Validation of Synergetic Control Theory Approach for Parameters Extraction of Four Parameters Model

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Abstract- In this paper we present a new method of parameters extraction for the equivalent circuit of photovoltaic cells or modules. This hybrid mathematical method in terms of calculation, called the synergistic control theory approach, is based on two steps of calculation, one analytical and the other numerical. However, the principle of this method is based essentially on manipulation of nonlinear equations transforming them into differential equations of first order and finally the solution of these equations represent the unknowns parameters which can be visible graphically. From different results that can be obtained with the different initial values, the desired parameter is shown to be exact when all possible solutions converge in a single special region. In this work we have chosen to test the efficiency of the method by selecting the four-parameter model as a work model and by referring to some manufacturers of photovoltaic modules with various technologies, especially Shell SP75, Shell SQ150-PC, Shell ST40 and SST 230-60 P. The results of the tests carried out by making the comparison with other calculation methods showed the correctness of the method in terms of parameters calculation and in terms of the theoretical modeling at different temperatures and at different irradiations, which makes it possible to be adopted as a new method of calculation.

Keywords Four parameter model, Nonlinear problem, Parameter extraction, Synergetic Control Theory, Simulation validation.

1. Introduction

The depletion of fossil fuels and the high pollution levels observed in recent years require us to adopt a diversification strategy of energy sources, in particular those that respect the environment. Renewable energies presumed to be inexhaustible, free and non-polluting [1] can constitute a gold mine for future generations. Thanks to the appearance of the photovoltaic effect in 1839 that allows to the photovoltaic cells a great expansion at the level of their manufacture due to their diversified application and especially in the areas related to the production of electric energy. The process of conversion of light into electricity explained in [2], allows a good understanding of the phenomena incurred during the generation of electricity. In give a model for a photovoltaic panel or a cell, many mathematical models exist to schematize there behaviors; there are those with single diode [3], [4] and with double diode [5, 7]. For the single diode model, there is also another substituted model the model with four parameters [8], this model considers that the value of the shunt resistor Rsh is very large and his effect is negligible for modeling. To calculate the parameters of photovoltaic cells or modules multiple algorithms has been used, such as Single-Variable Optimization (SVO) [9], Artificial Bee Colony optimization (ABC) [10], Genetic Algorithm (GA) [11], [12], Sequential Optimization [13], Simulated Annealing (SA) [14], Harmony Search (HS) [15], Particle Swarm Optimization (PSO) [16] and so on. In this paragraph we give an overview on some extraction methods widely used in the literature. In Genetic Algorithm (GA) [11], [12], the parameters extraction of the single-diode model is accomplished by defining an objective function. The test of efficiency is proven by carrying out the calculation on cells and photovoltaic modules. In Simulated Annealing (SA) [14] used for the extraction of a cell and photovoltaic module parameters, the two equivalent working circuits were the single and the double diode models, the results obtained by the method were acceptable and fall within the standards. In Harmony Search (HS) [15], the algorithm was mainly inspired from the phenomenon of music instruments adaptation; the HS used for the parameters extraction of a photovoltaic cell included two models, the single and the double diodes based on an objective function. In Artificial Bee Colony optimization (ABC) method [10], the work was carried out mainly to extract the parameters of photovoltaic cells using two and one diode models and this was made in order to compensate the objective function noise generated with excess in the case of GA, SA and HS algorithms. In general, these algorithms named heuristics are applied when the analytical calculations fail to find a solution for a given problem, due to the nonlinearity and multiple unknowns. These algorithms do not guarantee to find the perfect solution but at least to approach the right one. The parameters identification of the single or the double diode models remain crucial for modeling or extracting the maximum power which presents the interest of MPPT researchers [17], [18]. In general, there is two principal methods used to make this identification; we distinguish the analytical methods [19], [20] and the numerical methods [21], [22]. For analytical methods there is a rapidity at the level of the computation which is not the case generally for the numerical methods, this later presents a long time calculation ,in addition to the choice of the initial values which can lead to the non-convergence of calculus [12], [23]. In this work, Synergetic Control Theory is introduced as a new approach to extract the four parameters model with the novelty that provides an accurate results and this is thanks to the attractors generated in a spatial region for each calculated parameter. For its use this approach does not require experimental I-V characteristic or an objective function, which is necessary for most of the cited algorithms and uses only four values for calculating these values, the short circuit current I_{sc} , the maximum current I_m, the open-circuit voltage V_{oc} and the maximum voltage V_m. The SCT method knows other advantages which are the simplicity in level of the initial values search and with the rapidity in terms of calculation convergence. In level of the resolution speed, the SCT method remains fast and presents a low iteration number. Finally, for this approach the only non-soliciting factor remains that related to the heavy literals equations. Following this introduction, the different parts will be organized as a follow-up; Section II will present the working model (four parameters). Section III will explain the synergetic control theory approach. Section IV will show the different steps of the parameters calculation using the STC approach. Section V will present the results obtained by applying the method to different photovoltaic modules technologies and Section VI will be the conclusion of this work.

2. Four parameters Model

All In Figure.1, we show the mathematical model to schematize the behavior of a cell or a photovoltaic module.

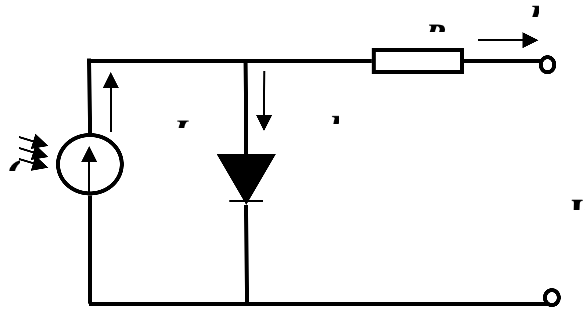

Figure.1 . Equivalent Circuit of four parameters Model

For its representation, the four-parameter model knows the presence of a current generator which represents the ideal current without loss after received irradiation G. The generated photocurrent I_{ph}, knows a subdivision during its circulation, a portion passes through the diode (I_D Current) and the rest of the current appears at the output of the circuit with a little lose essentially due to the series resistance Rs. Indeed, the characteristic equation of this model which link the current to the voltage is given as follows [8], [24].

$$I = I_{ph} - I_S\left[\exp \alpha\left(R_S I + V\right) - 1\right] \quad (1)$$

Where: $\alpha = \dfrac{q}{nN_S\, kT}$

In equation (1), I_{Ph} represents the Photo-current, I_S the saturation current of the Diode, R_S the series resistance. Then In the variable α, q represents the elementary charge (1.602×10-19 C), k the Boltzmann's constant (1.381×10-23 J/K), T the temperature of cell in Kelvin, Ns the number of cells connected in series and n represents the ideality factors. According to eq. (1), four essential equations are required which will be used for calculating the four parameters of photovoltaic modules. For this work the difference with the previous one [25], is that the present will allow to make a system equations of first order differential equations in order to calculate most of parameters graphically, which was not the case for the first work, in first one we've obtained one parameters graphically and all remaining parameters was founds by replacing them into others equations. However, these equations are obtained based on the use of various remarkable points equations at the Current –Voltage characteristic which are given as follows [26]:

- At the Short Circuit Point (I_{sc}, 0):

$$I_{ph} - I_S\left[\exp\left(\alpha R_S I_{Sc}\right)-1\right]-I_{Sc}=0 \qquad (2)$$

- At the open circuit voltage (0, Voc):

$$I_{ph} - I_S\left[\exp\left(\alpha\ V_{oc}\right)-1\right]=0 \qquad (3)$$

- At the maximum points (I_m, V_m):

$$I_{ph} - I_S\left[\exp\ \alpha\ \left(R_S I_m + V_m\right)-1\right]-I_m=0 \qquad (4)$$

The last equation to be used is that of the derivative at the maximum power point which is obtained by applying the power equation.

$$P = VI \qquad (5)$$

- The derivative of eq. (5) with respect to the voltage gives:

$$\frac{dP}{dV} = V\frac{dI}{dV} + I = 0 \qquad (6)$$

- Equation (6) at the maximum points (I_m, V_m), allows to write.

$$\left.\frac{dI}{dV}\right]_{(I_m,V_m)} = -\frac{I_m}{V_m} \qquad (7)$$

- The use of eq. (1) with eq. (7) allows finding the fourth equation.

$$I_S\,\alpha\left(R_S I_m - V_m\right)\exp\ \alpha\ \left(R_S I_m + V_m\right)+I_m=0 \qquad (8)$$

These equations once obtained, eq. (2), eq. (3) and eq. (4), will facilitate the calculation of the parameters sought using the theory exploited in this work.

3. The Synergetic Control Theory Approach

The non linearity of the equations encountered in many problems leads us to seek a method of solving these equations. For this purpose the synergetic control theory exists, the STC is a method for solving non linear equations system and the idea is based on the transformation of a non-linear equations system into a dynamic system to finally end up with a numerical curves resolution of these equations, the attractors of a equations system is a spatial region of the solution obtained, and exists where the roots of the system exist, the equations manipulated by SCT, represent the control targets and are represented by a macro viable $\psi i \equiv \psi i$ (x, u) which must to be zeroed, In this macro variable x represents the set of system variables and u is a control signal. For this theory the general equation used is given as follows [27]:

$$T\cdot\dot{\psi} + \psi = 0 \qquad (9)$$

In equation (9), T represents the convergence rate of an attractor, $\dot{\psi}$ is the derivative with respect to the time of the macro variable and ψ is the macro variable cited above. This first order differential equation admits as a solution.

$$\psi(t) = \psi_0 \cdot \exp\left(-t/T\right) \qquad (10)$$

In equation (10), t represents the time and ψ_0 is the initial value of this function and the fig.2 shows the attraction of the function $\psi_{(t)}$ for several initial values $\psi 0$.

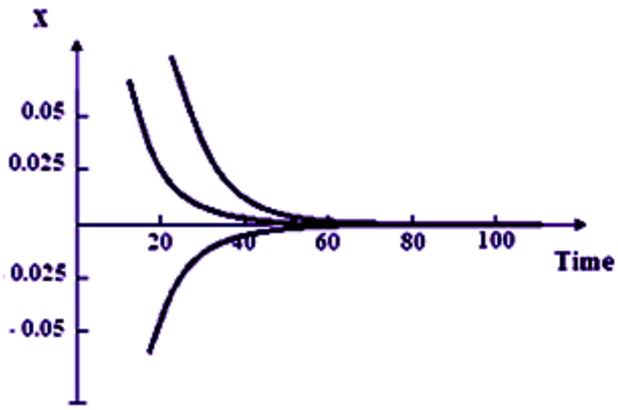

Figure.2. Convergence of ψ from different initial conditions to the attractor at $\psi = 0$.

To allow a good understanding of the theory in terms of an equations system manipulation, we write.

$$f_j\left(x_1, x_2, \ldots, x_N\right) = 0 \qquad (11)$$

In equation (11) fj (.) represents the macro variable, $1 \le j \le M$ represents the number of equations that present the subject of the control and the use of eq. (9) makes it possible to create the dynamical system shown by eq. (12), which gives:

$$T.\left(\frac{\partial f_i(x_1,..,x_N)}{\partial x_1}\dot{x}_1 + \frac{\partial f_i(x_1,..,x_N)}{\partial x_N}\dot{x}_N\right) + f_j\left(x_1,..,x_N\right) = 0 \qquad (12)$$

According to the equations obtained during the dynamization of the system, we can proceed directly to the analytical calculation of the linear system equations which the unknowns are the first derivatives of the desired parameters.

Finally, the resolution of the differential equations found must be done on software calculator. In this work we choose MathCAD software which offers this possibility.

4. Identification of Parameters

In this part, the four parameters of the chosen model will be calculated. In this diagram we show the different steps used in this method to calculate the unknown parameters.

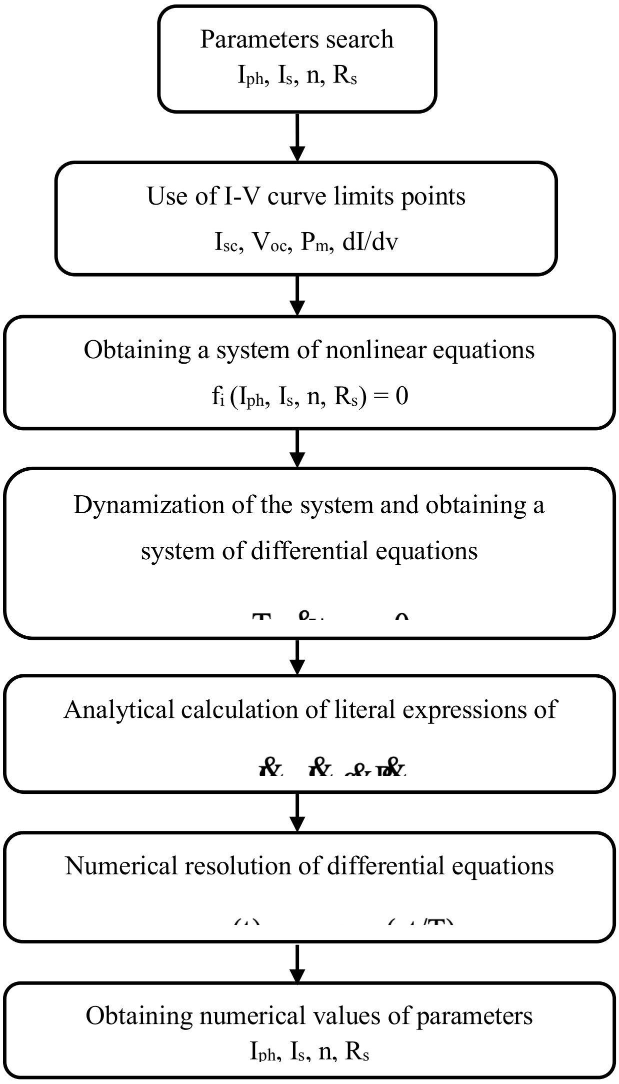

Figure.3. Flowchart of SCT method

However, the use of eq. (2), eq. (3), eq. (4), and eq. (8) previously presented in Section II, with the application of eq. (9) on the set of equations allows us to obtain this system of differential equations.

$$T\dot{I}_{ph}(t) - T\,a(t)\dot{I}_s(t) - T\,b(t)\dot{n}(t) - T\,c(t)\dot{R}_S(t) + d(t) = 0 \quad (12)$$

$$T\dot{I}_{ph}(t) - T\,e(t)\dot{I}_s(t) - T\,f(t)\dot{n}(t) + g(t) = 0 \quad (13)$$

$$T\dot{I}_{ph}(t) - T\,h(t)\dot{I}_s(t) - T\,i(t)\dot{n}(t) - T\,j(t)\dot{R}_S(t) + k(t) = 0 \quad (14)$$

In this system, a minimizing of variable has been applied in order to reduce the charge of equations (see appendix). In the equations above the new unknowns are the first derivatives of each parameter. If we replace with eq. (12) in eq. (13) and eq. (14), and with eq. (15) in the new equations, we obtain two equations with two unknowns $\dot{R}_S(t), \dot{n}(t)$.

$$\dot{R}_S(t) = \frac{1}{T}\cdot\left[\begin{array}{c}\dfrac{[l(t)(k(t)-g(t))-o(t)(e(t)-f(t))][(b(t)-f(t))l(t)-m(t)(a(t)-e(t))]}{[j(t)l(t)+n(t)(l(t)-h(t))][(b(t)-f(t))l(t)-m(t)(a(t)-e(t))]} \\ \dfrac{+[l(t)(f(t)-i(t))-m(t)(e(t)-f(t))][d(t)-g(t))l(t)-o(t)(a(t)-e(t))]}{+[c(t)l(t)-n(t)(a(t)-e(t))][l(t)(f(t)-i(t))-m(t)(e(t)-h(t))]}\end{array}\right] \quad (18)$$

$$\dot{n}(t) = \frac{1}{T}\cdot\left[\begin{array}{l}\dfrac{o(t)(a(t)-e(t))+d(t)-g(t))l(t)}{(b(t)-f(t))l(t)-m(t)(a(t)-e(t))} \\ -\dfrac{c(t)l(t)-n(t)(a(t)-e(t))}{(b(t)-f(t))l(t)-m(t)(a(t)-e(t))}\cdot T\cdot\dot{R}_S(t)\end{array}\right] \quad (19)$$

The substitution with these equations respectively in eq. (13) and eq. (15) makes it possible to find the equations of $\dot{I}_{ph}(t)$ and $\dot{I}_s(t)$

$$\dot{I}_s(t) = -\frac{1}{T}\cdot\left[\frac{o(t)}{l(t)} - \frac{n(t)}{l(t)}\cdot T\cdot\dot{R}_S(t) - \frac{m(t)}{l(t)}\cdot T\cdot\dot{n}(t)\right] \quad (21)$$

$$\dot{I}_{ph}(t) = -\frac{1}{T}\cdot\left[\frac{e(t)\,o(t)}{l(t)} + \frac{e(t)\,n(t)}{l(t)}\cdot T\cdot\dot{R}_S(t) - \left(f(t) - \frac{e(t)\,m(t)}{l(t)}\right)\cdot T\cdot\dot{n}(t) - g(t)\right] \quad (20)$$

These equations, eq. (18), eq. (19), eq. (20), and eq. (21) represent a first order differential equations which require a numerical resolution to find the unknowns of four-parameters model. In this model, the parameter I_S (saturation current) represents a small value compared to the other parameters, which can introduce an ambiguity when reading this parameter graphically. Indeed, the numerical resolution will only operate on eq. (10), eq. (18), and eq. (20). The value of I_S will be calculated from eq. (3). Finally the application of the SCT allows us to obtain the unknowns parameters.

5. Identification Of Parameters

In this section, we propose to test the efficiency of the theory in terms of computation and make it possible the validation of its use, first by choosing the Shell SP75 [28] module and then making a comparison to other calculation methods. In another part a test will be carried out by shoosing three types of photovoltaic module technologies, the mono crystalline Shell SQ150-PC [29], the thin film Shell ST40 [30] and the Poly crystalline SST 230-60 P [31].

5.1. Extraction shell SP75 parameters

Extracting parameters of Shell SP75 module is done by using the equations developed in the Section IV, but this task requires the use of module's technical data. In Table 1, the technical's Data supplied by the Manufacturer are given under STC conditions at T = 25 ° C and at G = 1000 W / m².

Table 1 . Technical Shell SP75 Module Data

I_m (A)	4.4
V_m (V)	17
I_{sc} (A)	4.8
V_{oc} (V)	21.7
N_S	36
K_I (mA/°C)	2
K_V (mV/°C)	-76

By using the technical data in Table 1, the equations calculated previously and the numerical resolution in the MathCAD Software, gives us the desired values of the three parameters I_{ph}, R_s and α.

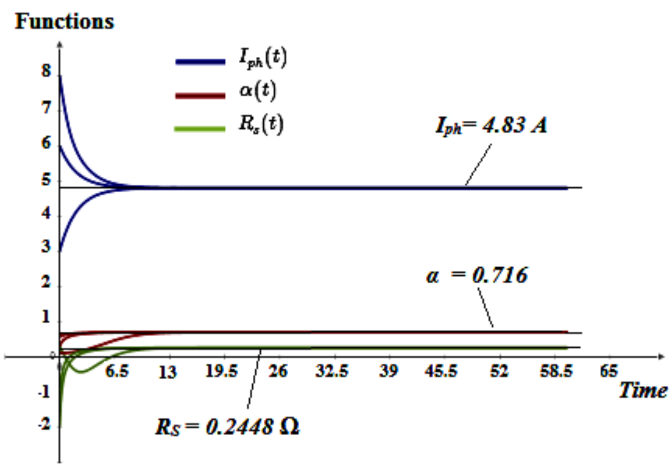

Figure.4. Calculated parameters of Shell SP75 using numerical resolution for several initial conditions

In figure. 4, we show the results of solving differential equations of the three parameters, I_{ph}, I_S and R_S and we notice that for each initial value which corresponds to a given parameter, we obtain an exponential form which converges to a single special region, thus makes it possible to calculate with exactitude the value of an unknown parameter, since the value of this one is extracted graphically from the convergence area. For the parameter n (ideality factor) its obtaining is done by replacing in the expression of the variable α, and I_s (saturation current) by replacing in eq. (3). In Table 2, the numerical values of the calculated parameters are presented in comparison with other methods of calculation [8].

Table 2. Numerical Values Of Different Parameters Compared To Other Methods At T= 25 °C , G =1000 w/m²

Estimated Parameters				
Methods	*I_{ph}(A)*	*I_S (µA)*	*n*	*R_S (Ω)*
Present Method	4.83	85.835	1.5098	0.2448
Explicit Method	4.8	24.594	1.3978	0.3381
Slope Method	4.8	77.196	1.5	0.2860
Iterative Method	4.8	84.836	1.5091	0.28

In Table 2, the obtained values using this method and the values of the other methods require a simulation of the IV characteristic at T = 25 ° C to see their accuracy by adjusting them with experimental data. In this work, experimental data used to test the correctness of the method were obtained using the Origin software; this one makes it possible to extract the points of the experiment from the manufacturer's file. In Fig. 5 and fig. 6, we show the fitting between experimental and theoretical models and the offset generated.

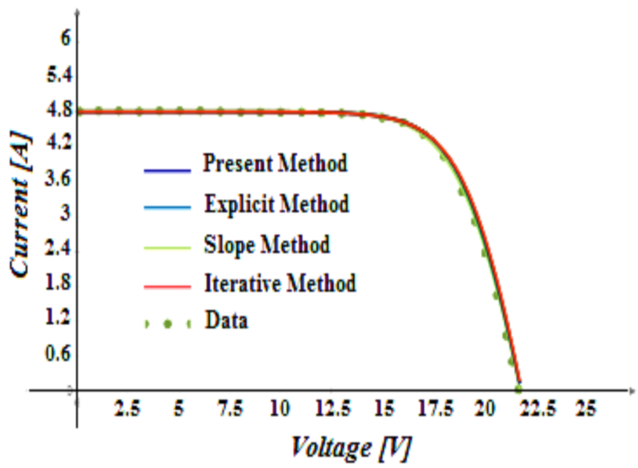

Figure. 5. Fitting between experimental and theoretical model's

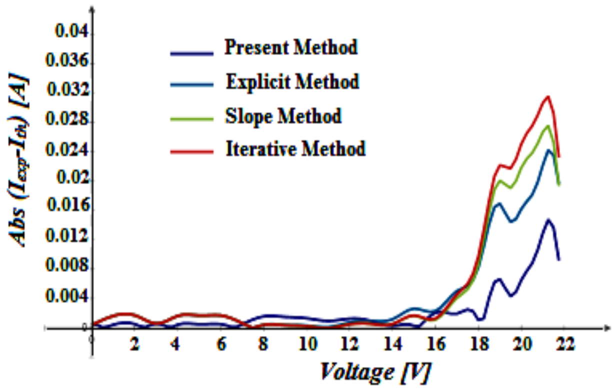

Figure 6. Offset between experimental and theoretical model's.

From Figure 5, it can be seen that the results obtained from the different methods are in the same order of coincidence regarding the theory and the experiment. This agreement is mainly due to the influence of each parameter on the I-V curve, for the point in the vicinity of the short-circuit current, its adjustment is controlled by the value of the photonic current I_{ph}, the saturation current I_s influences the slope in the vicinity of the short-circuit current I_{sc}, the series resistor R_s controls the value of the slope in the vicinity of the open circuit voltage V_{oc} and the ideality factor n impacts the slope in the vicinity of the maximum power point. In figure 6 the error curve allows us to make a great comparison between the fourth methods, we can note that the method developed in this work presents the minimum error comparing to other methods (an error up to 0.012 A for a voltage range between 20 V and 22 V), then we can conclude that the method has an efficiency in terms of calculation, but generally these errors remain low for the four methods, which also shows the accuracy of the other methods.

5.2. *Application of the Method for Various technologies.*

In this section, we decide to test the efficiency of the method by choosing three types of photovoltaic modules technologies, Shell SQ150-PC, Shell ST40 and SST 230-60 P. In Table 3, we present the technical characteristics of the three modules taken at T = 25 ° C and G = 1000 W / m².

TABLE 3
Technical Data of the three Technologies At STC

Technical Data	Monocrystalline Shell SQ150-PC	Multicrystalline SST 230-60 P	Thin-film Shell ST40
I_m (A)	4.4	7.83	2.41
V_m (V)	34	29.4	16.6
I_{sc} (A)	4.8	8.52	2.68
V_{oc} (V)	43.4	36.7	23.3
N_S	72	60	42
K_I (mA/°C)	1.4	3.83	0.35
K_V	-161	-128	-100

For the three types of technologies, the application of the SCT in addition to a numerical resolution allows to obtain the numerical values of the three unknowns parameters. In Figure 7 we show these values.

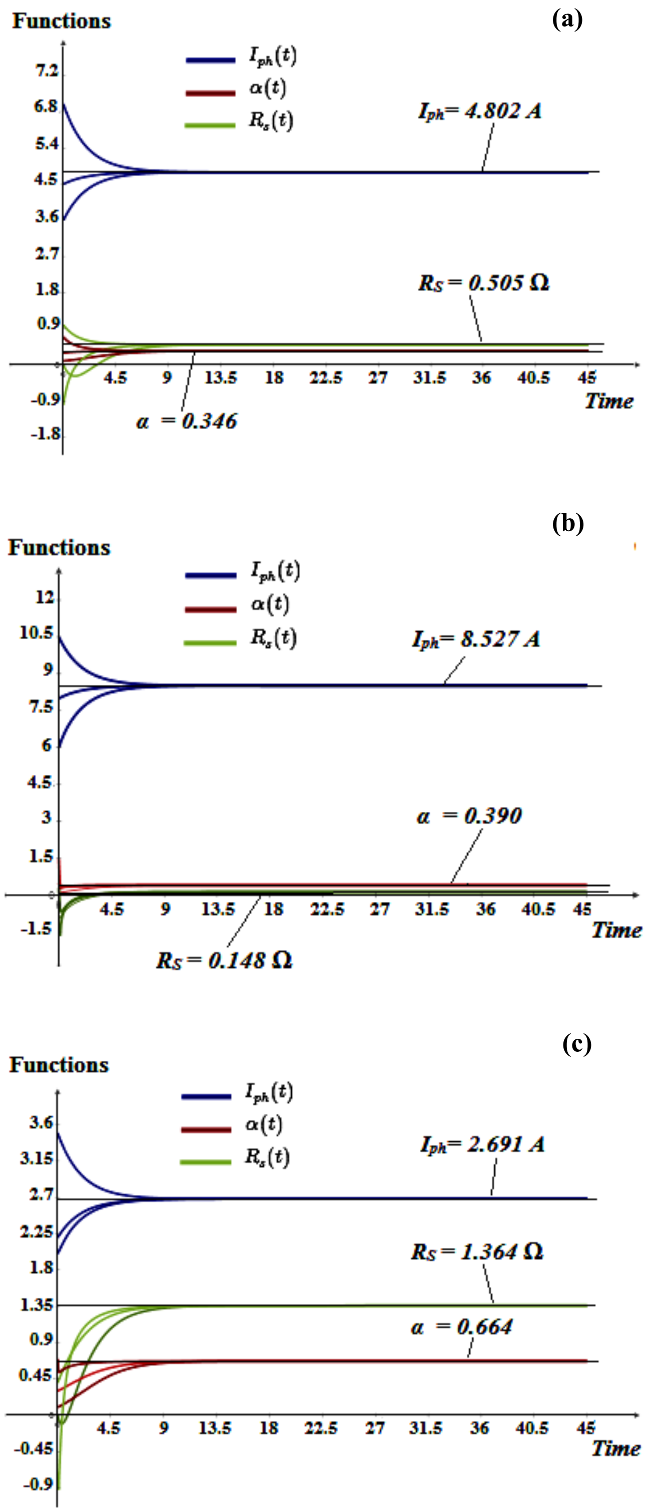

Fig. 7. Calculated parameters for each technology using STC approach for several initials conditions. (a) Shell SQ 150-PC, (b) SST 230-60 P, (c) Shell ST40

According to Fig. 7, the use of several initial values, allow us to obtain the numerical resolution of the desired parameters. As mentioned previously; the convergence in a single spatial region makes it possible to extract with exactness the numerical value of parameters. Then in Table 3, we report the values of various parameters for the three evaluated technologies at T = 25 ° C and G = 1000 W / m².

TABLE 4

Estimated Parameters for each technology at T= 25 °C , G =1000W/m²

Estimated Parameters	PV Modules Technology		
	Monocrystalline Shell SQ150-PC	Multicrystalline SST 230-60 P	Thin-film Shell ST40
$I_{ph}(A)$	4.802	8.527	2.691
$I_S\,(\mu A)$	1.445	5.181	51.39
n	1.562	1.663	1.628
$R_S\,(\Omega)$	0.505	0.148	1.364

From the values obtained in Table 4, it can be seen that the test of these parameters remains a primordial step to prove the accuracy of the method in terms of calculation. In this step, we choose to validate these values by simulating the behavior of each photovoltaic module under several conditions of irradiations and temperatures, but the realization of this task requires the use of an additional formula of several parameters, these later depend also on irradiation and temperature. These formulas are given by the following equations [8], [32], and [33].

$$I_{Ph} = \frac{G_r}{G}\left(I_{Phr} + K_i\left(T - T_r\right)\right) \tag{19}$$

$$I_S = I_{Sr}\left(\frac{T}{T_r}\right)^3 \exp\left(\frac{qE_g}{nk}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right) \tag{20}$$

$$I_{Sc} = I_{Scr}\,\frac{G}{G_r} + K_i\,(T - T_r) \tag{21}$$

$$E_g = E_{gr}\left(1 - 0.0002677\left(T - T_r\right)\right) \tag{22}$$

$$n = n_r\,\frac{T}{T_r} \tag{23}$$

In eq. (19), eq. (20), and eq. (23), I_{phr}, I_{Sr}, and n_r, represent the parameters calculated at the standard test conditions STC. In equation (21), I_{Sc} represents the short circuit current at STC, K_i the coefficient of the current variation. In (22), Egr represents the gap energy of material at 25 ° C (1.12 ev for the mono crystalline silicon and the thin film and 1.14 ev for the polycrystalline silicon). Other formulas of these parameters which depend on temperature also exist as (V_{Oc}, I_m ,V_m), but here we present only the formulas necessary for modeling. However, Using equation. (19), eq. (20), eq (21), eq (22) and (23), the technical data shown in table 3 and the obtained values of various parameters, We obtain the simulated curves of the I-V characteristic for the three modules. Figures (8), (9) and (10) show these variations.

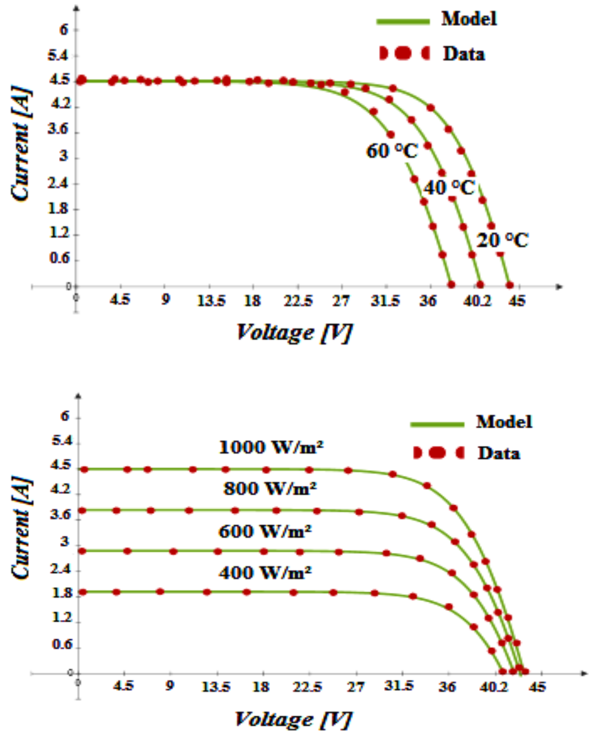

Fig.8. Simulated curves for the Shell SQ 150- PC module, in several temperature and irradiation conditions.

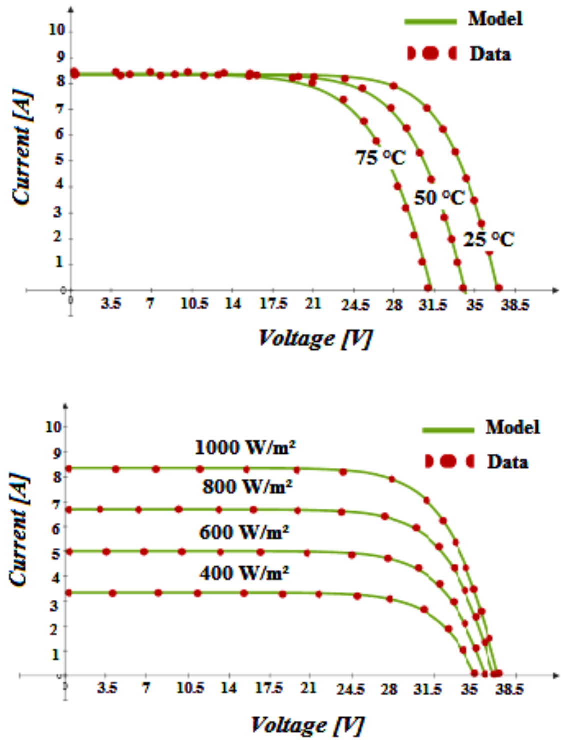

Fig.9. Simulated curves for the SST 230-60 P module, in several temperature and irradiation.

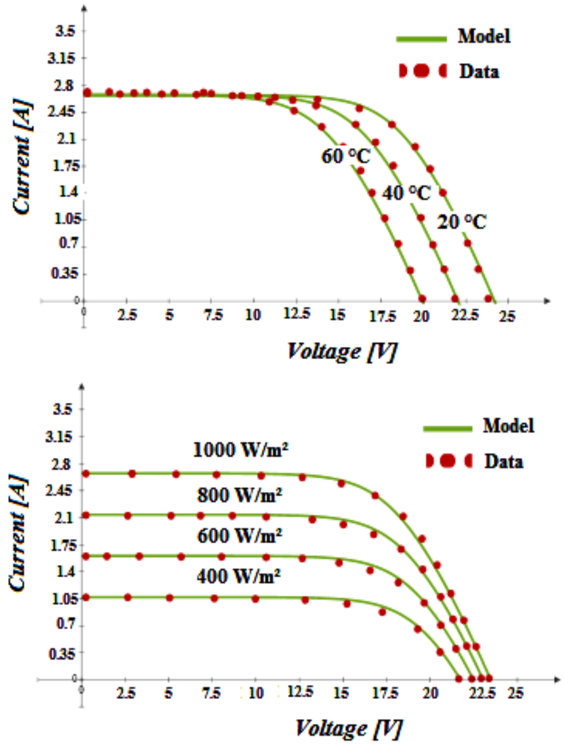

Fig.10. Simulated curves for the Shell ST40 module, in several temperature and irradiation conditions.

According to the curves shown above of various modules (SQ150-PC, SST 230-60 P), it is noted that the results obtained are satisfactory in terms of accuracy and goes well with theoretical and experimental models but except for ST40 module , Which has a small offset for certain points of the two irradiation and temperature curves. This offset is mainly due to the formulas used which are characterized as empirical, then they lead to a small offset when evaluating at multiple temperatures and at multiple irradiations. In this simulation, the temperatures chosen are between 20 ° C and 60 ° C, which makes it possible to give the remark that the temperature influences the efficiency of a photovoltaic module and also the irradiation which is chosen between 400 W /m² and 1000 W /m²..

6. Conclusion

In this work, a new method of extraction called synergetic control theory approach was discussed in order to calculate the parameters of photovoltaic modules, the application of this method on the Shell SP75 module, and on three types of Pv module technologies has shown its ability to give an exact values in the terms of precision. The main objective of this work was to show that the present method can be used as a calculation tool independently of the chosen mathematical model. Finally, we conclude that this method can also be considered as a new tool of calculating parameters added to existing accurate methods.

Appendix

Variables In (13), (14), (15), and (16)

$$a(t)=\exp\left(\alpha(t)R_S(t)I_{SC}\right)-1,$$

$$b(t)=R_S(t)I_{SC}I_S(t)\exp\left(\alpha(t)R_S(t)I_{SC}\right).$$

$$c(t)=\frac{\alpha(t)}{R_S(t)}b(t)\ ,\ d(t)=I_{Ph}(t)-I_S(t)\ a(t)-I_{SC},$$

$$e(t)=\exp\left(\alpha(t)V_{oc}\right)-1;\ f(t)=I_S(t)V_{oc}\exp\left(\alpha(t)V_{oc}\right),$$

$$g(t)=I_{Ph}(t)-I_S(t)e(t),$$

$$h(t)=\exp\ \alpha(t)\left(V_m+R_S(t)I_m\right)-1.$$

$$i(t)=I_S(t)\left(V_m+R_S(t)I_m\right)\exp\ \alpha(t)\left(V_m+R_S(t)I_m\right),$$

$$j(t)=I_S(t)\alpha(t)I_m\ \exp\ \alpha(t)\left(V_m+R_S(t)I_m\right).$$

$$k(t)=I_{Ph}(t)-I_S(t)h(t)-I_m,$$

$$l(t)=\alpha(t)\left(R_S(t)I_m-V_m\right)\exp\ \alpha(t)\left(R_S(t)I_m+V_m\right).$$

$$m(t)=I_S(t)\left(R_S(t)I_m-V_m\right)\left(\exp\ \alpha(t)\left(R_S(t)I_m+V_m\right)+\frac{\alpha(t)}{I_S}i(t)\right)$$

$$n(t)=I_S(t)\alpha(t)\left(I_m\exp\ \alpha(t)\left(R_S(t)I_m+V_m\right)+I_m\ l(t)\right),$$

$$o(t)=I_S(t)\alpha(t)l(t)+I_m.$$

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