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A NEW FIVE-PARAMETER MODEL FOR PV PANELS - EXPERIMENTAL VALIDATION ON A POLYCRYSTALLINE MODULE

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ABSTRACT

A new five-parameters model to describe the relation between the electric current and the voltage for a photovoltaic module is experimentally validated on the field, with variable conditions of operative temperature and solar irradiance. The electrical parameters of the one diode equivalent circuit are found by solving an equations system based on the data commonly issued by manufacturers in standard test conditions. To verify the capability of the new model to fit PV panel characteristics, the model was tested on two different panels comparing the results both with the data issued by manufacturers and with the results obtained using the five-parameters model already proposed by other Authors. The comparison shows that the new model is able to reproduce with very good precision the I-V curve issued by manufactures. Furthermore, the reliability of the proposed model was assessed performing an experimental validation connecting a PV panel to several different electrical resistances. The simultaneous measurement of the silicon temperature, air temperature, wind speed and direction, solar irradiance and voltage drop across the load, has permitted to verify a very good correspondence between the measured and the calculated data.

INTRODUCTION

Predictive performance tools are an important factor in the success of any new technology because they permit to demonstrate whether or not a system will be efficient and economically feasible. That is even more significant in the field of renewable energy systems whose effectiveness is usually affected by many erratic parameters. A good predictive tool should allow the designer to optimize the system performance and to maximize the cost effectiveness of the system before installing it. The Authors, who already presented a new five-parameter model [1], describe in this paper the results of the experimental validation performed on a polycrystalline photovoltaic (PV) module.

1. THE FIVE PARAMETER MODELS

The need of increasing the PV panel efficiency has induced the manufactures to experiment new technological processes aiming to the reduction of the energy losses due to the contact resistances between the electrodes and the silicon, the voltage drop across the silicon slabs and the parasite currents caused by construction defects. As a result, at standard test conditions (STC) - irradiance G_{ref} = 1000 W/m^2 & cell temperature T_{ref} = 25°C - the modern PV panels show a good fill factor and, consequently, a I-V characteristic with a very sharp bend that can be well reproduced by a five-parameter model. For this reason some Authors [2] [3] [4] [5] have focused on the five-parameter model and have recently proposed new interesting improvements that allow the five parameters determination on the base of the performance data typically provided by manufactures.

Such model, which is based on the equivalent one diode circuit of Fig.1:

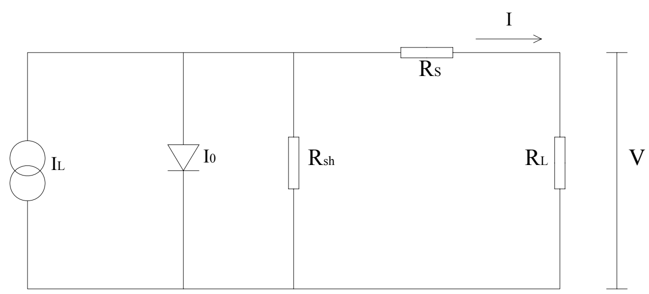

Fig.1. Equivalent one diode circuit for a PV panel

is described by the following implicit Eq.(1):

$$I = I_L - I_0\left(e^{\frac{V+IR_s}{nT}} - 1\right) - \frac{V + IR_s}{R_{sh}} \qquad (1)$$

in which, following the traditional theory, the photocurrent I_L depends on the solar irradiance, the reverse saturation current I_0 is affected by the PV cell temperature and n, R_s and R_{sh} are constant.

Using the one-diode model proposed by Hadj Arab et Al. [3], Celik et Al. [5] performed an experimental verification of the operating current of mono-crystalline PV modules. In order to calculate the five parameters, Hadj Arab et Al. used the values of the short circuit current I_{sc}, open circuit voltage

V_{oc} and of the maximum power voltage V_{mp} and current I_{mp} at STC to verify the Eq.(1) in correspondence of such I-V points. Moreover they also evaluated the derivatives of Eq.(1) in the short circuit and open circuit points and made them equal to the reciprocal of slopes of the characteristic curve in these points, called R_{sho} and R_{so}, which can be graphically evaluated from the standard I-V curves issued by manufactures. To evaluate the PV panel behaviour at temperature T and irradiance G other than the reference values T_{ref} and G_{ref}, the following expressions were used:

$$I_{sc} = I_{sc,ref} \frac{G}{G_{ref}} + \mu_{I,sc}(T - T_{ref}) \tag{2}$$

$$V_{oc} = V_{oc,ref} + nT \ln\left(\frac{G}{G_{ref}}\right) + \mu_{V,oc}(T - T_{ref}) \tag{3}$$

in which $I_{sc,ref}$ and $V_{oc,ref}$ are the short circuit current and the open circuit voltage at STC, and $\mu_{I,sc}$ and $\mu_{V,oc}$ are the short circuit current and the open circuit voltage temperature coefficients, respectively.

As a consequence of the dependence of the explicit expressions of I_L, I_0, n, R_s on the Eqs.(2) and (3), these parameters will change if T and/or G are changed. The parameter n is calculated with an expression containing V_{oc}, I_{mp} and V_{mp} and for this reason it is not clear how the calculation of n should be carried on: as a matter of fact V_{oc} depends on n itself and usually the values of I_{mp} and V_{mp} for the generic irradiance are not known. Anyway, the method allows a good representation of the STC characteristic, even though some inaccuracies can occur when the characteristics are calculated far from those conditions.

With the aim of improving the accuracy of the five-parameter model, the Authors have proposed [1] the following new expression of the Eq.(1):

$$I(\alpha_G, T) = \alpha_G I_L(T) - I_0(\alpha_G, T)\left(e^{\frac{\alpha_G[V + K\,I(T - T_{ref})] + I\,R_s}{\alpha_G n T}} - 1\right) + \\ - \frac{\alpha_G[V + K\,I(T - T_{ref})] + I\,R_s}{R_{sh}} \tag{4}$$

in which the quantity $\alpha_G = G/G_{ref}$ denotes the ratio of the generic solar irradiance to the irradiance at STC. K is a thermal correction factor similar to the curve correction factor described by the IEC 891 and the photocurrent $I_L(T)$ can be evaluated with the Eq.(5):

$$I_L(T) = I_{L,ref} + \mu_{I,sc}(T - T_{ref}) \tag{5}$$

in which $I_{L,ref}$ is the value of the photocurrent at STC. The parameters n, R_s and R_{sh}, which are calculated at STC, are constant for each temperature and irradiance. The current $I_0(\alpha_G,T)$ can be obtained by the following interpolating equation:

$$I_0(\alpha_G, T) = \exp\left[\left(\frac{\alpha_G - 0.2}{1 - 0.2}\right)\ln\frac{I_0(1,T)}{I_0(0.2,T)} + \ln I_0(0.2,T)\right] \tag{6}$$

for G = G_{ref} =1000 W/m^2 (α_G = 1) and G = 200 W/m^2 (α_G = 0.2), respectively. To take into account of the variation V_{oc} with the temperature, the following equation can be used:

$$V_{oc}(\alpha_G, T) = V_{oc,ref}(\alpha_G) + \mu_{V,oc}(T - T_{ref}) \tag{7}$$

The procedure to determine the parameters $I_{L,ref}$, n, R_s, R_{sh} and K, which for sake of conciseness is not reported in this paper, needs the knowledge of I_{sc}, V_{oc}, I_{mp} and V_{mp} at STC and of V_{oc} at the standard temperature T_{ref} and at the lowest available irradiance (usually 200 W/m^2). For the determination of K, the values of I_{mp} and V_{mp} at a temperature different from T_{ref} (usually 75°C) and at G=1000 W/m^2 are necessary. The model parameters are found solving a five equations system based on the condition that, in STC, the open circuit, short circuit and maximum power points belong to the Eq.(4) and that the reciprocal of the derivatives of the characteristic at its edges corresponds to R_{sho} and R_{so}.

The above models were used for a 175 W polycrystalline PV panel, made up of 48 cells and with a total area of 1.277 m^2. To evaluate the model parameters the following performance data were used:

- **at G = 1 kW/m^2 — T = 25°C:**
  V_{oc} = 29.35 V — I_{sc} = 8.07 A
  V_{mp} = 23.60 V — I_{mp} = 7.57 A
  R_{sho} = 99.44 Ω — R_{so} = 0.42 Ω
  $\mu_{I,sc}$ = 2.2210^{-3} A/°C — $\mu_{V,oc}$ = -1.07·10^{-1} V/°C

- **at G = 0.2 kW/m^2 — T = 25°C:**
  V_{oc} = 27.20 V

- **at G = 1kW/m^2 — T = 75°C:**
  V_{mp} = 18.00 V — I_{mp} = 7.50 A

and the following results were obtained:

Hadj Arab et Al. model

I_L = 8.09264 A	n = 3.59586·10^{-3} V/K
I_0 = 1.00329·10^{-11} A	
R_s = 0.281 Ω	R_{sh} = 99.440 Ω

Lo Brano et Al. model

I_L = 8.09277 A	n = 3.58974·10^{-3} V/K
	K = 1.12182 ·10^{-3} Ω/°C
$I_0(1)$ = 9.60241·10^{-12} A	$I_0(0.2)$ = 1.43561·10^{-12} A
R_s = 0.282 Ω	R_{sh} = 99.158 Ω

Using these parameters and the procedures above described, the I-V characteristics of the PV panel were calculated. In the Figs.2-3 the characteristics issued by the manufacturer are compared with the curves evaluated using both models. Because of the previously mentioned difficulty in evaluating the value of n related to the generic irradiance, the model of Hadj Arab et Al. was used assuming the constant value of n calculated in STC.

2. EXPERIMENTAL VALIDATION

The experimental validation was performed connecting the PV panel to four different electrical resistances, selected for their high stability and precision. Due to the presence of the constant electrical load R_L, the PV panel works in operating points that are put on the current-voltage characteristic corresponding to the chosen value of R_L. That line is travelled up and down during the day since the operating point position also depends on the current values of the irradiance and of the temperature. The values of the resistances have been chosen in order to investigate the PV panel behaviour in correspondence of numerous working points in the plane of the I-V characteristics. In the Figs.2-3 are shown the characteristics of the electrical loads plotted on the current-voltage planes of the examined PV panel.

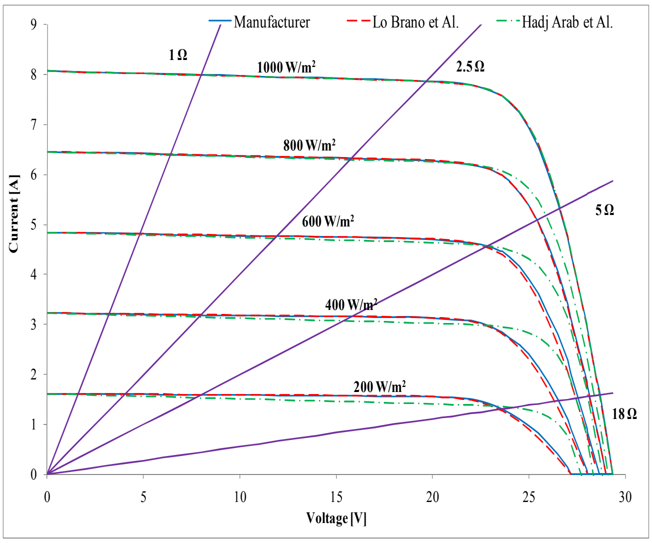

Fig.2. Comparison between calculated and issued Current-Voltage characteristics at T=25°C

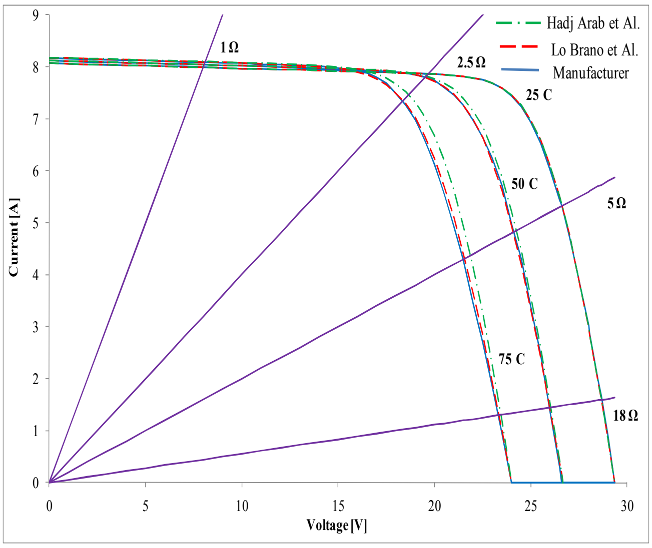

Fig.3. Comparison between calculated and issued Current-Voltage characteristics at G=1000 W/m².

To perform the measurements an experimental system was made up and situated on the top of the DREAM,in Palermo (38°07' N, 13°22' E). It consists of a silicon PV panel, a precision resistance set, a multimeter Fluke189/FVF2 and a Delta Ohm pyranometer mod. LP PYRA 02 AV, which is a first class according to ISO 9060, linked to an Advantech ADAM 6024 module. A Davis Vantage PRO2 Plus Weather station was used to collect the measurements of air temperature and relative humidity, wind speed and direction, horizontal global solar irradiance and atmospheric pressure.

The PV panel and the pyranometer were tilted at an angle that is equal to the latitude of the location. The four values of R_L were obtained by the parallel and/or series compositions of 3 and 4 **Ω** precision resistances (Vishay RH250) with a tolerance of ±1% and a temperature coefficient of ±50 ppm/°C. Since the resistances never exceeded a temperature of 150°C, their nominal values were considered known within the precision of ±1.625%. To avoid that the presence of an amperometer altered the value of the electrical load really connected to the panel, especially with the lowest values of R_L, the current was calculated on the basis of the measured voltage, accepting the error due to the resistances precision. The silicon temperature was measured using three thermocouples (type T, copper-constantan) installed into little holes made in the PET (Polyethylene terephthalate) rear film of the panel, in order to improve the thermal contact with the cell silicon back face. As it was easily predictable, due to the temperature gradient related to the heat transmission across the PV module, the sensors measured slightly different values (within a 0.5 °C range) and for this reason averaged values were used. All data were collected every 30 minutes and stored for the further calculations and comparisons.

3. RESULTS AND DISCUSSION

The results of predictions of the operating current and power from the Lo Brano et Al. and the Hadj Arab et Al. models were analysed for each value of the connected electrical loads using four meteorological data-sets consisting of one-day long data, from sunrise to sunset. According to the permitted weather conditions, in order to examine the panel working in almost steady-state conditions the data-sets of the summer 2009 sunniest days were used. During those days the irradiance on the panel plane reached a maximum value of about 1000 W/m² and the silicon temperature averagely varied between 20 and 50°C.

Before beginning the analysis and discussion of the results a methodological observation must be made. As it is easily predictable, the evaluated results will never perfectly fit the measured data because, as previously observed, many physical parameters, other than the irradiance and the silicon temperature, can affect the PV panel performance when it is tested in the field. Moreover the parameters of the panel models were not calculated on the basis of the characteristics of the panel specimen really tested, which actually are unknown, but using the data provided by the manufacturer. It is well known that the silicon doping technology makes difficult to produce components with characteristics contained into a narrow tolerance band. Since for the used PV panel the manufacturer declared a maximum power value tolerance of +10/−5%, it could be misleading to estimate the reliability of a panel model only on the basis of the numerical differences between the evaluated and the measured data. On the contrary, it could be significant to compare the data in order to check if a model behaves in a way that does not correspond to any physical condition or that is in contrast with the observed behaviour of the tested panel. Indeed, the presence of such anomalous situations could better prove that the PV panel model does not properly work.

In the Figs.4-7 for each electrical load the power of the PV module calculated with the Lo Brano et Al. and the Hadj Arab et Al. models are compared with the measured data.

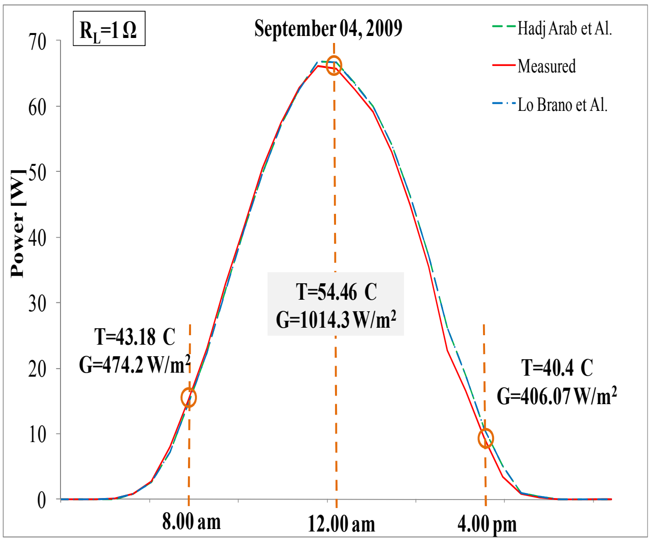

Fig.4. Comparison between the measured and evaluated power calculated with R_L=1 Ω

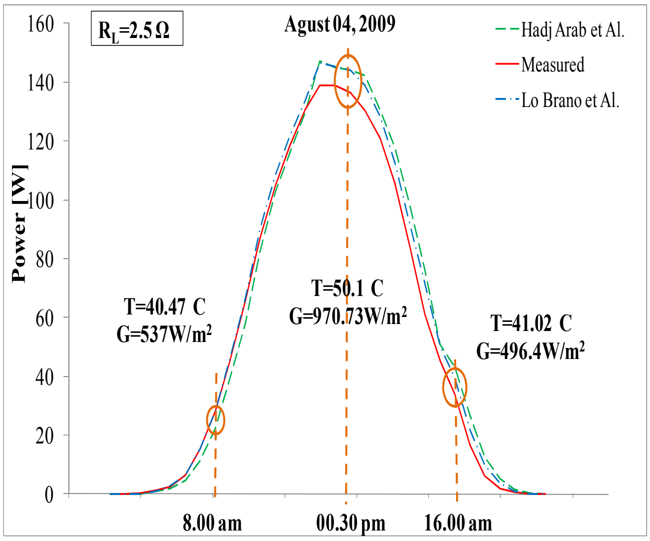

Fig.5. Comparison between the measured and evaluated power calculated with R_L=2.5 Ω

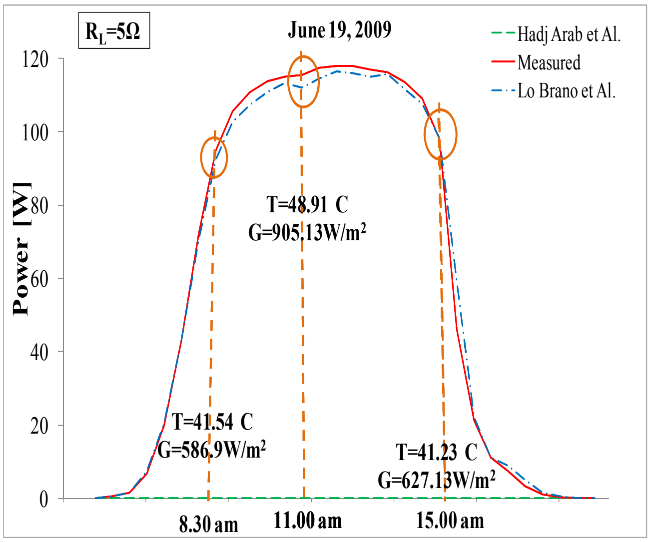

Fig.6. Comparison between the measured and evaluated power calculated with R_L=5 Ω

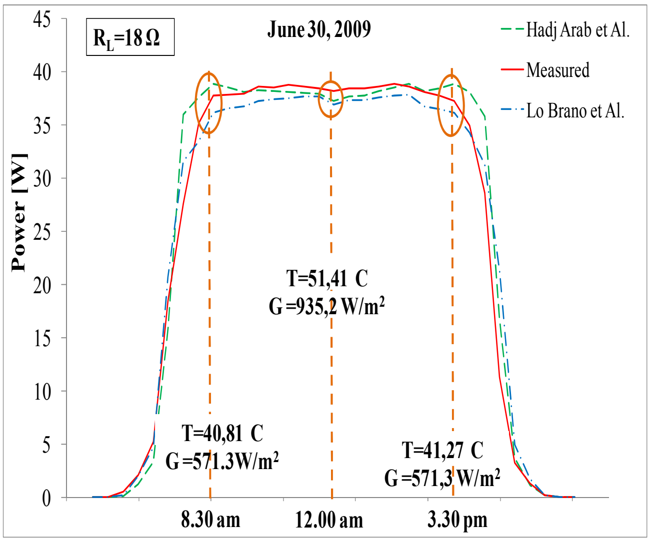

Fig.7. Comparison between the measured and evaluated power calculated with R_L=18 Ω

Since the used data-sets are referred to regular summer sunny days, the irradiance and the temperature variations are quite similar for each figure. Nevertheless, the shapes of the power curves significantly change with the electrical connected load: the regular shape related to small R_L values, which resembles the daily irradiance's one, changes to an almost flat and squared shape as greater electrical loads are connected. Obviously also the maximum power values change with the value of R_L. In particular:

- with a R_L less than 2.5Ω the power regularly increases with the solar irradiance, whereas with R_L > 2.5Ω some saturation effects occur, which are as more evident as greater the value of the electrical load and of the irradiance are. Moreover, if the panel temperature changes to 50°C, saturation occurs with irradiance values smaller than those ones in correspondence of which saturation occurred at 25°C;
- for a load resistance equal to 2.5Ω both models overestimate the power even though the Lo Brano et Al. model seems to be slightly more accurate;
- for a load resistance equal to 5Ω the Lo Brano et Al. model underestimates the power while the Al. model shows an opposite behaviour;
- for a R_L greater than 18Ω both models slightly underestimates the power near noon, but the Hadj Arab et Al. model overestimates it before and after that time.

The above mentioned saturation effect can be better understood observing the Figs.8-9 where the characteristics of the electrical loads are also plotted. Again, due to the presence of the constant electrical load R_L, the PV panel works in operating points that are put on the current-voltage characteristic corresponding to the chosen value of R_L.

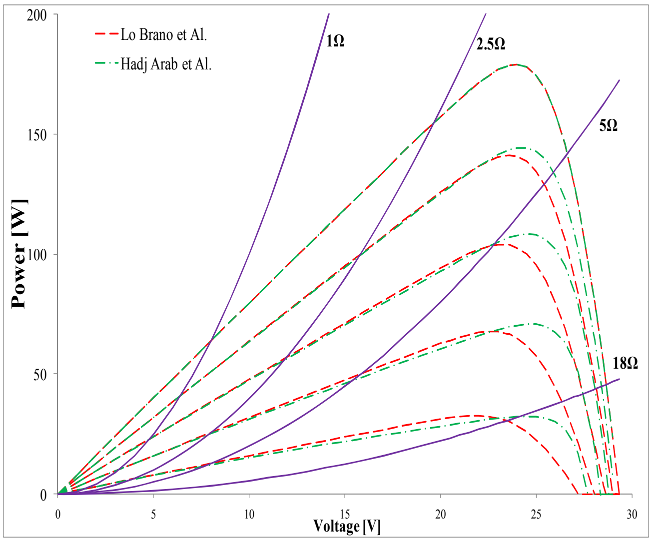

Fig.8. Comparison between calculated and issued Power-Voltage characteristics at T=25°C

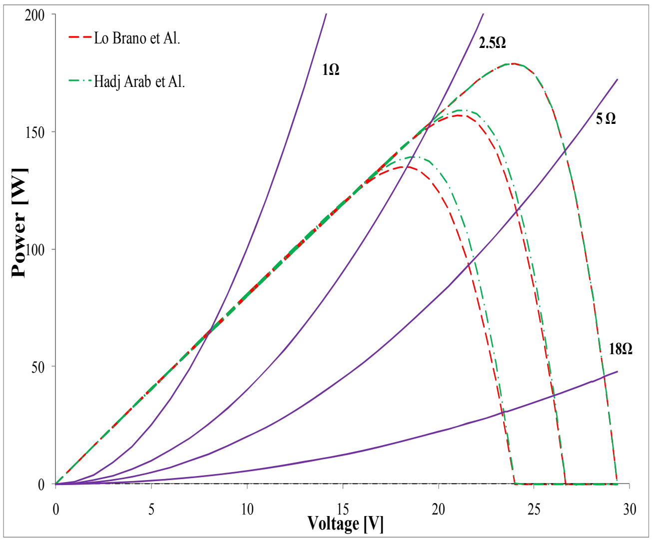

Fig.9. Comparison between calculated and issued Power-Voltage characteristics at G=1000W/m²

Observing the Figs.8-9 it could be guessed that the Hadj Arab et Al. is less accurate, especially if the voltage is greater than the value corresponding to the maximum power. Nevertheless, such assertion cannot be generalized since it is based on the comparison with the PV panel characteristics only related to 25°C or to 1000 W/m^2. If the characteristics issued by the manufactures corresponded to the performances of the tested PV panel, it would be easy to deduce what is the most accurate model. Unfortunately, due to the declared tolerance, which is greater than the differences between the evaluated and the measured data, no reliable judgment can be made. Nevertheless the behaviour shown by the Hadj Arab et Al. in the Fig.7 with R_L =18 Ω seems to be quite strange since the panel is supposed to produce the maximum power at noon. Actually, it is true that the panel absorbs the daily maximum solar energy at noon, but for the same reason, it also reaches the highest silicon temperature and consequently the smallest efficiency.

In order to verify if an increase in temperature could justify the behaviour of the Hadj Arab et Al. model, in the previous figures the hours when the solar irradiance and the silicon temperature are almost 1000 W/m^2 and 50°C, respectively, have been highlighted. In the figures are also indicated the hours when the above parameters are almost 500 W/m^2 and 40°C. Obviously, since only data measured in the field are available, it is quite impossible to select couples of irradiance and temperature perfectly matching with the wished values of 1000 W/m^2 and 50°C or of 500 W/m^2 and 40°C. Nevertheless, it is easy to see that for R_L < 18 **Ω**, even though the temperature has reached almost 50°C, the panel produces its maximum power according to maximum daily irradiance value. On the contrary, the increased efficiency related to a lower silicon temperature of 40°C does not counterbalance the presence of a smaller irradiance. Such physical behaviour of the tested panel is always confirmed by the Lo Brano et Al. model, whereas the Hadj Harab et Al. seems to became inconsistent when R_L = 18 Ω.

Despite the fact that the models yield to different results, the evaluated daily power are quite similar even though the Lo Brano et Al. model better represents the physical behaviour also for conditions far from the STC. This skill of the Lo Brano et Al. model can be very useful especially for the PV panels that are mounted on surfaces with particular tilt angles, like the building facades, in correspondence of which the solar irradiance will difficult reach the value of 1000 W/m^2 and for this reason the estimation of the collected power should be much more accurate. In the Tabs.1 and 2 some accuracy parameters are resumed.

Tab.1 Accuracy parameters from the experimental validation of the Lo Brano et Al. model

Data-set	R_L [Ω]	**Current difference** [A]		**Power difference** [W]	
		Mean value	Max. value	Mean value	Max. value
Sep. 04/09	1.0	-0.0417	-0.3893	-0.3545	-3.4125
Aug. 04/09	2.5	-0.1168	-3.6200	-2.4152	-10.5846
Jun. 19/09	5.0	-0.0064	0.0718	-0.3469	3.3513
Jun. 30/09	18.0	-0.0035	-0.2996	0.0450	-10.1520

Tab.2 Accuracy parameters from the experimental validation of the Lo Brano et Al. model

Data-set	R_L [Ω]	**Daily collected energy**		
		Measured [MJ]	Calculated [MJ]	Error [%]
Sep. 04/09	1.0	1.324	1.345	1.494
Aug. 04/09	2.5	2.926	3.087	5.497
Jun. 19/09	5.0	3.234	3.214	-0.637
Jun. 30/09	18.0	1.473	1.471	-0.181

As it is shown in the tables, the mean differences for the current and for the power do not exceed -0.12 A and -2.42 W, respectively; the maximum current deviation is -3.62 A and the maximum power deviation is -10.58 W. The percentage relative error for the daily collected energy is less than 5.5 %. The model accuracy can be considered satisfactory since it is comparable with the data tolerance declared by the manufacturer. Obviously the above accuracy parameters are related to the value of the current calculated from the voltage drop measured on the resistance R_L whose value is known between a declared tolerance range of ±1.625%.

4. CONCLUSIONS

The new proposed one diode equivalent circuit allows the assessment of the power output of a PV panel for any operating temperature and solar irradiance.

The five parameters R_s, R_{sh}, n, I_L and I_0 are obtained by imposing both on the calculated I-V characteristics and on those issued by manufacturers the following conditions: equality of the short circuit current, equality of the open circuit voltage, correspondence in the maximum power point and equal values of the curve derivative in the points of short circuit and open circuit for nominal conditions.

To better reproduce the real phenomena that occur in the PV panel, R_s, R_{sh}, and I_0 are assumed changing with the solar irradiance. The comparison with the data issued by the manufacturer of a silicon PV module has confirmed the reliability and the quality of the new analytical model. Furthermore, the accuracy of the new model has been tested by a comparison with another recently model proposed by other Authors. The new model showed the best correspondence with the technical data issued in conditions.

Lastly, an experimental validation was performed monitoring a PV panel connected to four different electrical resistances, which were selected for their high stability and precision. The comparison between the real monitored data and those ones forecasted by the Lo Brano et Al. Model and by the Hadj Arab et Al. Model has permitted to state that the proposed model better represents the physical behaviour of the PV panel working in real operative conditions.

NOMENCLATURE

G	solar irradiance [W/m^2]
G_{ref}	solar irradiance at STC (1000 W/m^2)
I	current generated by the panel [A]
I_L	photocurrent [A]
$I_{L,ref}$	photocurrent at STC [A]
I_{mp}	current at the maximum power point [A]
I_{sc}	short circuit current of the panel [A]
$I_{sc,ref}$	short circuit current of the panel at STC [A]
I_0	reverse saturation current [A]
K	thermal correction factor [Ω/°C]
n	diode quality factor
R_L	electrical load [Ω]
R_s	series resistance [Ω]
R_{so}	reciprocal of slope of the I-V characteristic of the panel for $V = V_{oc}$ and $I = 0$ [Ω]
R_{sh}	shunt resistance [Ω]
R_{sho}	reciprocal of the slope of the I-V characteristic of the panel for $V = 0$ and $I = I_{sc}$ [Ω]
T	temperature of the PV cell [°K]
T_{ref}	temperature of the panel at STC (25°C – 298.15°K)
V	voltage generated by the PV panel [V]
V_{mp}	voltage at the maximum power point [V]
V_{oc}	open circuit voltage of the panel [V]
$V_{oc,ref}$	open circuit voltage of the panel at STC [V]
α_G	ratio between the current irradiance and the irradiance at STC
$\mu_{I,sc}$	thermal coefficient of the short circuit current [A/°C]
$\mu_{V,oc}$	thermal coefficient of the open circuit voltage [V/°C]

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