Models for evaluating the maximum power produced by a Photovoltaic generator

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ABSTRACT

The size of a photovoltaic system up to determine the necessary number of the installed solar panels photovoltaic to adopt a PV system sufficient to meet the needs of the load at any moment and the carrying capacity of the battery, it is necessary that the mathematical model used to calculate the power delivered by the solar panel is more practical. In this work, we presented several mathematical models for calculating the maximum power at the output of a photovoltaic module depending of conditions meteorological (Illumination solar and temperature). A comparative study based on Lu Lin 2004 essays was made for the purpose of deducing the most reliable mathematical model, which can be used to calculate the power delivered by a photovoltaic panel.

I. Introduction

Renewable energy resources have become the major attention in the power sector, there is a growing awareness that renewable energies that utilises photovoltaic system has created. Solar arrays are useful in many terrestrial and space applications [1]. Solar energy is the most promising and powerful of the renewable energy sources [2]. Photovoltaic electricity is produced by converting sunlight directly into electricity using photovoltaic cells [3, 4]. Nowadays, the use of solar photovoltaic energy seems to be a necessity for the future. For best utilisation, the photovoltaic cells must operate at their maximum power point (MPP). However, the MPP varies with several factor such as temperature, solar radiation and other ageing effects. The energ radiated by the sun on a bright sunny day is approximately 1kw/m^2, Usually in PV systems, a power point tracking system is used and therefore PV modules often operate at their maximum power, this explains why the maximum power of the PV module becomes an important point in the modeling of the PV module and its estimation represents in our study.

I.1. II. Mathematical models for evaluating maximum power:

I.2. Benchmark model

The following benchmark model, allows us to determine the maximum power supplied by a PV module for a given solar irradiation and module temperature, with only four constant parameters to be determined, a, b, c and d, This model was developed and experimentally validated by Lu Lin in 2004 [5,6].

$$P_m = -(a.G + b)T_c + c.G + d \tag{1}$$

With Pm: the maximum power produced (W). G: Solar irradiation on an inclined plane (W / m^2) a, b, c, and d: are positive constants that can be obtained experimentally, according to the experimental benchmark measurements on a module (BP Solar 340), the constants a, b, c and d are 0.0002, 0.0004, 0.1007 and 0.1018 respectively. [5], T c: the module temperature, which varies according to the lighting and the ambient temperature, and can be described by the relation [7, 8]:

$$T_c = T_a + (\frac{NOCT-20}{800}) \tag{2}$$

With: Ta: is the ambient temperature, NOCT: Nominal Operating cell Temperature and defined as the temperature of the cell when the module is under certain conditions (solar irradiation 800W / m2, spectral distribution (AM1.5), ambient temperature: Ta = 20 ° C, wind speed> 1 m / s).

I.2 Input / output power model

The energy produced by a photovoltaic generator is estimated from the data global irradiation on an inclined plane, the ambient temperature and the manufacturer's data for the photovoltaic module used. The produced power of the photovoltaic generator can be calculated from the following equation [9]:

$$P_m = \eta.S.N.G \tag{3}$$

η : efficiency instantaneous, *S*: The area of photovoltaic module (m^2). *N*: the number of modules constituting the photovoltaic field.
The efficiency instantaneous is given by the following equation: [9, 10]

$$\eta = \eta_r\ (1 - y(T_c\ - T_0)) \tag{4}$$

η_r: the module reference efficiency under standard conditions (T=25°C, G=1000W/m^2 et AM1.5)

I.3. Borowy and Salameh model

This model was developed by borowy and salameh in 1996. The principle of this model is based on the circuit equivalent to a single diode (Fig .1).

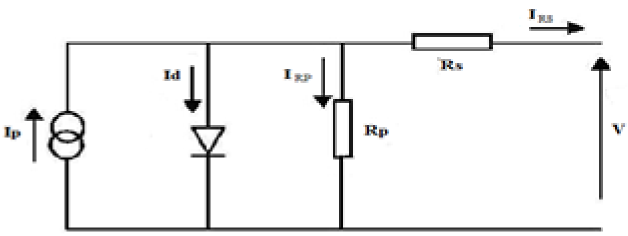

Figure 1. Equivalent circuit of a solar cell [7]

This model uses the specifications of the photovoltaic modules given by the manufacturers, therefore it allows to offer a very simple way to know the power produced by the photovoltaic modules [11,12].

$$I_m = I_{cc}.\left\{1\text{-}\left(C_1.\exp\left(\frac{V_m}{C_2.V_{CO}}\right)\text{-}1\right)\right\} + \Delta I \tag{5}$$

I_{cc} : the short circuit current of the module (A),

V_{co} : the open circuit voltage of the module (V),C_1 et C_2 are parameters that can be calculated by the equation (6) et (7).

$$C_1 = \left(1 - \frac{I_{mp}}{I_{cc}}\right).\exp\left(\frac{-V_{mp}}{C_2.V_{CO}}\right) \quad (6)$$

$$C_2 = \left(\frac{V_{mp}}{V_{CO}} - 1\right)/\ln\left(1 - \frac{I_{mp}}{I_{cc}}\right) \quad (7)$$

I_{mp} : The maximum current under standard conditions (A), V_{mp} : The maximum voltage of the module under standard conditions (V), ΔI : Parameter that depends on the temperature difference and solar illumination.

It is given by the following equation:

$$\Delta I = \alpha_0\left(\frac{G}{G_0}\right)\Delta T + \left(\frac{G}{G_0} - 1\right)I_{CC} \quad (8)$$

$$\Delta T = T_C - T_0 \quad (9)$$

α_0: Current coefficient as a function of temperature (A/°C), T_0 : the cell temperature at the reference condition. T_c : cell temperature, which varies depending on the ambient temperature, depending on the equation (2), The voltage V_m of the module is determined by the following equation

$$V_m = V_{mp}\left(1 + 0.0539\log\left(\frac{G}{G_0}\right)\right) + \beta_0.\Delta T - R_s.\Delta I \quad (10)$$

β_0 : The coefficient of voltage as a function of temperature (V/°C), G_0 : Reference solar irradiation under standard conditions (1000W/m^2), R_S : series resistance. So the optimum power at the output of a module is determined by:

$$P_m = I_m.V_m \quad (11)$$

I.4. Cristofari model

In this model, the power delivered by a photovoltaic module is a non-linear function of illumination and temperature [13, 14, 15].

$$P_m = A.G.\eta_r.\left(1 - y(T_c - T_r) + y_c\log\left(\frac{G}{G_0}\right)\right) \quad (12)$$

With : η_r : the reference efficiency under standard temperature conditions (25°C) and illumination (1000 W/m^2), Tc : the junction temperature of cells expressed in degrees Celsius **(°C),** Tr : is the reference temperature taken equal to 25°C, y_c : correction coefficient in relation to the illumination G. (y_c = 0.0053 °C^{-1}for c-Si : 0.004–0.006°C^{-1}), y : coefficient of variation of efficiency as a function of temperature, it is assumed to be constant and its value for silicon cells is in the range (0,004 – 0,006)/°C, A : The area of the module.

I.5. Marion's model

This model is based on the notion of the efficiency of photovoltaic modules [13, 14, 16].

$$P_m = P_{m.r}\left(\frac{G}{G_0}\right)\left(1 - y(T_c - T_0)\right) \quad (13)$$

$P_{m.r}$: is the maximum reference power under standard temperature conditions (25°C) and illumination (1000 W/m^2), γ: coefficient of variation of efficiency as a function of temperature, (°C^{-1}), it is assumed to be constant and its value for silicon cells is in the range (0, 0035 – 0,005)/C°.

I.6. Kroposki model

According to kroposki, the calculation of the maximum power is based on parameters provided by the constructor and meteorological data. the maximum power is given by the following expression [16].

$$P_m = P_{m.r}.\left(\frac{G}{G_0}\right)\left(1+\alpha_0(T_c\text{-}T_r)\right)\left(1+\beta_0(T_c\text{-}T_r)\right)\left(1+y_c.\log\left(\frac{G}{G_0}\right)\right) \quad (14)$$

$P_{m.r}$: is the maximum reference power under standard conditions; α_0: Current coefficient as a function of temperature (A/°C), β_0 : The voltage coefficient depending on temperature (V/°C), y_c : correction coefficient in relation to the illumination G, G_0 : The reference solar irradiation under standard conditions (1000W/m^2).

I.7. Hatziargyriou model

By knowing the technical characteristics of the photovoltaic module and conditions meteorological local, the empirical equation for determining the maximum power is given by [17].

$$P_m = \left(\frac{G}{G_0}\right)\left(P_{m.r} + \mu_{p.max}(T_c - T_0)\right) \quad (15)$$

$\mu_{p.max}$: The coefficient of maximum power as a function of temperature. $P_{m.r}$: is the maximum reference power in the standard condition.

II. Comparative study and interpretation of the results:

After the presentation of the seven mathematical models, we designed for each model, a Matlab program so that each of these calculation programs can deliver maximum power and relative error committed according to the temperature of the module between the values estimated by the lu lin test model and those estimated by the other models.

$$\text{Err} = \frac{|P_{essai}\text{-}P_{simplifié}|}{P_{essai}} \quad (16)$$

In our study, we used the BP solar 340 photovoltaic module which consists of 34 cells connected in series. The characteristics of the module under standard conditions are given in the table.1 [5].

II.1. Variation of maximum power as a function of temperature:

In our study we used three values of solar irradiance namely 300 w / m2 500 w / m2 and 900 w / m2. Figures (2), (3) and (4) represent the results of the variation of the maximum power as a function of the temperature of the photovoltaic module.

Based on the results obtained, we note that the maximum power delivered by the photovoltaic panel is inversely proportional to the temperature for approaches 2, 3, 4, 5, 6 and 7. For the model of borowy and salameh, we note that the power increases from 280k until reaching a maximum value which corresponds to 300k, then this value drops in a linear fashion (see fig (2)). For the other cases (fig (3) and fig (4)) we observe the same behavior except that the maximum powers obtained are different according to the values of the irradiations.

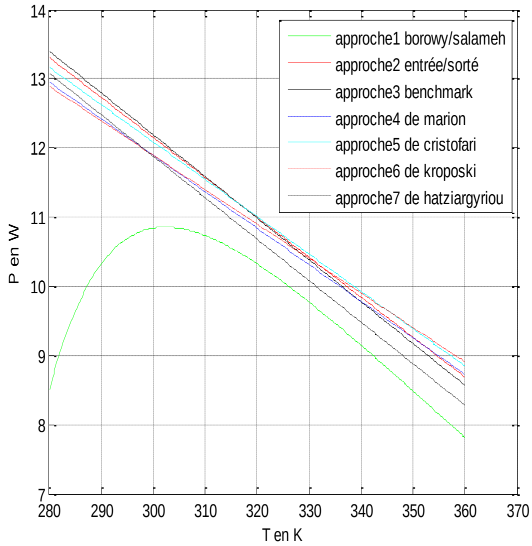

Figure.2. Maximum power as a function of temperature, with G=300W/m^2

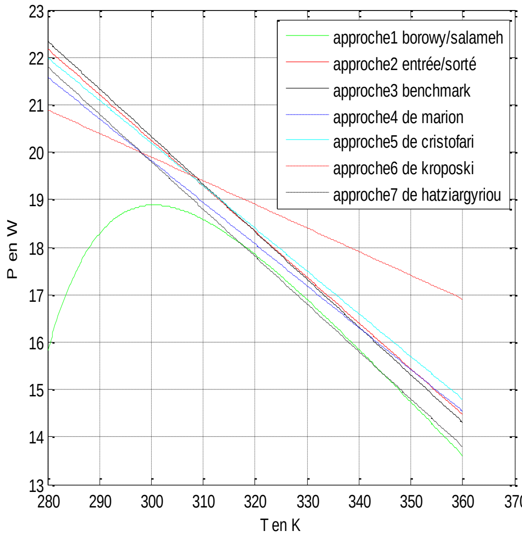

Figure.3. Maximum power as a function of temperature with G=500W/m^2

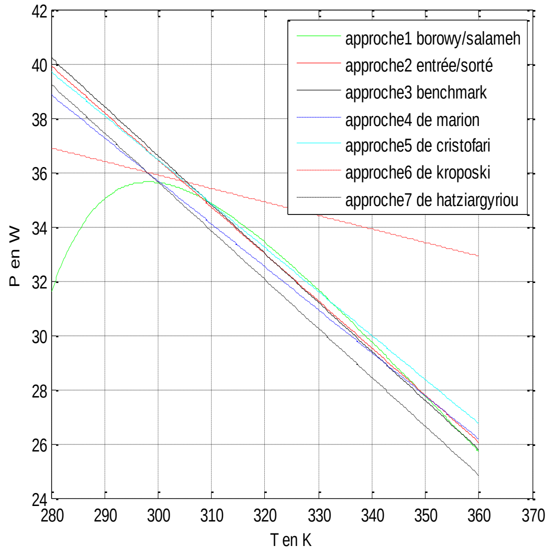

Figure.4. Maximum power as a function of temperature, with G=900W/m^2

Table 1: Electrical characteristics of a BP solar photovoltaic module [8]

The maximum power of the module (Pc)	40 (W)
Open circuit voltage (Vco)	20 (V)
The short circuit current (I_{cc})	2.6 (A)
The maximum voltage (Vm)	16.5(V)
Themaximum current (Im)	2.42 (A)
The surface of the photovoltaic module (S)	0.351 (m^2)
Coefficient of efficiency as a function of temperature (°C) (γ)	0.0045
The coefficient of variation of the short circuit current as a function of the	+0.065%/°C temperature (α_0)
The coefficient of variation of the open circuit voltage as a function of	-90 mV/°C the temperature (β_0)
The coefficient of variation of the maximum power as a function of	-0.5%/°C the température ($\mu_{p.max}$)
NOCT : Nominal operating temperature of solar cell 43 +/- 2°C	(Nominal Operating Cell (T°)

Figures (5), (6) and (7) represent the relative error made for the different models. We notice that the simulation results of approach 2, approach 4, approach 5 and approach 7, are in very good agreement with the reference model, in all cases, the error does not exceed 5% (see fig (5), fig (6) and fig (7)). On the other hand for approach 1 and approach 7 the results are very dispersed compared to the reference model, this case is very visible in low temperatures for approach 1, where the error exceeds 30%, we also notice that when the solar irradiance exceeds 900w / m2 and the temperature is between 300K and 360K the error becomes low.

II.2. Simulation of the maximum power for different types of panels:

To determine the most adequate mathematical model to simulate the maximum power of the various panels manufactured on the market and in the absence of the experimental parameters of the benchmark model, we used the following modules (Table 2):

Tableau. 2: Electrical characteristics of the modules given by the manufacturers.

module	Techno-logy	P_m (W)	V_{co} (V)	I_{sc} (A)	V_m (V)	I_m (A)	μ P_m (%)	μ V_{co} (mV/°C)	μ I_{sc} (%/°c)	A (m^2)	η (%)
SP75 siemens	Mono	75	21.7	4.8	17	4.4	-0.35	-77	0.26	0.562	13.5
US-64 Uni-solar	a-si :H	64	23.8	4.8	16.5	3.88	-0.21	-38	0.1	1.01	6.32
ST40 Shell solar	CIS	40	23.3	2.68	16.6	2.41	-0.6	-43	0.0131	0.43	9.4

Table 3 gives the values of the maximum power obtained for each model of the photovoltaic modules for different irradiations and a constant temperature of 298k. The results given in the table below shows as the model Browy / salameh gives maximum power values closest to those given by the manufacturers under standard conditions 1000 w / m^2 and 298k.

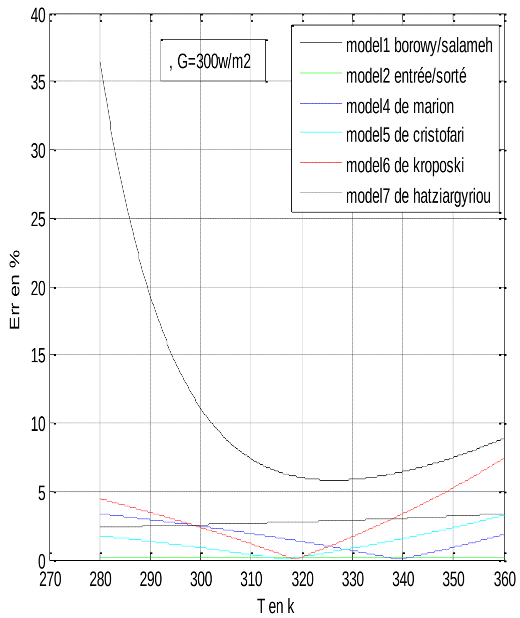

Figure.5. Relative error for different models, with G=300w/m^2

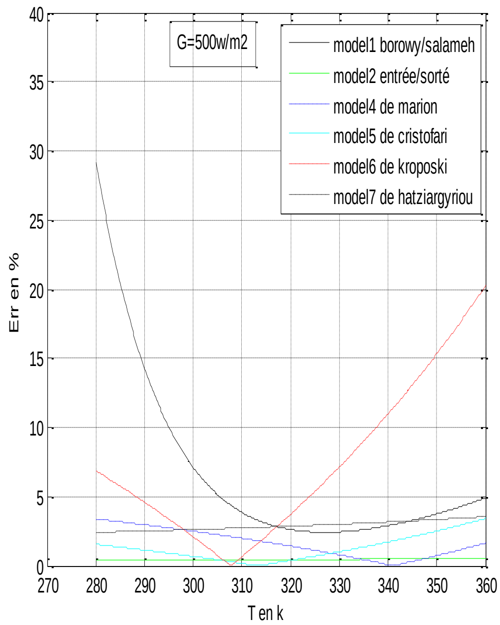

Figure.6. Relative error for different models with G=500w/m^2

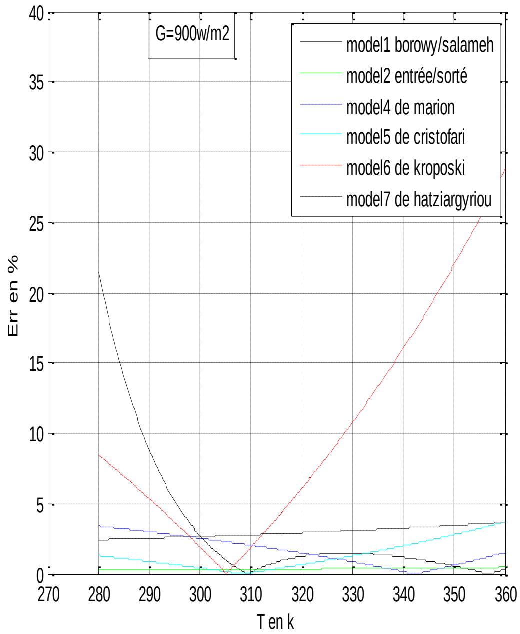

Figure.7. Relative error for different models, with G=900w/m^2

Tableau 3: the maximum power obtained for each model of the different PV modules and for different irradiations

modules	SP 75				US-64				ST 40			
irradiations (w/m^2) / Templates Of Power	**300**	**500**	**900**	**1000**	**300**	**500**	**900**	**1000**	**300**	**500**	**900**	**1000**
1 :Browy/salameh	19.66	37.74	66.6	74.81	13.81	26.94	56.5	64.38	9.77	17.95	35.77	40.42
2 : Entrée/sortie	24.69	41.15	74.06	82.29	20.77	34.62	62.31	69.23	13.15	21.92	39.46	43.84
3 : marion	24.30	40.46	72.84	80.93	20.72	34.53	62.15	69.06	12.95	21.58	38.85	43.16
4: cristofri	24.42	40.8	73.65	81.87	20.55	34.33	61.96	68.88	13.01	21.74	39.227	43.62
5 : kroposki	23.83	38.83	68.84	76.34	19.86	32.66	58.26	69.66	12.76	20.77	36.77	40.77
6:Hatziargyriou	24.39	40.64	73.16	81.29	20.66	34.43	61.97	68.85	13.08	21.8	39.226	43.59

III. Conclusion

In this work, we present the modeling of a photovoltaic module using mathematical models to calculate the maximum power. From the results of the numerical simulation we found that the values delivered by the input / output model are in good agreement with the reference model or the error does not exceed 1%. We also noticed that the model developed by borowy and salameh is favorable for very high solar illumination values (G> 900w / m^2) and for modulus temperature values which are greater than or equal to 300 ° K.Indeed, this model can be applied for practical applications for normal conditions (illumination of 1000 W / m^2, cell temperature 300 ° K).

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