Modeling and Simulation of Photovoltaic Module in MATLAB

Alex Dev and S. Berclin Jeyaprabha

Abstract--- *This paper defines a novel and simplified electrical based mathematical modelling and its MATLAB simulation of photovoltaic cell in order to estimate the physical and electrical behaviour of the PV cell with respect to changes on environmental parameter of temperature and irradiance. An accurate PV module is presented based on the electrical characteristics of PV module. The general model was implemented on MATLAB script file, and the same is modelled using MATLAB SIMULINK which accepts irradiance and temperature as variable parameters and outputs the I-V characteristic. Based on the I–V curves of a photovoltaic (PV) module, it can be used to improve PV module performance for different engineering applications. Five parameters are introduced in this model to account for the complex dependence of the PV module performance upon solar-irradiance intensity and PV module temperature. Accordingly, the most important parameters, i.e. the short-circuit current, open-circuit voltage, fill factor and maximum power-output of the PV module, may be determined under different solar irradiance intensities and module temperatures. This model is simple and especially useful for engineers to calculate the actual performances of the PV modules under operating conditions, with limited data provided by the PV module manufacturers needed.*

Keywords--- *Photovoltaic Module, Photovoltaic Cell, MATLAB, Short Circuit Current, Open Circuit Voltage, Modeling, Simulation*

I. Introduction

THE renewable energy sources which are also called as non-conventional type of energy are the sources which are continuously renewed by natural process. It includes, solar energy, bio-energy - bio-fuels, wind energy, ocean energy, tidal energy and hydropower etc., are some of the examples of renewable energy sources. A renewable energy system convert the energy found in sunlight, falling-water, wind, sea-waves, geothermal heat, or biomass into a usable form, such as in the form of heat energy or electrical energy. The majority of the renewable energy comes either directly or indirectly from sun and wind and can never be fatigued, and therefore they are called renewable energy.

However, in the modern world majority of the world's energy sources are from the conventional sources (non-renewable)-fossil fuels such as coal, natural gases and oil.

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These fuels are often termed non-renewable energy sources, as they cannot be renewed at the rate of its consumption. Though, the available amount of the fuels is extremely large, but due to steep increase in the energy demand day by day, the availability of fuels are reduced and hence after a few years it will end. Hence the importance of renewable energy is dominant, as it doesn't make any disturbance to the surrounding environment such as green house effect.

Photovoltaic (PV) modules based renewable energy generation systems, nowadays represent the most suitable and prominent solution, for both domestic as well as industrial power levels, to reduce CO_2 emissions and the energy consumption produced by oil and gas. Moreover in different countries, the Government as well as some electric companies are providing money as incentives directly or indirectly for the energy produced by renewable sources and injected into the utility grid. The cost and the performance of PV plants strongly depend on the modules. However, the performance and electrical parameters of the modules, i.e. open circuit voltage and short circuit current, can be different than those provided by the manufacturer; moreover, such parameters can change as the module is getting older. Therefore, the behaviour of the mathematical model of a PV module can't match with the real operating conditions.

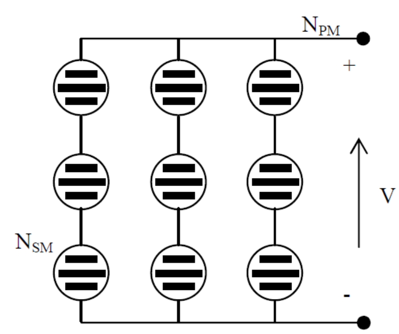

Figure 1: Photovoltaic Cell

The photovoltaic energy is a clean energy, with a long lifespan and a high reliability. So, it can be considered as one of the most sustainable renewable energy. These systems can be located where the demand of electric energy arises, avoiding losses of transmission and contributing reductions to the CO_2 emission in urban centres The photovoltaic module is the result of associating a group of photovoltaic cells in series and parallel (figure 1), with their protection devices, and it represents the conversion unit in this generation system. Besides, the obtained energy depends on the solar radiation, the temperature of the cell and the voltage produced in the photovoltaic module.

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Although the mathematical and simulation photovoltaic modules development began time ago, improvements of these models are analysed and presented continually. One of the objectives of this paper is a review of those existing methods and models. Also, a model has been realised in MATLAB that is based on other existing ones.

II. Photovoltaic Cell

The solar cell is the basic unit of a photovoltaic module and it is the element in charge of transforming the sun rays or photons directly into electric power. The solar cell used is the PN union, whose electrical characteristics differ very little from a diode, represented by the equation of Shockley

$$I = I_s(e^{(V_d/nV_t)} - 1) \quad (1)$$

So, the process of modelling this solar cell can be developed based on being the net current of the cell, the difference of the photocurrent I_l or I_{ph}, (the current generated by the incident light, directly proportional to the sun irradiation) and I_d (the normal diode current), as shown in equation below

$$I = I_l - I_d \quad (2)$$

Therefore, the ideal solar cell can, theoretically, be modelled as a current source in anti-parallel with a diode. Improving the PV cell model includes the effects of series and shunt resistance,

Different model of solar cells were presented in literature. The most accurate model, denoted as double-diode model uses an equivalent circuit with two diodes but it is quite complex due to the presence of a double exponential and six parameters to assign. A different model, based on a single diode circuit, was then proposed. In both cases, the mathematical models require the knowledge respectively of six and five parameters that are not directly available on manufactures datasheets. A simplified one-diode model, shown in Figure.2, using only four parameters was accepted widely.. However, in such model the voltage is independent from solar irradiance. As a consequence, a significant voltage error in the I-V curves is present especially at open circuit and maximum power point conditions. Finally a model with all parameters achievable from manufactures datasheet is proposed. The parameters determination of such model requires the use of numerical methods.

The paper proposes an improved model of a PV module that makes use only parameters provided by manufacturers datasheets and, moreover, doesn't require any numerical methods. In the paper after the detailed description of the proposed model, different simulation results are pointed out. Finally an experimental validation of the model is presented together with a suitable procedure that takes into account the real operating parameters in the PV model.

III. Characteristics of PV Cell

An ideal PV cell is modelled by a current source in parallel with a diode. However no solar cell is ideal and thereby shunt and series resistances are added to the model as shown in the PV cell diagram above. R_S is the intrinsic series resistance whose value is very small. R_P is the equivalent shunt resistance which has a very high value.

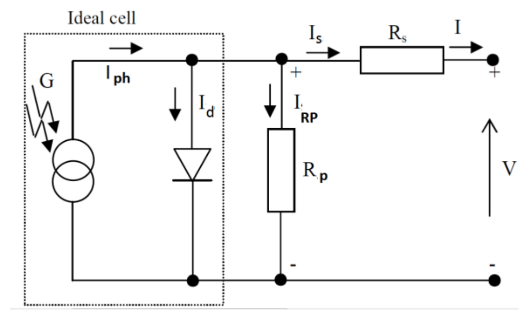

Figure 2: Electrical Equivalent Model of a Photovoltaic Cell

Applying Kirchoff's law to the node where Iph, diode, Rp and Rs meet, we get

$$I_{ph} = I_d + I_{Rp} + I \quad (3)$$

We get the following equation for the photovoltaic current:

$$I = I_{ph} - I_{Rp} - I_d \quad (4)$$

$$I = I_{ph} - I_o[\exp(\frac{V + IR_s}{V_T}) - 1] - [\frac{V + IR_s}{R_p}] \quad (5)$$

Where,
I_{ph} = Insulation current or photocurrent
I = Cell current
I_0 = Reverse saturation current
V = Cell voltage
R_s = Series resistance
R_p = Parallel resistance
V_T = Thermal voltage
K = Boltzman constant
T = Temperature in Kelvin
q = Charge of an electron.

IV. Efficiency of PV Cell

The efficiency of a PV cell is defined as the ratio of peak power to input solar power.

$$\eta = \frac{V_{mp} I_{mp}}{I(\frac{W}{m^2}) A(m^2)} \quad (6)$$

where,
Vmp = voltage at peak power,

Imp = current at peak power,

I = solar intensity per square metre,

A = area on which solar radiation fall

The efficiency of PV cell will be maximum, if we track the maximum power from the PV system at different environmental condition such as solar irradiance and temperature by using different methods for maximum power point tracking.

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V. Modeling of PV Array

The building block of PV arrays is the solar cell, which is basically a p-n junction that directly converts light energy into electricity: it has a equivalent circuit as shown below

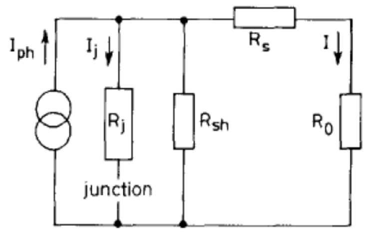

Figure 3: Equivalent Circuit of a PV Cell

The current source I_{ph} represents the cell photo current; Rj is used to represent the non-linear impedence of the p-n junction; R_{sh} and R_s are used to represent the intrinsic series and shunt resistance of the cell respectively. Usually the value of Rsh is very large and that of Rs is very small,hence they may be neglected to simplify the analysis. PV cells are grouped in larger units called PV modules which are further interconnected in series-parallel configuration to form PV arrays or PV generators[3].The PV mathematical model used to simplify above PV array is represented by the equation:

$$I = n_p I_{ph} - n_p I_{rs}[\exp(\frac{qv}{KTAn_s}) - 1] \quad (7)$$

Where,
I =PV array output current;

V = PV array output voltage;

n_s = number of cells in series and

n_p = number of cells in parallel;

q = charge of an electron;

k = Boltzmann's constant;

A = p-n junction ideality factor;

T = cell temperature (K);

I_{rs} = cell reverse saturation current.

The factor A in equation (7) determines the cell deviation from the ideal p-n junction characteristics; it ranges between 1-5 but for our case A=2.46. The cell reverse saturation current I_{rs} varies with temperature according to the following equation:

$$I_{rs} = I_{rr}[\frac{T}{T_r}]^3 \exp(\frac{qE_G}{KA}[\frac{1}{T_r} - \frac{1}{T}]) \quad (8)$$

Where
T_r = cell reference temperature

I_{rr} = cell reverse saturation temperature at Tr

E_G = band gap of the semiconductor used in the cell.

The temperature dependence of the energy gap of the semi conductor is given by

$$E_G = E_G(0) - \frac{\alpha T^2}{T + \beta} \quad (9)$$

The photo current Iph depends on the solar radiation and cell temperature as follows:

$$I_{ph} = [I_{scr} + K_i(T - T_r)]\frac{s}{100} \quad (10)$$

Where,
Iscr = cell short-circuit current at reference temperature and radiation

Ki = short circuit current temperature coefficient

S = solar radiation in mW/cm2.

The PV power can be calculated using equation (7) as follows:

$$P = IV = n_p I_{ph} V[(\frac{qV}{KTAn_s}) - 1] \quad (11)$$

VI. Matlab Code for PV Array

```
close all;
clear all;
clc;
T=302;
Tr1=40;
Tr=298;
S=[100 80 60 40 20];
%S=70;
ki=0.00023;
Iscr=3.75;
Irr=0.000021;
k=1.38065*10^(-23);
q=1.6022*10^(-19);
A=2.15;
Eg0=1.166;
alpha=0.473;
beta=636;
Eg=Eg0-(alpha*T*T)/(T+beta)*q;
Np=4;
Ns=60;
V0=[0:1:300];
for i=1:5
Iph=(Iscr+ki*(T-Tr))*((S(i))/100);
Irs=Irr*((T/Tr)^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/T)));
I0=Np*Iph-Np*Irs*(exp(q/(k*T*A)*V0./Ns)-1);
P0 = V0.*I0;
figure(1)
plot(V0,I0);
axis([0 50 0 20]);
xlabel('Voltage in volt');
ylabel('Current in amp');
hold on;
figure(2)
plot(V0,P0);
axis([0 50 0 400]);
xlabel('Voltage in volt');
ylabel('Power in watt');
hold on;
figure(3)
plot(I0,P0);
axis([0 20 0 400]);
xlabel('Current in amp');
```

```
ylabel('Power in watt');
hold on;
end
```

VII. SIMULINK MODELING OF PV ARRAY

Modelling can be done in MATLAB by many ways; common methods includes by programming and using SIMULINK modelling. Modelling a PV panel using SIMULIK is explained in this section along with the example. As explained above, the PV panel is influenced by temperature, light intensity, etc. For each formulae separate blocks are made and finally, all are combined to get the PV panel.

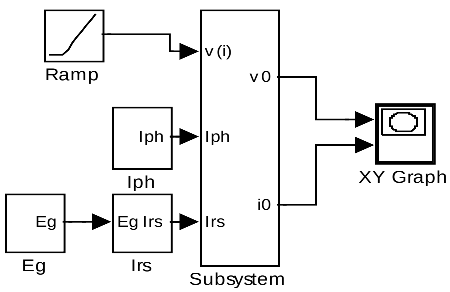

Figure 4: Final Block

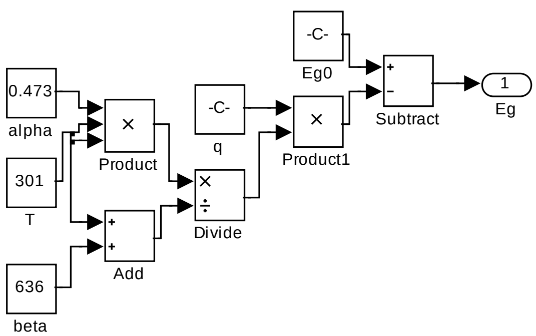

Figure 5: Calculation of Eg

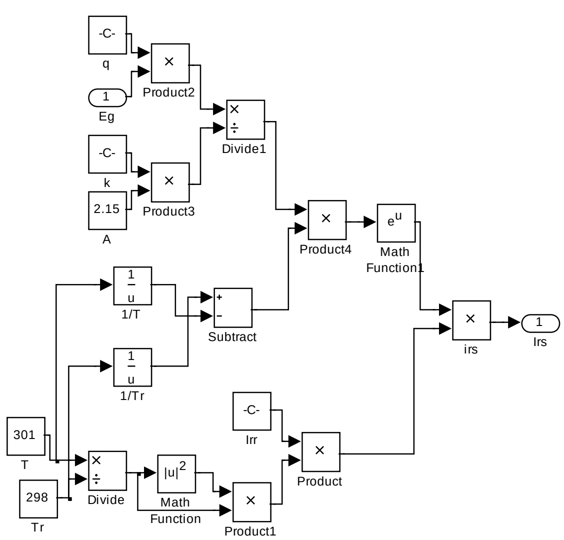

Figure 6: Calculation of Irs

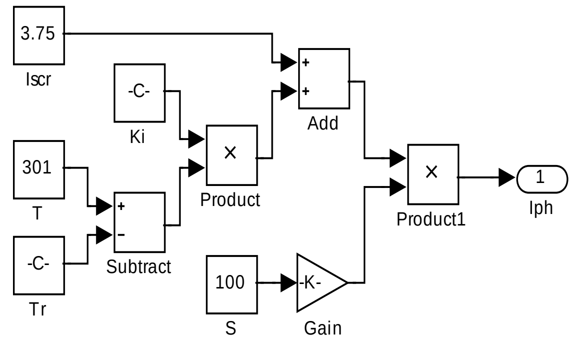

Figure 7: Calculation of Irs

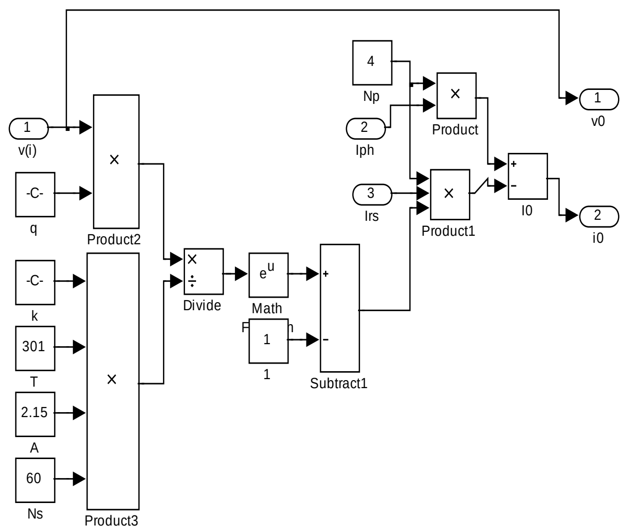

Figure 8: Subsystem of PV Cell

VIII. RESULTS AND DISCUSSION

The IV and PV curves for various irradiance but a fixed temperature (25^0C) is shown below in figure 9, 10, 11. The characteristic I-V curve tells that there are two regions in the curve: one is the current source region and another is the voltage source region. In the voltage source region (in the right side of the curve), the internal impedance is low and in the current source region (in the left side of the curve),the impedance is high. Irradiance temperature plays an important role in predicting the I-V characteristic, and effects of both factors have to be considered while designing the PV system. Whereas the irradiance affects the output, temperature mainly affects the terminal voltage. From the PV characteristics we can observe that, there is a point at which the power output is maximum for a given condition of irradiance and load. If we are operating the PV panel at this point, operation of PV panel at this region gives the maximum efficiency.

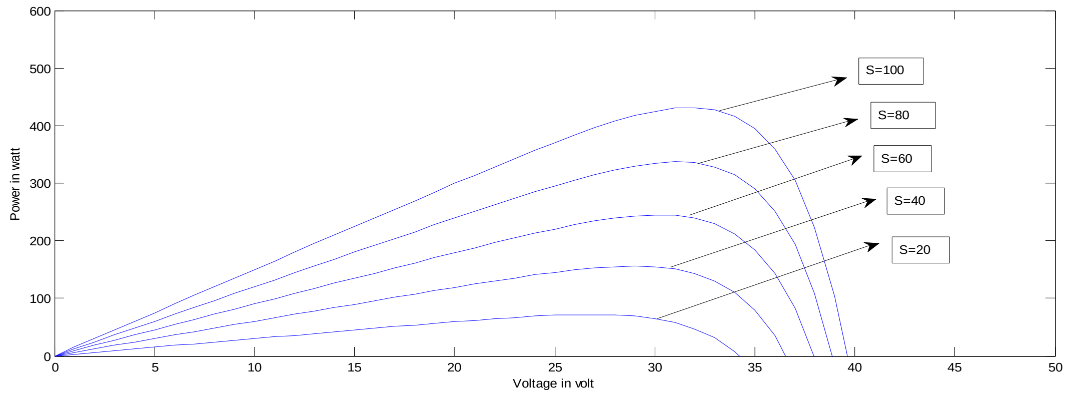

Figure 9: P-V Characteristics

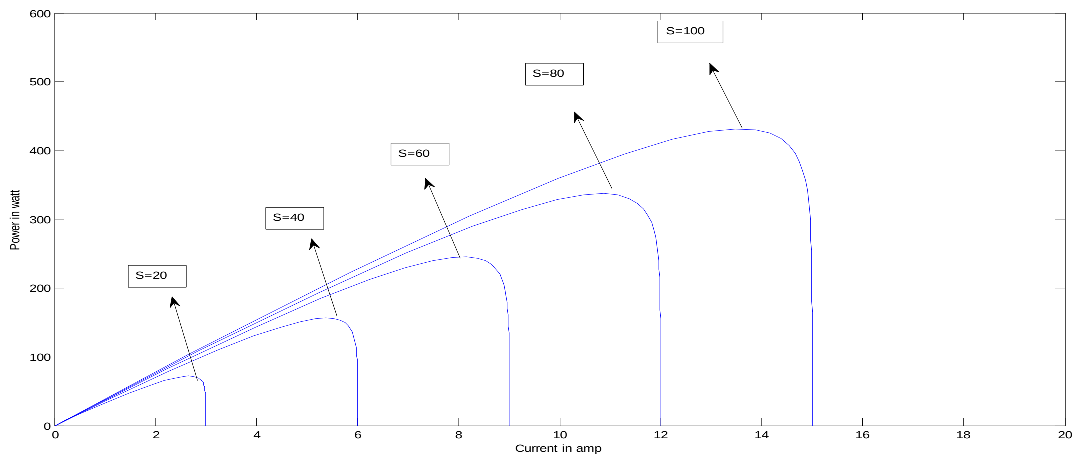

Figure 10: P-I Characteristics

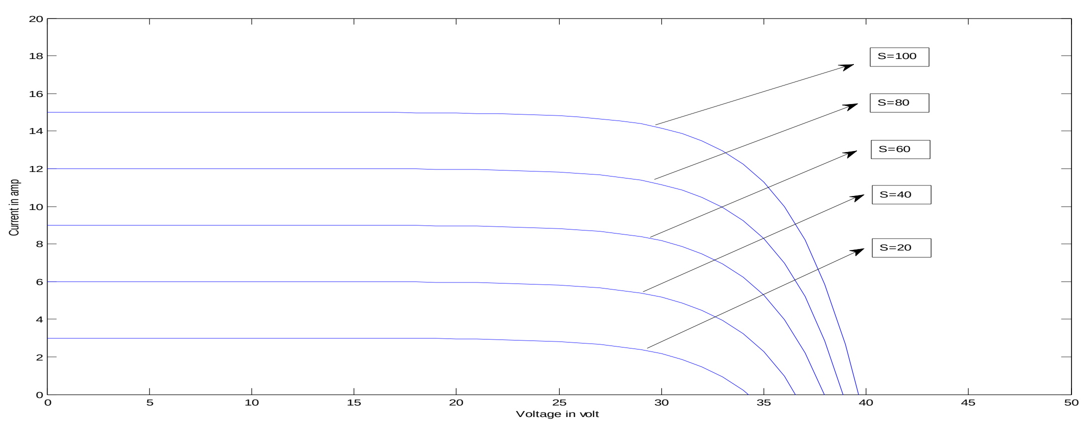

Figure 11: V-I Characteristics

IX. CONCLUSION

The paper presents an improved mathematical model for photovoltaic modules that employs only parameters provided by manufacturers datasheets without requiring the use of any numerical methods. The model is derived from by applying several improvements such as function of the solar irradiance, function of temperature. However, the electrical parameters of the modules, i.e. open circuit voltage and short circuit current, can be different than those provided by the manufacturer; moreover, such parameters can change as the module is getting older. Therefore, the behaviour of the mathematical model of a PV module can't match the real operating conditions. In such framework, authors propose a suitable modification to the model to take into consideration the real operating parameters in the PV model. Several simulation and an experimental results have been pointed out in order to validate the mathematical model. The results show that the proposed model demonstrates a good agreement with that of the manufacturer's data sheet.

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