Abstract—This paper discusses the modeling of single-diode photovoltaic cell to estimate the maximum power with respect to changes in environmental factors that effects its efficiency performance. The parameters, i.e. resistances for the modeling of PV cell are determined for nonlinear I-V characteristics to replicate the maximum power point. These values are determined at various environmental factors like; dust, solar radiation intensity, shadow, temperature and wind velocity.

Index Terms—PV array, modeling, maximum power point

I. NOMENCLATURE

\begin{align*}
I_0 & \quad \text{Diode saturation current} \\
I_{\text{photo, cell}} & \quad \text{Photon current} \\
T_0 & \quad \text{Actual temperature in K} \\
T_n & \quad \text{Nominal temperature in K} \\
G_0 & \quad \text{Solar radiation on the cell surface in \( \frac{W}{m^2} \)} \\
G_n & \quad \text{Nominal solar radiation in \( \frac{W}{m^2} \)} \\
K_t & \quad \text{Current coefficient} \\
K_v & \quad \text{Voltage coefficient} \\
N_s & \quad \text{Number of series cells of the module} \\
V_t & \quad \text{Thermal voltage of the cell}
\end{align*}

II. INTRODUCTION

Photovoltaic resource among all the renewables is considered to be increasingly important for power generation in last few decades. This has resulted not only decreased dependence on fossil fuel but also in emission of greenhouse gases. Photovoltaic for power generation is considered ideal resource in the distributed generation system, which are located at or near to the load point.

A single PV cell being too small for practical power application is usually connected as series-parallel combination to give a required voltage and current in so called PV module. This PV module forms a series-parallel combination to work as PV array. The DC output is converted into AC at standard frequency through an inverter. The PV system application can be as grid connected, stand alone or hybrid.

The PV cell/module output is highly nonlinear and its simplified form model as a constant voltage source or a current controlled voltage source is often not practicable in field. Over the years, several models have been proposed. There exists three basic types of PV system models based on (i) PV array characteristics [1-3], (ii) inverter structure characteristics [4-7], (iii) overall PV system [8-9]. The nonlinear PV array characteristics which varies not only with temperature and solar intensity, but also with other environmental factors like, dust and wind velocity still remains a major challenge to model. It is important to understand the PV module/array characteristics for effective installation under all weather conditions.

In the past, researchers have already studied the characteristics of PV module and the factors that influence their performance [10-13]. Walker [10] proposed a MATLAB based model of PV module for study of temperature, solar intensity and load variation. The influence of partial shading effect was discussed in [11-13]. A fast MPPT algorithm for tracking the maximum under fast changing environmental conditions is investigated in [14]. The authors have considered study for rapidly changing solar radiation. A theoretical model to estimate the solar cell performance degradation due to dust accumulation is carried out in [15].

Recently an analytical approach to determine the PV cell parameters, i.e. resistances by adjustment of I-V equation with experimental characteristics was suggested in [16].

This paper discusses the modeling of PV cell/array based on the approach mentioned in [16] for various environmental factors that affect the output performance.

III. SINGLE DIODE PHOTOVOLTAIC CELL MODEL

Without much emphasis given on physics of how the PV cell transforms the solar photons into direct current power, this section starts with modeling concept of single diode PV cell. The standard PV cell is represented as a current source in parallel with a single diode. The equivalent circuit diagram is shown in Fig. 1. The output, \( I_{\text{photo, cell}} \) is directly proportional to amount of solar incident on the PV cell. It is the diode that determines the shape of I-V characteristics of a PV cell. A
more detailed model can be represented by inclusion of following:

- Temperature dependence of the diode saturation current, $I_0$
- Temperature dependence of the photon current, $I_{\text{photo,cell}}$
- Series resistance, $R_s$ that represents the internal losses
- Shunt resistance, $R_{sh}$ in parallel with diode to take into account leakage current to the ground
- Diode quality factor, $a$

Applying KCL:

$$I_{\text{photo,cell}} - I_{d,\text{cell}} - \frac{V_d}{R_{sh}} - I_{\text{pv,cell}} = 0$$  \hspace{1cm} (1)

$$I_{\text{pv}} = I_{\text{photo,cell}} - I_{d,\text{cell}}$$  \hspace{1cm} (2)

Where,

$$I_{d,\text{cell}} = I_{0,\text{cell}} \left[ \exp \left( \frac{qV}{akT} \right) - 1 \right]$$  \hspace{1cm} (3)

The complete model of PV module should include the effect due to series-parallel combination of each PV cells. Thus the above equation is expressed as:

$$I_{\text{pv}} = I_{SC} - I_0 \left[ \exp \left( \frac{q(V + I_{pv}R_s)}{akT_{V}} \right) - 1 \right] - \frac{V + I_{pv}R_s}{R_{sh}}$$  \hspace{1cm} (4)

Where $I_{SC} = I_{\text{photo,cell}}N_p$, $I_0 = I_{0,\text{cell}}N_p$, $V_{T} = N_q kT/q$.

The photon generated current of the PV cell depends linearly on the solar radiation and is also determined by the temperature according to:

$$I_{\text{photo,cell,}\text{n}}(T_n) = [I_{\text{photo,cell,0}}(T_0) + K_e \Delta T] \frac{G_0}{G_n}$$  \hspace{1cm} (5)

Where, $I_{\text{photo,cell,0}}$ is the photon generated current at 25°C and 1000 W/m², $\Delta T = T_n - T_0$.

The temperature dependence of diode saturation current $I_0$ can be expressed as:

$$I_0 = I_{0,n} \left( \frac{T_n}{T_0} \right)^{3} \exp \left[ \frac{qE_g}{akT_n} \left( \frac{1}{T_n} - \frac{1}{T_0} \right) \right]$$  \hspace{1cm} (6)

Where, $I_{0,n}$ is the nominal saturation current given by:

$$I_{0,n} = \frac{I_{pv} - V_{oc,n}}{R_{sh}} \exp \left( \frac{V_{oc,n}}{V_{aN_0}} \right) - 1$$  \hspace{1cm} (7)

A considerable effort is being put into the development of robust mathematical model for PV with low computational cost so as to take into account the variation of output with the weather conditions.

The improvement over (6) that takes into temperature dependency of saturation current with current and voltage coefficients $K_e$ and $K_v$ is given as [16]:

$$I_0 = \frac{I_{SC,n} + K_e \Delta T}{\exp \left[ \left( V_{oc,n} + K_v \Delta T / aV_r \right) \right] - 1}$$  \hspace{1cm} (8)

The authors [16] have proposed an approach for iterative solution to determine the resistance, $R_s$ and $R_{sh}$ which gives the maximum power point on the I-V curve.

IV. MODELING WITH ENVIRONMENTAL FACTORS

The influence of solar radiation, cell temperature, dust, shadow and wind is important to estimate the performance under all weather conditions. The photo current $I_{\text{photo,cell}}$ is directly proportional to solar radiation (5). In fact, PV cell performance does not degrade significantly from full sun shine to partial cloud conditions. The variation of saturation current as a function of temperature is described by (8). The deposition of dust particles on the glazing surface of PV cells significantly decreases the performance. Similarly, wind velocity has an important impact on cell performance drop. High wind speeds lead to high dust accumulation on a cell, resulting into sharp decrease performance.

The dust influence on the PV cell can be expressed as:

$$I_{wp} = I_{wp,0} \left[ \frac{I_{pv} - d}{I_{pv}} \right]$$  \hspace{1cm} (9)

An empirical relation that provides the actual PV module temperature $T_m$ as a function of nominal temperature $T_n$, solar radiation $G_0$ and wind velocity can be formulated as:

$$T_m - T_n \times 1000 = 0.0712 (w_e)^2 - 2.411 (w_e) + 32.96$$  \hspace{1cm} (10)
for wind velocity, \( w_v < 18 \text{ m/s} \).

Series resistances of PV cells and diodes is temperature dependent and increases with temperature increase, \( 0.65\% K^{-1} \) [17]. Thus it is very necessary to have PV module being modeled with consideration of environmental factors.

![Graph](image1)

(a) P-V and I-V characteristics at 25°C.

![Graph](image2)

(b) P-V and I-V characteristics at 50°C.

Fig. 2: Adjusted curves at different temperatures on EN2060.

V. RESULTS AND DISCUSSION

The study in the paper uses the parameters of solar PV module, EN2060 and Kyocera KC200GT. The parameters are given in Appendix. Figure 2 shows the adjusted curves of solar PV module EN2060 at two different temperatures. The effect of dust particles on Kyocera KC200GT solar module is shown in Fig. 3. It is noted that open circuit voltage remains unchanged, while the cell current has decreased noticeably, resulting into reduction in maximum power point too. The same study for changes in solar radiation intensity is represented in Fig. 4. In case of lowered solar radiation, there is slight decrease in open circuit voltage with respect to reduction in value of short circuit current. Next the influence of variation in wind velocity on I-V and P-V characteristics is shown in Fig. 5. As observed, the variation in wind velocity in the range of 7 to 18 m/sec does not significantly affect the performance of PV module. The maximum power point (MPP) remains almost the same. The determined values of resistances which adjust the PV curve to the experimental one is given in Table I. The series resistance increases with higher dust factor and shadow effects. On the other hand, its value decreases on reduced solar radiation.

![Graph](image3)

(a) P-V characteristics.

![Graph](image4)

(b) I-V characteristics.

Fig. 3: Effect of dust deposition on PV module output on KC200GT.

![Graph](image5)

(a) P-V characteristics.

Fig. 4: Effect of solar radiation variation on PV module output.
TABLE I
EFFECT OF ENVIRONMENTAL FACTORS ON RESISTANCES IN PV MODEL.

(a) Dust effect:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>d= 0.0</th>
<th>d= 0.2</th>
<th>d= 0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{r,\text{max}}$</td>
<td>0.86728</td>
<td>1.0841</td>
<td>1.4454</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.23</td>
<td>0.28</td>
<td>0.37</td>
</tr>
</tbody>
</table>

(b) Solar radiation intensity effect:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>G= 0.0</th>
<th>G= 0.2</th>
<th>G= 0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{r,\text{max}}$</td>
<td>0.8672</td>
<td>1.084</td>
<td>1.4454</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.23</td>
<td>0.21</td>
<td>0.15</td>
</tr>
</tbody>
</table>

(c) Shadow effect:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>G= 0.0</th>
<th>G= 0.25</th>
<th>G= 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{r,\text{max}}$</td>
<td>0.8672</td>
<td>1.1563</td>
<td>1.7345</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.23</td>
<td>0.38</td>
<td>0.76</td>
</tr>
</tbody>
</table>

(c) Temperature effect:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>25°C</th>
<th>50°C</th>
<th>75°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{r,\text{max}}$</td>
<td>0.86728</td>
<td>0.8583</td>
<td>0.8495</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.23</td>
<td>0.41</td>
<td>0.63</td>
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</table>

(d) Wind effect:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>18 m/sec</th>
<th>13 m/sec</th>
<th>10 m/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{r,\text{max}}$</td>
<td>0.862726</td>
<td>0.862361</td>
<td>0.861531</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.32</td>
<td>0.33</td>
<td>0.34</td>
</tr>
</tbody>
</table>

VI. CONCLUSION
The paper presented the determination of resistances of PV cell with adjustment of characteristics that correspond to maximum power point. The influential environmental factors that affect the PV module performance were considered in the study. The study was carried out at parameters of two different commercially available PV modules.

VII. APPENDIX
**VIII. REFERENCES**


**IX. BIOGRAPHIES**

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