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Modeling of Photovoltaic Cell Using Free Software Application for Training and Design Circuit in Photovoltaic Solar Energy

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Additional information is available at the end of the chapter

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1. Introduction

There are numerous studies that develop the mathematical modeling of photovoltaic cells and verified by software, for example [1] or [2]. The model presented is based on an equivalent circuit implemented in free software. Free software used is Quite Universal Circuit Simulator (*QUCS*), [3]. *QUCS* uses a generic diode for adjust the current and voltage curve (IV curve) at photovoltaic cell. Additionally, you can use equations to define the model of photovoltaic cell and represent the characteristic curves on the same page, [4]. *QUCS* is a multiplatform application that runs on Windows and Linux, this software is available in Linux distributions for electronics. [5].

This model can be used for training in photovoltaic solar energy, using: subcircuits, curves, tables and equations. Further, can be used an attractive presentation to the student with a real representation of PV cell. Also, can be used to test circuit with photovoltaic solar cell as power supply, in applications such as: micropower systems for harvesting energy, stand alone PV system for control battery charge.

The model of PV cell can be used to simulate a PV module, because PV module is an association of cells in series and parallel. The model PV module can use to study mismatch effects due to different electrical characteristics of PV cells and the use of pass diode to reduce loss due to partial shadows. Then, can be use PV module study PV grid connection and energy production prediction.

2. Equivalent circuit of photovoltaic cell

The equivalent circuit of an ideal cell is formed by a current source in parallel with a diode (figure 1a). There are several circuits that include resistors for real effects of a photovoltaic cell, for example, figure 1b includes a resistor in series, [2], figure 1c includes parallel and series resistance, [1] and [6]. Other models include two diodes as in figure 1d, [7] and [8].

The circuit of figure 1c is the more commonly used, although in several simulations simplifies the parallel resistance value with a high value, using the series resistance to include effect of fill factor, gets a similar circuit of figure 1d and used R_p to avoid problem with simulation. Then, this circuit has a simple and accurate model to simulate a photovoltaic cell.

The problem is the parameter values of circuit components. Therefore, in Section 4 are calculated parameters using data from the photovoltaic cell indicated in datasheets, for equivalent circuit on figure 1c.

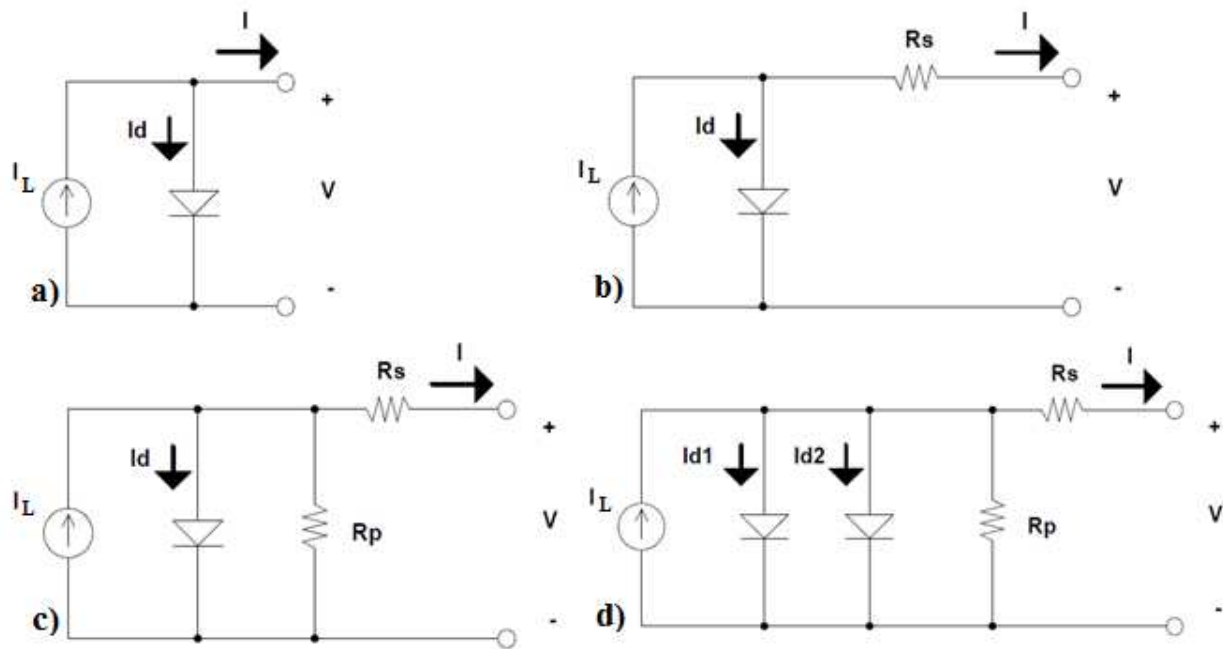


Figure 1. Equivalent circuits of photovoltaic cell

3. Current-Voltage (I-V) Curve

Calculate equivalent circuit parameters need to know the I - V curve. In the I - V curve (figure 2) can extract the electrical characteristics of the photovoltaic cell in standard conditions of measurement (SCM): I_{SC} (short circuit current) is maximum intensity that can generate a photovoltaic cell or module when measuring the current if performing a short circuit (output voltage of 0 volts), V_{OC} (open circuit voltage) is maximum voltage that can generate a

photovoltaic cell or module when measuring the voltage if not flowing current (current of 0 amps), P_{MAX} (Maximum power) is maximum power that can generate a photovoltaic cell or module and it's the product of maximum voltage and current, V_{MAX} (Maximum Voltage) is the voltage at maximum power (around 80% of open circuit voltage) and I_{MAX} (Maximum Current) is the current at maximum power.

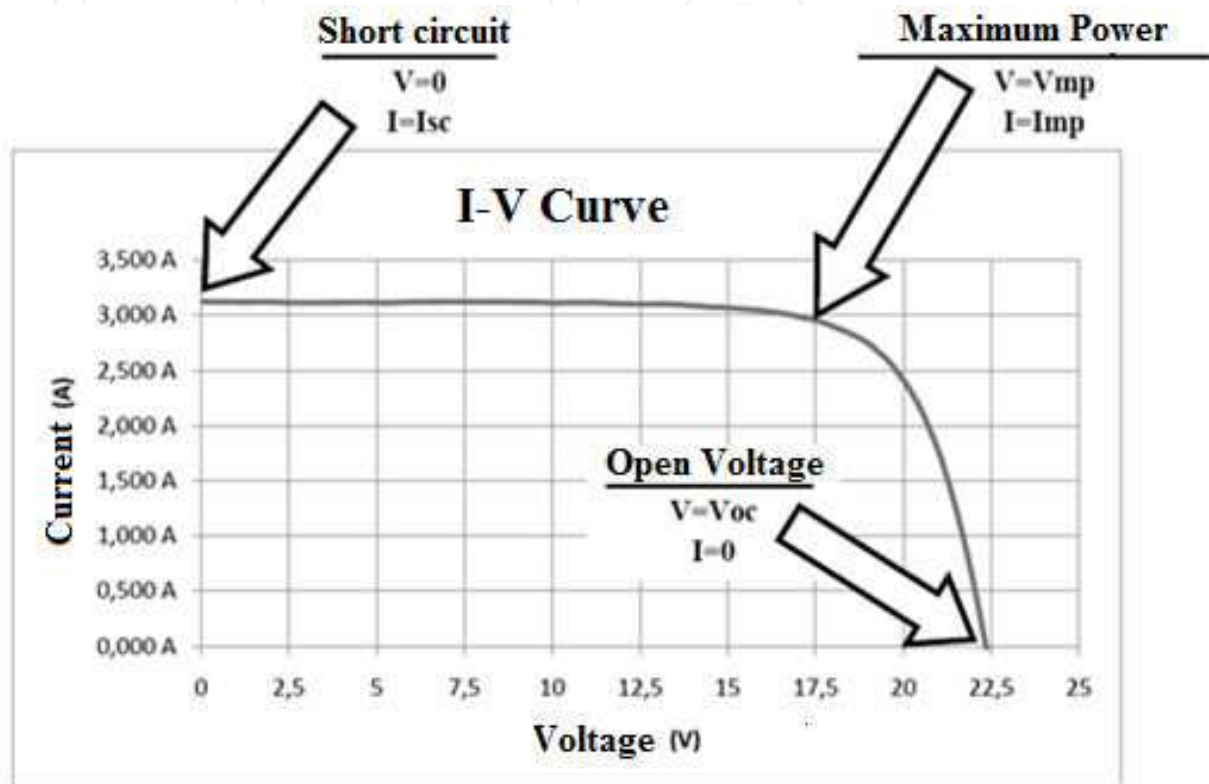


Figure 2. IV Curve of photovoltaic module

Compare the figure 2 with equivalent circuit (figure 1b), value of I_{SC} related with I_L and value of V_{OC} related with voltage and current diode (I_d). Then diode includes effects of exponential of I-V curve. Finally R_s adjusts value of P_{MAX} . All parameter information is extract to datasheets, and SCM are: $25^{\circ}C$ for cell temperature (T_C), $1000 W/m^2$ for irradiance (G), 1,5 for spectrum solar and $3m/s$ for wind speed.

4. Modeling equations of photovoltaic cell

Reference to the circuit of figure 1c, then show all equations needed to obtain all the parameters that define the model in standard conditions of measurement (SCM). In equation 1 shows the intensity value generated by the photovoltaic cell, [9]: I is output current of photovoltaic cell, V is output voltage of photovoltaic cell, I_L is the photogenerated current, I_0 is the saturation current of diode, R_s is series resistance due to the junction between the semi-

conductor and the metal contacts (interconnects), R_p is parallel resistance due to non-linearity of union PN , m is ideal factor of diode and Vt is thermovoltage shown in equation 2 (where: k is the Boltzmann constant, q is the electron charge and T is temperature in degree Kelvin).

$$I = I_L - I_0 \left[e^{\left(\frac{V + I \cdot R_s}{m \cdot Vt} \right)} - 1 \right] - \left[\frac{V + I \cdot R_s}{R_p} \right] \quad (1)$$

$$Vt = \frac{k \cdot T}{q} \quad (2)$$

Equation 1 can simplify the last term with a high value of R_p (for example 100kΩ). Furthermore, I_L is considered equal to the short circuit current in SCM (I_{SC_SCM}), [1]. Then we obtain the equation 3 at SCM.

$$I = I_{SC_SCM} - I_{0_SCM} \left[e^{\left(\frac{V + I \cdot R_s}{m \cdot Vt} \right)} - 1 \right] \quad (3)$$

The value of I_0 is obtained for SMC (I_{0_SMC}) using equation 4, based on [10], considering open voltage circuit in SCM (V_{OC_SCM}) and cell temperature in SCM (T_{C_SCM}).

$$I_{0_SCM} = \frac{I_{SC_SCM}}{\left(e^{\left(\frac{q \cdot V_{OC_SCM}}{m \cdot k \cdot T_{C_SCM}} \right)} - 1 \right)} \quad (4)$$

There is an empirical relationship between the value of V_{OC_SCM} and I_{SC_SCM} with R_s , [9]. Then, needs calculate fill factor of ideal device (FF_0) at equation 5, using parameter voc of equation 6, and calculate R_s using equation 8. The fill factor (FF) of photovoltaic cell shows at equation 7. This approach only use when R_p is high, therefore fill factor depends of R_s value.

$$FF_0 = \frac{voc - \ln(voc + 0,72)}{voc + 1} \quad (5)$$

$$voc = \frac{V_{OC_SCM}}{Vt} \quad (6)$$

$$FF = \frac{V_{MAX_SCM} \cdot I_{MAX_SCM}}{I_{SC_SCM} \cdot V_{OC_SCM}} \quad (7)$$

$$R_S = \left(1 - \frac{FF}{FF_0}\right) \left(\frac{V_{OC_SMC}}{I_{SC_SMC}}\right) \tag{8}$$

Changes in temperature affect the values of I_{SC} , v_{OC} and P_{MAX} , when cell temperature increase the V_{OC} decrease, same with the P_{MAX} , and when irradiation increase the I_{SC} also increase. The datasheet used parameters of *table 1*, establishing the relationship between units (voltage, current and power) and temperature. Temperature can be expressed on degree Celsius or Kelvin, depends of manufacturer.

| Parameters | Affect to... | Units |
|------------|--------------|---------------|
| β | V_{OC} | mV/°C or %/°C |
| α | I_{SC} | mA/°C or %/°C |
| δ | P_{MAX} | mW/°C or %/°C |

Table 1. Parameters that include temperature variations on photovoltaic cell

Also, changes in irradiance (G) affect the value of I_{SC} and V_{OC} . Therefore, using approximation of Luque-Sala and Duffie & Beckman, [10], we obtain the equation 9 for I_L . Besides empirical tests simulation to study the effects of temperature on I_0 , used for get equation 10, based on the approximation Duffie&Beckman.

$$I_L = I_{SC_SCM} \cdot \frac{G}{G_{SCM}} \cdot (1 + \alpha \cdot (T_C - T_{C_SCM})) \tag{9}$$

$$I_0 = \frac{I_{SC_SCM} \cdot \frac{G}{G_{SCM}} \cdot (1 + \alpha \cdot (T_C - T_{C_SCM}))}{\left(e^{\left(\frac{q(V_{OC_SCM} + \beta \cdot (T_C - T_{C_SCM}))}{m \cdot k \cdot T_{C_SCM}} \right) - 1} \right)} \tag{10}$$

The relationship between temperature ambient (T_A) and cell (T_C), can used equations 11 and 12, [11]. It is based on normal operating temperature cell (T_{NOC}), is defined as the average temperature of equilibrium within a photovoltaic cell to an irradiance of $800W/m^2$ and an outside temperature of $20^{\circ}C$. Use this approximation is interesting because there are statistics of temperature ambient on geographic situation but temperature cell depends to PV cell and module.

$$T_C - T_A = C \cdot G \Rightarrow T_C = C \cdot G + T_A \tag{11}$$

$$C = \frac{T_{NOC} - 20}{800 \text{ W / m}^2} \tag{12}$$

Figure 3 shows the simulation window with all the necessary equations and the visualization of results using *QUCS*. Photovoltaic cell simulated in figure 3 is *C3ISF200SB* of Isofoton, [12]. *QUCS* allows represented on the same page a circuit and results of simulation, for example in figure 3 included: *IV Curve*, output power curve, output current curve, output voltage curve and a table with numerical results. For functions used in *QUCS* see on [13], in figure 3 used following equations: eqn1 for parameters of photovoltaic cell, eqn2 for change temperature ambient to cell temperature, eqn3 for parameters adjust to equivalent circuit and eqn4 to calculate variables to represented results on graphical depends to output measurement of equivalent circuit.

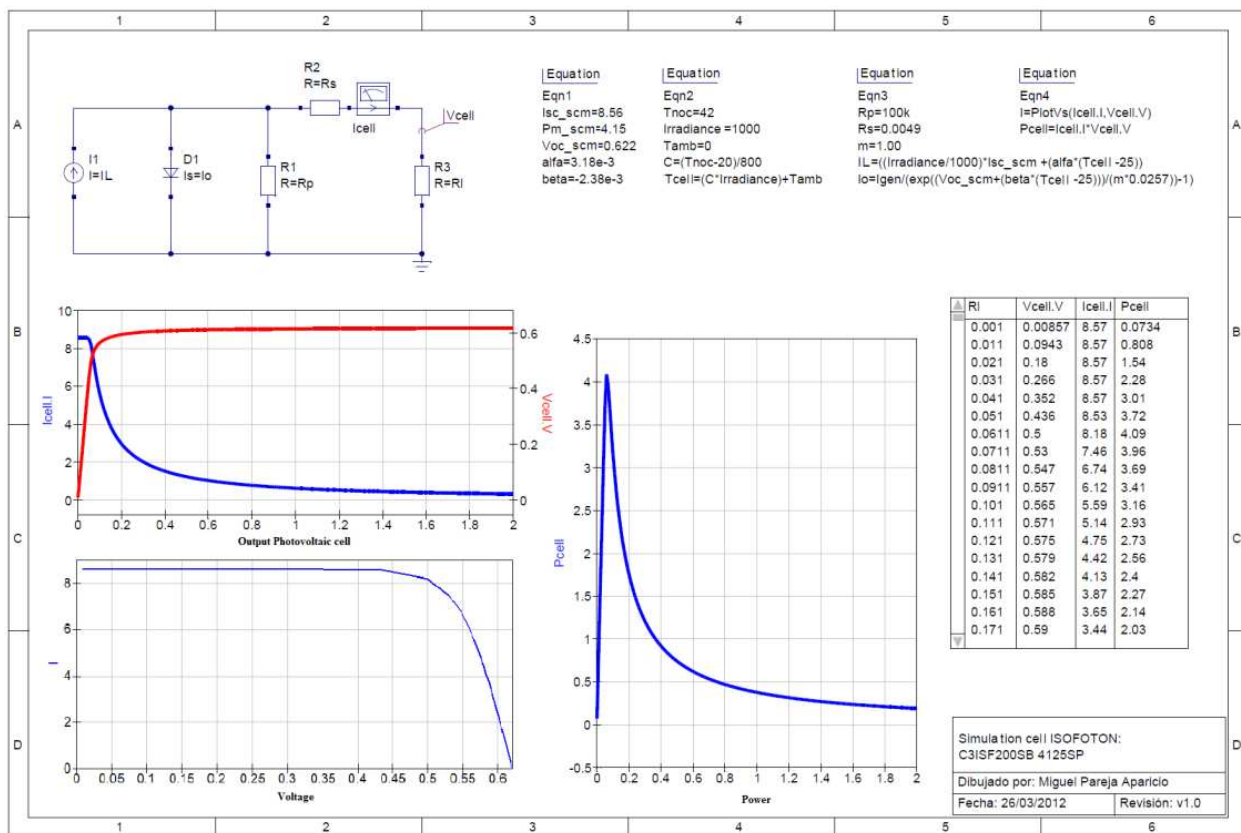


Figure 3. Final result of the simulation Qucs photovoltaic cell

The equivalent circuit is formed by following components: current source (*dc current source* on *source* library), diode (*diode* on *non linear components* library) and resistors (*resistor* on *lumped components* library). The value of current source is calculate on variable *IL* (current generate) on equ3 based on equation 9, the value of current saturation on diode is calculate on variable *I0* on equ3 based on equation 10, the value of resistor series and parallel its calculate manually and indicate on eqn3. The model of diode simulation includes ohmic series

resistance (R_s) and zero bias junction capacitance (C_{j0}), to adjust to PV cell model must change to 0Ω and $0F$ respectively.

Current measurement of PV cell model used current probe (I_{cell}) on probe library, for voltage measurement used a wire label (V_{cell}) to get voltage on node. Power generate (P_{cell}) of PV cell is calculated using equ4 as the product of current ($I_{cell}.I$) and voltage ($V_{cell}.V$) measurement. To represent a IV curve is needs to get a variable I using function $PlotVs()$ on equ4. The results on simulation show on graphical ($Cartesian$ on diagrams library) and table ($Tabular$ on diagrams library).

In QUCS is a used component of library simulations for configuring simulation, for example to get IV curve need components: *dc simulation* and *parameter sweep* (figure 4). The configuration of simulation that show on figure 4, changes value of variable Rl from $0,01\Omega$ to 10Ω , variable Rl is used to change value of resistor $R3$ (figure 3).

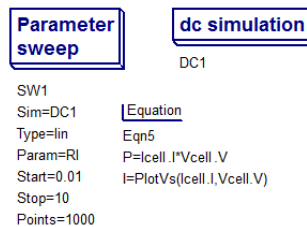


Figure 4. Simulation configuration

Also, if changes value of *Irradiance* variable on eqn2 (figure 3), changes the solar condition and current generate of PV cell. For example on figure 5 shows IV curve to different values of solar irradiance at the same value of cell temperature ($25^{\circ}C$): $1000W/m^2$ (G_{1000}), $750W/m^2$ (G_{750}) and $500W/m^2$ (G_{500}).

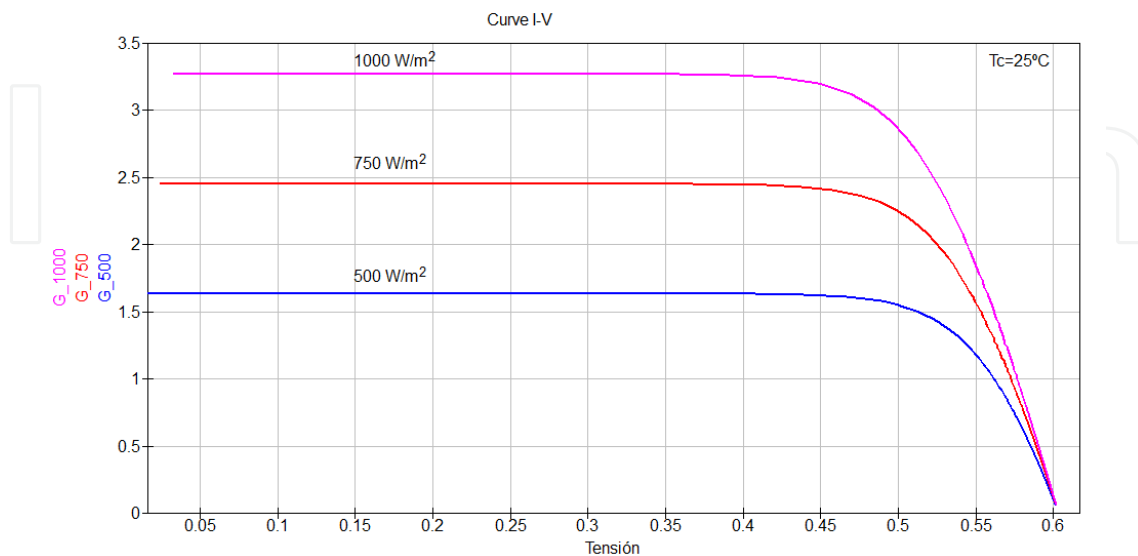


Figure 5. IV Curve for different values of irradiation

Further, if changes value T_{amb} variable on eqn2 (figure3), change ambient temperature and therefore the cell temperature condition based on equations 10 and 11. For example on figure 6 shows IV curve to different values of cell temperature at the same value of irradiance (1000W/m^2): 50°C (T_{50}), 25°C (T_{25}) and 0°C (T_0). Then, combining the two variables can adjust weather conditions.

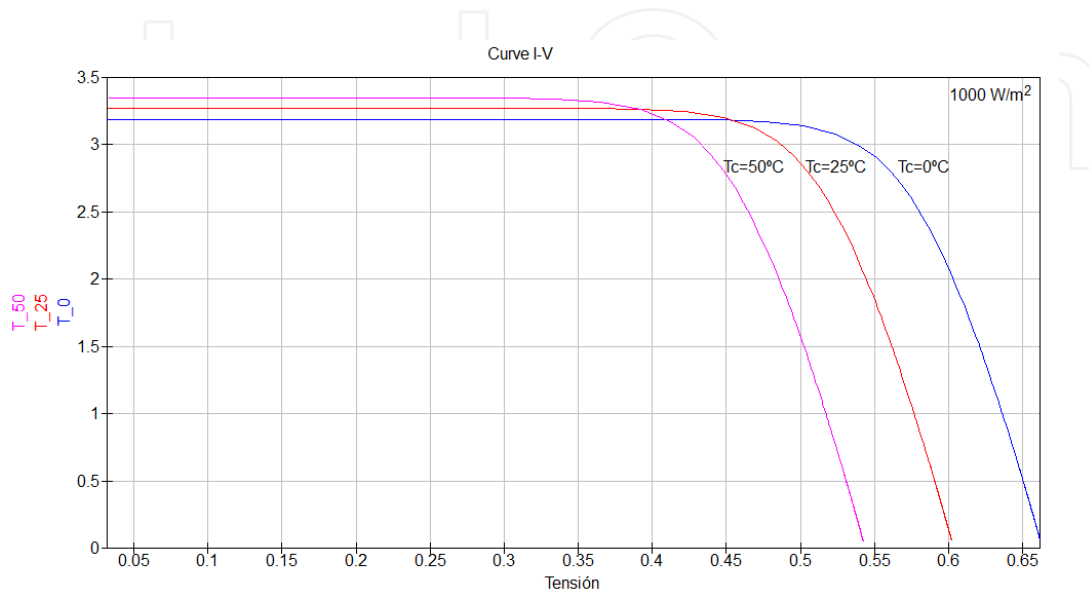


Figure 6. IV Curve for different values of cell temperature

5. Educational application

The model shown in Section 4 can be used for the formation of PV system. In particular, using subcircuit for an attractive presentation for the student, [10]. In addition to evaluating the effects of: association series and parallel, potential losses, weather conditions, non-ideality of photovoltaic cells and effect of partial shadow. Figure 7 shows steps for modelling by subcircuits of a PV cell and module, first represented a equivalent circuit and include parameters gets of datasheet, second create a symbol to represented a PV cell, third the subcircuit used to external variables for irradiance (G) and cell temperature (T_c), fourth associate cells to build a PV module, and finally create a symbol to represented a PV module.

To create a subcircuit needs connection for output PV cell, after to select all component of equivalent circuit (figure 3) the output connection of PV cell (in series with R_s for positive connection) connects used insert port (figure 8). Once finish equivalent circuit can be edit representation of subcircuit pressing $F9$, for edit representation can be used painting library, [13].

Model for PV module can be create using PV cell subcircuit and connection in series and parallel, for example a PV module for 12V nominal voltage can be formed by 36 PV cells connects in series, in figure 9 shows connections of PV module with 2 pass diodes and external ports connections (positive for $P1$ and negative for $P2$). Representation used for PV cell

and module shows on figure 7, after can be used subcircuit of PV cell or module on different practices.

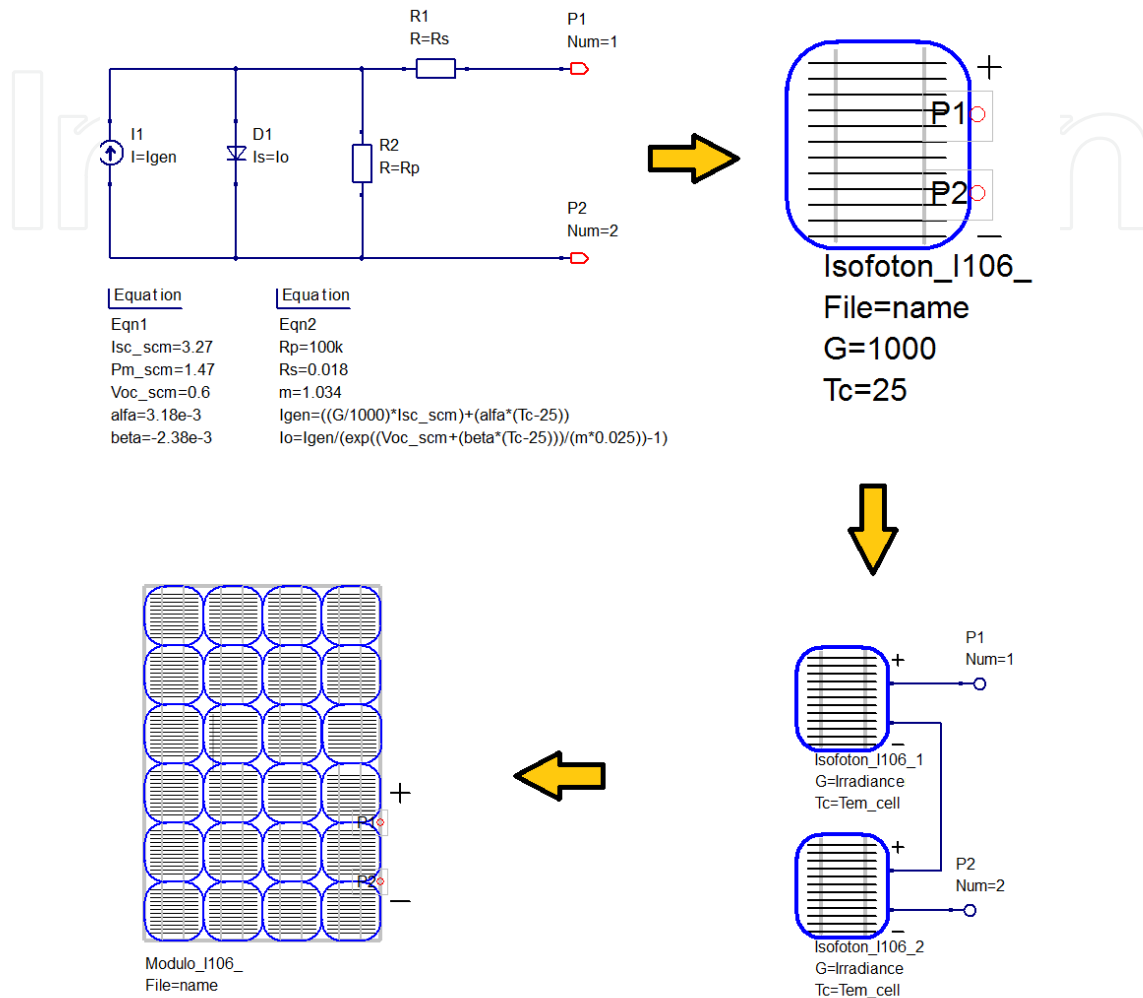


Figure 7. Steps modeling subcircuit

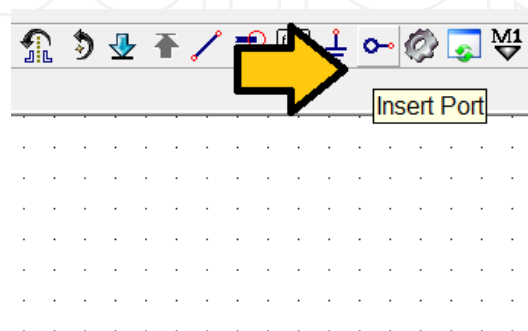


Figure 8. Insert connection to subcircuit

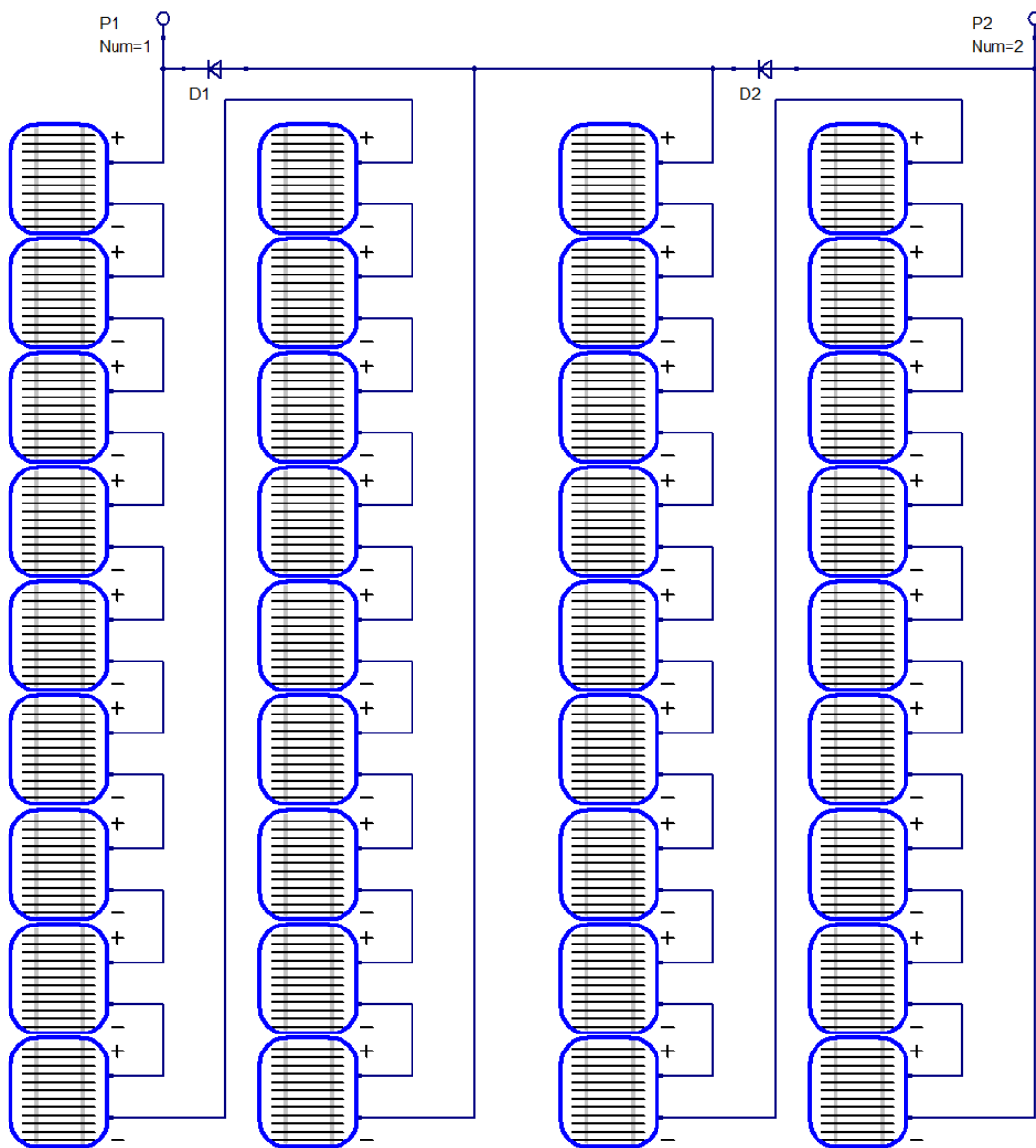


Figure 9. Model of PV module based on subcircuit PV cell

Then, student works directly with subcircuits independently of equivalent circuit model, because student can be used the same representation for different PV cells. The material used will consist of a compressed file, which contains a project *QUCS* (for example *practices_solar_prj.rar*), this file contains a number of files to be need for practical work (files used on *QUCS* use extension *sch* and a project contains all files on *QUCS* directory). The practices developed show in table 2, for study for photovoltaic training on stage generation, after can be complete with model of all components on photovoltaic system (battery, regulator or inverter) and can be used on renewable energy training. Practices on table 2 can be complete with a previous work: select values for equivalent circuit and introduction of *QUCS*.

| Pratiques | Descriptions |
|--|---|
| Obtaining IV Curve | This practice consists in the practical realization of obtaining an IV curve, connecting a resistor to photovoltaic cell, how it is done in laboratory, the student modify the values of resistance load and take measurements of voltage and current generate by photovoltaic cell. |
| Connecting PV cells | In this practice the student performed tests: vacuum, short circuit and load. Also, performed measurements with various connections: serial, parallel and mixed. This practice can be extent compare with a real measurement. |
| Effect of irradiance and temperature on PV cell | This practice is to see the effects on curve IV by changing irradiance and temperature. Simulation can be used by scanning parameter to be directly represents the curve IV and only change the values of irradiance and cell temperature. Can use the same practice of PV module. |
| Partial and total shadowing effect | This practice associated series and parallel solar cells and see the effects for partial shadowing about current and voltage generate by PV cell. After can repeat practice for total shadowing effect. After, the student can extract conclusion about the shadow problem on PV cell. |
| Using bypass diodes and losses from partial shading on PV module | This practice is to see the utility about bypass diodes in the manufacturing on PV module. Must create two models about PV module, one with diode and other without diode. After the student compare results. |
| Connection blocking diodes | This practice is to see the effect and necessity of blocking diodes. Must connect a circuit PV cell and battery between blocking diode, after remove blocking diode and compare results. |
| Mismatch losses in PV Module | This practice is to see effects to use different PV cells to manufacturing PV module, must create two models about PV module, one with ideal PV cells and other with different values of short current. After the student compare results. |
| Voltage drop in PV cells connection | This practice is to see the losses associated with wiring to connect photovoltaic devices. Can show the effect of using one or another section, and the length between the module and circuit regulator. It creates a new subcircuit corresponding to the calculation of the resistance of the wiring with copper conductors. |

Table 2. Examples of practical using modeling and GPL application

Figure 10 shows several examples for use subcircuits model for educational, and are directly applicable to any practices described. As parameters such as temperature (variable T_c in $^{\circ}\text{C}$) and irradiance (variable G in W/m^2) cell, see the effects of partial shading on the association of cells and the use of bypass diodes in the manufacture of photovoltaic modules, and the measurement of short circuit current.

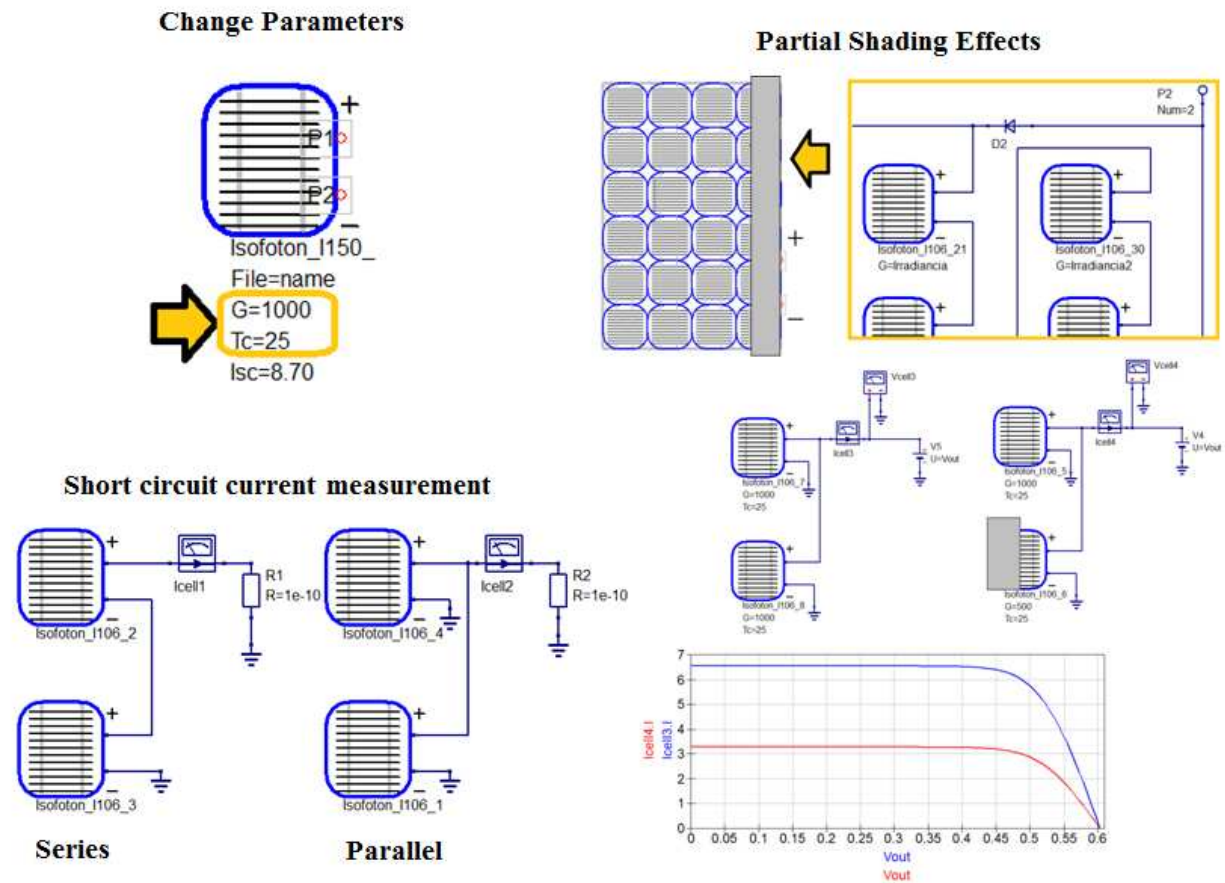


Figure 10. Examples for subcircuit model

6. Design circuit application

The availability of the model described in section 4, allows design circuits power management when energy source are PV cells or modules. For example, in power supply of sensor nodes, [14], to design efficient harvesting energy control, because *QUCS* dispose different electronic components for simulation by means of changing parameters to adjust to real component. *QUCS* has generic devices electronic *on non lineal* library and adjust parameter on properties menu to adjust real component, or use component library (selected on *Tools* menu or *Ctrl+5*) for used component with properties adjusted to real device (figure 11).

Also, working in selection PV cells to power supplies performing a comparative commercial device to adapted for applications at climatologic conditions of system localization, for example to study PV cell to weather station [15] or irrigation actuator [16]. Further, to test regulator circuit using in stand-alone PV system and control circuit to obtain maximum power point tracker, [17].

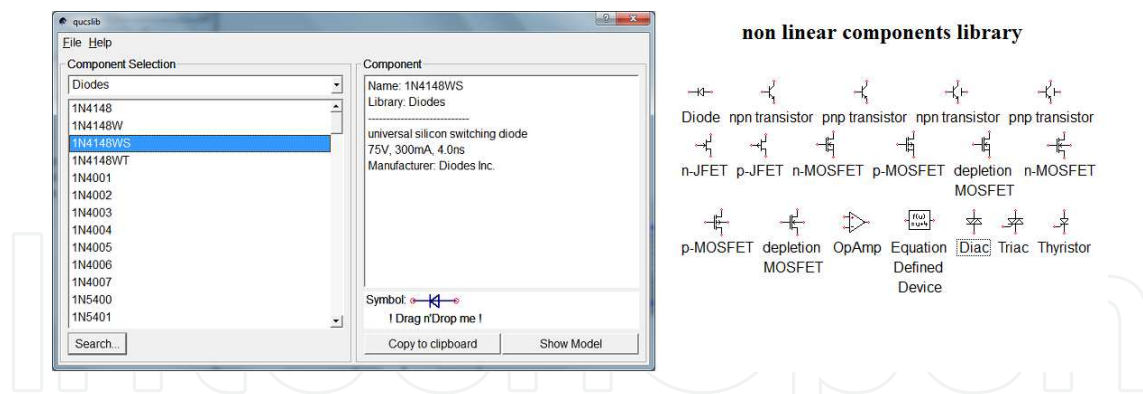


Figure 11. Component library for QUCS

Other application, its predict power generation from PV cells and modules, using a variable parameter for irradiance and ambient temperature. In addition, can be include partial shadow for same object (for example: tree or building) in PV grid connection or stand-alone.

For example, in figure 12a shows curve of irradiation variation of irradiance (G) around day. Value used can be extracted to Photovoltaic Geographical Information Systems (*PVGIS*) [18] mean values per moths. After connection a constant resistor to photovoltaic cell and get outputs: power, voltage and current (figure 12b). After can complete modifying load connected. Also, can included ambient temperature around day using variable T_c . The PV cell characteristics used on figure 12 is: $3,27A$ for I_{SC} and $0,6V$ for V_{OC} on SCM.

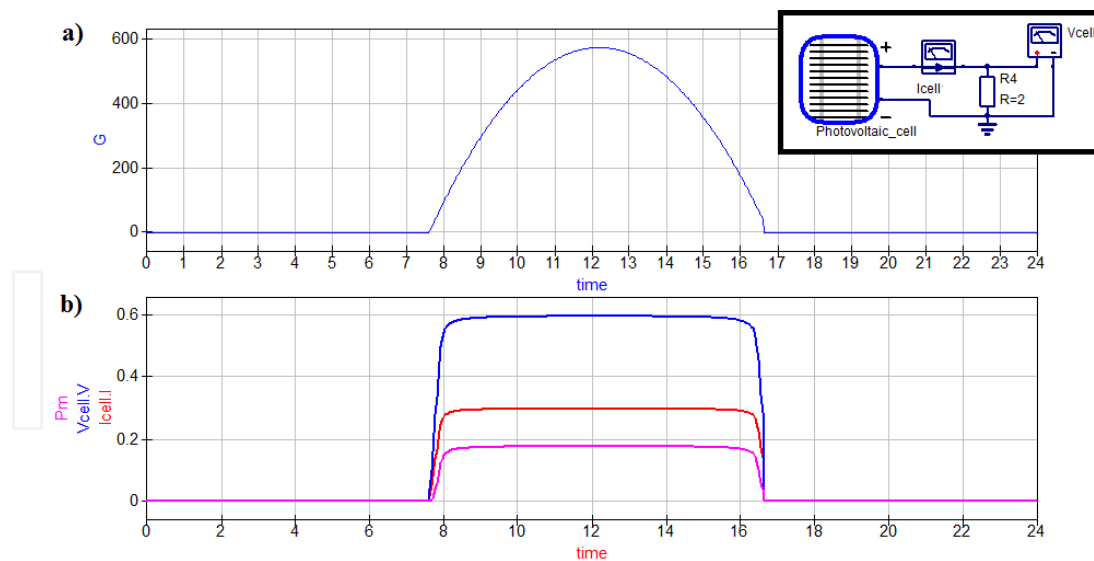


Figure 12. Variation Irradiance (G) around day with a constant load

Other example shows on figure 13 to use PV cell model for simulate a circuit control to obtain the maximum power point to PV cell. In figure 13a show a subcircuit connect to dc converter, and figure 13b show output voltage and control signal, the output is controlled modify duty cycle, then the duty cycle decrease when the output voltage arrive to maximum power voltage

and increase when output voltage away from maximum power voltage. The PV cell characteristics used on figure 13 is: $150mA$ for I_{SC} and $0,62V$ for V_{OC} on SCM.

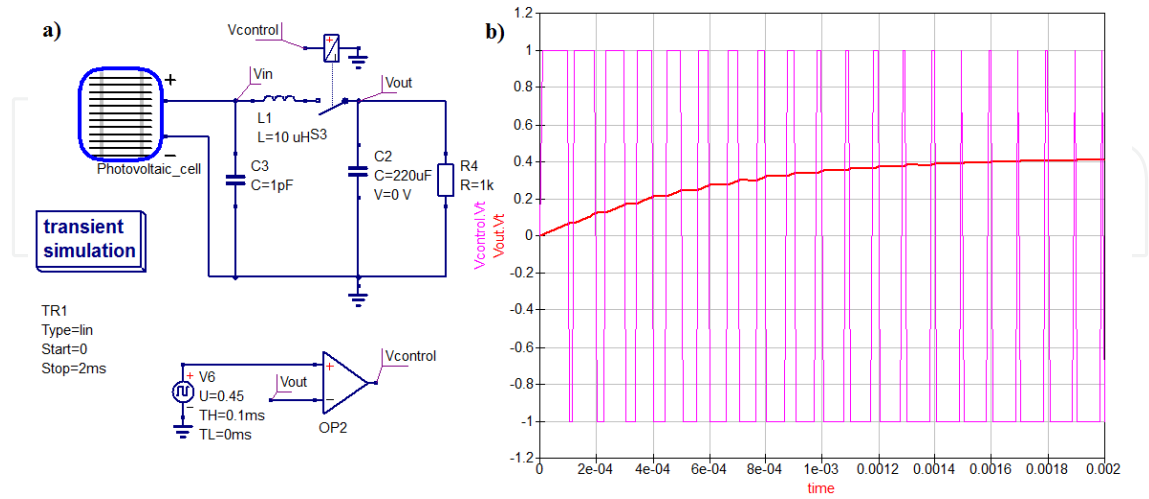


Figure 13. Used model to study circuit control of PV cell

Also, model PV cell can be used to study number of PV cells need to supply energy to the system, for example figure 14 show 16 PV cells for simple circuit supply of 5V source formed by: block diode ($D1$) and a regulator circuit ($LM140$). Then, change number of PV cells and configure climatic conditions (Irradiance and temperature) can see if has enough or need more PV cells, too if has more PV cells that is need. On figure 14 show: output voltage ($V_{load.V}$), output current ($I_{load.I}$) and voltage cells ($V_{cells.V}$), to different values of irradiation, therefore study irradiance needs to obtain 5V on load resistor. Conclusions on figure 14 is than needs 16 PV cells on series and irradiance value around $500-550 W/m^2$ or higher to obtain 5V and $0,5A$ output (on load). The PV cell characteristics used on figure 14 is: $1A$ for I_{SC} and $0,6V$ for V_{OC} on SCM.

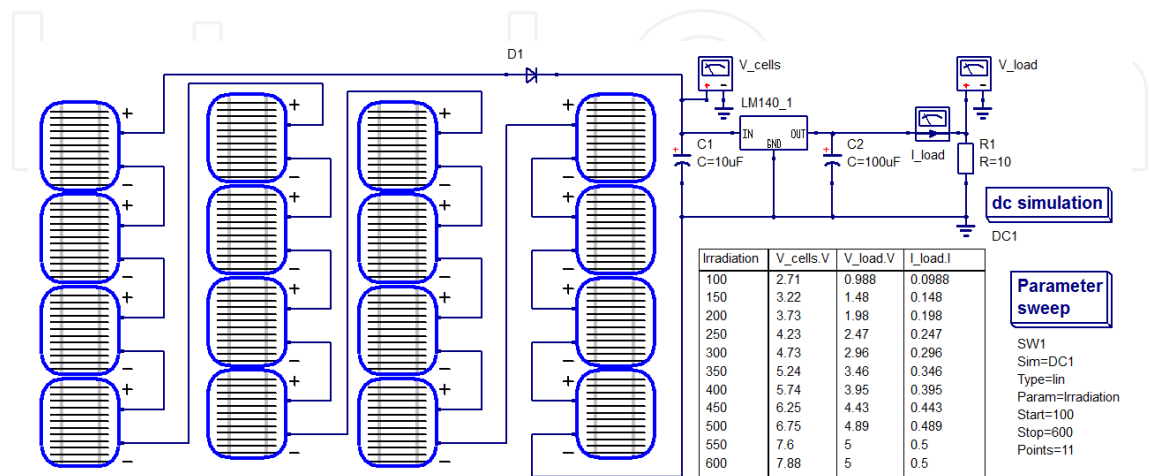


Figure 14. Study irradiation for simple regulator circuit

7. PV cells of module

Some case has available information of PV module on SCM to emulate PV module (figure 15), then needs calculate values for PV cells: division between module open voltage (V_{OC_MODULE}) and number PV cells series (N_{CELLS_SERIES}) to obtain open voltage of cell (V_{OC_CELL}), division between module current short (I_{SC_MODULE}) and number of strings cells connection ($N_{CELLS_STRINGS}$) to obtain current short of cell (I_{SC_CELL}), and repeat by module maximum values of voltage (V_{MAX_MODULE}) and current (I_{MAX_MODULE}) to obtain maximum values of voltage (V_{MAX_CELL}) and current (I_{MAX_CELL}) of cell; equations 13 to 16 respectively.

$$V_{OC_CELL} = \frac{V_{OC_MODULE}}{N_{CELLS_SERIES}} \quad (13)$$

$$I_{SC_CELL} = \frac{I_{SC_MODULE}}{N_{CELLS_STRINGS}} \quad (14)$$

$$V_{MAX_CELL} = \frac{V_{MAX_MODULE}}{N_{CELLS_SERIES}} \quad (15)$$

$$I_{MAX_CELL} = \frac{I_{MAX_MODULE}}{N_{CELLS_STRINGS}} \quad (16)$$

Values obtained on equations 13 and 14 used to obtain: v_{oc} , R_s , I_L , and I_0 , on equations: 6, 8, 9 and 10. The values obtained on equations 13 to 16 used to obtain FF on equation 7. This approximation is based on a PV module is union of PV cells connected in series and parallel strings. Model of PV module included connections cells loss inside module.

On figure 15 shows an example for PV module based on subcircuit on PV cells, characteristic of PV module on SCM is: 150W to P_{MAX} , 22,6V to V_{OC} , 8,7A to I_{SC} , 18,5V to V_{MAX} and 8,12A for I_{MAX} . The module used in figure 15 used 36 cells connected in series on a string.

Advantage to use model PV cells on model PV module is that change parameter of irradiation and temperature by cell (figure 7), and so study effects: partial shading, number pass diode, different connections of pass diode, hot cells, etc. Also can be study effect on mismatch on module used PV cell with different electrical characteristics. For example on figure 16 show effects of partial shading on module using 2 diodes pass (figure 9): figure 16a without shadow, figure 16b shadow affect to same number of cell connects on parallel by diode and figure 16c shadow affect only to cells connects on parallel with 1 diode pass.

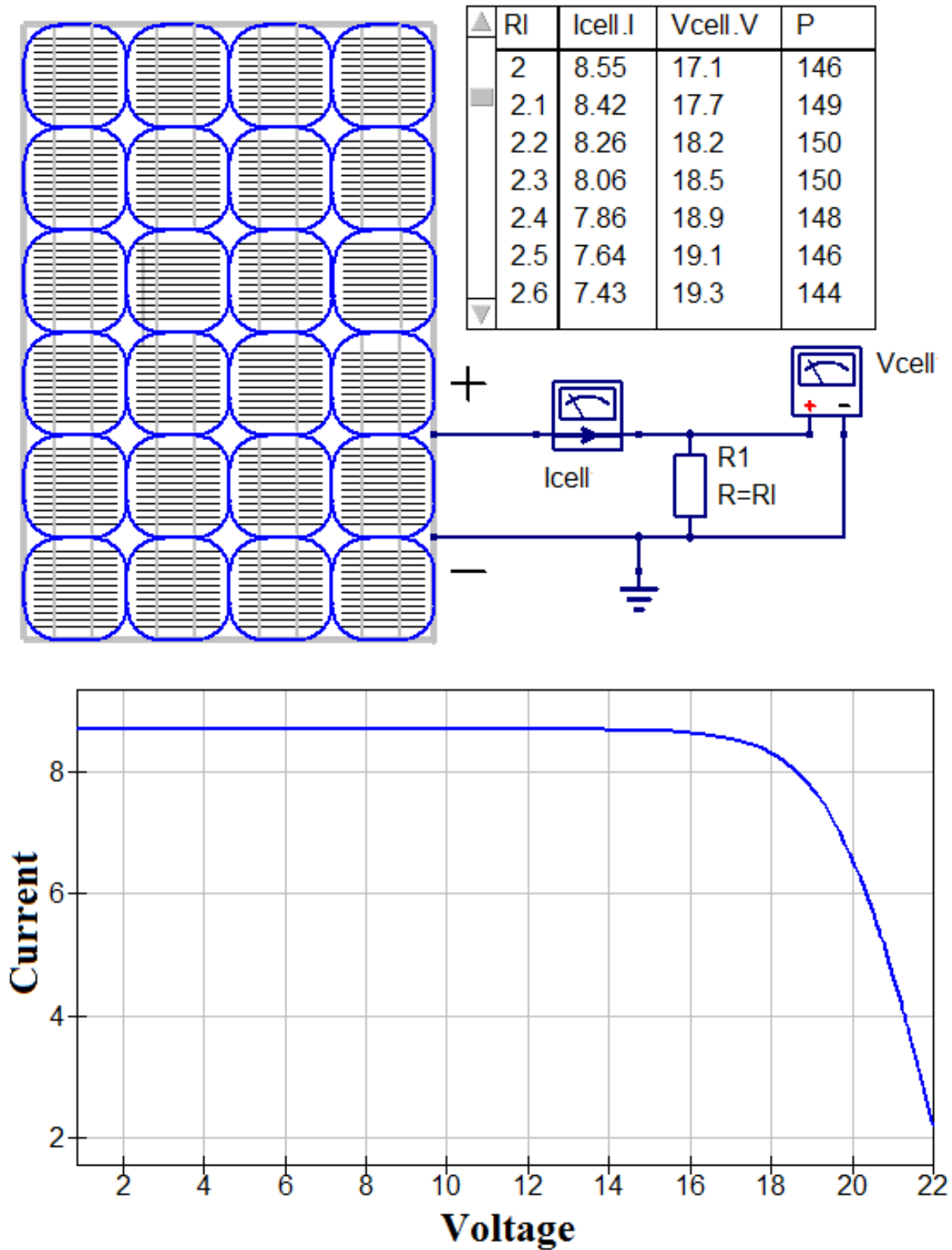


Figure 15. Simulate PV module based on PV cell model

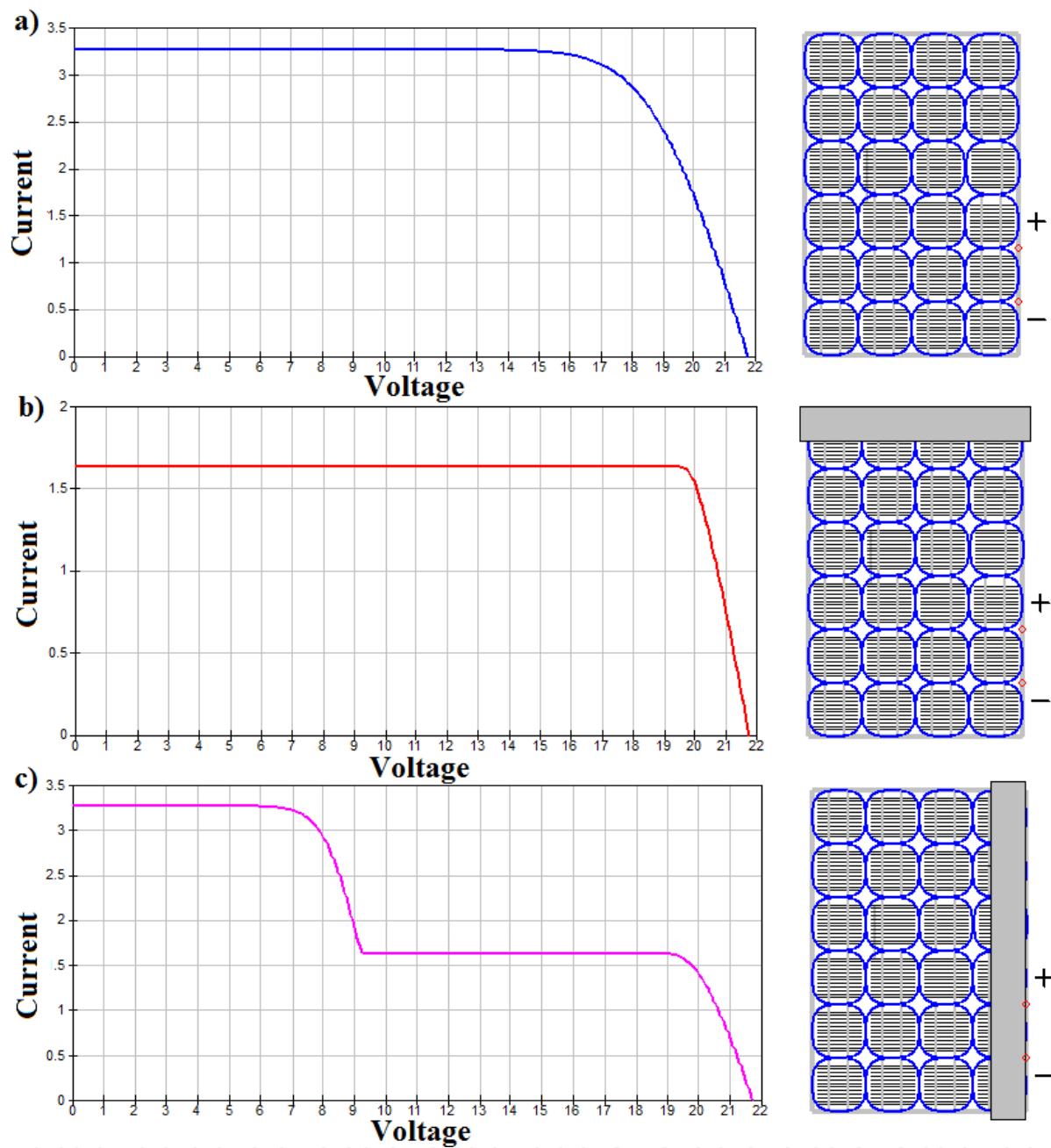


Figure 16. Partial shading on PV module use model PV cell.

8. Conclusion

In this chapter show a equivalent circuit for simulate PV Cell, then show equation to obtain all parameters to circuit based on PV cell datasheet. To check model is implemented on free software and compare results of output PV Cell model represented on IV Curve and output measurements with datasheet information. The software application selected is QUCS be-

cause can be include equations to calculate circuit parameters and a real representation of subcircuit.

The PV cell model can modelled any PV cell using datasheet information, also the model include variations of temperature and irradiance for output PV cell. Therefore used PV cell model connected in series and parallel can modelled a PV module. In section 4 shows all necessary equations to obtain parameters of circuit to PV cell model and section 7 shows process and equations to obtain PV module cell.

Using *QUCS* to model a PV cell allows subcircuit and a real representation to a attractive presentation for teaching. In section 5 show examples of practices used on formation, further can be used on: courses of photovoltaic, online formation or distance learning, because only need download *QUCS* application, and is a good complement to a previous works on laboratory or concepts review for theory. Advantage to used *QUCS* is that allow several PV cells with a few mouse click, also does not needs buy additional PV cells to used on laboratory because can be modelled the PV cell available on laboratory. Further, is not a problem the availability material on laboratory, because the material of PV system can be expensive, then is best provide a good photovoltaic devices that a devices for all student in a class.

Other application for model of PV cell or module is used to design of supply circuits, for example in a network sensors node, to design power control. In section 6 shows examples to used electronic devices available on *QUCS* library to control output PV cell, with the advantage to change weather condition to study operation circuit and is surer for designer and electronic devices. Also, can emulate various conditions to which the PV cell work (irradiance and temperature), which can reduce design time, detecting errors. Further, the availability of weather conditions that need for tested circuit.

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