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Modelling and Simulation of Photo Voltaic Array

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Abstract— *The purpose of this research paper was modeling and simulation of the photovoltaic system that to show the effect of different temperature and solar irradiance on the PV array by using MAT LAB software. As a result, showed that the simulation analysis on the short circuit current I_{SC} was linearly proportional to the solar radiation over a wide range and when the radiation intensity is low (and thus also the photocurrent, Iph), and the current had its maximum at the short-circuit point, the voltage is zero and thus the power is also zero. The situation for current and voltage was reversed at the open-circuit point, so again the power here was zero, since power is the product of current and voltage.*

Index Terms— Current, Irradiance, Mat Lab Software, Open Circuit Voltage, Short Circuit Current, Solar PV, Temperature, Voltage,.

1. Introduction

Renewable energy, especially solar power, is an indispensable part of the power supply in the future, worldwide. In Ethiopia, with "13 months of sunshine", it is a good option to produce electrical power in remote areas without a grid connection. This technology has the potential to change the life of many people throughout the country.

Renewable energy sources also called non-conventional type of energy are the sources which are continuously replenished by natural processes. Such as, solar energy, bio-energy - bio-fuels grown sustainably, wind energy and hydropower etc., are some of the examples of renewable energy sources. A renewable energy system convert the energy found in sunlight, falling-water, wind, sea-waves, geothermal heat, or biomass into a form, which we can use in the form of heat or electricity. The majority of the renewable energy comes either directly or indirectly from sun and wind and can never be fatigued, and therefore they are called renewable [1].

However, the majority of the world's energy sources came from conventional sources-fossil fuels such as coal, natural gases and oil. These fuels are often term non-renewable energy sources. Though, the available amount of these fuels are extremely large, but due to decrease in level of fossil fuel and oil level day by day after a few years it will end. Hence renewable energy source demand increases as it is environmental friendly and pollution free which reduces the greenhouse effect [1].

1.1 Statement of the Problem

Solar energy is one of the most important renewable energy sources. Compared to conventional nonrenewable resources such as gasoline, coal, etc..., and it is clean, inexhaustible and free. But the output characteristics of a PV array are influenced by the environmental factors and the conversion efficiency is low. Therefore, a maximum power point tracking (MPPT) technique is needed to track the peak power to maximize the produced energy by modeling and simulating the array using MATLAB software. Therefore, the objective of this research paper was modeling and simulation of solar PV array capable of accurately predicting the effects of non- uniform changing shadows and dust e.g., i.e. a passing cloud or a tree's shadow on the output power of solar PV arrays.

2. Literature Review

2.1 Solar Energy

Solar energy is a non-conventional type of energy, and it has been harnessed by humans since ancient times using a variety of technologies. Solar radiation along with secondary solar powered resources such as wave and wind power, hydroelectricity, and biomass, account for most of the available non-conventional type of energy on earth. Only a small fraction of the available solar energy is used [2].

Solar powered electrical generation relies on photovoltaic system and heat engines. Solar energy's uses are limited only by human creativity. To harvest the solar energy, the most common way is to use photo voltaic panels which will receive photon energy from sun and convert to electrical energy. Solar technologies are broadly classified as either passive solar or active solar depending on the way they detain, convert and distribute solar energy. Active solar techniques include the use of PV panels and solar thermal collectors to strap up the energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties and design spaces that naturally circulate air [3]. Solar energy has a vast area of application such as electricity generation for distribution, heating water, lightening building, crop drying etc.

2.2 Distribution of Solar Radiation

Below figure shows that solar radiation, Earth receives 100% of incoming solar radiation at the upper atmosphere out of this 30% back to space due earth's albedo and scattered and 19% absorbed by atmosphere and cloud. The only 51% absorbed at the surface.

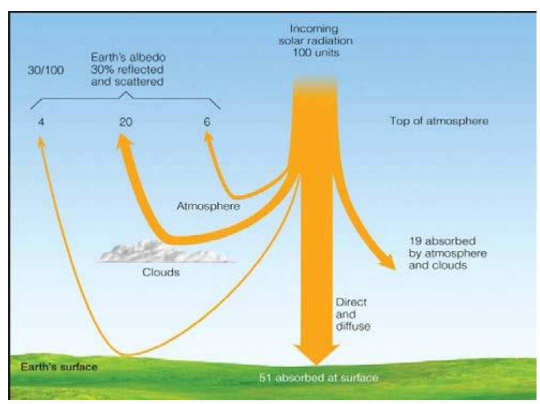

Figure 2.1 Solar radiation distributions [4].

2.3 Solar Radiation Reaching Earth Surface

The total amount solar radiation intercepted by the Earth is the Solar Constant multiplied by the cross section area of the Earth. If we now divide the calculated number by the surface area of the Earth, we shall find how much solar radiation is received in an average per square meter of the Earth's surface [5]. Hence the average solar radiation R per square meter of the Earth surface,

$$R = \frac{s * \pi r^2}{4 * \pi r^2} = \frac{1369}{4} \approx 342 \frac{w}{m^2}$$

Where, **S** is solar constant and **r** is radius of earth.

2.4 Spectrum of Sun

The performance of Photovoltaic device is reliant on the spectral distribution of solar radiation. The standard spectral distribution is mainly used as reference for evaluation of PV devices. There are two standard terrestrial distribution defined by the American Society for Testing and Materials (ASTM), global AM1.5 and direct normal. The solar radiation that is perpendicular to a plane directly facing the sun is known as direct normal. The global corresponds to the spectrum of the diffuse radiations. Diffuse radiations are the radiations which are reflected on earth's surface or influenced by atmospheric conditions. To measure the global radiations an instrument named pyrometer is used. This instrument is designed in such a way that it responds to each wavelengths and so that we get a precise value for total power in any incident spectrum [2].

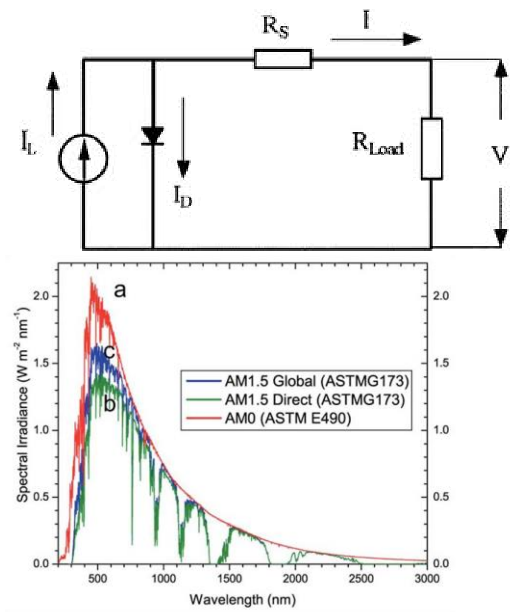

Figure 2.2 Spectral distributions of black body radiation and sun radiation [6].

Two standards are defined for terrestrial use. The AM1.5 Global spectrums is designed for flat plate modules and has an integrated power of 1000 W/m². The AM1.5 Direct spectrums is defined for solar concentrator work. [6].

3. Modeling and Simulation of Solar PV Array

Modeling of PV modules or arrays is required in order to design and monitor these systems. Usually, a Grey Model process is used to model PV arrays. In such models, physical parameters are determined using the measured data given in the datasheets (by manufacturers).

3.1 Representation of PV Devices

The PV devices are basically represented in two different models viz.

- Single diode model
- Double diode model

3.1.1 Single Diode Model

In a single diode model, there is a current source parallel to a diode. The current source represents light-generated current, I_{ph} that varies linearly with solar irradiation. This is the simplest and most widely used model as it offers a good compromise between simplicity and accuracy Figure below shows the single diode model circuit.

Figure 3.1 Equivalent model of a photovoltaic cell, single diode model

$$I = I_{ph} - I_{diode} \quad (1)$$

But,

$$I_{diode} = I_0 \left[\exp\left(\frac{q*v}{\alpha*k*T}\right) - 1\right] \quad (2)$$

$$I = I_{ph} - I_0[\exp\left(\frac{q*v}{\alpha*k*T}\right) - 1] \quad (3)$$

Or, $I = I_{ph} - I_0 \left[\exp\left(\frac{eV}{k*T_c}\right) - 1\right]$ (4)

Where:- $I_{Ph}$is the current generated by the incident light, $I_{diode}$is the Shockley diode equation, I_o is the reverse saturation or leakage current of the diode, q is the electron charge [$1.602*10^{-19}$C], K the Boltzmann constant [$1.3806503*10^{-23}$ J/K], T [K] is the temperature of the p-n junction, α is the diode ideality constant which lies between 1 and 2 for mono crystalline silicon

The basic equation (3) of the elementary PV does not represent the I-V characteristic of practical PV arrays. Practical modules are composed of several connected PV cells requires the inclusion of additional parameters Rs and Rp, with these parameters (3) becomes (4).

$$I = I_{Ph} - I_0 \left[\exp\left(\frac{V+Rs*I}{Vt*\alpha}\right) - 1\right] - \frac{V+Rs*I}{Rp}$$

(6)

3.1.2 Double Diode Model

In this model an extra diode attached in parallel to the circuit of single diode model. This diode is included to provide an even more accurate I-V characteristic curve that considers for the difference in flow of current at low current values due to charge recombination in the semiconductor's depletion region.

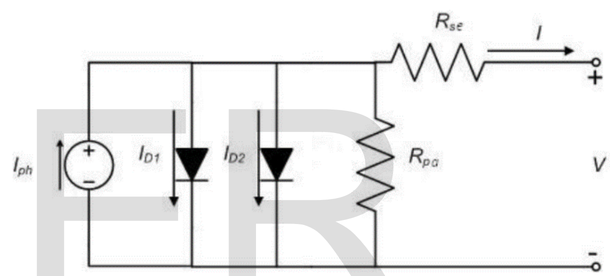

Figure 3.1 Double Diode Model [15].

The characteristic equation for double diode model is given by [20]:

$$I = I_{Ph} - I_{01} \left[\exp\left(\frac{V+Rs*I}{Vt}\right) - 1\right] - I_{02} \left[\exp\left(\frac{V+Rs*I}{2*Vt*\alpha}\right) - 1\right] - \frac{V+Rs*I}{Rpa} \quad (5)$$

Where, I_{01}i -Saturation current due to recombination in the space charge layer, I_{02}- Saturation current due to diffusion.

3.2 Modeling of PV Array

The simplest model of a PV cell is shown as an equivalent circuit below that consists of an ideal current source in parallel with an ideal diode. The current source represents the current generated by photons (often denoted as Iph or I_L constant incident radiation of light [20].

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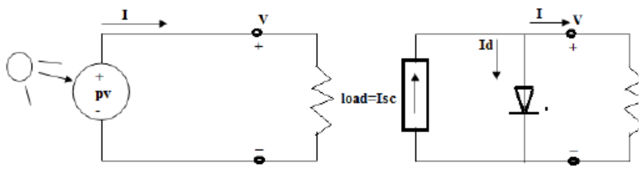
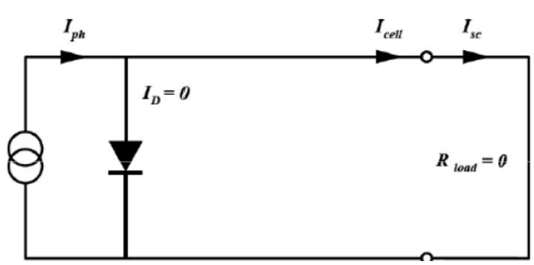


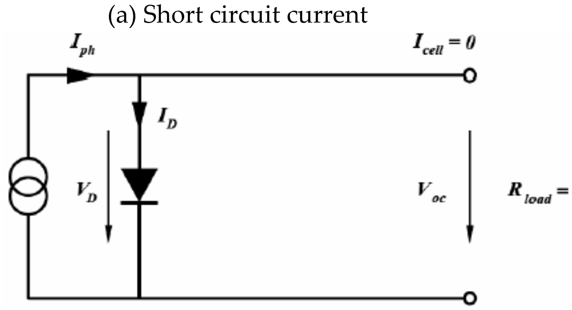
Figure 3.2 PV cell with a load and its simple equivalent circuit.

There are two key parameters frequently used to characterize a PV cell. Shorting together the terminals of the cell, as shown in Figure 3.3 (a), the photon generated current will follow out of the cell as a short-circuit current (Isc). Thus, Iph = I

As shown in Figure 3.3 (b), when there is no connection to the PV cell (open-circuit), the photon generated current is shunted internally by the Isc intrinsic p-n junction diode. This gives the open circuit voltage (Voc). The PV module or cell manufacturers usually provide the values of these parameters in their datasheets.



(a) Short circuit current



(b) open circuit voltage

Figure 3.3: Diagrams Showing a Short.

The output current (I) from the PV cell is found by applying the Kirchhoff's current law (KCL) on the equivalent circuit. Circuit and an open-circuit condition.

$$I = I_{sc} - I_d \tag{7}$$

Where; I_{ph} is the short-circuit current that is equal to the photon generated current, and Id is the current shunted through the intrinsic diode.

The diode current Id is given by the Shockley's diode equation [18]:

$$I_d = I_0\left[\exp\left(\frac{qv_d}{K*T}\right) - 1\right] \tag{8}$$

Where, I_o is the reverse saturation current of diode (*A*), q is the electron charge (1.602×10-19 *C*), V_d is the voltage across the diode (*V*), K is the Boltzmann's constant (1.381×10-23 *J/K*), T is the junction temperature in *Kelvin (K)*.

Replacing Id of the equation (8) by the equation (4) gives the current-voltage relationship of the PV cell [3].

$$I = I_{sc} - I_0\left[\exp\left(\frac{qv_d}{K*T}\right) - 1\right] \tag{9}$$

Where: V: is the voltage across the PV cell (module voltage/number of cells in series), and I_{call} is the output current from the cell (same as module current). *T:* is the cell temperature in Kelvin (K).

It is possible to approximate, the generated current, which is equal to Isc, is directly proportional to the irradiance, the intensity of illumination to the PV cell. Though, if the value, Isc, is known from the datasheet, under the standard test condition, E=1000W/m2 at the air mass (AM) = 1.5, then the photon generated current at any other irradiance, E in (W/m2), is given by:

$$I_{sc(E_i)} = \left(\frac{E_i}{E_{in}}\right) I_{sc(E_{in})} \quad (10)$$

The reverse saturation current of diode (*Io*) is constant under the constant temperature and found by setting the open-circuit condition as shown in Figure 3.3 (b). Using the equation (9), let $I = 0$ (no output current) and solve for *Io*.

$$\boldsymbol{I_0 = \frac{I_{sc}}{\left[\exp\left(\frac{qv_d}{K*T}\right)-1\right]}} \quad (13)$$

The value of the series resistance is multiplied by the number of series-connected cells. Parallel resistance (or shunt resistance) is a loss associated with a slight leakage current through a parallel resistive path to the device. Recombination in the depletion region of PV cells provides a non-resistive current path in parallel with the intrinsic PV cell, and can be represented by a second diode in the equivalent circuit.

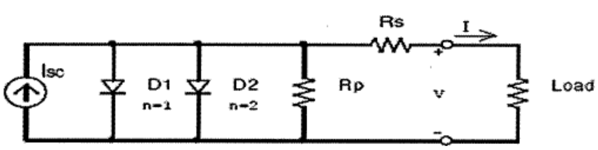


Figure 3.4: Equivalent circuit of PV cell.

Taking in to account these additional elements adds to the equation:

$$I = I_{sc} - I_{01}\left[\exp\left(q\,\frac{(v+I*R_S)}{K*T}\right) - 1\; I_{02}\left[\exp\left(q\,\frac{(v+I*R_S)}{2*K*T}\right) - 1\right] - \frac{(v+I*R_S)}{R_p}\right] \quad (14)$$

But, Rp and Rs are used to represent the shunt resistance and intrinsic series of the cell respectively. Usually the value of Rp is very large and that of Rs is very small, hence they may be neglected to simplify the analysis. PV cells are grouped in larger units called PV modules which are further interconnected in series-parallel configuration to form PV arrays or PV generators [3]. The PV mathematical model used to simplify our PV array is represented by the equation: Therefore, we can assume Rp = ∞ and Rs= ∞.

$$I(0) = N_p I_{ph} - N_P I_{rs}\left[\exp\left(\frac{q}{KTA} * \frac{V}{N_S}\right) - 1\right] \quad (15)$$

The two diode can be combined to simplify the equation to:

$$I = I_{sc} - I_0\left[\exp\left(q\,\frac{(v+I*R_S)}{n*K*T}\right) - 1\right] - \frac{(v+I*R_S)}{R_p} \quad (16)$$

Where **n** is known as "ideality factor" and take a value between one and two. Since a single PV cell produces an output voltage of less than 1volt, it is necessary to string together a number of PV cell in series to achieve a desired output voltage. Generally, 36 cells in series will provide a large enough voltage to charge a 12 Volt battery, and 72 cells would be suitable for a 24 Volt battery. However, the voltage can be adjusted with DC/AC converter so that either type of battery can be charged.

The BPSX150 PV module, which contains 72 cells, was selected for the purpose of this project. The data sheet for the BP SX 150 provides the following information on the module:

Table 4.1: Values from BP SX 150 data sheet [16].

Electrical Characterstics	BP SX 150s
Maximum power(Pmax)	150W
Voltage at Pmax (Vmp)	34.5V
Current at Pmax(lmp)	4.35A
Warranted minimum Pmax	140W
Short-circuit current (Isc)	3.75A
Open-circuit voltage (Voc)	43.5V

Temperature coefficient of Isc	(0.065±0.015)%/ºc =use 0.00023%A/K
Temperature coefficient of Voc	-(160±20)mV/ºc
Temperature coefficient of power	-(0.5±0.05)%/ºc
NOCT	45±2ºc
Maximum system voltage	600V (U.S.NEC rating)

The short circuit current (Isc) can be calculated at a given temperature (T) using:

$$I_{sc} * I_T = I_{sc} * I_{Tref} * [1 + \alpha * (T - T_{ref})] \quad (17)$$

Where: I_{scr} at T_{ref} is found on the datasheet (measured under irradiance of 1000 /m^2)

- T_{ref} is the reference temperature of the PV cell in Kelvin, usually 298K,
- α is the temperature coefficient of Isc in percent change per degree temperature
- Go = 1000W/m^2

The photon generated current at any other irradiance, G (W/M^2), is given:

$$I_{sc} * I_G = I_{sc} * I_{Go} * \frac{G}{G_o} \quad (18)$$

The reverse saturation current is dependent of temperature, and is given by the equation:

$$I_o(T) = I_o(T_{ref}) * \left(\frac{T}{T_{ref}}\right)^3 * \exp\left[\left(q\frac{v}{n*k}\right) * \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

(19)

Or

$$I_o(T) = I_o(T_{ref}) * \left(\frac{T}{T_{ref}}\right)^3 * \exp\left[\left(q\frac{E_g}{n*A*k}\right) * \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

Where:- $E_g = \frac{v}{A}$

The temperature dependence of the energy gap of the semiconductor is given by

$$E_G = E_{Go} - \frac{\alpha T^2}{T+\beta} \quad (20)$$

The photo current Iph depends on the solar radiation and cell temperature as follows:

$$I_{ph} = \frac{G}{G_0}[I_{sc} + Ki(T - T_r)] \quad (21)$$

Where: - $I_{sc}$is the cell short-circuit current at reference temperature and radiation, Ki is the short circuit current temperature coefficient, and G is the solar radiation in mW/cm2

The PV power can be calculated using equation as follows:

$$P = IV = N_p I_{ph} * V\left[\left(\frac{q}{KTA} * \frac{v}{N_s}\right) - 1\right] \quad (21)$$

Now equation (4.16) can be solved using Newton's Raphson method, which can be described as:

$$X_{n+1} = X_n - \frac{f(X_n)}{f'(X_n)} \quad (22)$$

$$f(I) = I_{sc} - I - I_0\left[\exp\left(q\frac{(v+I*R_s)}{\boldsymbol{n}*K*T}\right) - 1\right] = 0 \quad (23)$$

Then, Newton' equation:

$$I_{n+1} = I_n - \frac{I_{sc} - I_n - I_0 * \left[e^{q\frac{V+I_n*R_s)}{\boldsymbol{n}*K*T}-1}\right]}{-1 - I_0 * q * R_s * e^{q\frac{V+I_n*R_s)}{\boldsymbol{n}*K*T}}/\boldsymbol{n} * K}$$

The MATLAB function written to solve this equation performs the calculation five times iteratively to ensure convergence of the results.

3.3 Temperature and Solar Radiation Effects on PV Performance

The two most important effects that must be considered are due to the variable temperature and solar radiation. The effect of these two parameters must be taken into account while sizing the PV system.

3.3.1 Temperature Effect

This has an important effect on the power output from the cell. The temperature effect appears on the output voltage of the cell, where the voltage decreases as temperature increases. This decrease for silicon cell is approximately 2.3 mV per 1°C increase in the solar cell temperature. The solar cell temperature Tc can be found by the following equation [14]

$$T_c = T_a + \left(\frac{NOCT-20}{800}\right) E_i \qquad (25)$$

Where: - *Ta ambient* temperature in ºC, *Ei* solar radiation in W/m² NOCT: Normal Operating Cell Temperature which is defined as the cell temperature when the module operates under the following conditions at open circuit; Solar radiation = 800W/m² Spectral distribution =AM1.5 Ambient temperatures = 20ºC, Wind speed >1m/s.

3.3.2 Solar Radiation Effect

The solar cell characteristics are affected by the variation of illumination. Increasing the solar radiation increases in the same proportion the short circuit current. The following equation illustrates the effect of variation of radiation on the short circuit current:

$$I_{sc}(E_i) = I_{sc}\left(@\frac{100W}{m^2}\right) * \frac{(E_i(in\, W/m\hat{}2))}{1000} \qquad (26)$$

The output power from the PV cell is affected by the variation of cell temperature and variation of incident solar radiation. The maximum power output from the PV cell can be calculated using the following equation.

$$P_{out,cell} = P_{r,pv} * \frac{E_i}{E_{in}} * [1 + K_T(T_c - T_a)] \quad (27)$$

(K_T = - 3.7 x10 – 3 / 1°C for mono and poly crystalline Si)

The following equation can be used to calculate the cell temperature approximately if the NOCT is not given by the manufacturer.

$$T_c = T_a + 0.25 * E_i \qquad (28)$$

3.4 Simulation of solar PV array

The simulation of the Mat lab code program of the solar PV array based on the modeling equations is given bellow:

```
% Matlab simulation of Solar PV array
BAHIR DAR UNIVERSITY
% Written by TARIKU NEGASH March 2- 2013
%////////////////////////////////////////
///////////////////////////////
T=28+273;
Tr1=40; % Reference temperature in
degree fahrenheit
Tref=((Tr1-32)*5/9)+273; % Reference
temperature in kelvin
G=[100 80 60 40 20]; % Solar radiation
in MW/sq.m
%G=70;
ki=0.00023; % in A/K
Iscr=3.75; % SC Current at ref. temp. in
A
Irr=0.000021; % in A
k=1.38065*10^(-23); % Boltzmann constant
q=1.6022*10^(-19); % charge of an
electron
A=2.15;
Ego=1.166;
alpha=0.473;
beta=636;
Eg=Ego-(alpha*T*T)/(T+beta)*q; % band
gap energy
Np=4;
Ns=60;
V0=(0:1:300);
for i=1:5
Iph=(Iscr+ki*(T-Tref))*((G(i))/100);
I0(T)=Irr*((T/Tref)^3)*exp(q*Eg/(k*A)*(
(1/Tref)-(1/T)));
I0=Np*Iph-Np*
I0(T)*(exp(q/(k*T*A)*V0./Ns)-1);
P0 = V0.*I0;
figure(1)
plot(V0,I0);
axis([0 50 0 20]);
xlabel('Voltage in volt');
ylabel('Current in amp');
grid on
hold on;
figure(2)
plot(V0,P0);
axis([0 50 0 400]);
xlabel('Voltage in volt');
ylabel('Power in watt');
grid on
hold on;
figure(3)
plot(I0,P0);
axis([0 20 0 400]);
```

```
xlabel('Current in amp');
ylabel('Power in watt');
grid on
hold on;
end
```

4. RESULT AND DISCUSSION

4.1 The simulation results of Mat Lab 2007 software are as follows

The waveforms obtained by varying the solar insolation and at fixed temperatures which are fed into the PV array model have been plotted as shown below:

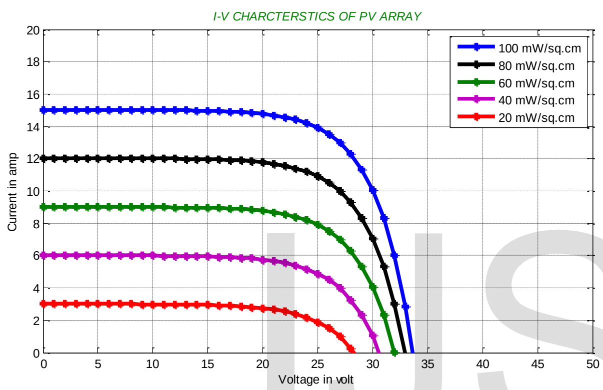


Figure 5.1 I-V curves obtained at 28°C for various irradiance levels.

According to the relation of the photocurrent to the irradiation, the short-circuit current ISC is linearly proportional to the solar radiation over a wide range. From Figure (5.1), we observed that by increasing the solar radiation at constant temperature the voltage is increased rapidly when compare to the increasing the output current from PV array also increases. Hence at higher insolation we can get our required level voltage. Since electric power is the product of current and voltage, I–V characteristic curve indicates the power delivered by a solar cell for a given radiation level.

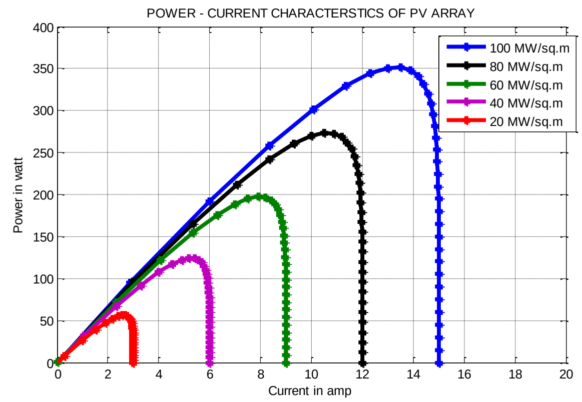


Figure 4.2 P-I curves obtained at 28°C for various irradiance levels

From figure (4.2), we observed that by increasing the solar radiation level, the current and power increased output from PV array increases and power is the product of voltage and current. From this at 100 MW/ m^2 we can get 350 Watt and about 15amp of voltage.

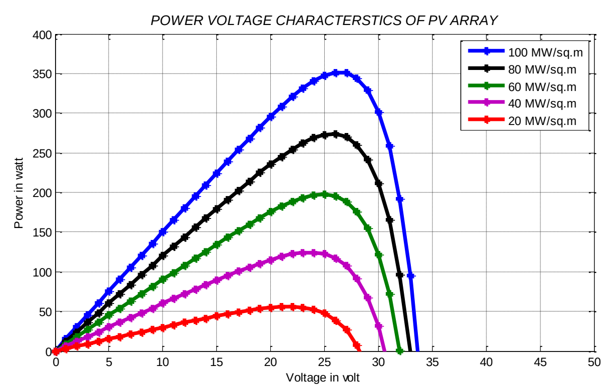


Figure 3.2 P-V curves obtained at 28°C for various irradiance levels.

From Figure (3.2), we observed that by increasing the solar insolation level, the power output highly increased than the increasing of voltage.

5. Conclusion and Recommendation

5.1 Conclusion

Solar cells in PV array work only in part of volt-ampere characteristic near working point where maximum voltage and maximum current is. We assume that photovoltaic system works most of time with maximum efficiency. It means that for modeling of PV cell we should use constants for specific kind of cell near working point. The performance of the photovoltaic device depends on the spectral distribution of the solar radiation.

5.2 Recommendation

To develop renewable energy sources from solar PV system, it is recommended to analyze the solar radiation characteristics since PV system mainly depends on solar insulation. And I will recommend making model and simulation on difference of temperature to see the effect of on PV array.

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