T.R.
ERCIYES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF ELECTRICLAL-ELECTRONICS
ENGINEERING

INVESTIGATION OF THE ENERGY EFFICIENCY FACTORS FOR PHOTOVOLTAIC SYSTEMS IN CONCENTRATED SOLAR POWER PLANTS

Prepared By
Ekhlas AZA KHAN

Supervisor
Prof. Dr. Mustafa ALÇI

MSc. Thesis

August 2017
KAYSERİ

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SCIENTIFIC ETHICS SUITABILITY

I declare that all informations in this work were obtained in accordance with academic and ethical rules. All results and material that not been at the essence of this work are also transferred and expressed by giving reference as required by these rules and behavior, I have fully cited and referenced all material and results that are original in this work.

EKHLAS AZA KHAN

SUITABILITY FOR GUIDE

The M.Sc. thesis entitled “Investigation Of The Energy Efficiency Factors For Photovoltaic Systems In Concentrated Solar Power Plants” has been prepared in accordance with Erciyes University School of Natural and Applied Sciences Thesis Preparation and Writing Guide.

Student

EKHLAS AZA KHAN

Supervisor

Prof. Dr. Mustafa ALÇI

Electrical – Electronics Engineering

Prof. Dr. Necmi TAŞPINAR

ACCEPTANCE AND APPROVAL PAGE

This study entitled "Investigation Of The Energy Efficiency Factors For Photovoltaic Systems In Concentrated Solar Power Plants" prepared by Ekhlas Aza Khan under the supervision Prof. Dr. Mustafa ALÇI was accepted by the jury as M.Sc. Thesis in computer engineering.

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JURY:

Supervisior	: Prof. Mustafa ALÇI	
Juror	: Assoc. Prof. Mustafa TURKMEN	
Juror	: Assist. Prof. B. Hakan AKSEBZECI	

APPROVAL

That the acceptance of this thesis has been approved by the decision of the Institute's Board of Directors with the 22/08/2017 date and 2017/36-51 numbered decision.

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Director of the Institute

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Ekhlas AZA KHAN

Kayseri, August 2017

GÜNEŞ ENERJİ SANTRALLERİNDE FOTOVOLTAİK SİSTEMLER İÇİN ENERJİ VERİMLİLİK FAKTÖRLERİNİN İNCELENMESİ

Ekhlas AZA KHAN

Erciyes Üniversitesi, Fen Bilimleri Enstitüsü
Yüksek Lisans Tezi, Ağustos 2017
Danışman: Prof. Dr. Mustafa ALÇI

ÖZET

İnsanlar, yaşadıkları hayatın gelişen uygulamalarında artan ihtiyaçlarını karşılamak için her zaman yeni enerji kaynakları arıyorlar. Birçok enerji kaynağı tükenme, yüksek maliyet ve çevre üzerindeki olumsuz etkileri ile karşı karşıyadır. Modern çağda yenilenebilir enerji ve tükenmez nitelikte olan güneşin enerjisinden yararlanılmaya çalışılmaktadır. Güneş enerjisi, başta enerji santralleri olmak üzere araçlar, uydular ve uzay istasyonları gibi birçok uygulamada elektrik üretmek için kullanılmaktadır.

Güneş panellerinin yaygın kullanımı, güç artışındaki sürekli eğilim, sürekli gelişen türler ve yüksek verim talepleri sonucunda, piyasada voltaj, güç ve akım yoğunluğu açısından pek çok farklı güneş paneli bulunmaktadır.

Güneş panelleri, bazı aletleri çalıştırmak veya şarj edilen ve bir kereden fazla kullanılan pillerde saklamak için kullanılabilecek DC elektriği üretmek için birlikte gruplandırılmış güneş pilleri olup bu hücrelerin gücü ‘Watt’ biriminde ölçülür. Büyük binalar ve fabrikalarda kullanılmak üzere 5 Wat’tan yüzlerce watta ulaşan paneller birbirlerine bağlanarak GW güç elde edilebilir. Kullanım özelliklerine göre bağlantı kurmanın birden fazla yolu vardır:

1. Paralel Bağlantı.

2. Seri Bağlantı.

3. Paralel ve Seri (Karışık) Bağlantı.

Bu tezde, çeşitli çevresel faktörler için, farklı PV bağlantı türlerine ait simülasyon çalışmaları yapılmış ve sunulmuştur. Çıkışta arzu edilen voltaj, akım ve güç değerlerinde oluşabilecek sapmaları minimize etmek için tek tip panel kullanılmıştır.

Simülasyon çalışmalarında 305 wattlık Sun Power firmasına ait SPR-305-WHT paneli kullanılmıştır.

Güneş radyasyonu, sıcaklık ve PV dizisinin bağlantı türü gibi sistem parametrelerine PV dizisinin bağımlılığının belirlenmesi için tek bir panele ait matematiksel analizler kullanılmıştır.

Tezin amacı radyasyon, sıcaklık ve bağlantı türüne göre Maksimum Güç Noktası (MPP)'nin maksimum değerinin elde edilmesidir. Farklı bağlantı durumlarının MPP'sinin elde edilmesi için seçilen panelin simülasyonunda Matlab/Simulink'te modellenen 100 kW'lık güneş istasyonu kullanılmıştır.

Anahtar Kelimeler: Maksimum Güç Noktası, Güneş Panelleri, Radyasyon ve Sıcaklığa bağımlılık

INVESTIGATION OF THE ENERGY EFFICIENCY FACTORS FOR PHOTOVOLTAIC SYSTEMS IN CONCENTRATED SOLAR POWER PLANTS

Ekhlas AZA KHAN
Erciyes University Graduate School of Natural and Applied Sciences
Master Thesis, August 2017
Advisor: Prof. Dr. Mustafa ALÇI

ABSTRACT

People are always looking for new sources of energy to cover their growing needs in the evolving applications of life they live in. Many energy sources are faced the depletion, high cost, and the negative impact of their use on the environment. In modern age, it is searched for utilizing of the heat of the sun which is characterized as renewable energy and inexhaustible. Solar energy has been used to generate electricity in many applications, including power plants, desalination plants, the operation of the satellites, vehicles and space stations.

As a result of the widespread use of solar panels, the constant tendency to increase power, the constant development in the type and high efficient demands, there are now many solar panels on the market.

Solar panels are solar cells grouped together to produce DC electricity that can be used to operate some equipment or store it in batteries that are recharged and used more than once, the power of these cells is measured in Watt unit. There are many types of solar panels starting from 5 W to hundreds of Watts could be connected together to obtain GW for using in factories and large buildings. It has more than one way to connect according to the nature of use:

1. Connect in parallel.

2. Connect in series.

3. Parallel and series connecting.

In this thesis, different types of PV connections are simulated and presented for various environmental factors. In the simulation study, SPR-305-WHT 305 Watt panels, which are produced by Sun Power, are just used. In order to minimize the error in output voltage, current and power values, only one type of panel is used. Mathematical analysis of one panel used due to define the PV arrays dependency to the system parameters such as solar irradiation, temperature and the connection type of the PV array.

The goal is to obtain the maximum power point (MPP) according to the connection type, temperature and irradiation. A 100 kW solar plant which is implemented by MATLAB/Simulink is used to simulate the chosen panel to obtain the MPP of the different connection cases.

Key Words: Maximum Power Point, Solar Panels, Dependency of Temperature and Irradiation

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NOMENCLATURE

Symbole	Maning	The Unite
AC	Alternative current	(A)
AM	Air mass	--
Bell Labs	Bell Laboratory	--
CdS	Cadmium sulfide	--
CPV	Concentrator Photovoltaic System	--
CPVT	Concentrated Photovoltaics and Thermal	--
CSP	Concentrated Solar Power	--
CuS	Copper sulphide	--
DC	Direct Current	(A)
DIY	Do It Yourself Technology	--
DNI	Direct Normal Irradiance	--
E	Energy of a Photon	(Joule)
Ego	The Semiconductor Band Gap Energy	(eV)
FSES	Florida Solar Energy Center	--
G	Intensity of Solar Irradiation	(W/m^2)
Ga	Germanium	--
GaAs	Gallium Arsenide	--
GW	Gigawatt	--
h	Planck’s Constant	(Hz)
HCPV	High Concentration Photovoltaic	--
Irs	Module Reverse Saturation Current	(A)
Isc	Short Circuit Current	(A)
k	Boltzmann’s constant	(J/K)
kW	Kilowatt	(kW)
LCPV	Low Concentration Photovoltaic	--
MJ	Multijunction	--
MJSCs	Multijunction solar cells	--
MPP	Maximum Power Point	--
MPPT	Maximum Power Point Tracking	--
NASA	National Aeronautics and Space Administration	--

nm	nanometer	--
NREL	National Renewable Energy Laboratory	--
Ns	Number of Series Cells	--
P	Phosphorus	--
PV	Photovoltaic	--
q	Electron Charge	(C)
Rs	Series Resistance	(Ω)
Rsh:	Shunt Resistance	(Ω)
Se	Selenium	--
Si	Silicon	--
STC	Standard Test Condition	--
T	Temperature	(0 K)
T	Cell Temperature	(^{0}C)
TWh	Tera Watt Hours	(TWh)
v	Frequency of the Light	
Voc	Open Circuit Voltage	(V)
W	Watt	(W)

INTRODUCTION

Humanity has relied on fossil fuels for decades, including the ease of transport and storage, but it has caused severe climate changes to the planet. The composition of fossil fuels depends on the carbon cycle in nature, it is extracted from fossil materials such as coal, black coal, natural gas and petroleum. The industrial revolution of the 18th and 19th centuries was coincided with the use of fossil energy in the technical field, especially the coal. Later, crude oil plays a bigger role in meeting energy needs because of its ease of extraction, processing and transportation; making it less expensive. One of the disadvantages of using fossil energy is the burning of fossil fuels, which is considered an air pollution factor causing global warming.

The use of renewable energy sources has increased in recent years significantly, whether that energy derived from "renewable" natural resources or the energy that is not exhausted "sustainable energy". Such as the use of wind and hydroelectric power from floodwaters through dams, tidal energy, wind energy, wind power, geothermal energy, solar power and nuclear fuel, as it was the reduction of fossil fuels, such as coal, oil and natural gas that brought these resources to the fore. Over time, developing countries have also started to look at renewable energy sources.

Solar energy, has relatively small technology compared with other energy sources and providing an environmental safety factor. As solar energy is a clean energy that does not pollute the atmosphere and leave the waste, which earns a special situation in this field, especially in the next century. Solar energy can be converted into electrical energy and thermal energy through the two photovoltaic conversion and solar thermal conversion. Photovoltaic conversion is intended to convert solar or optical radiation directly into electrical energy by means of solar cells PV (photovoltaics). This phenomenon was discovered by some physicists in the late nineteenth century where they had found that light can free electrons from some metals. Thus, many concerns about the materials that could be utilize in this technology started. As it known, there are some materials that conduct the photoelectric conversion process, such as silicon, germanium, and others. Whereas, the increase and improvement of the power that is produced from the solar panel which is the goal of all inventions and innovations. This thesis is one of the concerns and methods that focus on the power produced from the solar panels. Certainly the first thing we need is a solar panel for testing and simulation. Recently, solar panel companies have grown in various specifications, so there are lots of choices. This model was tested and simulated according to MATLAB program, which was a successful and quick tool in extracting the results.

CHAPTER 1

BACKGROUND

1.1. Literature Review

Despite the many energies used in the present age, the sun remains the main source of energy in the environment without which the wind does not move and the cycle of water is not the source of fossil fuels (oil, gas and coal). whereas the average power intercepted at any time by the surface of the earth is about (25.4×1015) Watts, and over the whole year the total solar energy will be (222.504.000 Tera Watt hours (TWh) [1].

Actually solar cells history back to the 18th century as it was the first discovery of photovoltaic phenomenon. The ability of light to generate electricity was in 1839 AD by the French physicist Alexandre-Edmond Becquerel, in his experiments he observed that "if an electrode is exposed to light when it is immersed in a conductive solution, it produces an electric current".

In 1905, Albert Einstein understood that this effect can be explained by assuming that the light consists of well-defined energy quanta, called photons. The energy of such a photon is given by $E = h \times v$, where h is Planck's constant and v is the frequency of the light [2]. For his explanation of the photoelectric effect Einstein received the Nobel Prize in Physics in 1921 [3].

Then, in 1941, the American inventor (Russell Ohl), who accidentally found that silicon could be made to be very sensitive to light. This lead to produce the first solar cell made of silicon with 6% efficiency in the mid-1950s [4]. Attention to this phenomenon develops until the early fifties when the development of high-strength segments of silicon have been placed in certain shapes and geometric dimensions and able to conversion of sunlight into electrical energy efficiently converted good but the cost was very high. These cells are an ideal source of electricity production because they do not cause environmental damage and do not produce toxic chemical residues and gases. Research on their development and exploitation has been supported extensively in various fields and around the world.

The first use of silicon solar panels in telecommunications in remote areas was then used to supply satellites with electricity, where the sun supplied satellites with electric power.

In 1954 The Birth of Photovoltaics, David Chapin, Calvin Fuller and Gerald Pearson of Bell Labs were credited with the world's first photovoltaic cell [5], whereas throughout the 1960s solar cell was used to provide electrical power for earth-orbiting satellites [6].

The 1960s had witnessed another important period of interest in solar energy as an alternative source of energy and in the second half of the 1970s when the Arabs prevented oil exports to the West. Many countries had begun to pay great attention to solar energy and its use. This period has resulted in the diffusion and development of solar technology.

In 1976, the NASA's Lewis Research Center had began installing 83 solar systems on all continents except Australia, these systems provide energy for a number of applications such as vaccine cooling in health centers, room lighting, medical clinic lighting, water pumping, television operation and providing classrooms with the necessary energy.

In 1980, ARCO company had achieved a commercial race where it became the first company to produce more than one megawatt power of solar cells per year. In the same year, the University of Delaware had produced 10% solar cell chips which are of made of Copper sulphide (CuxS) and Cadmium sulphide (CdS) .

In 1981, Paul Mac Cready had a solar-powered aircraft. The following year California witnessed the first solar power plant with one megawatt of capacity. The same year, the world saw the first solar cell car in Australia, and the US Department of Energy in the same year had launched a number of solar projects with a number of companies.

First Solar Parks constructed in Hesperia, California 1982, had generated 1,000 kilowatts (Kw) per hour, while it was operating at full capacity [7]. Followed by the second one in 1983, was containing 100,000 PV arrays that generated 5.2 megawatts at full capacity [8].

In 1982, Volkswagen of Germany had used solar cells on vehicle surfaces to feed the ignition system. In the same year, the Florida Solar Energy Center (FSES), with the support of the US State Department had promoted the use of solar energy in engineering journals, in that year, global production of solar energy was exceeded 9.3 megawatts.

Solar cell technology kept on using and developing. Next year ARCO had built a 6 megawatt power plant in central California.

1994 – 1999 , the National Renewable Energy Laboratory (NREL) had developed a new solar cell from gallium indium phosphide and gallium arsenide that exceeded 30% conversion efficiency. By the end of the century, the laboratory had created thin-film solar cells that converted 32% of the sunlight it was collected into usable energy [9]. Thus, by the year 2000 construction of solar panels at the largest photovoltaic manufacturing plant had reached an estimated capacity of producing 100 megawatts a year [10].

In 2005 Do It Yourself (DIY) solar panels started, the method of building, modifying, or repairing things without the direct aid of experts or professionals, probably rquired a little more specific information [11], which had started hitting the market in 2005 and becomes more prevalent with each new year [9].

In 2015 Solar cells as thin as paper which required only an industrial printer to be manufactured and were inexpensive to produce, had developed rapidly as shown in Figure 1.1, rising from 3% efficiency to 20 percent in just a few years. A 10×10 cm solar cell film is enough to generate as much as 10-50 watts per square meter [9, 12].

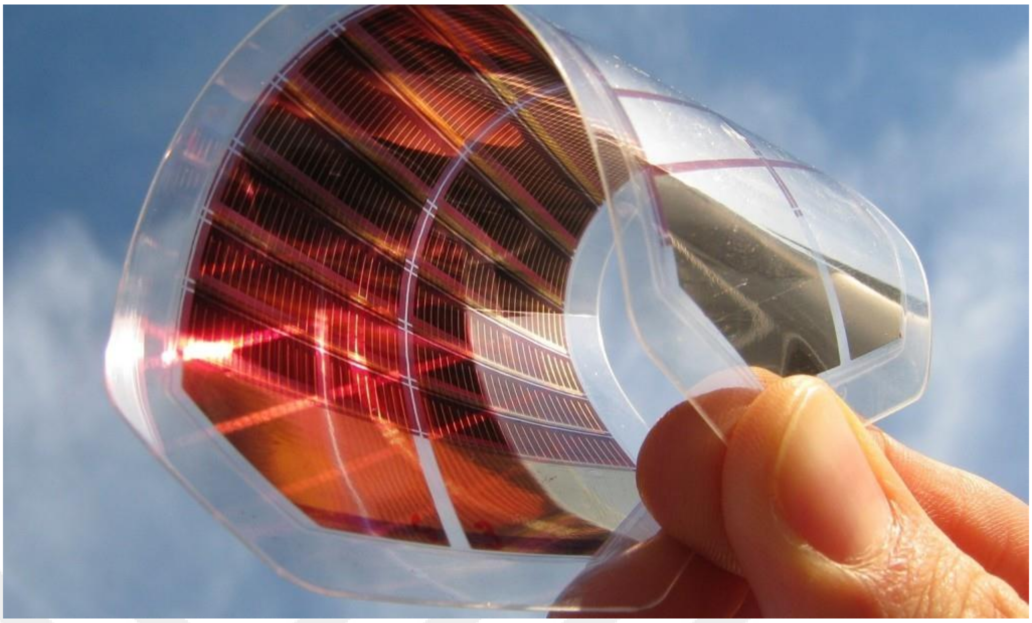

Figure 1.1. Paper-thin printed solar cells

After that time so far solar cells have evolved and the various systems in which they are used are virtually innumerable, where evolution has become at the level of simple parts of efficiency, we had to know the history of the development of this technology and the use of solar energy, to know how much effort has been made in order for this technology inorder to reach to us with the images that we observe in many areas today.

1.2. Purpose of The Thesis

In this thesis we had used an identifier panel data sheet that is the SunPower SPR-305-WHT to simulate and obtain the P-V, I-V characteristics under elected weather conditions (temperature and radiation). Thus the maximum power point of a 72 solar panel which is connected in different methods must be calculated to do the appropriate elect according to its power. For this purpose we used a 100 kW solar plant, which was implemented by MATLAB program.

The thesis is organized as follows: In Chapter 2 we have described in details the standard model and the physical structure of solar cells, solar power technologies and application, theoretical model that is implemented in the simulator and the numerical methods which are used for the solution of the power. In Chapter 3 there is a detail about the types of photovoltaic solar panels, their characteristic curves produced. Solar cell plant simulated by MATLAB, the results of the simulation are discussed. In the final Chapter, i.e. Chapter 4 the summary and future work haven been stated.

CHAPTER 2

SOLAR CELL TECHNOLOGIES

2.1. Introduction

It is obvious that our conventional and best source of energy will be depleted after 100 years at the most. Furthermore, when we look at photovoltaic solar cell technology which is one of the sources of alternative energy, it provides the most solar energy in the world. The use of the this energy has two benefits: first, to make the use of oil energy long and second to develop another source of energy alongside the current sources.

In order to make this technology play a major and competitive role in the energy production market, it must provide abundant and affordable electricity compared to conventional power sources, many uses of solar energy have emerged since the middle of the last century and continues to evolve ceaselessly. This coincided with the steps of the evolution of the solar cells which began with the material from which the solar cells were made of, but most of these materials are rare in nature.

Cadmium Telluride (CdTe) is the first chip used in photovoltaic technology, designed to absorb a large amount of sunlight and convert it into a current, best cell efficiency has plateaued at 16.5% since 2001 (a record held by NREL) [13].

Another type of cells are the Amorphous silicon (a-Si or a-Si:H), these cells are silicone-shaped, where their crystalline configuration is cracked due to the presence of a hydrogen element or other elements intentionally doped to acquire the electrical characteristic. The ranges efficiency of these cells are from 4-9% for large surface area [14].

There is however also another types of solar cells use other types of materials, but due to the possibility of changing its electrical properties by adding some impurities to its pure crystals, silicon still the most widespread. This technologies continued until it is still not known how far this technology will reach.

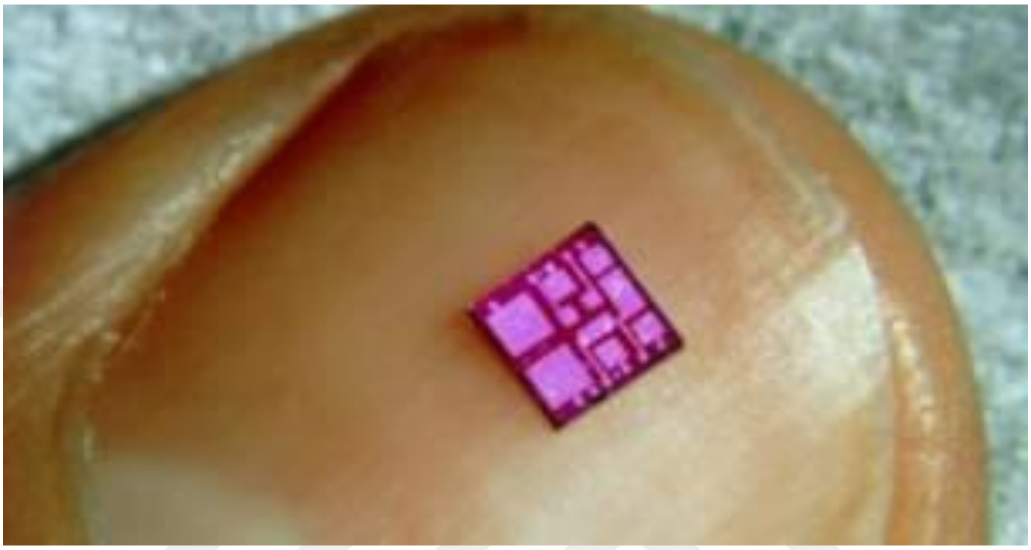

Figure 2.1. Electronic slides made of purified silicon

2.2. The Solar Cell as a PV Cell

Silicon has some chemical properties in its crystalline structure. The silicon atom contains 14 electrons distributed over three energy levels [15]. The first and second energy levels or the closest to the nucleus which are completely filled with electrons, the third or outer level contains only 4 electrons, which means half of which is full and half is empty, whereas the orbit is completed with 8 electrons. The silicon atom seeks to complement the shortage of electrons at the outer level. To do this, they share four electrons of nearby silicon atoms. Thus, silicon atoms are connected to each other in a crystalline form, this crystalline structure has great utility in the solar cell.

Pure silicon crystallization does not deliver power efficiently, because there are no free electrons to transfer the electricity, whereas all electrons have been restricted in crystalline structure. So, in order to use silicon in solar cells, we need to make a simple adjustment to the crystalline structure. This simple modification is the addition of atoms of other elements by” doping”, these extra atoms named as impurities. Phosphorus (P) atoms are added at a very simple rate of up to 1:1.000.000, and the phosphorus atom contains 5 electrons in its outer orbit. Therefore, when the crystalline network enters silicon atoms, it will participate with 4 electrons and remain a free electron.

When pure silicon is supplied with energy and has thermal energy, for example, some electrons are released and left a" hole", this hole allows the electron in the neighborhood to move to it leaving another hole. Thus, the movement of electrons continues in the direction and movement of the hole in the opposite direction, this movement is called the electric current. Semiconductors that vaccinate by atoms containing additional electrons are called " N-type", another type of vaccination where cells provide seeds with fewer electrons, the substances resulting from this vaccination are called "P-type". In fact, the solar cell contains both types.

2.3. Factors Affecting the Solar Cell Efficiencies

Solar energy is closely related to the environment, which certainly means that the efficiency of these cells affected by the environmental factors like temperature, irradiation, dust, etc. Certainly, the are effect of these factors relatively variable, e.g. As we will explain below:

2.3.1. Solar Irradiation

the solar irradiation amount that reaches the surface of the earth vary due to the weather changing, and the variable location of the earth related to the sun during the day and over the year. Clouds are one of the major weather factors which decides the amount of solar irradiation that reaches to the earth. Therefore, areas with cloudy climate receive fewer solar irradiation compared with its counterpart desert atmosphere. Generally, the largest amount of the solar irradiation is received by the Earth is at noon, when sunlight is vertical on the surface of the earth.

The set of irradiations that hit the optical cell surface in the horizontal position or a certain area on the surface of the earth consists of three parts; direct beam radiation, diffuse irradiation; forms the great majority during the cloudy days, which is almost zero, and finally the albedo irradiation; which is a irradiation that is reflected by various media around the cell. On the other hands humidity affects solar cells in one way or another.

2.3.2. Temperature

Most of us may think that the higher the temperature of solar cells are the greater the electric current will be, but this is a mistake. Where a high temperature or a large drop will negatively affect the amount of electricity that can be drawn from solar cells. Whereas, high temperature may negatively affect solar cell output from 10% to 25% [16]. This is due to materials that make semiconductors, such as Silicon (Si) and Germanium (Ga), which are affected by heat. Gallium Arsenide (GaAs) cells are the best solar cells operating at high temperatures (50-80) ^{0}C, but because of their high cost are not favorite cells for the manufacturers and the decision makers .

The best temperature of the solar cell is 25 ^{0}C under 1 kW/m^2 [17]. We would also like to mention again that the electricity is generated by the solar cell through the virtue of the light falling on the solar cell and not heat. Heat plays a minor factor and affects the current that can be extracted from the solar cell. The solar cell is a photovoltaic cell.

2.3.3. Solar Cell Materials

The type of material from which the solar cell is made is an important factor affecting the effectiveness of these cells. The type of material is not often taken into consideration, this is because most common cell types are made of silicon, and is still the favorite of many companies working in this field [18].

2.3.4. Reflection

Vaporized water molecules can reduce the levels of sunlight, which is a requirement for solar cells to give the best possible performance, if the surfaces of the solar cells are wet, it is possible that the irradiation coming to it when it hits the water drops is scattered in all directions, either by reflection, refraction or diffraction. Studies have shown us that the higher the temperature or humidity are, the lower the efficiency of solar cells will be. After the analyzing of the total solar, we can increase the irradiation amounts which fall on the cell that is illustrated previously, by installing the photovoltaic cells at a precisely selected tilt angle to achieve the maximum received energy, as will be explained later in chapter three. So the researchers set up the sun tracking system directs the cell always to a place with a high concentration of radiation.

2.3.5. Dust

Solar panels are exposed to the dust. Therefore, these panels should be cleaned regularly and maintained for their continued purity. The tests have shown that exposure the solar cells to dust for six months without any cleaning leads to a reduction in energy that is produced by 2% until 50% in different area [19]. That is due to the accumulation of dust on them, noting that there are many dust accumulation reasons as illustrated in Figure 2.2 below. Where, we can observe that for both the environment and location different factors cause different types of dust accumulation.

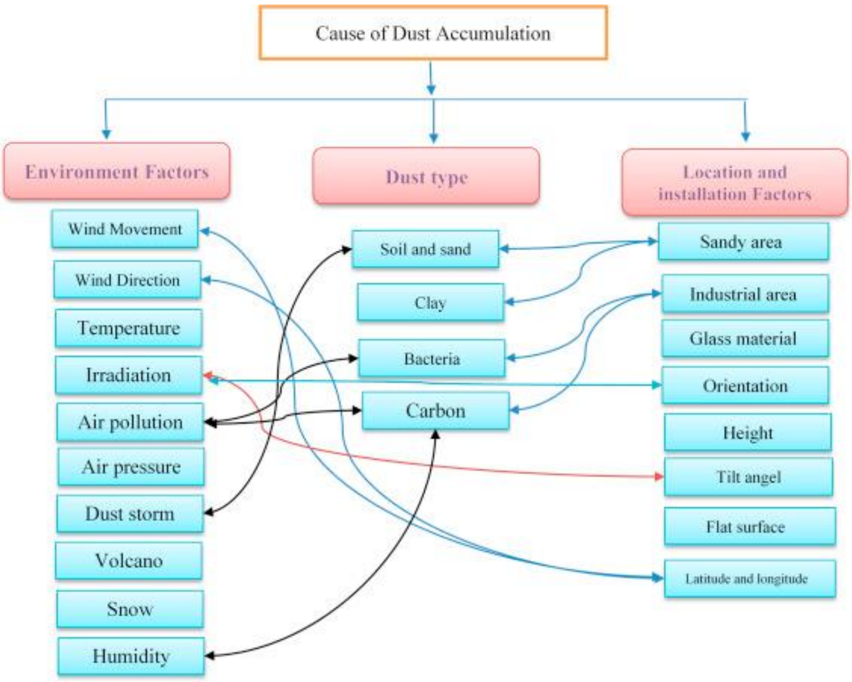

Figure 2.2. Cause of dust accumulating on the surface of solar arrays [19].

Solutions can be applied to overcome the impact of dust on solar cells:

1. Cool and ventilate solar cells or place cool water tanks down to cool them.

2. Prevent sand crawling and overcome soil fragmentation, which causes dust volatilize easily whenever wind blows.

3. Installation of wind breakers and walls that reduce wind speed, stabilize soil and reduce dust arrival.

4. Cover soil with natural materials such as gravel, granite and marble.

5. Identification of areas of solar cell plant as natural reserves that are not entered by vehicles which cause soil volatilization and dust.

2.3.6. Power Inverter

The inverters are important when using solar cells to generate high variable electricity that can operate large electrical and electronic devices in homes or factories. Here we use this equipment, which converts the DC, whether 12 volts, 24 volts or any other value to a high AC of (110 V AC or 220 V AC) in order to operate the devices that are operated on the variable current and heavy equipment. So the losses will be in accordance with its performance.

2.3.7. Spectrum

The parameters of solar cell output change when the spectrum falls on the cell changing at constant irradiation and temperature; where the short circuit current changes with the signal length. The spectral response is low at the wavelength of 452 nm, because the short wavelengths are absorbed very soon from the surface, re-unification of electron pairs - a gap at the surface is more clear, causing light attenuation. While the spectral response increases at the wavelength of 509 nm (green), the highest response is at the highest wavelength length of 587 nm (yellow) .Other proposed wavelengths of (614,656 nm) (orange and red), Photons are deeply absorbed in the crystal and far from the junction [20, 21].

2.3.8. DC and AC Wiring

The AC and DC losses are the cable resistance which is lost through their path throughout the whole PV plant.

2.3.9. Mismatching

This type of loss occurs due to the PV inequality of one production line in a factory which causes the production modules to compromise on common voltage and current when they are connected in series or parallel in an array [19].

Figure 2.3 below illustrates the factors affecting the efficiency of the solar cell, and the percentage of their impact, it can be observed that the temperature and the shading dominant to other factors.

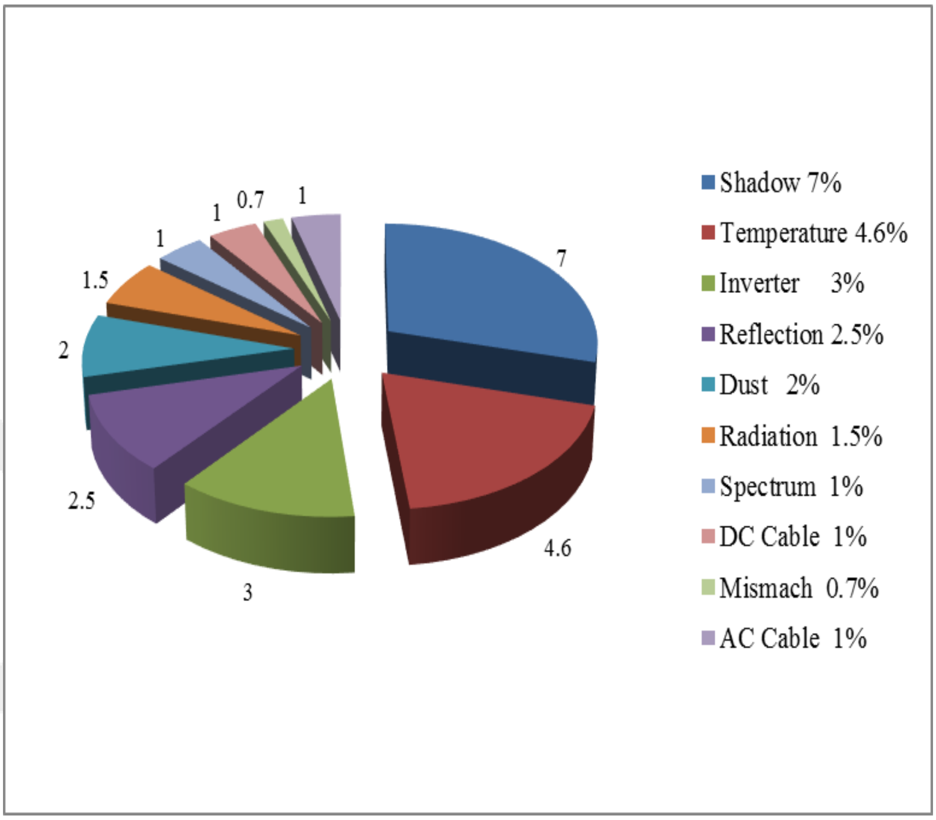

Figure 2.3. Factors affecting the solar cell efficiencies

2.4. Solar Cell Maximum Power

Power is the most commonly used parameter to compare the performance of a photovoltaic cell with another, it is the proportion of output energy from the cell to the energy of the sun's input. Although the power reflects the cell's own performance, it varies according to the spectrum and intensity of the incoming solar radiation as well as the temperature of the cell. Therefore, it is measured in the standard test conditions (STC) [22].

- The intensity of solar radiation G=1000 W/m^2.
- Cell temperature T=25 ^{0}C.
- Air mass: AM = 1.5.

Raising the value of solar cell output to a highest value is desirable in order to raise the yield of solar cells to a higher value. From the equation P=V×I we can obtain the solar cell power, and then its maximum; which will be later the basic of the panel power, the power equation parameters obtained at the situations of no current through the cell I=0 than $V=V_{oc}$; that what will represent the solar cell maximum voltage and name the open circuit voltage, and at V=0, than $I=I_{sc}$ the short circuit current, as illustrated in Figure 2.4. It is obvious that clearly seen that this figure has a maximum point that represents the operation point and it is called the maximum power point or the operating point for given irradiation and temperature. Thus, the importance of the MPP lies in finding the efficiency of the cell, which is defined at the mentioned point and is:

$$\eta = \frac{P_{out-max}}{P_{in}} \qquad (2.1)$$

where:

The input power for efficiency calculations is 1 kW/m^2 or 100 mW/cm^2 [17].

$P_{out-max} = I_{sh} \times V_{OC} \times FF$

The fill factor (*FF*) is also another important parameter that defines the solar cell performance, which is the measured area of the square of the *I-V* curve and is defined as:

$$FF = \frac{V_{OC} - \ln(V_{OC} + 0.72)}{V_{OC} + 1} \qquad (2.2)$$

So it's clear that the performance of a solar cell depends strongly on V_{oc}, and V_{oc} is also related to I_{sc} as described in this formula:

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_l}{I_D} + 1\right) \qquad (2.3)$$

Where I_l is the light that generates the current (which is equal to I_{sc} for most cases), and I_D is the dark current of the diode. Isc depends on several factors, such as the area of the solar cell, incident light intensity and optical properties of the cell.

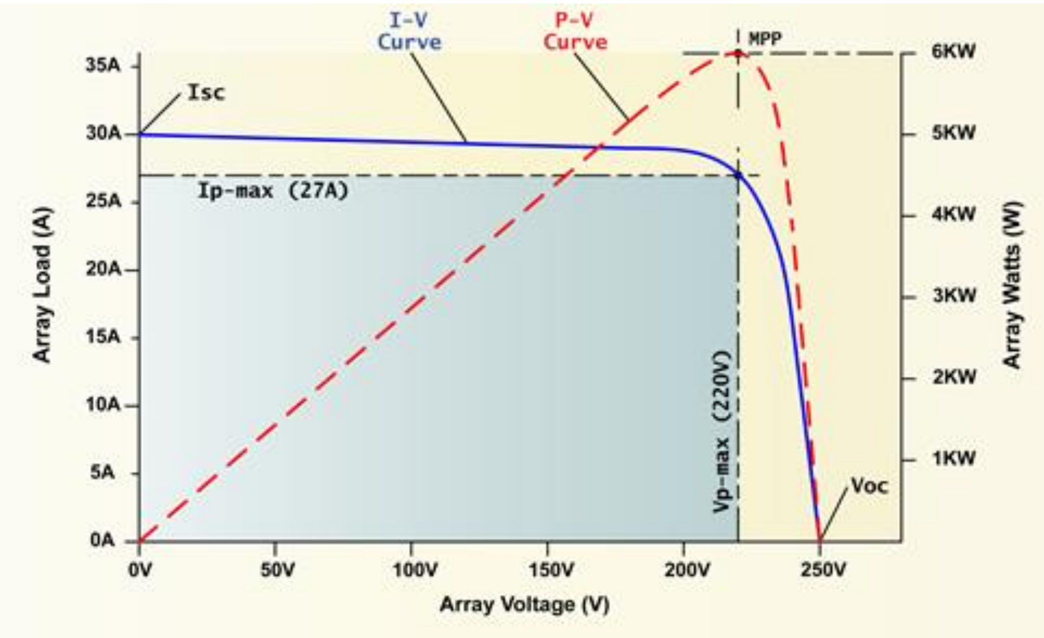

Figure 2.4. Maximum power for an I-V, P-V solar cell characteristic curves [23]

2.5. PV Tracking System

We know that the sun is not constant throughout the day in a certain direction but moves from the beginning of the day to the end. This shows the importance of solar tracking and tracking systems. PV tracking system is a system which is installed on a moving frame; it tracks the movement of the sun from east to west. Thus, collecting as much solar energy as possible to maximize the performance of the solar system. Some solar tracking systems can change their angle depending on time of year [24]. In order to make sure that the solar system is vertically exposed to sunlight in its daily path. Solar tracking systems can produce up to 40% more energy than standard installed systems [25].

The maximum power point tracking (MPPT) devices have two functions:

I. Try to run the cells at the highest point in the curve.

II. Try to track solar radiation throughout the day mechanically.

There are three different types of PV tracking systems:

1. Installed cells without any mechanical tracking are called Fixed Flat panels solar cells. This method is used for standard homes, they are also used by some countries, where the tilt angle of the sun is determined in this country or region and then cells are installed. So that they can be exposed to the maximum possible irradiation throughout the day without any mechanical movement and rely on electrical tracking only. The advantages of this method is, its simple and easy to be installed and there are no moving parts, but they have significant disadvantages and their efficiency is not high. One of the fundamental disadvantages is that it requires a large amount of land; especially in cases of extracting a quantity of energy, which means increasing the space to stabilize the cells. It also shows what is known as the effect of the shadow, because the exposure of a small part of one cell, even by 10% of the shadow may lead to a low efficiency by more than a half. Especially if all cells are bound to a single controller.

Figure 2.5. Fixed Flat panels solar cells

2. Mechanical tracking in one axis is called Single axis tracking, in which the slop of the cells is adjusted at a tilt angle similar to the maximum sun radiation in that region, but it is different from the previous one; in that the cells that move in one direction are followed by the sun often from the east to the west. It is advantageous that it increases efficiency as it reduces the area of land that is used because it is not installed on the ground, but one of its main drawbacks is that the angle of the sun's tilt on the earth

gradually changes over time; this significant change is appeared clearly throughout the changeable seasons. Therefore, the system must be monitored, and the change of the angle throughout the changeable seasons. Experiments have shown that the increase in system efficiency is not fitted with the cost that is paid in system work.

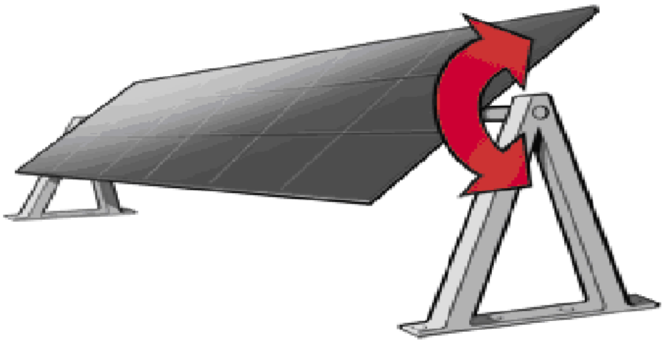

Figure 2.6. Single axis tracking

3. Mechanical tracking in two directions is called Double axis tracking, it is efficient more than the previous systems in that the tracker is moving in both directions from east to west. In addition to a second direction, which is the direction of the tendency of the sun in that region. Thus, avoiding the problem of changing the tendency of the sun in order to change the various days and seasons.

Figure 2.7. Double axis tracking

Sometimes they provide electric motors run on a DC and feed from the solar cells themselves, as well as timers and controllers. Mechanical and electronic parts may also be added to remove dust from solar cells to ensure higher efficiency.

2.6. Concentrator Photovoltaic System

A typical concentrator photovoltaic (CPV) system will consist of three main parts: the cell, the concentrating optics and the tracking mechanism which are illustrated by Figure 2.8 and 2.9 a range of optical elements and materials are used to achieve the required concentration of solar irradiance, such as domed and flat Fresnel lenses [26, 27], small individual reflectors and large parabolic reflective dishes [28]. In some systems, a homogenizer is installed as a secondary element to ensure that light reaches the solar cell which is evenly distributed spatially. The transmission profile of the material which is used, glass or silicone-on-glass, is particularly an important consideration, as it changes the solar spectrum incident on the cell. Optical aberrations and changes in temperature can often affect the effectiveness of the optics, often by changing the position of the focal point [29, 30].

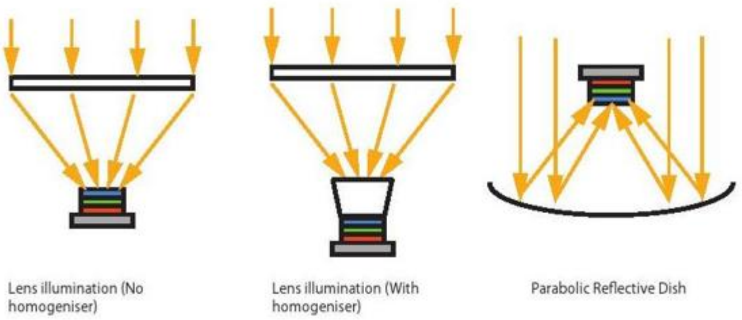

Figure 2.8. Common CPV system optics - lenses with and without homogenisers and parabolic reflective dishes.

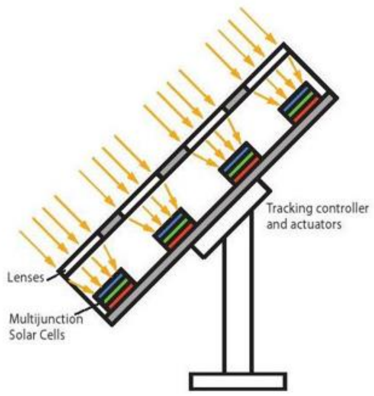

Figure 2.9: Fresnel lens CPV system with tracking controller and actuators, in a pedestal mount.

The maximum achievable concentration ratio is often limited by the heat dissipation is required from the solar cell. Most systems employ passive cooling, commonly heat sinks and fins at the rear of modules to provide a larger surface area for heat to be transferred to the environment. Some types of systems, particularly the parabolic dish optical structures with a central receiver, often required active cooling [31]. In addition, tracking systems with higher precision must be used due to the greater accuracy demands. With greater concentration come smaller devices, where thermal dissipation becomes more challenging. Systems where active cooling is presented are deployed. It is likely that there will be large utility-scale used for heat, such as district heating or hot water and desalination in the future. Tracking mechanisms orientate the module so that the maximum amount of the Direct Normal Irradiance (DNI) is captured. For high concentration ratios, the accuracy requirement becomes much more stringent. An electronic tracker controller supplies information to actuators which allow the movement of the module (cells and optics). A number of 2-axis tracking module designs have been trialled, but most have been opted for a pedestal-based tracking system - a central pole is sunk into a foundation, with the panels mounted onto the support structure and tracking is driven by hydraulic actuators. A pedestal dish system is used by solar systems, where a parabolic dish is mounted on a pedestal and tracks the sun's position, with an array of a multijunction solar cells MJSCs which is placed at the dish's focal point.

2.6.1. Low Concentration

Low concentration (LCPV) are systems with a solar concentration of 2-100 suns [32]. For economic reasons, conventional or modified silicon solar cells are typically used and at these concentrations the heat flux is low enough that the cells do not need to be actively cooled. The laws of optics dictate that a solar collector with a low concentration ratio can have a high acceptance angle and thus in some instances does not require active solar tracking.

From concentrations of 100 to 300 suns, the CPV systems require two-axes solar tracking and cooling (whether passive or active) [33], which makes them more complex.

2.6.2. High Concentration Photovoltaic

High concentration photovoltaic (HCPV) systems employ concentrating optics consist of dish reflectors or Fresnel lenses that concentrate sunlight to intensities of 300 suns or more. The solar cells require high-capacity heat sinks to prevent thermal destruction and to manage temperature related to the performance losses. Multijunction (MJ) solar cells are currently favored over silicon as they are more efficient. The efficiency of both cell types rises with increased the concentration, MJ efficiency also rises faster, and originally designed for non-concentrating space based satellites, than have been re-designed due to the high-current density encountered with CPV (typically 8 A/cm^2 at 500 suns). Though the cost of MJ solar cells is roughly 100 times than that of comparable silicon cells, the cell cost remains a small fraction of the cost of the overall concentrating PV system, so the system economics might still favor the multijunction cells.

2.6.3. Concentrated Photovoltaics and Thermal

Concentrating Photovoltaics and Thermal (CPVT) technology produce both electricity and thermal heat in the same module. Thermal heat that can be employed for hot tap water, heating and heat powered air conditioning (solar cooling), desalination or solar process heat.

2.7. Concentrated Solar Power Generation

Concentrated solar power (CSP) systems are divided into :

2.7.1. Parabolic Trough

A parabolic trough consists of a linear parabolic reflector that concentrates light onto a receiver which is positioned along the reflector's focal line. The receiver is a tube which is direct positioned above the middle of the parabolic mirror and is filled with a working fluid. The reflector follows the sun during the daylight hours by tracking along a single axis. A working fluid (e.g. molten salt) is heated to 150–350 ^{0}C as it flows through the receiver and is then used as a heat source for a power generation system. Trough systems are the most developed CSP technology.

Figure 2.10. Parabolic trough reflector [28]

2.7.2. Linear Fresnel Reflectors

Concentrating Linear Fresnel Reflectors are uses a series of long concentrating solar plants (CSP) [34] which use many thin mirror strips instead of parabolic mirrors to concentrate sunlight onto two tubes with working fluid. This has the advantages of flat mirrors that can be used, which are much cheaper than parabolic mirrors and that more reflectors can be placed in the same amount of space; allowing more of the available sunlight to be used. Concentrating Linear Fresnel reflector can come in large plants or more compact plants.

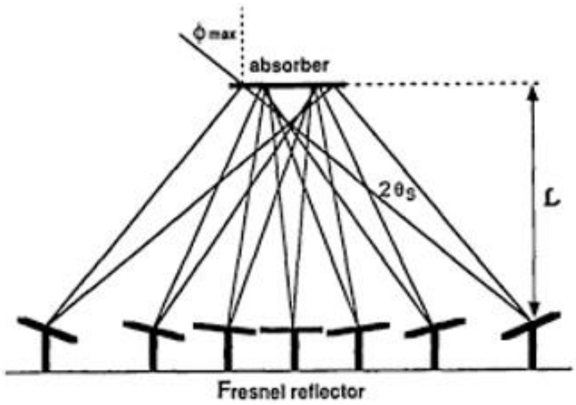

Figure 2.11. Linear Fresnel Reflector

2.7.3. Parabolic Dish Stirling

A Dish Stirling or dish engine system consists of a stand-alone parabolic reflector that concentrates light onto a receiver which is positioned at the reflector's focal point. The reflector tracks the sun along two axes. The working fluid in the receiver is heated to 250–700 ^{0}C (523–973 ^{0}K (482–1,292 ^{0}F) [34] and it is then used by a Stirling engine to generate power [34]. Parabolic dish systems provide the highest solar-to-electric efficiency among CSP technologies, and their modular nature provides scalability. There are two key phenomena that should be understood in order to comprehend the design of a parabolic dish. The first is that the shape of a parabola which is defined such incoming rays that are parallel to the dish axis will be reflected towards the focus, no matter where they might arrive the dish. The second key is the light rays from the sun which arrive to the earth surface are almost completely parallel. So if dish can be aligned with its axis pointing at the sun; almost all of the incoming irradiation will be reflected towards the focal point of the dish, than most losses will be due to the imperfections in the parabolic shape and imperfect reflection. Losses due to atmosphere between the dish and its focal point are minimal. As the dish is generally designed specifically to be small enough that this factor is insignificant on a clear sunny day to compare this with some other designs, we will see that it could be an important factor and if the local weather is hazy or foggy, it may reduce the efficiency of a parabolic dish significantly.

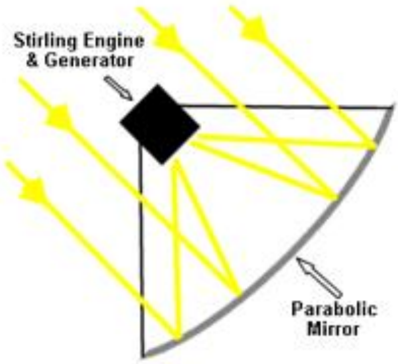

Figure 2.12. Parabolic Dish Stirling

2.7.4. Solar Updraft Tower

A Solar updraft tower consists of a transparent large room (usually completely in glass) which is sloped gently up to a central hollow tower or chimney. The sun heats the air in this greenhouse-type structure which then rises up the chimney, hereby driving an air turbine as it rises. This air turbine hereby creates electricity. Solar chimneys are very simple in design and could therefore be a viable option for projects in the developing world.

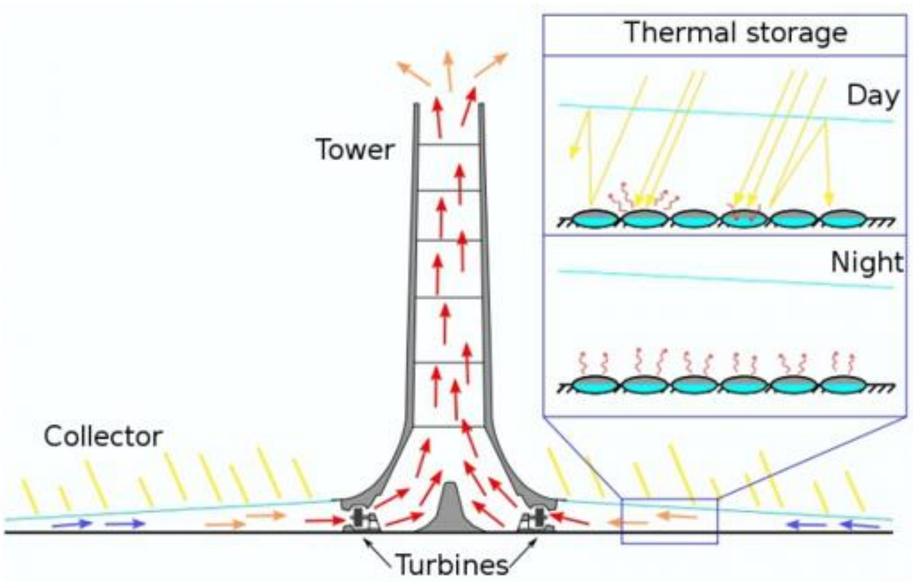

Figure 2.13. Solar updraft tower

2.7.5. Solar Power Tower

A solar power tower consists of an array of dual-axis tracking reflectors (heliostats) that concentrate light on a central receiver atop a tower, the heliostat locations take into account the typical solar radiation at the site [35] ; the receiver contains a fluid deposit which can consist of sea water. The working fluid in the receiver is heated to 500–1000 ^{0}C (773–1,273 ^{0}K (932–1,832 ^{0}F)) and then it is used as a heat source for a power generation or energy storage system. Power tower development is less advanced than trough systems, but they offer higher efficiency and better energy storage capability.

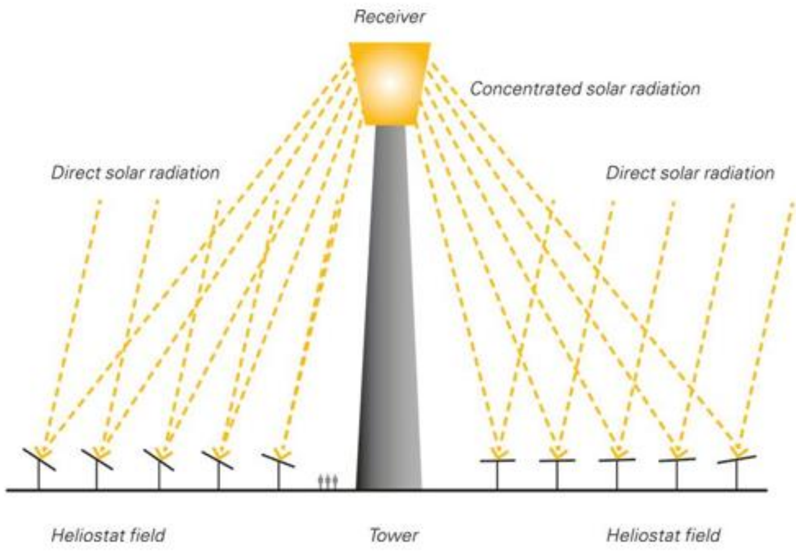

Figure 2.14: Solar power tower

CHAPTER 3

PV ARRAY SIMUATIONS AND RESULTS

3.1. Module or PV Solar Panels

Solar panels to generate electricity or so-called PV solar panels, is a collection of solar cells, connected one to another and connected to each other in series or parallel communication. If a group of solar panels is assembled in a larger frame, in this case we call it a matrix of solar panels, or solar array, as shown in Figure 3.1.

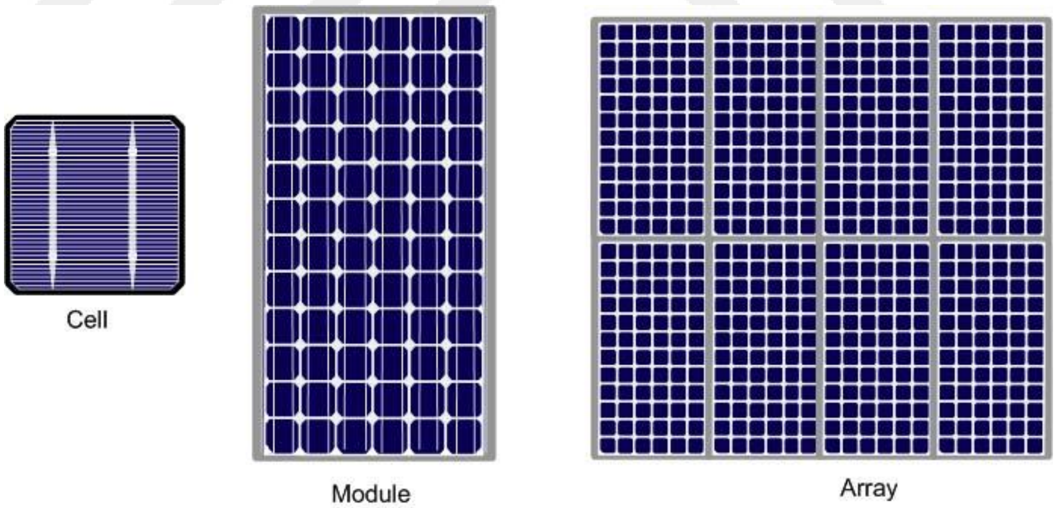

Figure 3.1. Solar cell, module, and array [36]

3.2. Materials of Photovoltaic Panels

When looking for the installation of solar panels to generate electricity, we should know very well that knowing how to choose the type of solar panels, which is something that should be carefully considered. The choice of solar panels more efficient or expensive price is not always the best solution. There are several criteria must be entered into calculations, the cost and the amount of electrical energy needed and space available, as well as geographical location, with the required efficiency at the lowest cost. The technology of solar panels deployed now depends mostly on silicon crystals and this technology had begun about 50 years ago.

Solar panels for generating electricity have three main types namely thin film solar panels, polycrystalline silicon solar panels, and monocrystalline silicon solar panels.

3.2.1. Monocrystalline Silicon Solar Panels

Or so-called single panels, solar panels for generating electricity of this type are the most expensive types in their price since they are made from pure silicon crystals as they give higher efficiency which range from 15-21% [37]. High efficiency makes us need less number of solar panels to cover the same amount of electricity required. It also works more efficiently than others in low light condition.

3.2.2. Polycrystalline Silicon Solar Panels

Or so-called polycrystalline solar panels, characterized by a lower price compared to single solar panels, their efficiency ranges between 13-17% [37]. It is clear that reducing the efficiency of the monocrystalline counterpart makes us need more space to get the same amount of electricity. It has also a defect that does not matter to many, but sometimes it takes into account that its appearance is not aesthetic, as in the case of the beautiful smooth blue appearance of the monocrystalline solar panels.

3.2.3. Thin Film Solar Panels

Thin film solar panels takes the shape of the surface that is installed on it and has several types depending on the type of alloy made. Most of the developments and researches are going on this type precisely, because it is easier in manufacturing as well as because of its weight, smoothness, and cheapness. In the case of large quantities, the cost is very low and is not significantly affected by climate change and clouds. But its disadvantages are that it is the least efficient type and its efficiency may not exceed 7-13% [37], this require more space to meet the electricity needs and this makes them ineffective in the case of limited spaces, especially for residential uses.

3.3. Mathematical Equivalent Model of PV Cell

The solar cell, or photovoltaic cell, is a device that convert light to an electrical current. In 1883, American inventor Charles Fritts had made the first solar cells from Selenium (Se) [38]. In 1931 German engineer, d. Bruno Lang, had developed a photovoltaic cell using silver instead of copper oxide1 [39].

Nowadays a computer program to simulate and design solar cell systems is one of the most important parts of solar cell performance measurement equipment, using physical block of solar cells, and mathematical expression or formulas, solar cell characteristic can be well understood [40,41]. The equivalent circuit of a PV cell is shown in Figure 3.2, including a current source, a diode, a series resistance and a shunt resistance [42].

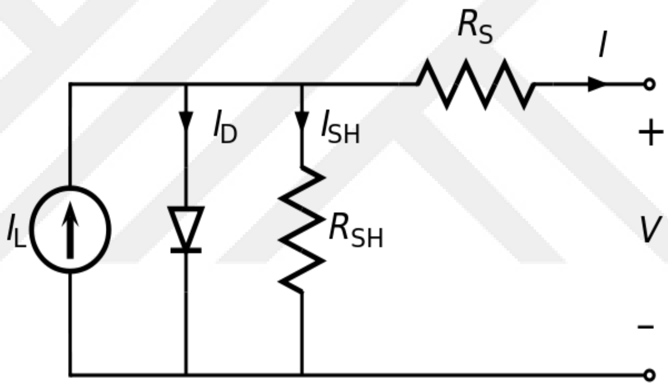

Figure 3.2. The equivalent circuit of a PV cell

I_l (=*Np* I_l,cell) is the photo-generated current in the *PV* module given as:

$$I_l = \left[I_{sc} + \left(K_i \times (T_{aK} - 298)\right)\right] \times \lambda/1000 \qquad (3.1)$$

Where:

I_{sc}: short circuit current.

*K*i: short-circuit current coefficient

T: operating temperature (*K*)

λ: is the PV module illumination *(W/m²)*.

Module reverse saturation current, $I_{rs,}$ this current is given by:

$$I_{rs} = I_{SCr}/[e^{\frac{q\times V_{oc}}{N_S\times K\times A\times T}} - 1] \tag{3.2}$$

Where:

q: electron charge = 1.6×10^{-19} C

V_{oc}: open circuit voltage (V); N_s: number of series cells; K: Boltzmann's constant, = 1.3805 × 10−23 J/K. A is the ideality factor of the diode.

The module saturation current I_0 is given by:

$$I_0 = I_{rs} \times [\frac{T}{T_r}]^3 \exp\left[\left[\frac{q\times E_{g0}}{B\times K}\right] \times \left\{\frac{1}{T_r} - \frac{1}{T}\right\}\right] \tag{3.3}$$

Notably that this current varies with the cell temperature

Here, T_r: nominal temperature = 298 ^0K; E_{g0}: is the semiconductor band gap energy, = 1.1 eV; The current output of PV module will be given by:

$$I_{pv} = N_p \times I_{Ph} - N_P \times I_0 \times \left[\exp\left\{\frac{q\times(V_{pv}+I_{pv}\times R_S)}{N_S\times A\times K\times T}\right\} - 1\right] \tag{3.4}$$

With

$$V_t = \frac{k\times T}{q} \tag{3.5}$$

$$I_{sh} = \frac{(V\times N_p)/((N_S+(I\times R_S))}{R_{sh}} \tag{3.6}$$

Here: N_p: represent the number of PV modules connected in parallel.

R_s: is the series resistance (Ω).

R_{sh}: is the shunt resistance (Ω).

V_t: is the diode thermal voltage (V).

3.4. MATLAB Module and Panel Simulation

Since our goal is to obtain the maximum power point for the module and the panel and then for several panels which are connected in different ways or methods, MATLAB with its high technology has been providing us the possibility to know it for all the previous cases. We used the blocks implementation method, which required the definition of mathematical equations of the PV model that we had explained in section 3.3 above, as shown in Figure 3.3 below.

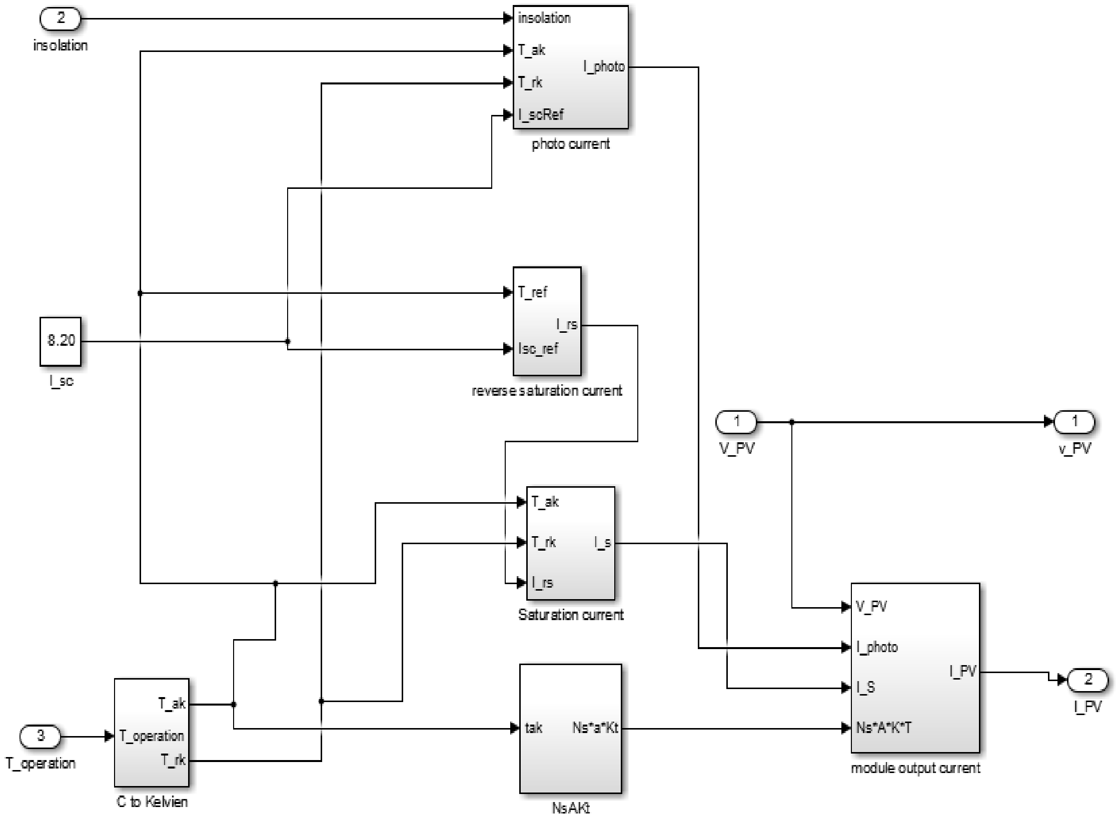

Figure 3.3. PV module Simulink

We have used a 100 kW power plant implemented by MATLAB program as illustrate in Figure 3.4, according to this solar plant and MATLAB technology, to defined the parameters of our chosen module and any number that is connected to it, various methods of connections to simulate and obtain the maximum power points with high accuracy.

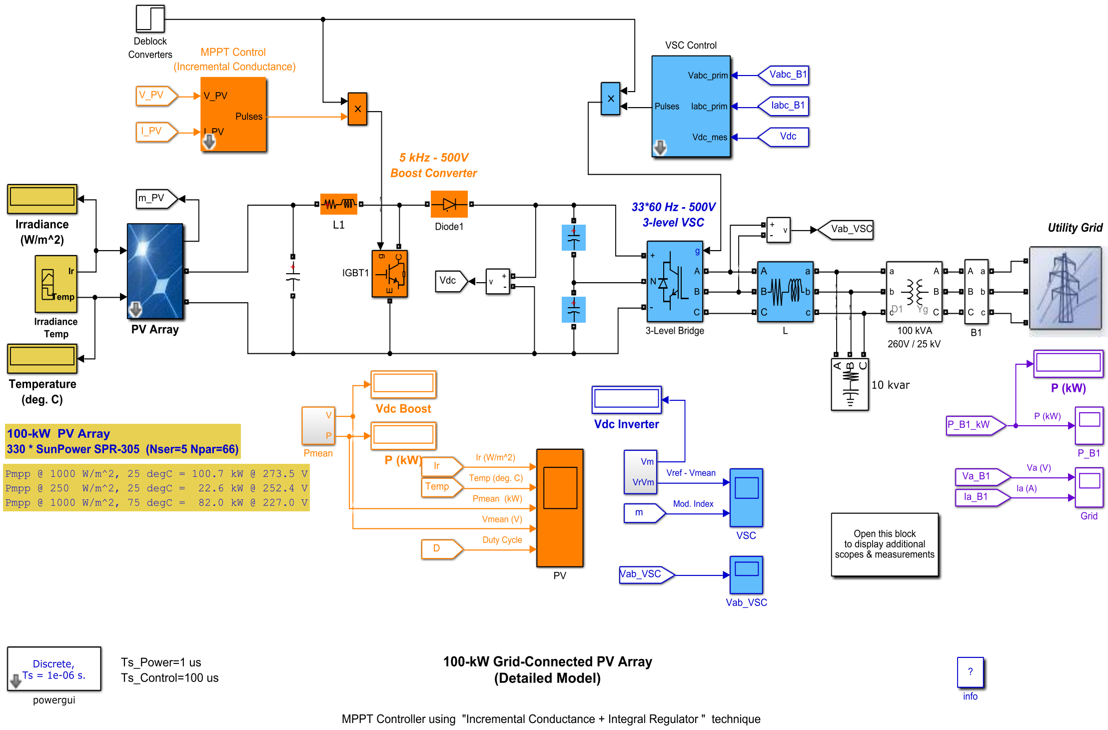

Figure 3.4. 100 kW power plant by MATLAB program

In these blocks we define the needed constant parameters such as the electron charge, Boltzmann's constant, the semiconductor band gap energy, etc. A block is implemented to convert the celsius temperature to kelvin with keeping an output port for kelvin as we will need in our simulation. These blocks represent the base of the solar panel whereas the other parameters such as the Isc and Voc, etc, can be taken from any data sheet for any solar panel from any manufacturer for the purpose of simulation and to obtain the results and compare them with their counterpart in the panel.

3.5. Installation of Solar Panels

Method of installing solar panels is so important and so simple at the same time. In the imagination of many people who are interested in solar energy, the installation of solar panels is complicated and needs specialists. We need to know how to install solar panels on the direction hand (the direction in which angle will direct our solar panels depending on our location.). We have to know that there are other calculations which are the weight of the steel plates and frames that will be need to carry solar panels without any vibration or breakdown.

3.5.1. Select the Direction and Angle of the Solar Panels

The path of the sun that is compared to a fixed point in the earth varies from month to month. However, it is clear that the sun rises from the east and sets from the west. The circle which is the path of the sun is vertical on the equator, which means a person in an area on the equator will see that this path of the sun is a vertical area on the horizontal ground that is on it as in Figure 3.5 .

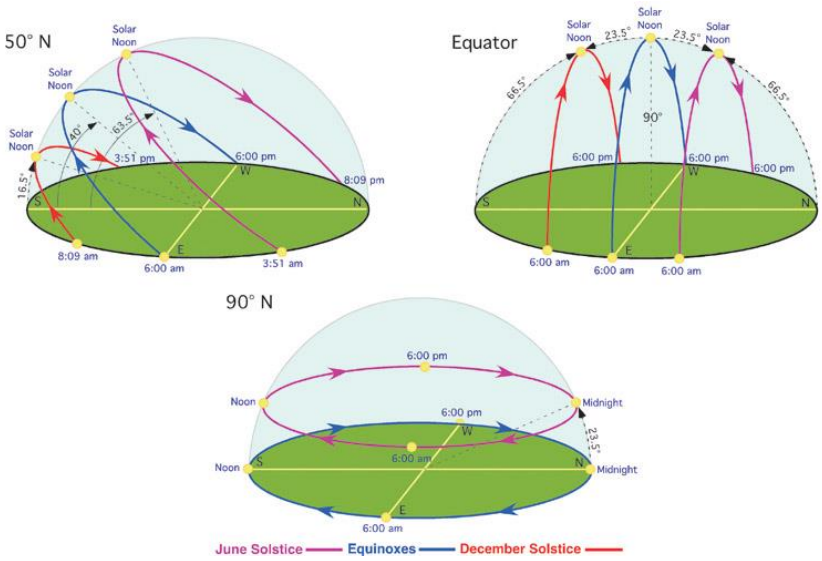

Figure 3.5. The path of the sun from different latitudes

In the same figure, we can observe the path of the sun from the latitude 50 ^{0}N (50 ^{0}N), i.e, the latitude above the equator. In this line, the sun often appears in the south. If the area is in a southern latitude, the sun will be predominantly in the north [43].

3.5.2. Choose a Tilt Angle for Solar Panels

After selecting the direction of the solar panels, we now have to know the angle of installation panels. The value of the inclination angle of the solar panels is connected to the latitude of the line where we are located and the local in which we are. The angle can be calculated using the following rules:

- Spring season: inclination angle = latitude.
- Summer season: inclination angle = latitude degree - 15 degrees.

- Winter season: inclination angle = latitude + 15 degrees.

We can select a latitude in our area using Google Maps, we can also use this data to calculate the number of solar panels which are needed [44].

3.5.3. Installation of Solar Panels in Parallel and Series

Dealing with connecting solar panels together is like dealing with batteries, its parallel structure maintains the voltage constant and increases the current, and their series installation increases the voltage and maintains the current constant.

3.6. Solar Panel I-V Characteristic Curves

Solar panels can be connected in parallel and series, and they have their own characteristics, Figure 3.6 illustrate the I-V, P-V characteristic curves according to the different connection method. According to the mentioned figure there are three cases. The first case of single PV module, which depends on the power and the characteristics that the module is designed for, as well as the quality of production to achieve the required specifications. The second case is of the parallel PV array connection case, which causes an increase in current, in contrast of the third case which relates to the series PV array connection, and caused an increase to voltages. As a result the power = V×I.

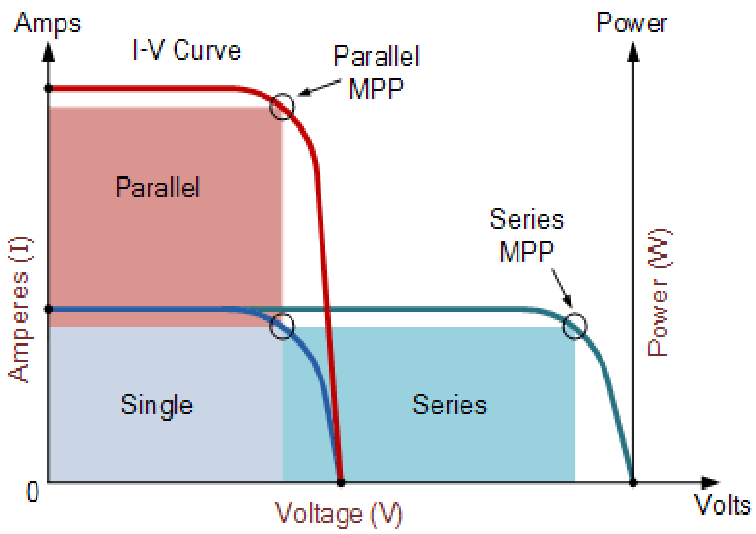

Figure 3.6. Solar panel I-V characteristic curves[45]

3.7. Data of Solar Panels (Module)

Main data of solar panels are:

- Maximum Power at STC (P_{max}): It represents the maximum power that the panel can be produced, under the weather condition of 25 ^{0}C temperature and irradiation 1kW/m^2. This power varies from one panel to another, this means the greater power, the larger size of the panel.
- Optimum Operating Voltage: It means the panel voltage in the case of charging, and can be used to know the system of the panel if it works on 12 Volts or 24 Volts. Whereas the panel system is 12, these voltages are 17 Volts or 18 Volts or their limits according to the manufacturer, in a 24 Volt system, these voltages are within 30 Volts.
- Optimum Operating Current: It is the maximum value of the current that can be produced from the panel in the event of resistance.
- Open Circuit Voltage: It is the voltage of the panel between the positive and negative terminals in the absence of a load, or charging on the panel, it is the panel voltage in the normal state.
- Short Circuit Current: It is the maximum current that the panel can reach in the absence of resistance, or near zero and is considered an important measure or test to express the quality of the panels.
- Module Efficiency: Which expresses the efficiency of the solar cell and the more efficient panel.
- Operating Module Temperature: It expresses the operating temperature that solar cells can have on the panels.
- Maximum System Voltage: It expresses the system voltage that can be added to the panels so that the system will not be exceeded its total amount.

3.8. Connecting More Than a Different Type of Solar Panels

There are now many solar panels on the market, sometimes different from each other in voltage, power and current intensity. It is not advisable to connect different solar panels in technical specifications, but it is not prohibited. The voltage, current and power are always taken into account. We will explain some ways to connect more than one solar panel in different power, type and specifications

3.8.1. Series Connection

The series connection is to get a high voltage. However, the solar panel maximum voltage must be taken into consideration. In the case of the series connection the total power is calculated simply by the algebraic expression of each solar panel, as they all have the same power, as follows:

Total power = 150+150+150+150=600 W

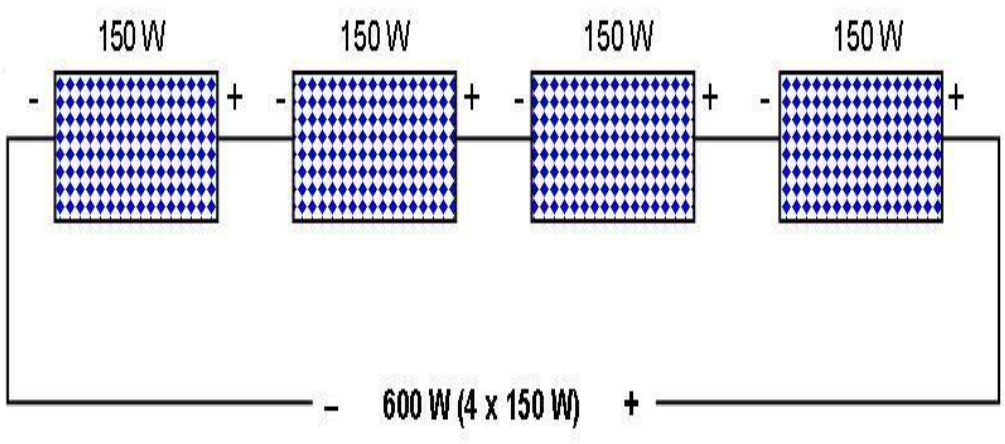

Figure 3.7. Series connection of solar cell

But in the case of connecting different power rated modules, the total power calculated according to t the lowest one as follows:

The total power is = $140 \times 4 = 560$ W.

It is therefore clear why mixing different solar panels or module is not recommended

3.8.2. Parallel Connection

In case of the compatible solar panels in the specifications, where they have the same type, volts, power and current the power will be as following:

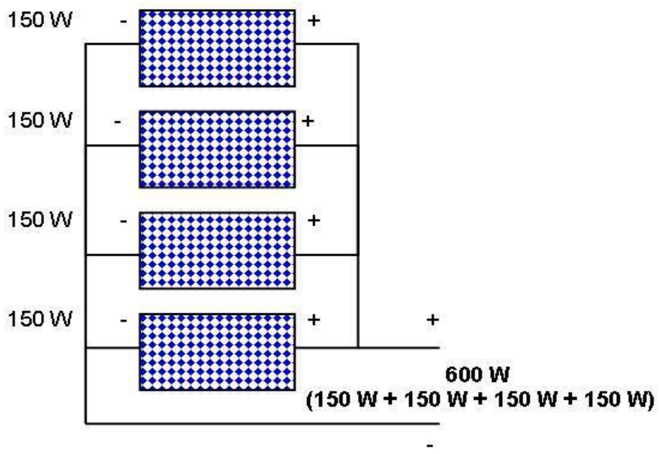

Figure 3.8. Parallel connection of same type solar cell

Total power = 150 + 150 + 150 + 150 = 600 W.

It is clear that the total power is not different from the series connection but varies in voltage, we will get low voltage and high current. In the case of different panel rated power the total power calculated as follows:

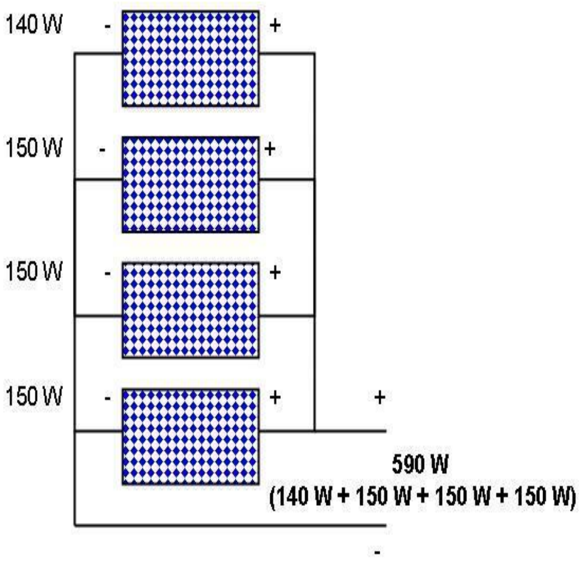

Figure 3.9. Parallel connection of different type solar cell

Total power = 150 + 150 + 150 + 140 = 590 W.

Taking into account in all previous connections that the voltage does not exceed the value that is borne by the inverter, and also being under the values of carrying the solar panel, taking into account temperature and weather conditions.

As a result, if the solar panels match in standard specifications, it will better be connected serially, where they give the largest voltage and power differes at the same time. If one of them is different, it will better be connected in parallel to obtain the greatest possible power [46].

3.9. Simulation of Solar Panels Using MATLAB

This software enables the simulation and studies all thin layer solar cell technologies, along with the latest and most advanced solar cell principles, by providing a flexible interactive environment and easy communication with any user. The project will, of course, be addressed the presentation and simulation of the performance of solar modules, in order to choose the best way of connection to a solar cell system. The simulation will be according to the most influential factors on the solar cells and their performance which they are the temperature and radiation. According to the previous parameters the simulation will be by the following phases.

1. Simulate 36 series and 36 parallel PV array.
2. Simulate 6 series and 66 parallel PV array.
3. Simulate 66 series and 6 parallel PV array.
4. Simulate 70 series and 2 parallel PV array.
5. Simulate 2 series and 70 parallel PV array.

3.10. Simulation of SunPower SPR-305-WHT Module

First we will illustrate the simulation results of the chosen module, SPR-305-WHT Module, as in Figure 3.10 which illustrates the module data sheet containing its parameters information [47]. These parameters are used as a database to implement the module as a panel.

Electrical Data Measured at Standard Test Conditions (STC): irradiation of 1000 /m^2, air mass 1.5 g, and cell temperature 25 ^{0}C		
Peak Power (+/-5%)	P_{max}	305 W
Rated Voltage	V_{mp}	54.7 V
Rated Current	I_{mp}	5.58 A
Open circuit voltage	$V_{o.c}$	64.2 V
Short circuit current	I_{sc}	5.96 A
Maximum System voltage	IEC, UL	1000 V, 600 V
Temperature Coefficient		
	Power	-0.38% / ^{0}C
	Voltage (V_{oc})	-176.6 mV / ^{0}C
	Current (I_{sc})	3.5 mA / ^{0}C
Series Fuse Rating		15 A
Peak Power, Pear Unit Area		187 W /m^2, 17.4 W /ft^2
CEC PTC Rating		282.1 W

Figure 3.10. SunPower SPR-305-WHT module specification

Also the producing company illustrate the dimension of its solar module which is (1.630 m^2) as in the Figure3.11 below, whereas the panel dimension should be taking into consideration to calculate the needed area according to the required power.

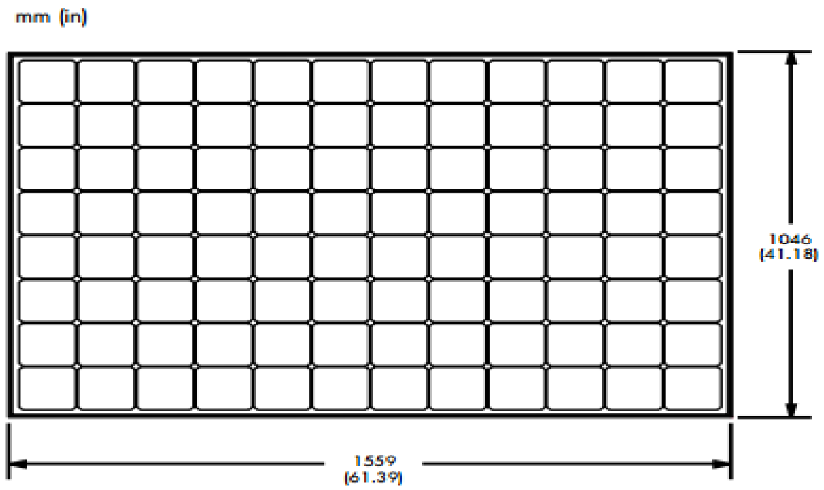

Figure 3.11. SunPower SPR-305-WHT module dimensions [47]

We have subjected the module to obtain its I-V and P-V characteristics with vary in irradiation to four different values, and kept the temperature constant at 25 ^{0}C as it is illustrated in the Figures 3.12 and 3.13 below.

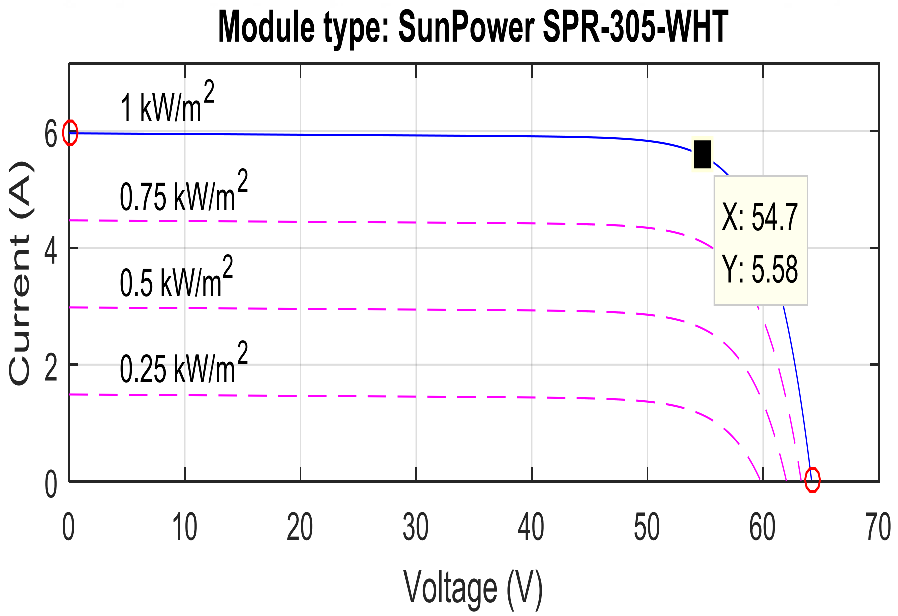

Figure 3.12. I-V characteristic of one module at 25 ^{0}C

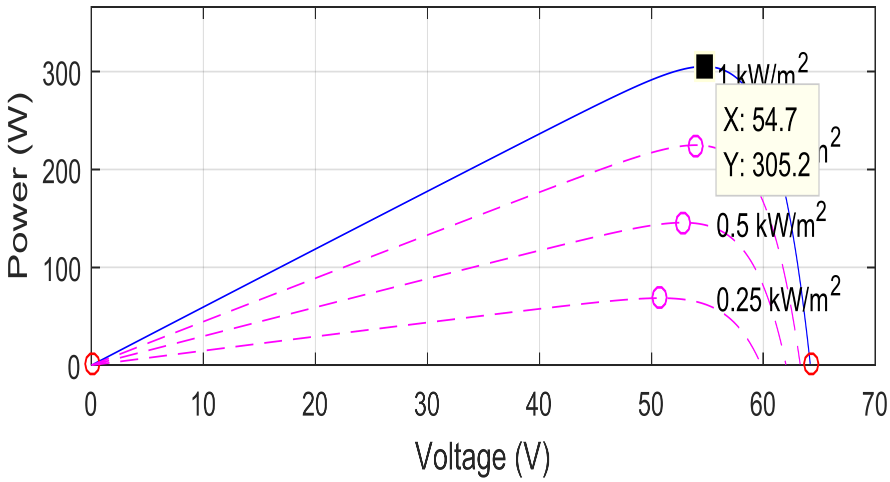

Figure 3.13. P-V characteristic of one module at 25 ^{0}C

The simulation results as in Table 3.1 below shows that the power value at the standard test condition is identical with its counterpart in the company's data sheet of 305.2 W, notably that the effect of radiation cannot be denied. Whereas, the power is gradually decreased according irradiation decreasing.

Table 3.1. SunPower SPR-305-WHT Module simulation results

Temperature (^{0}C)	Irradiation (kW/m^2)	Maximum Power Point (MPP) (W)
(Constant) 25 ^{0}C	1	305.2
	0.75	224.8
	0.50	145.7
	0.25	68.54

3.11. Simulation PV Array

We have used 72 models from the previous model, and controlled the connection method according to the steps mentioned in the section 3.9. Furthermore, we have obtained the simulation results twice, this is because of the changing of temperature with keeping the irradiation constant at the first time, and the change of irradiation with keeping temperature constant at the second time. The aim of this simulation is to obtain the maximum power point of the array.

3.11.1. Simulation of 36 Series and 36 Parallel PV Array

As we have mentioned previously, the simulation will be into two phases, and uses the 100 kW solar plant is implemented by MATLAB Simulink. Here we have connected 32 series, and 36 parallel array.

3.11.1.1. Varying Temperature, with Fixed Irradiation

In this case we have distributed the solar panels equally, keeping the irradiation fixed to 1000 W/m^2, and varying the temperatures to four different values and obtain the I-V, P-V as in the Figure 3.14 and the Figure 3.15 which illustrate the values of the current, voltage, and the maximum power.

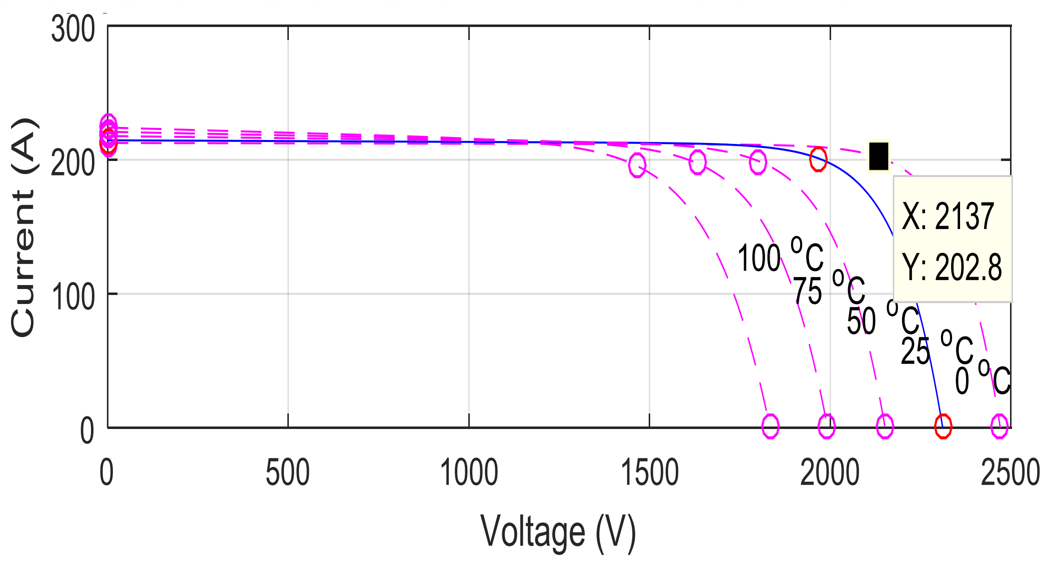

Figure 3.14. I-V characteristic of 36 series and 36 parallel PV array at 1000 W/m^2

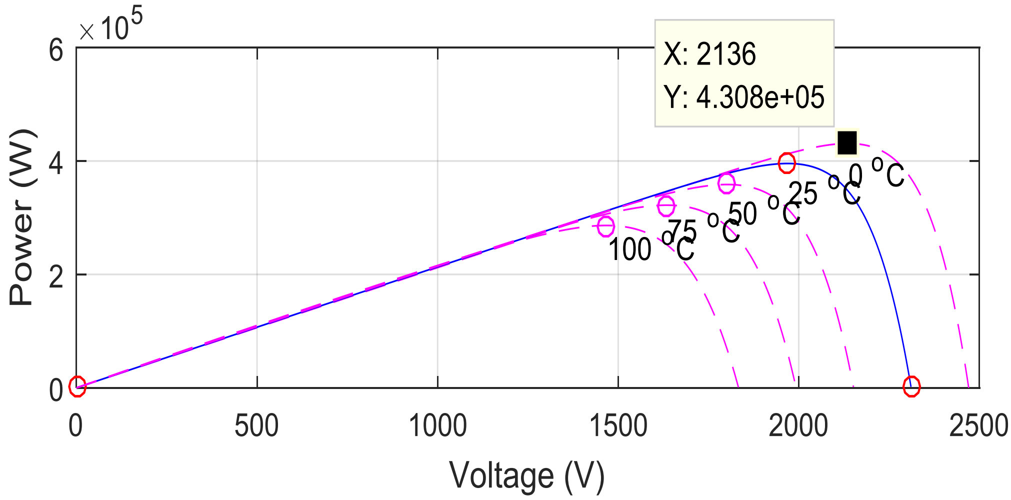

Figure 3.15. P-V characteristic of 36 series and 36 parallel PV array at 1000 W/m^2

We can observe that both voltages and current are affected closely of 2137 V, 202.8 A respectively. This compatible values has led to the maximum power output of PV panels of 4.308×10^5 W at the 0 ^{0}C temperature as it is shown in Table 3.2 below.

Table 3.2. Simulation results of 36 Series and 36 parallel PV array at variable temperature

Irradiation (kW/m^2)	Temperature (^{0}C)	Maximum Power Point (MPP) (W)
(Constant) 1	0	4.308×10^5
	25	3.956×10^5
	50	3.585×10^5
	75	3.221×10^5

3.11.1.2.Varying Irradiation, with Fixed Temperature Simulation

The same array distributed panels, but keeping the temperature constant at 25 ^{0}C and vary in irradiation to four different values simulated, to obtain the output results as illustrate in the Figures 3.16 and 3.17 .

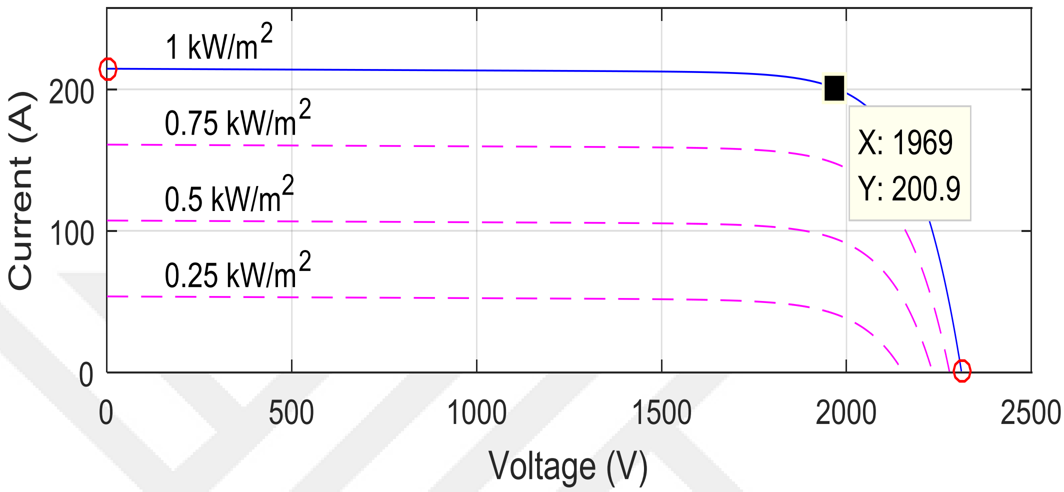

Figure 3.16. I-V characteristic of 36 series and 36 parallel PV array at 25 ^{0}C

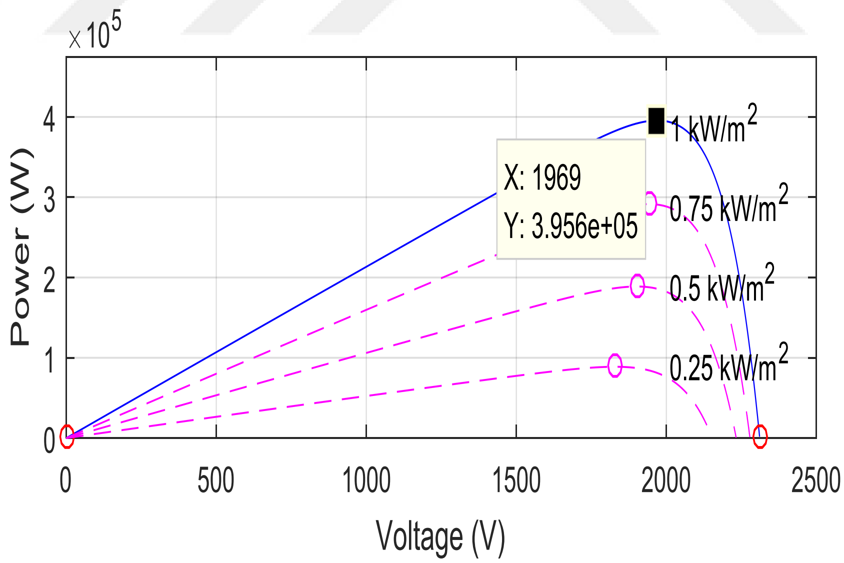

Figure 3.17. P-V characteristic of 36 series and 36 parallel PV array at 25 ^{0}C

It's turns out that irradiations affect the voltage and current output, but the effect on the voltages differes in this case, whereas it is decreased by 168 volts, this decrease explain why we have a lower power of 3.956×10^5 W, compared to its value in the first case of the constant temperature as shown in the Table 3.3.

Table 3.3. Simulation results of 36 series and 36 parallel PV array at variable irradiation

Temperature (^{0}C)	Irradiation (kW/m^2)	Maximum Power Point (MPP) (W)
(Constant) 25 ^{0}C	1	3.956×10^5
	0.75	2.914×10^5
	0.5	1.888×10^5
	0.25	8.882×10^4

3.11.2. Simulation of 66 Series and 6 Parallel PV Array

We have already indicated that we will simulate 72 PV panels, using different connection distribution methods. So in this time we have distributed the PV panels as 66 series and 6 parallel array to study and analyze the output power, through the change in the current and voltages parameters.

3.11.2.1. Varying Temperature, with Fixed Irradiation Simulation.

Keeping the irradiation constant and changing the temperature lead to uneven change between both of the voltages and current as illustrated in the Figures 3.18 and 3.19 of the I-V, P-V characteristics of this connection method.

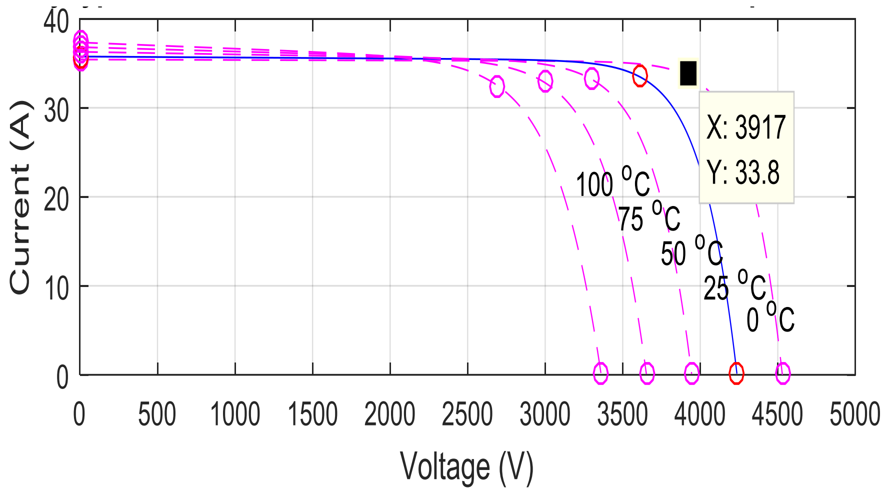

Figure 3.18. I-V characteristic of 66 series and 6 parallel PV array at 1000 W/m^2

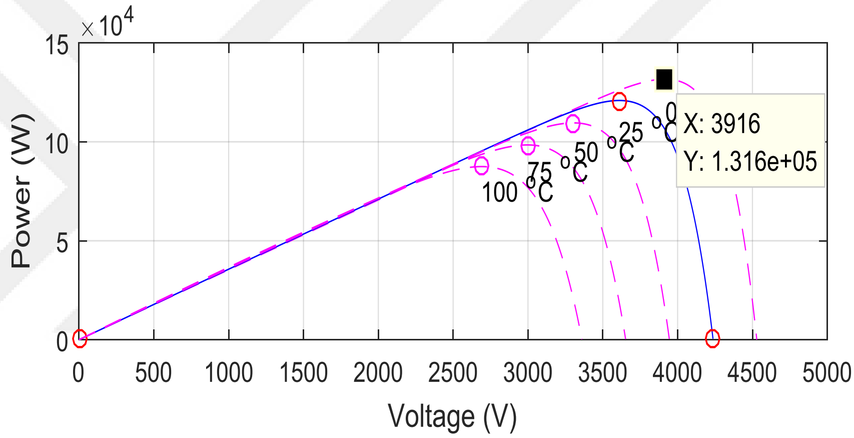

Figure 3.19. P-V characteristic of 66 series and 6 parallel PV array at 1000 W/m^2

The effect of the temperature changing on the current was greater than its effect on the voltages, which were 33.8 A at 25 ^{0}C while the voltage was 3917 V at the same temperature, to achieve a maximum power of 1.316×10^5 W as in Table 3.4.

Table 3.4. Simulation results of 66 series and 6 parallel PV array at variable temperature

Irradiation (kW/m^2)	Temperature (^{0}C)	Maximum Power Point (MPP) (W)
(Constant)	0	1.316×10^5
	25	1.209×10^5
	50	1.095×10^5
1	75	9.841×10^4

3.11.2.2. Varying Irradiation, with Fixed Temperature Simulation

The results of the second simulation by varying the irradiation to its same values of the previous simulations is illustrated in the I-V, P-V characteristics curves of the 66 series and 6 parallel array, in the Figures 3.20 and 3.21 below.

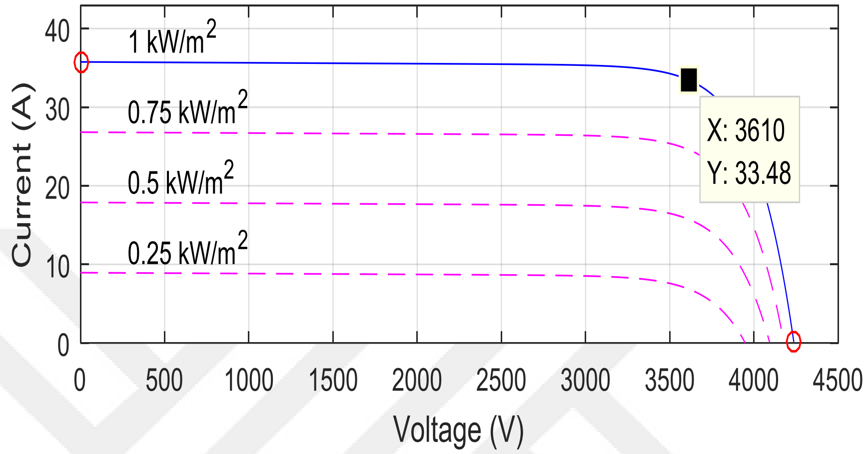

Figure 3.20. I-V characteristic of 66 series and 6 parallel PV array at 25 ^{0}C

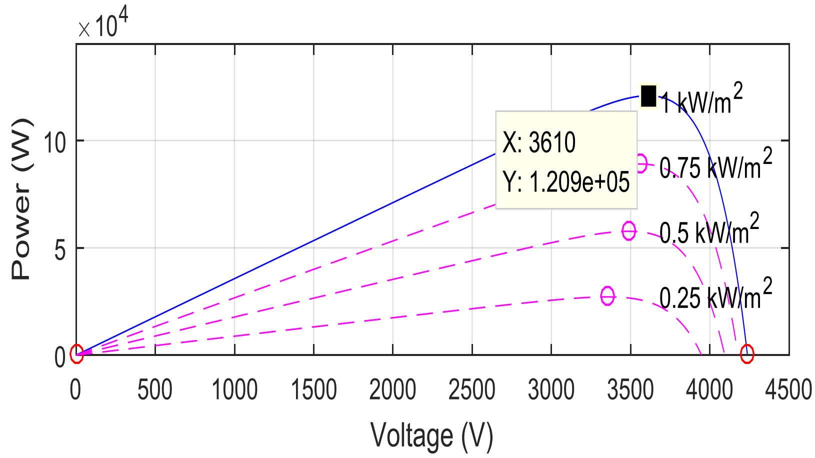

Figure 3.21. P-V characteristic of 66 series and 6 parallel PV array at 25 ^{0}C

In this case the effect of the irradiation changing has changed the value of the output current very slightly of 33.48 A is compared to its value in the case of temperature change. However, a noticeable change is occurred on the voltage, which is a 3610 V, and causes a drop in the maximum power of $1.209{\times}10^{5}$ W as in the Table 3.5.

Table 3.5. Simulation results of 66 series and 6 parallel PV array at variable irradiation

Temperature (^{0}C)	Irradiation (kW/m^2)	Maximum Power Point (MPP) (W)
(Constant) 25 ^{0}C	1	1.209×10^5
	0.75	8.904×10^4
	0.5	5.768×10^4
	0.25	2.714×10^4

3.11.3.Simulation of 6 Series and 66 Parallel PV Array

Unlike the previous connection method, we connect the array by 6 series and 66 parallel array, and repeat the same procedures of the temperature and irradiation changing.

3.11.3.1. Varying Temperature, with Fixed Irradiation Simulation

Changing the method of connection to this method leads to the values of current and voltage converging of 371.8 A, 356.1 V, according to the I-V, P-V characteristics curves in the Figures 3.22 and 3.23

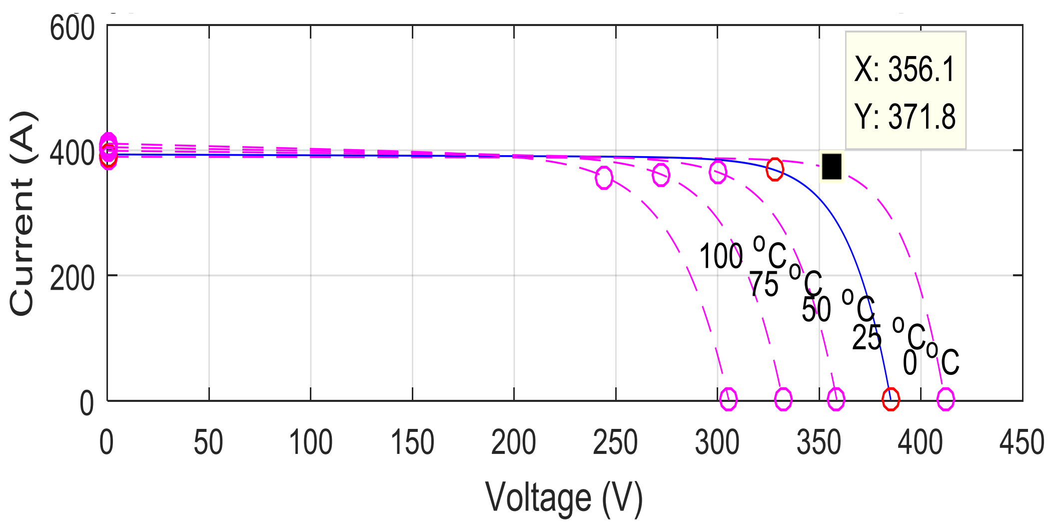

Figure 3.22. I-V characteristic of 6 series and 66 parallel PV array at 1000 W/m^2

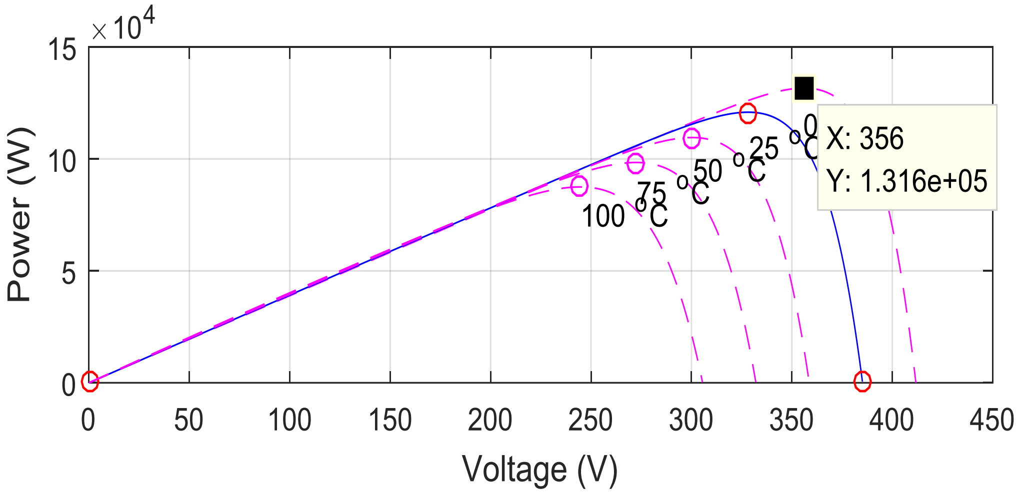

Figure 3.23. P-V characteristic of 6 series and 66 parallel PV array at 1000 W/m^2

When comparing both current and voltages in this connection method with the previous method, we will find that the current values of this case is higher than their counterpart in the previous connection case. While the voltage is lower significantly. Thus, a maximum power of 1.316×10^5 W is achieved at a temperature of 0 ^{0}C, as in the Table 3.6 below, which is the same in the case of 66 series and 6 parallel connection method.

Table 3.6. Simulation results of 6 series and 66 parallel PV array at variable temperature

Irradiation (kW/m^2)	Temperature (^{0}C)	Maximum Power Point (MPP) (W)
(Constant) 1	0	1.316×10^5
	25	1.209×10^5
	50	1.095×10^5
	75	9.841×10^4

3.11.3.2. Varying Irradiation, with Fixed Temperature Simulation

Changing the irradiation values leads to the current of 368.3 A and voltage of 328.2 V at an irradiation of 1 kW/m^2 , as it is shown in the Figures 3.24 and 3.25.

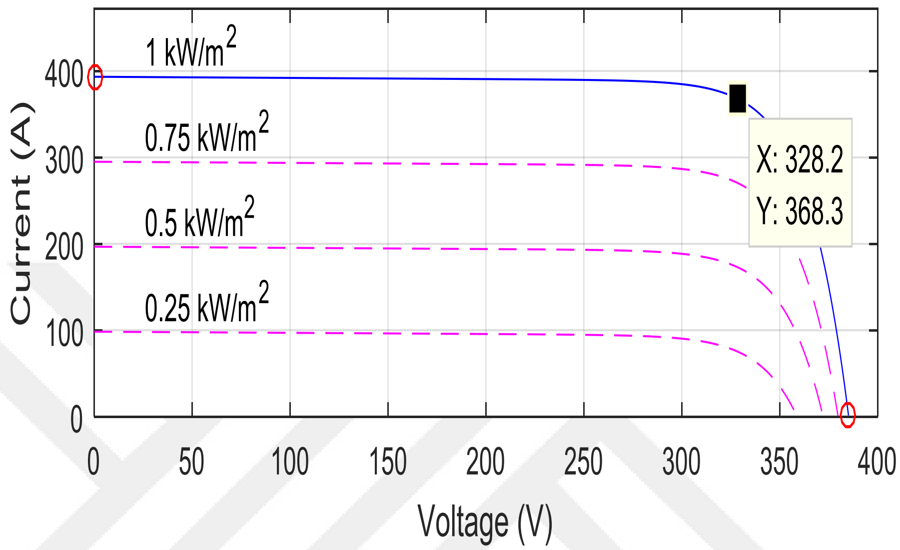

Figure 3.24. I-V characteristic of 6 series and 66 parallel PV array at 25 ^{0}C

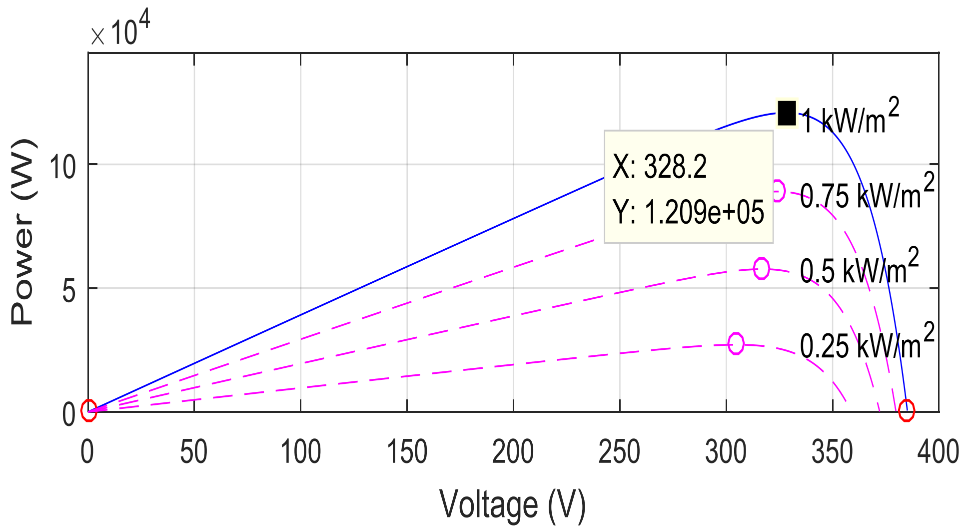

Figure 3.25. P-V characteristic of 6 series and 66 parallel PV array at 25^0 C

In this case, the current and voltage was reduced form the case of the temperature change by 3.5 A and 27.9 V, which effected the maximum output power to be 1.209×10^5 W as in the Table 3.7. When we applied the same comparison with the previous connection method, the current remained higher than its counterpart and the voltage also still the lowest.

Table 3.7. Simulation results of 6 series and 66 parallel PV array at variable irradiation

Temperature (^0C)	Irradiation (kW/m^2)	Maximum Power Point(MPP) (W)
(Constant) 25^0C	1	1.209×10^5
	0.75	8.904×10^4
	0.5	5.768×10^4
	0.25	2.714×10^4

3.11.4. Simulation of 70 Series and 2 Parallel PV Array

In the previous cases of the 66 series, with the 6 parallel and of the 6 series, with 66 parallel PV arrays, the change in temperature and irradiation was effecting the current and voltage according to what we have studied and discussed, but as a result the maximum output power is matched for both cases of the temperature and irradiation changes. Therefore, we will study just as one case of this type of connection. Which is the 70 series and 2 parallel PV array connection method.

3.11.4.1. Varying Temperature, with Fixed Irradiation

The Figures 3.26 and 3.27 illustrate the simulation result of this type of connection at irradiation of 1 kW/m^2, where a current and voltage are 11.27 A and 4155 V is obtained.

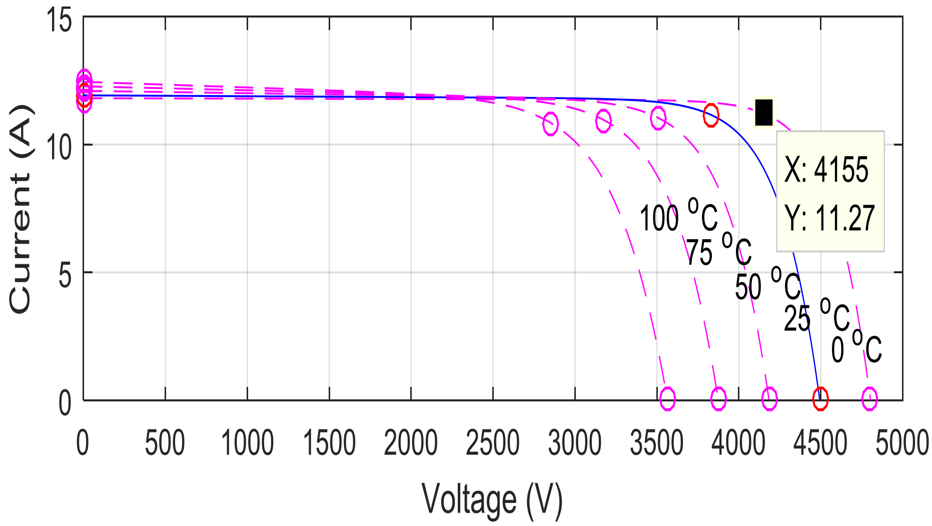

Figure 3.26. I-V characteristic of 70 series and 2 parallel PV array at 1000 W/m^2

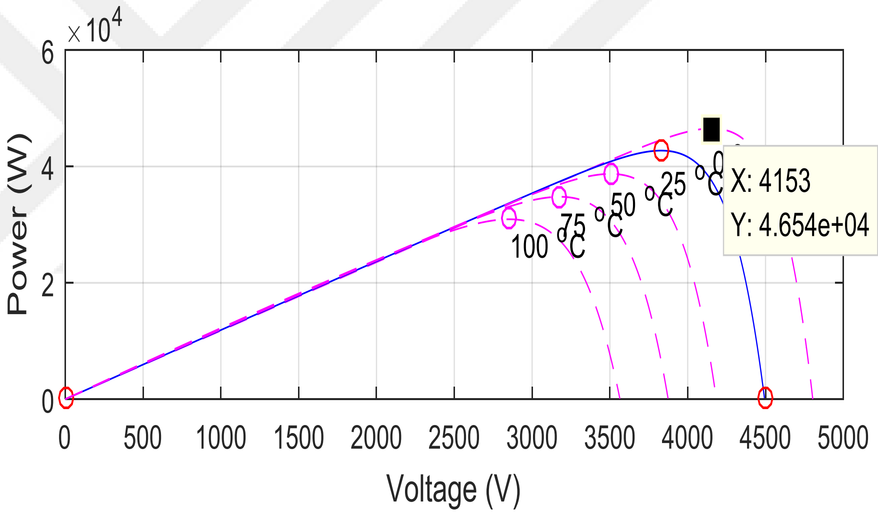

Figure 3.27. P-V characteristic of 70 series and 2 parallel PV array at 1000 W/m^2

We can note that the current that is compared to the voltage is very low. This what causes the low value of the maximum power of $4.654{\times}10^4$ W as in Table 3.8.

Table 3.8. Simulation results of 70 series and 2 parallel PV array at variable temperature

Irradiation (kW/m^2)	Temperature (^0C)	Maximum Power Point(MPP) (W)
(Constant) 1	0	4.654×10^4
	25	4.273×10^4
	50	3.873×10^4
	75	3.479×10^4

3.11.4.2. Varying Irradiation, with Fixed Temperature Simulation

As shown in the Figures 3.28 and 3.29 of the simulation results, where is the current and voltage of 11.6 A and 3829 V at the temperature of 25 ^0C.

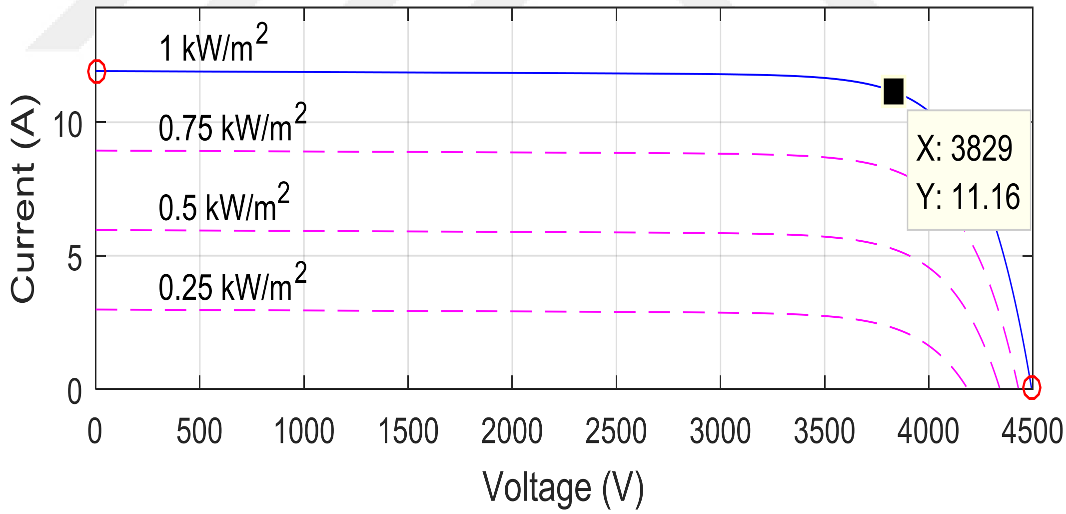

Figure 3.28. I-V characteristic of 70 series and 2 parallel PV array at 25 ^0C

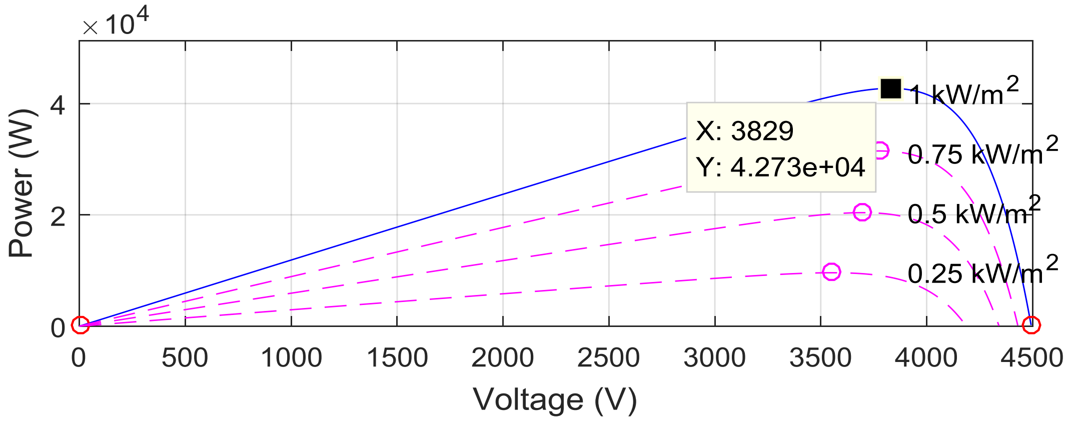

Figure 3.29. P-V characteristic of 70 series and 2 parallel PV array at 25 ^{0}C

The effect of changing the radiation on the current is as weak as when the temperature changes, but its impact on the voltages is greater, where it decreases by 326 volts. This decrease in voltages negatively affected the value of the maximum power which is of 4.273×10^4 as shown in the Table 3.9.

Table 3.9. Simulation results of 70 series and 2 parallel PV array at variable irradiation

Temperature (^{0}C)	Irradiation (kW/m^2)	Maximum Power Point (MPP) (W)
(Constant) 25 ^{0}C	1	4.273×10^4
	0.75	3.141×10^4
	0.5	2.039×10^4
	0.25	9595

3.12. Final Results

The effect of both irradiation and temperature changes in the different connection methods have been given in Table 3.10 and Table 3.11.

Table 3.10. The best simulation results of the connection methods

Array Connecting Method	Irradiation and Temperature	Maximum Power Point (MPP) of PV array (W)
36 series,36 parallel	(Constant) 1 kW/m^2 0 ^{0}C	4.308×10^5
66 series, 6 parallel		1.316×10^5
6 series, 66 parallel		1.316×10^5
70 series, 2 parallel		4.654×10^4

Table 3.11. Simulation results of the connection methods at STC

Array Connecting Method	Temperature and Irradiation	Maximum Power Point (MPP) of PV array (W)
36 series,36 parallel	(Constant) 25 ^{0}C 1 kW/m^2	3.956×10^5
66 series, 6 parallel		1.209×10^5
6 series, 66 parallel		1.209×10^5
70 series, 2 parallel		4.273×10^4

In the cases of varying the temperature , irradiation and connection type, the 36 series, 36 parallel PV array connection provides the highest output power of 4.308×10^5 W at temperature of 0 ^{0}C and irradiation of 1 kW/m^2, while the 70 series, 2 parallel connection provides the least output power of 4.654×10^4 W at temperature of 25 ^{0}C and irradiation of 0.25 kW/m^2.

In case of STC the highest output power has been obtained as 3.956×10^5 W for 36 series and 36 parallel connection, while the least power has been obtained as 4.273×10^4 W for 70 series and 2 parallel connection.

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1. Conclusions

Studying and researching solar cell systems is an important topic, for the possibility of generating electricity in useful quantities of the solar energy. This thesis presents the design and simulation of an independent and efficient solar cell panel, taking into account, a theoretical study of solar cell panels and how to model them on the MATLAB Simulink program, and the effects of the environmental parameters, such as the solar irradiation and cell temperature. With the possibility of additional new panels according to the speed of implementation and operation in this program, for calculating and plotting the I-V and P-V characteristics and MPP. Proposed model and solar array procedures can be iterated for any selected solar model, or any number of panels, which makes it more precise to choose the best module or connection methods. This model also allows designer to test and analyze the PV panels for the most desired output for given input operating conditions.

For 72 solar panels, four different connection cases are simulated. The goal is to get the best value of the output power.

It is obtained that MPP is affected by the connection cases, which means that:

1. MPP of the array can be increased by varying the connection cases.
2. The highest MPP is obtained for the balanced connection.

Thus, it is important to choose the appropriate connecting to have the desired MPP. Also, the PV arrays are more efficient at lower temperature and higher irradiation.

In this thesis, simulation results prove that the effect of the temperature and the irradiation on the MPP should not be neglected. Because the output voltage and current of the panels are affected by the them.

In addition, there is a problem related to the limitation of the MATLAB simulation model. The simulation model does not allow to use more than one panel , which means that it does not support hybrid or mixed PV panel arrays.

4.2. Future Work

It was not possible to connect two different model of solar panels as an array to simulate them, therefore we look forward to developing MATLAB Simulink so that more than one type of solar panel can be simulates. Thus, more than one of them can be compared to a better selection.

It is known that sometimes the Iraqi government pay for the electricity by the prices of the oil. This matter should be taken into account when comparing the cost of electricity generation using solar energy. But the unstable security situation and the cost of the raw materials for solar energy devices are the main obstacles to usage, despite of the availability of the large appropriate area for the installation of these devices. Also most of the field and laboratory experiments to utilize solar energy still in their early stages and must be activated.

I have an ambition in my Iraqi government to utilize this source of energy. So it is proposed to take into account the following recommendations:

1. It should be supported to activate the researches in the field of solar energy.
2. Data bank should be established about the potential of the country for solar energy.
3. The solar plants still in use in Iraq should be revised and improved.
4. Citizens should be supported to use the solar energy in their homes.

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CURRICULUM VITAE

Personal information

First name(s) / Surname(s): EKHLAS AZA KHAN

Nationality: IRAQI

Date of birth: 21.8.1969 – IRAQI

phone(s): +90 5377776656

E-mail: ek.essa@yahoo.com

Address: Bahçelievler mahallesi Bahçelievler Cad. Ümit Apt. A blok 6 daire

Education

College of Engineering	Mustansiriya University	2003
Institute of Technology		1990

Work experience

Working at the Engineering Department of the Iraqi Ministry of Education

Mother tongue(s): Arabic

Other language(s): English