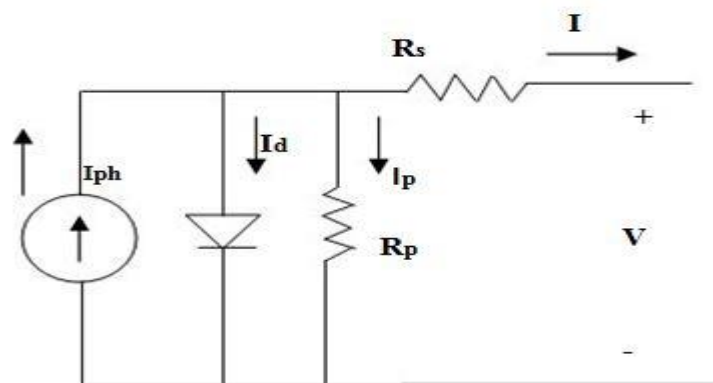


Fig. 4.1 Equivalent circuit model of solar cell.

Neglecting the series and shunt resistance, diode current can be obtained from the Shockley diode equation as [34]

$$I_d = I_0 \left[\exp\left(q \frac{V}{kT}\right) - 1 \right] \quad (4.1)$$

Chapter 4: Mathematical Modelling of Solar Photovoltaic

Where,

I_d is diode current

I_o is reverse saturation current

V is voltage imposed across the diode

q is charge of electron ($1.602 \times 10^{-19} \text{C}$)

k is Boltzmann constant ($1.381 \times 10^{-23} \text{J/K}$)

T is the junction temperature (K)

Hence, the cell output current for the equivalent circuit model of ideal solar cell is [34,46]

$$I = I_{ph} - I_d = I_{ph} - I_o \left[\exp \left(q \frac{V}{AkT} \right) - 1 \right] \quad (4.2)$$

Where, I_{ph} is the photo current generated by incident light, A is diode ideality factor which has values ranging from 1 to 2 [34, 49].

A PV module can be formed if there are N_s number of cells in series connection. Hence, the output current for PV module can be expressed as follows [34]:

$$I = I_{ph} - I_d = I_{ph} - I_o \left[\exp \left(q \frac{V}{N_s AkT} \right) - 1 \right] \quad (4.3)$$

When the series resistance (R_s) is accounted for internal losses of module and shunt resistance (R_p) is considered for losses due to leakage current, the equation can be written as

$$I = I_{ph} - I_o \left[\exp \left(q \frac{V + IR_s}{N_s AkT} \right) - 1 \right] - \frac{V + IR_s}{R_p} \quad (4.4)$$

Where, R_s and R_p are shunt and series resistance respectively and other terms have their usual meaning. The photon current in above equation is determined as [34,46]

$$I_{ph} = \{I_{sc} + k_i(T - 298)\} \frac{G}{1000} \quad (4.5)$$

Where,

I_{sc} is the short circuit current

k_i is the temperature coefficient of I_{sc} ,

T is the junction temperature and

G is the solar insolation (W/m^2)

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The reverse saturation current I_0 of the cell varies with the temperature and can be expressed by following equation [34,46]

$$I_0 = I_{rr} \left(\frac{T}{T_s} \right)^3 \exp \left[\frac{\frac{qE_g}{k} \left(\frac{1}{T_s} - \frac{1}{T} \right)}{1} \right] \quad (4.6)$$

Where,

E_g is band gap energy of the semiconductor,

T is junction temperature

T_s is reference temperature and

I_{rr} is nominal saturation current and is given by [34,46]

$$I_{rr} = \frac{I_{sc}}{\exp \left[\frac{V_{oc}}{AV_t} - 1 \right]} \quad (4.7)$$

Where, V_{oc} is open circuit voltage

$$V_t = \frac{N_s k T}{q} \quad (4.8)$$

V_t is the thermal voltage

A PV array consists of number of PV modules connected in series and parallel depending upon the required voltage and current level. So the terminal output current of PV array becomes [34,46]

$$I = N_p I_{ph} - N_p I_0 \left[\exp \left(q \frac{\frac{V}{N_s} + \frac{I R_s}{N_p}}{A k T} \right) - 1 \right] - \frac{V \frac{N_p}{N_s} + I R_s}{R_p} \quad (4.9)$$

Where,

N_p is number of cell in parallel and N_s is number of cell in series

Based on assumption for a module or array that parallel resistance is infinite, i.e. $R_p = \infty$, the above equation can be written as [34,46]:

$$I = N_p I_{ph} - N_p I_0 \left[\exp \left(q \frac{\frac{V}{N_s} + \frac{I R_s}{N_p}}{A k T} \right) - 1 \right] \quad (4.10)$$

Here it can be seen that $N_p = N_s = 1$ for PV cell, for PV module $N_p = 1$ and N_s is the number of cell for module.

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These mathematical equations for representation of PV cell, module, and array have been implemented in Matlab Simulink as discussed in next section.

4.1.1 Simulink Model of the PV Cell, Module and Array

In this test system-I, equivalent circuit model of single diode four parameters (I_{ph} , I_0 , A , R_s) PV cell is considered. The above equations presented in previous section describe the complete behaviour of the cell, module and array. Different Simulink models are developed and the simulation is done. The specification of high efficiency multi-crystal Kyocera KC85TPV module is considered for the simulation [34]. The complete specification of considered PV module is given in Table 1.

Table 2: Kyocera KC85T specification at STC of 1000W/m^2 to 200W/m^2 at 25°C [34].

Parameter	Value
Maximum Power (P_{max})	$87(+10\%/-5\%)\text{W}$
Maximum Power voltage (V_{mp})	17.4V
Maximum Power current (I_{mp})	8.20A
Open circuit voltage (V_{oc})	21.7V
Short circuit current (I_{sc})	8.45A
Maximum system voltage	600V
Temperature coefficient of V_{oc}	$-8.21 \times 10^{-3}\text{V}/^\circ\text{C}$
Temperature coefficient of I_{sc}	$2.12 \times 10^{-3}\text{A}/^\circ\text{C}$
Number of cells per module (N_s)	36

The photo current generated in PV cell is expressed by the mathematical equation given in Eqn. 4.5. The photo current subsystem can be implemented in Simulink as given in following figure.

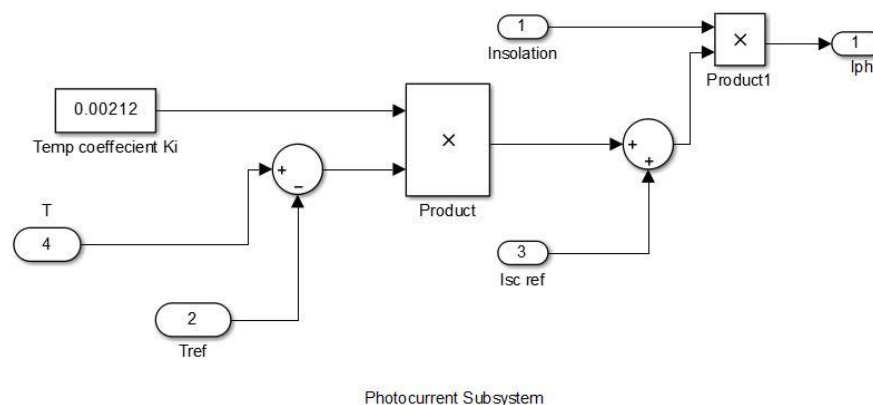


Fig. 4.2 Photocurrent subsystem.

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Similarly the reverse saturation current given by Eqn. 4.6 of PV module can be expressed in Matlab Simulink as follows:

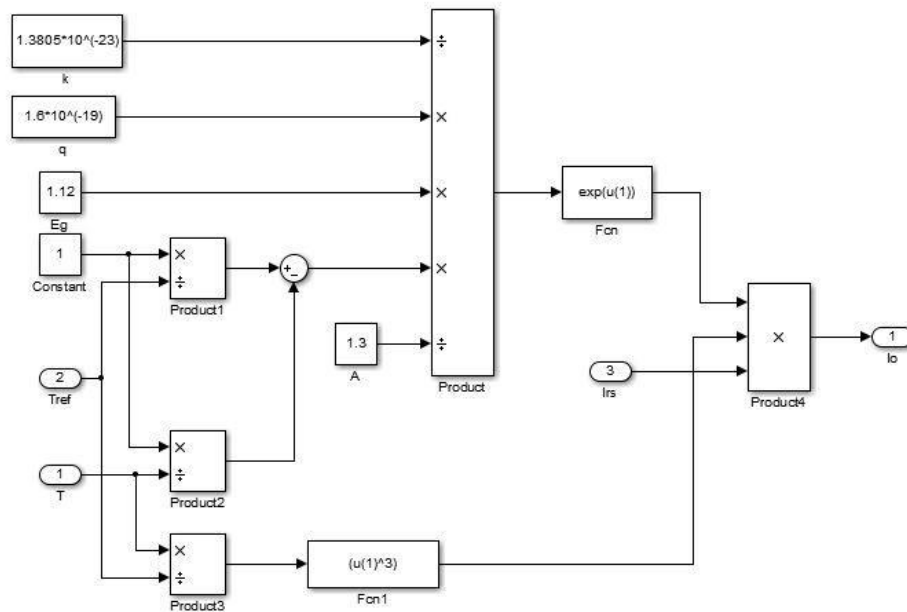


Fig. 4.3 Module saturation current.

The reverse saturation current expressed by Eqn. 4.7 is implemented by Matlab Simulink and model is given below:

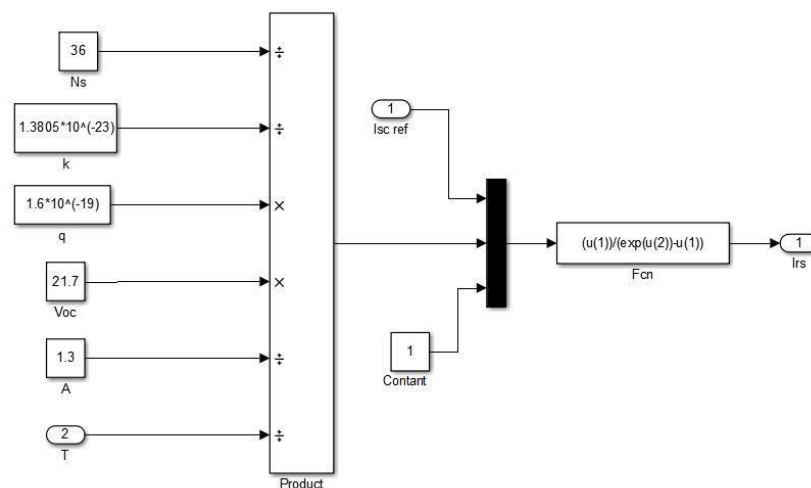


Fig. 4.4 Module reverse saturation current.

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The product term $N_s A k T_c$ can be implemented by the subsystem as follows:

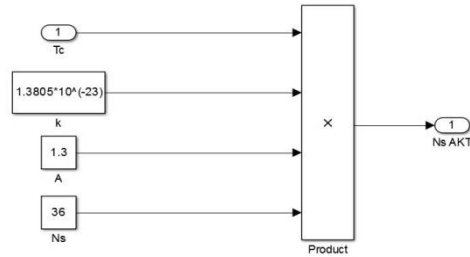


Fig. 4.5 Output product of $N_s A k T_c$.

The output current of PV module considering the parallel resistance as infinity as given in Eqn. 4.10 is implemented by the system as given in following figure

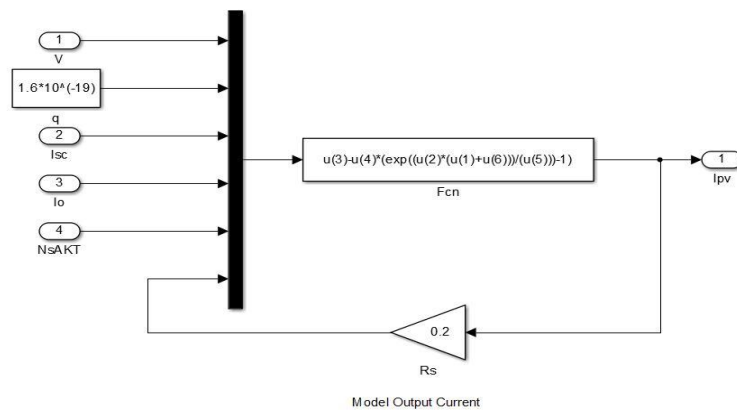


Fig. 4.6 Module Output Current.

The temperature given in the specification is in Centigrade or Celsius whereas Simulink recognize the unit Kelvin. So the conversion is given in following subsystem.

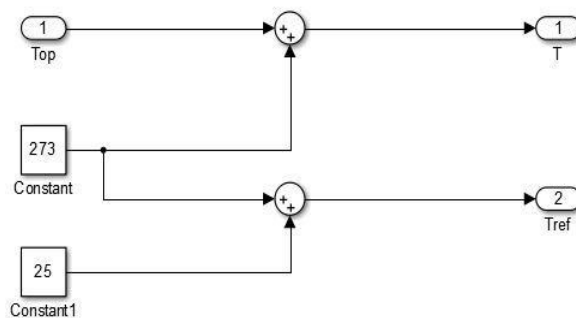


Fig. 4.7 Celsius to Kelvin converter subsystem.

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The module output current and voltage is determined by combining above subsystems and is given below:

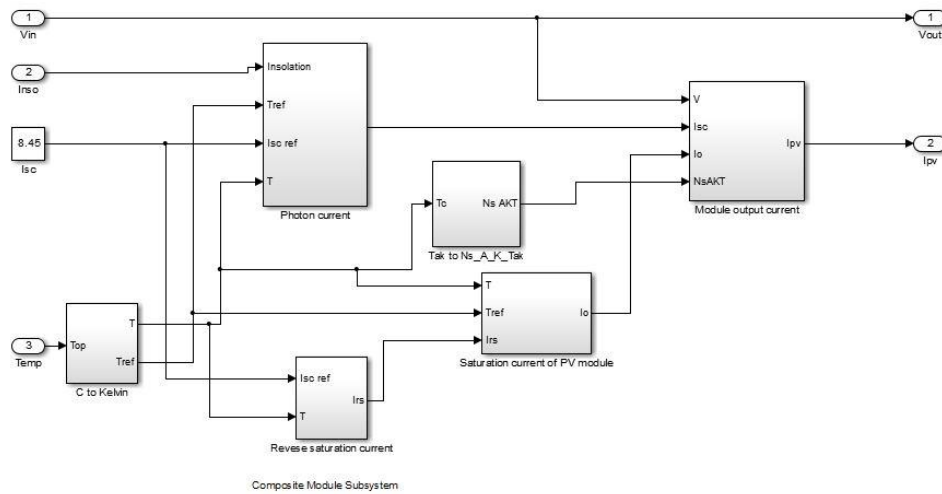


Fig. 4.8 Composite module showing subsystem.

Therefore, the complete simulink model of PV module can be expressed by the given figure.

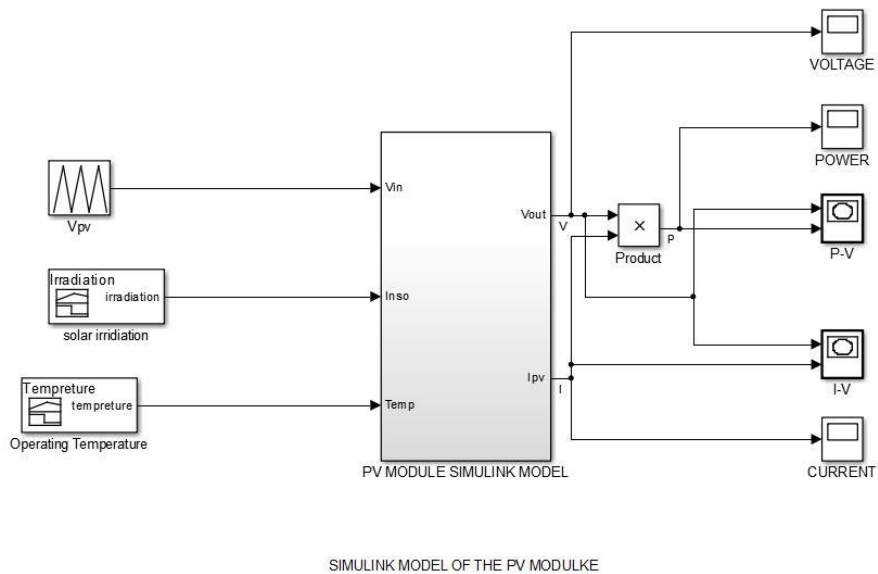


Fig. 4.9 Simulink model of PV module

The PV array consists of multiple numbers of PV module connected in series and parallel for specified voltage and current ratings is implemented by following model

Repeating Sequence

The repeating sequence block outputs a periodic scalar signal having a waveform which is specified by using the time values and output values. The time value

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specifies a vector of output times. The output value specifies a vector of signal amplitudes at the corresponding output times. The two parameters specify a sampling of the output waveform at points measured from the beginning of the interval over which the waveform repeats. In this system the repeating sequence block defines time values as [0 2 4] and the output values as [0 40 0].

Signal builder block

The signal builder block allows to create an interchangeable groups of piecewise linear signal source and use them in model. In this system the two input parameters of solar module or array are temperature and solar irradiation. The temperature and solar irradiation will not remain same throughout a day. For this purpose the variation of these two parameters are represented as signal, developed in the signal builder block. The different signals developed are used as input to find out the performance characteristics of a solar module or array.

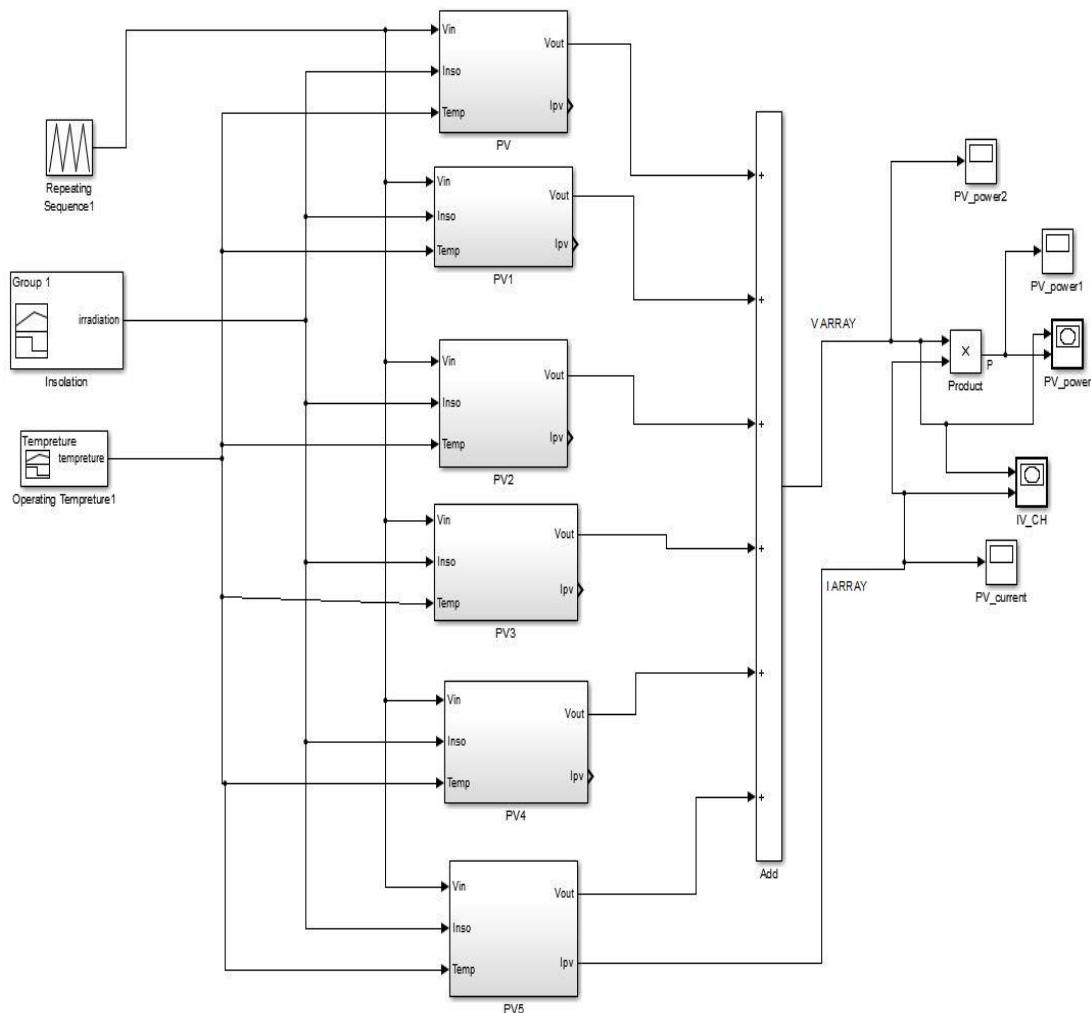


Fig. 4.10 Simulink model of PV array.

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4.2 Test System-II

A practical PV system is considered as Test System-II and its modelling is carried out in Simulink. The test system consists of a PV module which is developed connecting six solar cells, a dc-dc converter, a resistive load, and a generic battery. A simple block diagram of the Test System-II is given below.

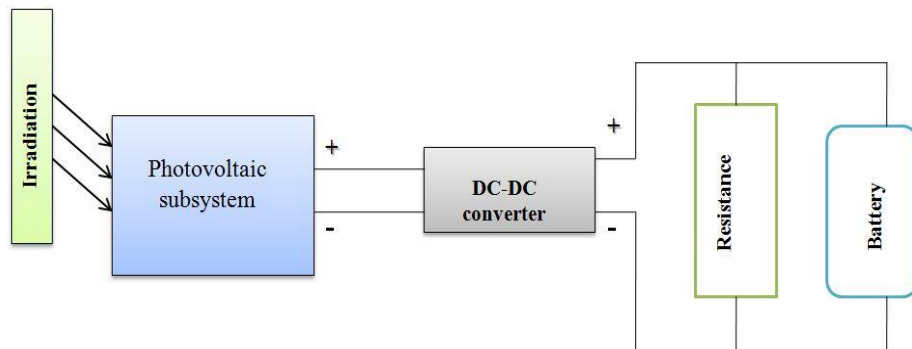


Fig. 4.11A simple block diagram of Test System-II.

The modelling of each component of PV system in Simulink is described in following section.

4.2.1 Solar cell

PV module is developed considering six PV cells connected in series. The Simscape block of solar cell has three ports: incident irradiance (I_r), positive electrical voltage (+), and negative electrical voltage (-). To design this system five parameter model of solar cell is considered [54].

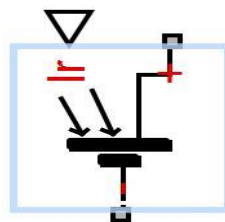


Fig. 4.12A typical solar cell model of Matlab / Simscape.

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Table 3. Specific value of solar cell parameter

Parameter	Value
Short circuit current (I_{sc})	25A
Open circuit voltage	20V
Solar irradiation	1000W/m ²
Ideality factor	1.5
Operating temperature	25 ⁰ C
Energy band gap	1.11ev
Series resistance	0.048ohm

The PV module consisting of such six cells in series is also simulated in Matlab and is given below:

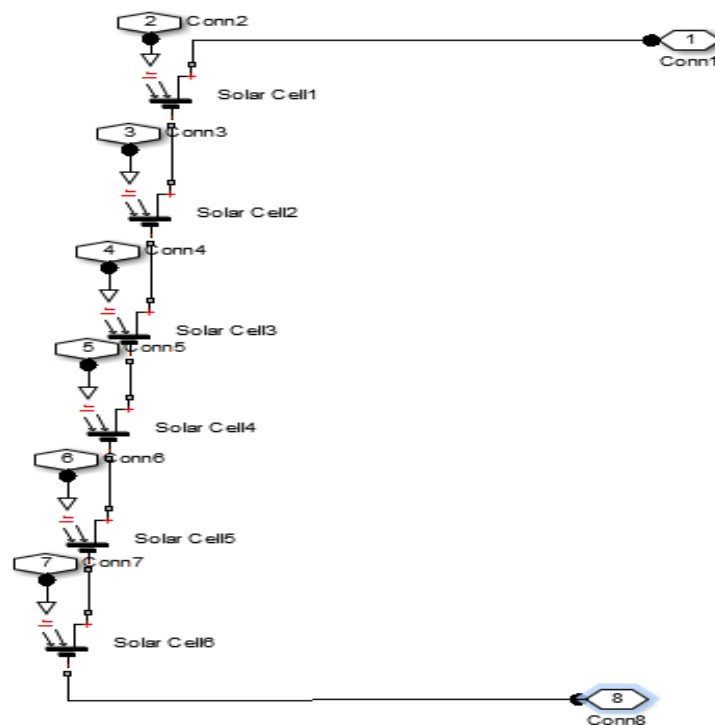


Fig. 4.13 Internal connection of Solar photovoltaic Module.

4.2.2 DC-DC converter

Here the power converter behaviour is represented by the dc-dc converter block. A DC-to-DC converter is an electronic circuit or device that converts a source of direct current (DC) from

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one voltage level to another. This power converter regulates voltage on the load side, and the required amount of power is drawn from the supply side as to balance input power, output power, and losses. The converter block is shown in figure below.

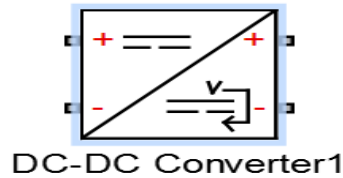


Fig. 4.14A typical block diagram of dc-dc converter in Matlab/ Simscape.

Table 4 specific value of DC-DC converter parameter

Parameter	value
Output voltage reference	48V
Output droop with output current	0.1
Maximum supply side current	25A
Rated output power	3000Watt
%of efficiency at rated output power	90%
Fixed converter loss independent loading	10Watt

The following circuit illustrates the behavior of the converter[54]

The P_{fixed} component draws a constant power, and corresponds to converter losses that are independent of load current. The power drawn is set by the Fixed converter losses independent of loading parameter value. The resistor R_{out} corresponds to losses that increase with load current, and is determined from the value you specify for the Percentage efficiency at rated output power parameter

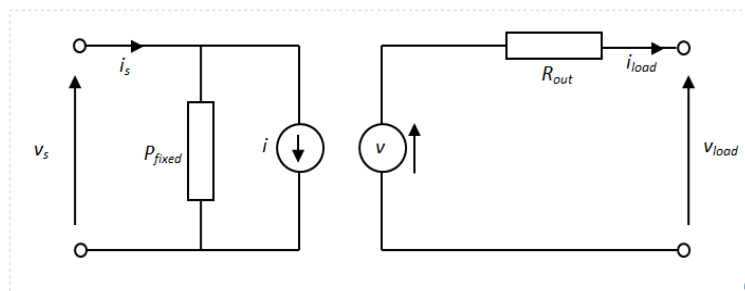


Fig. 4.15 Internal circuit diagram of dc-dc converter[54]

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4.2.3 Generic Battery

Generic battery block represents a simple battery model. It is assumed that the battery charge capacity at the initial condition is finite. The block model of the battery is a series resistor and a charge-dependent voltage source whose voltage is a function of charge. It has the following reciprocal relationship [54].

The simple model of battery is presented in Fig.4.16.

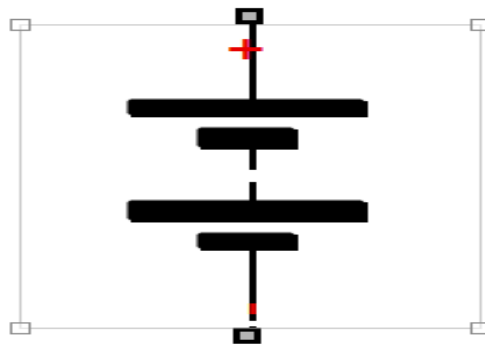


Fig. 4.16A simple model of Generic Battery

Table 5 specific value of Generic battery parameter

Parameter	Value	
	Case-I	Case-II
Nominal Voltage	48V	48V
Internal resistance	1ohm	1ohm
Ampere hour rating	100AH	100AH
Initial charge	80%	10%
Voltage $V_1 < V$ nominal when charge AH1 is	45V	45V

In the test system-II a solar PV system is connected with a dc-dc converter whose reference voltage level is 48V. A battery and a resistive load are connected across the dc-dc converter. The value of the resistive load is 1.2 ohm. In case-I initially it is assumed that the initial charge of the battery is 80%. During this condition the battery become discharge and the output power across the load is equal to the summation of the PV output power and power extract due to battery. Due to discharging mode of the battery the extracted power form the battery become decreases. Therefore the output power across the load is also decrease. After full discharge of the battery, it is working in a floating condition and maintains the dc-dc converter operation instruction.

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Similarly in case-II it is assumed that the initial charge of the battery is 10%. During this condition, initially the battery becomes in charging mode. In that condition the battery current magnitude is high but after full charging the battery become in steady condition.

The complete system modelled in Matlab is given in figure below.

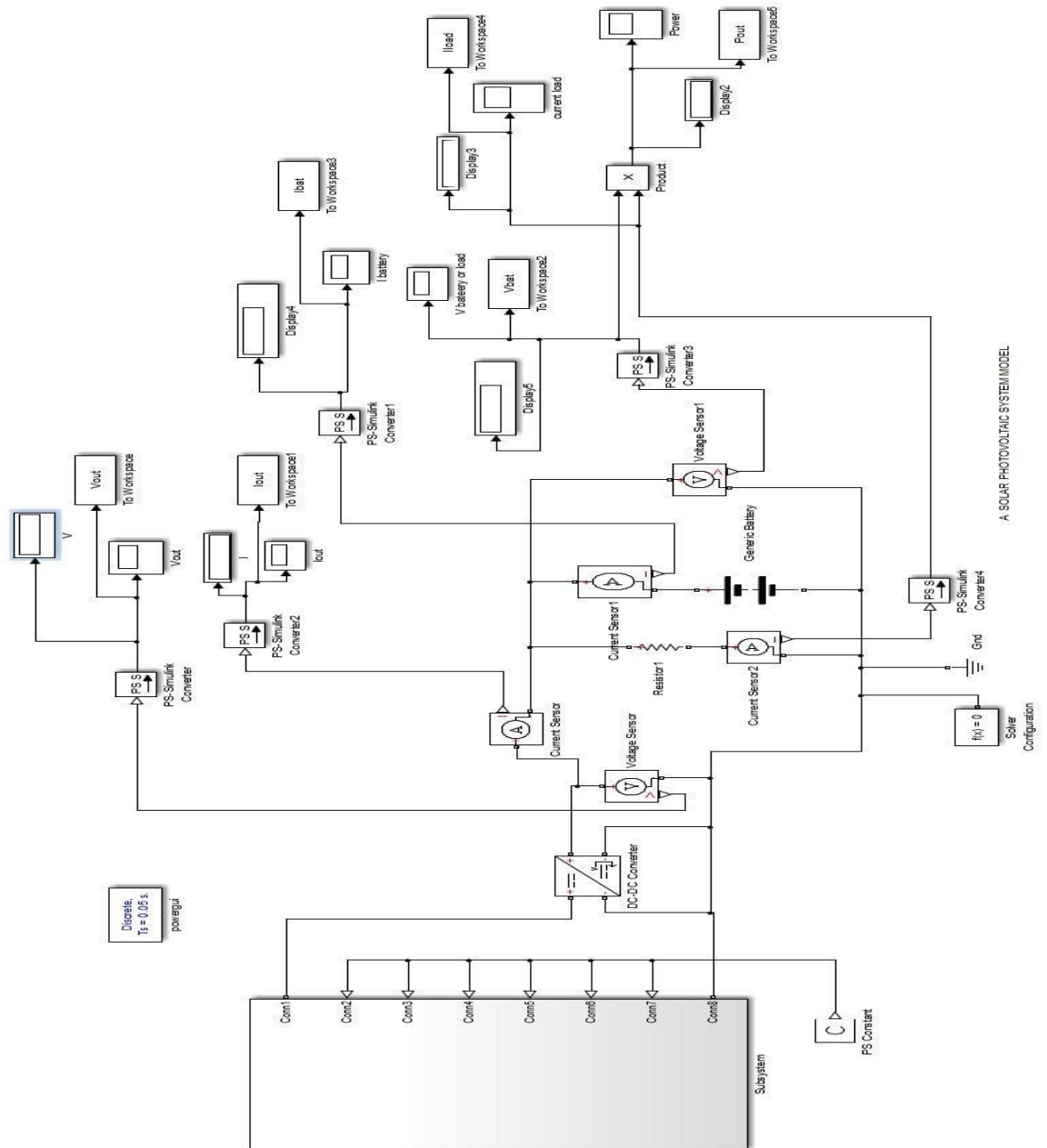


Fig.4.17 Complete PV system model with battery and resistive load.

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4.3 Conclusion

In this chapter a solar photovoltaic module and array model are developed through Matlab/Simulink with the help of available equations. Moreover a simple dc solar photovoltaic system with a resistive load and a battery is modelled by MatlabSimulink with the help of Simscape block parameter. In the next chapter the simulation result are presented and their performance characteristics are discussed in details.

Chapter 5

Results and Discussions

5.1. Introduction

A mathematical model for a solar photovoltaic system with resistance and generic battery has been developed in this dissertation using MATLAB/SIMULINK. Based on this mathematical model, the objective in this chapter is to discuss the system performance characteristics (voltage, current and power responses) obtained through simulation. The results are represented graphically and in tabular form

5.2. Test system –I

The simulation result of mathematical modelling of solar photovoltaic module and array obtained through MATLAB software with the help of Kyocera KC85T parameter datasheet (given in the previous chapter) has been presented here. In test system-I the main objective is to observe the P-V & I-V characteristics of the PV module and array through simulation. Here the simulation result is based on three conditions: effect of change in irradiation with constant temperature, effect of change in temperature with constant irradiation and combined effect of both the temperature and irradiation on the solar photovoltaic module and array. During the simulation of the model, it is assumed that $N_p=N_s=1$.

5.2.1. Performance characteristics of PV module

In previous discussions presented in chapter 3, from the I-V characteristic response curves, values of maximum currents (I_{sc}) can be observed for corresponding values of voltage. Similarly, from P-V characteristic curves, responses for power with respect to voltage can be studied. In practice however, the effects of variation of temperature and irradiation needs to be taken into account for the above analysis. The following subsections shall discuss such results where practical scenarios of irradiation and temperature variation have been considered.

5.2.1.1. Effect of different irradiation with constant temperature

The simulation is run for a time period of zero to six seconds considering a constant temperature of 25⁰C. Initially the value of irradiation is 0.2sun or 200W/m², after 2 second the value is taken as 0.6 sun or 600W/m² and after another 2 second the value is changed to 1 sun or 1000W/m². Form the I-V curve we can say that initially the value of current and voltage are approximately 1.8amp and 19 volt. Later the magnitudes change to 5.1 amp and 22volts. Finally currents and voltages take up magnitudes of 8.5 amp and 23.5 volt

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respectively. Therefore the current initially remains almost constant as the voltage is increased. But after a certain voltage level, the current drops. The instant when the current becomes zero, the voltage recorded is maximum and this value can be termed as open circuit voltage. This response curve decreases in magnitude with decrease in irradiation. The related figure is given below.

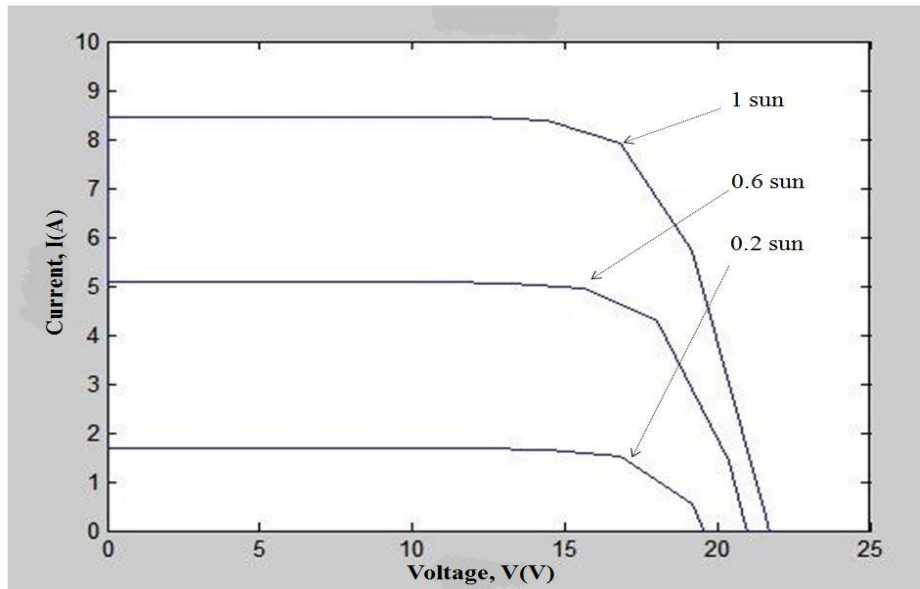


Fig 5.1 I-V characteristics for change in irradiation at constant temperature 25⁰C.

Now for P-V characteristics it can be seen that at constant temperature, initially the output power is nearly 28watt and as with the increasing the with the increasing the irradiation value the output power become 75watt and 125watt approximately. The related figure is given below.

From the figure 5.2, the power response curve has a higher magnitude for increased irradiation. As observed from the previous graph, upon increase in voltage, the currents falls to zero at some value of voltage. Therefore at this instant, the power becomes zero. Hence the power curve first increases with voltage and then decreases with a sharp decrease in current. Finally it becomes zero when the current becomes zero

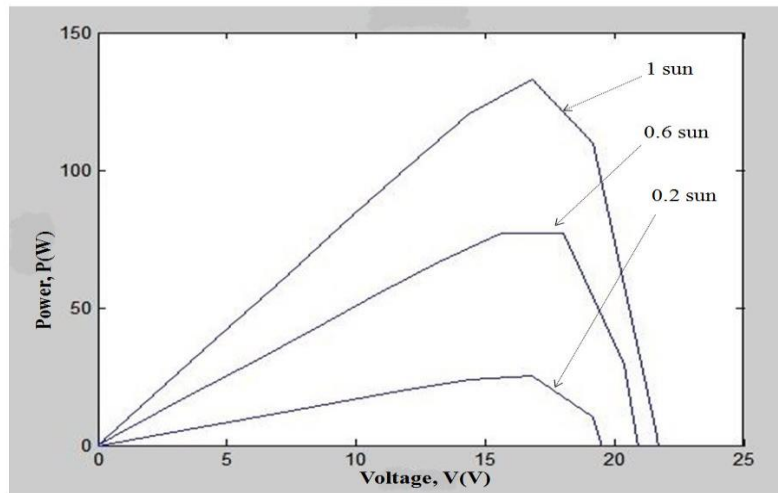


Fig 5.2 P-V characteristics for change in irradiation with constant temperature 25⁰C.

Now for the Test System-I, for the PV module temperature is kept constant at a value of 25 degrees. The simulation is run for 10 seconds and throughout the runtime, irradiation is gradually varied after every 2 seconds. The quantities of voltage, current and power are then recorded and the magnitudes of these three quantities are listed in the form of a table in table 6. In this system, for simulation repeating sequence block is used. When the critical current limit is exceeded maximum output of PV system, in that condition the value of the current becomes negative, so the magnitude of the power is also negative.

Table.6 Effect of irradiation variation at constant temperature 25⁰C on solar PV module.

Sl.no	Time (sec)	Irradiation (W/m ²)	Voltage (V)	Power (Watt)	Current (A)
1	0	0.20	0	0	1.68
2	0.20	0.20	4	6.75	1.68
3	0.40	0.20	8	13.51	1.68
4	0.60	0.20	12.00	20.26	1.68
5	0.80	0.20	16	25.49	1.59
6	1	0.20	20	-5.50	-0.27
7	1.20	0.20	24	-232.85	-9.70
8	1.40	0.20	28	-690.41	-24.65
9	1.60	0.20	32.00	-1333.17	-41.66
10	1.80	0.20	36	-2144.89	-59.58
11	2.00	0.20	40.00	-3119.96	-77.99
12	2.00	0.40	39.99	-3115.25	-77.88
13	2.20	0.40	35.99	-2139.50	-59.43
14	2.40	0.40	31.99	-1326.65	-41.45
15	2.60	0.40	27.99	-681.74	-24.34
16	2.80	0.40	23.99	-219.13	-9.13
17	3.00	0.40	19.99	19.59	0.97
18	3.20	0.40	15.99	52.44	3.27
19	3.40	0.40	11.99	40.85	3.40

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20	3.60	0.40	7.99	27.30	3.41
21	3.80	0.40	3.99	13.62	3.41
22	3.99	0.40	2.48	8.510	3.42
23	4.00	0.60	3.19	1.63	5.11
24	4.20	0.60	4.00	20.44	5.11
25	4.40	0.60	8.00	40.89	5.11
26	4.60	0.60	12.00	61.27	5.10
27	4.80	0.60	16.00	79.10	4.94
28	5.00	0.60	20.00	43.28	2.16
29	5.20	0.60	24.00	-206.18	-8.59
30	5.40	0.60	28.00	-673.33	-24.04
31	5.60	0.60	32.00	-1320.22	-41.25
32	5.80	0.60	36.00	-2134.12	-59.28
33	6.00	0.60	39.99	-3110.56	-77.76
34	6.02	0.60	39.60	-3005.63	-75.89
35	6.02	0.80	39.59	-3001.16	-75.78
36	6.22	0.80	35.59	-2040.28	-57.31
37	6.42	0.80	31.59	-1241.80	-39.29
38	6.62	0.80	27.59	-610.18	-22.10
39	6.82	0.80	23.59	-158.10	-6.69
40	7.02	0.80	19.59	76.95	3.92
41	7.22	0.80	15.59	102.97	6.60
42	7.42	0.80	11.59	78.34	6.75
43	7.62	0.80	7.59	51.37	6.75
44	7.82	0.80	3.59	24.33	6.75
45	7.95	0.80	0.80	5.40	6.75
46	7.96	0.80	0.79	5.40	6.75
47	7.96	0.80	0.79	5.40	6.75
48	7.99	0.99	1.13	9.60	8.44
49	8	1.0	0	0	8.44
50	8.00	1.0	2.27	1.92	8.44
51	8.20	1.0	4.00	33.79	8.44
52	8.40	1.0	8.00	67.59	8.44
53	8.60	1.0	12.00	101.26	8.43
54	8.80	1.0	16.00	130.59	8.16
55	9.00	1.0	20.00	85.36	4.26
56	9.20	1.0	24.00	-183.10	-7.62
57	9.40	1.0	28.00	-657.95	-23.49
58	9.60	1.0	32.00	-1308.29	-40.88
59	9.80	1.0	36.00	-2124.07	-59.00
60	10	1.0	40	-3101.64	-77.54

5.2.1.2. Effect of different temperature with constant irradiation

From the given figure we can observe that at the initial condition the temperature is 25⁰C, after 2 second the temperature value becomes 50⁰C and after another 2 second the value of temperature becomes 75⁰C. With increasing the value of temperature from 25⁰C to 75⁰C the voltage level is decreased from 23volt to 14.5volt approximately. During the simulation the value of current is almost same. It is seen that the response curve for current initially remains the same and then decreases sharply for a fixed temperature. As the temperature increases, the response curves shift to decrease

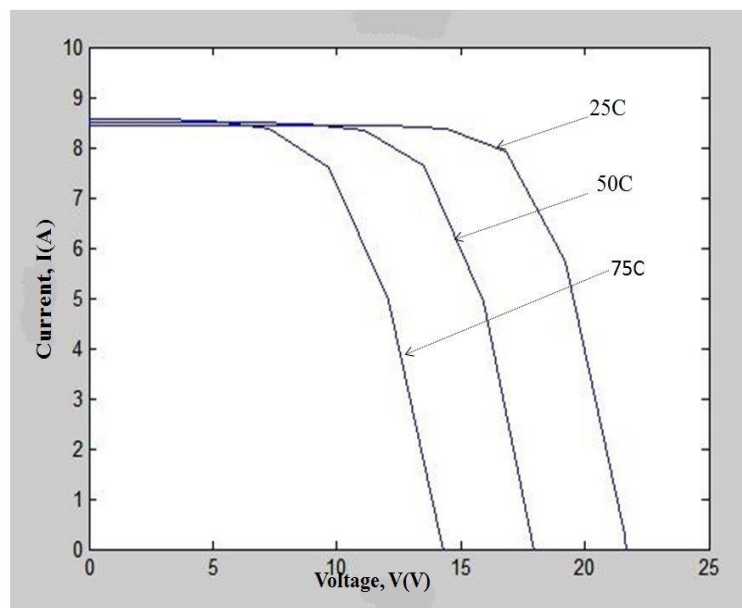


Fig 5.3 I-V characteristics for change in temperature with constant irradiation 1sun.

On the other hand in P-V characteristics of PV module it was determined that the value of output power is decreased with the increasing of temperature value at constant irradiation of 1sun or 1000W/m².

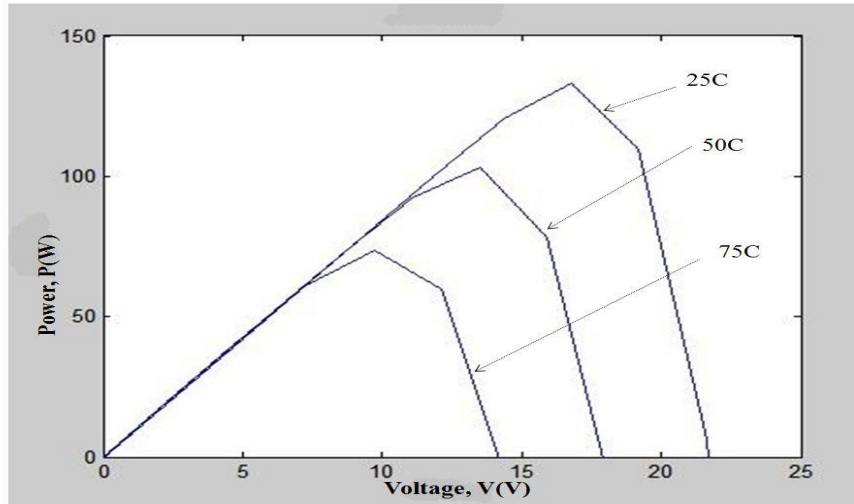


Fig 5.4 P-V characteristics for change in temperature with constant irradiation 1sun.

For the system I, for the PV Module, a simulation is run similar to the previous simulation. Only here, instead of the variation of irradiation, temperature is varied keeping the irradiation constant. As done in the previous simulation, for a simulation runtime of 10 seconds, the values of voltages, currents and power are recorded and tabulated as follows.

For the system I, for simulation repeating sequence block is used. When the critical current limit is exceeds maximum output of PV system, in that condition the value of the current is becomes negative, so the magnitude of the power is also negative.

Table.7 Effect of temperature variation at constant irradiation on solar PV module

Sl.no	Time (sec)	Temperature (°C)	Voltage(V)	Power(Watt)	Current(A)
1	0	25	0	0	8.44
2	0.20	25	4	33.79	8.44
3	0.40	25	8	67.59	8.44
4	0.60	25	12.00	101.26	8.43
5	0.80	25	16	130.59	8.16
6	1	25	20	85.36	4.26
7	1.20	25	24	-183.10	-7.62
8	1.40	25	28	-657.95	-23.49
9	1.60	25	32.00	-1308.29	-40.88
10	1.80	25	36	-2124.07	-59.00
11	2.00	25	40.00	-3101.64	-77.54
12	2.00	35	39.99	-3360.06	-84.00
13	2.20	35	35.99	-2354.34	-65.39
14	2.40	35	31.99	-1509.16	-47.16
15	2.60	35	27.99	-826.88	-29.53
16	2.80	35	23.99	-313.52	-13.06

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17	3.00	35	19.99	12.86	0.64
18	3.20	35	15.99	120.35	7.52
19	3.40	35	11.99	101.12	8.42
20	3.60	35	7.99	67.75	8.46
21	3.80	35	3.99	33.88	8.47
22	3.99	35	2.48	2.10	8.47
23	4.00	45	3.19	2.71	8.49
24	4.20	45	4.00	33.96	8.4920
25	4.40	45	8.00	67.88	8.4850
26	4.60	45	12.00	99.96	8.330
27	4.80	45	16.00	95.46	5.9662
28	5.00	45	20.00	-76.98	-3.8492
29	5.20	45	24.00	-450.30	-18.7626
30	5.40	45	28.00	-998.61	-35.6647
31	5.60	45	32.00	-1711.61	-53.48
32	5.80	45	36.00	-2585.66	-71.82
33	5.99	45	39.99	-3619.31	-90.48
34	6.00	55	39.99	-3879.31	-96.98
35	6.20	55	35.99	-2817.92	-78.27
36	6.40	55	31.99	-1915.37	-59.85
37	6.60	55	27.99	-1172.53	-41.87
38	6.80	55	23.99	-591.52	-24.64
39	7.00	55	19.99	-178.18	-8.90
40	7.20	55	15.99	51.39	3.21
41	7.40	55	11.99	95.78	7.98
42	7.60	55	7.99	67.88	8.48
43	7.80	55	3.99	34.04	8.51
44	7.99	55	7.46	6.35	8.51
45	8.00	65	3.90	3.33	8.53
46	8.20	65	4.00	34.11	8.52
47	8.40	65	8.00	67.49	8.43
48	8.60	65	12.00	84.48	7.04
49	8.80	65	16.00	-9.66	-0.60
50	9.00	65	20.00	-286.84	-14.34
51	9.20	65	24.00	-736.00	-30.66
52	9.40	65	28.00	-1348.20	-48.15
53	9.60	65	32.00	-2120.27	-66.25
54	9.80	65	36.00	-3051.02	-84.75
55	10	65	40	-4140.03	-103.50

5.2.1.3. Combined effect of change in temperature and irradiation

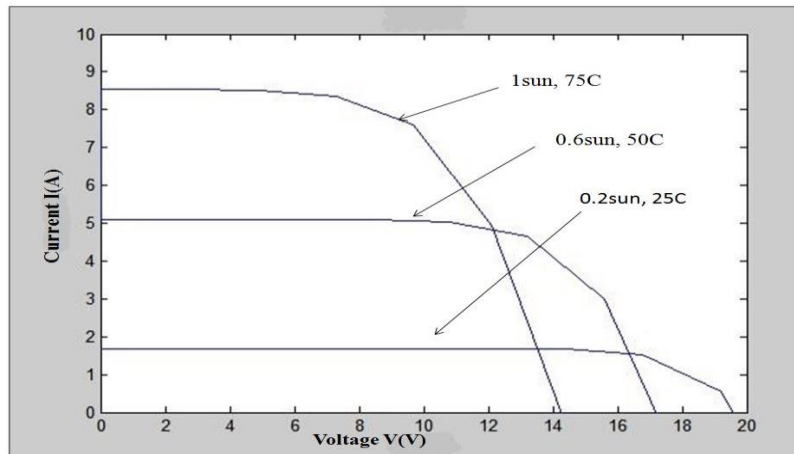


Fig 5.5 I-V characteristics on combined effect of temperature and irradiation.

When a combination of temperature and irradiation variation is applied, initially the value of irradiation and temperature are 0.2sun or 200W/m^2 at a temperature of 25°C , after 2 second they become 0.6sun or 600W/m^2 and 50°C and after another 2 second the value becomes 1sun or 1000W/m^2 and 75°C . During the change of the value of temperature and irradiation a, the output current is increases with change of input but the voltage level reduces with respect to temperature and irradiation variation.

Similarly for P-V characteristics it is observed that at the initial condition the output power is nearly 25watt. With change in parameters such as temperature and irradiation, after a certain time period the output power changes and becomes 58watt and 75watt approximately.

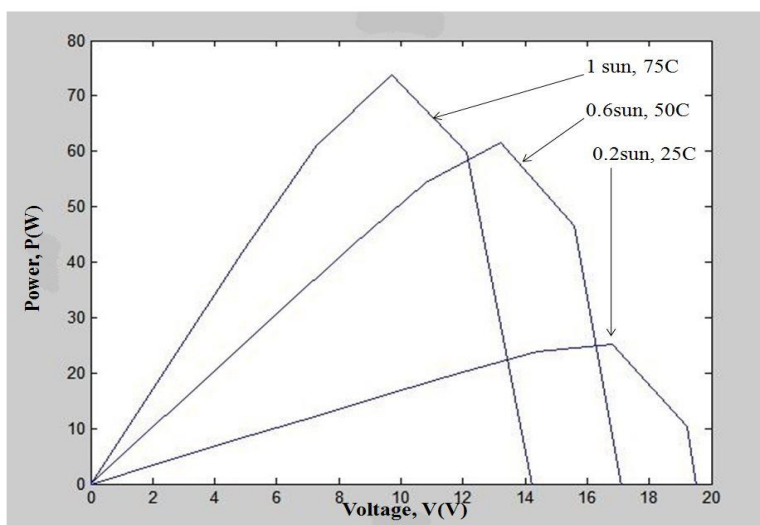


Fig 5.6 P-V characteristics on combined effect of temperature and irradiation.

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Now for the first system, scenarios of varying temperature and irradiation is studied and for this purpose the simulation is run for 10 seconds and throughout the runtime, the magnitudes of temperature and irradiation are subjected to random variation. Range of variation of temperature is taken from (25-65)degrees with an uniform increase of 10 degrees, while the range of irradiation is set from 0.20 Sun to 1 Sun with an uniform increase of 0.20 Sun. Voltage, current and power quantities are then observed and tabulated in the form as given in table 8. In this system, for simulation repeating sequence block is used. When the critical current limit is exceeds maximum output of PV system, in that condition the value of the current is becomes negative, so the magnitude of the power is also negative.

Table 8. Combined effect of temperature and irradiation on solar PV module

Sl.no	Time (sec)	Temperature(⁰ C)	Irradiation (W/m ²)	Voltage (V)	Current (A)	Power (Watt)
1	0	25	0.20	0	1.68	0
2	0.20	25	0.20	4	1.68	6.75
3	0.40	25	0.20	8	1.68	13.51
4	0.60	25	0.20	12.00	1.68	20.23
5	0.80	25	0.20	16	1.59	25.49
6	1	25	0.20	20	-0.25	-5.50
7	1.20	25	0.20	24	-9.70	-232.85
8	1.40	25	0.20	28	-24.65	-690.41
9	1.60	25	0.20	32.00	-41.66	-1333.17
10	1.80	25	0.20	36	-59.58	-2144.89
11	2.00	25	0.20	40.00	-77.99	-3119.96
12	2.00	35	0.40	39.99	-84.32	-3373.19
13	2.20	35	0.40	35.99	-65.80	-2368.96
14	2.40	35	0.40	31.99	-47.69	-1526.12
15	2.60	35	0.40	27.99	-30.28	-847.89
16	2.80	35	0.40	23.99	-14.28	-342.86
17	3.00	35	0.40	19.99	-1.84	-36.80
18	3.20	35	0.40	15.99	2.95	47.33
19	3.40	35	0.40	11.99	3.39	40.78
20	3.60	35	0.40	7.99	3.42	27.37
21	3.80	35	0.40	3.99	3.42	13.70
22	3.99	35	0.40	2.48	3.43	8.53
23	4.00	45	0.60	3.19	5.13	1.64
24	4.20	45	0.60	4.00	5.13	20.55
25	4.40	45	0.60	8.00	5.13	41.06
26	4.60	45	0.60	12.00	5.04	60.49
27	4.80	45	0.60	16.00	3.43	54.95
28	5.00	45	0.60	20.00	-5.08	-101.37
29	5.20	45	0.60	24.00	-19.42	-466.30
30	5.40	45	0.60	28.00	-36.10	-1010.89

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31	5.60	45	0.60	32.00	-53.80	-1721.91
32	5.80	45	0.60	36.00	-72.07	-2594.76
33	5.99	45	0.60	39.99	-90.69	-3627.60
34	6.00	55	0.60	39.99	-97.18	-3887.37
35	6.02	55	0.60	39.60	-95.30	-3774.15
36	6.02	55	0.80	39.59	-95.20	-3770.12
37	6.22	55	0.80	35.59	-76.54	-2724.93
38	6.42	55	0.80	31.59	-58.18	-1838.80
39	6.62	55	0.80	27.59	-40.31	-1112.80
40	6.82	55	0.80	23.59	-23.28	-549.60
41	7.02	55	0.80	19.59	-7.98	-156.59
42	7.22	55	0.80	15.59	3.00	46.94
43	7.42	55	0.80	11.59	6.49	75.36
44	7.62	55	0.80	7.59	6.79	51.64
45	7.82	55	0.80	3.59	6.81	24.56
46	7.95	55	0.80	0.80	6.81	5.44
47	7.96	55	0.80	0.79	6.81	5.44
48	7.96	55	0.80	0.79	6.81	5.44
49	7.99	55	0.99	1.13	8.51	9.67
50	8	65	1	0	8.53	0
51	8.00	65	1	2.27	8.53	1.94
52	8.20	65	1	4.00	8.52	34.11
53	8.40	65	1	8.00	8.43	67.49
54	8.60	65	1	12.00	7.04	84.48
55	8.80	65	1	16.00	-0.60	-9.66
56	9.00	65	1	20.00	-14.34	-286.84
57	9.20	65	1	24.00	-30.66	-736.00
58	9.40	65	1	28.00	-48.15	-1348.20
59	9.60	65	1	32.00	-66.25	-2120.27
60	9.80	65	1	36.00	-84.75	-3051.02
61	10	65	1	40	-103.50	-4140.03

5.2.2 Performance characteristics of PV array

In the above figures, P-V and I-V characteristics are evaluated for a photovoltaic module. Similarly to determine the P-V & I-V characteristics for a photovoltaic array, an array can be designed with 6 PV modules in series connection. For this array the three conditions of temperature and irradiation as considered in the previous section is applied.

5.2.2.1. Effect of different irradiation with constant temperature

The simulation is run for a time period of zero to six second at constant temperature 25⁰C. At the beginning the value of irradiation is 0.2sun or 200W/m², after 2 second the value becomes 0.6 sun or 600W/m² and after another 2 second the value becomes 1 sun or 1000W/m². From

the I-V curve it can be seen that with change in temperature the value of current increases. The related figure is given below

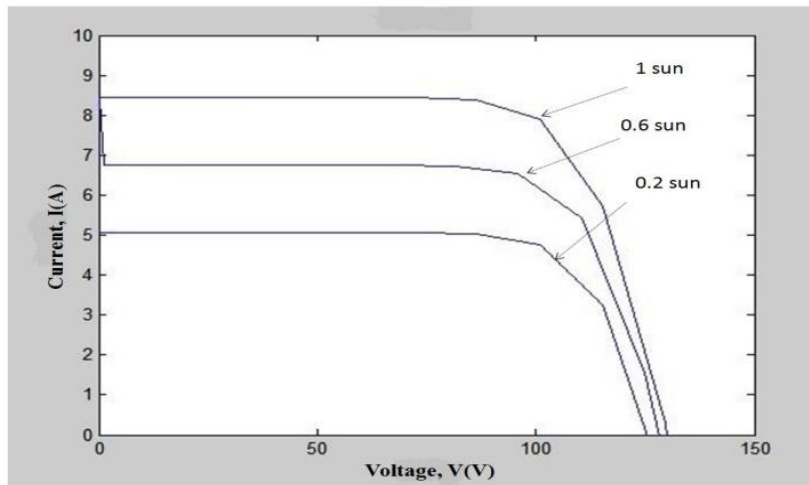


Fig 5.7 I-V characteristics for change in irradiation at constant temperature 25⁰C

For second case, the output power increases with the increase in irradiation and it can be observed from the following figure.

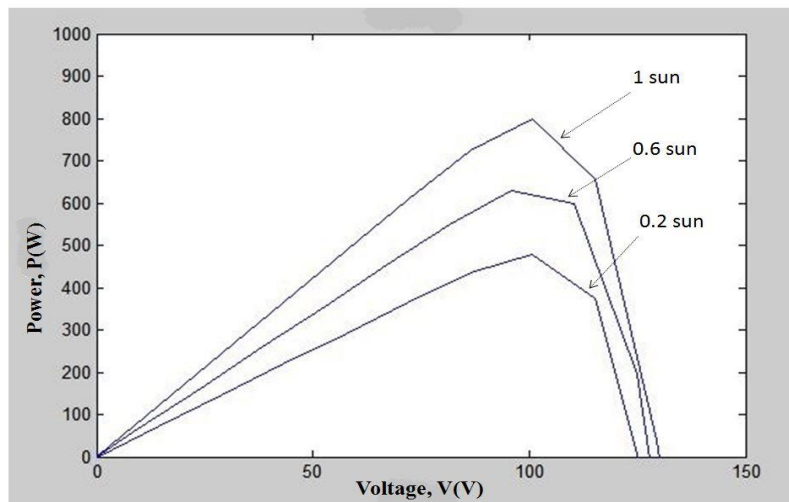


Fig 5.8 P-V characteristics for change in irradiation at constant temperature 25⁰C.

Now for the Test System-I, for the PV array temperature is kept constant at a value of 25 degrees. The simulation is run for 10 seconds and throughout he runtime, irradiation is gradually varied after every 2 seconds. The quantities of voltage, current and power are then recorded and the magnitudes of these three quantities are listed in the form of a table in table 9.

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Table.9 Effect of irradiation variation at constant temperature 25⁰C on solar PV array.

Sl.no	Time (sec)	Irradiation (W/m ²)	Voltage (V)	Power (Watt)	Current (A)
1	0	0.20	0	0	1.68
2	0.20	0.20	24	40.55	1.68
3	0.40	0.20	48	81.11	1.68
4	0.60	0.20	72.00	121.48	1.68
5	0.80	0.20	96	152.97	1.59
6	1	0.20	120	-33.03	-0.25
7	1.20	0.20	144	-1397.14	-9.70
8	1.40	0.20	168	-4142.51	-24.65
9	1.60	0.20	192.00	-7999.06	-41.66
10	1.80	0.20	216	-12869.36	-59.58
11	2.00	0.20	240.00	-18719.76	-77.99
12	2.00	0.40	239.99	-18691.55	-77.88
13	2.20	0.40	215.99	-12837.01	-59.43
14	2.40	0.40	191.99	-7959.91	-41.45
15	2.60	0.40	167.99	-4090.45	-24.34
16	2.80	0.40	143.99	-1314.83	-9.13
17	3.00	0.40	119.99	117.58	0.97
18	3.20	0.40	95.99	314.65	3.27
19	3.40	0.40	71.99	245.15	3.40
20	3.60	0.40	47.99	163.85	3.41
21	3.80	0.40	23.99	82.03	3.41
22	3.99	0.40	1.49	5.10	3.42
23	4.00	0.60	1.91	9.80	5.11
24	4.20	0.60	24.00	122.98	5.11
25	4.40	0.60	48.00	245.37	5.11
26	4.60	0.60	72.00	367.63	5.10
27	4.80	0.60	96.00	474.60	4.94
28	5.00	0.60	120.00	259.71	2.16
29	5.20	0.60	144.00	-1237.12	-8.57
30	5.40	0.60	168.00	-4040.01	-24.04
31	5.60	0.60	192.00	-7921.34	-41.25
32	5.80	0.60	216.00	-12804.76	-59.28
33	6.00	0.60	239.99	-18663.15	-77.76
34	6.02	0.60	237.60	-18033.83	-75.89
35	6.02	0.80	237.59	-18006.99	-75.78
36	6.22	0.80	213.59	-12241.72	-57.31
37	6.42	0.80	189.59	-7450.81	-39.29
38	6.62	0.80	165.59	-3661.11	-22.10
39	6.82	0.80	141.59	-948.61	-6.69
40	7.02	0.80	117.59	461.73	3.92
41	7.22	0.80	93.59	617.84	6.60
42	7.42	0.80	69.59	470.08	6.75
43	7.62	0.80	45.59	308.24	6.75
44	7.82	0.80	21.59	146.01	6.75

45	7.95	0.80	4.80	32.44	6.75
46	7.96	0.80	4.79	32.44	6.75
47	7.96	0.80	4.79	32.44	6.75
48	7.99	0.99	6.82	5.76	8.44
49	8	1	0	0	8.44
50	8.00	1	1.36	1.15	8.44
51	8.20	1	24.00	202.79	8.44
52	8.40	1	48.00	405.58	8.44
53	8.60	1	72.00	607.61	8.43
54	8.80	1	96.00	783.58	8.16
55	9.00	1	120.00	512.16	4.26
56	9.20	1	144.00	-1098.00	-7.65
57	9.40	1	168.00	-3947.70	-23.49
58	9.60	1	192.00	-7849.74	-40.88
59	9.80	1	216.00	-12744.40	-59.00
60	10	1	240	-18609.83	77.54

5.2.2.2. Effect of different temperature with constant irradiation

While temperature is varied, keeping irradiation constant, the I-V characteristic is shown in fig. 5.9.

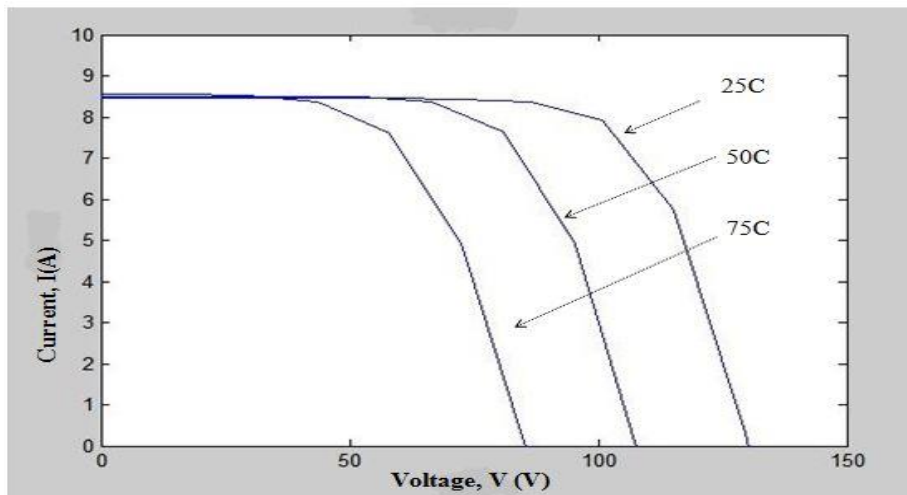


Fig 5.9 I-V characteristics for change in temperature with constant irradiation 1 sun.

Here in P-V characteristics the output power reduces due to increase in temperature at constant irradiation.

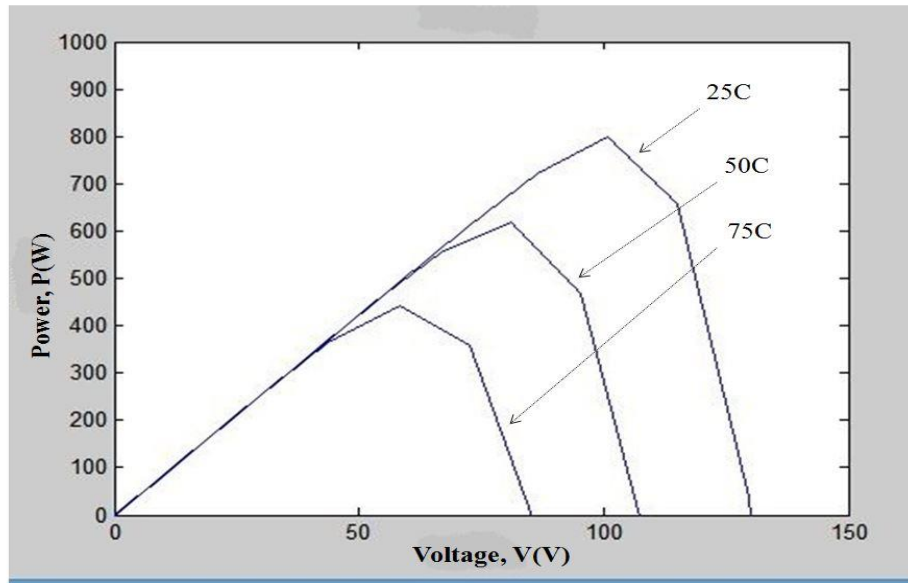


Fig 5.10 P-V characteristics for change in temperature with constant irradiation 1sun.

For the system I, for the PV Module, a simulation is run similar to the previous simulation. Only here, instead of the variation of irradiation, temperature is varied keeping the irradiation constant. As done in the previous simulation, for a simulation runtime of 10 seconds, the values of voltages, currents and power are recorded and tabulated as follows

Table.10 Effect of temperature variation at constant irradiation on solar PV array.

Sl. no	Time (sec)	Temperature (⁰ C)	Voltage (V)	Power (Watt)	Current (A)
1	0	25	0	0	8.44
2	0.20	25	24	202.79	8.44
3	0.40	25	48	405.58	8.44
4	0.60	25	72.00	607.61	8.43
5	0.80	25	96	783.58	8.16
6	1	25	120	512.16	4.26
7	1.20	25	144	-1098.60	-7.62
8	1.40	25	168	-3947.70	-23.48
9	1.60	25	192.00	-7849.74	-40.88
10	1.80	25	216	-12744.40	-59.00
11	2.00	25	240.00	-18609.86	-77.54
12	2.00	35	239.99	-20160.39	-84.00
13	2.20	35	215.99	-14126.05	-65.39
14	2.40	35	191.99	-9055.00	-47.16

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15	2.60	35	167.99	-4961.28	-29.53
16	2.80	35	143.99	-1881.14	-13.06
17	3.00	35	119.99	77.21	0.64
18	3.20	35	95.99	722.13	7.52
19	3.40	35	71.99	606.75	8.42
20	3.60	35	47.99	406.53	8.46
21	3.80	35	23.99	203.30	8.47
22	3.99	35	1.49	1.26	8.47
23	4.00	45	1.91	1.62	8.49
24	4.20	45	24.00	203.08	8.49
25	4.40	45	48.00	407.28	8.48
26	4.60	45	72.00	599.78	8.33
27	4.80	45	96.00	572.76	5.96
28	5.00	45	120.00	-461.90	-3.89
29	5.20	45	144.00	-2701.82	-18.76
30	5.40	45	168.00	-5991.67	-35.66
31	5.60	45	192.00	-10269.66	-53.48
32	5.80	45	216.00	-15513.97	-71.82
33	5.99	45	239.99	-21715.86	-90.48
34	6.00	55	239.99	-23275.91	-96.98
35	6.20	55	215.99	-16907.52	-78.27
36	6.40	55	191.99	-11492.24	-59.85
37	6.60	55	167.99	-7035.18	-41.87
38	6.80	55	143.99	-3549.16	-24.64
39	7.00	55	119.99	-1069.08	-8.90
40	7.20	55	95.99	308.35	3.21
41	7.40	55	71.99	574.70	7.98
42	7.60	55	47.99	407.31	8.48
43	7.80	55	23.99	204.29	8.51
44	7.99	55	4.47	3.81	8.51
45	8.00	65	2.34	2.00	8.53
46	8.20	65	24.00	204.10	8.52
47	8.40	65	48.00	404.97	8.43
48	8.60	65	72.00	506.89	7.04
49	8.80	65	96.00	-57.99	-0.68
50	9.00	65	120.00	-1721.07	-14.34
51	9.20	65	144.00	-4416.03	-30.66
52	9.40	65	168.00	-8089.24	-48.15
53	9.60	65	192.00	-12721.65	-66.25
54	9.80	65	216.00	-18306.16	-84.75
55	10	65	240	-24840.21	-103.57

5.2.2.3. Combined effect of change in temperature and irradiation

For the study of combined effect of temperature & irradiation, both the I-V and P-V characteristics are observed from the graphical plot. The characteristics are similar to the PV array characteristics.

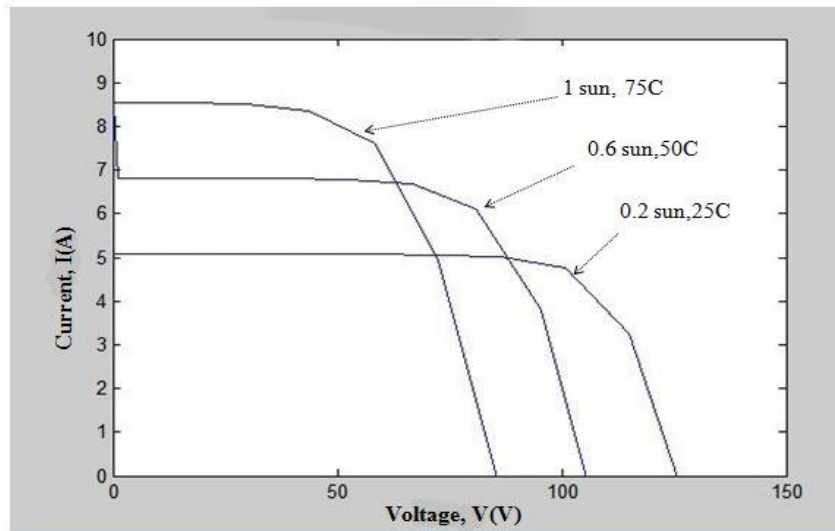


Fig 5.11 I-V characteristics on combined effect of temperature and irradiation.

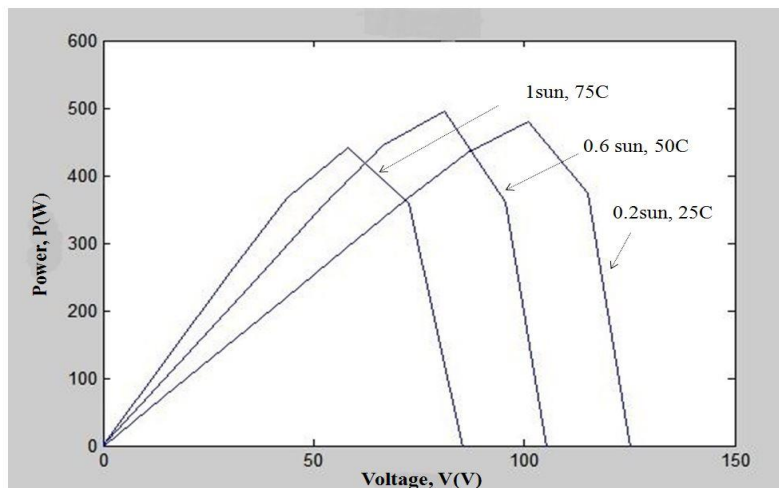


Fig 5.12 P-V characteristics on combined effect of temperature and irradiation.

Now for the first system, scenarios of varying temperature and irradiation is studied and for this purpose the simulation is run for 10 seconds and throughout the runtime, the magnitudes of temperature and irradiation are subjected to random variation. Range of variation for

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temperature is taken from (25-65)degrees with an uniform increase of 10 degrees, while the range of irradiation is set from 0.20 Sun to 1 Sun with an uniform increase of 0.20 Sun. Voltage, current and power quantities are then observed and tabulated in the form as given in table 11.

Table11. Combined effect of temperature and irradiation on solar PV array

Sl. no	Time (sec)	Temperature (°C)	Irradiation (W/m ²)	Voltage (V)	Current (A)	Power (Watt)
1	0	25	0.20	0	1.68	0
2	0.20	25	0.20	24	1.68	40.55
3	0.40	25	0.20	48	1.68	81.11
4	0.60	25	0.20	72.00	1.68	121.40
5	0.80	25	0.20	96	1.59	152.97
6	1	25	0.20	120	-0.25	-33.03
7	1.20	25	0.20	144	-9.70	-1397.14
8	1.40	25	0.20	168	-24.60	-4142.51
9	1.60	25	0.20	192.00	-41.66	-7999.06
10	1.80	25	0.20	216	-59.58	-12869.36
11	2.00	25	0.20	240.00	-77.99	-18719.76
12	2.00	35	0.40	239.99	-84.32	-20239.16
13	2.20	35	0.40	215.99	-65.80	-14213.81
14	2.40	35	0.40	191.99	-47.69	-9156.75
15	2.60	35	0.40	167.99	-30.28	-5087.34
16	2.80	35	0.40	143.99	-14.28	-2057.17
17	3.00	35	0.40	119.99	-1.840	-220.84
18	3.20	35	0.40	95.99	2.95	284.00
19	3.40	35	0.40	71.99	3.39	244.69
20	3.60	35	0.40	47.99	3.42	164.23
21	3.80	35	0.40	23.99	3.42	82.23
22	3.99	35	0.40	1.49	3.43	5.11
23	4.00	45	0.60	1.91	5.13	9.85
24	4.20	45	0.60	24.00	5.13	123.30
25	4.40	45	0.60	48.00	5.13	246.40
26	4.60	45	0.60	72.00	5.04	362.94
27	4.80	45	0.60	96.00	3.43	329.74
28	5.00	45	0.60	120.00	-5.01	-608.28
29	5.20	45	0.60	144.00	-19.49	-2797.81
30	5.40	45	0.60	168.00	-36.10	-6065.36
31	5.60	45	0.60	192.00	-53.80	-10331.50
32	5.80	45	0.60	216.00	-72.07	-15568.59
33	5.99	45	0.60	239.99	-90.69	-21765.65
34	6.00	55	0.60	239.99	-97.18	-23324.26
35	6.02	55	0.60	237.60	-95.30	-22644.95
36	6.02	55	0.80	237.59	-95.20	-22620.73
37	6.22	55	0.80	213.59	-76.54	-16349.59

38	6.42	55	0.80	189.59	-58.18	-11032.81
39	6.62	55	0.80	165.59	-40.31	-6676.82
40	6.82	55	0.80	141.59	-23.28	-3297.64
41	7.02	55	0.80	117.59	-7.989	-939.54
42	7.22	55	0.80	93.599	3.00	281.67
43	7.42	55	0.80	69.599	6.49	452.17
44	7.62	55	0.80	45.599	6.79	309.84
45	7.82	55	0.80	21.599	6.81	147.09
46	7.95	55	0.80	4.8000	6.81	32.69
47	7.96	55	0.80	4.7999	6.81	32.69
48	7.96	55	0.80	4.7999	6.81	32.69
49	7.99	55	0.99	6.8212	8.51	5.80
50	8	65	1	0	8.53	0
51	8.00	65	1	1.36	8.53	1.16
52	8.20	65	1	24.00	8.52	204.71
53	8.40	65	1	48.00	8.43	404.97
54	8.60	65	1	72.00	7.04	506.89
55	8.80	65	1	96.00	-0.61	-57.99
56	9.00	65	1	120.00	-14.34	-1721.50
57	9.20	65	1	144.00	-30.66	-4416.03
58	9.40	65	1	168.00	-48.15	-8089.24
59	9.60	65	1	192.00	-66.25	-12721.62
60	9.80	65	1	216.00	-84.75	-18306.16
61	10	65	1	240	-103.53	-24840.21

5.3. Test System-II

The model of a simple photovoltaic system is simulated using SimScape toolbox incorporated with Matlab/Simulink. For this, a battery and a resistance with parallel of DC-DC converter is used. Here six Solar cells are connected in series. The two output terminals of the module (positive & negative) are connected to dc-dc converter. A resistance and a generic battery are connected across the dc-dc converter. The simulation is run for 86400 second.

5.3.1. Case-I

Initially it is assumed that the initial charge of generic battery is 80% and the value of resistance is 1.2Ω . The output current of dc-dc converter gets divided into two currents, one that passes through the resistance and the other that passes through the battery.

Due to the assumption of battery initial charge, it is observed that the value of battery current is negative. It means that the flow direction of current is from the battery. This is referred to as discharging mode of battery. After a certain time when the battery is fully discharged, the

battery works in floating condition and maintains operation according to the dc-dc converter instruction. After the simulation the results with respect to time and different parameters are obtained and are given below.

5.3.1.1. Converter output voltage characteristics

At the initial condition the output voltage of the dc-dc converter is 44.54V (approx.), after complete the simulation the magnitude of the voltage is 44.33V. from fig.5.13 shows that after the simulation the voltage magnitude is continue almost at a steady condition.

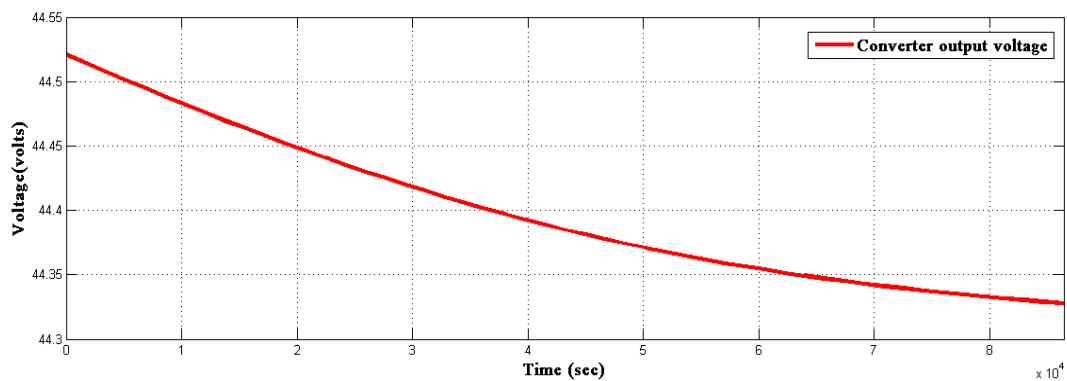


Fig 5.13 Output voltage characteristics (Zoomed Y axis response)

5.3.1.2. Converter output current characteristics

The magnitude of the output current from dc-dc converter increase from 34.55A to 36.33A. This amount of current is passing through the connected load and battery. From the table give below it is observed that the summation of battery current and current passing through the load equal to the dc-dc converter output current.

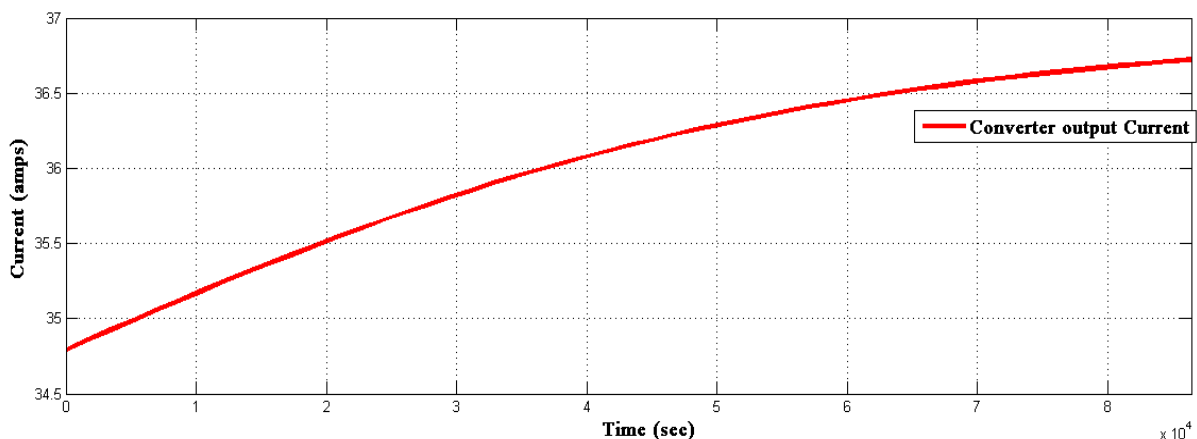


Fig 5.14 Output Current characteristics (Zoomed Y axis response).

5.3.1.3. Output current characteristics through load resistance

Initially it is assumed that the initial charge of the battery is 80%. Due to this assumption it can be seen that at the beginning of the simulation the battery discharges. During this period the magnitude of the output current is 37.1A (approx.). Due to discharging of the battery the value of the current decreases and becomes 36.92A.

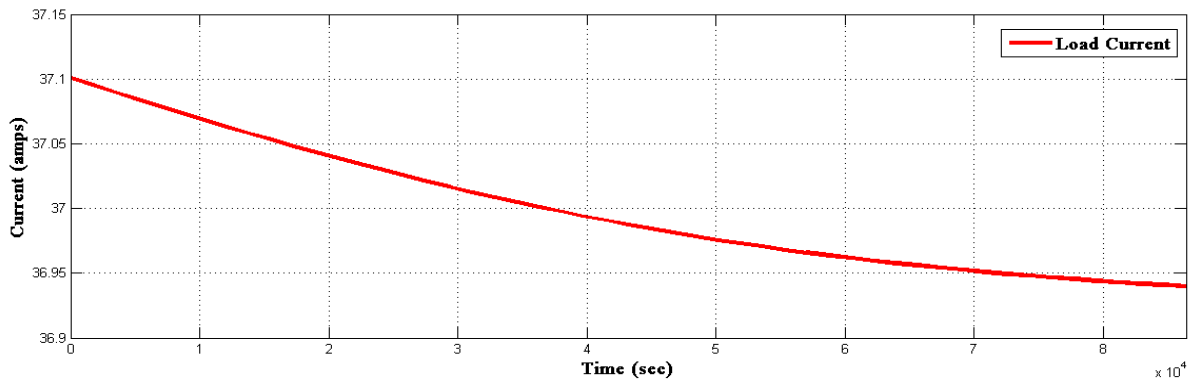


Fig 5.15 Load Current characteristics (Zoomed Y axis response).

5.3.1.4. Power characteristics through load resistance

Initially the power output is 1651.29 Watt. After the full discharges of the battery the magnitude of the power is 1636.22Watt. The related figure is given below.

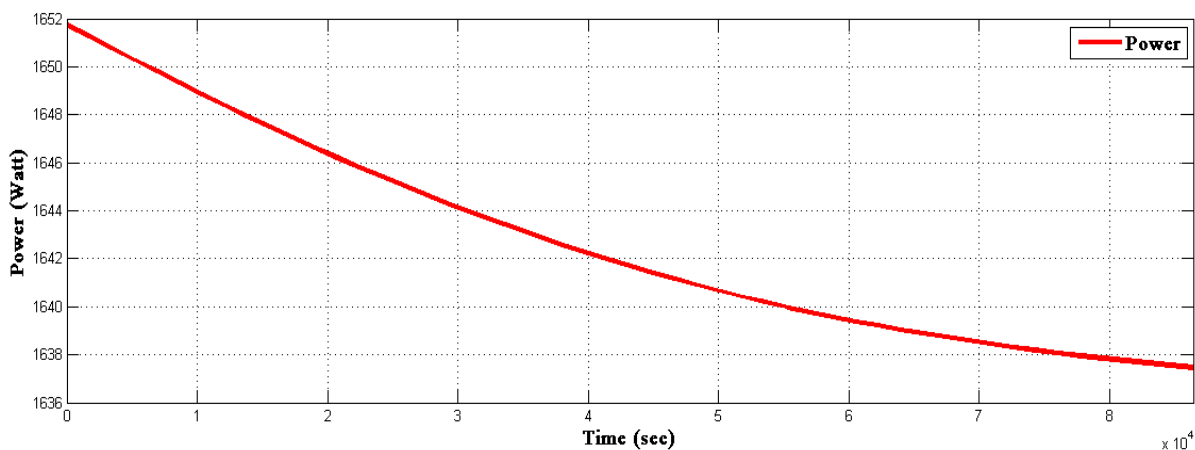


Fig 5.16 Power characteristics (Zoomed Y axis response).

5.3.1.5. Characteristics of current through battery

Due to the assumption of the battery initial charge 80%, in fig. 5.17 it can be seen that the magnitude of the battery current is negative. After completion of the simulation, the battery current magnitude is -0.036A and during this period it undergoes floating mode. At that time the battery maintains the dc-dc converter operating instruction which is shown in fig 5.17

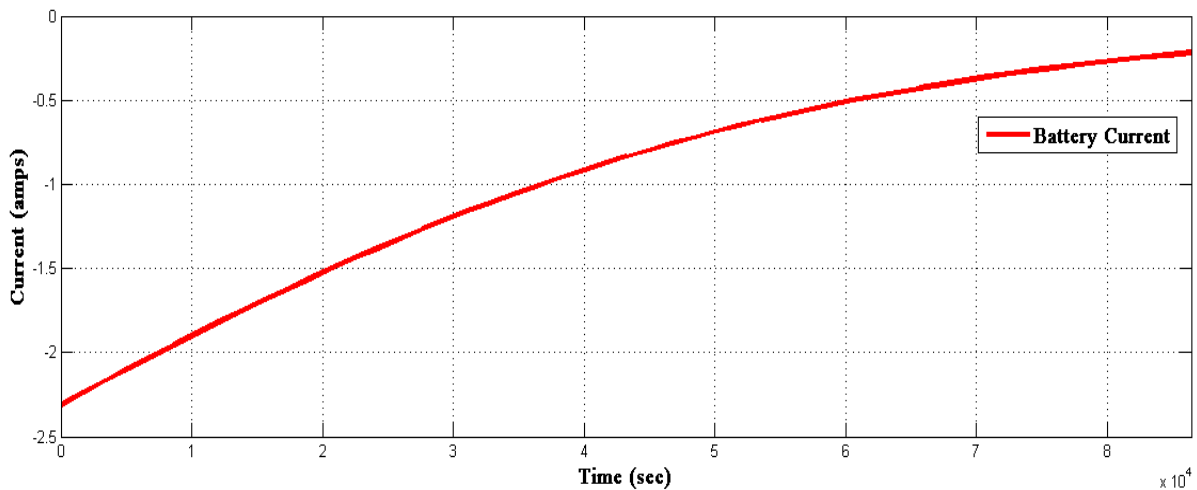


Fig 5.17 Battery current characteristics (Zoomed Y axis response).

5.3.1.6. Voltage across Battery characteristics

Here the battery is connected across the dc-dc converter. So the voltage across the battery is equal to the output voltage across the dc-dc converter which is shown in fig.5.18

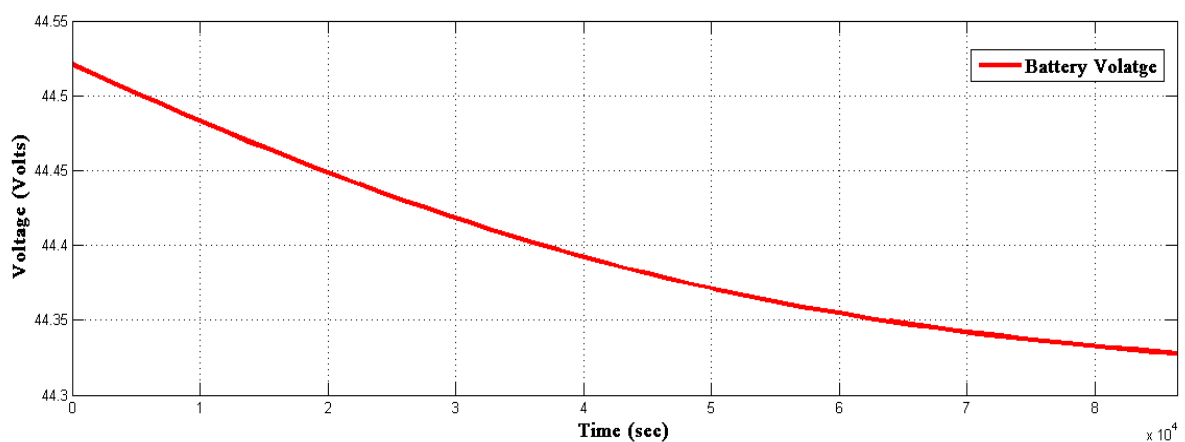


Fig 5.18 Voltage across Battery characteristics (Zoomed Y axis response).

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In Test system-II(case-I), the configured system is simulated for 86400 seconds with corresponding value of the parameters. The output quantities voltage, current of the converter, power, battery current and voltage across the battery are given below in tabular form. Here the value of the current is negative due to the discharging mode of the battery/.

Table12. System Parameter's specific value during the simulation with time

Sl.no	Time (sec)	V _{out} (V)	I _{out} (A)	V _{battery} (V)	I _{battery} (A)	I _{load} (A)	Power (W)
1	0	44.36	36.33	44.36	-0.63	36.97	1640.29
2	1728	44.36	36.36	44.36	-0.60	36.96	1640.08
3	3456	44.36	36.39	44.36	-0.57	36.96	1639.87
4	5184	44.35	36.42	44.35	-0.54	36.96	1639.67
5	6912	44.35	36.44	44.35	-0.51	36.96	1639.48
6	8640	44.35	36.47	44.35	-0.48	36.96	1639.30
7	10368	44.35	36.49	44.35	-0.48	36.95	1639.12
8	12096	44.34	36.51	44.34	-0.46	36.95	1638.96
9	13824	44.34	36.54	44.34	-0.43	36.95	1638.80
10	15552	44.34	36.56	44.34	-0.41	36.95	1638.65
11	17280	44.34	36.58	44.34	-0.39	36.95	1638.50
12	19008	44.34	36.59	44.34	-0.37	36.95	1638.37
13	20736	44.33	36.61	44.33	-0.35	36.94	1638.24
14	22464	44.33	36.63	44.33	-0.33	36.94	1638.12
15	24192	44.33	36.64	44.33	-0.31	36.94	1638.00
16	25920	44.33	36.66	44.36	-0.29	36.94	1637.89
17	27648	44.33	36.67	44.33	-0.28	36.94	1637.78
18	29376	44.33	36.69	44.33	-0.26	36.94	1637.68
19	31104	44.32	36.70	44.325	-0.25	36.94	1637.59
20	32832	44.32	36.71	44.32	-0.23	36.94	1637.50
21	34560	44.32	36.72	44.32	-0.22	36.93	1637.41
22	36288	44.32	36.73	44.32	-0.18	36.93	1637.33
23	38016	44.32	36.74	44.32	-0.17	36.93	1637.26

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24	39744	44.32	36.75	44.32	-0.16	36.93	1637.18
25	41472	44.32	36.76	44.32	-0.15	36.93	1637.12
26	43200	44.32	36.77	44.32	-0.14	36.93	1637.05
27	44928	44.32	36.78	44.32	-0.14	36.93	1636.99
28	46656	44.32	36.79	44.32	-0.13	36.93	1636.93
29	48384	44.31	36.80	44.31	-0.12	36.93	1636.88
30	50112	44.31	36.80	44.31	-0.11	36.93	1636.83
31	51840	44.31	36.81	44.31	-0.11	36.93	1636.78
32	53568	44.31	36.82	44.31	-0.10	36.93	1636.73
33	55296	44.31	36.82	44.31	-0.09	36.93	1636.69
34	57024	44.31	36.83	44.31	-0.09	36.93	1636.65
35	58752	44.31	36.83	44.31	-0.08	36.93	1636.61
36	60480	44.31	36.84	44.31	-0.08	36.92	1636.57
37	62208	44.31	36.84	44.31	-0.07	36.92	1636.54
38	63936	44.31	36.85	44.31	-0.07	36.92	1636.51
39	65664	44.31	36.85	44.31	-0.06	36.92	1636.47
40	67392	44.31	36.85	44.31	-0.06	36.92	1636.45
41	69120	44.31	36.86	44.31	-0.06	36.92	1636.42
42	70848	44.31	36.86	44.31	-0.05	36.92	1636.39
43	72576	44.31	36.86	44.31	-0.05	36.92	1636.37
44	74304	44.31	36.87	44.31	-0.05	36.92	1636.34
45	76032	44.31	36.87	44.31	-0.05	36.92	1636.32
46	77760	44.31	36.87	44.31	-0.04	36.92	1636.30
47	79488	44.31	36.88	44.31	-0.04	36.92	1636.28
48	81216	44.31	36.88	44.31	-0.04	36.92	1636.27
49	82944	44.31	36.88	44.31	-0.04	36.92	1636.25
50	84672	44.31	36.88	44.31	-0.03	36.92	1636.23
51	86400	44.31	36.88	44.31	-0.03	36.92	1636.22

5.3.2. Case-II

It is now assumed that at the start of simulation, the initial charge of generic battery is 10%. After the simulation it can be observed that the current of the battery is positive which indicates that the flow of current is towards the battery. After charging, the value of current reduces with increase in time and after a certain time the current achieves steady state. The graphical characteristics of the system parameters and their specific value with respect to time are given below.

5.3.2.1. Converter output voltage characteristics

From the fig.5.19 it can be seen that the output voltage of the dc-dc converter is 42.69 V and after the simulation the magnitude of the voltage becomes 44.29V.

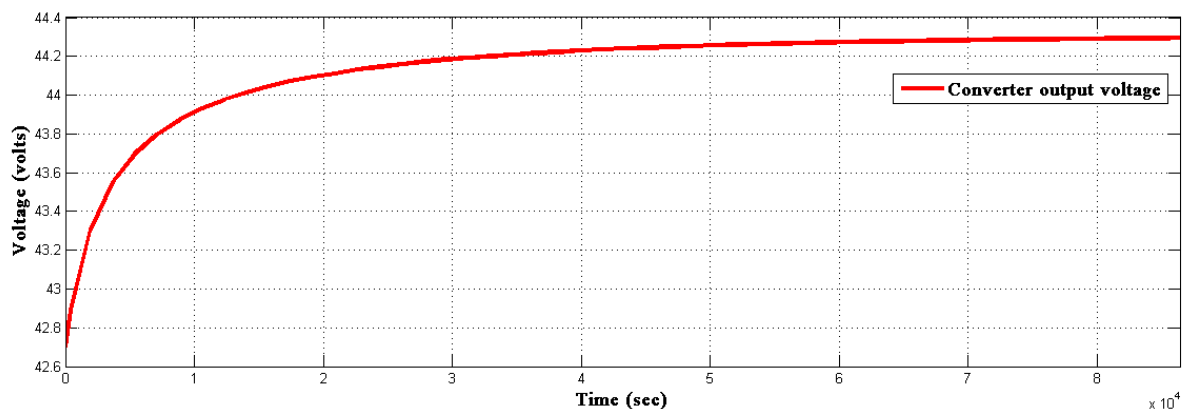


Fig 5.19 Output voltage characteristics (Zoomed Y axis response).

5.3.2.2. Converter output current characteristics

Initially the magnitude of the output current of the dc-dc converter is 53.01A. Due to the assumption of the initial charge of the battery being low (10%), the battery is in charging mode. After the simulation the magnitude of the current becomes 37.05A.

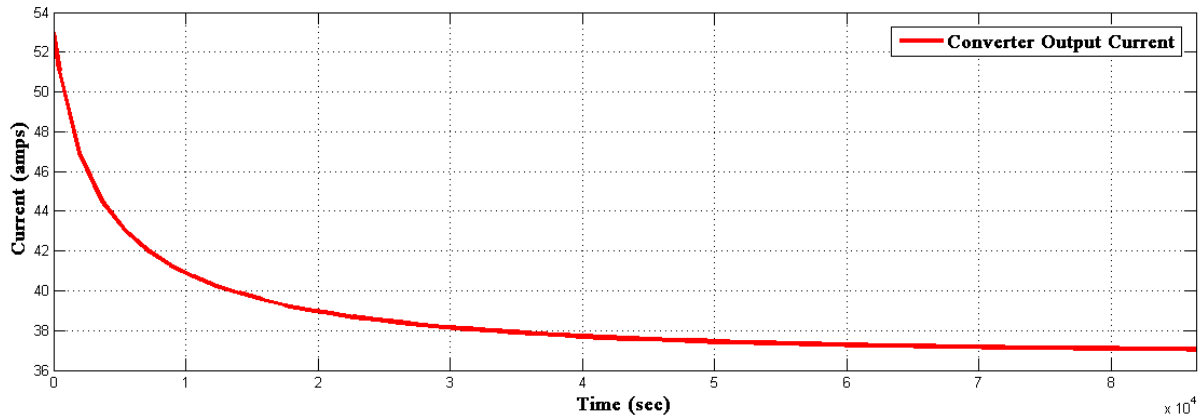


Fig 5.20 Converter Output Current characteristics (Zoomed Y axis response).

5.3.2.3. Power characteristics across load resistance

For test system-II simulation was run to study the system performance during charging of the battery. Simulation run time was set to 86400seconds and the power across the load was obtained as shown in fig.5.21. The power is seen increase with time.

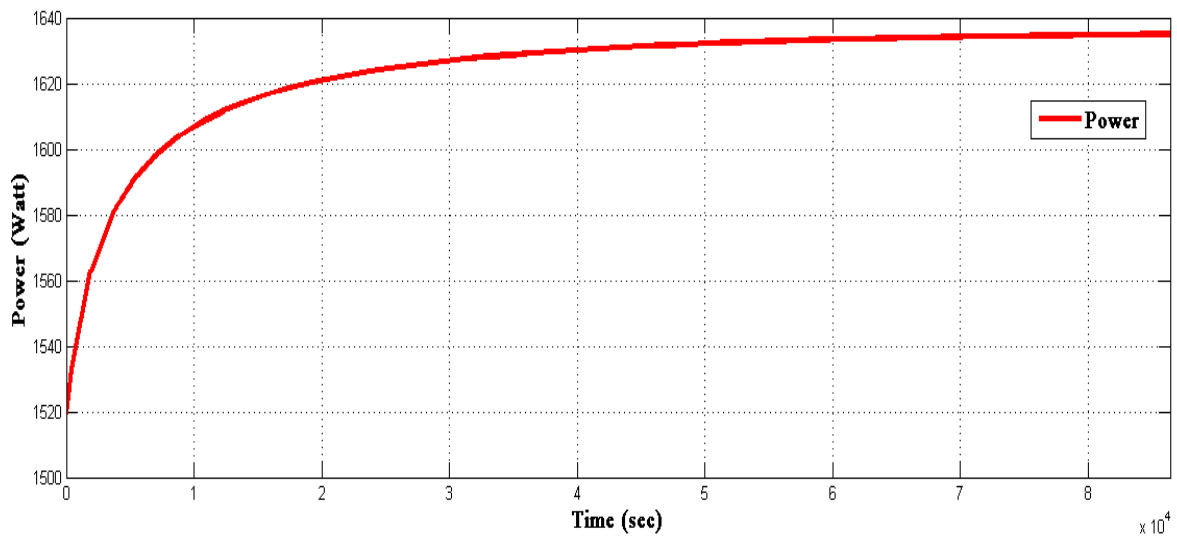


Fig 5.21 Power characteristics across load, (Zoomed Y axis response).

5.3.2.4. Battery current characteristics

For the system above with similar simulation parameter the model was simulated. Response of the battery current is now studied and the result has been presented in fig.5.22. the battery current is seen to decrease sharply with passage of time.

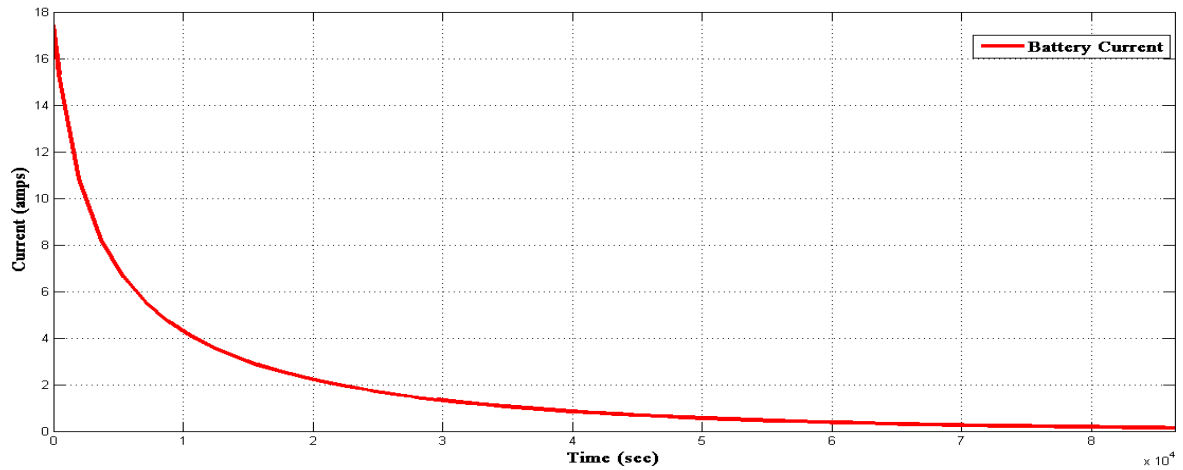


Fig 5.22 Batter Current characteristics

5.3.2.5. Battery voltage characteristics

Here the battery is connected across the dc-dc converter. So the voltage across the battery is equal to the output voltage across the dc-dc converter which is shown in fig 5.23 with passage with time slight increase in battery voltage with time.

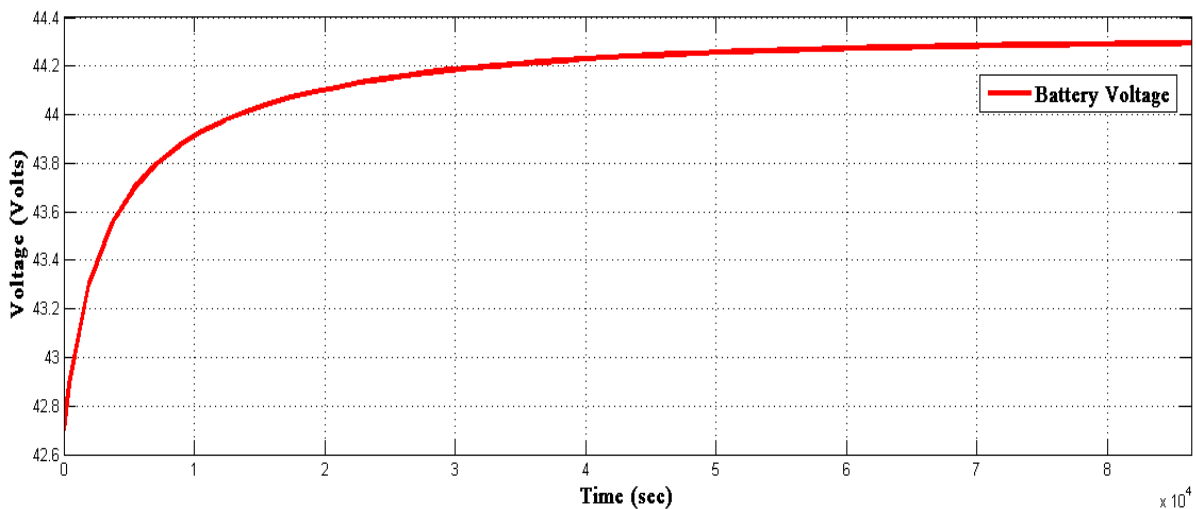


Fig 5.23 Voltage characteristics across battery (Zoomed Y axis response).

5.3.2.6. Characteristics of current through load resistance

Initially it is assumed that the initial charge of the battery is 10%. Due to this assumption it can be seen that at the beginning of the simulation the battery charges. During this period the

magnitude of the output current is 35.58A (approx.). Due to charging of the battery the value of the current increases and becomes 36.92A.

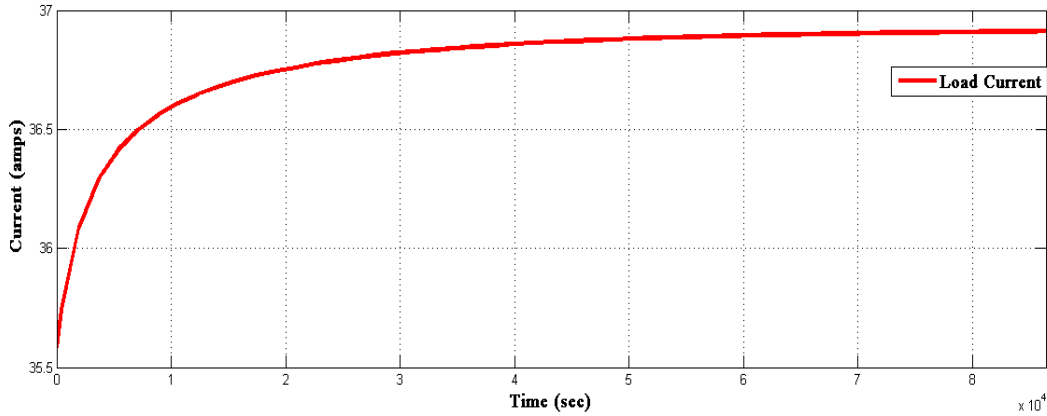


Fig 5.24 Characteristics of current through load resistance (Zoomed Y axis response).

In Test system-II(case-II), the configured system is simulated for 86400 seconds with corresponding value of the parameters. The output quantities voltage, current of the converter, power, battery current and voltage across the battery are given below in tabular form.

Table 13. System Parameter specific value during the simulation with time

Sl. No	Time (sec)	V _{out} (V)	I _{out} (A)	V _{battery} (V)	I _{battery} (A)	I _{load} (A)	Power (W)
1	0	42.69	53.01	42.69	17.43	35.58	1519.28
2	414.92	42.89	51.0	42.89	15.33	35.74	1533.13
3	1938.52	43.30	46.92	43.30	10.83	36.08	1562.95
4	3666.52	43.54	44.50	43.54	8.216	36.29	1580.44
5	5394.52	43.69	43.03	43.69	6.61	36.41	1591.16
6	7122.52	43.79	42.02	43.79	5.52	36.49	1598.54
7	8850.52	43.87	41.27	43.87	4.71	36.56	1603.99
8	10578.52	43.92	40.70	43.92	4.09	36.60	1608.20
9	12306.52	43.97	40.24	43.97	3.59	36.64	1611.56
10	14034.52	44.01	39.86	44.01	3.18	36.67	1614.31
11	15762.52	44.04	39.55	44.04	2.84	36.70	1616.61

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12	17490.52	44.07	39.28	44.07	2.56	36.72	1618.56
13	19218.52	44.0	39.05	44.09	2.31	36.74	1620.23
14	20946.52	44.11	38.86	44.11	2.10	36.76	1621.68
15	22674.52	44.13	38.68	44.13	1.91	36.77	1622.95
16	24402.52	44.14	38.53	44.14	1.74	36.78	1624.07
17	26130.52	44.15	38.40	44.15	1.60	36.79	1625.07
18	27858.52	44.17	38.28	44.17	1.47	36.84	1625.95
19	29586.52	44.18	38.17	44.18	1.35	36.81	1626.75
20	31314.52	44.19	38.07	44.19	1.24	36.82	1627.46
21	33042.52	44.20	37.98	44.20	1.15	36.83	1628.11
22	34770.52	44.20	37.90	44.20	1.06	36.84	1628.70
23	36498.52	44.21	37.83	44.21	0.98	36.84	1629.23
24	38226.52	44.22	37.77	44.22	0.91	36.85	1629.72
25	39954.52	44.22	37.70	44.22	0.85	36.85	1630.17
26	41682.52	44.23	37.65	44.23	0.79	36.86	1630.57
27	43410.52	44.23	37.60	44.23	0.73	36.86	1630.95
28	45138.52	44.24	37.55	44.24	0.68	36.87	1631.29
29	46866.52	44.24	37.51	44.24	0.63	36.87	1631.61
30	48594.52	44.25	37.47	44.25	0.59	36.87	1631.91
31	50322.52	44.25	37.43	44.25	0.55	36.88	1632.18
32	52050.52	44.25	37.40	44.25	0.51	36.88	1632.43
33	53778.52	44.26	37.37	44.26	0.48	36.88	1632.66
34	55506.52	44.26	37.34	44.26	0.45	36.88	1632.88
35	57234.52	44.26	37.31	44.26	0.42	36.89	1633.08
36	58962.52	44.27	37.28	44.27	0.39	36.89	1633.26
37	60690.52	44.27	37.26	44.27	0.37	36.89	1633.44
38	62418.52	44.27	37.24	44.27	0.34	36.89	1633.60
39	64146.52	44.27	37.22	44.27	0.32	36.87	1633.75
40	65874.52	44.27	37.20	44.27	0.30	36.85	1633.89
41	67602.52	44.28	37.18	44.28	0.28	36.90	1634.02
42	69330.52	44.28	37.17	44.28	0.26	36.90	1634.14
43	71058.52	44.28	37.15	44.28	0.25	36.90	1634.26

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44	72786.52	44.28	37.14	44.28	0.23	36.90	1634.36
45	74514.52	44.28	37.12	44.28	0.22	36.90	1634.46
46	76242.52	44.28	37.11	44.28	0.20	36.90	1634.55
47	77970.5	44.28	37.10	44.28	0.19	36.90	1634.64
48	79698.52	44.29	37.09	44.29	0.18	36.90	1634.72
49	81426.52	44.29	37.08	44.29	0.17	36.90	1634.80
50	83154.52	44.29	37.07	44.29	0.16	36.91	1634.87
51	84882.52	44.29	37.06	44.29	0.15	36.91	1634.94
52	86400	44.29	37.05	44.29	0.14	36.91	1634.99

From the above figures and tables, performance of the PV system in terms of various voltage, current and power of the different components of the system during charging and discharging of the battery can be observed and the results are validated through response curves.

Chapter-6

CONCLUSION & FUTURE SCOPE

6.1. Conclusion

In this thesis, with an aim to study a photovoltaic system, PV cells along with PV modules and PV arrays have been developed in a simulation platform provided by Matlab/Simulink. Models are developed on the basis of standard equations available in extensive related literature. Moreover to validate the results obtained, similar models are prepared with existing Matlab toolbox and then the results are studied. From the results obtained and the discussions that followed in the previous chapter, a detailed study has been carried out

This dissertation is divided into two case studies. In the first study, modelling of components of a photovoltaic system, namely solar photovoltaic module and solar photovoltaic array have been carried out. Modelling has been carried out based on mathematical equations which are extensively available in related literature. For this purpose 36 PV cells have been connected in series to obtain one PV module. Next, 6 number of such PV modules have been connected in series to obtain one OV array. Therefore using PV cells, first a module is prepared and using these modules, an array is prepared. Here only the system components are modelled and not the entire system. Therefore the model is devoid of any load and storage element. Now, after this model is completed, it is subjected to three kinds of operating condition variation. These are:

- Constant temperature with irradiation variation
- Constant irradiation with temperature variation.
- Combined irradiation and temperature variation

These three conditions are applied to the developed model and then power, voltages and current responses of the module and the array are observed through Matlab. Results obtained are analysed and desired output is validated.

For the second case study, an entire PV system is modelled including storage element in the form of a battery and a resistive load has been incorporated into the system. The model has been prepared in Matlab/Simulink with the help of Simulink toolboxes already available with Matlab/Simulink Library Browser. In this case study, performance study is carried out by varying the level of initial battery charge. For this purpose, two conditions are considered. First, initial battery charge is taken to be 80% and then for the second case it is assumed to be 10%. Therefore charging and discharging of battery and its effects on the PV system is now

available for study. Responses of Power, Voltage and current have been then studied and analysed thoroughly in order to validate them with practical scenarios.

6.2. Future Work

This model has been prepared with a view to study and analyse a PV system along with a storage element, upon application of a resistive load. A much effective and detailed study can be carried out in this regard, if such a software model can be practically implemented in real hardware. Such a system would then signify and involve all practical problems which are difficult to simulate. Studying a PV system considering such practical anomalies shall be a very challenging job.

Modern day electric power industry involves usage of alternating power in most sectors of the power consumption. Any modern day power generation technique is therefore in dire need of proper interface with alternating current scheme. Hence considering this important practical applicability, introduction of effective, efficient and suitable inverter systems are a must which will ensure proper and reliable use of solar energy with alternating current.

Another very effective and practical work in this regard might involve the introduction of control systems with PV solar generation in order to achieve transition points in battery state of charge while charging and discharging. The use of proportional-integral controllers along with pulse width modulation techniques shall very effectively efficiently and accurately track and determine the transitions points of the battery states while the battery discharges or charges. This will then enable close control, monitoring and subsequent changing of system performance in order to meet and provide desired output.

A populous country has huge need space requirements, whatever might be its land area. As is well known, solar generation requires extensive land area in order to implement a large number of PV cells in series connection. But scarcity of land sometimes result in various kinds of obstacles in the way to solar cells. Physical obstacles such as birds, trees, canopy, undesired vegetation, and most importantly deposits of dust arising out of poor maintenance, along with partial shading and blocking in the path of light to reach the cell for reasons such as cloud cover, sudden storm and other such factors might impart partial blocking of the PV cell surface. This shall result in undesirable system performance due to reduced radiation received by the cell. Therefore specialized algorithms that can take care of such partial shading have become a subject in research study that has gained paramount importance.

Chapter 6: Conclusion and Future Scope

Maximum Power Point Tracking or MPPT algorithms have now been developed in recent research developments which can track the operating point at which, when the PV cell is operated, will provide maximum possible power irrespective of climatic conditions. Implementing such an algorithm in the PV system model would make such a system more appealing in terms of practicality and would pave way for further future research work in the field of solar power generation.

The system modelled in this dissertation possesses a unique feature that shall provide huge practical benefit in terms of socio economic growth for a developing country like India. A country such as ours is in dire need of power generation, but such generation from renewable sources alone shall only add to the carbon emission which we cannot afford. Therefore the use of such a solar PV system in island mode, devoid of any grid connectivity shall provide ample and substantial abilities to be used in small scale and large scale industries for partial or total fulfilment of individual and industrial needs. Therefore bulky power system outreach to rural India which has always been a major problem in our power sector can be avoided as dependency on fossil fuels and our already congested power system can be greatly reduced. Therefore practical 'in the field' application of such a device shall provide rural development along with reduction in industrial energy demand and therefore in the long run, aid the country's continuous attempt to achieve sustainable development

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