Design of photovoltaic systems on virtual learning platform

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***Abstract*—This article presents the development of a virtual learning platform for the design of solar photovoltaic systems. The work carried out involves the inclusion of mathematical models of solar radiation, photovoltaic panels, regulators, batteries and inverters that are integrated to offer a virtual component operation that intervenes in a system for obtaining electrical energy from the solar source. The virtual environment was implemented using the possibilities offered by a graphic programming environment, to facilitate the learning of the design parameters of solar photovoltaic systems.**

***Index Terms*—Design of photovoltaic systems, Mainel and meinel model, modeling of photovoltaic panels.**

I. INTRODUCTION

Among the multiple possibilities of obtaining electricity in a clean way is the transformation of solar radiation into electricity through the use of photovoltaic panels. This resource is available in the entire planet; however it is not always possible to access this resource for different reasons such as economic, technological or simply for not having the knowledge of how to design the system. The latter is possible to solve if it is made available to the Internet community, educational tools that allow access to the required knowledge. Taking advantage of the software of object-oriented programming, mathematical models and virtual learning platforms, it is proposed to build a tool that facilitates learning in the design of photovoltaic systems.

For the development of the virtual platform was raised and followed the methodology shown in figure (1), where it is possible to observe four general stages; the first stage refers to the solar irradiance estimation model, the second stage refers to the development of a circuit model that allows modeling the behavior of photovoltaic panels, The third stage refers to the development of a model that allows to size an isolated photovoltaic system, taking into consideration the electrical characteristics of the installation, the performance of the installation, among others. The above in order to obtain the design characteristics of the photovoltaic installation. Finally, the fourth stage has as reference the development of the learning platform, which in order to serve in the applications of teaching in the design of isolated photovoltaic systems.

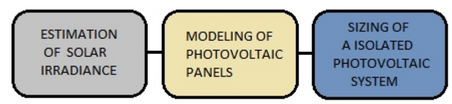

Fig. 1. Methodology used

II. MATHEMATICAL MODEL FOR THE ESTIMATION OF SOLAR IRRADIANCE

For the development of the solar irradiance estimation model, the Mainel and Meinel mathematical model was used taking into consideration clear sky conditions, this model is described in equation (1).

$$Rh = Ra * 0,7^{m^{0,678}} * Cos(\theta) \quad (1)$$

Where Rh is the global hourly solar irradiance incident on a inclined surface at an angle θ with respect to the normal component thereof [1]. In addition, Ra is the extraterrestrial irradiance incident on the inclined surface and is described by equation (2).

$$Ra = Rsc * [1 + 0,033 * Cos(\frac{2\pi J}{365})] * Sin\alpha \quad (2)$$

Rsc refers to the constant solar and is equivalent to 1367 (W/m^2), the mass of the air (m) is an effect of the earth's atmosphere and is defined as the relative length of the path of the sunrays direct through the earth's atmosphere in contrast vertical path of the rays directly at sea level. The parameter is defined by equation (3). Where α is the altitude angle of the sun [2].

$$m = [1229 + (614 * Sin(\alpha))^2]^{\frac{1}{2}} - 614 * Sin(\alpha) \quad (3)$$

The altitude angle of the sun is obtained with the expression shown in equation (4), where ϕ is the geographical latitude, δ corresponds to the solar declination angle and W is a measure of angular time that is described in equation (5) with positive values for the morning and negative for the

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afternoon, which depends on the local solar time ST [2]. Equations (6) and (7) show the mathematical expression to obtain the local solar time, where the local time standard LT intervenes, the standard meridian of the local time zone Ls and the geographical longitude Ll in degrees [3]. In addition, parameter B is calculated with equation (8) and is dependent on the day of the year J.

$$Sin(\alpha) = (Cos(\phi) * Cos(\delta) * Cos(w) + Sin(\phi) * Sin(\delta)) \quad (4)$$

$$W = 15(12 - ST) \quad (5)$$

$$ET = 9,87 * Sin(2B) - 7,53 * Cos(B) - 1,5 * Cos(B) \quad (6)$$

$$ST = LT + \frac{ET}{60} + \frac{4}{60}(Ls - Ll) \quad (7)$$

$$B = \frac{360 * (J - 81)}{365} \quad (8)$$

To obtain the solar declination angle, the mathematical expression shown in equation (9) is used, which depends on the day of the year.

$$\delta = 23,5 * Sin[\frac{360}{365} * (J + 284)] \quad (9)$$

Finally, for the test of the hourly global solar irradiance estimation model, were taken into consideration the geographical parameters of the city of Bogotá as the geographical latitude, longitude and the standard meridian of the local time zone established for the city, which is UCT-5 (-75). In this way, the solar irradiance estimation model was obtained in the year for the city, which is presented in figure (2). The graph shows the variation in solar irradiance throughout the year and the peak irradiance values between 900 and 1100 (w/m^2).

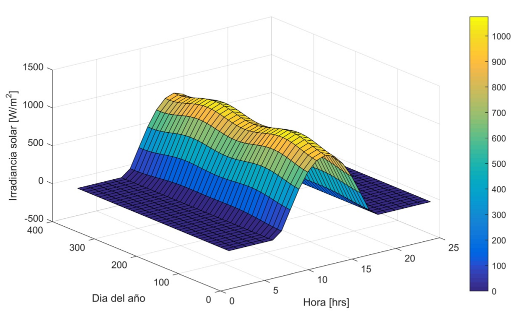

Fig. 2. Estimation of global hourly solar irradiance obtained throughout the year for the city of Bogotá

For the design of photovoltaic systems it is of vital importance to know the number of peak solar hours of the location where the installation is planned, in this way, with the irradiance data obtained, an algorithm is developed to calculate the average of peak solar hours throughout the year, the above, finding the area on the irradiance curve with the help of the method of the trapeze, the mathematical expression used is presented in equation (10), where Hd is the daily solar radiation in W/m^2, R_n is the instantaneous radiation in W/m^2, t_n is the time in hours for the measurement "n" and, finally, n is the number of measures of radiation obtained [7]. For example, if a peak hour corresponds to 1000 (w/m^2), if the measured daily irradiance is 5800 ($w/m^2 day$) then a number of peak solar hours equal to 5.8 [4]. Therefore, figure (3) shows the average of peak solar hours for each month of the year.

$$Hd = \sum_{1}^{n-1} [\frac{(R_n + R_{n+1}) * (t_{n+1} - t_n)}{2}] \quad (10)$$

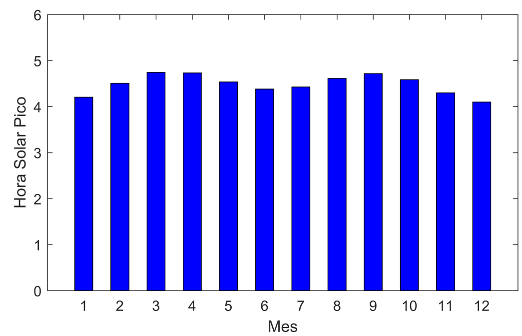

Fig. 3. Solar hours average peak obtained for each month.

The model proposed by Mainel and Meinel has been studied in different investigations such as [1]-[8]-[9],where you can see the good behavior of the model in clear sky conditions, in this way, taking into account that the virtual platform is focused on teaching, the Mainel and Meinel model can help explain the approximate behavior of the global solar irradiance in a point of the earth, however, a city like Bogotá presents serious problems of atmospheric pollution [9], which affect the solar irradiance received on a surface in the city, thus, the number of average monthly peak solar hours is less, so that in the user interface developed the option of entering the number of solar hours peak is implemented, this can be obtained based on measured solar irradiance data, figure (4) shows as an example the average daily radiation measured by a meteorological station located at the El Dorado airport in Bogotá D.C. [10]

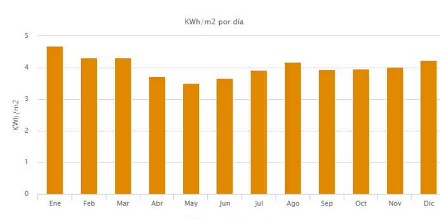

Fig. 4. Monthly average of solar irradiance measured by the meteorological station in El Dorado airport in Bogotá D.C

III. MODELING OF PHOTOVOLTAICS PANELS

As a model of the solar cell the schematic of the figure (4) is used, which is considered adequate because it takes into account different forms of losses in real situations.

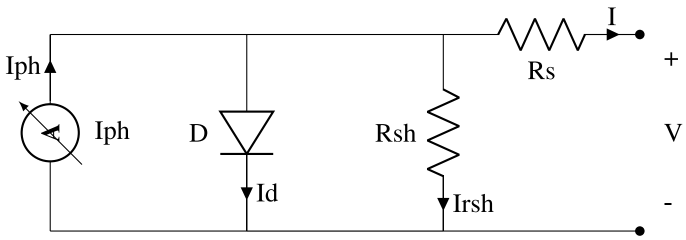

Fig. 5. Circuit model of photovoltaic cell

Where I is the output current of the solar panel, I_{ph} is the current photogenerated by the solar cell, I_{Rsh} is the current of losses in the resistance in parallel, Rs the parasitic resistance in series due to the contacts between cells and V is the voltage generated by the solar cell. Performing the circuit analysis following the laws of Kirchoff, the following mathematical expressions are determined:

$$I = I_{ph} - I_d - I_{Rsh} \tag{11}$$

$$V = N_s(V_d - I * R_s) \tag{12}$$

A. Photo-generated current I_{ph}

Photo-generated current is directly proportional to the incidence of solar irradiance in the solar cell, equation (13) shows the relationship between the photogenerated current I_{ph} and the solar irradiance influencing the solar cell. Where G is the solar irradiance affecting the panel, G_{stc} the solar irradiance to standard conditions $(1000W/m^2)$, A is the area of the solar cell, J_{sc} is the short-circuit current density of the cell, αJ_{sc} is the temperature coefficient of the short-circuit current density, T_k is the absolute incidence temperature in the solar panel and T_{stc} is the absolute temperature in standard conditions $(300K)$.

$$I_{ph} = \frac{G}{Gstc}[A * Jsc + \alpha Jsc * (T_k - T_{stc})] \tag{13}$$

Some parameters shown in the previous expression are provided by the manufacturer, however, the coefficient and the short-circuit current density are not very common in the datasheets of the manufacturers, therefore, the equations (14) and (15) are necessary to perform the respective calculation. With I_{sc} the short-circuit current and C the temperature coefficient of the short-circuit current, are provided by the manufacturer.

$$J_{sc} = \frac{I_{sc}}{A} \tag{14}$$

$$\alpha J_{sc} = \frac{C}{A} \tag{15}$$

B. Diode current I_d

The diode current in the solar cell model is defined by equation (16), where I_o refers to the saturation current of the diode, therefore for the calculation of this, some parameters dependent on the semiconductor from which the solar cells are manufactured are taken into account, such as the energy of the GAP dependent on the semiconductor material E_g as a function of the incident temperature T_k, the GAP energy dependent on the semiconductor material $E'g$ as a function of the temperature under STC standard conditions, the thermal voltage V_T under conditions of incidence temperature T_k and the thermal voltage V'_T in STC conditions.

$$I_o = \frac{Jsc * A * Tk^3 * e^{\frac{-E_g}{V_T}}}{(e^{\frac{Vcell}{n*V_T}} - 1) * Tsc^3 * e^{\frac{-E'_g}{V'_T}}} \tag{16}$$

Taking into consideration that the solar panels are formed by arrays of interconnected cells in series or in parallel, the model for solar panels with a number of cells in series Ns is provided by the manufacturer, therefore, the equation (17) describes the relationship of existing voltages in a solar panel, where V_{oc} is the short-circuit voltage also provided in the datasheet.

$$V_{cell} = \frac{V_{oc}}{Ns} \tag{17}$$

To find the saturation current of the diode, it is necessary to calculate the parameters E_g, E'_g, V_T y V'_T, whose expressions are shown in the equations (18), (19), (20) and (21) respectively, where E_{go} is the GAP energy dependent on the semiconductor material, αGAP y βGAP are parameters of the temperature of the semiconductor material.

$$E_g = E_{go} - \frac{\alpha GAP * T_k^2}{T_k + \beta GAP} \tag{18}$$

$$E'_g = E_{go} - \frac{\alpha GAP * T_{stc}^2}{T_{stc} + \beta GAP} \tag{19}$$

$$V_T = \frac{K * T_k}{q} \tag{20}$$

$$V'_T = \frac{K * T_{stc}}{q} \tag{21}$$

Figure (6) presents the corresponding data for αGAP, βGAP and E_{go} according to the semiconductor material of the solar cells manufacture.

C. Current and output voltage of the photovoltaic module

Equation (22) shows the expression of the behavior of the output current of a solar panel, in turn, equation (23) describes the voltage in a photovoltaic module. It can be seen that the solution to obtain the values of V and I are not explicit, therefore, the Newton Raphson method is used to solve the expression and get the corresponding voltage and current values [5]. However, it is necessary to perform a data

	Germanio	Silicio	GaAs
Eg_0[eV]	0.7437	1.166	1.519
α_{GAP}[eV/K]	4,77 x 10^{-4}	4,73 x 10^{-4}	5,41 x 10^{-4}
β_{GAP}[K]	235	636	204

Fig. 6. Characteristic parameters of a photovoltaic panel according to the material[1]

sweep of Vd, from zero to the voltage of the solar cell $Vcell$, taking into account that the diode can not enter the conduction region, and thus obtain a value of V and I for each Vd.

$$I = I_{ph} - I_o * (e^{\frac{V+Rs*I}{n*V_T}} - 1) - \frac{V + R_s * I}{R_{sh}} \quad (22)$$

$$V = Ns * (Vd - I * Rs) \quad (23)$$

D. Estimation of losses Rs and Rsh

In order to make the proposed model behave more approximately, it is necessary to correctly calculate the loss resistances. To perform this calculation, in the first instance the equations (22) and (23) are developed under conditions of temperature and standard solar irradiance STC, in addition, the loss resistances are taken as ideals, where Rsh = ∞ and Rs = 0, as well the corresponding voltage and current values of the panel are obtained in STC conditions and without losses, as a result of this, the power Pmax that corresponds to the maximum power of operation of the panel, is greater than the power Pmp given by the manufacturer. Therefore, to calculate the loss resistance, the mathematical expression of equation (24) is taken into account and a sweep of the loss resistance Rs is calculated by calculating its corresponding Rsh, this is done until the value of the maximum power is similar to the power of the panel provided by the manufacturer, which is calculated with the mathematical expression of equation (25), and is equivalent to the multiplication of the voltage and current in the point of operation, also given by the manufacturer.

$$Rsh = \frac{Vmp + Rs * Imp}{Imp - Iphstc - Iostc * (e^{\frac{Vmp+Rs*Imp}{n*VT'}} - 1)} \quad (24)$$

$$Pmp = Vmp * Imp \quad (25)$$

Therefore, applying the model described above in a commercial photovoltaic panel with the characteristics of the table (1), the characteristic curves of the solar panel are determined, the figures (7) and (8) show the behavior of the solar panel comparing the ideal model under STC conditions and the not ideal model taking into account the losses.

Hereby there is obtained an algorithm capable of shaping a photovoltaic panel according to its electrical characteristics and the incidental irradiance on its surface, therefore, applying

TABLE I
CHARACTERISTICS OF TECHNO-SUN SOLAR PANEL 150 W

Parameter	Value	Unit
P	150	[W]
Vmp	18.99	[V]
Imp	7.9	[A]
Voc	22.42	[V]
Isc	8.45	[A]
C	0.04	%

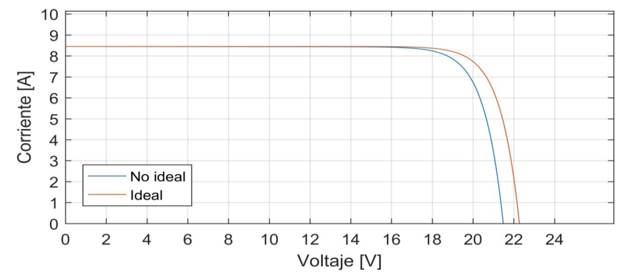

Fig. 7. Curve Voltage-Current obtained in STC conditions for a panel of 150 [W], contrasting the effect of the model with ideal and non-ideal loss resistors calculated.

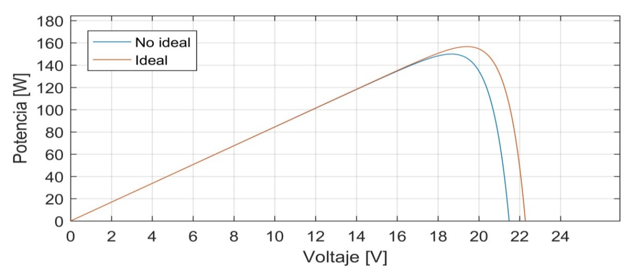

Fig. 8. Voltage-Power curve obtained in STC conditions for a panel of 150 [W], contrasting the effect of the model with ideal and non-ideal loss resistance calculated.

the solar irradiance estimation model, under critical solar irradiance conditions, that is to say, the day of the year with the lowest irradiance rate, it is possible to obtain the behavior of the panel of 150 [w] according to the global hourly irradiance, the figures (9) and (10) show the behavior of the solar panel of 150 [w] under conditions of solar irradiance estimated according to the time of day.

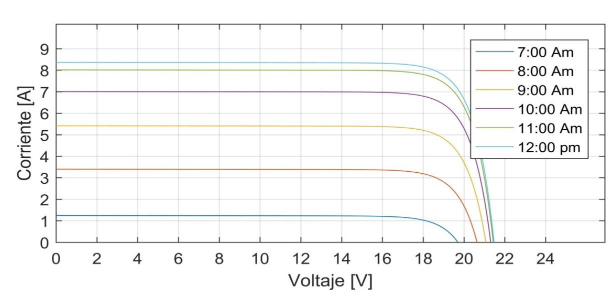

Fig. 9. Behavior Curve Current-Voltage of a solar panel of 150 [W] according to the global hourly solar irradiance obtained.

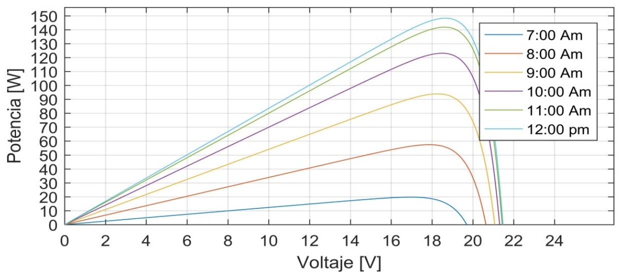

Fig. 10. Behavior curve Voltage-Power of a solar panel of 150 [W] according to the obtained global solar irradiance.

IV. MODEL FOR SIZING OF A ISOLATED PHOTOVOLTAIC SYSTEM

To achieve the correct sizing of the isolated photovoltaic installation, the process of each of the following items was followed:

A. Calculation of the total system energy

For the calculation of the total system energy, it is necessary to know the load distribution table of the electrical installation, the above in order to obtain the energy daily consumption in (KWh) and also the simultaneous nominal power of the loads in (W). Therefore, equation (26) shows the mathematical expression to obtain the total energy E that has to be supplied by the photovoltaic array and the charge regulator.[11]

$$E = \frac{E_T}{R} \tag{26}$$

Where E_T is the daily energy consumption of the loads, R is the global performance factor, that can be calculated with the mathematical expression of equation (27), where k_b is the coefficient of losses per performance of the accumulator, k_c is the coefficient of losses of the inverter, k_v is the coefficient of other losses, k_a the self-discharge coefficient of the accumulator, N is the number of days of the installation autonomy, P_d is the depth of the accumulator discharge.[11]

$$R = (1 - kb - kc - kv)(1 - \frac{ka * N}{Pd}) \tag{27}$$

To calculate k_a it is taken into account, for example, According to the manufacturer's data, the battery to be used tends to discharge 25% in six months, therefore, this must be divided by the percentage that the battery is discharged expressed in value per unit (0.25) in six months, between the number of equivalent days (180 days). [6]

$$ka = \frac{0.25}{180} \tag{28}$$

Some design recommendations to take into account are; if intense discharges are not foreseen in the designed system, it is recommended to use a value of k_b of 0.05, in turn for sine wave inverters a value of k_c of 0.2 is recommended [6], finally, if the losses of the wiring and the losses of the loads have not been taken into account, it is recommended to use a value of k_v of 0.1 [6].

B. Calculation of the capacity and determination of the accumulator

Equation (29) shows the mathematical expression to calculate the nominal capacity of the accumulator based on the total energy required and the number of days of the installation autonomy.[11]

$$Cu = E * N \tag{29}$$

It is necessary to know the voltage of the bus DC of the installation, In this way, accumulators with this nominal voltage are looked for, therefore, the capacity of the accumulator in (Ah) is calculated with the mathematical expression of equation (30), where V is the nominal voltage of the accumulator.[11]

$$C = \frac{Cu}{V * pd} \tag{30}$$

C. Calculation of the photovoltaic array

Due the total energy that must be supplied by the photovoltaic array and must pass through the charge regulator, it is necessary to assume losses in the regulator, it is recommended to use a factor of 0.9, equation (31) shows the expression to calculate the energy to be supplied by the photovoltaic array.[6]

$$Ep = \frac{E}{0.9} \tag{31}$$

For the calculation of the photovoltaic array, the peak power of the chosen panel is taken into account, therefore, proceed to find the number of panels to supply the necessary energy of the photovoltaic array calculate the number of panels required, where Pp is the peak power per photovoltaic panel and $H.S.P$ is the number of peak solar hours.[6]-[11]

$$Np = \frac{Ep}{Pp * H.S.P} \tag{32}$$

D. Determination of the Regulator

For the determination of the charge regulator, the voltage of the DC bus of the photovoltaic installation is taken into account, in addition, the current produced by the photovoltaic array can not be greater than the maximum current of the regulator, therefore, a minimum security factor of 10% is suggested.

E. Determination of DC-AC inverter

For the determination of the DC-AC voltage inverter, the simultaneous nominal power of the installation is taken into account, because the maximum power of the inverter can not be less than the simultaneous power, in such a way that a safety factor of 20% for the system to be adaptable. In addition, The input DC bus voltage, the output AC voltage and the operating frequency are also taken into account.

V. Results

A virtual learning platform for the design of isolated photovoltaic systems was developed, the development of solar irradiance estimation models, photovoltaic panel modeling and sizing of isolated photovoltaic systems was integrated, the platform was developed as a GUI user interface in matlab, figure (11) shows the developed graphical interface.

Fig. 11. User interface of virtual learning platform developed.

The platform has interactive buttons that allow the user to configure each of the existing elements in an isolated photovoltaic system, so that pressing any of the five buttons represented with images will open a menu for the user to perform the respective configuration of the item then, some of the displayed menus are presented when you click on the interactive buttons.

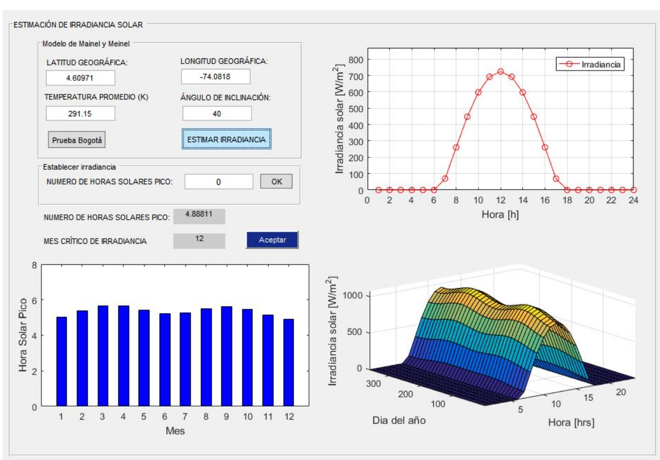

Fig. 12. Configuration menu displayed by pressing the solar irradiance button.

When the user has entered the necessary parameters for the sizing of the isolated photovoltaic installation, taking into account the previously developed models, at the time the user presses the "ACEPTAR" button the platform performs the sizing of the installation, and thus the design characteristics of the photovoltaic system will be obtained.

VI. Conclusion

The creation of new content for learning in the design of isolated photovoltaic systems is of great importance, mainly

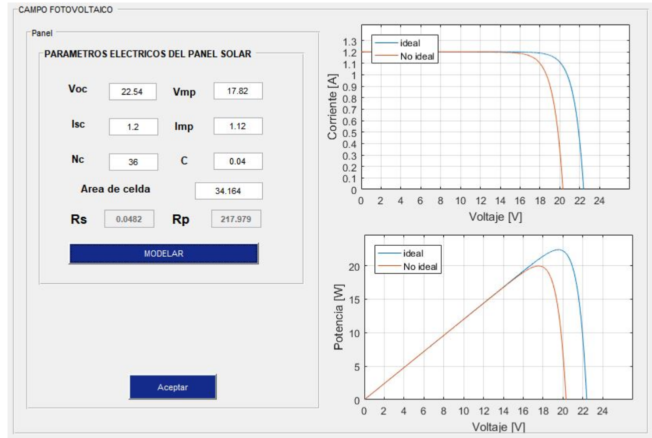

Fig. 13. Configuration menu displayed by pressing the button of the photovoltaic array.

because these photovoltaic systems represent an efficient solution to current energy consumption problems,in such a way that the possibility exists that every day there are more tools that allow engineering students to learn more about this topic, facilitate the expansion of the implementation of this type of solutions and promote the development of new technologies in the area, this research intends to make a contribution to the future knowledge society, interested in the development of this type of solutions.

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