

A Comparative Study of PV Models in Matlab/Simulink

Mohammad Seifi, Azura Bt. Che Soh, Noor Izzrib. Abd. Wahab, and Mohd Khair B. Hassan

Abstract—Solar energy has a major role in renewable energy resources. Solar Cell as a basement of solar system has attracted lots of research. To conduct a study about solar energy system, an authenticated model is required. Diode base PV models are widely used by researchers. These models are classified based on the number of diodes used in them. Single and two-diode models are well studied. Single-diode models may have two, three or four elements. In this study, these solar cell models are examined and the simulation results are compared to each other. All PV models are re-designed in the Matlab/Simulink software and they examined by certain test conditions and parameters. This paper provides comparative studies of these models and it tries to compare the simulation results with manufacturer's data sheet to investigate model validity and accuracy. The results show a four- element single-diode model is accurate and has moderate complexity in contrast to the two-diode model with higher complexity and accuracy.

Keywords—Fill Factor (FF), Matlab/Simulink, Maximum Power Point (MPP), Maximum Power Point Tracker (MPPT), Photo Voltaic (PV), Solar cell, Standard Test Condition (STC).

I. INTRODUCTION

SOLAR system energy is the most important renewable and sustainable energy system. Solar-electric-energy system has grown consistently and become a popular resource of energy. The main reasons for this huge attention are; 1) increase in efficiency of solar cells; 2) recent technological improvements; 3) green and environmental friendship. Typical applications of solar energy are supply the residential loads and far off electrical installations. It also has a major role in distributed generation network. Right now solar cell efficiency is relatively low around 12 to 20 %, it means that PV panel can harvest a little amount of sunlight energy (a prototype solar panel with 33.9% efficiency is announced recently by Siemens and North Carolina's Semprius Inc). Therefore, to preserve this little harvested energy, the whole system such as energy conversion stage has to be designed carefully and efficiently. It enforces system integrator to design very high efficient DC/DC and DC/AC converters.

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The most common type of solar cells is made of silicon materials such as silicon, polycrystalline thin films and single-crystalline thin film. Solar cell converts photons energy (photovoltaic effect) to electrical DC energy [1]. A solar cell alone can produce only 1 to 2 Watt [2]. To get more power, more solar cells are necessary. PV module is made by connecting some cells to form larger units. Several modules are concatenated serially and parallel to make PV array (panel). A solar cell is a p-n junction semiconductor diode [3]. In the dark (without photon), the I-V curve characteristic of a solar cell has an exponential characteristic. Solar cell V-I, V-P curves are highly non-linear. These curves have the main role in solar energy system.

A PV panel acts as stationary (non-moving part) power generator. The amount of energy harvested by PV panel is mostly a function of sun irradiation and ambient temperature. However, the solar generators are affected by air pollutants, dust, the number of cloudy days, rain and snow. Solar system energy generally contains PV panel as generator, Maximum Power Point Tracker (MPPT) and DC/DC converter to work in Maximum Power Point (MPP), storage block to increase stability, Inverter to produce AC current, sun tracking mechanism and controller. MPPT controller will relocate operating point to desired MPP by controlling the power electronic gates in DC/DC converter in DC side. An inverter controller maintains the AC bus voltage and frequency by modifying signals on the inverter's gate. A solar system may work as a stand-alone or grid-connected generator. PV system configurations highly depend on system size, investment, mode of operation and system availability.

Modeling and simulation of physical system in computer become more attractive than ever due to advanced software like Matlab/Simulink. An electric circuit model of a solar cell can represent thoroughly the Mathematical relations (Lumped circuit). The simplest model has only one diode and one photo current source as function of sun irradiation (I_{ph}). The simple one has one extra series resistance R_s [4-6]. The four-element model has shunt resistance (R_p) and finally two-diode model has five-element with one extra diode. Another PV classification is based on the number of parameters that are used in the model. Therefore, there is three-, four-, five- and seven-parameter models. There are plenty of PV models represented by researchers, and each model has its own advantages. However, to the researcher's knowledge no study has yet been dealing with the comparison of these models. In some studies, the effect of temperature has intentionally been neglected, but this model may be suitable for very stable climates. Some others simply neglect the shunt resistance to

decrease complexity and lessen computations and some even ignore series resistance (lossless model). It is obvious that only in the equator that the ambient temperature is relatively stable. On the other hand, in some areas like Sahara desert or areas with four seasons, high ambient temperature will decrease total energy harvesting significantly.

This paper tries to evaluate how this kind of assumptions will affect the solar energy system efficiency. This study also compares the most common PV models and simulation results. To validate findings, simulation results are compared by industrial PV panel datasheet. The results show each model's accuracy. All models are implemented in Matlab/Simulink family software.

II. PV MODEL

Similar to two-port networks, open circuit voltage (V_{oc}) and short circuit current (I_{sc}) are used to establish circuit model of solar cell. Voltage at maximum power point (V_{mpp}), Current at maximum power point (I_{mpp}) and maximum power peak of PV module (P_{mm}) are important to shape the models. These data are given by manufacturer in STC (temperature is $T_n=25^\circ\text{C}$ and sun irradiation is $G_n=1000\text{W}/\text{m}^2$) and can be found in PV manufacturer's datasheet. The first step to modeling is finding the mathematical relationships. An ordinary engineering model of PV cell will be studied in this paper without getting involved into details that need semiconductor physics and light phenomena. A lumped circuit model will be used in this study.

A. Single-diode PV Model

Single-diode models, presented by Townsend in 1989, are depicted in Fig.1. In this model, one diode is used to modeling. Fig. 1(a) is PV lossless model (Ideal model without resistance), Fig. 1(b) has three elements with thermal loss (series resistance R_s) and Fig. 1(c) has four-elements circuit model with leakage current to ground (shunt resistance R_p). So the single-diode model is classified as:

1. Two-element ($R_s=0$ & $R_p=\infty$) or three-parameter
2. Three-element ($R_p=\infty$) or four-parameter
3. Four-element or five-parameter

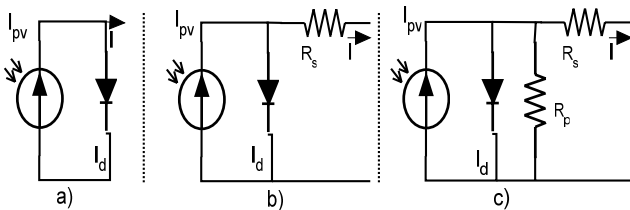


Fig. 1 Single-diode lumped circuit model a) two-element model, b) three-element model c) four-element model

Equation (1) shows the mathematical function of this model [7].

$$I = I_{pv} - I_o \left[\exp \left(\frac{q(V+R_s I)}{akT} \right) - 1 \right] - \frac{V+R_s I}{R_p} \quad (1)$$

where, I_o is diode reverse saturation current, k is Boltzmann constant, q is elementary charge on an electron constant, a is ideality factor, V is terminal voltage, I is terminal current and T is Kelvin ambient temperature. The quality factor (Ideality factor) a depend on solar cell technology, and it is typically between 1 and 2 for polycrystalline cell (see appendix A). I_{pv} is light generated current and it is depend on short circuit current. Parameters are I_o , R_s , R_p , I_{pv} and a . Short circuit current (I_{sc}) and I_o are functions of ambient temperature. There are several methods to show the ambient temperature dependency [8]. Equations (2) and (3) show the temperature effects on I_{sc} and I_o .

$$I_{sc@T_x} = I_{sc@T_n} (1 + K_i(T_x - T_n)) \quad (2)$$

$$I_o@T_x = I_o@T_n \left(\frac{T}{T_n} \right)^3 e^{\left[\frac{qV}{nk} \left(\frac{1}{T_x} - \frac{1}{T_n} \right) \right]} \quad (3)$$

where K_v is open voltage temperature coefficient, K_i is short circuit current temperature coefficient and I_{scn} and T_n are short circuit current and ambient temperature at STC, respectively. $I_{sc@T_x}$ and $I_o@T_x$ is short circuit and reverse saturation current at ambient temperature T_x respectively. $I_{sc@T_n}$ and $I_o@T_n$ is short circuit and reverse current at STC respectively [9]. $I_{sc@G_x}$ is a function of sun irradiation (G). Equation (4) shows this relation.

$$I_{sc@G_x} = I_{sc@G_n} * \left(\frac{G}{G_n} \right) \quad (4)$$

where G_n is $1000\text{W}/\text{m}^2$ and $I_{sc@G_n}$ is short circuit current at STC. By assuming series resistance, low and parallel resistance enough high, the $I_{sc}=I_{pv}$. Equation (5) shows the I_{pv} .

$$I_{pv} = (I_{sc} + K_i(T_x - T_n))G/G_n \quad (5)$$

B. Two-diode PV Model

The two-diode model (Fig.2) has one extra diode. It is also called seven-parameter model. This model is more accurate than the single diode model especially in low irradiance level [10-11]. The voltage-current relation is depicted in (6). Here I_{o1} and I_{o2} are diodes reverse saturation current. Unfortunately, reverse saturation current, resistances and ideality factors are unavailable in PV panel data sheet, so some recursive and incremental methods are needed to calculate these parameters. Some papers suppose a_1 and a_2 , 1 and 2, respectively. Here KCL shows $I=I_{pv}-I_{d1}-I_{d2}-I_{Rp}$, therefore terminal current is:

$$I = I_{pv} - I_{o1} \left[\exp \left(\frac{q(V+IR_s)}{a_1 k_1 T} \right) - 1 \right] - I_{o2} \left[\exp \left(\frac{q(V+IR_s)}{a_2 k_2 T} \right) - 1 \right] - \frac{V+IR_s}{R_p} \quad (6)$$

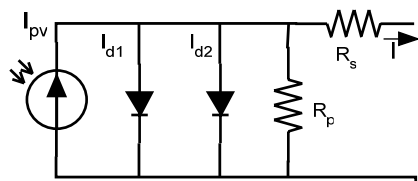


Fig. 2 Two-diode or five-element PV model

III. METHODOLOGY

In PV models, some parameters are not addressed in data sheet. The amount of V_{oc} , I_{sc} , K_i , K_v , P_{mp} , V_{mpp} and I_{mpp} are listed in the solar panel data sheet. The rest of parameters such as R_s , R_p , α and I_0 are unknown, so they will be calculated according to the given data. In [12] D. Sera and R. Teodorescu show how to calculate these parameters from given manufacturer's data sheet. In [13] by neglecting shunt resistance, they calculate unavailable parameters for single-diode model. These parameters have effect on other parameters like I_{sc} and V_{oc} . In seven-parameter-model, identification of the second diode parameters I_{o2} and α_2 calls for more assumption and calculation. Adamo, F., et al [14] use the two-diode electrical equivalent circuit to estimate these parameters.

The same strategies are adopted to calculate series and shunt resistances. Iterative and recursive methods are accepted method. In the simplified single-diode three-element model, the series resistance is easy to find. Some researchers use experimental methods under certain test conditions and get more points in V-I and V-P curves, so by replacing these points to (1)to(6), the unknown parameters could be found.

IV. DEVELOPMENT OF PV MODELS AND VALIDATION

To validate the model and simulation results, it is common to compare findings by solar panel datasheet. In this study, two different PV modules from different companies were examined. In order to shorten paper length only one datasheet will be shown here. Table I shows a 270-Watt poly-crystalline solar panel data sheet from Suntech Company. Fig.3 shows the V-I and V-P curves that were published by manufacturer. Three curves that pass through the origin are power curves and the rest are current curves. The given points in data sheet are (V_{mpp}, I_{mpp}) , $(V_{oc}, 0)$ and $(0, I_{sc})$.

TABLE I
ELECTRICAL DATA FOR SUNTECH STP 270-24/VB

Nominal output power (P_{mp})	[Watt]	270 [watt]
Max. power tolerance		+/- 3 [%]
Max. Voltage system	[Volt]	1000 [V]
Nominal Voltage (V_{mpp})	[Volt]	35 [V]
Nominal current (I_{mpp})	[Ampere]	7,71 [A]
Open circuit voltage (V_{oc})	[Volt]	44,8 [V]
Short circuit current (I_{sc})	[Ampere]	8,14 [A]
Temperature coefficient of open circuit Voltage		-0,34 [% / °C]

Temperature coefficient of short circuit current	0,055 [% / °C]
Temperature coefficient Output	-0,48 [% / °C]
Module conversion efficiency	14,4 [%]

Fill Factor (FF) is another index to evaluate the solar panel efficiency. FF is the ratio of the maximum power and product of V_{oc} and I_{sc} . FF will decrease when temperature increases or irradiation decreases. FF is typically between 0.7 and 0.85.

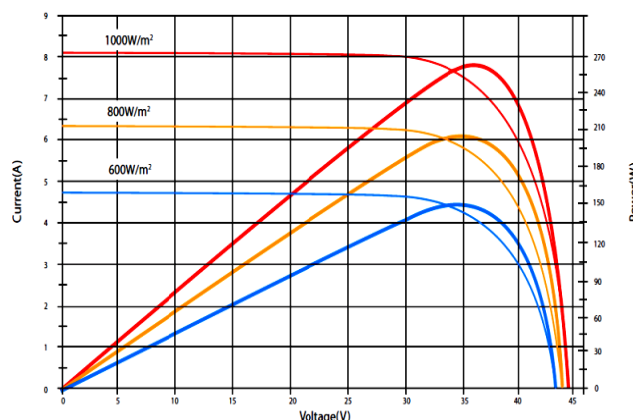


Fig. 3 Manufacturer's published V-I, V-P curves

Solar cell efficiency is ratio of power harvested from sun intensity to electrical power (7). P_{in} is sunlight power incident to PV panel surface.

$$\eta = \frac{V_{oc} \cdot I_{sc} \cdot FF}{P_{in}} \quad (7)$$

In the following pages, the single-diode and two-diode models in the Matlab/Simulink software will present.

A. Simulink Model

If the purpose of study is investigating the PV module abstractly or examining MPPT algorithm without further investigation in power stage, the Simulink model is straightforward and fast enough. To prevent algebraic loop in the PV model, the model has to be initialized. It is also possible by adding a delay to feedback signals I in (1) and in (6) as well to prevent algebraic loop, because I appears in two sides of the equations. The only difference between two (1) and (6) is one extra diode in (6), so in Simulink model by simply adding $I_{d2}=f(v)$, the single-diode model will be expanded to two-diode model. Fig.4 shows the two-diode model in Simulink. In two-diode model, some researchers use $\alpha_1=1$ and $\alpha_2=2$ [15], but their approach don't converge to a good estimation for resistance. Another assumption in that research is $I_{o1}=I_{o2}$. Calculation results for two-diode model are: $\alpha_1=1$, $\alpha_2=1.2$ and $I_{o1}=I_{o2}=1.5249e^{-7}$.

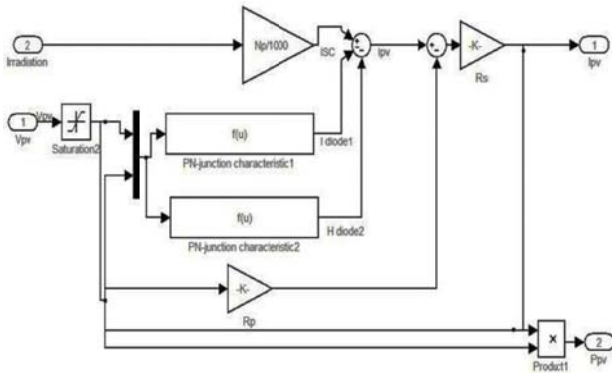


Fig. 4 Simulink two-diode solar cell model

B. Simpowersystems Model

Simpowersystems in Matlab/Simulink is popular software to study the whole solar system behavior in power stage, such as steady state and transient study [16]. There are plenty of built-in power system components and powerful Graphical User Interface. In this model, I_{pv} and diode are modeled separately. Fig. 5 shows an implemented PV model in simpowersystems. Temperature effect is also considered.

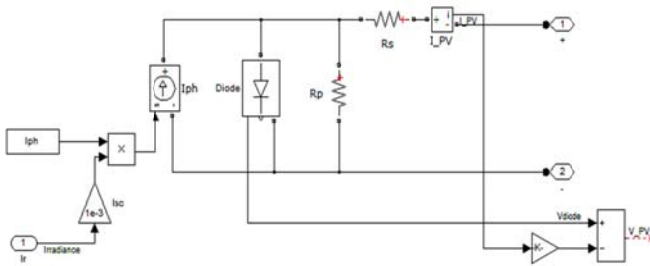


Fig. 5 Simpowersystems PV model

C. Simscape Model

Matlab/Simulink has two-diode five/eight- parameter built-in solar cell model. In the Simscape, sun irradiation is considered as a parameter. To make Suntech PV module by a solar cell, 72 cells have to be connected in series. It is convenient to make a block with 6 cells, so there are 12 cascaded blocks to model Suntech PV module (Fig.6 and Fig.7). There is an option to select five-parameter or eight-parameter model for solar cell in Simscape. Two options also exist for five parameters. Parameters in option one are: I_{sc} , V_{oc} , I_r , α and R_s for the next option, parameters are: I_o , I_{pv} , I_r , α and R_s . However, in eight-parameter model, three more extra parameters are I_o , α_2 and R_p .

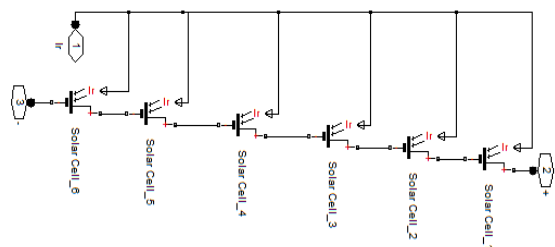


Fig. 6 Six Simscape solar cells in series to build a block

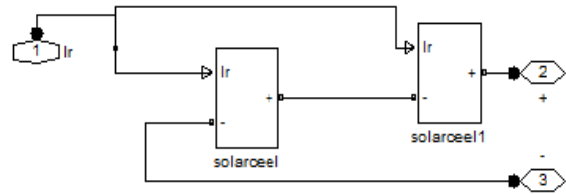


Fig. 7 Simscape model to build a Suntech STP270-24 v/b

V. SIMULATION RESULTS

All models are simulated in constant irradiation and temperature, various temperature and irradiation and -10% changes in quality factor. Ideal solar cell model (two-element) shows poor results (i.e. $P_{mp}=287.68$ Watt instead of 270Wattat STC) as it was expected. It was due to neglecting the loss in the resistances. Three-element model shows better results; however, neglecting shunt resistance (R_p) has great influence on MPPT algorithm [12]. Therefore, simulation results for two simple models are omitted intentionally due to poor simulation results. Fig.8 shows the Simpowersystems single-diode model simulation results (V-P curves). It shows the V-I and V-P curves at STC. The sun irradiation is simulated in three levels as 1000,750 and 500 W/m^2 to show the sunlight dependency. This model accurately follows the manufacturer's curve and data sheet. Fig. 9 shows two-diode simulation result in Simpowersystems. P_{mm} is 271.1 (0.407% error) in single-diode and is 270.6W (0.22% error) in two-diode model. The calculated parameters for all single-diode models are $R_s=0.320\Omega$, $R_p=3360\Omega$ and $\alpha =1.5$ [15].

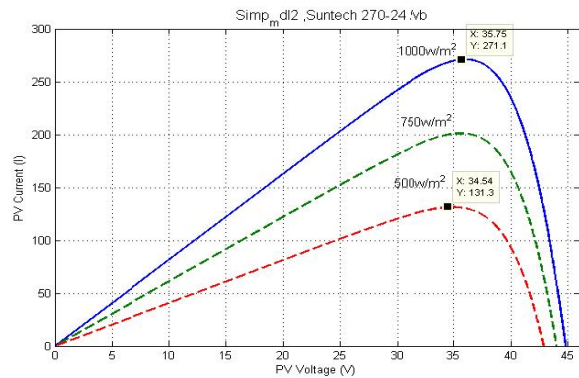


Fig. 8 Simpowersystems single-diode model, variant irradiation

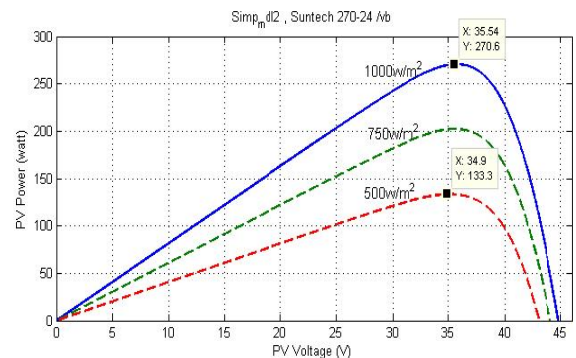


Fig. 9 Simpowersystems two-diode model, variant irradiation

Table II shows simulation results for different models in detail. The first column is Suntech manufacturer data to compare results. In the rest columns, single-diode four-element and two-diode model results are depicted. The result seems very close to each other's for the selected PV panel. However, it will vary when we implement it in real few megawatt solar farms instead of one single module. The main parameters are extracted from simulation results and important points are addressed in relevant curves.

TABLE II
THE SIMULATION RESULTS FOR PV MODELS IN MATLAB/SIMULINK

Model parameter	Suntech datasheet	Simpower-systems single-diode	Simpower-systems two-diode	Simulink single-diode	Simscape two-diode
Open circuit voltage (V_{oc})	44.499	44.5	44.8	44.4	44.49
Short circuit current (I_{sc})	8.19	8.2	8.14	8.183	8.199
Maximum Power (P_{mp})	269.84	271.1	270.6	274.5	270.2
Fill Factor (FF) %	73.995	74.29	74.20	75.552	74.073

As mentioned earlier and some researchers reported [11], two-diode model is more accurate than others are. However, there are a few parameter that were not addressed by the manufacturer, so to establish a model for conducting study, these parameters have to be estimated carefully. Parameters calculation for two-diode model is more complicated than for single-diode model. Another problem is that parameter calculations may never converge and it depends on the method you used. As mentioned later, simulation results highly depend on these parameters. In some application in large-scale solar cell with MPPT algorithm and sun tracker, the simulation will be slow and will affect the other sub-systems.

To show the effect of parameters in the simulation result, quality factor is examined. In appendix A, the quality factors for different solar cell technologies are listed [17]. Fig.10 and Table III show the simulation results for -10% changes in quality factor. Important points are highlighted (by small square sign (*)) in these curves with their dimensions. The results show that PV module is constant and electrical parameters are highly affected by quality factor changes.

TABLE III
SIMULATION RESULT FOR -10% CHANGE OF QUALITY FACTOR

Parameter	V_{oc}	V_{mpp}	I_{sc}	I_{mpp}	P_{mp}
Test condition	Volt	Volt	Ampere	Ampere	Watt
Quality factor $\alpha=1.5$	44.8	35	8.14	7.71	270
Quality factor $\alpha=1.35$	40.05	31.3	8.293	7.622	238.6

Changing -10% in α , will change all the other parameters. By using relative error formula (8), the error for each parameter in table III are -9.60% in V_{oc} , -10.57% change in V_{mpp} , -11.63% change in P_{mp} , +1.88% in I_{sc} , +5.58% in I_{mpp} .

Therefore, evaluating unknown parameters may have great impact on PV module and the simulation results. By these inaccurate data, the MPPT controller will transfer operating point in non-MPP point, so the system efficiency will decrease.

$$Error = \frac{Actual - Measured}{Actual} \quad (8)$$

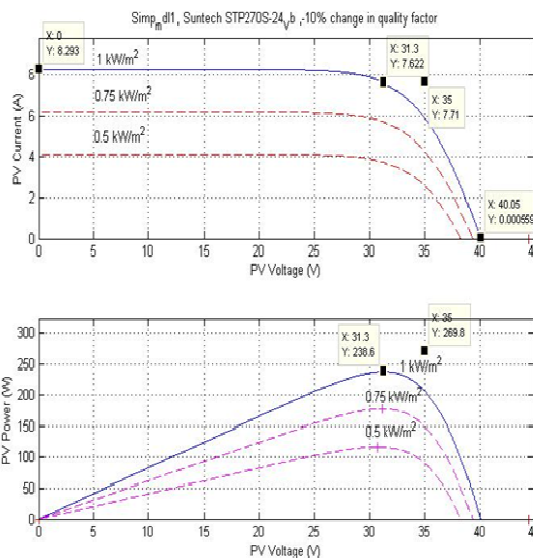


Fig. 10 Simulation result by -10% changes in quality factor

It is obvious that by increasing the ambient temperature, the maximum power will decrease. In some cases, the temperature deviation is not too high during daytime with sunlight. To examine the temperature dependency, $\pm 25^\circ\text{C}$ deviation from standard temperature simulated (STC). Fig.11 shows the simulation result for single-diode model. The results that show at $T=0^\circ\text{C}$ P_{mp} is 284.4 Watt (increase 5.4%) and at $T=50^\circ\text{C}$, P_{mp} is 240.2 Watt (decrease 11%). Therefore neglecting the temperature effects in the modeling stage is not a good assumption, especially in variable climate.

VI. CONCLUSION

Two models show relatively good response in this study. The simulation results also are validated by manufacturer's data sheet. Model accuracy highly depends on accuracy of Parameters calculation. Single-diode model has less unavailable parameters than two-diode model. These parameters play the main role in the modeling stage. As the simulation shows, with slight change in the quality factor (as estimated parameter), all other parameters as well as all electric quantities are changed. The Ideal model shows very poor results. The V-I and V-P curve also did not coincide with real PV model. A three-element model shows relatively good results, but it still inapplicable in most cases. If designers are interested to consider thermal loss in their model, they have to apply series resistance. If the leakage current loss is also needed, the shunt resistance must be added.

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In low sun irradiation level, two-diode model is more accurate. The sun irradiation pattern usually starts in low irradiation in the morning and in the evening; therefore, two-diode model will be the best choice and is very close to real situation. In fact, all practical PV modules will finally be installed outside; therefore neglecting ambient effect is not a good assumption. The model's error will be considerable for large-scale grid-connected solar farms around megawatt. In equator area with stable temperature, these assumptions may be considerable. Simpowersystems based models have its intrinsic advantages that researcher has verity of built in tools for further study. It means PV model is able to integrate by abundant built-in power system components available in the software library. In this survey, we have only used the most popular models represented in Matlab/Simulink.

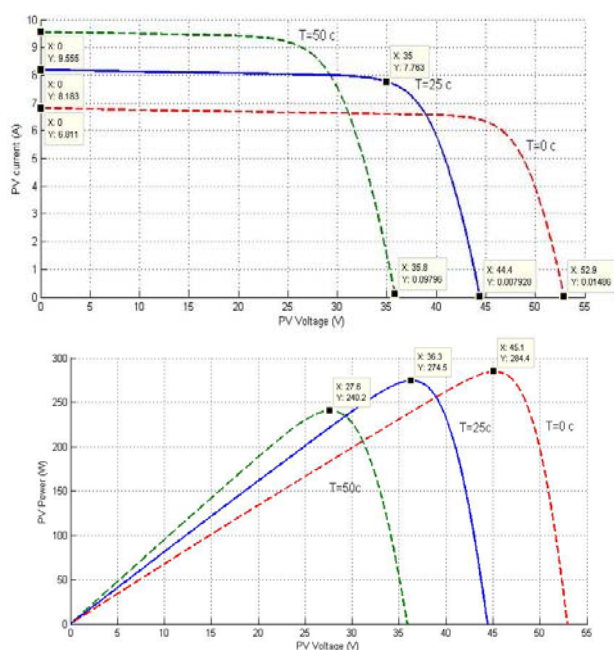


Fig. 11 Simulation results by changing temperature

In this study, the effect of air pollutants, dust and many other factors are not addressed. It will be interesting to show how much these factors will decrease the total energy harvested from the Sun. It also will be valuable to examine triple-diode model.

VII. APPENDIX A

TABLE IV

IDEALITY FACTOR CONSTANT FOR DIFFERENT TECHNOLOGY

Technology	Ideality Factor
Si-mono crystalline	1.2
Si-polycrystalline	1.3
a-Si:H (amorphous silicon)	1.8
a-Si:H tandem	3.3
a-Si:H triple	5
CdTe (Cadmium Telluride)	1.5
CIS (Copper indium Selenide)	1.5
AsGa (gallium arsenide)	1.3