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Modeling and Simulation of Solar Photovoltaic module using single diode PV cell model in Matlab/Simulink

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Abstract - This paper defines a detailed modeling of solar PV module based on single diode PV cell equations in MATLAB/SIMULINK in order to estimate the characteristics of the PV module with respect to changes in environmental parameter like irradiance and temperature. An accurate PV module is presented based on the electrical characteristics of PV module LG300N1C-G3. The model developed in SIMULINK accepts irradiance and temperature as inputs and provides current and voltage as an output. The I-V and P-V curves can be plotted in MATLAB for each input. The simulation results are compared with the datasheet information and they are found to be in close agreement.

Index terms: Solar energy, photovoltaic, PV module, MATLAB, SIMULINK.

I. INTRODUCTION

Solar energy is a commonly used renewable energy since it is free, plentiful, and pollution free during operation. Renewable Energy resources are attractive among electrical power resources because they bring a more advantages in terms of environment.

Photovoltaic cell is a device based on a semiconductor material that converts energy of sunlight into electrical energy. Due to its low power, it is necessary to combine multiple cells into series or into parallel, forming a photovoltaic module with the required values of current and voltage. Output parameters of cells are most affected by environmental conditions, especially by solar irradiation and also by temperature at the input modules. Therefore, modeling this device necessarily requires ambient temperature and solar radiation as input variables. The output of the model can be voltage, current or power of the module. Any changes in the input variables are reflected by changes on the output.

The common approach is to utilize the electrical equivalent circuit, which is primarily based on a light generated current source connected in parallel to a p-n junction diode. Many models have been proposed for the simulation of a solar cell or for a complete photovoltaic (PV) system at various solar intensities and temperature conditions [1-4]. However, these papers don't provide detailed modeling approach to researchers to build a PV module by themselves in Simulink.

II. MATHEMATICAL MODEL OF PV CELL

The most common and simplest approach to model a PV cell is using the single diode equivalent circuit as shown in Figure 1. The equivalent circuit of an ideal PV cell consists of a current source and a diode connected in anti-parallel with it. A general model of the solar cell is the combination of current source (Iph) connected in anti-parallel to a diode 'D', series resistance (R_s) and parallel resistance (R_p) [5].

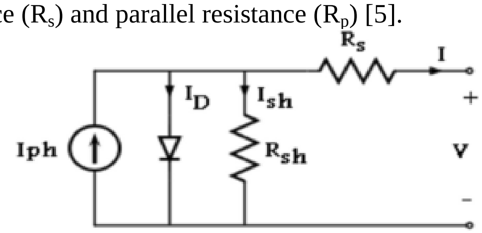

Figure1:.Single diode equivalent circuit of PV Cell

I-V and P-V characteristics of PV cell are shown in Figure 2.9. Open circuit voltage (V_{oc}) is the maximum voltage a cell can generate under open circuit condition at I=0 and the short circuit current (I_{SC}) is the current corresponds to short circuit at V=0. Through the operation, the PV cell generates maximum power at only one point and this point is called as Maximum Power Point (MPP). I_m, V_m and P_m in the graph are maximum current, maximum voltage and the maximum power of the solar cell respectively.

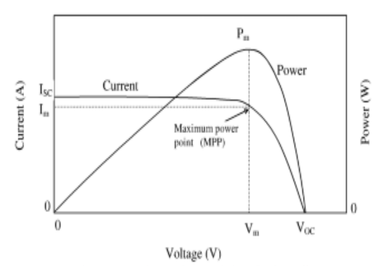

Figure 2: I-V and P-V characteristics of Solar cell

The voltage and current generated by a single PV cell is very low. So, solar cells are interconnected in a series-parallel combination to achieve the desired power. Desired voltage is generated by connecting the solar cells in series and the desired current is generated by connecting the cells in parallel. Generally, PV module contains a number of solar cells connected in series.

Following are the equations that define the model of a PV module [6-9]:

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$$V_t = \frac{k\,T_{op}}{q} \quad \ldots\ldots \quad (1)$$

$$I_{sh} = \frac{V + IR_s}{R_p} \quad \ldots\ldots \quad (2)$$

$$I_{ph} = \left[k_i\left(T_{op} - T_{ref}\right) + I_{sc}\right]\frac{S}{S_n} \quad \ldots\ldots \quad (3)$$

$$I_{rs} = \frac{I_{sc}}{\exp\left(\frac{V_{oc}}{V_t C n}\right) - 1} \quad \ldots\ldots \quad (4)$$

$$I_s = I_{rs}\left(\frac{T_{op}}{T_{ref}}\right)^3 \exp\left[\frac{q\,E_g}{Kn}\left(\frac{1}{T_{op}} - \frac{1}{T_{ref}}\right)\right] \quad \ldots\ldots \quad (5)$$

$$I_d = N_p I_s\left[\exp\left(\frac{V + IR_s}{N_s V_t n C}\right) - 1\right] \quad \ldots\ldots \quad (6)$$

$$I = I_{ph} N_p - I_{sh} - I_d \quad \ldots\ldots \quad (7)$$

Where
Vt: Thermal voltage in volts
k, q: Boltzmann's constant (1.38e-23J/K), Electronic charge (1.6e-19C)
T_{op}, T_{ref}: Operating Temperature of module in Kelvin, Reference temperature of 25^0 C
I_{sh}: Shunt current in Ampere
S, S_n: Irradiation in device surface in W/m^2, Reference irradiation of 1kW/m^2
I_{ph}, Id: Light generated current in Ampere, Diode current in Ampere.
I_{sc}, V_{oc}: Short circuit current in Ampere, Open circuit voltage in Volt
I_{rs}: Reverse saturation current at reference temperature in Ampere
I_s: Diode saturation current in Ampere
k_i: Temperature coefficient of short circuit current
E_g, n: Band gap energy of cell (1.12eV), Diode ideality factor
R_s,R_p: Resistance in series in ohm, Resistance in parallel in ohm
N_s, N_p: Number of modules in series, Number of modules in parallel
C: Number of cells in module
I, V: Module current in Ampere, Module voltage in Volts

III. MODELING OF PV MODULE IN SIMULINK

The above equations that are derived from the single diode model of PV cell are implemented in Simulink whose every detail is given in the following figures from Figure 3 to Figure 9.

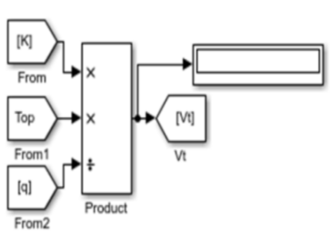

Figure 3: Implementation of equation (1) in Simulink

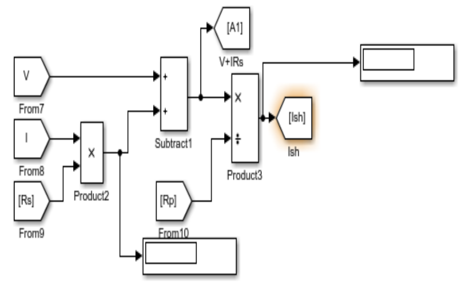

Figure 4: Implementation of equation (2) in Simulink

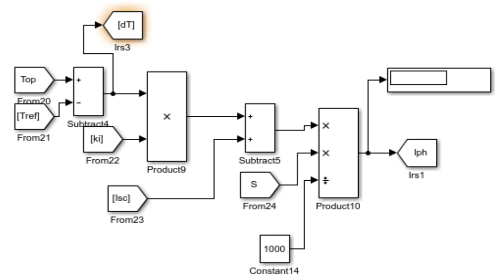

Figure 5: Implementation of equation (3) in Simulink

The go to tags and go from tags are used commonly to model the mathematical equations along with add, subtract, product and exponent blocks. As an example, go from tags are used as an input to product block consisting of 3 inputs, upper two having multiplication input and the last one having division input. The output of product block is fed to go to block. The first two inputs are k and T_{op}, the last input is q and the output is V_t thus giving equation 1 in Simulink. Similarly, the remaining equations are written in Simulink to represent equation 2 to 6 as shown in Figure 4 to Figure 8 respectively.

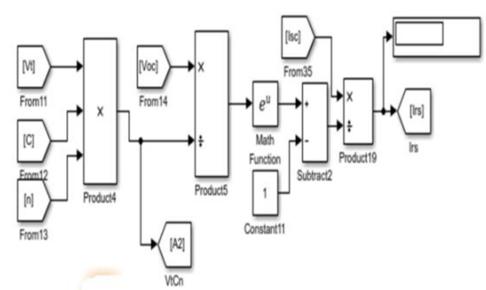

Figure 6: Implementation of equation (4) in Simulink

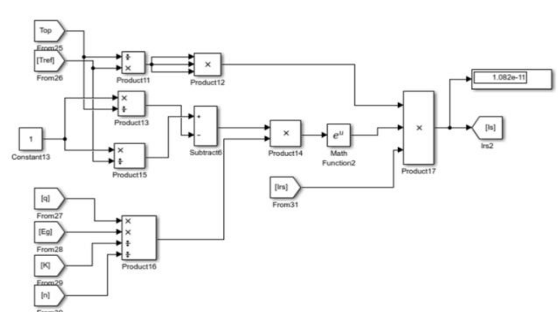

Figure 7: Implementation of equation (5) in Simulink

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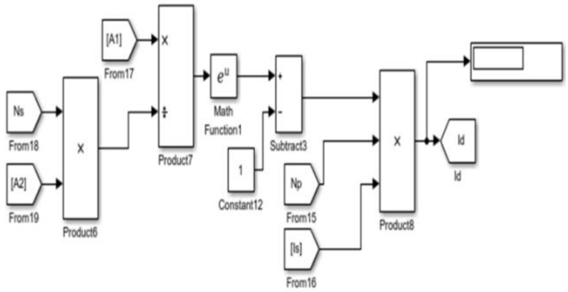

Figure 8: Implementation of equation (6) in Simulink

To model equation 7 in Simulink, circuit based approach have been used. Since a single module has N_s=N_p=1, this value of N_p has been used. The generated current is thus the difference between I_{ph} and (I_d + I_{sh}). Hence, I_d is subtracted from I_{ph} using subtract block and the output is fed to controlled current source. The rest of the model is drawn as shown in Figure 1 to get simulink model of equation 7 which has been shown in Figure 9.
The blocks as seen in Figure 9 in Simulink can now be used to create a subsystem which is the required model of PV module.

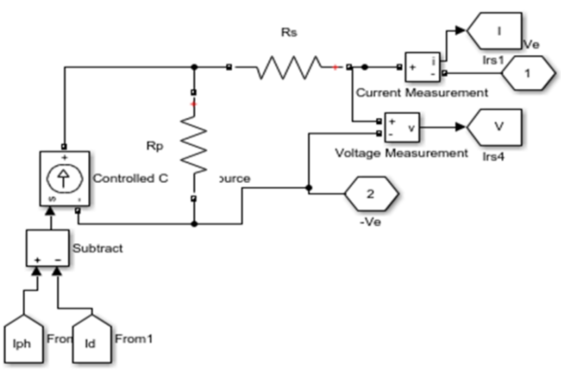

Figure 9: Implementation of equation (7) in Simulink

The 300 W LG300N1C-G3 solar module is taken as the reference module for modelling and simulation .The parameters of the module is given in Table1.

Module Data	STC parameters(25^{0}C,1kW/m^2)
Maximum Power	300 W
MPP voltage	32 V
MPP current	9.42 A
Open circuit voltage	39.5 V
Short circuit current	10 A
Number of cells	60
k_i	0.03

Table 1: Module Data of LG300N1C-G3 solar module

The value of series resistance is small , usually in the range of (0-1) Ω while that of parallel resistance is large, usually in the range of (100-1000) Ω. Similarly, ideality factor is in the range of (2/3 -2). In this paper, the value of Rp, Rs and n are chosen as 212.8143, 0.31448 and 0.96984 respectively
Table 1: Module Data of LG300N1C-G3 solar module
The above data and other required constants involved in equations are implemented in Simulink using go to tags and constant block which has been shown in Figure 10.

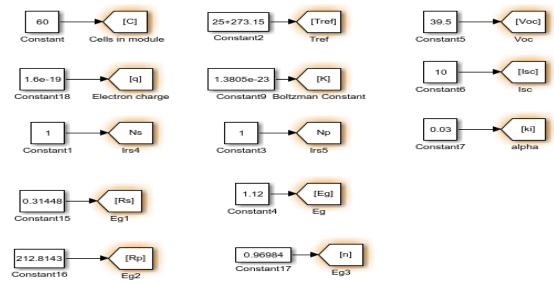

Figure 10: Providing required data of module in Simulink

All the blocks as shown in Figure 3 to Figure 8 and Figure 10 are grouped into a separate subsystem in Simulink .
Since irradiation and temperature are the two inputs for the PV module, they are implemented in Simulink using input block, Adder block and go to tag as shown in Figure 11. The irradiation input has to be provided in W/m^2 while temperature input has to be provided in degree centigrade. The adder block adds 273.15 with the temperature input in degree centigrade and converts it into degree Kelvin as required in the implemented equations.

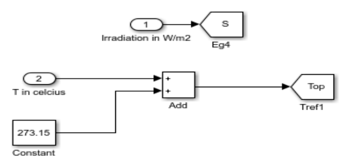

Figure 11: Creating input for PV module in Simulink

Now, the blocks shown in Figure 9 and Figure 11 are grouped into subsystem to form a PV module in Simulink that accepts irradiation in W/m^2 and temperature in degree centigrade and provides module current and voltage that can be measured using current measurement and voltage measurement block respectively.

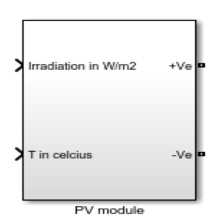

Figure 12: Formation of PV module subsystem in Simulink

In order to plot I-V and P-V characteristics, block called to workspace is used. The current and voltages of the module are stored in go to tags namely I and V. To evaluate power, a product block is used that multiplies I and V. Since, current, voltage and power are involved in I-V and P-V characteristics, three blocks for to workspace is required. The variables are named as I, V and P to represent current, voltage and power of a module and they are used in save format array to store data.

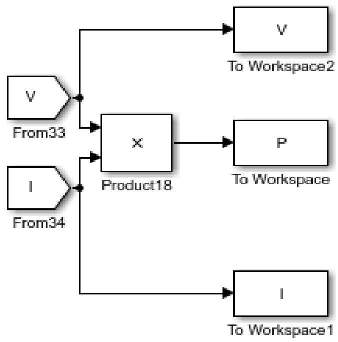

Figure 13: Use of To Workspace block in Simulink

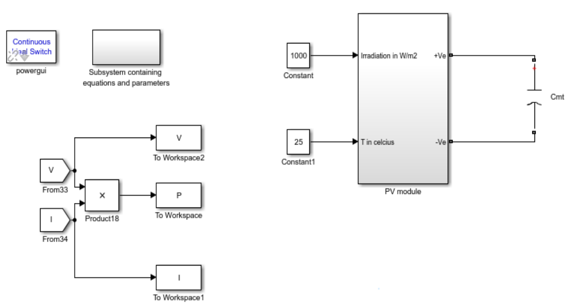

Figure 14: Complete model developed in Simulink

Figure 14 shows the complete model of PV module developed in Simulink. A capacitance of 1pF is used while simulation. Since the library components used in the model are of Simscape, it requires powergui block available in library to run the simulation. Hence, Powergui block has been added and used in continuous mode and ideal switching device. Constant block is used to provide input.

IV. RESULTS AND DISCUSSIONS

The inputs were provided in the constant block of Figure 14 and simulation time was set to 10 seconds. First of all, temperature input was fixed to 25^0C and irradiation input was set to 200 W/m^2 and simulation was run. After successful completion of simulation, plot command was used in MATLAB to plot I-V and P-V characteristics. Input irradiation was changed to 400, 600, 800 and 1000 and simulation was repeated for each input irradiation and curves were plotted. Similarly, curves were plotted for 20, 25, 30, 35 and 40 degree centigrade keeping irradiation input constant at 1000 W/m^2.

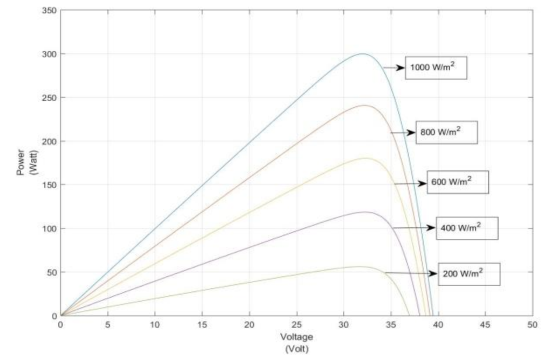

Figure 15: P-V characteristic of module at varying irradiance

Figure 15 shows that the module peak power increases from approximately 50 W to 300 W when irradiation is increased from 200W/m^2 to 1000 W/m^2. Also, the open circuit voltage of the module increases from approximately 35.5 V to 35.9 V as the solar irradiation increases from 200 W/m^2 to 1000 W/m^2.

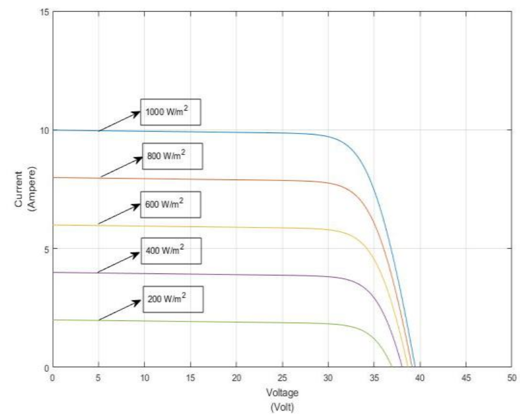

Figure 16: I-V characteristic of module at varying irradiance

Figure 15 shows that both open circuit voltage and short circuit current of PV module increases when irradiation increases. It can be seen from the figure that short circuit current has increased from 2.5 A to 10 A while open circuit voltage has increased from 35.5 V to 35.9 V when the solar radiation has increased from 200 W/m^2 to 1000 W/m^2.

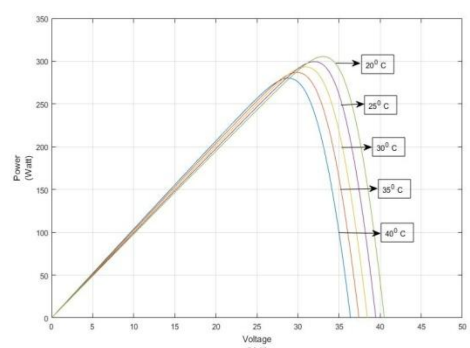

Figure 16: P-V characteristic of module at varying temperature

Figure 16 shows that the peak power of the module decreases with increase in temperature provided that irradiation is constant. It can be seen from the figure that the peak power has fallen from 310 W to 270 W when the temperature has increased from 20^0C to 40^0C.
Similarly, open circuit voltage has also decreased from 40.1 V to 35.3 V when temperature has increased from 20^0 C to 40^0C at a constant irradiation of 1000 W/m^2.

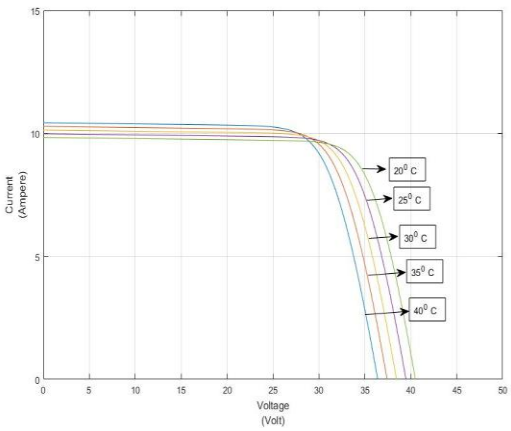

Figure 17:I-V characteristic of module at varying temperature

Figure 17 shows that short circuit current of the module increases if the temperature is increased at constant irradiation. Similarly, open circuit voltage of the module decreases when the temperature is increased at constant irradiation. It can be seen from the figure that short circuit current has increased from 9.9 A to 11 A while open circuit voltage has decreased from 40.1 V to 35.4 V as the temperature is increased from 20^0 C to 40^0 C at constant irradiation of 1000 W/m^2.

V. CONCLUSION:

This paper has presented a simple photovoltaic module modeled using Matlab,Simulink. PV module has been modeled by using its equivalent circuit and the equations involved, for the system simulation. Using datasheet of LG300N1C-G3 solar module, the PV module has been developed and simulated using Simulink of Matlab R2016b software package. The simulated results of the PV module have provided a good matching with result of PV module given in the datasheet. The effect of irradiation at constant temperature has shown that peak power generated by module increases with increasing irradiation and the effect of temperature at constant irradiation has shown that peak power generated by module decreases with increasing temperature. A step-by-step procedure for simulating a PV module with Matlab/Simulink block libraries is shown. This modeling procedure serves as an aid to help people to closer understand of I–V and P–V operating curves of PV module. In addition, it can be considered as a robust tool to predict the behavior of any solar PV cells, modules and arrays under varying environmental conditions as temperature and irradiation. This paper serves as a guide for the newbie researchers who are looking to model and study PV module using Matlab/Simulink.

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