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Sensitivity Analysis Through Error Function of Crystalline-Si Photovoltaic Cell Model Integrated in a Smart Grid

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Abstract - The paper is based on the device representation of PV cell there are different internal parameters that representing their behaviour. The internal parameters have impacts on the PV power generation. In this work, a single diode solar cell five parameter model is used to understand the internal parameters' sensitivity not the efficiency. Sensitivity is important because of giving idea about parameters response to the total system. The more a parameter is sensitive, the more the system is dependent on those parameters. Here the internal parameters called photocurrent, diode saturation current, series resistance, shunt resistance, diode ideality factor, and cell temperature are investigated through the simulation for getting their sensitivity which aims to identify the parameters having much impact on total system, this identification would help to make a better model for the PV panel which could be more faster in real time system to give estimation of the power generation. Better understanding about the parameters is identically significant for modelling the PV system. At the end of this work a simplified model is built with simplified PV structure.

Keywords Photovoltaic cell, error function, sensitivity, internal parameters, smart grid.

1. Introduction

Since the fast climate change all over the world as threatening issue all nations have taken initiative to save the world from the effect of global warming. In this digital era, energy is the main thing which is needed for the growth of civilization and development of the world [1-4]. The source of energy producing less harmful greenhouse gases is needed for sustainable development. People need cleaner energy source that has least effect on the environment and keep the environment clean [2]. Renewable energy which is cleaner and cheap and available all over the world can meet those requirements stated earlier. There are different types of renewable energy among which solar energy, namely PV energy is getting more concern [3,5-7].

From a single tiny PV cell the output is low but when these cells are connected with each other in series or parallel it becomes significant and can inject electrical power into an electrical grid or a smart grid. Nowadays there are several PV systems connected to the electric grid and the generated power energy is distributed to industrial, household systems or other sectors [8,9]. Numbers of PV cells create a PV panel, numbers of PV panels build a PV array and numbers of PV arrays make a PV system or PV plant. Large PV plants are built all over the world and connected to the country's electric grid. To understand the behaviour of a large PV plant is quite complex, it can be started from knowing and understanding about a PV cell. Industry provides the characteristic parameters value for PV cell or PV panel, these values help to get the other parameters value. More precise value helps to get other internal parameters value more precisely. These internal parameters and ambient environmental condition have great impact on getting the estimated the power production, i.e., output value for a PV system. If internal parameters and ambient environmental condition are identified properly and gained the knowledge of their behaviour to each other, it gives better estimated value for a PV system which can be used for smart grid [10-14].

In this paper, a single PV cell's different internal parameters are analysed to identify their sensitivity. Here both measured values are derived from the standard value and also estimated value. Simulation is done using these measured and estimated parameters values. The sensitivity analysis helps to design the PV system by an equivalent electric circuit and a new equation excluding less important parameters having less sensitivity. Parameters like series resistance shunt resistance, diode ideality factor, photocurrent, dark saturation current and cell temperature are analysed and their sensitivity are identified [15,16].

The error function *E (I)* is introduced for the PV cell by which internal parameters' sensitivity are analysed. Using the sensitivity function a parameter is described and helps to get a simple equation for the PV system.

The rest of the paper is organized as follows: Section 2 presents brief about PV integrated in smart grid for sustainable development. Section 3 presents the modelling for this work. Section 4 presents the case study with different outcome of the simulation. Section 5 presents the conclusion.

2. PV Integrated in a Smart Grid

The current trend in energy supply and usage are perceptibly economic, environmental and social unsustainable. Nowadays renewable energy sources (RES) power producers are included in sustainable development to protect the environment, to keep it green and reverse the global warming. RES is directly related to energy generation and energy is needed for economic and social development [17]. The existing electric grid needs modification for utilization of total energy distribution. So, a highlighting thought about the electric grid is needed and the smart grid (SG) conception is on the way. A SG will benefit from cloud solutions allowing data interchange between end users and producers for transparency on energy consumption and on energy conversion of other forms of energy into electric energy [12,18].

The SG will be a source of information able to interact with other kinds of data, not only monitoring the flow of electric energy, but also an entire set of environments, leading to a foreseen increase data to be processed by SG management systems. So, the SG architecture has to be implemented with ensured security and reliability. A layered framework is one option gathering information about the SG components offering an awareness of the behaviour, enabling people or machines to act accordingly over a services platform [11]. Fig. 1 gives a clear image about SG system [19].

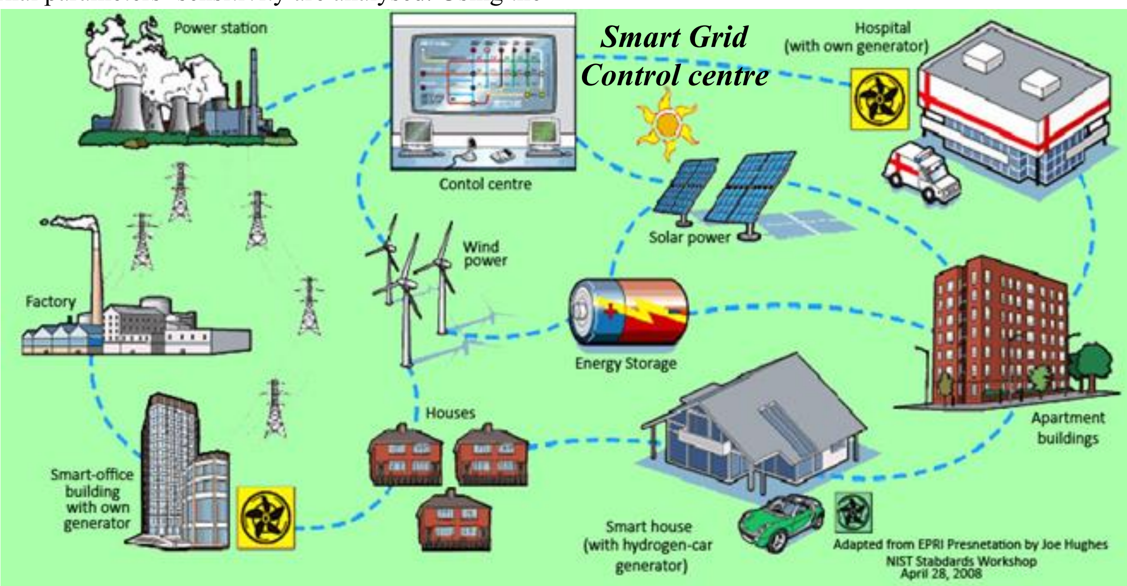

Fig. 1. Smart grid system [19].

In Fig. 1 SG control centre is the main core of electricity flow that control distribution among consumers having cyber physical structure [12].

Among all RES that connected with SG, PV is getting more concern because of its rapid growth of efficiency and decrease of the price. PV has promising future for sustainable development; it could be built at existing rooftop of a building and could be built in big area for large scale of power generation. PV plants are connected with the SG to distribute energy. The significant of PV is that during production time period it does not produce any greenhouse gases and keep the environment clean and sustainable [17-23].

3. Modelling

3.1. PV Model

The solar cell is modelled by the five parameters equivalent circuit. The single diode PV cell [24-26] is shown in Fig. 2.

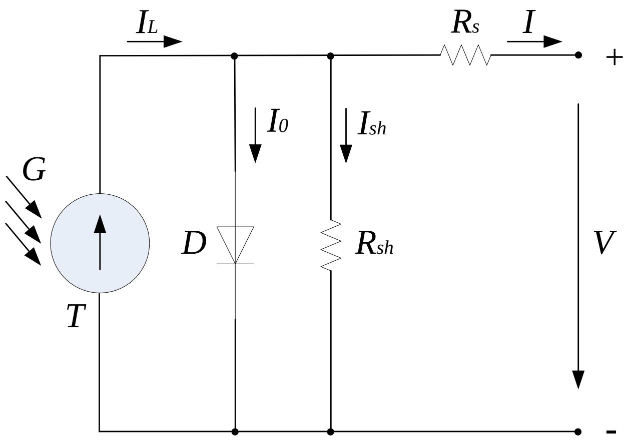

Fig. 2. Single diode PV cell.

The current I is given by:

$$I = I_L - I_0\left[\exp\left(\frac{e(V+IR_s)}{nkT}\right)\right] - \frac{V+IR_s}{R_{sh}} \tag{1}$$

In (1), I is the output current, it give the total output of the PV with knowledge about other parameters. Here the photocurrent I_L is the photocurrent, I_0 stands for diode saturation current, q is the electron charge, V is the voltage at the cell terminals, R_s is the series resistance, R_{sh} is the shunt resistance, n is the ideality factor, K is the Boltzmann's constant, T is the cell temperature [27-29]. In (1), the photocurrent I_L is getting from (2):

$$I_L = \left(\frac{G}{G_n}\right)[I_{LS} + K_i(T - T_n)] \tag{2}$$

In (2) the photocurrent I_L is directly depends on irradiance G and cell temperature [30,31] given by:

$$I_0 = I_{0n}\left(\frac{T}{T_n}\right)^3 \exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \tag{3}$$

I_0 gives the value for diode saturation current that include cell temperature for present and STC condition with other parameters. Excluding series and shunt resistance (1) become like (4) and the representation of the Fig. 2 is without these parameters look as Fig. 3.

$$I = I_L - I_0\left[\exp\left(\frac{ev}{nkT}\right) - 1\right] \tag{4}$$

The ideal single diode without series and shunt resistance, represented by (4) [30-33] is shown in Fig. 3.

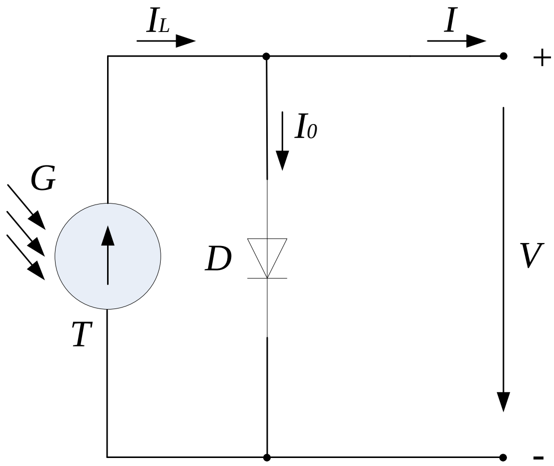

Fig. 3. Ideal single diode without series and shunt resistance.

3.2. Error Function

For doing this simulation an error function is built that give value for output current using (1). Fig. 2 presents the electric diagram of the five parameters model those are internal parameters of the PV cell. For every internal parameter with cell temperature the error function is created and analysed sensitivity with that function. The function gives the deviation of measured data from the estimated data. At a time single parameters is take in account and get the measured value under STC condition and then get the estimated value using different value of that parameter. These values are used to create error function analysis graph using (2) given by:

$$E(I) = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(I_{std} - I_{err})^2} \tag{5}$$

where I_{std} is the value from measured data and I_{err} is the value of estimated data.

The details overview for identifying the error function using (4) is shown in Fig. 4.

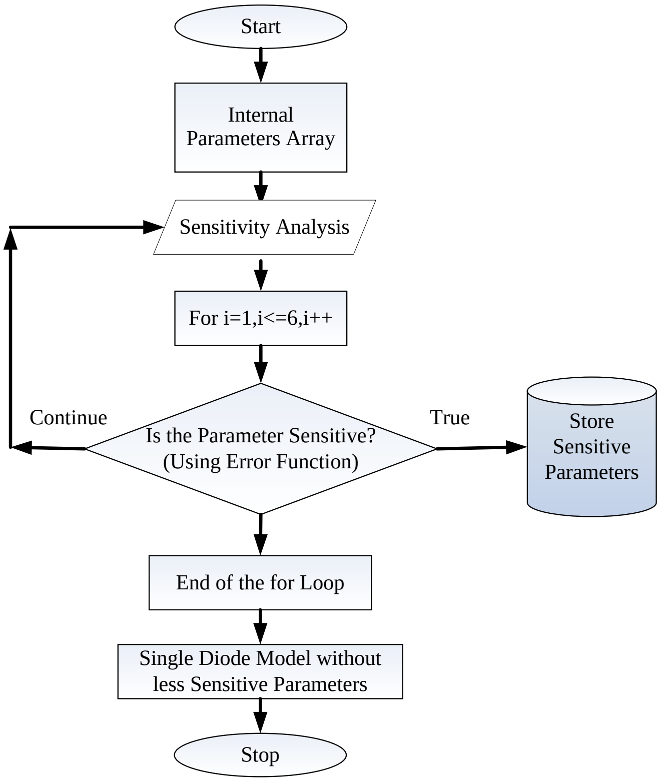

Fig. 4. Details overview for identifying the error function using (4).

Error function does not give the efficiency of the PV rather is give depth knowledge about each parameter's sensitivity to PV cell.

4. Case Study

4.1. c-Si PV Cell under STC Condition

The mathematical model for the PV system with the five parameters cell equivalent circuit module, shown in Fig. 1 is implemented in Matlab/Simulink. The five parameters model is featured by a single diode model. For a PV cell there is STC by which the parameters and characteristics of the cell are described [34-36]. Here the c-Si PV cell is used and its values are used for simulation. Table 1 presents the data for the c-Si solar cell at STC under standard condition.

Table 1. Data for the c-Si solar cell at STC

Solar cell	V_m^*	I_m^*	V_{oc}^*	I_{sc}^*	α_{sc}
c-Si	0.55 V	1.98 A	0.64 V	2.1 A	1.7 mA/ºC

The parameters values are changed when the standard value of the surrounding is changing and during that time the internal parameters values are also affected by the ambient condition of PV cell.

In this simulation, the computational analytical model is used to analyse six internal parameters to understand their behaviour to PV, i.e., the cell temperature. Here single parameter is analysed at a time to view its specific sensitivity.

The I-V curve considering the standard values [10] is shown in Fig. 5. The P-V curve considering the standard values is shown in Fig. 6.

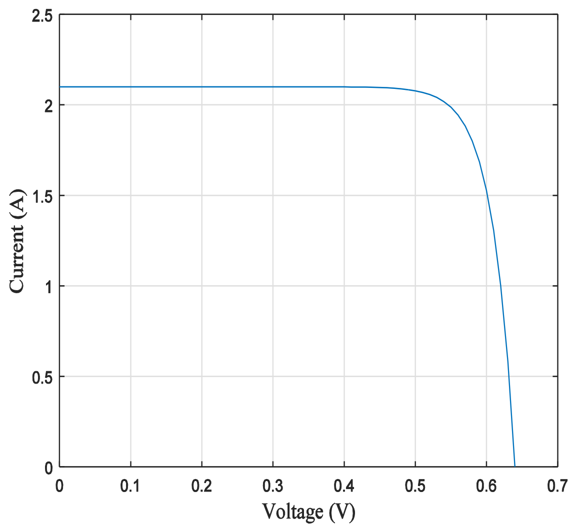

Fig. 5. I-V curve using standard values.

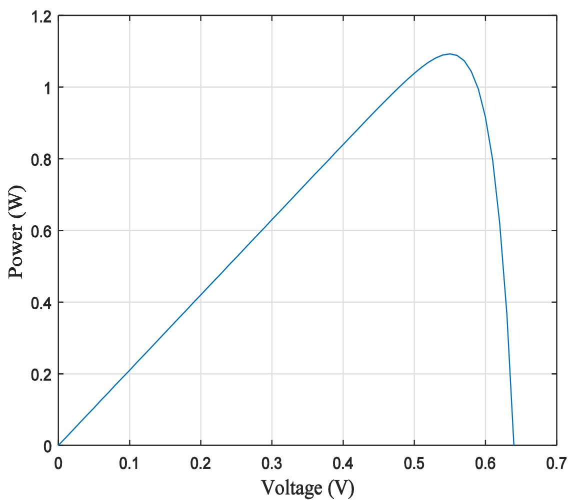

Fig. 6. P-V curve using standard values.

In Fig. 5 and in Fig. 6 curves are given in STC for c-Si PV cell. The I-V curve shows the open circuit voltage and short circuit current. The P-V curve shows the maximum point for the PV.

4.2. Parameters and Error Function

This section describes the result of the simulation. Mainly six internal parameters of PV cell are analysed with error function. These parameters are light current, cell temperature, diode ideality factor, series resistance, shunt resistance and diode saturation current. Their sensitivity is tested with PV output power.

4.2.1. Photocurrent and Error Function

Photocurrent is the main part of PV power generation; this part is directly related with irradiance. PV mainly works as photodiode. Light with enough strength start to get out the electron from the material and causes electron flow. Photocurrent varies with the irradiance; in this simulation value for this parameter is varying from 0 A to 4.2577 A. Using (1) the value for the current is get. By using (5), the error function is found from the measured value under STC and different estimated value under different conditions. The change of the error function with different photocurrent is shown in Fig. 7.

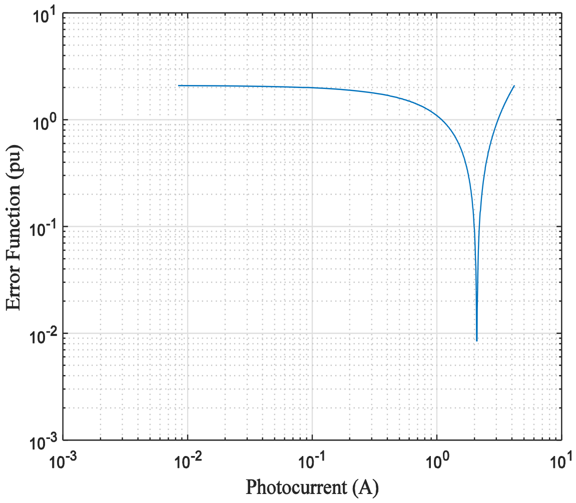

Fig. 7. Change of the error function with different photocurrent.

In Fig. 7, the significant behaviour is found. The curve behaviour is changing with the change of the photocurrent value. It is viewed that the curve is changing even with very small change in value of the photo current. Photocurrent is one of the principal parts of the PV and its value is very significant for the output power generation.

4.2.2. Cell Temperature and Error Function

Cell temperature is another internal variable which has a great impact on the output performance of a PV cell. For finding the error function of cell temperature, process of finding the photocurrent is followed. It starts from very low cell temperature 273 K and increases gradually till 353 K to understand sensitivity to PV power generation. By using (5), the error function is generated. From graph, a significant behaviour is identified for this parameter. The change of the error function with different cell temperature is shown in Fig. 8.

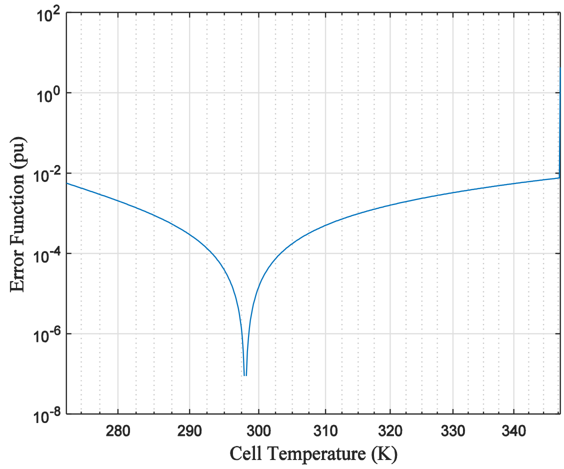

Fig. 8. Change of error function with different cell temperature.

In Fig. 8, it is significant that the behaviour of cell temperature's values have abundant sensitivity. The curve is sense small change of this parameter. Small value makes a greater change in error function which show very sensitive element.

4.2.3. Diode Idealtiy Factor and Error Function

In (1) diode ideality factor is another parameter that shows how closely a diode follows the ideal diode equation. Mainly value of this parameter is around one and it may vary for different semiconductor that used for the PV. In this simulation, value of this parameter is varied from one to two that changes in error function are counted and important behaviour is counted. Small change in value of this parameter makes significant change in error function. The change of the error function with different diode ideality factor is shown in Fig. 9.

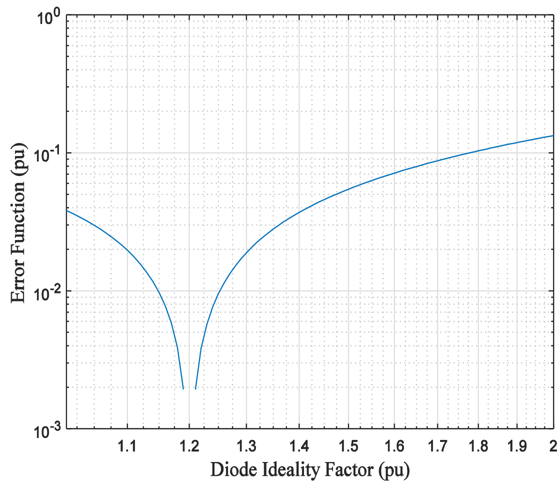

Fig. 9. Change of error function with different diode ideality factor.

Fig. 9 gives clear significant behaviour of this parameter which is identified as an important factor in (1).

4.2.4. Series and Shunt Resistances and Error Function

Using the analytical solution of PV, in simulation the error function for series resistance is created and it does not show any kind of change for error function. It is just a horizontal line along x axis. It does not have significant impact on PV. This parameter does not have impact on total output of PV cell.

For shunt resistance simulation is also done and gets the error function. This is the part of the internal parameter that used in (1) to get PV output current. From small value 50 Ω of this parameter the simulation starts and it changes in a very long range 2.5 kΩ. Between these ranges the error function is observed to identify sensitivity of this factor. In Fig. 10 the changing is clearly viewed. The change of the error function with different shunt resistance [16] is shown in Fig. 10.

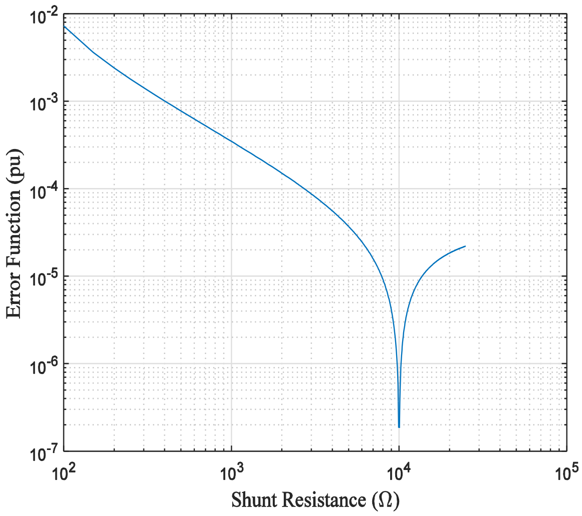

Fig. 10. Change of error function with different shunt resistance [16].

In Fig. 10, for changing the value of the parameter in a very large range the error function showed response that implies about the parameter as a less sensitive.

4.2.5. Diode Saturation Current and Error Function

Among internal parameters that include in Fig. 2 another important parameter is diode saturation current. Using (5) the error function is created. The value is varied in a range and for small change in the value of this parameter makes significant change in error function. The behaviour of the parameter denotes its significance. It is a very sensitive internal parameter. The change of the error function with different diode saturation current is shown in Fig. 11.

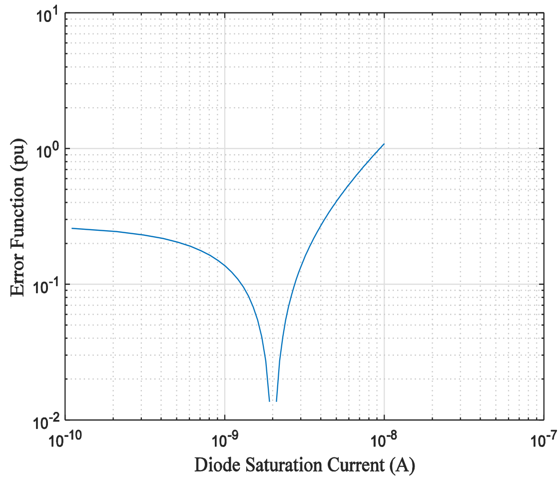

Fig. 11. Change of error function with different diode saturation current.

Fig. 11 shows that small changes of value make significant change in the error function.

Through the simulation part of this work, different important internal parameters' behaviour is viewed and their significant sensitivity to PV is identified through error function. This work identified important parameters for PV system which should be included in (1) and also identified those parameters which is less important and excluded in (4).

In total simulation, photocurrent I_L is analysed with error function and got the idea about its sensitivity to PV cell. Cell temperature is analysed and it is also shown as a very sensitive parameter. Small changes in cell temperature shows significant amount of changes in the error function. Diode ideality factor is simulated with error function and viewed its sensitivity. Series resistance is analysed and not much significant behaviour is found to take it into account as significant parameter. Shunt resistance is analysed, it did not show significant behaviour to take it into account as significant factor. Diode saturation current is analysed, it shows significant behaviour and is identified as an important parameter. After identifying the important factor of PV, the (1), is rewritten as (4) and Fig. 2 is presented as Fig. 3.

The I-V curve from (1) and (4) [16] is shown in Fig. 12.

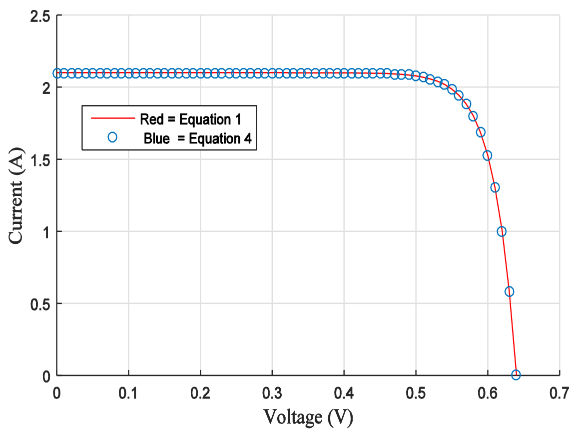

Fig. 12. I-V curve from (1) and from (4) [16].

The P-V curve from (1) and from (4) is shown in Fig. 13.

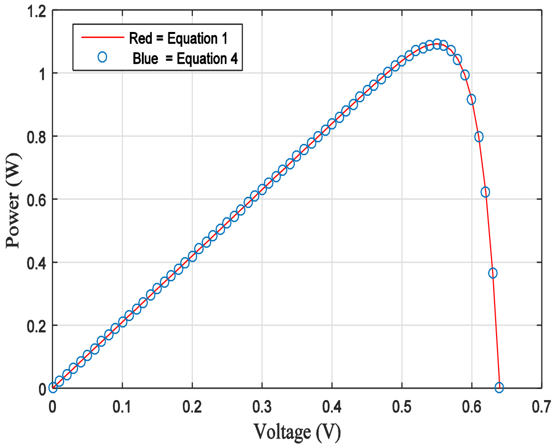

Fig. 13. P-V curve from (1) and from (4) [16].

In Fig. 12 and Fig. 13 are drawn from (1) and from (4). Their output has no very big difference between each other. Simulation and Sensitivity tests assisted by (5) that give less sensitivity of series and shunt resistance.

5. Conclusion

Six internal parameters are analysed in this simulation to identify their sensitivity to get a simple equation for PV System. After knowing about the parameters effect on PV, the ideal single diode model is design as Fig. 3. Series resistance and shunt resistance is excluded in the Fig. 3 and also excluded from (4). Internal parameters like light current, cell temperature, diode ideality factor, diode saturation current are important parameters for PV design and modelling which have great impact on system power generation.

This simulation work is done using computer not in real time atmospheric condition. Work is done using single cell, to see the impact on PV plant. Further investigation will be continued.

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