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# Analyzing Effects of Parameters and Partial Shadow on Characteristics of a Solar Module

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**Abstract:** *By presenting an analytical model of a PV cell as well as the whole panel this paper aims to investigate the effects of parameters and partial shadow on the energy output of various PV (Photo-Voltaic) module. Because of the practical strain of conducting experiments on diverse array sizes, a generalized MATLAB M-code has been advanced for any required array size, configuration, and shadow patterns. In this research work, we used some experimental models that can provide sufficient degree of precision without increasing the computational effort. We also observed the output power of a solar cell greatly depends on parasitic resistances and temperature. Moreover, this research work has examined the effects of temperature, series and shunt resistors on the output characteristics of a PV module along with partial shadowing effect on the performance of a solar panel.*

**Keywords:** *Parasitic resistance, Partial shadow, Photo-generated current, PV cells, STC.*

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## I. Introduction

A mathematical model of a solar cell is required to work within a simulation environment. Equivalent circuit of the cell should be more convenient and be in close characteristics to that of the practical. Hence, the number of unknown parameters also increase. But most of the manufacturer's datasheet does not provide sufficient information about the parameters that depend on weather conditions. So, in addition to the use of information provided by manufacturer assumptions are needed to establish a mathematical model of a **PV** cell as well as PV module (array of **PV** cells) **[1]**. Series and parallel resistances are not considered in some calculations. But to get a practical characteristic of a PV cell we need to take them into account. Three more parameters are to be determined as well- the photo-current ($I_{ph}$), the saturation current ($I_0$), the ideality factor ($A$).

## II. Mathematical modeling and presentation

Solar cell is a physical device that converts light into electrical energy. An equivalent circuit and corresponding mathematical model is needed to calculate the output power of a **PV** cell. We have considered several models of a **PV** cell. Though two or three **[11]** diode model of solar cell is available, we have considered single diode for simplicity.

**Single diode model:**

Since a **PV** cell is a p-n junction, it resembles diode property. A light generated current source and a diode connected in anti-parallel with it is assumed for the model of the **PV** cell. No other internal losses have been considered. The equivalent circuit is shown in figure-1.

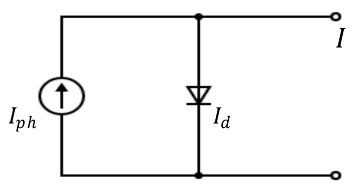



**Figure 1**: Ideal single diode model of a solar cell

The output current is obtained by applying Kirchhoff's current law.

$$I = I_{ph} - I_d \qquad \text{(i)}$$

Where $I_{ph}$ is photo-generated-current, $I_d$ is diode current that depends on the reverse diode saturation current ($I_0$)

$$I_d = I_0 \left[\exp\left(\frac{V.q}{A.N_S.k.T_c}\right) - 1\right] \qquad \text{(ii)}$$

Where $I_0$is the reverse saturation current of the diode, $V$is the voltage imposed on the diode, $T_c$is the cell temperature in kelvin (K), $k$ is the Boltzmann constant ($1.381\times10^{-23}$).
$N_s$ is the number of diodes connected in series. This situation arises when we use array of cells in case of practical fabrication.
$A$is the diode ideality factor which depends on the technology of the **PV** cell. The value of $A$is constant for a specific technology. Table-1 shows ideality factor of some technology.

**Table 1**: Ideality factor (**A**), Huan-Liang et al.,2008 [2]

| Technology | Ideality factor |
|---|---|
| Si-mono | 1.2 |
| Si-poly | 1.3 |
| a-Si-H | 1.8 |
| a-Si-H tandem | 3.3 |
| a-Si-H triple | 5 |
| CdTe | 1.5 |
| CTs | 1.5 |
| AsGa | 1.3 |

The term $k.T_c/q$in equation (ii) is called thermal-voltage for its exclusive dependence on temperature [3], and is expressed as $V_T$

$$V_T = \frac{k.T_c}{q} \qquad \text{(iii)}$$

The whole term divides $V$in equation (ii) is called modified ideality factor '$a$' [4].

$$a = \frac{A.N_S.k.T_c}{q} = A.N_S.V_T \qquad \text{(iv)}$$

**Practical model with $R_s$**

In practice it is impossible to neglect the series resistance. If we notice the short-circuit condition, total voltage drops across this parasitic series resistance. In this model we'll consider a series resistance along with ideal single diode model.

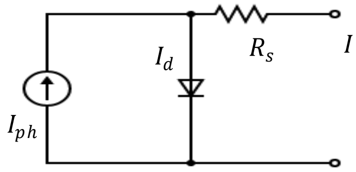



**Figure 2**: Practical model of a solar cell with $R_s$

If we consider the series resistance, the equation (ii) can be re-written as –

$$I_d = I_0 \left[exp\left(\frac{V+I.R_s}{a}\right) - 1\right] \qquad \text{(v)}$$

Although this model does not provide the practical characteristics of a solar cell, it is closer than that of ideal single diode model. Internal leakage current through shunt resistance is not considered here.

**Practical model with $R_s$and $R_p$**

Total photo-generated current does not reach to the load in any of the models. Small amount of current leaks through the diode. But in real case more loss of internal current occurs. Observing the data of physical device response, it can be concluded that there is another resistive component that draw current internally **[2]**. This model consists of a shunt resistance along with $R_S$model. The equivalent circuit is shown in Fig-3.

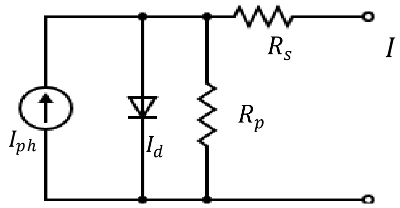



**Figure 3**: Practical model of a solar cell with $R_s$ and $R_p$

The output current is obtained by applying Kirchhoff's current law –

$$I = I_{ph} - I_d - I_p \qquad \text{(vi)}$$

$I_p$ is the current leak through parallel (shunt) resistor. The value of this current is -

$$I_p = \frac{V + I.R_s}{R_p} \qquad \text{(vii)}$$

In this model the output current of a module containing $N_s$ cells in series is –

$$I = I_{ph} - I_0 \left[exp\left(\frac{V + I.R_s}{a}\right) - 1\right] - \frac{V + I.R_s}{R_p} \qquad \text{(viii)}$$

Other models are containing two diodes, but with the appropriate value of shunt resistor, this model very closely resembles the experimental values and has less complexity in calculation.

## III. Parameter determination

Different model considers different number of parameters to characterize a solar cell. Four parameters are considered in this work and they are $I_{ph}, I_0, R_s, R_p$.

**Determination of photocurrent ($I_{ph}$)**

According to single diode model (*Fig. 1*) the output current is:

$$I = I_{ph} - I_0 \left[exp\left(\frac{V}{a}\right) - 1\right] \qquad \text{(ix)}$$

We can find $I_{ph}$ from this relation, that cannot be determined otherwise. When the **PV** cell is short circuited:

$$I_{short} = I_{ph} - I_0 \left[exp\left(\frac{0}{a}\right) - 1\right] = I_{ph} \qquad \text{(x)}$$

This equation can determine $I_{ph}$ only in ideal case. In practical case where parasitic resistances are present this equation is not correct. But it is a close approximation. So, we can rewrite the equation as:

$$I_{ph,ref} \approx I_{short,ref} \qquad \text{(xi)}$$

$I_{ph,ref}$ is photo-generated current in STC. In real weather condition the photo-current depends on both irradiance and temperature:

$$I_{ph} = \frac{G}{G_{ref}}\left(I_{ph,ref} + \mu_{SC}.dT\right) \qquad \text{(xii)}$$

Where, $G$: Irradiance (W/m$^2$), $G_{ref}$: Irradiance at $STC = 1000\, w/m^2$, $dT = T_c - T_{c,rerf}$ (Kelvin), $T_{c,rerf}$: Cell temperature at $STC = 25 + 273 = 298\, K, \mu_{SC}$: Temperature coefficient of short circuit current (A/K), provided by the manufacturer. A table of PWX 500 PV module (49 W) is shown here as an example.

**Table 2**: PWX 500 PV module characteristics [1]

| Parameters | Values |
|---|---|
| $P_{mp}$(w) | 49 |
| $I_{mp}$(A) | 2.88 |
| $V_{mp}$(V) | 17 |
| $I_{SC}$(A) | 3.11 |
| $V_{OC}$(V) | 21.8 |
| $R_S$(Ω) | 0.55 |
| $\mu_{SC}$(A/K) | $1.3*10^{-3}$ |
| $N_S$ | 36 |

**Determination of reverse saturation current of diode ($I_0$)**

The shunt resistance is regarded as great so the last term of equation (viii) can be neglected. For this approximation we will consider three test conditions- the voltage at open circuit, the current at short circuit, the voltage and the current at maximum power point. So, we will get the following equations:

$$I_{short} = I_{ph} - I_0 \left[exp\left(\frac{I_{short}.R_s}{a}\right) - 1\right] \quad \text{(xiii)}$$

$$0 = I_{ph} - I_0 \left[exp\left(\frac{V_{oc}}{a}\right) - 1\right] \quad \text{(xiv)}$$

$$I_{mp} = I_{ph} - I_0 \left[exp\left(\frac{V_{mp} + I_{mp}.R_s}{a}\right) - 1\right] \quad \text{(xv)}$$

From equation (xi) and (xiv) we can write:

$$0 \approx I_{short} - I_0 \left[exp\left(\frac{V_{oc}}{a}\right) - 1\right] \quad \text{(xvi)}$$

Since (-1) is very small compared to exponential term, it can be neglected from these above equations. Hence the reverse saturation current in standard test condition can be written as:

$$I_0 = I_{short}.exp\left(\frac{-V_{oc}}{a}\right) \quad \text{(xvii)}$$

But in any weather condition the reverse saturation current (of diode) depends on device temperature(K), band gap of material(eV), diode diffusion factor, diode ideality factor.

$$I_0 = D.T_c^3.exp\left(\frac{-q.E_G}{A.k}\right) \quad \text{(xviii)}$$

Where, $D$: diode diffusion factor, $A$: diode ideality factor, $E_G$: band gap of material, $q$: charge of electron, $T_c$: Cell temperature in Kelvin, $k$: The Boltzmann constant ($1.381\times10^{-23}$).

To get rid of calculating diode diffusion factor, equation (xvii) is calculated twice: at $T_c$ and at $T_{c,ref}$. Then the ratio of them is written as:

$$I_0 = I_{0,ref}.\left(\frac{T_c}{T_{c,ref}}\right)^3.exp\left[\left(\frac{q.E_G}{A.k}\right)\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right] \quad \text{(xix)}$$

$I_{0,ref}$ is saturation current corresponding to $T_{c,ref}$.

### Determination of $R_s$ and $R_p$

Though there are models including two diodes [**7**] that is closest model, we can calculate a verypractical characteristics of solar cell with this model (2.3) taking appropriate value of resistance which requires less complexity of calculation.

$R_p$ and $R_s$ are chosen so that computed maximum power $P_{mp}$ be equal to practical maximum power $P_{mp,ex}$. So, we can write [1]:

$$I_{mp,ref} = \frac{P_{mp,ref}}{V_{mp,ref}} = \frac{P_{mp,ex}}{V_{mp,ref}} = I_{ph,ref} - I_{0,ref}\left[exp\left(\frac{V_{mp,ref} + I_{mp,ref}.R_s}{a}\right) - 1\right] - \frac{V_{mp,ref} + R_s.I_{mp,ref}}{R_p} \quad \text{(xx)}$$

$$R_p = \frac{V_{mp,ref} + I_{mp,ref}.R_S}{I_{sc,ref} - I_{sc,ref}\left\{exp\left[\frac{V_{mp,ref} + I_{mp,ref}.R_S - V_{oc,ref}}{a}\right]\right\} + I_{sc,ref}\left\{exp\left(\frac{-V_{oc,ref}}{a}\right)\right\} - \frac{P_{max,ex}}{V_{mp,ref}}} \quad \text{(xxi)}$$

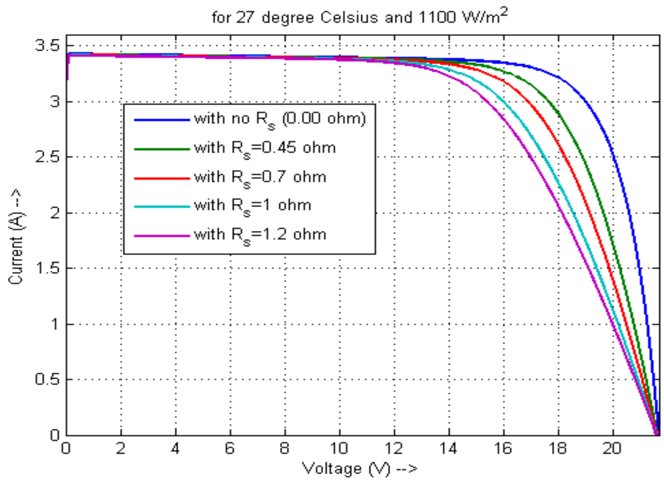
In this case, calculation starts at $R_s = 0$ which is increased gradually in order to move modeled maximum power point upto the experimental maximum power point. The corresponding $R_p$ is then calculated with equation (xx) and only one pair of $R_s$ and $R_p$ satisfies the condition.

## IV. Effect of parasitic resistance

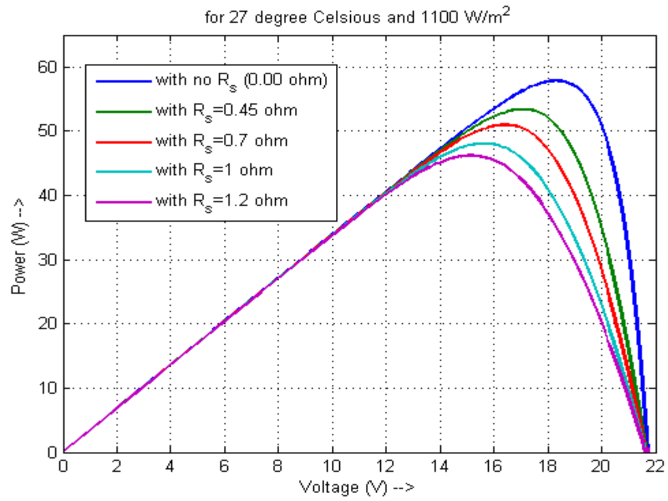
While fabricating photovoltaic cells, some unexpected resistances are automatically generated **[13]**. These resistances are called parasitic resistance. They are present both in series and parallel within the cell.In equation(viii), both of the negative terms contain $R_s$in the numerator and one term contain $R_p$in the denominator. So high value of $R_s$ will result low output current and high value of $R_p$ will result high output current close to $I_{ph}$.

### Effect of series resistance

Unfortunately, PV cells conforms some parasitic resistance both in series and in parallel with the photogenerated current source. A fraction of photogenerated voltage drops across series resistance hence we get reduced amount of voltage at the load. The value of dropped voltage depends on the value of series resistance and the amount of current flowing through the resistance. Since the current flowing through this resistance directly depends on the operating voltage of the cell, the dropped voltage depends on the operating voltage, in other wordsfor a fixed series resistance. Moreover, the output current faces more difficulty while passing through the series resistance, hence output current also gets reduced. The value of resistance depends on the manufacturing of the cell. **Fig.-4** illustrates the effect of series resistance by considering voltage-current and voltage-power relationship for different values of series resistance. The higher the series resistance the more it affects the output characteristics. The degraded power will be converted to heat that will increase the temperature of the device. For 5 different value of $R_s$ in 27 degree Celsius, current versus voltage and power versus voltage are computed as:




(a)




(b)

**Figure 4**: Effect of series resistance on a solar cell, (a) current - voltage relation, (b) power- voltage relation.

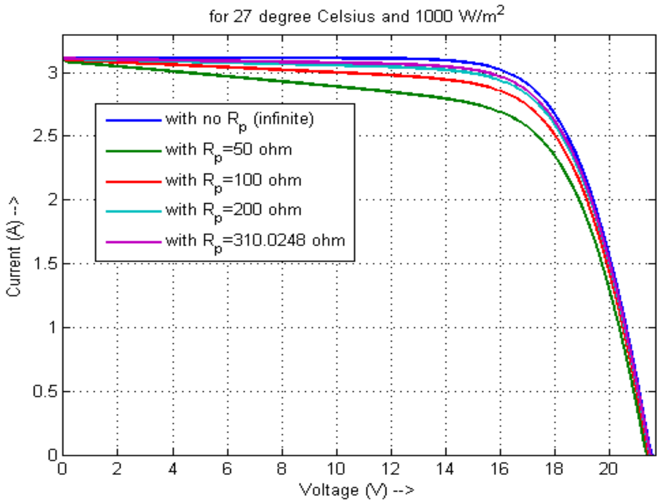
Module with 36 series cell is considered here and manufacturer data from PWX 500 PV module is used in this calculation. The value of $R_p$ is considered as $310.0248\Omega$

**Effect of shunt resistance**

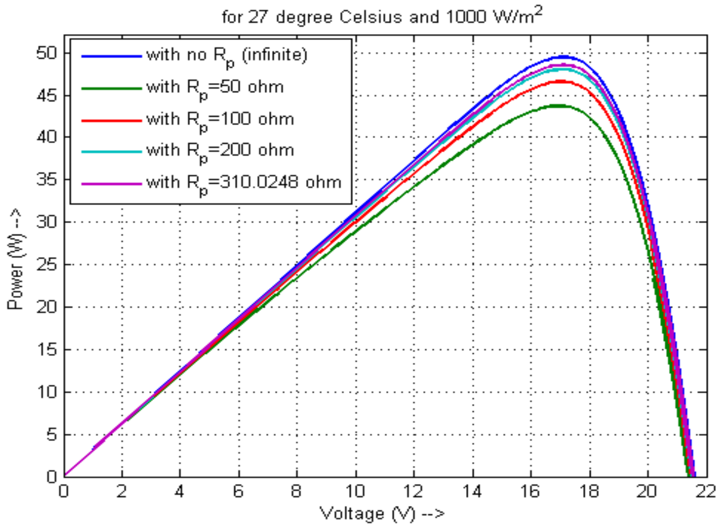
A fraction of photogenerated current flows through the parasitic shunt resistance internally thus it wastes power. Amount of leaked current through the shunt resistance depends on the voltage across the resistance and the value of resistance. Since the current depends on voltage in proportional manner and on resistance in inverse proportional manner, higher voltage would result higher current and higher resistance would result less current.

The effect of shunt resistance is illustrated in **Fig. 5** where voltage-current and voltage-power relation is shown for different values of shunt resistance. It is clear from the figure that the higher the shunt resistance the better the output current and power. And this resistance affects power from low voltage significantly.

For 5 different values of $R_p$ in 27 degree Celsius, current versus voltage and power versus voltage are computed as:




(a)




(b)

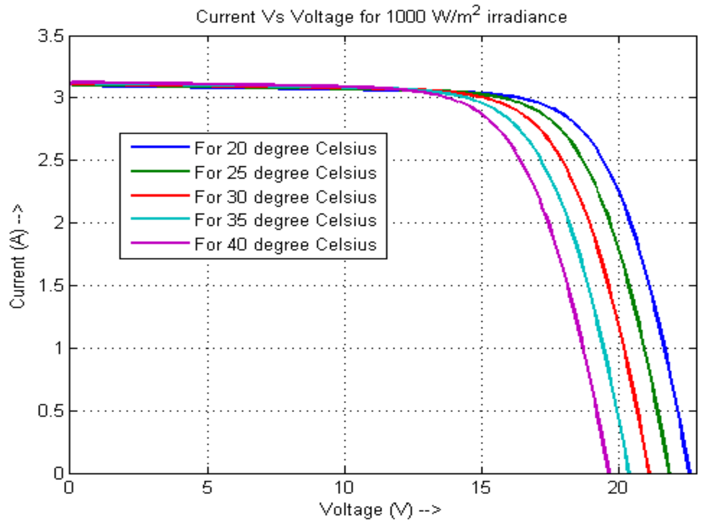
**Figure 5**: Effect of parallel resistance on a solar cell, (a) Effect on current, (b) Effect on power

The value of $R_s$ is considered as 0.45Ω here.

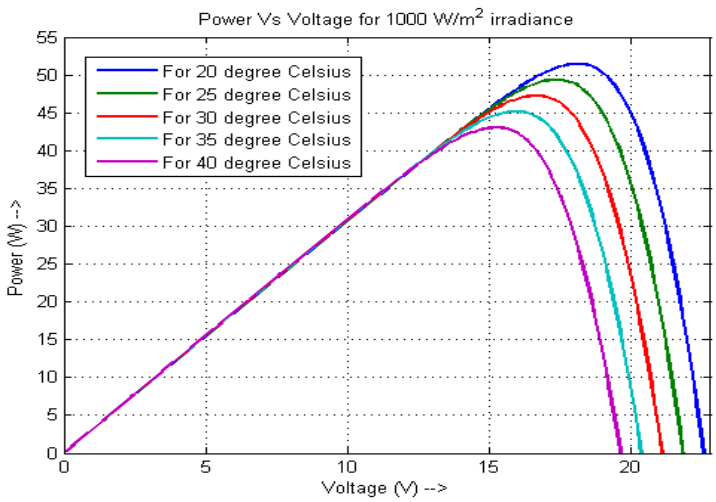
## V. Effect of temperature

Power conversion efficiency of a solar panel is inversely proportional to its operating temperature **[12]**. Since solar cell contains a diode property, it leaks some current internally. The value of leakage current increases with temperature. This current is the fraction of photogenerated current that was to reach the output. Reverse saturation current of internal diode controls the current leakage through the diode and that saturation current depends on the temperature **[6]**. In practice, a threshold voltage is required for a diode to start flowing current, so high temperature also affects output characteristics of a solar cell in high operating voltage. **[8]**

The output current and power curves for different temperature is calculated and graphed as **Fig. 6**.




(a)




(b)

**Figure 6**: Effect of temperature on a solar cell, (a) Effect on current, (b) Effect on power

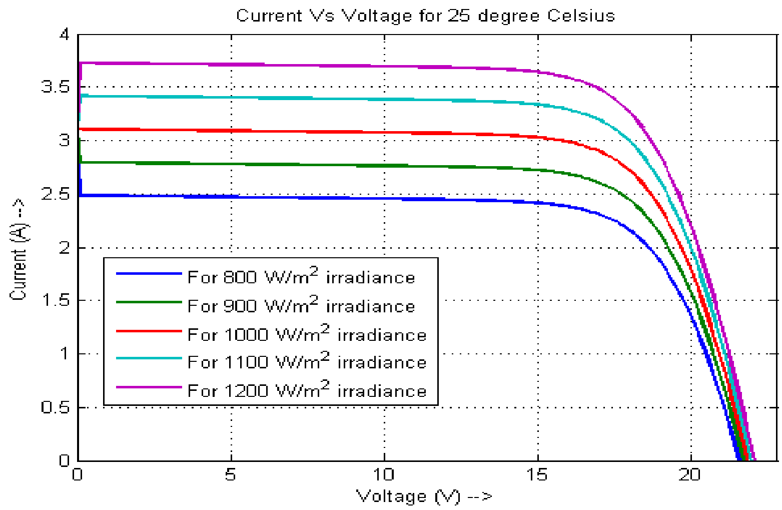
## VI. Effect of irradiance

In rough sense, the total output power of the PV cell is from the light power. So, output power directly depends on the illumination. Though all of the incident photons are not absorbed by the system, probability of absorbable photons being available gets higher for high power illumination from sufficient hot light source. Photo-current directly depend on the irradiance upon the cell. From equation-(xi):

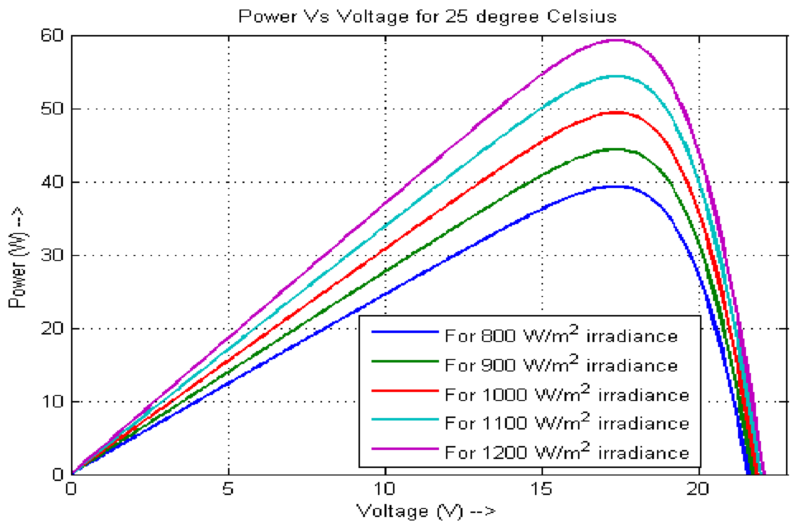
$$I_{ph} = \frac{G}{G_{ref}}\left(I_{ph,ref} + \square_{sc}.dT\right)$$

So, the ratio of incident irradiation to the reference irradiation is significant to know the output power relative to the rated power by manufacturer. **[9]**

Output characteristic curves for different irradiance is as follow:




(a)




(b)

**Figure 7**: Effect of irradiance on a solar cell, (a) Effect on current (b)Effect on power

**Characteristics for combination of modules**

Solar cells are connected in series as well as parallel connection to form a solar module and several modules are connected to form solar array. For combination of cells we get different characteristics than that of a single cell. Individual cells may have different weather conditions and electrical parameters. They act differently for series and parallel combination.

**Characteristics for parallel combination**

When two mismatched cells connected in parallel, overall performance is limited by low power cell **[10]**. Low power cell may be damaged, under shadow or in high temperature. The graph below shows how to get combined current of mismatched cells in parallel.

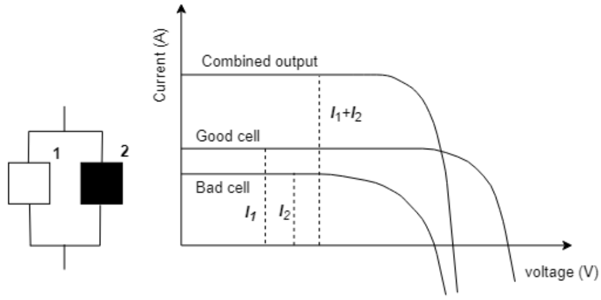



**Figure 8**: Mismatch of two parallel connected solar cells [10].

Current from the combination can be achieved by simply adding the individual currents. But there is a moderate level of open circuit voltage. If we just reflect one curve for one cell in the voltage axis, we get $(V_{oc})$ of the combination at the intersecting point.

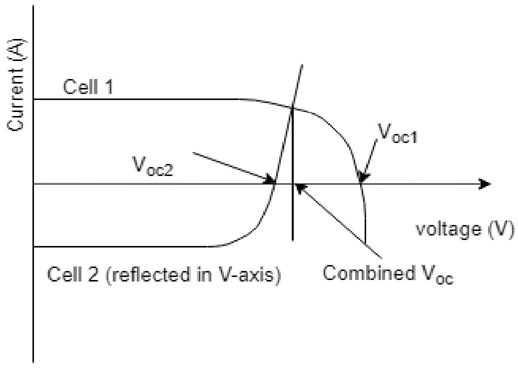



**Figure 9**: Open circuit voltage of two parallel combination of solar cells [10].

We can also get the characteristics of the combined modules with the same procedure.

For 36 series cells per panel, current for parallel combination is as follows:

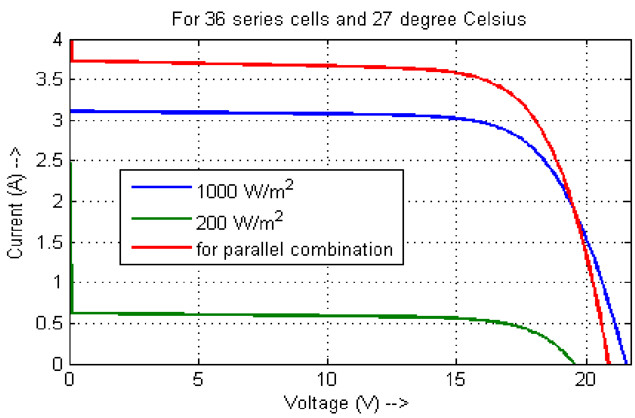



**Figure 10**: Output characteristic of two 36 cell panel solar cells under different illumination connected in parallel.

Here one module is under 200 W/m$^2$ and another is under 1000 W/m$^2$ illumination.

**Characteristics for series combination**

For series combination, combined open circuit voltage $(V_{oc})$ is the summation of individual open circuit voltages and current remains almost same as that of a single cell. For parallel combination, short circuit current $(I_{sc})$ of the combination is the summation of individual short circuit currents and open circuit voltage of the combination remains almost same as that of a single cell. Eventually power is added with addition of each cell. The scenario is as follows:

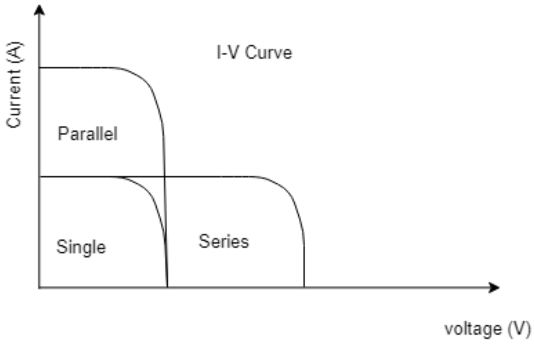


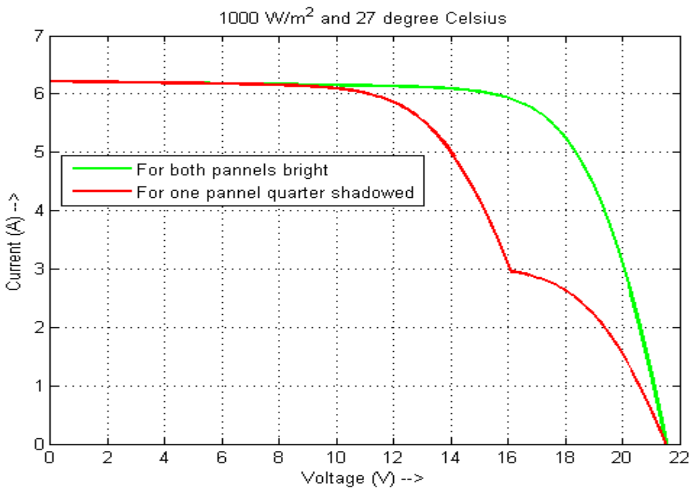

**Figure 11**: Alteration of characteristics of solar cell when extra cells are added in series and parallel.

From **Fig. 9** we can get that open circuit voltage gets higher and maximum power point moves to higher voltage if we connect cells in series. Same characteristics can be found if we work with whole module in place of a single cell.

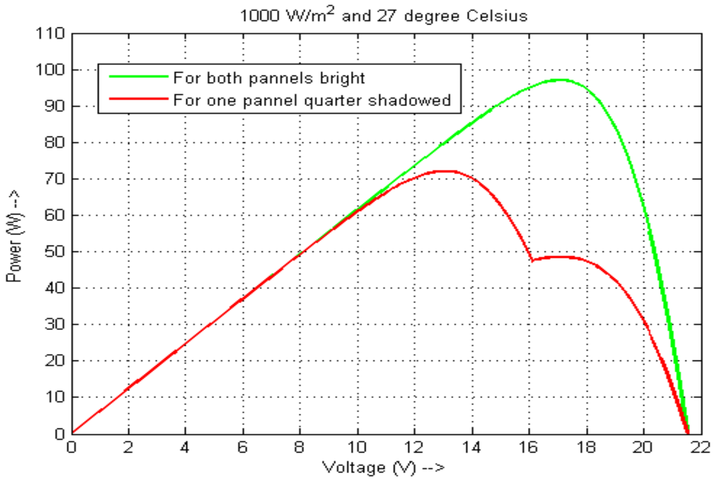
**Effect of partial shadow**

In case of whole module, large number of cells are in series (e.g. 36, 54). When in the module one or more cell become shaded, it stops generating current and works as a diode. But voltage generated from other cells drives shaded cells into reversed biased condition. This reversed bias could be very strong depending on the ratio of the number of illuminated cells and dark cells. High reverse bias voltage may reach upto the breakdown voltage of dark cell working as a diode. The shaded cell may survive from damaging, but it could produce a lot of heat locally as a result power generated by the illuminated cell may dissipated in dark cell. To get rid of this heating problem, the general solution is to connect a bypass diode on each module. It is connected in parallel with the solar cell with opposite polarity so that in normal condition the bypass diode operates in reverse bias condition, effectively open circuit condition and in shaded condition bypass diode can bypass the current generated from the illuminated cells, effectively short circuit condition. Thus, insertion of bypass diode can help a dark cell to avoid local heating or hot spot in series connection. When a module faces a partial shadow, we can get almost whole power generated from illuminated cells because of bypass diode.

If we connect two modules in parallel and apply partial shadow on one or both of the modules, we get the power generated from the illuminated cells via bypass diode. In this case for the module under partial shadow provides less open circuit voltage. And when we connect modules in parallel, the outputs are as follows:




(a)




(b)

**Figure 12**: Output characteristic of two 36 cell panel solar cells connected in parallel (one panel quarter shaded), (a) Output voltage versus current, (b) Output voltage versus power.

## VII. Summery and conclusion

In this paper, we have investigated interconnected PV arrays by adopting some existing PV module model. From different experiments, it is proven that partially shading effects change the maximum power point of PV arrays. Moreover, currently, the household and industrial demand for power can be met with a smart solar powered grid. Solar panel which is an outdoor module faces different weather conditions. Knowledge about the behavior of solar panels in different temperature can be handy while estimating solar powered power grid. From this work, it is also clear that power from solar panel is inferior in high temperature. Study about internal parasitic resistance effect is very useful for manufacturing solar panel to meet the specific power requirement. We observed thatat maximum power point, power is 57.84W and 46.1915 W respectively for 0 Ω and 1.2 Ω series resistance and it is 49.4393 W for infinite shunt resistance whereas 48.5068 W can be gained for 310.0248 Ω shunt resistance.So, Maximum possible shunt resistance and minimum possible series resistance is desirable to get better power form a solar panel. Finally, we also analyze the effects of parasitic resistance and cell temperature.

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