Analytical Model for a Photovoltaic Module using the Electrical Characteristics provided by the Manufacturer Data Sheet

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***Abstract*-- This paper proposes an analytical model for the performance of photovoltaic modules to be used in distributed power generation. The proposed solar panel model uses the electrical characteristics provided by the manufacturer data sheet. The required characteristics are short-circuit current (I_{sc}), open-circuit voltage (V_{oc}) and the temperature coefficients of I_{sc} and V_{oc}. The proposed model takes into consideration the nominal values provided by the Standard Test Conditions (STC). Also, the temperature and the effective irradiance level are derived analytically for the proposed model. Finally, simulations about V-I and P-V curves under different irradiance levels and temperatures are provided for different solar panel modules, data sheets.**

***Index Terms*-- Photovoltaic power systems, solar power generation, temperature, solar radiation.**

I. NOMENCLATURE

P, I, V	solar panel output power, current and voltage;
$P_{\max}$	maximum output power;
I_{sc}	short-circuit current at 25°C and 1000W/m^2;
I_{ph}, I_{SR}	photocurrent/reverse saturation current;
$I_{\max}$	ideal maximum current (when $V = -\infty$ at STC);
I_{op}, V_{op}	optimal output current and voltage;
V_{oc}	open-circuit voltage;
$V_{\max}$	open-circuit voltage at 25°C and 1000W/m^2;
$V_{\min}$	open-circuit voltage at 25°C and 200W/m^2;
V_T	thermical voltage;
Z, Y	solar panel internal impedance, admittance;
R_S, R_P	series/shunt resistance;
T	solar panel temperature in °C;
T_N	nominal temperature, 25 °C;
TCi	temperature coefficient of I_{sc}, (%/°C);
TCV	temperature coefficient of V_{oc}, (V/°C);
τ_i	rate of change for the current (A);
τ_v	rate of change for the voltage (V);
E_i	effective solar irradiation, (W/m^2);
E_{iN}	nominal effective solar irradiation, 1000 W/m^2;
α	percentage/100 of effective intensity of the light;
b	characteristic I-V Curve constant;
γ	shading linear factor;
k	Boltzmann constant, 1.38 x 10^{-23} J/Kelvin;
K	curve correction factor;
n	ideality factor;
q	charge of electron, 1.6 x 10^{-19} As;

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II. INTRODUCTION

In the last three decades, solar energy has been used as reliable energy for electric distribution. Use of the solar panel is the key component to convert solar energy into electrical energy. Sometimes the use of solar panels can be more practical than the typical solutions for power generation. An example of the last statement is that the solar panels can supply power for the electronic equipment aboard a satellite over a long period of time, which is a distinct advantage over batteries [2]. Applications of solar panels are not restricted to outer space. It is possible to obtain useful power from the sun in terrestrial applications using solar panels, even though the atmosphere reduces the solar intensity. Some examples are in urban distribution, electric drives, solar cars, etc [1]-[2].

Unfortunately, the actual models to describe solar panel performance are more related to physics, electronics and semiconductors than to power systems [2]-[8]. Some of the models require several parameters such as the temperature coefficients, photon current, open circuit voltage, series/shunt resistance of the device, etc. Also some of the required parameters in those models are not available by the manufacturer data sheets so it is required to find the information in other sources. At the same time, these models can be impractical and too complex for common tasks in power systems such as power flow, harmonic analysis, sensitivity analysis, load matching for maximum power transferred from the source to the load, etc. To solve these problems and to maximize the use of information provided by the manufacturer data sheets, this paper proposes a photovoltaic model based on the electrical characteristics, STC and I-V Curves. This model will be more beneficial and practical for different types of power systems analysis.

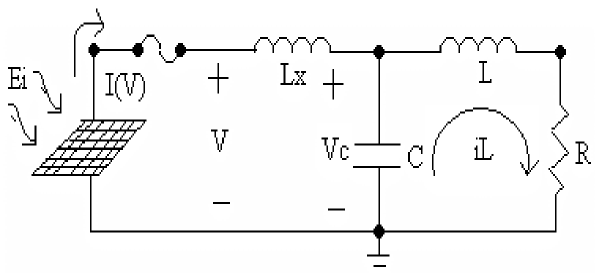

Fig. 1 PV Module Connected to a Transmission Line and a RL Load.

III. TYPICAL REQUIREMENTS FOR A PHOTOVOLTAIC MODULE DATA SHEET

The UL (Underwriters Laboratories) has developed a sample of information requirements for photovoltaic modules [10]. The UL mark is one of the most recognized, accepted and trusted symbols in the world. It means that a not-for-profit, independent laboratory tests samples of products to safety requirements and conducts periodic checks of manufacturers' facilities.

These ratings are to be based upon Standard Test Conditions (STC). The STC (also known as SRC or Standard Reporting Conditions) is defined with nominal cell temperature 25°C, nominal irradiance level 1000W/m^2 at spectral distribution of Air Mass 1.5 solar spectral content. In every photovoltaic module data sheet provided by the manufacturer, these ratings are to include:

- Rated voltage and current*
- Maximum power rating
- Short-circuit current rating
- Open-circuit voltage rating for each module
- Maximum system voltage rating

* This is the nominal voltage and current of an individual module when operating at maximum power.

These ratings are also required at Nominal Operating Cell Temperature (NOCT), which is defined as the equilibrium cell junction temperature corresponding to an open-circuit module operating in a reference environment of 800W/m^2 irradiance, 20°C ambient air temperature with a 1m/s wind across the module from side to side. These ratings include:

- Product NOCT rated current
- Product NOCT rated maximum power

IV. METHODS PROPOSED IN THE PAST

Different conversion methods have been proposed in the past, some of them working point by point and others model the solar cell performance with analytical equations. Some of the models and the conversion equations are made up of the following:

1) Method of Anderson [3]:

$$I_2 = \left[\frac{E_2}{E_1}\right] \cdot \frac{I_1}{[1 + TCi \cdot (T_2 - T_1)]}$$
$$V_2 = \frac{V_1}{[1 + TCV\ (T_2 - T_1)] \cdot \left[1 + \ln\left(E_2 / E_1\right) kT / q\right]} \tag{1}$$

2) Method of Bleasser [4]:

$$I_2 = I_1 \cdot \frac{E_2}{E_1}\left(1 + TCi \cdot (T_2 - T_1)\right)$$
$$V_2 = V_1 - R_S(I_2 - I_1) + \frac{kT}{q} \cdot \ln\left(\frac{E_2}{E_1}\right) + TCV \cdot (T_2 - T_1) \tag{2}$$

3) IEC-891 procedure [5]:

$$I_2 = I_1 + I_{SC}\left[\frac{I_{SR}}{I_{MR}} - 1\right] + TCi \cdot (T_2 - T_1)$$
$$V_2 = V_1 - R_S(I_2 - I_1) - K \cdot I_2(T_2 - T_1) + TCV \cdot (T_2 - T_1) \tag{3}$$

4) Solar Cell, Semiconductor Model [2]:

$$I(V) = I_{Ph} - I_{SR}\left\{\exp\left(\frac{q \cdot V}{k \cdot T}\right) - 1\right\} \tag{4}$$

5) Two-Exponential Model [6]:

$$I(V) = I_{Ph} - I_{S1}\left\{\exp\left(\frac{V + I \cdot R_s}{n_1 \cdot V_T}\right) - 1\right\} - I_{S2}\left\{\exp\left(\frac{V + I \cdot R_s}{n_2 \cdot V_T}\right) - 1\right\} - \frac{V + I \cdot R_s}{R_p} \tag{5}$$

The first three methods are working point by point [3]-[5] and the other two methods are analytical equations to describe the performance of a solar cell, [2], [6]. All the methods require several parameters that can be obtained from the manufacturer data sheet, such as the temperature coefficients, short circuit current, and open circuit voltage, etc. Unfortunately, some of the required parameters for these models cannot be found in the manufacturer data sheet, such that the photon current, the series/shunt resistance, thermal voltage, the ideality factor, the diode reverse saturation current, Boltzmann's constant, band gap for the material, etc. Also, the IEC-891 uses a fourth parameter curve correction factor K. The Two-Exponential model requires a curve-fitting and simulation computer program. In general, these models of the PV panels required additional parameter data not given by the manufacturer data sheets and most of the time; it is difficult to obtain the needed data [8].

V. PROPOSED PHOTOVOLTAIC POWER MODEL

The proposed I-V characteristic model takes into consideration the temperature over the solar panel, the percentage of effective intensity of the light over the solar panels, the characteristic constant for the I-V curves, a shading linear factor [9], the short-circuit current and the open-circuit voltage. The proposed PV model has the advantage of using the electrical characteristics provided by the solar panel data sheet, [11]-[14]. The I-V and P-V relations of the solar panel are:

$$I(V) = \alpha \cdot I_{\max} \cdot \tau_i - \alpha \cdot I_{\max} \cdot \tau_i \cdot \exp\left(\frac{V}{b \cdot (\gamma \cdot \alpha + 1 - \gamma) \cdot (V_{\max} + \tau_V)} - \frac{1}{b}\right) \tag{6}$$

$$P(V) = V \cdot I(V) = \alpha \cdot I_{\max} \cdot V \cdot \tau_i - \alpha \cdot I_{\max} \cdot V \cdot \tau_i \cdot \exp\left(\frac{V}{b \cdot (\gamma \cdot \alpha + 1 - \gamma) \cdot (V_{\max} + \tau_V)} - \frac{1}{b}\right) \tag{7}$$

The dynamic equations for P and I are obtained, taking the derivatives of (6) and (7) with respect to the voltage.

$$\frac{dI(V)}{dV}=\frac{I(V)-\alpha\cdot I_{\max}\cdot\tau_i}{b\cdot(\gamma\cdot\alpha+1-\gamma)\cdot(V_{\max}+\tau_V)} \tag{8}$$

$$\frac{dP(V)}{dV}=I(V)-\frac{V\cdot I(V)-\alpha\cdot V\cdot I_{\max}\cdot\tau_i}{b\cdot(\gamma\cdot\alpha+1-\gamma)\cdot(V_{\max}+\tau_V)} \tag{9}$$

$$\alpha={E_i}/{E_{iN}} \tag{10}$$

$$I_{\max}=\frac{I_{sc}}{1-\exp\left(-1/b\right)} \tag{11}$$

$$\gamma=1-\frac{V_{\min}}{V_{\max}+\tau_V} \tag{12}$$

The shading linear factor γ is defined as the percent of voltage (V_{max}) loss from a maximum intensity of light to a minimum intensity of light as indicated in (12). V_{min} is the open-circuit voltage rating of the solar panels array for an effective intensity of light less than 20% over the solar panels [1], [9].

$$\tau_i=1+\frac{TCi}{100}\cdot(T-T_N) \tag{13}$$

$$\tau_V=TCV\cdot(T-T_N) \tag{14}$$

An additional equation can be obtained using (6). It is the equation of the dynamic internal admittance (or impedance) of the solar panel. It depends on the voltage and it is given by

$$Y(V)=\frac{1}{Z(V)}=\frac{\alpha\cdot I_{\max}\cdot\tau_i}{V}-\frac{\alpha\cdot I_{\max}\cdot\tau_i}{V}\cdot\exp\left(\frac{V}{b\cdot(\gamma\cdot\alpha+1-\gamma)\cdot(V_{\max}+\tau_V)}-\frac{1}{b}\right) \tag{15}$$

Figure 2 shows the I-V characteristics of an illuminated solar panel. The shaded rectangle represents the maximum power obtained by the solar panel. The knee point is when the product of the current and the voltage is the maximum power [9]. The solar panel is working in the optimal current (I_{op}) and voltage (V_{op}) hence the maximum power is delivered to the load by the solar panel. Figure 3 shows the PV Curve and the relationship between P_{max} and the knee point. Finally, the optimal impedance curve is shown in figure 4 to be connected to the photovoltaic module transfer the maximum power.

The fill factor, (16) is a figure of merit for solar panel design [2]. It is defined as the percentage of area covered by P_{max} given the area produced by I_{sc} and V_{oc} (or V_{max}). Also using figure 2, the inequality (17) can be found where the maximum power will be less than the area of the VI Curve and more than a quarter of the product of I_{sc} and V_{oc} [1]. The inequality for the fill factor is given in (18) when (16) and (17) are combined. In [1], it was proved that the fill factor is more than one quarter of the lower part of the inequality (18) using numerical analysis.

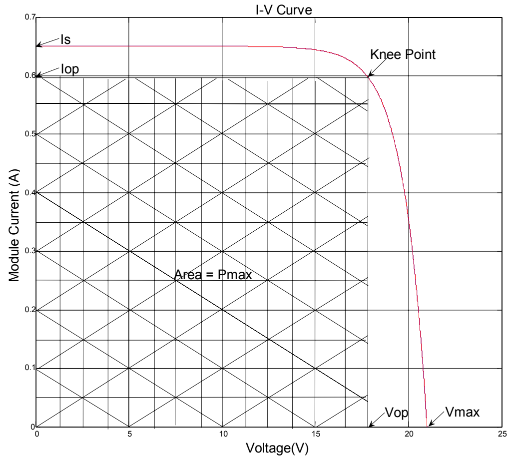

Fig. 2 I-V Curve for a Photovoltaic Module

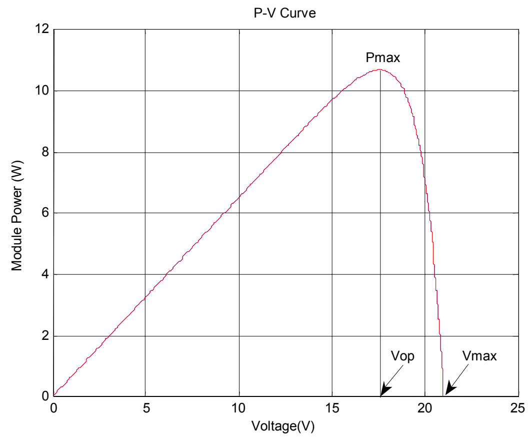

Fig. 3 P-V Curve for a Photovoltaic Module

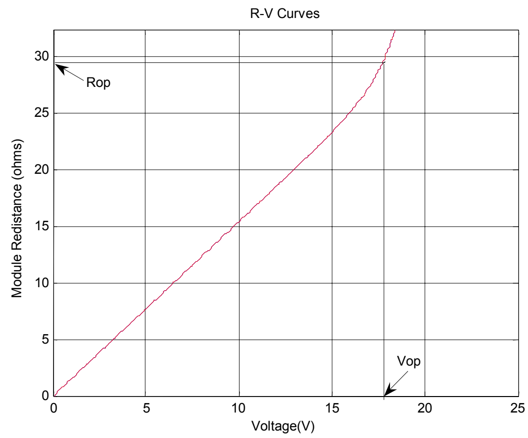

Fig. 4 R-V Curve for a Photovoltaic Module

$$fillfactor=\frac{P_{\max}}{I_{sc}\cdot V_{oc}}=\frac{I_{op}\cdot V_{op}}{I_{sc}\cdot V_{oc}} \tag{16}$$

$$\int_0^{V_{oc}} I(V)dV>P_{\max}>\frac{I_{sc}\cdot V_{oc}}{4} \tag{17}$$

$$\int_0^{V_{oc}}\frac{I(V)dV}{I_{sc}\cdot V_{oc}}>fillfactor>\frac{1}{4} \tag{18}$$

It is important to note that figure 4 can be used to maximize the efficiency of a solar power system when load matching is required. At the same time R_{op} represents the optimal resistance (or impedance) to obtain the maximum power. It can be seen from figure 4 that the resistance is quasi-linear up to the point that the optimal resistance to produce the maximum power is obtained.

VI. Model Verification

The proposed model was tested using different manufacturer data sheets [11]-[14]. Figures 5-10 show different simulations for the SX-10 module using the information provided by the manufacturer SOLAREX. For the products SX-10 and SX-5, see table 1.

Figures 5-7 show simulation results for the photovoltaic module under different temperatures of operation (i.e. 0°C, 25°C, 50°C and 75°C) with the irradiation level at 1000W/m^2. Figures 8-10 show the simulation results for photovoltaic module SX-10 with the temperature at 25 °C and the effective irradiance level changing (i.e. 200W/m^2, 400W/m^2, 600W/m^2, 800W/m^2, and 1000W/m^2). The effects of change in the irradiance level are more drastically visible than the effects of temperature over the solar panel. The changes in temperature can be used to determine now the photovoltaic modules will operate in tropical areas versus non-tropical areas.

Figure 5 shows the simulation results for the I-V curves under different temperatures. These I-V curves are similar to the I-V curves provided by SOLAREX [13]. At the same time other plots, not provided by the manufacturer, can be calculated using the proposed model such as P-V curves, R-V curves and I-P curves. Unfortunately, the manufacturer data sheet does not provide these figures despite the fact that this information is very important for solar power systems where the irradiance level changes quickly. An example is when the clouds are hiding the sun for a period of time, and then the irradiance level increases and the temperature constant. Figure 6 shows how the temperature can affect the maximum power supplied by the photovoltaic module under a constant irradiance level. Figures 7 and 10 show how the internal resistance of the photovoltaic module SX-10 changes when the output voltage changes.

Finally, all of these curves, equations, and relationships give valuable information to be considered for photovoltaic power systems and distributed power generation design.

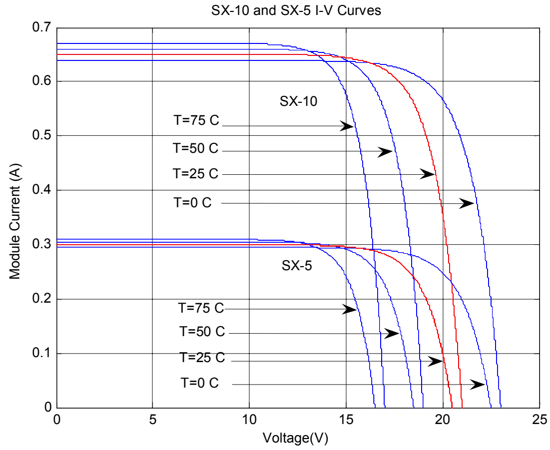

Fig. 5 I-V Curves for the SX-10 and SX-5 under different temperatures

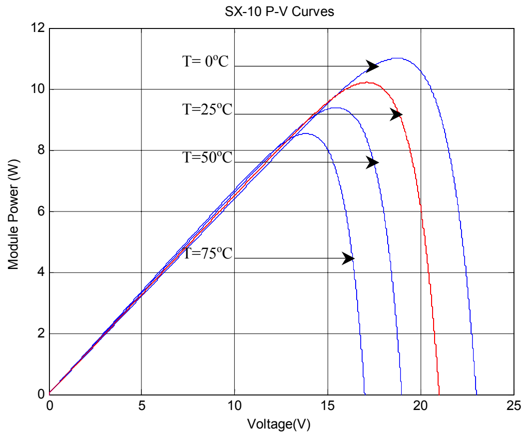

Fig. 6 P-V Curves for the SX-10 module under different temperatures

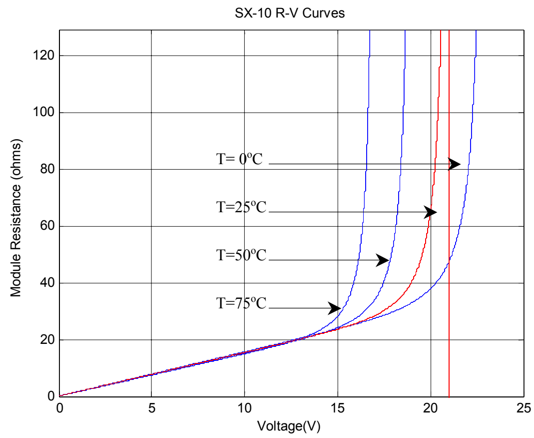

Fig. 7 R-V Curves for the SX-10 module under different temperatures

SOLAREX	SX-10	SX-5
I_{sc}	0.65A	0.3 A
V_{oc}	21.0V	20.5V
TCi	(0.065±0.015)%/°C	
TCV	-(80±10)mV/°C	

Table 1 Parameters for different PV modules data sheets

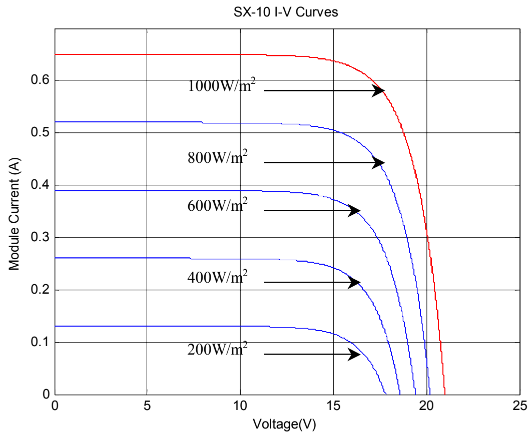

Fig. 8 I-V Curves for the SX-10 and SX-5 modules under different effective irradiance levels

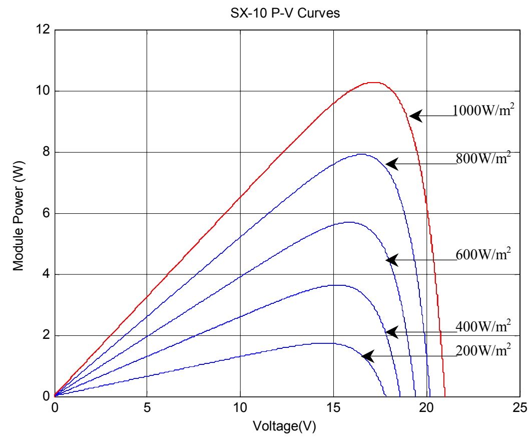

Fig. 9 P-V Curves for the SX-10 module under different effective irradiance levels

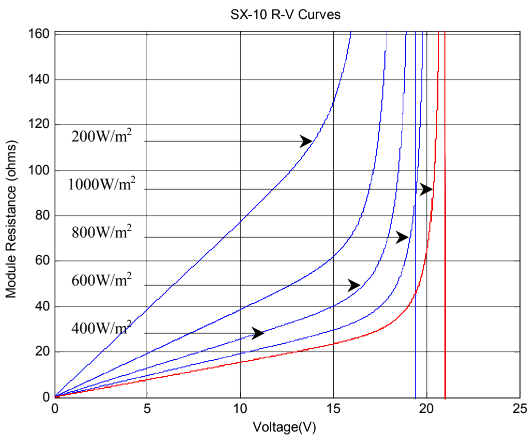

Fig. 10 R-V Curves for the SX-10 module under different effective irradiance levels

VII. Conclusions

An analytical model for the photovoltaic module was proposed for solar power generation. It takes into consideration the manufacturer data sheet, the temperature, and the irradiation level. The proposed model has the advantage of producing, not only the I-V curves provided by the manufacturer, but also the P-V curves, R-V curves, P-I curves under changes in the temperature and effective irradiance level. It is expected that this model will be used for future applications in the area of power systems where most of the existing models cannot be used to calculate power flow, harmonic analysis, optimal load for maximization of the power, etc.

VIII. Acknowledgment

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