A combined experimental and simulation study on the effects of irradiance and temperature on photovoltaic modules.

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Abstract

Solar cell is one of the crucial components in photovoltaic systems. Silicon solar modules are widely used in the Photovoltaic (PV) industry. The silicon PV electrical performance is described by its current–voltage (I–V) characteristic, which is as function of the device used and material properties. This study provides a comparison between a simplified PV-cell and module model and its parameterization, guaranteeing that the I–V characteristic curves fit with the typical points given by manufacturers’ datasheets and experimental data. The PV performance study is carried out as function of the junction temperature and insolation. This contribution gives an overview over PV module defects and degradation.

\section{1-INTRODUCTION:}

During the last decade the direct conversion of solar energy to electricity by photovoltaic (PV) cells has emerged from a pilot technology to one that produced 11 GW\textsubscript{p} of electricity generating capacity in 2009 [1]. The rapid evolution of PV as an alternative means of energy generation is bringing it closer to the point where it can make a significant contribution to challenge posed by the rapid growth of worldwide energy demand and the associated environmental issues, together with the main existing technology, which based on silicon (Si), the growth of the field is intertwined with the development of new materials and fabrication approaches [2]. Fundamental physical, chemical, and materials for energy is reported in [3] specific issues about (PV) plants can affect the PV modules or the inverters. Some of them regarding the PV modules are reported in [4]-[5], while specific models of defects implemented in Finite Element Method in FEM -based software are reported in [6]. Reliability issues about the several parts of PV plants

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Many PV devices exhibit a poor performance in the field (i.e., mainly in actual use conditions). A significant part of the loss in their performance is due to a variation in sunlight, Nominal Operating Cell Temperatures (NOCT) reflectivity at the device, surface and other localized climatic conditions. The Standard Test Conditions (STC) combines the irradiation of a clear summer day, the cell/module temperature of a clear winter day and the solar spectrum of a clear spring day. These measurement conditions obviously do not represent real operating conditions of PV devices at the site of installation. For the optimum design of PV power systems, it is desirable to measure their performances at the site of installation [8], a solar cell can be considered as a two-terminal device that is blocked like a diode in the dark and generates a photo current when illuminated. The current–voltage (I–V) characteristic of the solar cell describes its electrical performance. These I–V characteristics are determined by parameters such as diode saturation current, diode ideality photo generated current and the presence of parasitic resistances (series and shunt resistances). These parameters depend, in turn, on the solar cell structure, material properties and operating conditions, PV modules which generally consist of a set of series-connected solar cells, are rated at the maximum power output under standard test conditions (STC): 25°C, 1 kW/m², AM 1.5 global spectrum. The analysis of I–V characteristics at STC allows the determination of additional electrical performance parameters and also gives an indication of the presence of parasitic resistances [9]. The dark I–V characteristics enable the extraction of the device parameters and parasitic resistances. The presence of shunt paths in the solar cells of a PV module leads to excessive power loss at low irradiance levels. The performance of PV modules/cells can be fully characterized using a suite of electrical, optical and mechanical evaluation tools [10], to detect any degradation and possible failure, or by using the effect of outdoor conditions, such as, dust and shadow on the performance [11]. Sometimes, in the outdoor, the reliability measurements could be done by laser irradiation of the cell [12]. This work focused on electrical characterization of a silicon solar panel (polycrystallin) at external and internal conditions and to compare the practical results with the performance given by the manufacturer and to determine and analysis the different factors affects the performance of the panel.

2-PV CELL AND MODULE MODELLING:

The mathematical model associated with a cell is deduced from that of a diode PN junction. It consists on the difference between the photovoltaic current $I_{ph}$ (which is proportional to the illumination), and terms modelling the internal phenomenon. The electrical equivalent circuit is depicted in figure 1. The current $I$ in the output of the cell is then [13], more details on photovoltaic model reported in [14],[15].

$$I = I_{ph} - I_s \left( e^{\frac{V-R_s I}{kT}} - 1 \right) - \frac{V + R_s I}{R_{sh}}$$

$I_{ph}$: photocurrent, or current generated by the illumination (A)
$I_s$: saturation current of the diode (A) (about 100 nA)
$R_s$: serial resistor (Ω)
$R_{sh}$: shunt resistor (Ω)
$k$: Boltzmann constant, $k$: 8.62.10^{-5}
$q$: charge of the electron: 1.602.10^{-19}
$T$: cell temperature (K)

Fig.1. Equivalent circuit of a photo cell
3. Experimental Setup:

The purpose of our tests is to present the factors that affected the performance of the PV panel using a multimeter, the short circuit current (Isc) is measured together with the open circuit voltage (Voc). The maximum current (Imax) and the maximum voltage generated by the panel (Vmax) are also measured. A variable resistor (rheostat) from 0 to 120Ω, considered as a load resistor is used, the variation of this resistor implies a variation of the values of Imax and Vmax. The thermometer (HI 935005 Hanna) aims to follow the temperature variation of the cells. Figure 2 illustrate PV schematic connection and experimental setup used to measure the characteristics \( I = F (V) \). Aluxmeter (flux fc testo545) aim is to follow and fixed the illumination.

![Fig. 2. (a) Experimental setup outdoor, (b) Experimental setup indoor.](image)

4. Results and Discussion:

The outdoor and indoor tests started in April 2013 on a polycrystalline module at the University of Technology of Belfort-Montbéliard, France. In order to plot the current-voltage characteristic, and to ensure that the ambient conditions remain constant, the illumination was fixed at 0.35 kW/m².

The measurements of Imax and Vmax were taken at the same time with an ambient temperature of 25°C. Five indoor tests were conducted and the module I-V curve was measured.

![Fig. 3. (a) Experimental current-voltage characteristics; (b) Working zones of PV module.](image)

The cubic spline interpolation was used to fit the surface shown in figures 3(a) and (b) to estimate the working zones of the PV module from the first to the last test. This method fits a different cubic polynomial between each pair of data points.
The sum of squares due to the error in our study is \(\text{SSE} = 1.7265 \times 10^{-31}\) that indicates a fit that is more useful for prediction, and the square of the correlation between the response values and the predicted response values is \(\text{Rsquare} = 1\).

It has been observed that the module behaves like a current generator in zone \([AB]\) of Fig. 3(b), and this zone decreases at the end of our experiment. It can be noted that there is an increase in \(I_{sc}\) of 0.042 A, and the module behaves like a voltage generator in zone \([CD]\). Zone \([CD]\) increases at the end of the experiment with a decrease in \(V_{oc}\) of 0.98 V. The working of the module is optimal in zone \([BC]\), and this zone stays the same for the whole experiment. According to ambient conditions taken at the end of this experiment (test 5), where the irradiance was not changed \(0.35 \text{ KW/m}^2\) but the ambient and cell temperatures were changed (average temperature of 40.24 °C and ambient temperature of 27 °C), the temperature distribution (temperature of each cells in °C) is shown in figure 4.

![Fig.4. Temperature distribution in the module.](image)

It has been observed that there is a decrease in \(V_{oc}\) of about -64.3 mV/°C and an increase in \(I_{sc}\) of about 2.75 mA/°C. The increase in the cell temperature affects \(V_{oc}\) more than \(I_{sc}\). Thermal and radiometric effects on \(I_{sc}\) and \(V_{oc}\) are reported in [16] and [17]. The simulation data of the I-V characteristics, performed using Matlab and the manufacturer data, are shown in figure 5, together with the measured characteristics.

![Fig.5. The simulated and measured current-voltage characteristics.](image)

The I-V characteristics simulated using the values given by the manufacturer and the experimental data have almost the same shape. The current is relatively constant and the maximum voltage is variable in zone B. It can be noted that the maximum value of \(I_{sc}\) in the simulation is almost the same as the one with experimental data (test 1). The short circuit current given by the manufacturer is in the range of 1.2 A under STC, and the difference between the simulated and experimental values is below 0.04 A.
The current is low and the voltage is relatively constant in zone C. The difference between the simulated and experimental voltages is below 0.44 V (18.78 V measured and 18.34 V simulated). On the other hand, the real test conditions are not the same but are closer to STC in test1 where the temperature was 25°C (ambient, cells) and the irradiance fixed at 0.4 kW/m², the working of the panel is optimal in zone B, i.e. where the power is maximum. It is observed that the slope of the two curves (measured and simulated) is the same in tests 1 and 2. Indeed, the starting point of this area is about 13 V. Moreover, there is a degradation in power of about 0.22 W. In the measured characteristics, the starting point is only at 11 V at the end of our tests 3, 4 and 5 where the initial conditions were affected. Therefore, the simulated value is greater than the measured one. Concerning the power-voltage characteristics presented in figure 6 (b), the difference between the two curves is significant. In fact, there is a power loss of about 1.73W (16.23 W simulated and 14.5W measured). This loss is due to the increase of the PV cells temperature (a voltage decrease is observed: 18.6 V simulated and 17.86 V measured), and the power decrease is proportional to the voltage decrease. In addition, the ambient temperature is 27 °C and the air mass was not the same, which affects the PV cells. The PV conversion efficiency of the modules depends not only on the conversion efficiency of the individual cells but also on the light spectral transmittance of the cover glass, and the efficiency will be reduced with a decrease of the spectral transmittance of the cover glass [18]. The effect of the solar spectrum is reported in [19-22]. In simulation results where a mathematical model is used to model a PV module and cells, the effects of parasitic resistances were neglected and it is considered that $I_{ph} = I_{sc}$ and all the solar cells are the same and operate under the same conditions. For example, the series resistance $R_s$ of the module increases over time[23].

Figure 7 shows the simulation results of the temperature effect on the power characteristics by using Matlab

![Figure 6. Power-voltage characteristics: (a) measured and (b) simulated](image)

![Figure 7. The temperature effect on the I-V and power-voltage characteristics.](image)
There is an increase in the photocurrent in particular because of the decrease of the band gap, and this increase is of 1.46 mA/°C, i.e. a relative variation of 0.045 %/°C. At the same time, there is a net decrease in the open circuit voltage (approximately -79 mV/°C), that is a relative variation of -0.33 %/°C. The increase in temperature results in a reduction of the output power of 0.25 W/°C that is a relative variation of 0.45 %/°C, similarly, the variation in power as a function of the cell temperature is shown in figure 7. According to these simulated curves, when the temperature increases from 25 °C to 100 °C, the power decreases by about 54.54 %, i.e. from 55 W to 30 W. It is noted that there is an inverse relationship between the temperature and the power as increased temperature leads to decreased voltage and power. The PV panel power and temperature are proportional to the irradiation, the increase in panel temperature is due to the part of the solar spectrum that penetrates the junction and that is not converted into electricity [24]. There are other internal and external factors affecting the module output performance, more details in PV module failures reported in [25-30].

As shown in figure 7, the increase in panel temperature produces a decrease in the power output, the panel temperature reached 40.24 °C and the power cannot exceed 15 W, which implies that an increase of 15.25 °C in the temperature produces a power decrease of about 1.73 W. So the increase in temperature affects the panel efficiency: in the first test, the efficiency of our module was about 7% while in test 5 the efficiency became about 5.56 %, due to the presence of the connection box on the back of the panel, a higher temperature (46 and 45.8 °C) was noticed for two cells shown in figure 5 compared to the average cell temperature. This limits the cooling by convection and the corresponding surface is therefore warmer.

The outdoor I-V characteristics of the same module under different irradiation levels (0.75 kW/m², 0.3 kW/m², 0.25 kW/m² and 0.23 kW/m²) are shown in figure 8. It can be noted that V_{oc} and I_{sc} are affected by the increase in insolation level where V_{oc} has decreased by nearly -8.81 % relative to an increase in insolation of 26.66 % while I_{sc} has improved by nearly 67.16 % relative to the same increase in insolation. I_{sc} is more positively affected by the irradiation but the temperature negatively affects V_{oc} where the experimental temperature of the cells is higher than 25 °C. Obviously, the output power of a PV module is reduced as the irradiance decreases.

It can be noted that there are other outdoor factors that can affect the efficiency of PV cells and modules positively, for example: the wind (speed and direction) plays an important role by cooling the cells, and the tilt angle of the PV module that is correlated with the location latitude angle and the season. On the other hand, the modules are negatively affected by shadows of neighboring buildings, trees, clouds and dust, for these real operating reasons, some algorithms and techniques to track the maximum power and
improve the overall efficiency of PV systems are needed. Some of the algorithms and techniques used for this purpose are reported in [31-33].

5. CONCLUSIONS:

This work has shown that for the same irradiance level, the output power and therefore the efficiency decreases with increased cell temperature. The efficiency depends strongly on the temperature of the PV module and an overheating causes a decrease in the produced energy.

We have studied the influence of the ambient conditions on the PV panel performance, i.e. on the characteristics of the panel (power, current and voltage). The tests were performed on a standard solar panel with a rated output power of 55W. The simulation, using Matlab, was carried out by integrating the values given by the manufacturer to compare the simulated values with the experimental ones.

From experimental and simulation analysis, it is concluded that: The panel temperature and power are related to the irradiance and other external factors. The panel does not generate the same amount of power throughout and its temperature tends to stabilize over time. The variation of the temperature causes a variation of the PV panel efficiency. The panel output varies under outdoor environments (i.e. depending on the location) from the output rating quoted by the manufacturer (which is measured in the laboratory under STC). It is important to note that the field data, i.e. the rating of PV panels at the installation location, are used when designing and sizing PV power systems.

References


