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ESTIMATION OF IDEALITY FACTOR AND FILL FACTOR OF A PHOTOVOLTAIC MODULE

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Abstract-*To determine the quality of a PV cell/module, ideality factor and fill factor both play an important role. To estimate ideality factor from photovoltaic (PV) module some cases have been studied analytically. The cases depend on the generalized equivalent circuit, approximate equivalent circuit and simplified or ideal equivalent circuit of the photovoltaic module as well as photovoltaic cell. The following cases are treated separately: infinite shunt resistance and zero series resistance; finite shunt resistance or finite series resistance; finite shunt resistance and finite series resistance. To estimate fill factor, variation of fill factor with temperature is done. The values of ideality factor are found in the range of 1.55~1.7 and the fill-factor is in the range of 0.7~0.8.*

Keywords: Photovoltaic module, Equivalent circuits, Ideality factor, Fill factor, and Manufacturer's data

1. INTRODUCTION

A solar cell or photovoltaic cell is a device that converts solar energy into electricity by the photovoltaic effect. Photovoltaics are the field of technology and research related to the application of solar cells as solar energy. Assemblies of cells are used to make solar modules, which may in turn be linked in photovoltaic arrays. The performance of solar cell is normally evaluated under the Standard Test Conditions (STC), where an average solar spectrum at air mass (AM) 1.5 is used, the solar irradiance (i.e. insolation) is normalized to 1000W/m^2, and the cell temperature is 25^{0}C [1].

It is not easy to determine the quality of PV module in the field based on specification data provided in the manufacturers' datasheets because photovoltaic module temperature increases from 20^{0}C to 40^{0}C by comparing with outdoor temperature at clear day. During winter season, the temperature becomes less compared to summer season. Therefore, the measurement of ideality factor and fill factor is very necessary to evaluate the quality of PV module for changing weather conditions. We use KC40REB 40-watts high efficiency multi-crystalline photovoltaic module for estimating the ideality factor and fill factor.

Several works had done for estimating the ideality factor of a PV module. Phang et al. [2] proposed an analytical method for the rapid extraction of solar cell single-diode model parameters, namely series resistance R_s, photo generated current J_{ph}, saturation current J_0 and junction ideality factor n. However, the maximum power point, i.e. V_m and J_m, and R_{sh0} as well as R_{s0} must be known before calculating these parameters when using this method. Authors in [3] presented a direct method to measure n from the illuminated output J-V curve. With this method, junction ideality factors n of silicon solar cells of different structures are measured in the range 1.25-1.89. Compared with other methods, this method was used to measure n directly from the illuminated output J-V curve.

Authors in [4] presented single diode model parameters of solar cells which are extracted based on a new approach where the diode junction ideality factor is taken as an output characteristic dependent parameter. Compared to the conventional analytical methods where a constant diode junction ideality factor is assumed along the entire I-V curve, it is believed that the present method gives much more reasonable results for the diode model parameters. Authors in [5] described a method to determine value of ideality factor of solar cell from I–n plot using Lambert W-function. An explicit relation between n and I was determined at V=V_{oc} for plot.

In this paper, we measure the ideality factor from the manufacturer's data sheet directly for a PV module and use the similar concept as mentioned in [3]. We also measure the ideality factor analytically for different equivalent circuit of a PV module. Normally the ideality factor varies from 1 to 2 and fill factor varies from 0 to 1. To determine fill factor, variation of fill factor with temperature is observed.

This paper is organized as follows: Section 2 describes the PV model under different approaches. Section 3 explains the estimation of ideality factor of a PV module and results. Section 4 shows the estimation of fill factor. Finally, section 5 concludes the entire paper.

2. PV CELL AND MODULES

This section describes the basics of photovoltaic cell and module which are used to determine the analytical expression of ideality factor and fill factor.

2.1 Photovoltaic cell

A PV system not only consists of PV modules but also involves good deal of power electronics as an interface between PV modules and load for effective & efficient utilization of naturally available sun power [1]. A solar cell basically is a p-n semiconductor junction. When exposed to light, a current proportional to solar irradiance is generated [6]. Recently, it has been reported that experimental crystalline silicon solar cells have reached a confirmed efficiency of 24.7% & that commercial cells of 17-18% efficiency are now available [7]. Experimenting with actual PV cells in the laboratory is often an expensive and time consuming technique [8]. A PV cell is a basic unit that generates voltage in the range of 0.5 to 0.8 volts depending on cell technology being used [1].

2.2 Equivalent Circuit of a PV Cell

Figure 1 shows the equivalent circuit of an ideal photovoltaic cell as well as a practical PV cell. The basic I-V characteristics equation for the ideal PV cell is

$$I = I_{ph} - \underbrace{I_0\left[\exp\left(\frac{qV}{nkT_c}\right) - 1\right]}_{I_d} \tag{1}$$

Eq. (1) does not represent the practical I-V characteristics of PV cell. It includes the series and shunt resistance with the ideal PV cell which is shown in Fig. 1. Therefore, the *I-V* characteristic equation of a practical PV cell is given by Eq. (2) and the *I-V* characteristics curve is shown in Fig. 2.

$$I = I_{ph} - I_0\left\{\exp\left(\frac{q(V + IR_S)}{nkT_c}\right) - 1\right\} - \frac{V + IR_S}{R_{sh}} \tag{2}$$

Here, I_{ph} = generated photo-current (A), I_0=reverse saturation current (A), R_s=series resistance (Ω), R_{sh}=shunt resistance (Ω), n=ideality factor, T_c=absolute temperature (^{0}K), q=charge constant (1.602×10^{-19}C), k=Boltzmann constant (1.38×10^{-23} J/^{0}K), I=photovoltaic cell output current (A), and V=photovoltaic cell output voltage (V). Equation (2) describes the single-diode model representation of a PV cell. Here $V_{sh}=V+R_sI$, is the voltage across the diode or R_{sh}.

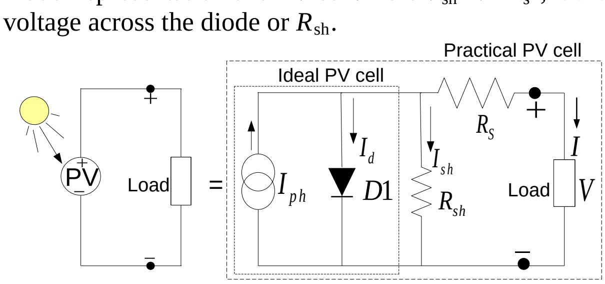

Fig1. Single-diode (1-D) model of an ideal photovoltaic cell and equivalent circuit of a practical PV cell including R_s and R_{sh}

The electrical power available from a PV device can be modeled with the well-known equivalent circuit shown in Fig. 1 [6, 8]. The circuit shown in Fig. 1 can be used for an individual cell, for a module consisting of several cells, or for an array consisting of several modules. Detailed descriptions were found in [9]. Moreover, the *I-V* characteristics equation of a PV cell can be expressed by using *J-V* characteristics equation, which is given in Eq. (3).

$$J = J_{ph} - J_0\left\{\exp\left(\frac{V + JR_S}{nV_t}\right) - 1\right\} - \frac{V + JR_S}{R_{sh}} \tag{3}$$

where, $V_t = kT_c / q$ is thermal voltage.

2.3 PV Module

Since a single PV cell produces an output voltage less than 1volt or 2W, it is necessary to string together a number of PV cells in series to achieve a desired output voltage. Cells connected in parallel increase the current and cells connected in series provide greater output voltage. If N_s cells are connected in series, then the value of voltage and current of the module may be expressed as:

$$\begin{aligned} &I_{phm} = I_{ph},\quad I_{dm} = I_d,\quad I_{om} = I_o \\ &R_{sm} = R_s N_s,\quad R_{shm} = R_{sh} N_s,\quad V_{pvm} = N_s V \end{aligned} \tag{4}$$

If the array is composed of N_p number of parallel cells the photovoltaic and saturation currents may be expressed as:

$$\begin{aligned} &I_{phm} = N_p I_{ph},\quad I_{dm} = N_p I_d,\quad I_{om} = N_p I_o, \\ &I_{pvm} = I,\ R_{sm} = \frac{R_s}{N_p},\quad R_{shm} = \frac{R_{sh}}{N_p}, V_{pvm} = V \end{aligned} \tag{5}$$

where, the subscript '*m*' stands for module and V_{pvm} and I_{pvm} stand for voltage and current across the output terminal of the module, respectively. Therefore, the general equivalent circuit for the solar module using N_p parallel connected cells and N_s series connected cells is shown in Fig. 2.

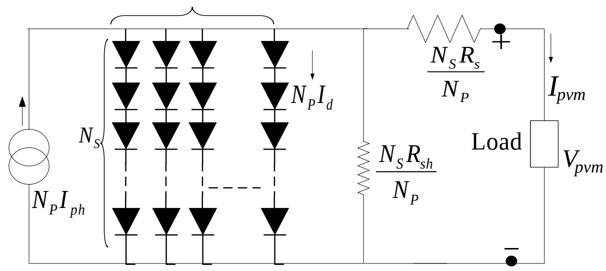

Fig. 2 General equivalent circuit of a PV module

$$I_{pvm} = I_{sm} - I_{0m}\left\{\exp\left(\frac{\frac{V_{pvm}}{N_S} + \frac{I_{pvm}R_S}{N_P}}{nV_t}\right) - 1\right\} - \left(V_{pvm} + R_s\frac{N_s}{N_p}I_{pvm}\right)\Big/\left(R_{sh}\frac{N_s}{N_p}\right) \tag{6}$$

For any given module formed by $N_S \times N_P$ identical cells, the expression of output current using the 1-D model is given by Eq. (6). Now, Eq. (6) can be rewritten as Eq. (7).

$$I_{pvm} = I_{phm} - I_{0m}\left\{\exp\left(\frac{N_p V_{pvm} + I_{pvm} N_s R_s}{n V_t N_S}\right) - 1\right\} - \frac{V_{pvm} N_P + N_S R_s I_{pvm}}{R_{sh} N_S N_P} \quad (7)$$

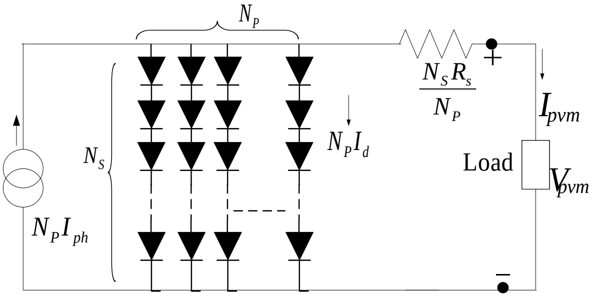

Fig. 3 General approximate equivalent circuit of a PV module

Usually, the efficiency of a PV module is sensitive to a small change in R_S but insensitive to R_{sh}. Therefore, R_s is important to consider rather R_{sh} for a PV module. In most cases, PV cells are connected in series to form a PV module in order to obtain sufficient working voltage. An approximate equivalent circuit of a PV module is shown in Fig. 3. This circuit is governed by Eq. (8).

$$I_{pvm} = I_{phm} - I_{0m}\left\{\exp\left(\frac{N_p V_{pvm} + N_s R_s I_{pvm}}{n V_t N_S}\right) - 1\right\} \quad (8)$$

Alternately, another approximate equivalent circuit of a PV module is shown in Fig. 4 by considering the shunt resistance rather series resistance and is governed by Eq. (9).

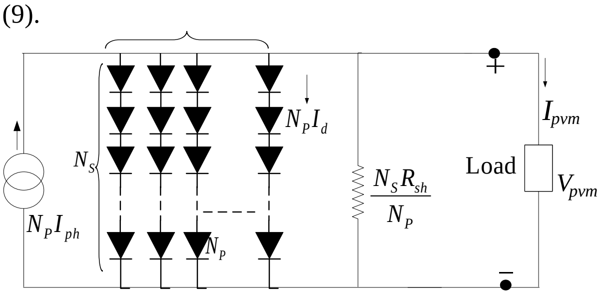

Fig.4 General approximate equivalent circuit of a PV module

$$I_{pvm} = I_{phm} - I_{0m}\left\{\exp\left(\frac{N_p V_{pvm}}{n V_t N_S}\right) - 1\right\} - \frac{V_{pvm}}{R_{sh} N_S} \quad (9)$$

The most simplified model of the generalized PV module is shown in Fig. 5. The simplified equivalent circuit is described by Eq. (10).

$$I_{pvm} = N_p I_{ph} - N_p I_0\left\{\exp\left(\frac{N_p V_{pvm}}{n V_t N_S}\right) - 1\right\} \quad (10)$$

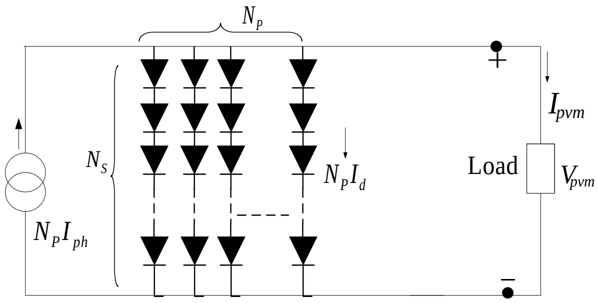

Fig. 5 General equivalent circuit of a simplified PV module

3. ESTIMATION OF IDEALITY FACTOR

The ideality factor is a fitting parameter that describes how closely the diodes behavior matches the predicted by theory, which assumes the p-n junction of the diode is an infinite plane and no recombination occurs within the space charge region. A perfect match to theory is indicated when recombination in the space charge region dominate other recombination, however, n=2 for most solar cells, which are quite large compared to conventional diodes, well approximate an infinite plane and will usually exhibit near-ideal behavior under STC (n=1). Under certain operating conditions, device operation may be dominated by recombination of the space charge region. This is characterized by a significant increase in I_0 (reverse saturation current) as well as in ideality factor to n=2.

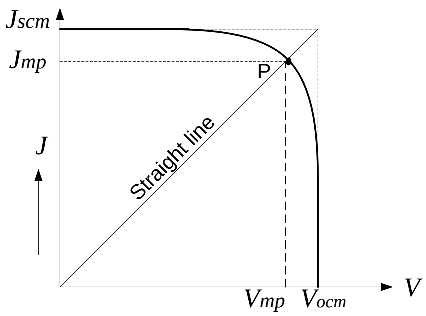

Fig. 6 The illuminated output J-V curve of a solar module

3.1 Analytical Analysis of Ideality Factor

Case 1: *For the generalized equivalent circuit of a PV module*

Figure 6 is a typical illuminated output *J-V* curve of a solar module, at STC, where P, which is not at the maximum power point, is a point of intersection of the straight line and illuminated output $J - V$ curve of a PV module. In Fig. 6, V_{ocm} and J_{scm} are open circuit voltage and short circuit current of a PV module. The coordinates of P are (V_{mp}, J_{mp}). Clearly, the equation of the straight line is

$$J = \frac{J_{mp}}{V_{mp}} V = \frac{J_{scm}}{V_{ocm}} V \quad (11)$$

The equation of illuminated output *J-V* curve of a solar cell was expressed in Eq. (7). In terms of current density, Eq. (7) can be written for the module as

$$J_{pvm} = J_{phm} - J_{0m}\left\{\exp\left(\frac{N_p V_{pvm} + J_{pvm} N_s R_s}{nV_t N_S}\right) - 1\right\} - \frac{V_{pvm} N_P + N_S R_s J_{pvm}}{R_{sh} N_S N_P} \tag{12}$$

Let us assume $r_s = N_S R_S$, $v_t = N_S V_t$, $v_{pvm} = N_P V_{pvm}$, $r_{sh} = N_S N_P R_{sh}$. Therefore Eq. (7) can be re-written as

$$J_{pvm} = J_{phm} - J_{0m}\left\{\exp\left(\frac{v_{pvm} + J_{pvm} r_s}{nv_t}\right) - 1\right\} - \frac{v_{pvm} + r_s J_{pvm}}{r_{sh}} \tag{13}$$

With J_{pvm}=0, we get V_{pvm}=V_{ocm},

$$0 = J_{phm} - J_{0m}\left\{\exp\left(\frac{V_{ocm}}{nv_t}\right) - 1\right\} - \frac{V_{ocm}}{r_{sh}} \tag{14}$$

Let us assume that the ratio of V_{mp} and V_{ocm} is p, i.e.

$$p = \frac{V_{mp}}{V_{ocm}} \tag{15}$$

At maximum power point condition, V_{pvm}=V_{mp} and J_{pvm}=J_{mp}

$$J_{mp} = J_{phm} - J_{0m}\left\{\exp\left(\frac{V_{mp} + r_s J_{mp}}{nv_t}\right) - 1\right\} - \frac{V_{mp} + r_s J_{mp}}{r_{sh}} \tag{16}$$

After some manipulations, we get Eq. (17) from Eq. (16)

$$pJ_{scm} = J_{phm} - J_{0m}\left\{\exp\left(\frac{pV_{ocm} + r_s pJ_{mp}}{nv_t}\right) - 1\right\} - \frac{pV_{ocm} + r_s pJ_{scm}}{r_{sh}} \tag{17}$$

Now, Eq. (17) – Eq. (14) gives

$$pJ_{scm} = J_{0m}\left\{\exp\left(\frac{V_{ocm})}{nv_t}\right)\right\} - J_{0m}\left\{\exp\left(\frac{pV_{ocm} + r_s pJ_{scm}}{nv_t}\right)\right\} + \frac{V_{ocm}(1-p)}{r_{sh}} - \frac{pJ_{scm} r_s}{r_{sh}} \tag{18}$$

With v_{pvm}=0, I_{pvm}=I_{scm} or J_{pvm}=J_{scm} and from Eq. (13), we get,

$$J_{scm} = J_{phm} - J_{0m}\left\{\exp\left(\frac{J_{scm} r_s}{nv_t}\right) - 1\right\} - \frac{r_s J_{pvm}}{r_{sh}} \tag{19}$$

Now, (19) – (14) gives,

$$J_{scm} = J_{0m}\left\{\exp\left(\frac{V_{ocm}}{nv_t}\right) - \exp\left(\frac{J_{scm} r_s)}{nv_t}\right)\right\} + \frac{V_{ocm}}{r_{sh}} - \frac{J_{scm} r_s}{r_{sh}} \tag{20}$$

Since, J_{scm}<37 mAcm^{-2} and R_{S} is typically of the order of 0.1Ω, so the term exp($J_{\text{scm}} r_{\text{s}}/nv_{\text{t}}$) can be neglected. Equation (20) becomes

$$J_{scm} = J_{0m}\exp\left(\frac{V_{ocm}}{nv_t}\right) + \frac{V_{ocm}}{r_{sh}} - \frac{J_{scm} r_s}{r_{sh}} \tag{21}$$

From (21), we obtain

$$\left(J_{scm} - \frac{V_{ocm}}{r_{sh}} + \frac{J_{scm} r_s}{r_{sh}}\right) / \exp\left(\frac{V_{ocm}}{nv_t}\right) = J_{0m} \tag{22}$$

Put the value of J_{0m} from Eq. (22) and put into Eq. (18),

$$pJ_{scm} = \left(J_{scm} - \frac{V_{ocm}}{r_{sh}} + \frac{J_{scm} r_s}{r_{sh}}\right)\left\{1 - \exp\left(\frac{(p-1)V_{ocm} + pJ_{scm} r_s}{nv_t}\right)\right\} + \frac{V_{ocm}(1-p)}{r_{sh}} - \frac{pJ_{scm} r_s}{r_{sh}} \tag{23}$$

Finally, we get

$$n = \frac{\dfrac{(p-1)V_{ocm} + pJ_{scm} r_s}{v_t}}{\ln \dfrac{J_{scm}\left(1 + \dfrac{r_s}{r_{sh}}\right)(1-p) - \dfrac{pV_{ocm}}{r_{sh}}}{J_{scm}\left(1 + \dfrac{r_s}{r_{sh}}\right) - \dfrac{V_{ocm}}{r_{sh}}}} \tag{24}$$

Equation (24) represents the ideality factor of generalized PV module.

Case 2: *For the approximate equivalent circuit of a PV module*

In this case (Fig. 3), R_{S} has a finite value and $R_{\text{sh}} \to \infty$. From Eq. (24), we obtain

$$n = \frac{(p-1)V_{ocm} + pJ_{scm} r_s}{v_t \ln(1-p)} \tag{25}$$

Case 3: *For approximate equivalent of a PV module*

In this case (Fig. 4), R_{S}=0 and R_{sh} has a finite value. From Eq. (24), we get

$$n = \frac{\dfrac{(p-1)V_{ocm}}{v_t}}{\ln \dfrac{J_{scm}(1-p) - \dfrac{pV_{ocm}}{r_{sh}}}{J_{scm} - \dfrac{V_{ocm}}{r_{sh}}}} \tag{26}$$

Case 4: *For the equivalent circuit of the ideal PV module or simplified PV module*

In this case (Fig. 5), R_{S}=0 and $R_{\text{sh}} \to \infty$. From Eq. (24), we get

$$n = \frac{(p-1)V_{ocm}}{v_t \ln(1-p)} \tag{27}$$

Table 1. Electrical Specification of KC40REB

Parameters	Single Cell	Module
Rated power, P	1.25W	40W
Voltage at Pmax (V_{mp})	0.52V	16.5V
Current at maximum power (I_{mp})	2.67A	2.67A
Open circuit voltage(V_{oc})	0.6V	19.2V
Short circuit current (I_{S})	2.96A	2.96A

Therefore, Equations (24), (25), (26) and (27) give the expression of ideality factor of any PV modules. We have used KC40REB PV module, from which the value of ideality factor at different conditions are determined. The manufacturer's sheet for the electrical specifications of KC40REB is shown in Table 1.

3.2 Estimation of Results

Case 1: *For generalized equivalent circuit of solar cell* [Ref. Fig. 2 and Eq. (7)]

In this case, R_S and R_{sh} have finite values. According to Eq. (24), $n = f(R_{sh}, R_s)$ and by putting the value V_{ocm}=19.2V, J_{scm}=0.0389A/m^2, v_t=0.8256 and p=0.86 except different R_s and R_{sh}, we obtain a 3D plot where z-axis represents the ideality factor.

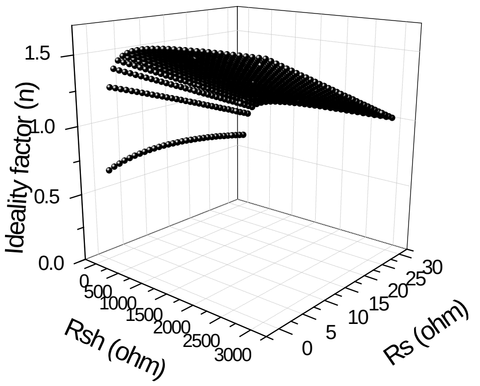

Fig. 7 Variation of ideality factor when R_s and R_{sh} both are finite

Figure 7 shows a 3D plot where shunt resistances (R_{sh}) in the X-axis, series resistances in Y-axis and the ideality factors (n) in the Z-axis. It indicates that n increases when R_{sh} is increased and R_s is decreased.

Case 2: *For the approximate equivalent circuit of a solar cell* [Ref. Fig. 3 and Eq. (8)]

In this case, R_S has a finite value and $R_{sh} \to \infty$. According to Eq. (25), $n = f(R_S)$ and by putting the value of the parameters except different R_s value, the value of the ideality factor is given below.

$$n = \frac{\{(0.86-1)\times 19.2\} + (0.86\times 0.0389\times 32R_S)}{0.8256\ln(1-0.86)}$$

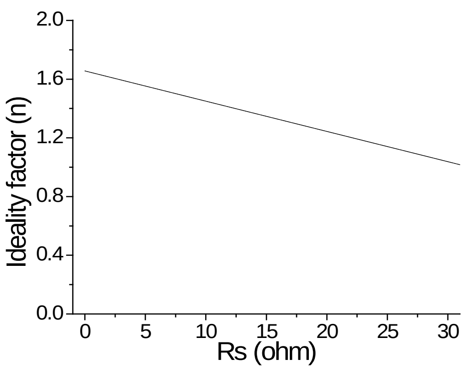

Fig.8 Variation of ideality factor when R_s is finite

Figure 8 shows series resistances (R_s) in the X-axis and ideality factors (n) in the Y-axis when $R_{sh} \to \infty$. It indicates that n becomes higher at R_s increases and with increasing Rs, n decreases.

Case 3: *For approximate equivalent of solar cell* [Ref. Fig. 4 and Eq. (9)]

In this case, R_S=0 and R_{sh} has a finite value. According to Eq. (26), $n = f(R_{sh})$ and by putting the value of the parameters except different R_{sh} value, the expression of ideality factor is given below.

$$n = \left[\frac{\{(0.86-1)\times 19.2\}}{0.8256} \times \frac{1}{\ln\left\{((1-0.86)\times 0.0389) - \frac{(0.86\times 19.2)}{r_{sh}}\right\} - \ln\left\{0.0389 - \frac{19.2}{r_{sh}}\right\}}\right]$$

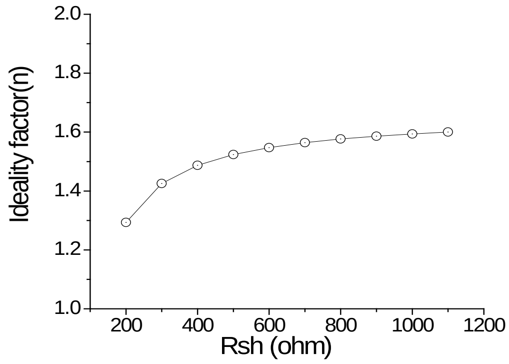

Fig. 9 Variation of ideality factor when R_{sh} is finite

Fig. 9 shows shunt resistances (R_{sh}) in the X-axis and ideality factors (n) in the Y-axis with R_s=0. It indicates that n increases when R_{sh} is increased for R_s=0.

Case 4: *For the equivalent circuit of the ideal solar cell or simplified solar cell* [Ref. Fig. 5 and Eq. (10)]

In this case, R_S=0 and $R_{sh} \to \infty$, v_t=0.8256V, p= V_{mp}/V_{ocm} = 16.5/19.2=0.86, and J_{sc}=0.0389A/m^2. Putting the above values in Eq. (27), we get n=1.67.

3.3 Comparison

For comparison, we employ an analytical method proposed by Phang et al. [2] to estimate value of the ideality factor at room temperature. By this model the analytical expression of the diode ideality factor is given by

$$n = \frac{V_m + I_m R_{so} - V_{oc}}{v_t\left\{\ln\left(I_{sc} - \frac{V_m}{R_{sho}} - I_m\right) - \ln\left(I_{sc} - \frac{V_{oc}}{R_{sho}}\right) + \frac{I_m}{I_{sc} - \frac{V_{oc}}{R_{sho}}}\right\}} \quad (28)$$

where V_{oc}, I_{sc}, V_m, I_m, R_{so} and R_{sho} are the open circuit voltage, short circuit current, maximum point voltage and current, and series and shunt resistances under illumination, respectively. By using the room temperature solar cell parameters of the module is (R_{so}= 10 Ω, R_{sho} = 15 × 10^4 Ω, V_{oc} = 0.6V, I_{sc} = 2.96A, V_m = 0.52V, I_m = 2.67A), the average value of n is estimated as about 1.589.

For comparison, we employ another analytical method proposed by Jia et al. [4] to estimate value of the ideality factor at room temperature. In that method, the analytical expression of the diode ideality factor is given by

$$n = \frac{V_m + I_m R_s - V_{oc}}{v_t \ln\left\{\dfrac{(I_{sc} - I_m)(1 + r_s / r_{sh}) + (V_{oc} - V_m)/r_{sh}}{I_{sc}(1 + r_s / r_{sh}) - V_{oc}/r_{sh}}\right\}} \qquad (29)$$

where V_{oc}, I_{sc}, V_m, I_m, r_s and r_{sh} are the open circuit voltage, short circuit current, maximum point voltage and current, and series and shunt resistances under illumination, respectively. Compare to Fig. (7), the plot of ideality factor, $n=f(r_s, r_{sh})$ is shown in Fig. 10.

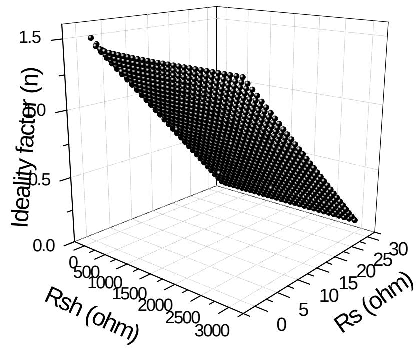

Fig. 10 Variation of ideality factor when R_s and R_{sh} both are finite (Jia et. al. method)

4. ESTIMATION OF FILL FACTOR

The Fill Factor is a measure of the junction quality and series resistance of a cell. It is defined as the ratio of maximum power (P_m) divided by the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}), and maximum power (P_m) is the product of voltage (V_{mp}) and current (I_{mp}) at maximum power points, i.e.

$$FF = \frac{P_m}{V_{oc} I_{scm}} = \frac{V_{mp} I_{mp}}{V_{ocm} I_{scm}} \qquad (30)$$

Obviously the nearer the fill factor is to unity the higher the quality of the cell. The fill factor determines the shape of the solar cell I-V characteristics. Its value is higher than 0.7 for good cell. The series and shunt resistances account for a decrease in the fill factor.

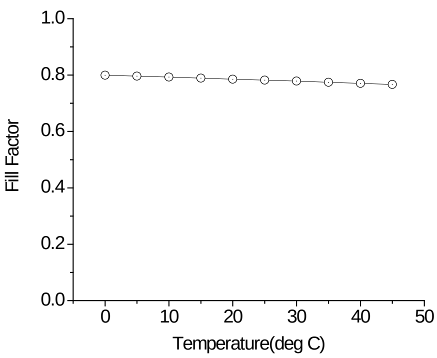

Fig. 11 Variation of fill factor with temperature

Increasing the shunt resistance (R_{sh}) and decreasing the series resistance (R_s) will lead to higher fill factor, thus resulting in greater efficiency, and pushing the cells output power closer towards its theoretical maximum. For module KC40REB, Fill Factor, FF= (16.5×2.67)/ (19.2×2.96) = 0.775. Figure 11 shows temperatures in the X-axis and fill factors in the Y-axis. It indicates that fill factor decreases slightly when temperature decreases.

5. CONCLUSIONS

In this paper, the estimation of two important parameters ideality factor and fill factor was done by analytical method. The contribution of this paper is to measure the ideality factor directly from the manufacturer's data sheet of a PV module. Another contribution of this paper is to measure the ideality factor analytically for different equivalent circuits of a PV module. Four important cases were considered from the PV module depending on the value of shunt resistance and series resistance. We determined the value of ideality factor which was 1.67 for ideal case in our module. We observed the variations of ideality factors in other different cases through analytical method. We also determined the value of fill factor which was 0.775 in case of our module. We also observed the variations of fill factors with temperature.

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