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1 INTRODUCTION

It is known the great value that is reaching the renewable energy in the present times. The aim of the Kyoto Protocol is to reduce CO_2 emissions. Taking care of the environment is an issue that belongs to all mankind. A lot of measures are taken by the governments in Europe to reach a *20 % energy production that comes from renewable* in the next years (before 2020). It's a good approach if we consider that Europe has not autonomy concerning energy needs. Therefore two great benefits are going to be reached: energy independence and reduction in the risk of the future escalation of energy costs. Photovoltaic energy will create an increasing contribution to electrical power supply all over the world. State of the art photovoltaic inverters normally use the specific radiation dependent V-I characteristic of photovoltaic panels to attain a high efficiency.

The *cost* of a PV generation system *is associated* to the total running *efficiency* of the system. The smaller the payback time , the bigger is the efficiency reached. Therefore, in order to increase the output efficiency of a grid-connected photovoltaic system it is important to have an efficient Maximum Power Point Tracker (MPPT). The total efficiency is defined as: **[1]**

$$\eta_{total} = \eta_{PV} \cdot \eta_{MPP_{track}} \cdot \eta_{inverter} \qquad \textbf{[1.1]}$$

η_{total} = Total efficiency of the PV system

η_{PV} = Efficiency of the photovoltaic array.

$\eta_{inverter}$ = Efficiency of the PV inverter.

$\eta_{MPP_{track}}$ = Efficiency of the MPPT algorithm

The *MPP of a PV* system *depends on* the solar *irradiation and* array *temperature* and therefore it is necessary *to track the MPP* constantly. We will keep our attention in this last point.

This work begins explaining some basic concepts about PV project, a summarized knowledge about solar panels and all equations which will be used to carry out all simulations are introduced.

Many MPPT algorithms have been proposed in researching. Perturb and Observe algorithm, Incremental Conductance algorithm and Constant Voltage algorithms are supposed to be the best of them by now. They are analysed in different irradiation conditions without one clear organization. *The simulation process or structure is clearly represented here to realise all steps that are going on in other separated section.*

The efficiencies provided are given sometimes in high irradiation and sometimes in low irradiation. And then, the question could come: Does high irradiation always high temperatures? Under a clear day of winter in the south of Europe not so high temperatures are expected. Because of this, slower temperature movements (not less important) are not implemented in depth. Therefore the simulation process has not structure connected with the reality. Therefore more realistic combinations should be done. *The weather conditions (changes in irradiation and temperature) cases are explained one by one. This section is very important because the algorithms do not behave in the same way in all different cases. Therefore it was thought over carefully about the conditions that were chosen. All this different cases are called with a key-letter to catch the information.*

Advantages and disadvantages are difficult to extract also because of the disorganization named. *This work will analyse in depth the algorithms Perturb and Observe, Incremental Conductance and Constant Voltage with some changes proposed which make them different (for example an approximation of the Incremental Conductance is mixed with the Constant Voltage getting a more robust structure). Also it will be analysed other new one, the Newton Raphson algorithm based in numerical method of Newton Raphson (fast convergence and goodness to gain non-linear equation make one of the best).*

Therefore, the goal is to become aware of their behaviours in different weather conditions and extract the advantages and disadvantages as a summarize. After it, in all weather conditions named before, an efficiency analysis of the MPP tracking will be done.

The most important criteria taken into account to go ahead in one project is the economical one. Economic assessment must always considered in Engineering decisions. This point motivated to make the last section. Therefore, at the end *an economic analysis in connection with efficiency is carried out. This analysis will consider how the power efficiency of the solar panel influences in the power production costs Thus, how much the costs are reduced in a PV project with tracker implementation will be known*.

This project hopes to provide some information else to get more efficiency in photovoltaic solar panel installations, so that a more competitive fixing solar cell can be developed. **[11]** and **[13].**

2 PV SYSTEM

2.1 CIRCUIT

A *Photovoltaic system* with all their elements is depicted in the ***Figure 2.1***.

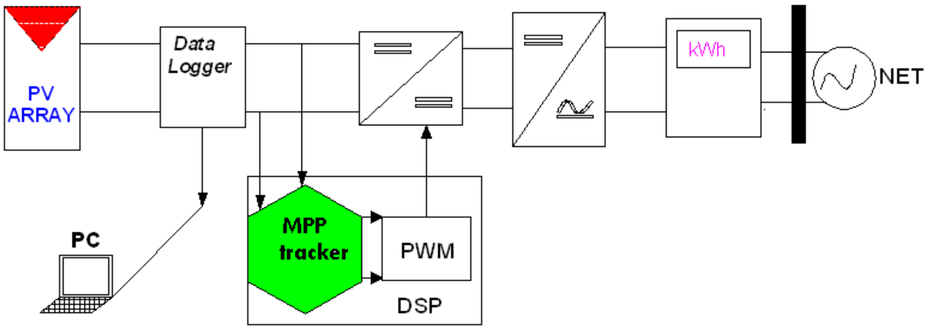


Figure 2.1: Depiction of the PV system working with MPP tracker

It depicts the *PV array* (in detail in the following section), a *data-logger* (it must not confused with a Data Acquisition –*DAQ or DAS*-) connected to a computer recording the cell temperature, solar irradiation, open circuit voltage and sometimes wind speed or direction and relative humidity would be useful.

Then the current and voltage are taken out towards the *DSP* (Digital Signal Processing). The algorithms described here are required to DSP. The microprocessor in the computer is the tool for all implementations here. The DSP module contains the maximum power point tracker algorithm implemented in software (next section) and the *PWM* (Pulse Width Modulation) including analogical to digital signal and digital to analogical signal conversion.

That DSP actuates on *DC-DC converter* knowing that the Voltage (in our project called Out Voltage) should be fixed in the solar panel array to extract the maximum power. On one hand this voltage is now known by the converter and on the other hand the voltage is determined by the load (battery or net). In other words the DC-DC converter is the link converting a source of direct current from one voltage level to another.

Then, the *inverter* should be necessary when the load is the net. It will convert direct current from the DC-DC converter to alternating current.

After the inverter, a *display unit* providing current, voltage among other information has been depicted.

The *Power Meter* measures the real power obtained the solar panel with all necessary and efficient electronic circuit named before and a *Net Protector* will be the end element before the *net*, which will fix the voltage required.

2.2 SIMULATION PROCESS

The next flow chart ***Figure 2.2*** explain how the simulations are going to be processed. It was just run the simulations on *Monocrystalline* because the equivalent circuit and the solar panel equations used in both technologies are exactly the same.

The equations, that have been developed in Solar Panel Model, do not consider thin film technology. In these equations, the number of cells are required and the thin film technology is not built in this method. Therefore Thin Film technology equations will be a proposal in the next works.

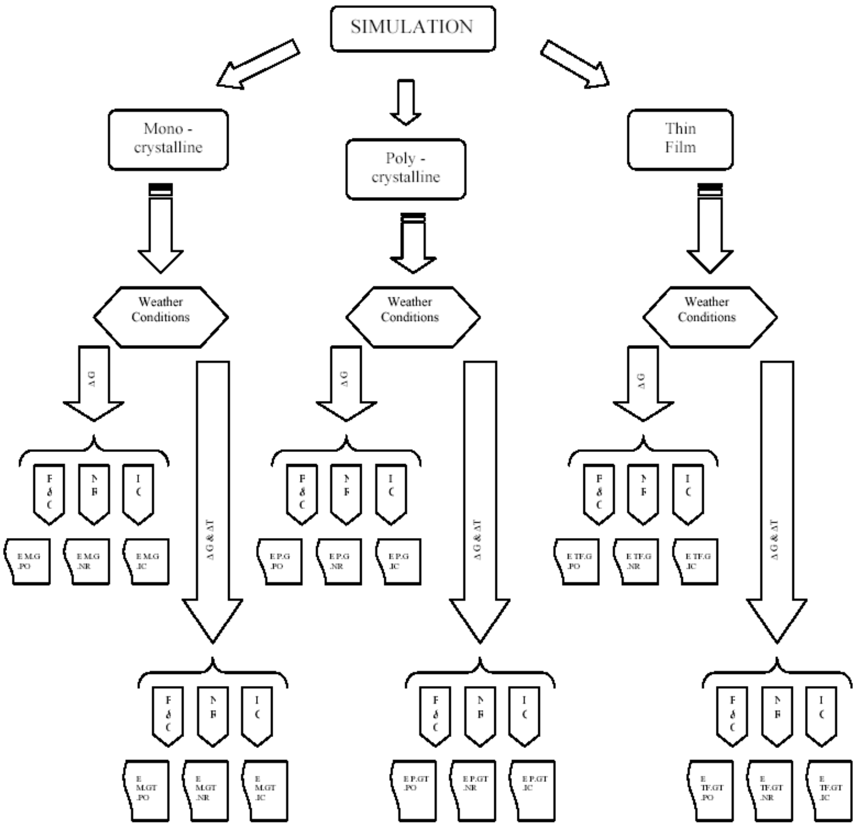


Figure 2.2: Flow Chart Simulation Process

Where ΔG means irradiation changes;

P&O : Perturb and Observe algorithm

E.M.G.PO : Efficiency in Monocrystalline Cells when ***G*** is changed followed up Perturb and Observe algorithm.

NR: Newton Raphson Algorithm

E.M.G.NR: Efficiency in Monocrystalline Cells when ***G*** is changed followed up Newton Raphson algorithm.

IC: Incremental Conductance

E.M.G.IC: Efficiency in Monocrystalline Cells when ***G*** is changed followed up Incremental Conductance algorithm.

Δ***G*** ***&*** Δ***T*** means irradiation and temperature changes together.

E.M.GT.PO: Efficiency in Monocrystalline Cells when ***G*** and ***T*** are changed followed up Perturb and Observe algorithm.

E.M.GT.NR: Efficiency in Monocrystalline Cells when ***G*** and ***T*** are changed followed up Newton Raphson algorithm.

E.M.GT.IC: Efficiency in Monocrystalline Cells when ***G*** and ***T*** are changed followed up Incremental Contuctance algorithm.

The next ones have the same nomenclature but ***P*** means Polycrystalline and ***TF*** means thin film technology. At the end a table will be made up with all efficiencies as a resume and it will be able to compare in a look all of them.

3 SOLAR PANEL

3.1 EQUIVALENT CIRCUIT

The equivalent circuit of the solar panel model is shown in ***Figure 3.1*** and the correspondent equations can be seen in the following.

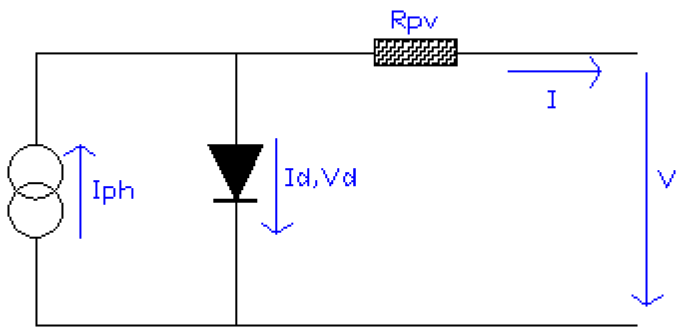


Figure 3.1: Solar Panel Equivalent Circuit

Only four parameters :

V_{oc} : *open-circuit voltage*

I_{SC} : *short-circuit current*

V_{MPP} : *voltage in the maximum power point*

I_{MPP} : *current in the maximum power point*

from the providers are needed to solve this model of solar cell where:

$R_{PV(G_0,T_0)}$: *Resistence of the solar model*

$V_{T_{(G,T)}}$: The *thermal voltage* in this model

$I_{s(G,T)}$: *Saturation current diode*

$I_{ph(G,T)}$: *Photocurrent.*

Here both resistences R_s and R_p of a standard model shown in **[11]** are transformed to $R_{PV(G_0,T_0)}$. This last resistance can take positive and negative values, that is means to be not an real ohmic resistance.

Standard conditions are fixed like:

Go = 1000 W/m2

To = 298 K

$$R_{PV(G_0,T_0)} = -M_{(G_0,T_0)} \cdot \frac{I_{sc_{(G_0,T_0)}}}{I_{MPP_{(G_0,T_0)}}} + \frac{V_{MPP_{(G_0,T_0)}}}{I_{MPP_{(G_0,T_0)}}} \cdot \left(1 - \frac{I_{sc_{(G_0,T_0)}}}{I_{MPP_{(G_0,T_0)}}}\right) \qquad [3.1]$$

Where ***M*** is a constant obtained as:

$$M_{(G_0,T_0)} = \frac{V_{oc_{(G_0,T_0)}}}{I_{sc_{(G_0,T_0)}}} \cdot \left(k_1 \cdot \frac{I_{MPP_{(G_0,T_0)}} \cdot V_{MPP_{(G_0,T_0)}}}{I_{sc_{(G_0,T_0)}} \cdot V_{oc_{(G_0,T_0)}}}\right) + k_2 \cdot \left(\frac{V_{MPP_{(G_0,T_0)}}}{V_{oc_{(G_0,T_0)}}}\right) + k_3 \cdot \left(\frac{I_{MPP_{(G_0,T_0)}}}{I_{sc_{(G_0,T_0)}}}\right) - k_4 \qquad [3.2]$$

with k_i constants:

$$k_1 = -5.411$$
$$k_2 = 6.450$$
$$k_3 = 3.417$$
$$k_4 = -4.422$$

These constants correspond to calculations using method of least squares.

And the thermal voltage is described on the next equation ***[3.3]:***

$$V_{T(G_0,T_0)} = -(M + R_{PV(G_0,T_0)}) \cdot I_{sc_{(G_0,T_0)}} \qquad [3.3]$$

This equation was taken from **[11]**

$$I_{s_{(T_0,G_0)}} = I_{sc_{(G_0,T_0)}} \cdot e^{\frac{-V_{oc(G_0,T_0)}}{V_{T(G_0,T_0)}}} \qquad [3.4]$$

$$I_{ph_{(G_0,T_0)}} = I_{sc(G_0,T_0)} \qquad [3.5]$$

n is the number of cells. (this ***n*** is necessary here because of ***Vt*** is taken from one cell, not from all panel).

The equivalent output values of current and voltage are:

$$I = I_{ph} - I_s \cdot \left(e^{\left(\frac{V + I \cdot R_{PV}}{V_T}\right)} - 1 \right) \qquad \textbf{[3.6]}$$

$$V = V_T \cdot \ln\left[\frac{(I_{ph} - I + I_s)}{I_s}\right] - I \cdot R_{PV} \qquad \textbf{[3.7]}$$

All the parameters in this equation above are obtained in standard conditions. All of them should take the ***index*** $_{(G_0,T_0)}$**.** Because of space out reasons we resume as ***[3.6]*** *and* ***[3.7]***

The term $I \cdot R_{PV}$ is ignored on equation ***[3.6]*** and ***[3.7]*** to calculate ***I*** because of the resistance is so small.

Using the equations above it, $I_{(G,T)}$ y $V_{(G,T)}$ can be calculated for all values of ***G*** (irradiance) and ***T*** (Temperature) if it was not because all manufacturers only provide data in standard conditions (***G***=1000 W/m2 and ***T***=298K) and sometimes in other conditions as ***G***=800 W/m2. And these data (like this equation says $I_{ph} = I_{sc}$ -which varies with irradiation data logically-) are needed to calculate $I_{(G,T)}$ and $V_{(G,T)}$. That is the argument why we have only used these particular equations to configure in Excel **[18]** and compare all photovoltaic modules in standard conditions (relate IEC 60904). That the reason why all equations here are written in $_{(G_0,T_0)}$ despite the reader can read them with some differences compared with **[11].**

Now new equations that can be used in changed conditions will be used to implement in Simplorer **[19]** *about other conditions.*

In Simplorer the equations are implemented as:

$$I_{(G,T)} = I_{ph(G,T)} - I_{s(T)} \cdot \left(e^{\frac{V}{A \cdot V_t \cdot n}} - 1 \right) \qquad \textbf{[3.8]}$$

$$I_{ph_{(G,T_0)}} = \frac{G}{G_0} \cdot I_{SC_{(G_0,T_0)}} \qquad \textbf{[3.9]}$$

A is a coefficient that takes values since 1 until 2 and it determines the cell deviation from the ideal p-n junction characteristics. When various cells are taken to build the solar panel, as here, the value of 1.3 is taken like a good advice. **[7]**

G is irradiation in W/m2

n is the number of cells connected in series (it is necessary to compare with ***Voc*** is given for all cells by the manufacturer).

And thermal voltage is given by ***[3.12]***

However the ***[3.9]*** equation could be so much simple because of $I_{ph(G,T)}$ (dependence Temperature and Irradiance). Therefore the equation ***[3.10]*** in will be used instead.

$$I_{ph(G,T)} = \left(I_{sc(G_0,T_0)} + \tau \cdot (T - T_0)\right) \cdot \frac{\lambda}{100} \qquad \textbf{\textit{[3.10]}}$$

$I_{sc(G_0,T_0)}$ short current in reference temperature and radiation;

τ temperature coefficient in short circuit current (0.0015 A/°C); **[8]**

$\frac{\lambda}{100}$ solar radiation in mW/cm2 (it can be checked that when landa is divided by 100 mW/cm2, $\frac{\lambda}{100}$ is made as a no dimensional factor).

It is known that Temperature and Irradiance stick together; if irradiance increase during a long time, the temperature should be increase also. The saturation current of the diode in any temperature (related to saturation current in the standard conditions) can be seen in the following **[c]**:

$$I_{s(T)} = I_{s(G_0,T_0)} \cdot \left(\frac{T}{T_0}\right)^{3/A} \cdot e^{\left(-\frac{q \cdot E_G}{k \cdot A} \cdot \left(\frac{1}{T_0} - \frac{1}{T}\right)\right)} \qquad \textbf{\textit{[3.11]}}$$

T_0 is the temperature in standard conditions

$I_{s(G_0,T_0)}$ is the saturation current in the standard conditions

A is the diode quality factor, we take A=1.

T is the absolute temperature of the p-n junction

q is the magnitude of charge on an electron

k is Boltzmann's constant

$$q = 1.6 \cdot 10^{-19}\,Coul$$
$$k = 1.38 \cdot 10^{-23}\,J/K$$

E_G it is considered band gap for Silicon (1.1 eV) monocrystalline and polycrystalline **[8]**

E_G it is considered band gap for Silicon (1.6 eV) amorphous thin film **[10]**

The thermal voltage is:

$$V_t = \frac{k \cdot T}{q} \qquad \textbf{\textit{[3.12]}}$$

Saturation current in the diode is obtained if $I_{(G,T)}$ = 0 A in ***[3.8]*** equation at standard conditions. Opering:

$$I_{s_{diode(T_0,G_0)}} = \frac{I_{ph_{(T_0,G_0)}}}{-1 + e^{\left(\frac{V_{oc(T_0,G_0)}}{V_{t(T_0)} \cdot n}\right)}} \qquad \textbf{\textit{[3.13]}}$$

This equation is used when only irradiation is changed.

That equation ***[3.13]*** comes from Shockley diode equation **[12]**:

$$I = I_s \cdot \left(e^{\frac{V_D}{n \cdot V_T}} - 1\right)$$
$$V_T = \frac{k \cdot T}{q} \qquad \textbf{\textit{[3.14]}}$$

Where:

I is the current across diode

V_D is the voltage across diode.

V_T is the thermal voltage

k is Boltzmann constant (1.38E-23 Nm/K)

T is the absolute temperature of the p-n junction.

q is the magnitude of charge on an electron(1.6E-19 C)

n is the number of cells conected in series.

I_s saturation current

3.2 FILL FACTOR

The fill factor describes QUALITY of solar cells **[11]:**

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{oc} \cdot I_{sc}} \qquad [3.15]$$

where:

I_{MPP} is the MPP current.

V_{MPP} is the MPP voltage

I_{sc} is the short-circuit current

V_{oc} is the open-circuit voltage.

In crystalline solar cells is around 0,75-0,85 and in amorphous cells is 0,5 – 0,7. Because of Current versus Voltage curves in Amorphous Cells are flatter than crystalline ones, the fill factor is smaller. The area required to provide the same energy is bigger in Amorphous technology.

The ***Figure 3.2*** shows the Fill Factor Graphic representation:

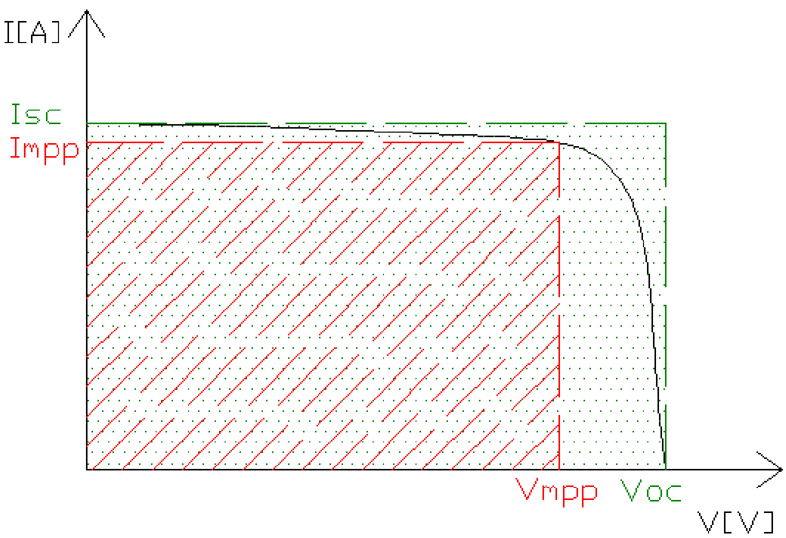


Figure 3.2: Fill Factor Graphic Representation

3.3 SPECTRAL SENSITIVITY

Depending on the material and the technology used, some solar cells are better able to convert the different colour bands of sunlight into electricity.

It is known that sunlight has the greatest energy in the visible light range between 400 and 800 nm.

The crystalline solar cells are working in higher 700 nm wavelength, where the relative intensity are not also so high. Approximately efficiencies of 15,18% are reached. In this area are founded monocrystalline and polycristalline cells. We will check the monocrystalline panel and polycristalline panel from Solarworld company. The Sunmodule ***SW 160*** mono (like the monocrystalline among other ones) and Sunmodule ***SW 200*** poly (like the polycristalline among other ones) have been selected to make all charts, simulations and tests.

Lower 500 nm wavelength are used by amorphous silicon cells, it could be thin film technologies. The thin film photovoltaic panel from Mitsubishi company will be used. The ***MA*** *100* T2 (like the thin film among other ones, although there are not so much thin film providers in nowadays) has been selected. The relative intensity of the energy is increasing at the first wavelengths and efficiencies of 12 % are gotten.

However medium wave lengths are optimized for CdTe (efficiencies around 16 %) and CIS (efficiencies around 18 %) or CIGS (efficiencies bigger than 18 %). They are called thin film technology but have not confused with thin film amorphous silicon cells. This last technology is not going to be studied in this work.

The solution to the spectral sensitivity is amorphous triple solar cell. Short-wavelength light, medium-wavelength light and long-wavelength light are absorbed in these stack cells (blue absorbing cells, green absorbing cell and red absorbing cell). **[13],[11]**

3.4 EFFICIENCY OF SOLAR CELLS AND PV MODULES

The equation *that define it is:*

$$\eta = \frac{P_{MPP}}{A \cdot G} = \frac{FF \cdot V_{OC} \cdot I_{SC}}{A \cdot G} \qquad \textbf{[3.16]}$$

FF**: fill factor **[3.15]

I_{MPP} *is the MPP current.*

V_{MPP} *is the MPP voltage*

I_{sc} *is the short-circuit current*

V_{oc} *is the open-circuit voltage.*

A is the solar panel area.

G *is the irradiance*

Efficiency of solar cells is always specified under standard test conditions (STC) *in data sheets*:

$$\eta_n = \eta_{STC} \rightarrow \eta_n = \frac{P_{MPP_{STC}}}{A \cdot 1000} \qquad \textbf{[3.17]}$$

The efficiency of solar cells is dependent on irradiance and temperature. *Efficiency at a particular irradiance or temperature is:*

$$\eta = \eta_n - \Delta\eta \qquad \textbf{[3.18]}$$

Crystalline cells:

$$\begin{aligned} \Delta\eta_G &= -0{,}04 \cdot \eta_n \cdot \ln(S) \\ \Delta\eta_T &= -0{,}45\% \cdot (25^{\circ} C - T_{\mathrm{mod}}) \cdot \eta_n \end{aligned} \qquad \textbf{[3.19], [3.20]}$$

$$S = \frac{G}{1000} \qquad \textbf{[3.21]}$$

Although we know:

$$T = f(G) \qquad \textbf{[3.22]}$$

*therefore **[3.19]** and **[3.20]** should be related in one equation.* **[11]**

3.5 KINDS OF SOLAR PANEL

Different classifications are done by photovoltaic solar panel manufacturers according to cell type, encapsulation material, encapsulation technology, substrate and frame structure.

Different solar panel according to cell type are being described: Crystalline silicon cells and Thin-film cells. Monocrystalline modules and Polycrystalline modules *are grouped in Crystalline Cells. And* amorphous, CdTe and CIS modules *are grouped in Thin-film technology.*

A summarize of these kinds of panels is redacted under it although detail information can be founded in **[10]** *and* **[11].**

3.5.1 CRYSTALLINE SILICON CELLS:

Silicon is the most important material to produce this panel. This element is in the SiO2. Oxygen has to be separated for getting the Si alone. After several steps and depending of the cooling way, monocrystalline and polycrystalline modules are obtained.

On the one hand, a unique crystal (monocrystalline) is produced controlling the heat and cool in a specific vertical direction. On the other hand, if this way is not reached, polycrystalline cells will be obtained (where there are not predictable crystal structure).

Spectral sensitivity where crystalline cells work most efficiently is distinguished here because of it´s worth when it is compared among all cells. Sunlight has the greatest energy in the visible light range between 400 and 800 nm. Crystalline cells works efficiently in long wave length solar radiation.

Some advantages of crystalline silicon cells are the availability of refined silicon wafers resulting from semiconductor development, availability of mature processing equipment development by that industry and simplicity of the Si-cell fabrication technology comparing with others.

3.5.2 THIN FILM CELLS:

Electrolytic baths, sputter processes and vapour disposition are used as ways to obtain thin film technologies.

Related on spectral sensitivity, amorphous silicon cells can absorb short-wavelength light optimally. *However,* CdTe and CIS absorb better medium wavelengths. *We have to say that we* can find stack cells in amorphous thin-film *technology.* In this stack cells, triple solar cell are optimized for almost all wavelength ranges anyway. *They would work in perfect efficiency but it is not easy finding a manufacturer that offers them in a good price. Prices of this technology are still high.*

It is known that cell parameters and characteristic curves of thin-film deviate from those of crystalline silicon cells. In crystalline cells, the MPP is around 0.6 V . However, in amorphous cells (thin film) *the MPP is around 0.4 V and* the characteristic curve is much flatter. *In these amorphous cells (thin film)* a lower current flows. *For this reason,* a larger cell surface area is required to achieve the same power as crystalline cells. *Also, the less clearly marked MPP demands better control technology of inverter and the MPP controller. That is one of the reasons why there are not many model of this one in the market.*

Some advantages of the Thin Film Photovoltaic Module are the environmental ones over the crystalline photovoltaic module (less energy used for manufacturing, less silicon required, shorter energy payback time) and a weatherproof structure and stable performance under high temperatures during summer.

One disadvantage of the Thin Film Photovoltaic Module is larger areas are required to get the same power that in Crystalline Solar Cells. Approximately the required area for 1000 W is:

Kind of PV panel	Area for 1000 W
Monocrystalline	8 m2
Polycrystalline	10 m2
Thin Film: CIS and CdTe	15 m2
Amorphous Silicon	18 m2

Table 3.1: Kind of PV panel with area required

Other disadvantage of the Thin Film Photovoltaic Module is the degradation of the modules must be taken into account in the design when amorphous modules are used. This degradation is considerably bigger that in the other panels cause higher power can be reached during the first months of running.

3.6 CELLS DATA

The data cells which were used in this work are represented as summarize in ***Table 3.2.*** Anyway the brochures are attached in ***Appendix.***

NAME		SW 160 Mono	SW 200 poly	MA 100 thin film	
Maximum power (Pmax [V])	Performance under Standard test conditions	160	200	100	
Open circuit voltage (Voc [V])		43,8	36,1	141	
MPP voltage (Vmmp [V])		35	28,3	108	
Short circuit current (Isc [A])		5	7,7	1,17	
MPP current (Immp [A])		4,58	7,07	0,93	
Cells per module	Component materials	72	60		
Cell type		Monocrystalline silicon	Polycrystalline sylicon	Amorphous Silicon	
Cell dimensions		125 x 125	156 x 156		
Panel dimensions		1610 x 810 x 34	1001 x 1675 x 34	1114 x 1414 x 35	
NOCT [°C]	Thermal characteristics	46	46	Pmax [%/°C]	-0,2
TC (Isc [%/K])		0,036	0,034	Vmmp [%/°C]	-0,3
				Immp [%/°C]	0,1
TC (Voc [%/K])		-0,33	-0,34	Voc [%/°C]	-0,3
				Isc [%/°C]	0,1

Table 3.2: Data Calculations Solar panels

All parameters above it have been defined before, only ***NOCT*** was not called

NOCT: it is the normal operating cell temperature. The temperature at which the cells in a solar module operate under standard operating conditions (SOC). These conditions are: irradiance of 0.8 kW/m^2, 20ºC ambient temperature, and average windspeed of 1 m/s, with the cell or module in an electrically open circuit state, the wind oriented parallel to the plane of the array, and all sides of the array fully exposed to the wind.

4 WEATHER CONDITIONS

4.1 IRRADIATION DATA.

The world irradiation data and the mean irradiation values all over the world are shown in ***CD attached***.: Averaged Solar Radiation 1990 –2004. In the ***Figure 4.1*** bellow the sample data of Iberian Peninsula and Northwest Africa as coloured maps during a month are represented.

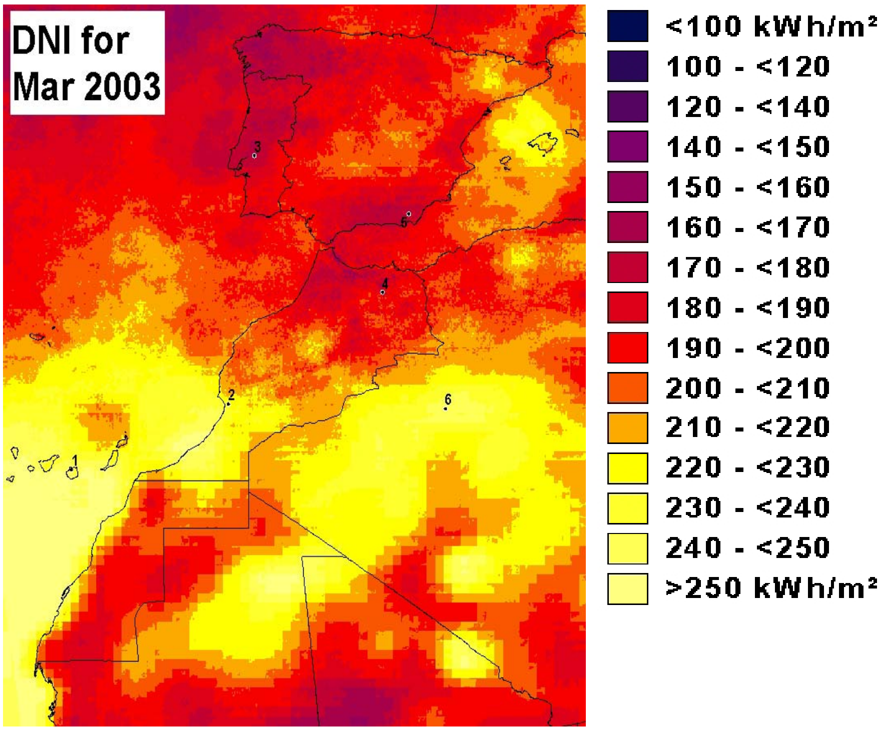


Figure 4.1: Sample Data - Iberian Peninsula and Northwest Africa. Monthly sum of the direct normal irradiance (DNI) for March 2003

The coloured maps are used to illustrate radiation data. Here the data are mean values during one month (March). If these data (170 kWh/m2) are divided by which are reached on 5 (Almeria) and by 31 days, around 5400 Wh/m2 are calculated in one day. On site 5 (Almeria) data hour by hour are represented. But now these data are in Power terms not in energy terms.

Date	hour	DNI
01. Jun	1	0
01. Jun	2	0
01. Jun	3	95
01. Jun	4	366
01. Jun	5	546
01. Jun	6	650
01. Jun	7	711
01. Jun	8	745
01. Jun	9	759
01. Jun	10	755
01. Jun	11	733
01. Jun	12	689
01. Jun	13	612
01. Jun	14	480
01. Jun	15	253
01. Jun	16	22
01. Jun	17	0
01. Jun	18	0
01. Jun	19	0
01. Jun	20	0
01. Jun	21	0
01. Jun	22	0
01. Jun	23	0
01. Jun	24	0

Table 4.1: Direct Normal Irradiance during March in Almeria

The ***DNI*** is the direct normal irradiance in W/m2

The rest of days are provided in the ***CD attached***.

This is the moment to distinguish between the data above . Some of them are in Power terms (W/m2) –as shown in ***Table 4.1***- and some of them in Energy terms (Wh/m2) –as shown in ***Figure 4.1*** When temperature changes are not concerned, Equation ***[3.9]*** can be used in power terms or energy terms. However if the temperature changes are concerned, Equation ***[3.10]*** should be used and it is expected to work in power terms (with ***DIN***).

The simulations (irradiance changes) will all use power terms.:

However, these data are mean values during a year, during a month or during one hour. It is meant that it is not useful for the work to implement the algorithm because of changes during seconds are needed to make the simulations. Irradiation changes during the day in a period of minutes (like a cloud passing, for example) can affect the algorithm.. The irradiation changes were at first studied and then a set of parameters for weather conditions were established accordingly to implement the algorithms.

At first, the next table is a resume of the maximum and minimum data among all which were enclosed in ***CD attached***: Weekly Averaged Solar Radiation in Almeria and Weekly Averaged Solar Radiation in Dresden.

MEAN IRRADIATION DATA		*Weekly Solar Radiation*	
	Almeria	*Dresden*	
June	8500	250	**Wh/m2**
December	2400	7000	

Table 4.2*: *Mean Irradiation Data (Maxim and Minimum Values)

If 10 hours of light are considered by day, the data above is in power terms obtained by dividing the values by 10 (although it is known that there is less daylight in Dresden that in Almeria). Here maximum and minimum radiation. (900 W/m2 –20 W/m2) are calculated. A realistic case during one day of summer in a hot place (***high radiation***) and a realistic case during one day of winter (***low radiation***) and several radiation changes in them will be implemented.

It is known as well that the tracker will work differently when changes on low radiation are produced during the day (a sunset or daybreak –sunrise-) –an algorithm with constant voltage is expected to work better than the rest. (when changes on high radiation occur -in the middle of the day) –here Incremental Conductance tracker or Perturb and Observed are expected to work better-. The technology must work as well as with ***high radiation as with low radiation.*** The current versus voltage curve are flatter in low radiation and that makes it more difficult to track the MPP. From these data the hypothetical conditions will be established.

Also the algorithms behave in different way when ***big variations*** of irradiance are produced or ***small variations*** –Perturb and Observe algorithm is not expected to reach high efficiencies with big variations-

. The flow chart shown in the ***Figure 4.2*** bellow illustrates the different conditions for the simulations.

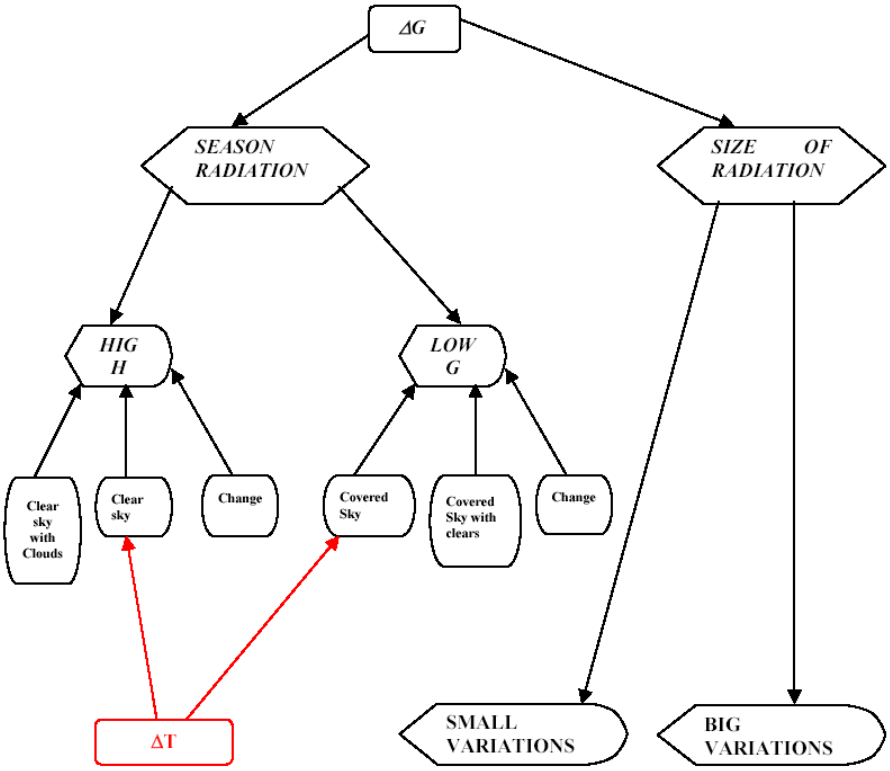


Figure 4.2 : Flow chart representing the weather conditions used in the following simulations.

4.1.1 SEASON RADIATION

4.1.1.1 HIGH RADIATION

A Clear sky in high irradiances.

The first simulation will be a realistic case with clear sky in high irradiances. A summer clear day.

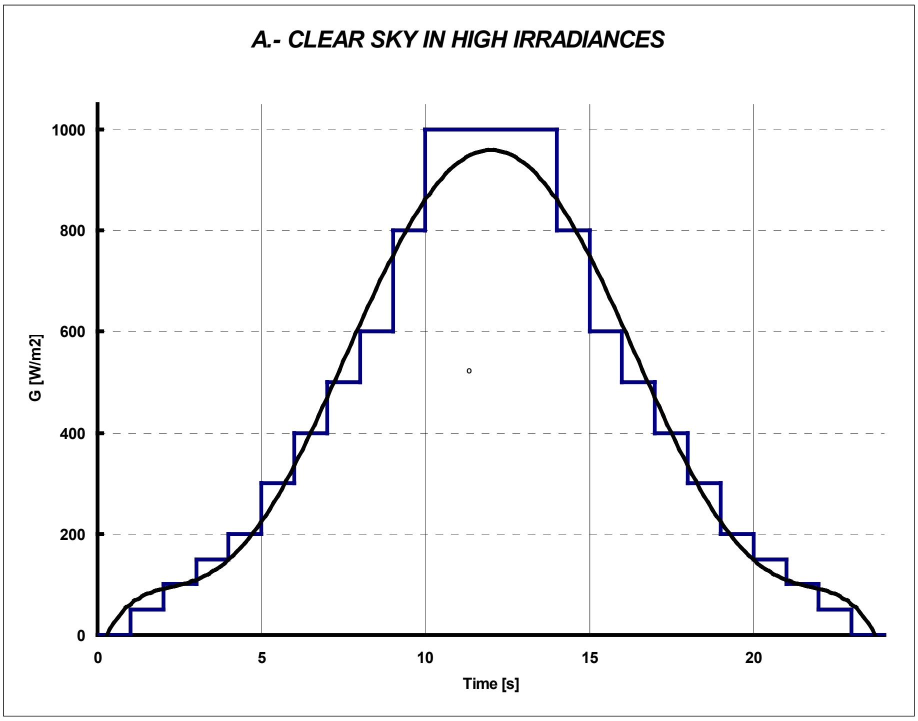


Figure 4.3: Clear Sky in High Irradiances Figure

In the first seconds and at the end 50 W/m2 steps are done. After the steps are 100 W/m2

Every second represent half an hour in the reality. Therefore would be the 10 h of sun approximately. The polynomial equation represents the steps changes of irradiation as a parabolic shape. **y = -0,0009x6 + 0,064x5 - 1,6629x4 + 18,408x3 - 80,403x2 + 165,51x - 41,008** Where ***y*** is the irradiation and ***x*** is the time.

B Clear sky with some clouds in high irradiances.

This is the typical day of summer with some modifications in the irradiance. Summer with some clouds.

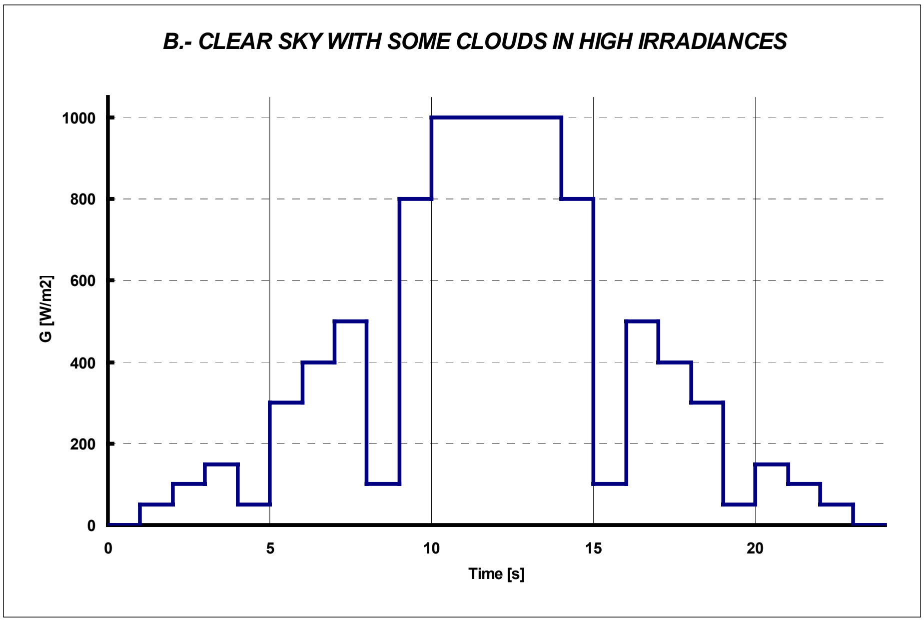


Figure 4.4: Clear sky with some clouds in high irradiances

Here the simulation will be implemented by ***G varying*** (without any change of temperature). It *would be like a cloud that pass rapidly (short time)*. Two increases and two decreases are done respectively. First movement is around 150 W/m2 and the second one around 700 W/m2 increasing. In the right zone happen the same just decreasing.

Here the irradiation signal are steps. It has to be said that for example in **[2]** was chosen a sinusoidal-shaped signal with a frequency of 0.5 Hz as solar irradiation. It would represent soft changes (close to reality). However *extreme condition* (laboratory conditions) was said to implement in simplorer and the next one has been chosen to carry out the simulations.

C Changes in high irradiation

In the Figure bellow, it can be observed how the 1000 W/m2 (STC) is kept constant for a long time. Therefore when it is processed to do changes, the tracker would be in stable conditions.

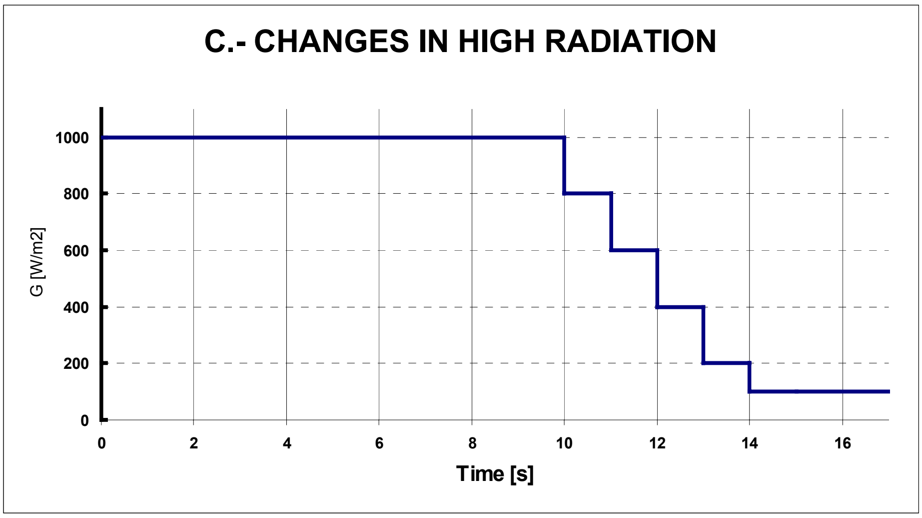


Figure 4.5: Changes in High Irradiation

This implementation would be enough correct to measure efficiencies and compare all the algorithms, because the changes in it are constant. . It will be examined how the trackers respond to these variations .

4.1.1.2 LOW RADIATION

D Clear sky in low irradiances.

The next analysis considers a realistic case with clear sky in low irradiances**.** It is the typical day of winter without any clouds.

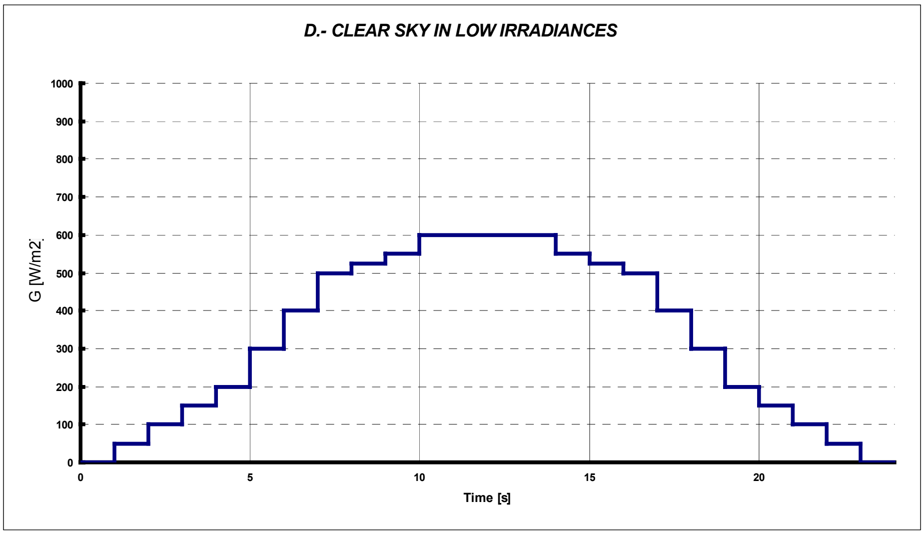


Figure 4.6: Clear Sky in low irradiances

E Covered sky with some clears in low irradiances.

A winter day with some clears is considered. It is supposed to represent the sky covered and sometimes some clears appear.

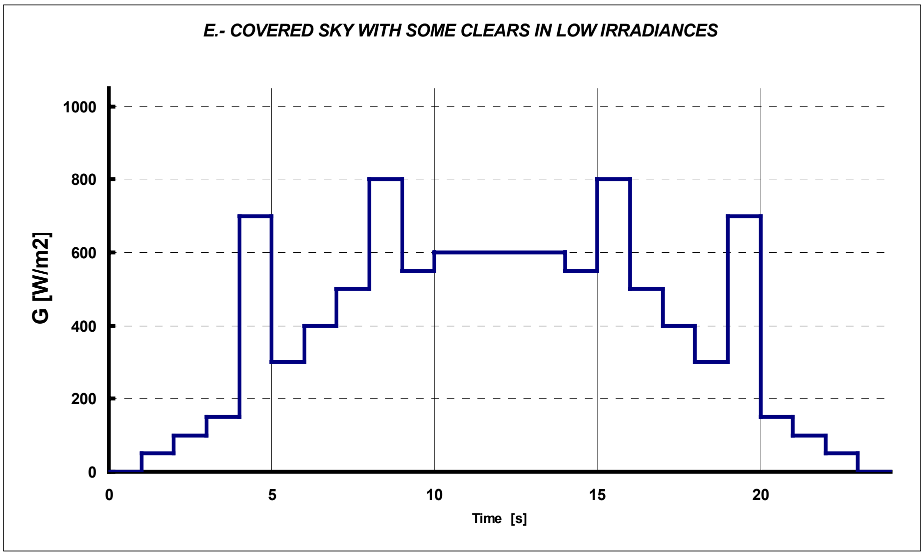


Figure 4.7: Covered sky with some clears in low irradiances

F Changes in low irradiation

It can be observed on the following Figure how the 100 W/m2 is kept constant for a long time. Therefore when it is processed to do changes, the tracker would be in stable conditions.

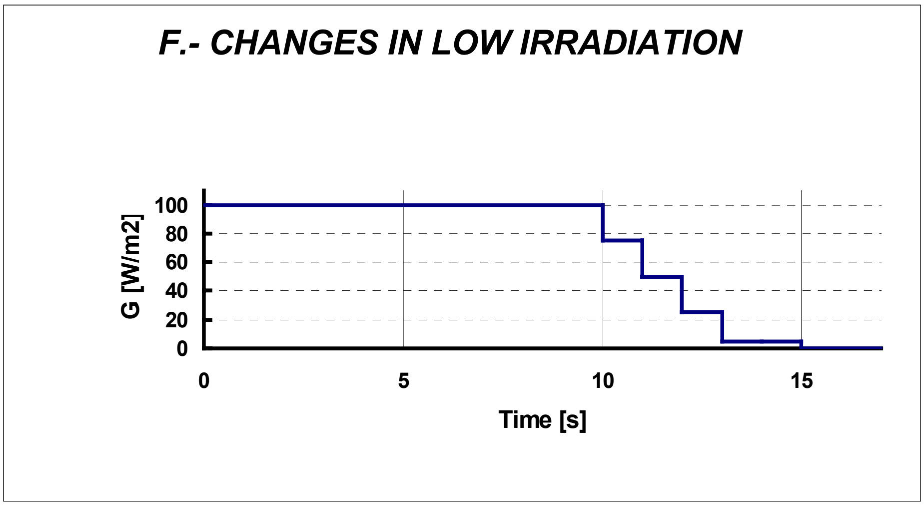


Figure 4.8: Changes in Low irradiation

4.1.2 SIZE OF VARIATION

G SMALL VARIATIONS

The size of variation depends on the density of clouds. A lot of thick clouds will produce different variations than light ones. In the following figure light clouds are represented.

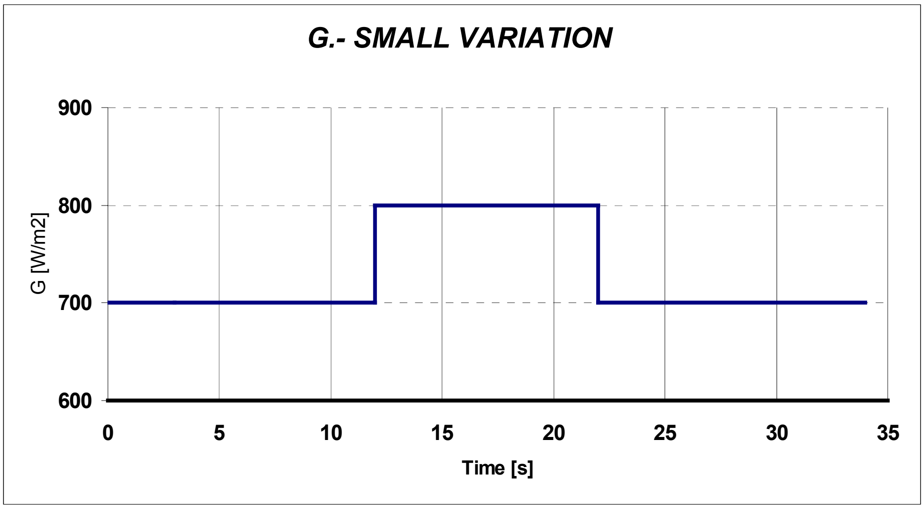


Figure 4.9: Small variations of irradiance

Just 100 W/m2 is represented.

H BIG VARIATIONS

In the figure bellow thick clouds are represented.

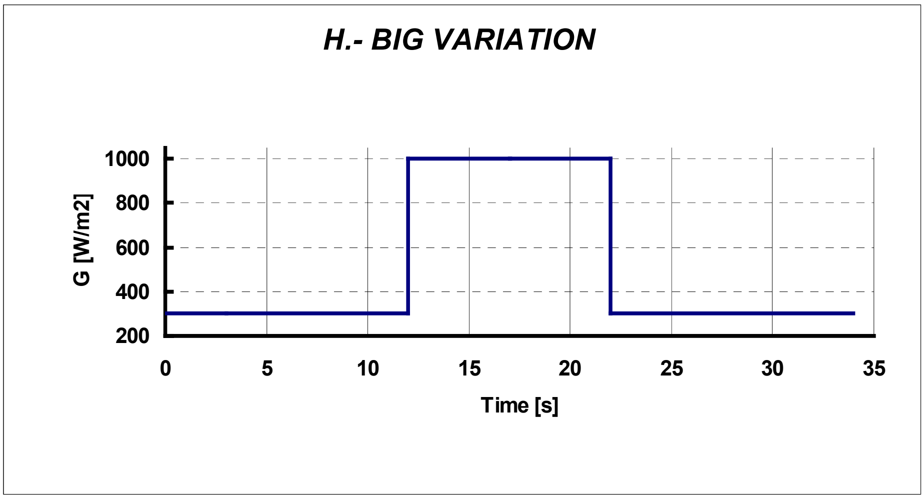


Figure 4.10: Small variations of irradiance

Around 700 W/m2 change is implemented. **[27], [28]**

4. 2 TEMPERATURE DATA

Data from weather stations placed in:

In Dresden: Weather station DRESDEN E.GERMANY is at about 51.10°N 13.80°E. Height about 246m / 807 feet above sea level. In Almeria:Weather station ALMERIA is at about 36.79°N 2.50°W. Height about 7m / 22 feet above sea level.

MONTH AVERAGE TEMPERATURE													
[°C]	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Dresden	0,10	0,80	4,10	8,30	13,40	16,80	18,40	17,80	14,30	9,60	4,20	1,20	9,10
Almeria	12,2	12,7	14,4	15,8	18,7	21,8	24,9	25,6	23,3	19,5	15,6	13,2	18,1

Table 4.3: Month Average Temperature in Almeria and in Dresden

Two kinds of simulations are chosen, one of them it could be a summer day. A summer day is more extreme in Almería than in Dresden, for this reason it has been selected. Afterwards the simulation of a winter day will be take from Temperature Data from Dresden, the panel will be requested in worst conditions.

4. 3 TEMPERATURE AND IRRADIATION CHANGING

The simulations are going to be carried varying *G and T during a day*. The implementation is however done *in a reduce time*. The temperature increases since first hours of the day until the middle of the day and then goes to decrease. Although the irradiance can go up and go down irregularly, the tendency is to increase until the middle of the day. Therefore temperature is usually increasing when irradiation does too. Although irradiation could fluctuate, it also has the tendency to always increase until the middle of the day. Temperature follows the same pattern, however not so much fluctuations can be observed in it.

Changes of temperature concerning a summer day and a winter day are selected to make the simulations.

All of studies can be observed since 25°C until 60°C as [7]. And the values shown above are mean values, it is supposed to be the maxim temperature, for example in Almeria, around 40 ºC in Summer and the minimum around 8 ºC in winter. The next simulations are be chosen to be implemented in Simplorer.

Symmetry distribution concerning irradiation and temperature are fixed to clarify differences in the next graphics.

4.3.1 SUMMER DAY

K CLEAR SKY IN HIGH IRRADIANCES

This is the typical summer day in Almería. **y = 5E-16x5 + 0,0007x4 - 0,0341x3 + 0,3666x2 + 1,0239x + 17,331**

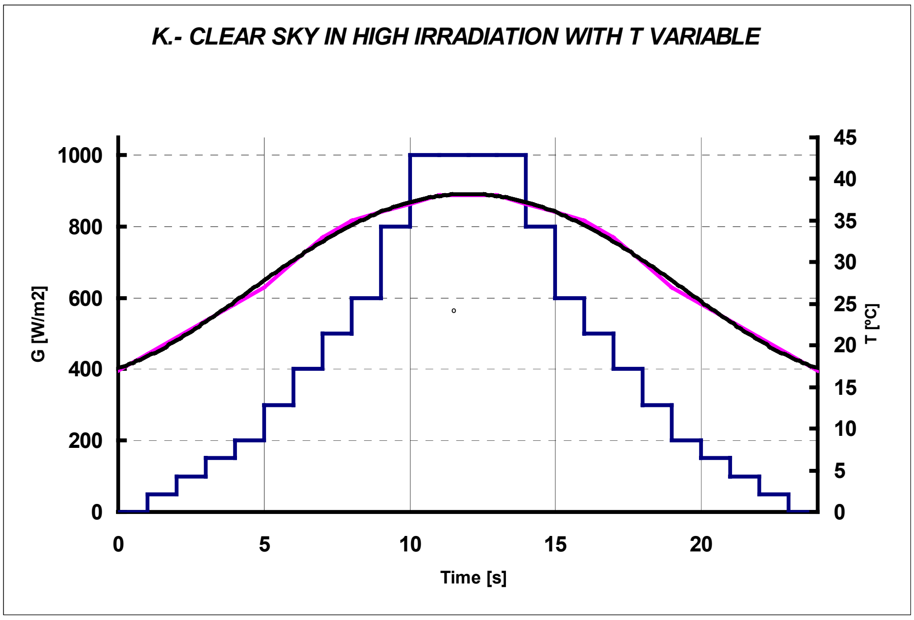


Figure 4.11: Clear Sky in High Irradiation with T Variable Figure

The equation written in the graph represents the changes of the temperature versus time. Variable ***y*** is the temperature and variable ***x*** is the time

4.3.2 WINTER DAY

M CLEAR SKY IN LOW IRRADIANCES

Here is represented one of the typical winter day in Dresden

y=-4E-06x6+0,0003x5-0,0069x4+0,068x3-0,2256x2+0,9057x+7,8877

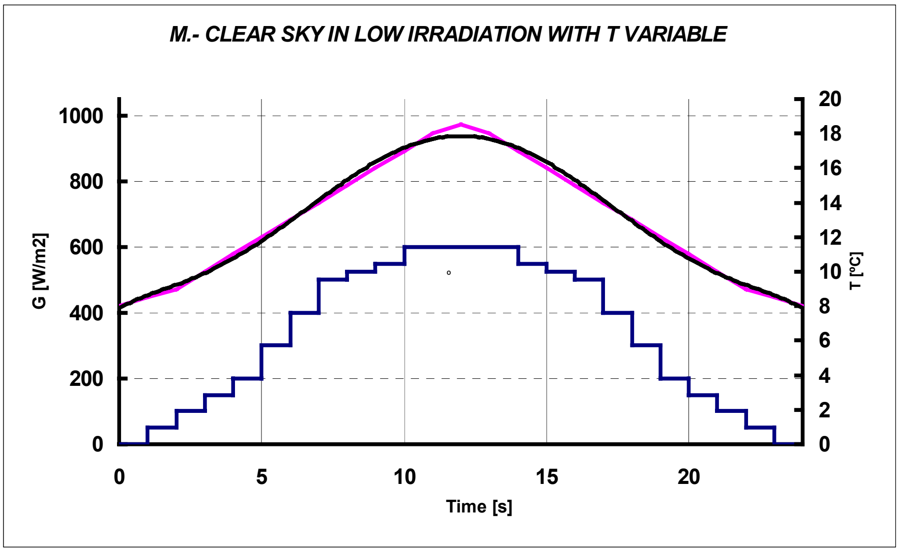


***Figure 4.12: Clear Sky in Low Irradiation with T variable* [29], [7]**

5 MPP TRACKERS

5.1 BACKGROUND

The battery voltage and the PV generator voltage vary with changes in weather conditions. This cause to the solar panel is not working every time in its maximum power point. Therefore more efficiency will be obtained if an approximate maximum power point is reached every time that weather conditions vary.

To solve this problem the solution is introduce a DC/DC converter to adjust the voltage properly. The control section consists of two control loops: one for the input and the other for the output. The input voltage controller keeps the PV generator voltage at a constant level by suitable adjustment of the DC/DC converter.

In one of the next algorithm the voltage level can also be constant (CV algorithm) or can track the actual MPP by an appropriate searching strategy (MPPT).

The algorithms that will be explained later can be grouped into two categories:

Indirect MPP trackers:

This type of MPP tracker estimates the MPP voltage by means of simple measurements.

1. The operating voltage of the solar generator can be adjusted seasonally. Higher MPP voltages can be expected in winter because of lower cell temperatures.
2. The operating voltage can be adjusted according to the module temperature.
3. The operating voltage can be derived from the instantaneous open-circuit voltage by multiplication with a constant factor, for example, 0,8 for crystalline silicon solar cells. The open-circuit voltage is measured periodically (e.g. every two seconds) by disconnecting the load for one millisecond.

The MPP tracker give an approximate optimum operation point. However they are simple. (See Constant Voltage algorithm in the following pages)

Direct MPP trackers:

In these systems, the optimum operating voltage is consequent from measured currents, voltages or the power of the PV generator. Therefore, they are able to respond to quick changes. (See Incremental Conductance algorithm and Newton Raphson in the next pages)

Sometimes the operating voltage is periodically changed in small steps. The increment can either be constant or can be adapted to the instantaneous operating point. If the module's power increases from one step to the next, the search direction is retained: otherwise it is reversed. In this way, the MMP is found and the operating point oscillates around the actual MPP. (See Perturb and Observe algorithm)

Here the ***Table 5.1*** represents the algorithm analysed in this work within the categories named before.

CATEGORIES OF TRACKERS	
INDIRECT	**DIRECT**
Constant Voltage	**Newton Rapshon**
	Perturb and Obseve
	Incremental Conductance
Flexible Area	

Table 5.1: Categories of trackers

The Flexible Area is a mixed between these two categories. And Flexible Area and Newton Rapshon are introduced here by first time. Although Flexible Area uses similar concepts that Incremental Conductance and Constant Voltage.

The energy losses are on the order of a few percent. Although it should be considered if the additional energy gained by optimum matching is so relevant to the functioning of the complete system.

For energy reasons, the use of an MPP tracker only makes sense with generator powers of 200 W and above. With lower-powered generators, the converter's conversion losses are generally higher that the gain from the controller. However in this last case, there is an advantage if MPP trackers are used: The generator voltage can be chosen higher (implies lower currents) and bigger wiring losses are avoided. It is useful in long wires installations.

5.2 PERTURB AND OBSERVE ALGORITHM

5.2.1 P&O BACKGROUND

Perturb and observe algorithm consists of incrementing (or decrementing) the array terminal voltage and contrast the actual out power versus previous cycle one.

If power increases when the voltage is increased, the next perturbation of voltage will increase towards the same direction. If the power reduce when the voltage is increased, the next perturbation of the voltage will decrease towards the opposite one. Perturb and Observe has a simple feedback.

The ***Figure 5.1*** shows the Perturb and Observe algorithm graphic of power versus voltage

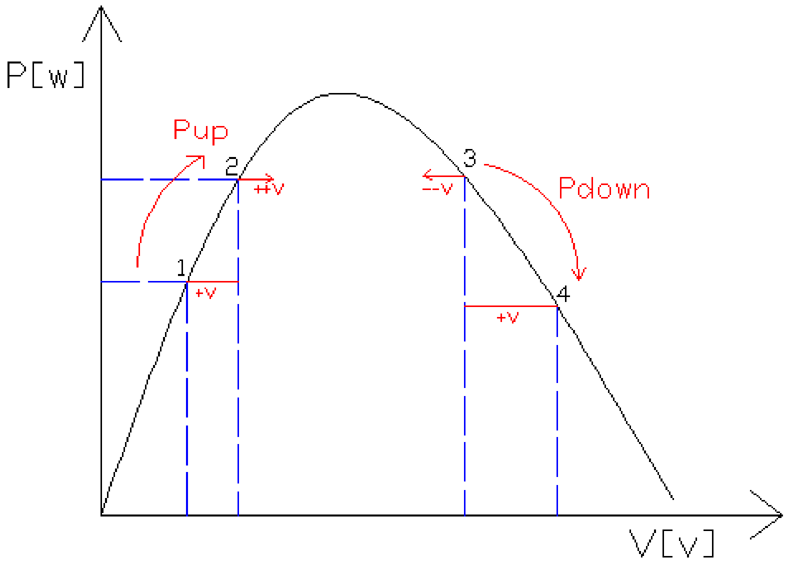


Figure 5.2: Movements of the P&O tracker.

++V means that Voltage has to be increased in this way when Power is moving up (after ***+V*** is done) in the left side.

--V means that Voltage has to be increased in this way when Power is moving down (after ***+V*** is done) in the right side.

The algorithm's flow chart is shown in the following ***Figure 5.3:***

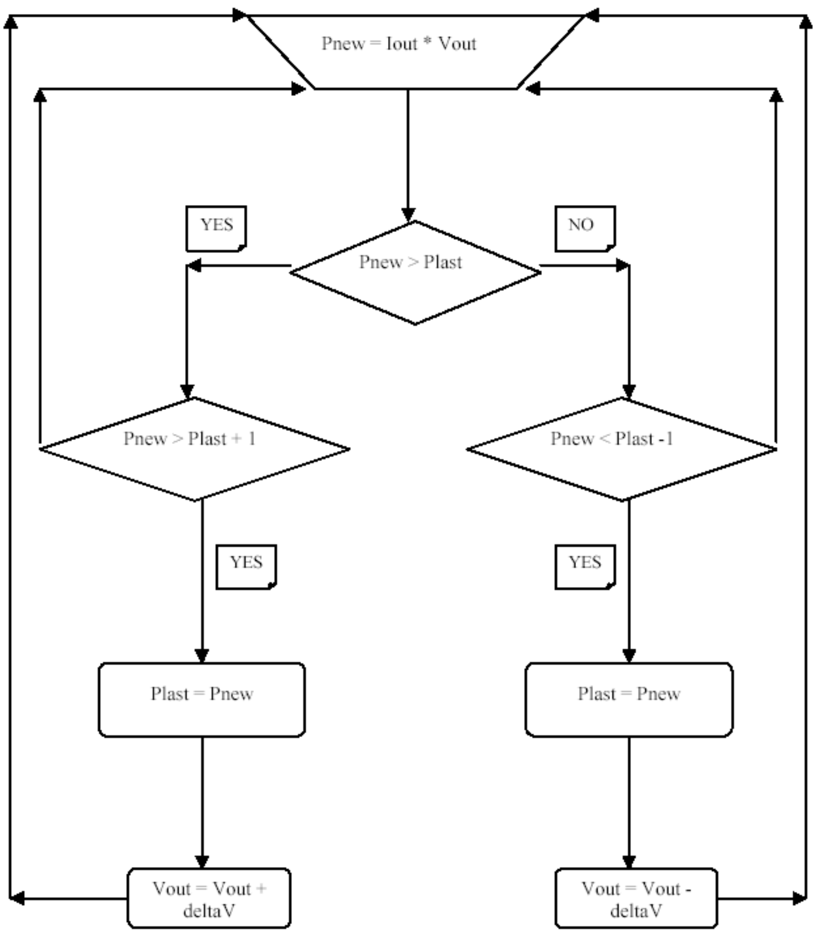


Figure 5.3: P&O Flow chart.

This flow chart or box diagram represents the algorithm has been explained before. Every time that the algorithm is going to repeat the process, the new output data is extracted and digitalized to ***Iout*** and ***Pnew*** is calculated every few seconds automatically as ***Pnew = Vout * Iout***. ***Vout*** was the last value of ***Vout*** recorded in the next step which only go ahead if ***Pnew*** is bigger or smaller than the previous one plus one or minus one respectively(*). The previous power was recorded as ***Plast***. Therefore ***Pnew*** and ***Plast*** can be compared in the one step by a simple way. Here is the key to understand the algorithm; if ***Pnew*** is bigger than ***Plast +1***, Vout will be increased one step. If ***Pnew*** is smaller than ***Plast – 1***, ***Vout*** will be decreased one step. In both of previous cases, a time is taken off to set up the new parameters (***Iout***). And if none of these conditions is reached, our algorithm continues calculating ***Pnew.***

It could be asked, why does not the algorithm increase the voltage until ***Pnew > Plast + 1***? (the same question could be make in the other side, ***Pnew < Plast - 1***). It is known in a digital signal processing the parameters are calculated as steps during the time is running out. ***Pnew*** is calculated as ***Iout * Vout*** and ***Iout*** takes digitalized values (small steps). Therefore ***Pnew*** is varying as steps also, Pnew is moving up and down around a mean value despites it should be constant. If ***Plast*** take in a determinate moment the value of ***Pnew***, sometimes ***Pnew*** will be larger than ***Plast*** and sometimes minor depending on the sampling frequency and just at time the next irradiation change will be produced. Let us consider a mean digital signal processing mistake solved in a simple way.

Sometimes this algorithm presents an unexpected behaviour. It can be anticipated. When the algorithm gets MPP, it continues moving around it and this movement causes loss power. It is represented it down (***Figure 5.4***)

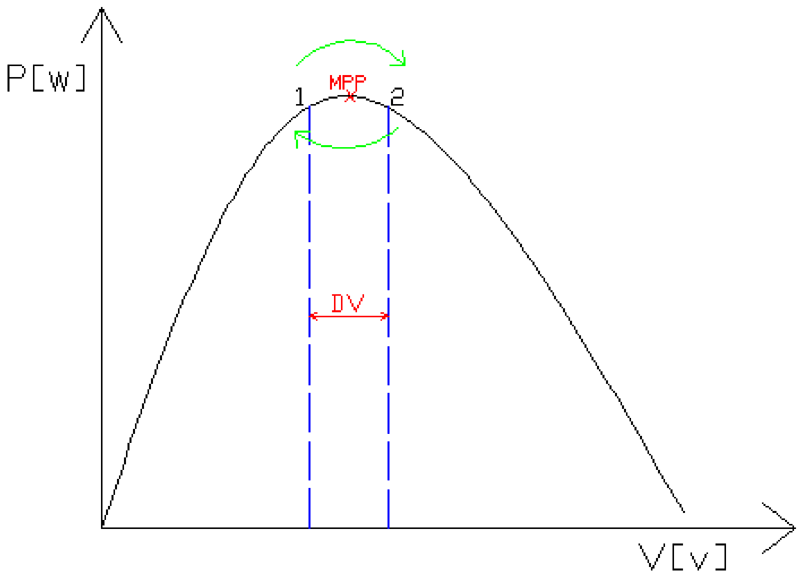


Figure 5.4: Movements around MPP of the P&O tracker.

This mistake can be repaired if a small voltage step is supplied. However in changeable conditions of temperature and insolation, the algorithm spends a long time to get the MPP, as shown in ***Figure 5.5:***

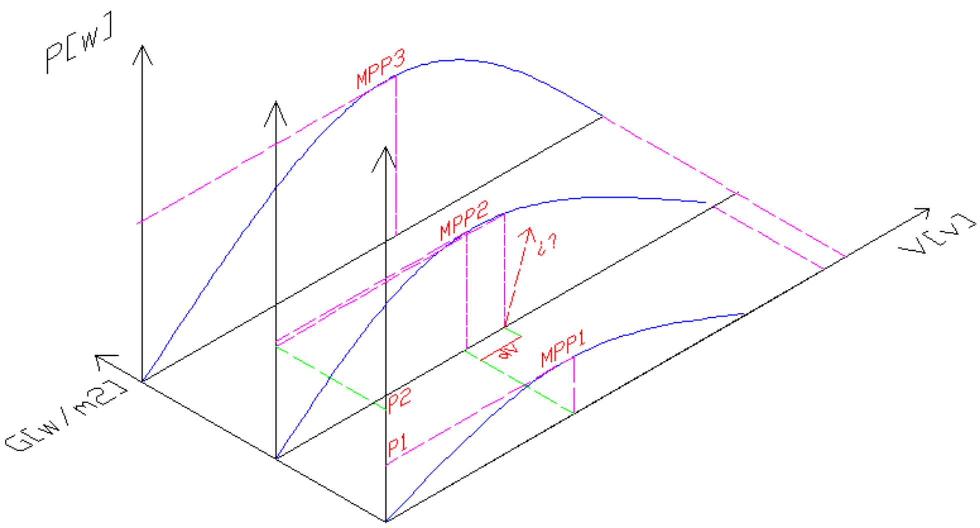


Figure 5.5: P&O Problem during tracking.

The Voltage is the calculated as: ***V1+dV=V2***, but now, in this state, ***P2>P1*** → the next step is going towards right direction, but it is in the opposite side of the actual maximum power point!

Until irradiation characteristics don't change or until ***P3<P1***, the tracker doesn't converge to the MPP.

5.2.2 P&O SIMULATION

The following section shows the implementation of the Perturb and Observe algorithm in Simplorer. At the first just irradiation changes will be simulated. It will be processed with the same conditions that have explained in 5.- WEATHER CONDITIONS.

The Solar Panel Equivalent Circuit corresponds to ***Figure 3.1***

The resistance is calculated according to the equations ***[3.1]*** and ***[3.2]***

The thermal voltage in the diode is calculating as ***[3.12]***

Cause just irradiation changes, Photocurrent is given by ***[3.9]*** and the saturation current of the diode by ***[3.13]***

Cause irradiation and temperature changes, Photocurrent is obtained from ***[3.10]*** and ***[3.11]*** after introducing saturation current in STC ***[3.13]*** in it, will be used to saturation current of the diode in different temperatures.

The equation are going to be used are ***[3.1]*** and ***[3.2]*** to calculate the resistance.

The voltage out initial is set up in stable state when the algorithm is starting. The delay time will be enough to make the parameters stable also. Sampling frequency can be changed also.

Just the most important results will be showed here. The rests of simulations and comments are in ***Appendix*** **.**The following simulations in other algorithms are using the same equations.

In the next two figures (***Figure 5.6 and Figure 5.7***) can be compared a Clear Sky in High Irradiation day simulation in ***Figure 5.6*** (**Congratulation1_jccb_finish.ssh**) where the irradiances changes were made by steps versus a parabolic representation of the same kind of day ***Figure 5.7*** (**Congratulation1_jccb_finish_proof.ssh**)

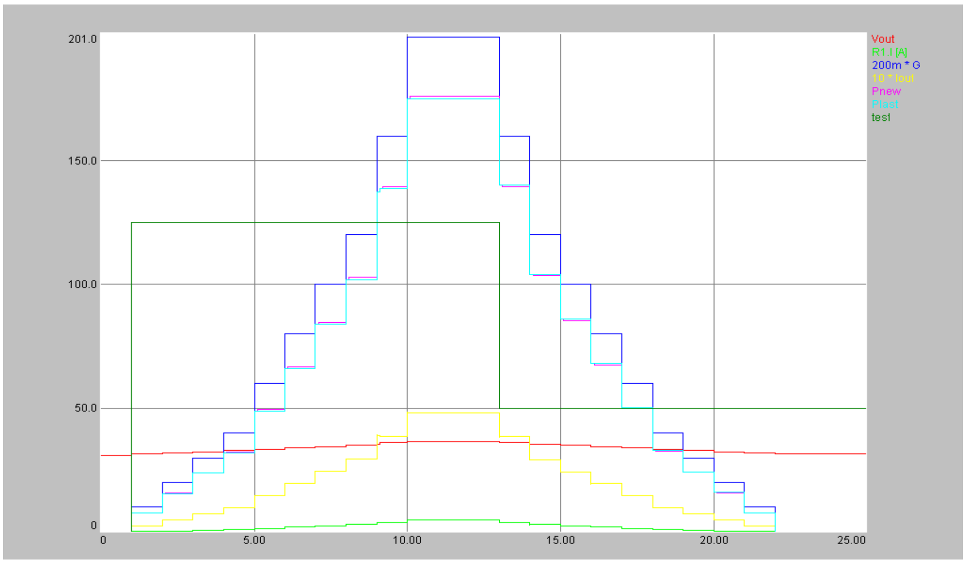


Figure 5.6: P&O Simulation of a Clear Sky in High Irradiation

The voltage out (red line) reach in ***Figure 5.6*** on STC 36,4 V and the voltage out in the ***Figure 5.7*** the Voltage out reach 39,2 V on the top. Here the sampling frequency is 200 micro seconds. It is enough to get accurate values.

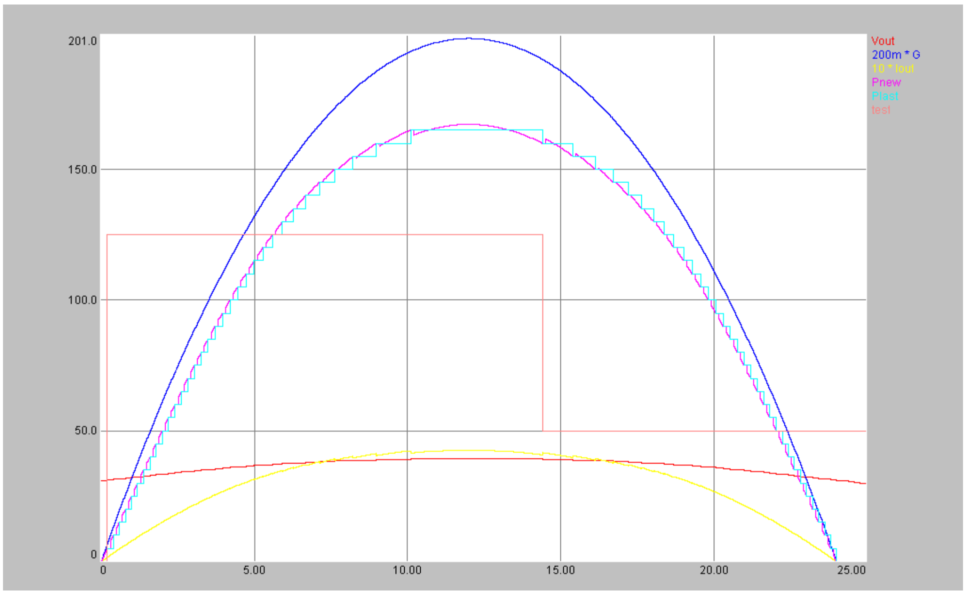


Figure 5.7:P&O Simulation of a Parabolic Simulation of a Clear Sky in High Irradiation

Therefore the algorithm can see the change in both of them, however *the proportion of change is not seen in non-parabolic representation*. It does not work in rapidly changes. This is one of the disadvantages.

In the next simulation of a Clear Sky with some clouds in High Irradiances ***Figure 5.8*** (**Congratulation1_jccb_finish_cschi.ssh**) an adjustment is made here. Just the margin is changed. When the differences of the power is bigger than 5, ***Plast = Pnew*** and the voltage is increased again. Until this tolerance is not reached, ***Pnew*** continues calculating on its own.

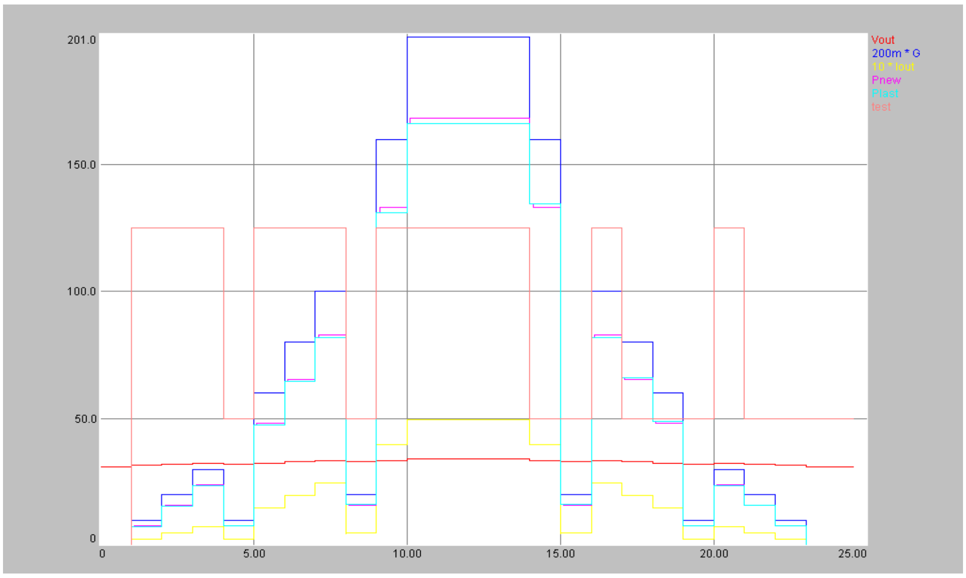


Figure 5.8:P&O Simulation of a clear sky with some clouds in high irradiances

Therefore in addition to unable to see the proportion of the changes, *it is not working well when the irradiation changes of direction* (increasing towards decreasing, for example). It can be solved if the margin Power is bigger. However, although it is closer to the reality because 1 W of Power differences is so little bit and accurate equipment is necessary to measure these values, Power losses are presents.

The delay to wait is approximately 3 minutes. And before the next alteration is kept constant the irradiation during 20 minutes.

It is important to know that this algorithm depends of the *configured voltage step*, here the step is V=0.5V how the next ***Figure 5.9*** **(Congratulation1_jccb_finish_chLI.ssh**) shows

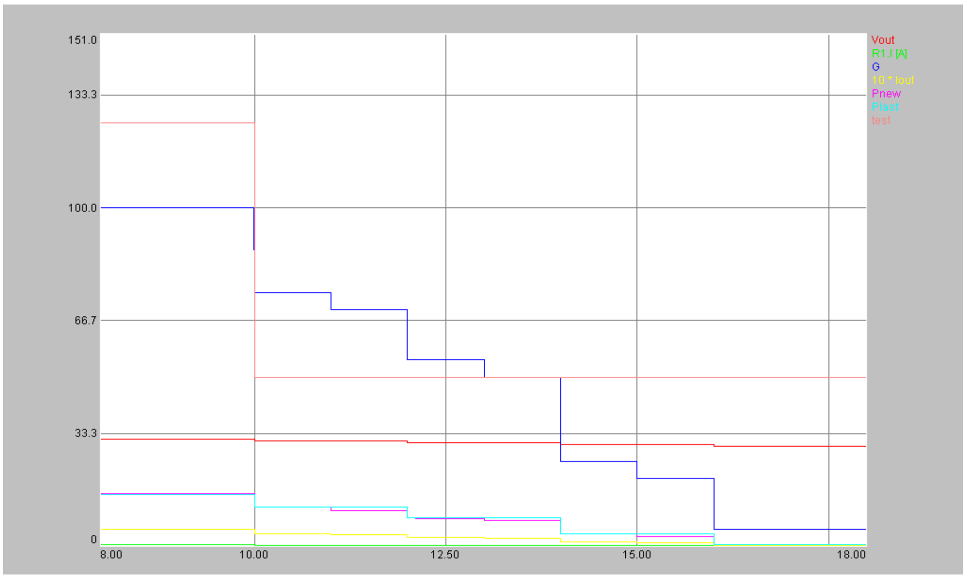


Figure 5.9: P&O Changes in Low Irradiation

It is pointed down in ***Figure 5.9*** that if the ***Pnew*** is smaller than ***Pnew*** (twice) but the difference is not so high (implementation must be 1 W of difference), thereby no Vout jumps are obtained. This configuration should be the same if the small jumps are avoided.

In the next ***Figure 5.10*** (**Congratulation1_jccb_finish_proof_BIGvariat.ssh**) can be observed that it is working well when there are not changes of irradiation direction produced

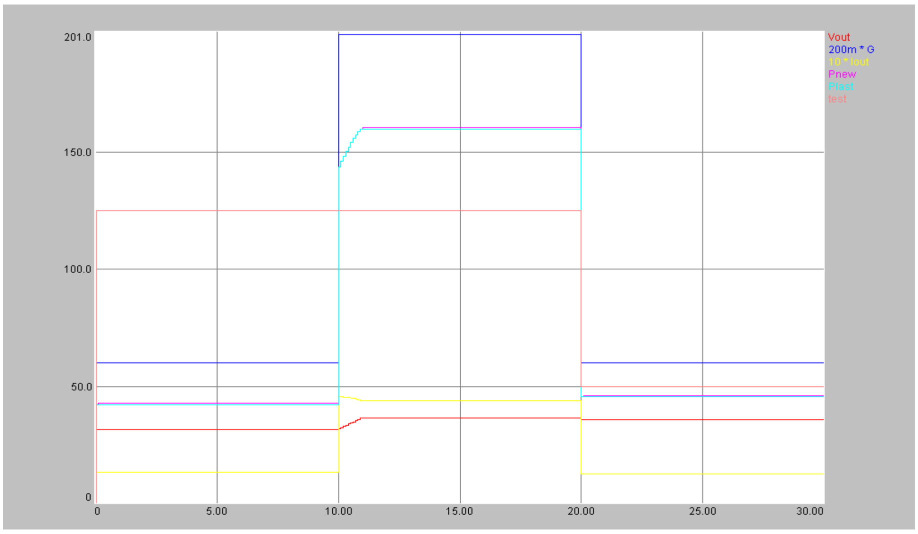


Figure 5.10: P&O Big Variation changes.

Logically at the first change, the voltage out is increasing several times because of it is no located around the maximum power point area. Later at the drop, the voltage moves down just once because of it is located close to the maximum power point and the algorithm just can see the change in this case, not the proportion of the change .

At the end, a clear sky with high irradiances and Temperature increasing simulation in the ***Figure 5.11*** (**Congratulation1_jccb_finish_temperature_summer.ssh**)

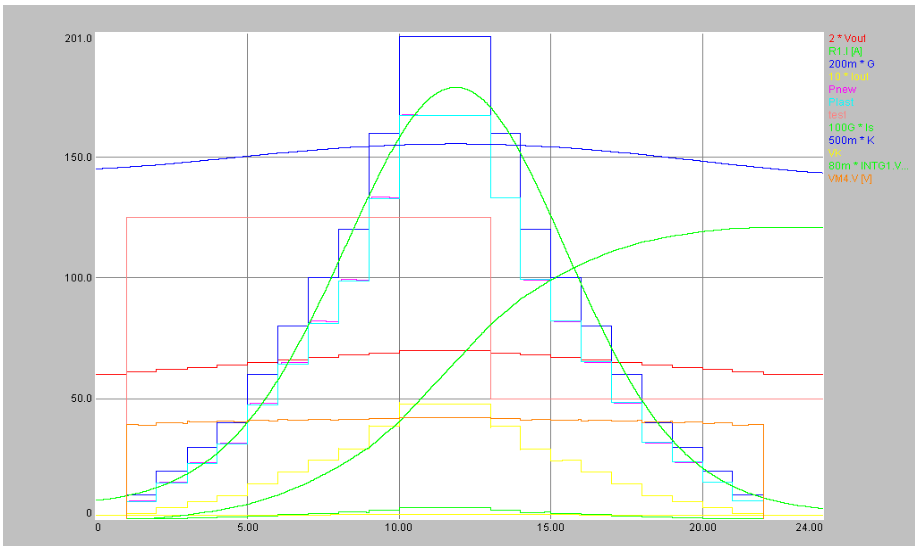


Figure 5.11: P&O Clear Sky with High irradiances and Temperature increasing

Two things to point out. The Voltage out increases until 35 V comparing with 39 V in ***Figure 5.6*** when the temperature was constant (298 K). That is a big difference if it is considered that the temperature just increased since 25 ºC until 35 ºC. ***So much volatge movement for not so big temperature change***. It is not working correctly in the softness of the temperature increases. And the energy (Energy=1512 J) is taken out with an Integrator (one of the green lines –INT) measuring the Pnew. Therefore the Mean Power is just calculated as Power= 1512J/22s =68,72 W. The saturation current was increasing how was expected also from Is=1,32E-10 A until 1,79E-9 A.

All simulation has been done using the data from the Sunmodule SW 160 Mono.The brochure is attached.

ADVANTAGES AND DISADVANTAGES:

The general **advantages** in this algorithm are robustness and simplicity. It can be improved (it will be seen in Efficiency Analysis later) the efficiency around 10 % using this algorithm and comparing fixing the voltage manually in summer and winter.

The **disadvantages** are the next ones: it does *not considers correctly irradiation and temperature effect together* (***Figure 5.11***). The *inability to relate the change* in the PV array power to the change in the atmospheric conditions, it can see the change but it can not appreciate the proportion of this change (in the ***Figure 5.8 and Figure 5.10*** is analysed this situation).

Other general disadvantage is it does not appropriate to be used with load batteries. The worst case is at low temperatures, when the open circuit voltage goes up to higher values and the high-voltage disconnection of the battery can be exceeded. A solution to correct this should be a charge controller fixed in the installation measuring the battery voltage and protect it against overcharging. "However since the circuitry is more complicated, the price of the MPP charge controller is somewhat higher. This means that, for reasons of economy, at present MPP charge controllers are often used only with PV generators of 500 W and more" **[c]**

The algorithm *doesn´t work so good when the radiation varies quickly*, for example, under rapidly changing atmospheric conditions (***Figure 5.10***). In a clear sky with some clouds or covered sky with some clears is observed this situation perfectly. Therefore some losses are reached. About power losses is the next disadvantage also: full power may not delivered to the load or net completly, due to the *power loss when the algorithm is moving continually around MPP without settle down on it*.

Some notes concerning to implementation: There are tow important compromises: There is a compromise between small step voltage (that means less losses) or big step voltage (that means to get more quick the MPP) has to be thought over. There a compromise between big or small Power margin and has to be thought over (***Figure 5.8***). A small Power margin means accurate equipment and small Power margin implies more time to reach the maximum power point. In ***Figure 5.9*** represented: It point down that if the Pnew is smaller than Pnew (twice) but the difference is no so high (implementation must be 1 W of difference), thereby no Vout jumps are obtained.

Concerning a Delay time: A small delay time implies time to make stable Iout in the equivalent circuit, however a delay is produced in our tracking.

A proposal should be when a big variation is produced, just could be bypassed and other algorithm enter in action. We can solve this one bypassing the perturbation stage when we catch the MPP. We can establish a smaller perturbation step also.

[2], [3], [4]

5.3 NEWTON RAPSHON ALGORITHM

5.3.1 N&R BACKGROUND

Newton-Rapshon algorithm is a mathematic algorithm that finds approximations to the roots of a function. Here, it is used to find a minimum or maximum of a function, by finding a zero in the function's first derivative.

It is easy to understand the method: It starts just an initial value close to the root, then the function is approximated by its tangent line. This tangent line cross the X axe at a point which could be known by mathematics equations. Therefore, this point or approximation to the root, will be better every time the algorithm is repeated by iterating.

This algorithm is one of the most simple. It has some characteristics similar to the MPP P&O algorithm. It uses Rapshon iterative method to obtain the voltage in the maximum power point when the derivative of the power is reached.

The equation of the current in a photovoltaic panel:

$$I = m \cdot \left[I_{ph} - I_s \cdot \left(e^{\frac{\alpha \cdot V}{n}} - 1 \right) \right] \qquad \textbf{\textit{[5.1]}}$$

where:

- ***m*** is the strings number or arrays.
- ***n*** cells conected in series.
- I_{ph} is the photo current or short circuit current
- I_s is the diode saturation current
- ***V*** the array voltage

and α :

$$\alpha = \frac{q}{A \cdot k \cdot T} \qquad \textbf{\textit{[5.2]}}$$

where:

- $q = 1.6 \cdot 10^{-19}\, coul$
- $k = 1.38 \cdot 10^{-23}\, j/K$
- T is the cell temperature in Kelvin.
- A is the diode quality factor, we take A=1.

The equation ***[5.1]*** is similar to ***[3.8].*** Just arrays and ***alfa*** have been entered in here.

To find the maximum power, the derivative of the power must be zero.

Under it the operations were calculated:

$$P = V \cdot I = \left[m \cdot \left[I_{ph} - I_s \cdot \left(e^{\frac{\alpha \cdot V}{n}} - 1 \right) \right] \right] \cdot V$$

$$\frac{\partial P}{\partial V} = m \cdot V \cdot \left(- I_s \cdot \frac{\alpha}{n} \cdot e^{\frac{\alpha \cdot V}{n}} \right) + m \cdot \left[I_{ph} - I_s \cdot \left(e^{\frac{\alpha \cdot V}{n}} - 1 \right) \right] = 0$$

[5.3] , [5.4]

Dividing by m and organising it:

$$\frac{\partial P}{\partial V} = f(V) = -V \cdot I_r \cdot \frac{\alpha}{n} \cdot e^{\frac{\alpha \cdot V}{n}} + I_{ph} - I_r \cdot e^{\frac{\alpha \cdot V}{n}} + I_r = 0$$ ***[5.5]***

Newton Rapshon iterative method is defined as (using $f(V)$):

$$V_{n+1} = V_n - \frac{f(V)}{f'(V)}$$ ***[5.6]***

$$\Delta V = \frac{|f(V)|}{|f'(V)|} = \frac{|f(V)|}{\frac{|f(V)|}{\Delta V}}$$ ***[5.7]***

Knowing than: $$f'(V) = \frac{\partial^2 P}{\partial V}$$ ***[5.8]***

For this reason :

$$f'(V) = -\frac{\alpha}{n} \cdot e^{\frac{\alpha \cdot V}{n}} \cdot \left(\frac{\alpha}{n} \cdot I_s \cdot V + I_s \right) + \frac{\alpha}{n} \cdot I_s \cdot \left(- e^{\frac{\alpha \cdot V}{n}} \right)$$ ***[5.9]***

simplifying it:

$$f'(V) = -I_s \cdot \frac{\alpha}{n} \cdot \left(e^{\frac{\alpha \cdot V}{n}} \right) \cdot \left[2 + \frac{\alpha \cdot V}{n} \right]$$ ***[5.10]***

And the next table is obtained. Some changes of notation are taken, ***fn_p*** means $f'(V)$, for example.

The box diagram is represented under ***Figure 5.12***:

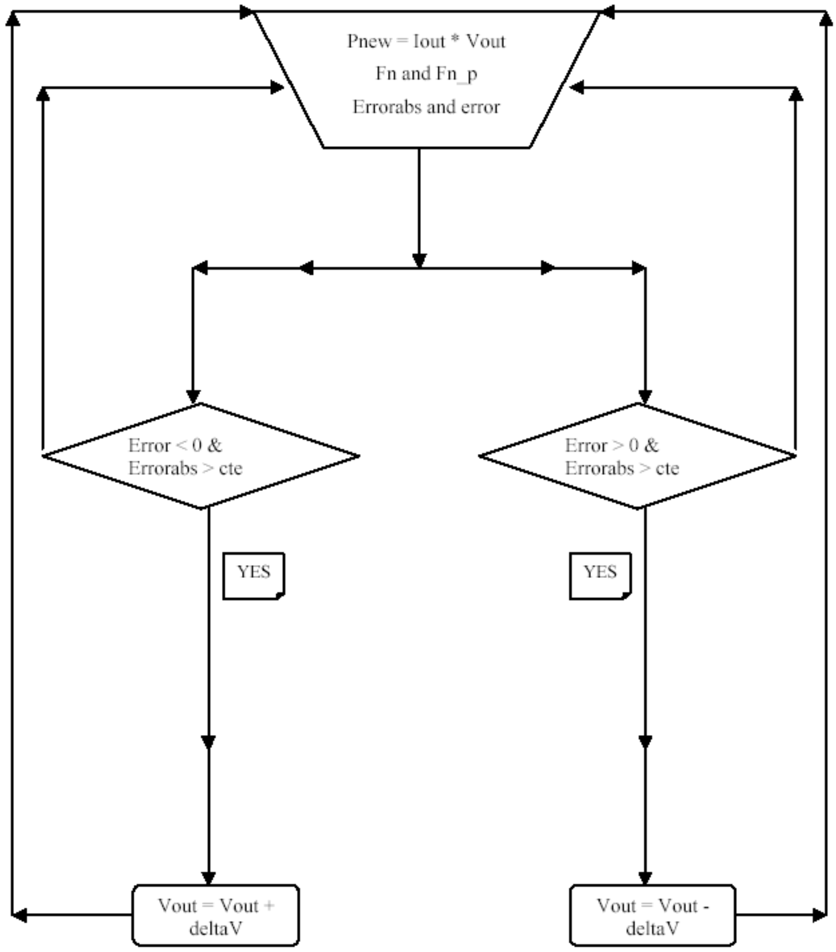


Figure 5.12: N&R Flow Chart

Where:

Fn : The first derivative to the Power.

Fn_p : The second derivative to the Power.

Error: It is the deltaV which as closest the root is as taking the zero value.

Errorabs: It is the absolute error to Error.

The digitalized mistake was talking about in the previous section is solved here comparing ***errorabs > cte***. If this condition is not gotten, the algorithm continues calculating the new errors.

If error is negative, that means that the actual voltage out is situated at the left side of the MPP, therefore Vout is increased. If error is positive, that means that the actual voltage out is situated at the right side of the MPP, therefore Vout is decreased. It can be observed calculating tangents on the $f'(V)$ vs V curve.

This new algorithm is not taken from the bibliography, it is a new improvement about the Perturb and Observe one. It may be asked what is it pretended with this modification? Let us study the next depiction (***Figure 5.13: Current and Power versus Voltage***):

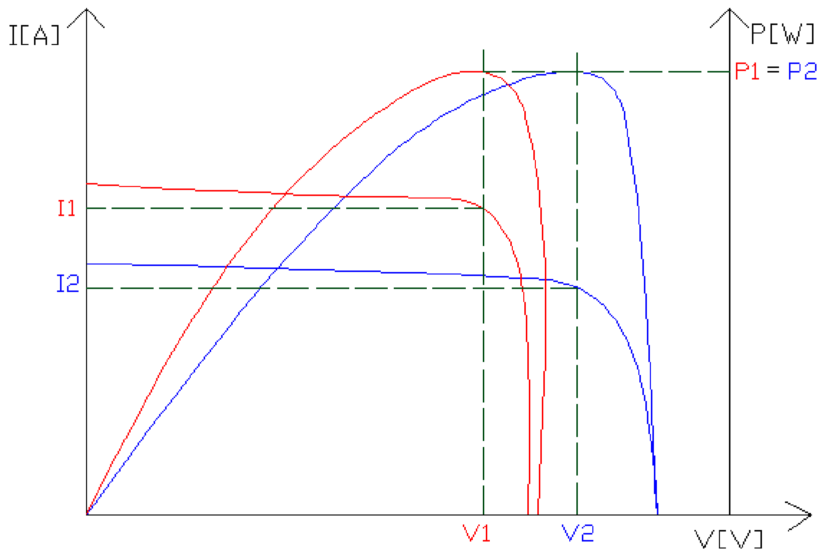


Figure 5.13: Current and Power versus Voltage

This situation could be executed (passing of 1 curve to 2 curve) when a cloud is coming (irradiation is decreased) and at the same time the wind blows strongly (the temperature is diminished). When the sky is covered immediately and some drops fall on the solar panel (this situation implied important and quick temperature changes).

This movement implies the same Power reached but different locations to the MPPs. The Perturb and Observe algorithm can not sense this situation and it would not move and Power losses consequently. Why? Because it just compare differences of Power. Here, Newton Rapshon algorithm is working on Mathematic Error, and this Error considers I and V, therefore this mistake is solved.

The solution is presented under it. Error is analysed. Let us have a look the next equation:

$$\Delta V = \frac{|f(V)|}{|f'(V)|} = \frac{|f(V)|}{\frac{|f(V)|}{\Delta V}} \qquad \textit{[5.7]}$$

If both of them are replaced by their correspondents ***[5.7]*** and ***[5.10]***, and every term equal is associated or grouped, the next one is obtained:

$$|\Delta V| = \frac{C_1 \cdot V_n + I_{ph} + C_2}{C_3 \cdot V_n + C_4} \qquad \textit{[5.11]}$$

Where all ***C*** are constants values obtained when solar cell data are replaced in the equations.

Here is clearly viewed that the Error = deltaV depends on current and voltage.

At first the irradiation changes have been made in Excel and then will be compared the values obtained by Simplorer.

At standard conditions:

Irradiance ***G*** of 1000 W/m2

Cell temperature ***T*** of 25°C with a tolerance of 2°C

Defined light spectrum with an air mass ***AM***=1.5

Two hypothesis have to be considered in Excel implementation:

1.- The PV resistance and Power losses in it are not considered

2.- ***A*** is the coefficient that determines the cell deviation from the ideal p-n junction characteristics and is considered here as ideal. ***A*** takes the value of ***1.***

However in Simplorer PV resistance is considered and therefore the losses Power. But ***A***, the p-n junction coefficient, is taken as ***1*** also. And the resistance model is under-dimensioned comparing with manufacturer provide.

The data are from Sunmodule Sw 160.

The data can be seen in [**Get_power_out_with_NR_G_and_T_CHANGES.xls**]

It estimates on bold letter the maximum power point. It´s located where **deltaV** is close to zero. ΔV calculated before is **deltaV** here. This point is for standard conditions approximately:

$V = 38v$

$I = 4{,}92A$

$\Delta V = 0{,}1179$

$P = 181{,}7w$

Here the difference of the MPP that provided by the manufacturer is dinguished. ***Vmpp*** is given as 35 V and the ***Pmpp*** = 160 W by the manufacturer. In ***Excel*** and in ***Simplorer*** greater values of Power will be obtained. The ideal characteristics of the p-n junction, the resistance model and all circuit implementation also make it. In the simulation a perfect cleaning of the solar panel is considered and the manufacturer considers also a degradation of the modules. It is bigger in the amorphous panel but it should be taken into account in the design. It is also considered by the manufacturer AM = 1,5 and here is considered ideal.

That is the data that can be seen in the sheets or brochures. They are shown in ***Appendix***.

Graphically the derivative of the power versus voltage ***Figure 5.15*** looks like the current function versus voltage ***Figure 5.14***:

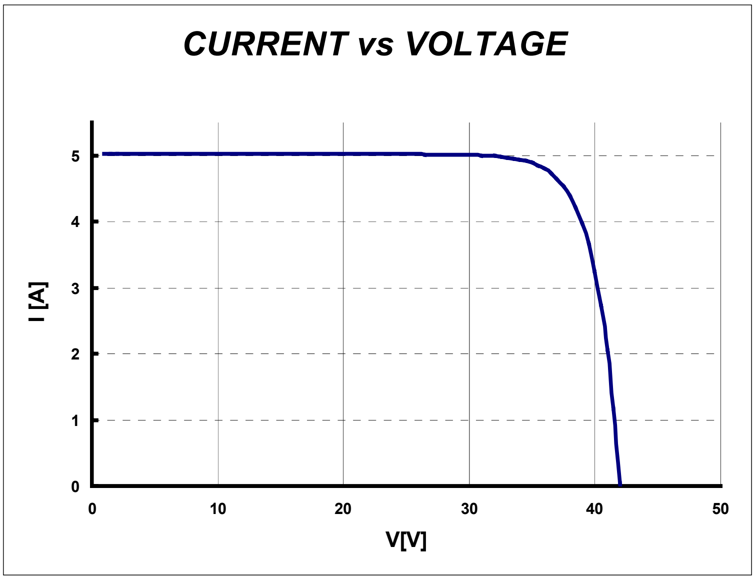


Figure 5.14: SW 160 Current vs array Voltage

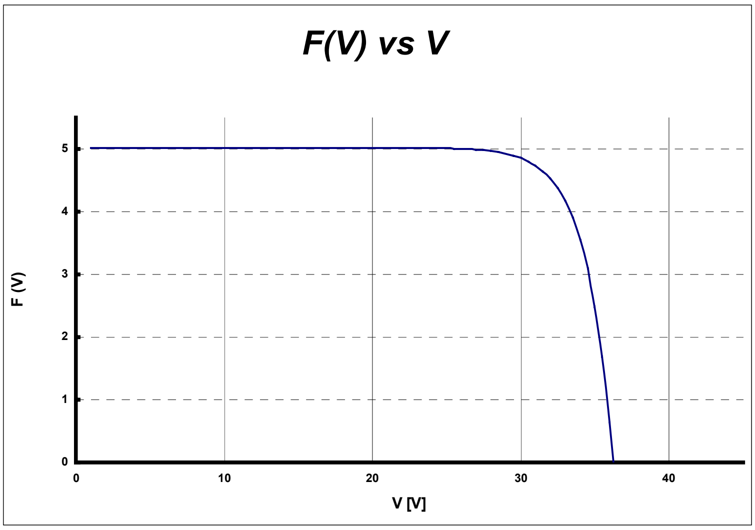


Figure 5.15: SW 160 First Derivative Power versus Voltage

The Precision of the MPP estimator is quite sensible to the position of the first points chosen. They have to be close to the last MPP to not make mistakes with Rapshon iterative method that could drive toward the wrong way. How can the algorithm know in which way move the next step is quite simple. The solution is to compare the power obtained with the previous measurement. If the previous it's smaller, the voltage is decreased and if the previous it's bigger, the voltage it's increased.

5.3.2.- N&R IMPLEMENTATION

The following section shows the implementation of the Newton and Raphson algorithm in Simplorer. At the first just irradiation changes will be simulated. It will be processed with the same conditions that have explained in 5.- WEATHER CONDITIONS.

The Solar Panel Equivalent Circuit corresponds to ***Figure 4.1***

The resistance is calculated according to the equations ***[4.1]*** and ***[4.2]***

The thermal voltage in the diode is calculating as ***[4.12]***

Cause just irradiation changes, Photocurrent is given by ***[4.9]*** and the saturation current of the diode by ***[4.13]***

Cause irradiation and temperature changes, Photocurrent is obtained from ***[4.10]*** and ***[4.11]*** after introducing saturation current in STC ***[4.13]*** in it, will be used to saturation current of the diode in different temperatures.

The equation are going to be used are ***[3.1]*** and ***[3.2]*** to calculate the resistance.

The voltage out initial is set up in stable state when the algorithm is starting. The delay time will be enough to make the parameters stable also. Sampling frequency can be changed also.

All simulations in Simplorer are attached in Appendix. However, the most significant simulations were selected here:

As it was done in Perturb and Observe section, in the next two figures can be compared a Clear Sky in High Irradiation day ***Figure5.16*** (**Newton_raph_sar.ssh**) where the irradiances changes were made by steps and a parabolic representation of the same kind of day ***Figure 5.17*** (**Newton_raphs_sar_sinusoidal_proof.ssh**)

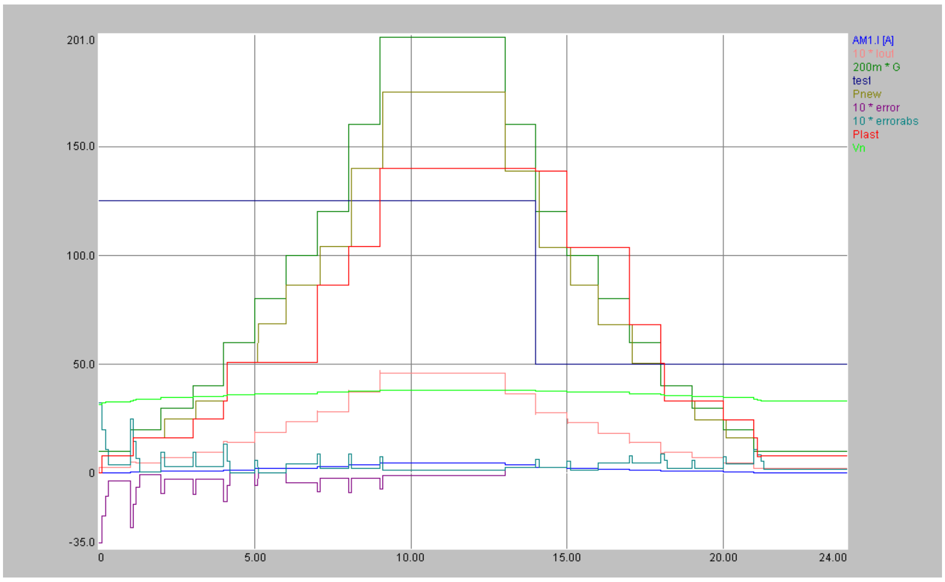


Figure 5.16: NR Clear Sky in High Irradiation

In this simulation above the Voltage out reachs 37, 9 V and the Maximum Power is 174,97 W

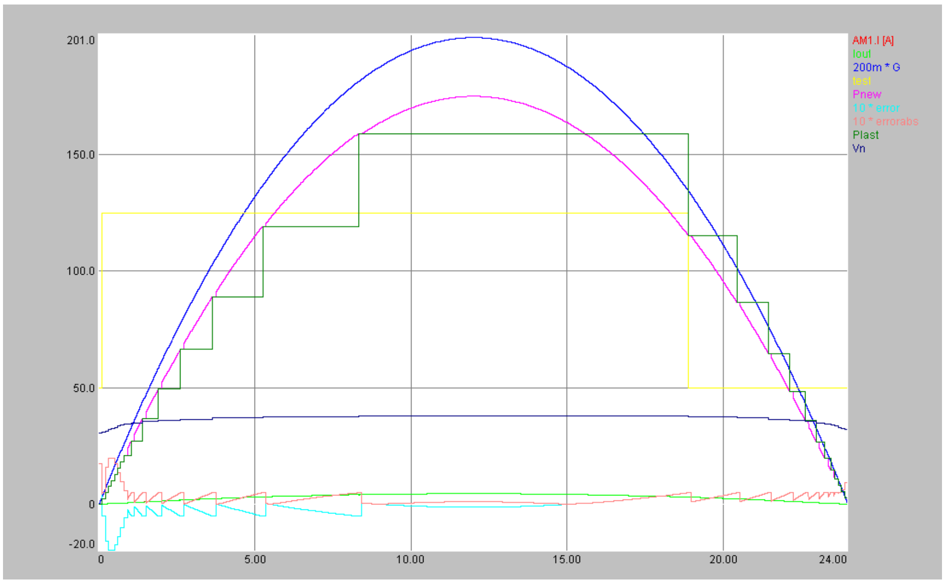


Figure 5.17: NR Clear Sky in High Irradiation

Also in this simulation above the maximum power takes the 174,9 W value and in that point the voltage out is around 37.9 V. Therefore one of the disadvantages of the Perturb and Observe has been solved

In the next ***Figure 5.18***: **Newton_Raph_sar_HisC.ssh** is represented a Clear Sky with Some Clouds in High Irradiances and the natural delays until the correct voltage is reached.

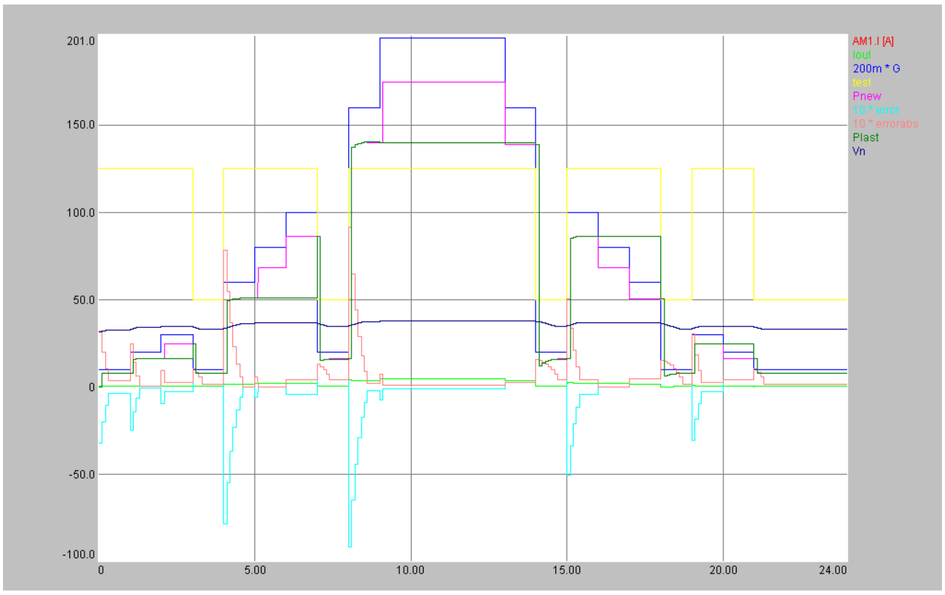


Figure 5.18: NR Clear Sky in High Irradiation with some clouds

It can be explained why this mistake is bigger than the rest of them because of at first not MPP is reached, the Vout is not located around the voltage is expected to be (35 V until 38 V). Which variation is produced here will imply a significant error.

In the next simulation ***Figure 5.19*** is showed how other disadvantage among Perturb and Observe ones are solved. **Newton_Raphson_sar_SMALLvariation2.ssh**

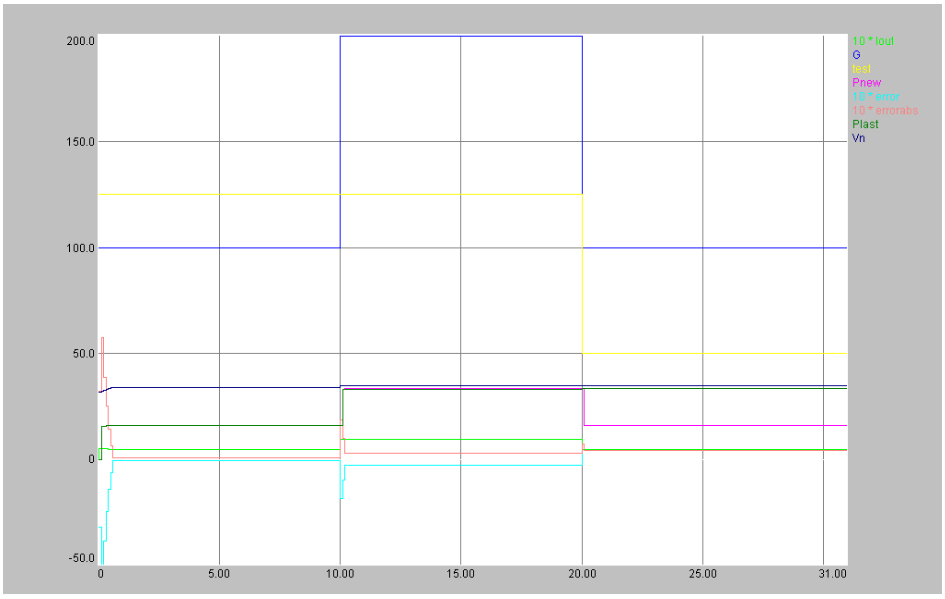


Figure 5.19: NR Changes in low irradiances

When the small variation is produced in low irradiances, the algorithm can see the change perfectly. However it notices that when it is the drop only one step down in V is made, differently that when irradiation increases. That is because of explained before, when the MPP in a high position is reached, a slight movement is done to reach the next one in a drop. Let us think about right side of the curve I vs V.

So, also in low irradiances the curve is flatter than is high irradiances. Therefore the algorithm is expected to move a little more the voltage than when in high irradiations are trying to find out.

At the end the clear sky in high irradiances with temperature variable is simulated and it can be observed a voltage out of 37,9 V similar without changes of temperature. Just it should be decrease a little bit, however the temperature in standard conditions is 298 K and the maximum temperature here is 311 K, not enough to move the algorithm when the step voltage is 0,5 V.

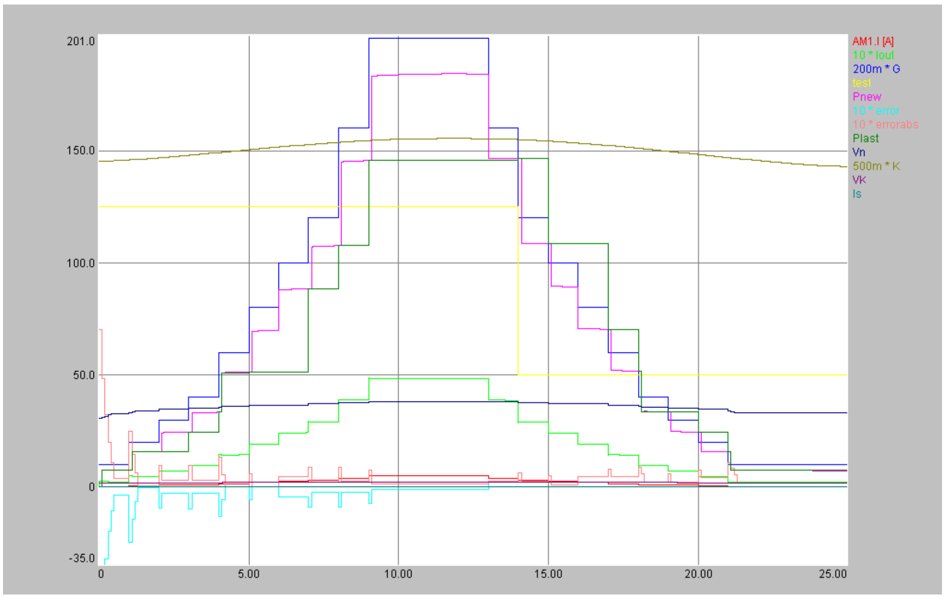


Figure 5.20: NR Clear sky in high in High irradiances with temperature variable.

The next ***Figure 5.21*** represents that was explained before in other case, a simulation of a small irradiation variation.**Newton_Raphson_sar_SMALLvariation.ssh**

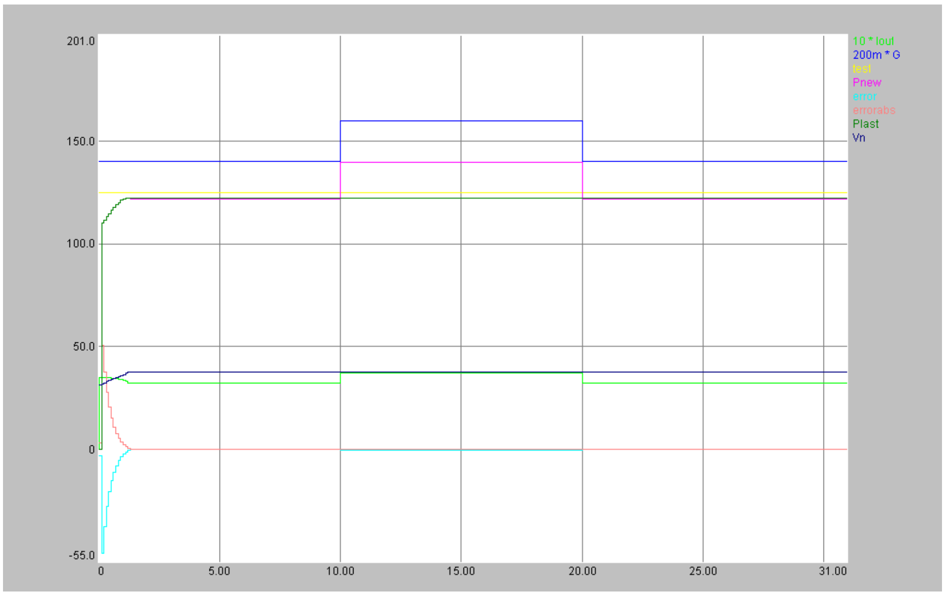


Figure 5.21: NR Small Irradiation Variation

Here the Voltage out goes Vout: 31,5 V→37,4 V and later keeps constant all the time. The algorithm does not move when a small irradiation change is done.

ADVANTAGES AND DISADVANTAGES

The **advantages** of this algorithm are: *Irradiation and temperature effects are considered correctly together* ***Figure 5.20***. *Maximizes the power* from the solar array in the most of the cases. The *proportion of the jump can be seen*, it means *ability to relate the change* in the PV array power to the change in the atmospheric conditions ***Figure 5.18***

The **disadvantages** are: Small changes in high irradiation like in ***Figure 5.21*** can not imply a movement in our algorithm because of the step Voltage 0.5 could be high and in the next point the error would be bigger. However, if we decrease the voltage out, it takes so much time to be stable in low irradiation because of the flatter shape of I vs V curves and to get the root. However, when the small variation is produced in low irradiances, the algorithm can see the change perfectly ***Figure 5.21*** (**Newton_Raphson_sar_SMALLvariation2.ssh**.)

5.4 FLEXIBLE AREA ALGORITHM

A new maximum power point tracking using similar concepts from Constant Voltage and Incremental Conductance is introduced here. Incremental Conductance and Constant Voltage methods will be studied here in detail. Then, these concepts are taken in the new Flexible Area Tracker.

5.4.1 INCREMENTAL CONDUCTANCE METHOD.

According to the author in **[2]** " The IC method seeks to overcome the limitations of the Perturb and Observe method by using the PV incremental conductance and by computing the sign of ***dP/dV*** without a perturbation. It is using the condition that on MPP ***dP/dV = 0***"

The MPP of a PV generator can be tracked accurately by comparing the incremental and instantaneous conductances of the PV array. It will be analysed in detail later.

As already stated, MPP (Vmáx, Imáx) changes when radiation and temperature move from standard conditions, implying continuous adjustement of array terminal voltage.

Now, the current that can be obtained from a PV solar panel is given by ***[3.10]***, the cell reverse saturation current *Is* varies with temperature is given by ***[3.11]***

The PV array power P can be calculated using ***[5.3]*** and ***[5.4]***:

$$P = I \cdot V = m \cdot \left[I_{ph} - I_s \cdot \left(e^{\frac{\alpha \cdot V}{n}} - 1 \right) \right] \cdot V \qquad \textbf{[5.12]}$$

And making the derivative. All operations are:

$$\frac{\partial P}{\partial V} = 0$$

$$I_{ph} - \left[I_S \cdot \left[e^{\frac{\alpha \cdot V}{n}} - 1 \right] + I_S \cdot V \cdot e^{\frac{\alpha \cdot V}{n}} \cdot \frac{\alpha}{n} \right] = 0$$

$$I_{ph} + I_S \cdot e^{\frac{\alpha \cdot V}{n}} \left[-1 - V \cdot \left(\frac{\alpha}{n} \right) \right] + I_S = 0 \qquad \textbf{[5.13]}$$

$$I_{ph} + I_S = I_S \cdot e^{\frac{\alpha \cdot V}{n}} \cdot \left[1 + V \frac{\alpha}{n} \right]$$

$$\frac{I_{ph} + I_S}{I_S} = e^{\frac{\alpha \cdot V_{max}}{n}} \cdot \left[1 + V \cdot \left(\frac{\alpha}{n} \right) \right]$$

Solving the double square equation or last equation ***[5.13]*** above using numerical methods, ***Vmáx*** can be cxalculated as a function ***Iph*** and ***Irs*** that both of them depends on atmospheric conditions ***G*** and ***T.***

The next Figure and Figure shows us the graphic of current versus voltage (array voltage) in different conditions of the temperature and irradiance.

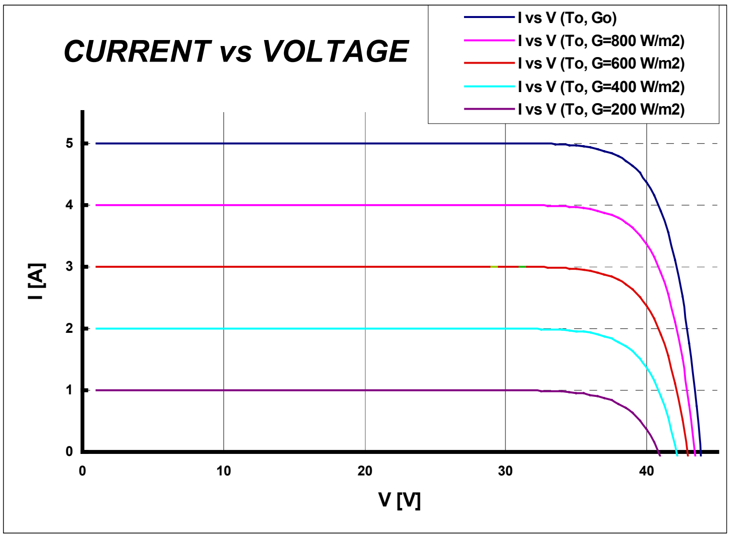


Figure 5.26: Current versus voltage in Radiaction changes and Temperature constant

Now the temperature is changed:

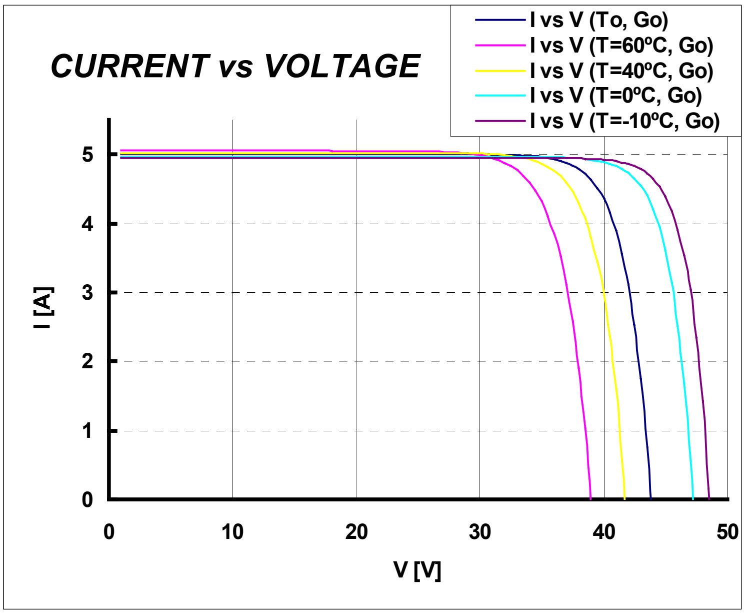


Figure 5.27: Current versus voltage in Temperature changes and Irradiation constant.

Here it is observed that the open circuit voltage variation when irradiation is constant and temperature variable is bigger than in the opposite one.

If ***Avt*** is calculated (medium difference voltage with changes of temperature) and ***Avg*** (medium difference voltage with irradiance) in all cases above, it is obtained that ***Avt>>Avg***. It can be graphically obtained, however also it is known in the equations before than ***Irs=Irs(Ta)*** and ***Iph=Iph(Ta,G)***, what reaffirm the fact. Temperature changes affect to two parameters when ***Vmax*** wants to be obtained in ***[5.13]*** .

All that has been argued above was checked. Although it takes longer to reach one temperature when radiation changes rapidly with a cloud (these ones are immediately). For this reason, radiation changes are fixed like the worst condition for the MPP tracking and next analysis.

The problem in the P&O algorithm was represented in ***Figure 5.5***. To solve this problem in P&O algorithm, authors develop this Incremental conductance method algorithm. In which one the array terminal voltage is adjusted according to its value relative to the MPP voltage.

The basic idea in the incremental conductance algorithm is that derivative of the power with respect to the voltage vanish (become zero) in MPP.

We can see in the next equation:

$$\frac{dP}{dV} = \frac{d(V \cdot I)}{dV} = I + V \cdot \frac{dI}{dV} \qquad \begin{array}{l} \frac{dP}{dV} = 0 \\ \frac{dP}{dV} > 0 \\ \frac{dP}{dV} < 0 \end{array} \qquad \textbf{[5.14]}$$

Therefore: ***dp/dv = 0*** at the MPP, ***dp/dv>0*** to the left of the ***MPP*** and ***dp/dv<0*** to the right of the MPP in terms of array current and voltage. The next ***Figure 5.28*** show us it:

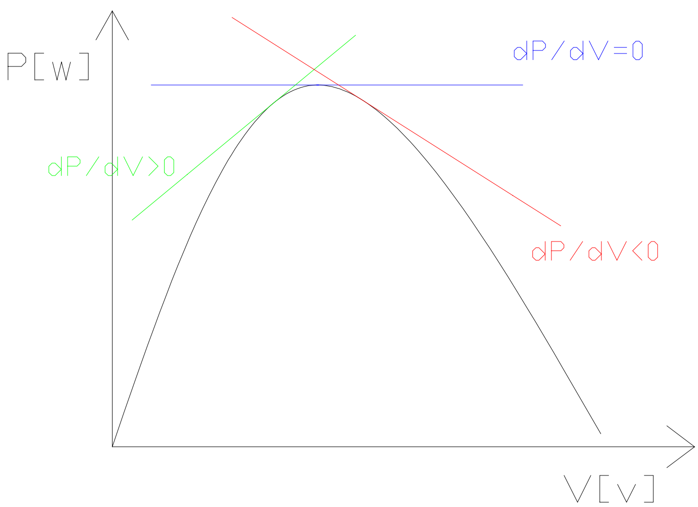


Figure 5.28: Power versus voltage in a solar cell

Hence, the PV array terminal voltage can be adjusted relative to the MPP voltage by measuring the incremental (***dI/dV***) and instantaneous (***I/V***) array conductance, making:

$$\frac{1}{V}\cdot\frac{dP}{dV}=\frac{I}{V}+\frac{dI}{dV}=\pm E \qquad \textbf{[5.15]}$$

The equation above is divided by ***V,*** and ***E*** (tolerance) has been added in the place of zero. Because of it is difficult to get exactly zero. Depending on this value ***E*** is the number of steps of the iteration.

The algorithm in box flow is shown in the following ***Figure 5.29***:

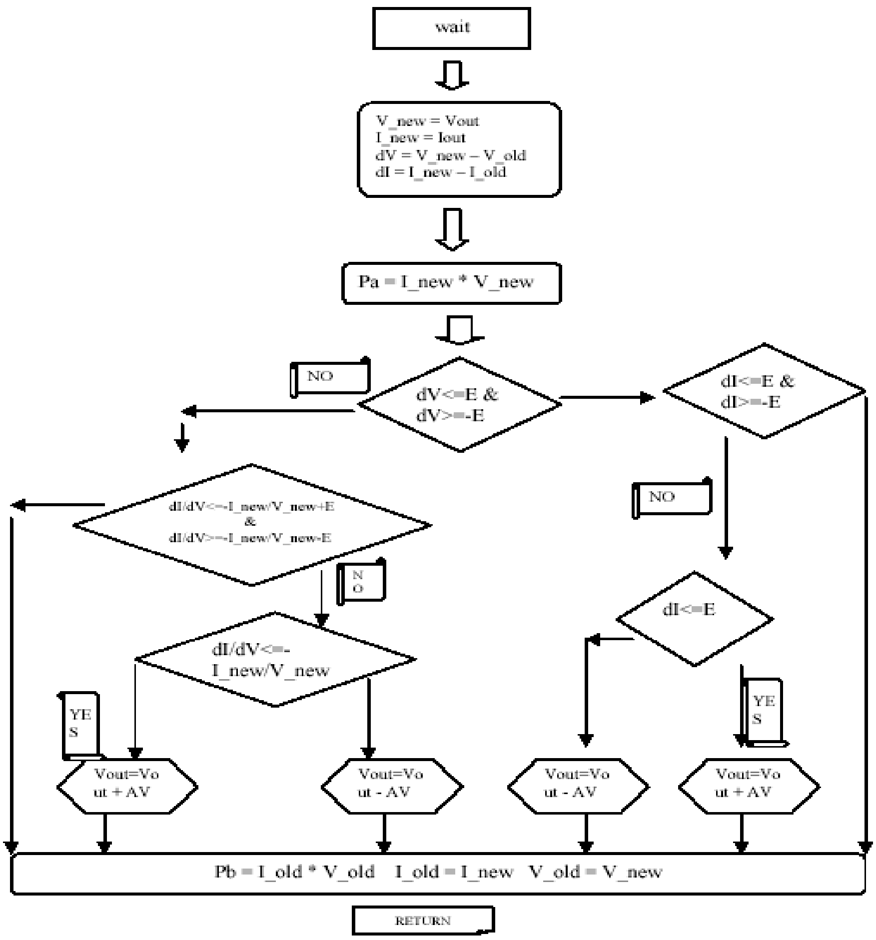


Figure 5.29: Incremental Conductance Algorithm

If the last point is found on the right side of the MPP:

From $\frac{1}{V}\cdot\frac{dP}{dV}=\frac{I}{V}+\frac{dI}{dV}=0$ it is done: ***tg (alfa MPP) + tg (alfa) = 0.*** The meaning is: if ***sen (alfa***) is increasing or ***cos (alfa)*** is decreasing implies ***tg (alfa)*** is going to increase. Because the last point was located on the right side trying to do ***[5.15]*** zero, ***tg (alfa***) has to be decreased (***sen (alfa)*** going to decrease and ***cos (alfa)*** going to increase). The analysis is idem on the left side of MPP. The next graph ***Figure 5.30*** and ***Figure 5.31*** represents all above.

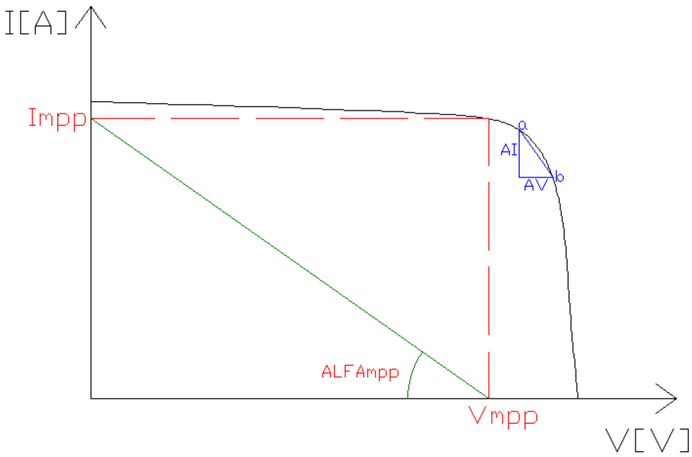
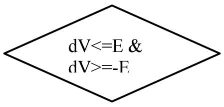


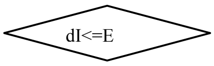
Figure 5.30: Detail of angles in a I vs V graph.

Concerning the algorithm (as a rule: the final point minus initial point when ***AV*** or ***AI*** are made), on the one hand:

If 

is true, the last point was located on the right side of MPP because of ***dV*** are more little on this area (big inclination).

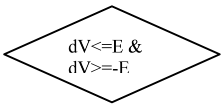
Then, if ***dI***=0 → the situation is just on the MPP and no movements are required.

If ***dI*** is negative 

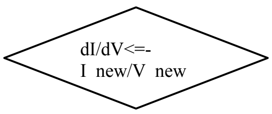
, (look small picture here) mean the attempt will be driven to move towards left side to get MPP.

If ***dI*** is positive, the movement required is going towards right side to get MPP.

On the other hand:

If 

is false, we are on the left side of MPP.

Now the question comes, 

If the last movement was from the right side to the left side (from a to b), ***Ib – Ia*** = + and ***Vb – Va*** = **-** → ***dI/dV*=-** therefore it does mean the algorithm is going far from MPP in this way and the voltage should be increased to close on MPP. Just the picture can be obtained from ***[5.14],*** when ***dV=0*** → ***I*** has not movement and if the ***dI*** (taking the last current from the previous cycle) is bigger than zero, the ***Vmmp*** in this situation is should be located a little bit more right than the last point.

It can be seen clearly why the voltage is increased or decreased at the end.

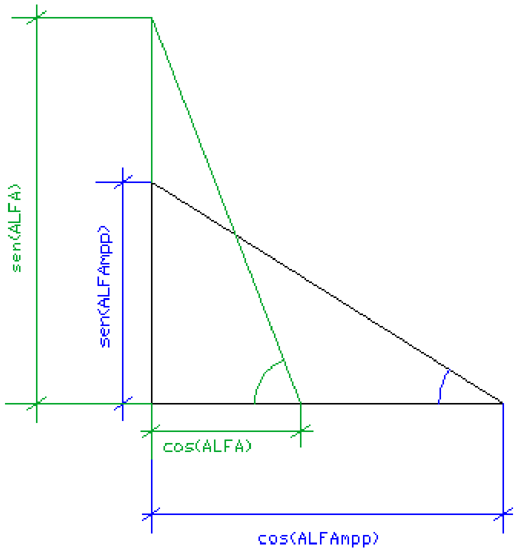


Figure 5.31: Depiction of InC movements using angles

ADVANTAGES AND DISADVANTAGES

The supposed **advantages** in this algorithm are:

Concerning efficiency, the *efficiencies obtained here will be bigger* that in Perturb and Observe algorithm.

Other advantage that it is observed in this algorithm is the *good performance* is expected to have under *rapidly changing atmospheric conditions*. That happens because of its ability to relate the change in the PV array power to the change in the atmospheric conditions (compare the array terminal voltage with the actual MPP voltage).

The **disadvantages** distinguished are:

The condition ***dP/dV=0*** or ***dI/dV=-I/V*** seldom occurred because of the approximation made in the calculation of ***dI*** and ***dV; dI=In-Ib***. However, this problem can be solved and this condition can be detected by allowing a small marginal errors (***E***) in the conditions.

Where ***E*** depends on the required sensitivity of MPP tracking. Obviously, computational costs are higher the smaller the value of ***E*** **.**

5.4.2 CONSTANT VOLTAGE ALGORITHM

This simple method uses the Open Circuit Voltage. The ratio ***Vmpp/Voc*** is usually fixed as 0,76 ***[30]*** and **[2]**. *The charge should be disconnected* sometimes to measure this Voc and then calculate with this ratio where approximately the maximum power point is found. This method was thought because the maximum power point Voltage does not move so much with irradiation changes. When Irradiation changes and temperature keeps constant (298 K) in the panel that was examinated, the maximum power point voltage is located in 3 V of margin. However because of temperature changes, in summer is located in 7 V of margin and in winter in 7 V of margin, that means 14 V the difference. Although each summer and winter can be fixed manually, *it is not saved the 7 V of difference in each stage*. The *losses should be also considered when the load is disconnected* to measure the open circuit voltage and to fix the new voltage. In addition to the maximum power point is not moving in the same way when there are temperature changes or when there are irradiation changes, so it *should be considered two different ratios*. That one of the reason because in the following Flexible Area Algorithm ***dVoc*** will be used to increase the reference voltage.

The **disadvantages** were named above. The method has also its **advantages**, like *simplicity, robust* and *easiest to implement* in a circuitry.

5.4.3 FLEX A BACKGROUND

It was written above that some concepts from Constant Voltage and Incremental Conductance algorithm are used here. It can be checked in some tests **[6], [2], [7]** how the maximum power point and the voltage open circuit among other parameters are moving on a current versus voltage diagram when radiation is increasing or decreasing. Also, some of these diagrams are provided when temperature changes by **[7].** A colored and general resume and graphs about all is given by **[11]**

When all these diagrams are examined carefully it can be emphasized that open circuit voltage movements are according to maximum power point voltage movements. If the temperature is increasing, both of them are moved towards the left side. However, if the irradiation is increasing, they will move towards right side. It was also checked that these movements ***ΔVoc*** and ***ΔVmpp*** are made in the approximately in the same proportion in Temperature changes and in Irradiation changes. That can be taken to approximate the area where the maximum power point voltage is located. Therefore the first hypothesis is ***ΔVoc = ΔVmpp*** in the left side ***Figure 5.29***. The ***dV*** in the flow chart ***Figure 5.29*** is now ***ΔVoc,*** the voltage out is taken as reference voltage and the open circuit voltage as ***V(k)*** represented in **[6]**. It can be observed the first similitude with Constant Voltage algorithm.

In the left side of this flow chart; (when ***dVoc*** is not zero), at the end voltage out is increasing or decreasing like ***Vout= Vout + ΔVoc*** (so, the first hypothesis to place in an flexible area is used). And in the equations above as ***[5.14]*** among other ***dV*** is changed to ***ΔVoc*** because of the first hypothesis ***ΔVoc = ΔVmpp***. So here the maximum power point is approximated to an small area.

Although here it was not calculated it is known that exists a function between open circuit voltage and maximum power point voltage when the temperature changes and other when temperature changes to each solar panel. That is considered as proposal to make this method work perfectly

$$F_T(T)=\left(\frac{\Delta V_{oc}}{\Delta V_{MPP}}\right)_{\Delta T} \qquad F_G(G)=\left(\frac{\Delta V_{oc}}{\Delta V_{MPP}}\right)_{\Delta G} \qquad \textbf{[5.16], [5.17]}$$

The open circuit voltage goes from zero value when irradiation is zero until around 32 V when irradiation is 5 W/m2 in the solar panel tested. This goes to say that this huge difference in only 5 W/m2 of irradiation has not be considered if mistakes want to be avoided. Voltage out initial starts in 32 V also and just changes open circuit voltage from here are summed.

In the right side of the flow chart (see ***Figure 5.29*** with the changes named before) comes the question, what happens when ***ΔVoc*** is almost zero? For example, when the temperature is kept constant and a light change of irradiation happens. Here ***dI*** is observed, if ***dI*** is increasing (in the example before), the ***Vmmp*** moves slightly to the right side and viceversa. So the voltage of reference here (voltage out) should be increased. But, how much should be increased this reference voltage? It is obvious not the same that in the left side of the flow chart. Answers to this questions are not solved in the papers **[2], [6], [7], [23]** among others. The arrangement is to fix a ratio between voltage and current and to sum this ratio multiply by ***dI*** to reference voltage or voltage out. That means a flexible area or variable area would be configured each cycle. It was defined above that open circuit voltage is around 32 V in the tested panel when irradiation is almost zero (5 W/m2), here the short circuit current is zero A. When the irradiation takes the maximum value (1000 W/m2) the short circuit current is 5 A and the open circuit voltage is 43,8 V in the tested solar panel. Therefore to calculate this new ratio, it is made:

$$ratio = \frac{(V_{oc})_{G=1000W/m2} - (V_{oc})_{G=5W/m2}}{(I_{sc})_{G=1000W/m2} - (V_{sc})_{G=5W/m2}} \qquad \textbf{[5.18]}$$

Therefore the ratio in these test reach a value of 2 on the solar panel tested. The reference voltage would increase or decrease in this way: ***Vout = Vout+dI*2***

All of this explains how the algorithm process in this right side. The losses to open the circuit and to measure the voltage open circuit have not been considered in the simulations because that depends on the circuitry used to open the circuit and the time that is takes to make it. However in the following analysis efficiency was considered an approximation of these losses and two different efficiencies have been calculated.

5.4.4 FLEX A SIMULATION

A clear sky high irradiation simulation is made in two different ways as before. One is increasing the irradiation as steps ***Figure 5.32*** (**JCCB_clear_sky_HI_A.ssh**).

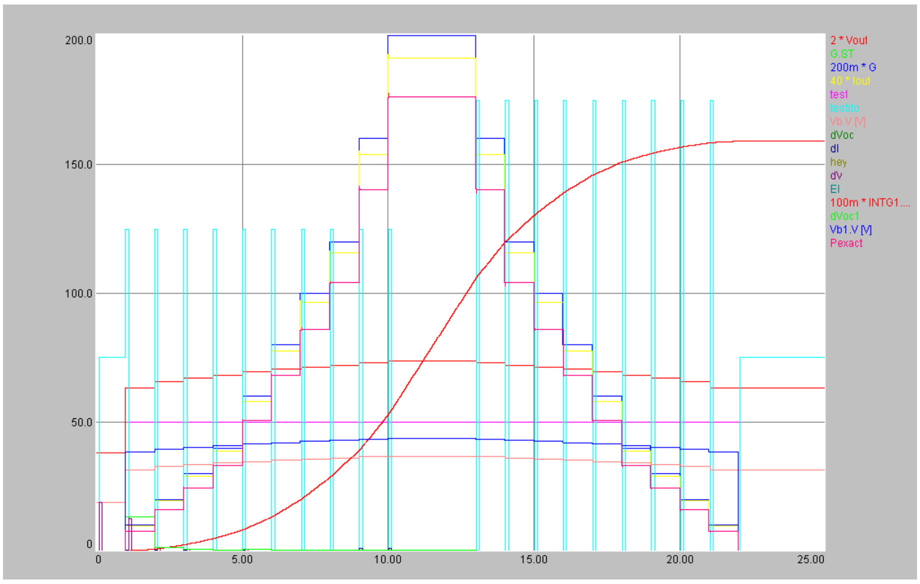


Figure 5.32: FA Clear Sky In High Irradiation simulation

In Figure 5.32 just the left side of the flow chart is working. It can be checked because the variable test is equal to zero all the time. The other one is increasing the irradiation as a parabolic way ***Figure 5.33*** **JCCB_clear_sky_HI_parabolic_A1.ssh .** Now in the parabolic representation ***Figure 5.33*** the right side of the flow chart begins to work. That is the most important difference between both of them .

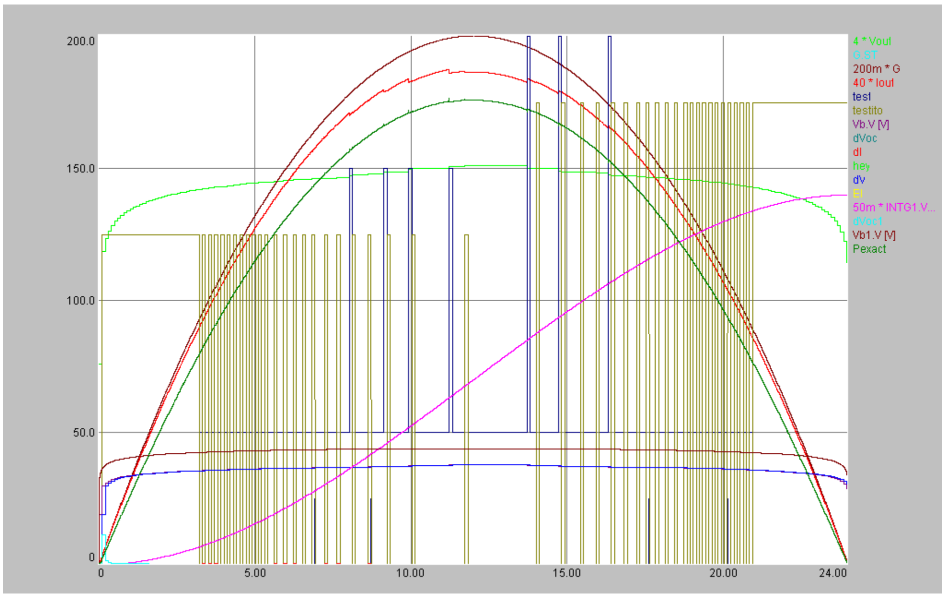


Figure 5.33 : FA Clear Sky In High Irradiation simulation

In the big variation of irradiance simulation, ***Figure 5.34*** it can be appreciated one wrong way of increasing the voltage out. Let us look the ***Iout*** variable. **JCCB_BIGvariat.ssh**

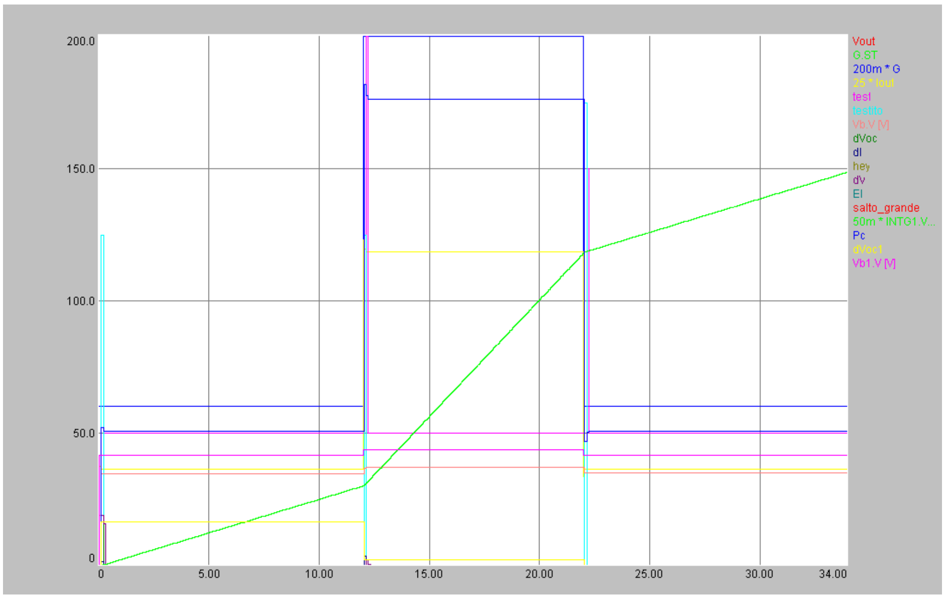


Figure 5.34 : FA Clear Sky In High Irradiation simulation

In ***Figure 5.35*** a small zoom of the area interested is made. Here is appreciated better that because of a huge current increase, and the later correction, Iold stored is bigger than the new Iout and dI is negative, therefore Vout would decrease (line red is 4*Vout). That is not right because Vout must increase.

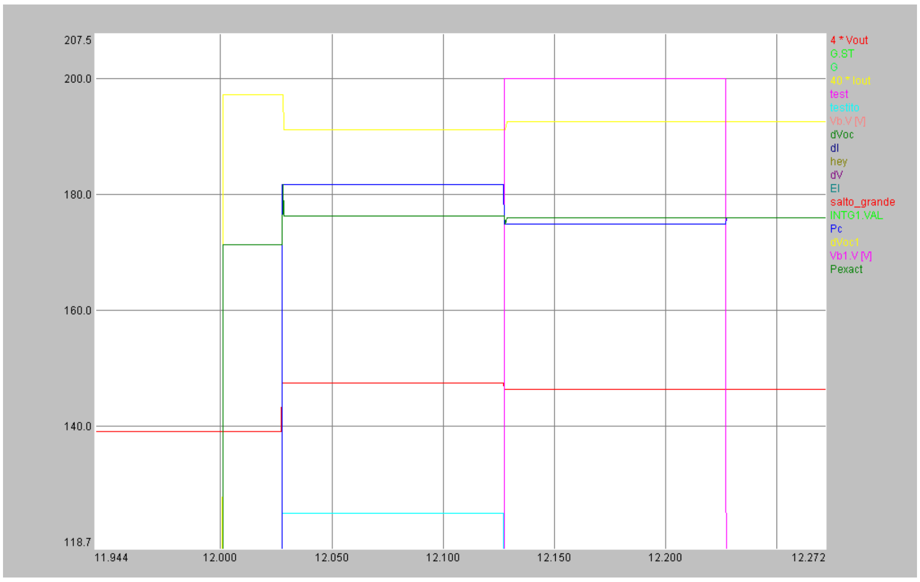


Figure 5.35: FA A small zoom of the area of the Figure 5.34

The solution is made when the ***Vout*** is bypassed if ***dI*** is so small, it means bypass the way. However Power losses can not be avoided and this can be depicted in the ***Figure 5.36.*** Just the exact power is given by the green line.

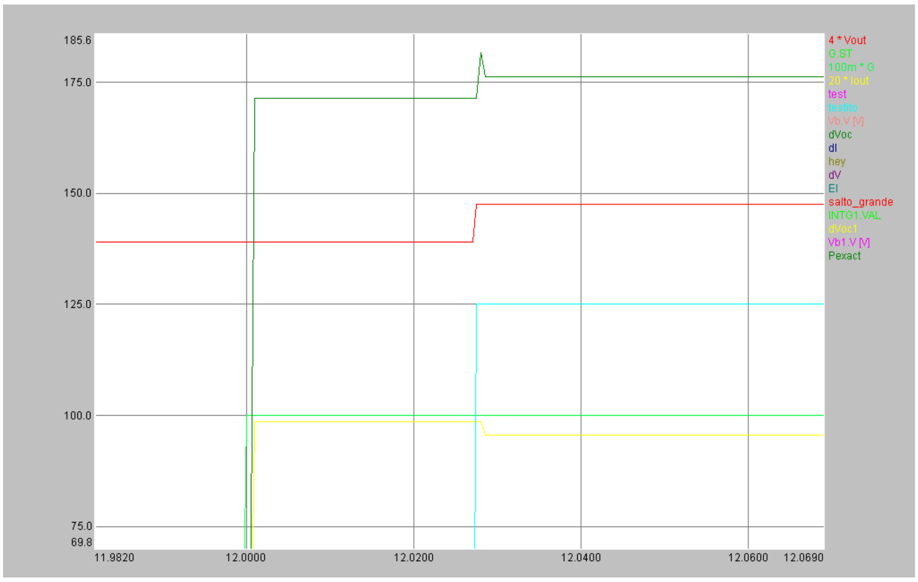


Figure 5.36: FA Power losses representation of the Figure 5.35

And now temperature and radiation changes together. The most representative one is the simulation of a clear sky in high irradiances when the temperature is variable (**JCCB_clear_sky_HI_G_and_T_changes_K.ssh**) in *Figure 5.37*:

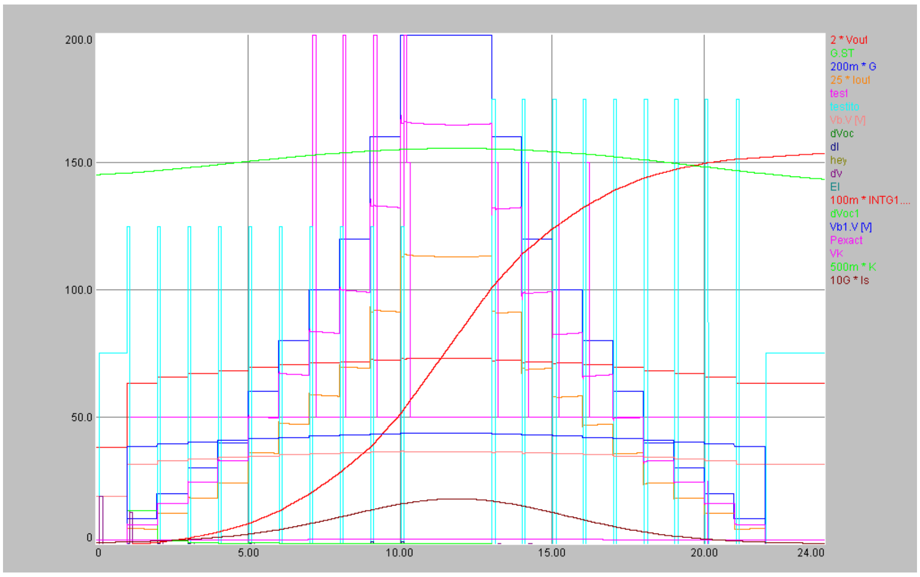


Figure 5.37: FA Clear sky in High irradiation with T changing.

The Vout is going from 31,6 V until 36,4 V when the irradiation reach the standard conditions. The maximum power in this point is Pmax: 168,64 W and the total energy given by the integrator 1536,00 J . Therefore the mean Power =1536/22=69,82 W. Open circuit voltage is decreased from 43,8 V until 43,6 V because of temperature increases.

<u>ADVANTAGES AND DISADVANTAGES:</u>

The most important **advantages** are the simplicity and the area where the maximum power point is located is fixed quickly. (***Figure 5.33***)

The most important **disadvantage** is that peaks of current could happen if the Voc is measured at the same time that the increase of Power. (***Figure 5.34*** and ***Figure 5.35***).

6 EFICIENCY ANALISYS

The Energy Conversion Efficiency of the Tracker ($\eta_{MPP_{track}}$) or Mean Power Conversion Efficiency (calculate as the energy divided by the time which is taken to measure this energy) is the ratio between the output energy extracted using the tracker and the theoretical energy that the solar panel could provide if the MPP tracker would track the maximum power point perfectly.

In this work the output energy extracted using the tracker is given by an integrator (it can be seen in all graphs as INT.) fixed in Simplorer with the algorithm and the circuit equivalent running out under the Temperature and Irradiance conditions described in the previous section (all these graphs can be observed in detail in [**radiation changes_AND_temperature changes_graphs_CORRECTED.xls**]. The theoretical energy that the solar panel could provide if the MPP tracker would track the maximum power point perfectly is calculated in the excel file [**Get_power_out_with_NR_G_and_T_CHANGES.xls**]according to Newton Raphson Method which works in accurate values on non linear equations. The data from Simplorer are introduced manually to [**POWER CALCULATIONS_AND_COSTS.xls**] and the data from [**Get_power_out_with_NR_G_and_T_CHANGES.xls**] are linked to [**POWER CALCULATIONS_AND_COSTS.xls**] where all efficiency and costs (in the following section) are calculated.

An example explaining these files is introduced here. The selected case was the K.- Irradiation and Temperature changes in a Clear Sky in High Irradiances.

At first the weather conditions were settled in the section Weather Conditions ***Figure 4.3 until 4.10*** . The changes in irradiation are introduced in Simplorer by states and transitions as steps (figuring the worst case), it can be checked in all Figures of the simulation behind it in the ***Appendix .*** The temperature condition is introduced as an equation (called K:=function (t)). In this example was:

K: = 2E-15*t^5 + 0,0007*t^4 - 0,0341*t^3 + 0,3666*t^2 + 1,0239*t + 290,33 ***[6.1]***

R2 = 0,9971

Where:

K is the Temperature in Kelvin

T is the time.

R2 is closer to 1 as better approximation to the realm trend.

The [**Get_power_out_with_NR_G_and_T_CHANGES.xls**] is made up by two sheets. One is called “temperature changes” where the temperature from ***[6.1]*** is calculated in every time and irradiation condition.

K)		G	At	t	T	VT	Iph	Is	I	V	Vcarga	Icarga	LN	VT*LN
IRRADIANCE AND TEMPERATURE CHANGES	K.- Clear Sky in High Irradiances	50	1	2	293,58	1,82	0,2	1,32E-10	0,2	38,9			24,3570	4,44E+01
		100	1	3	295,84	1,84	0,5	1,88E-10	0,5	39,9			24,0030	4,41E+01
		150	1	4	298,29	1,85	0,8	2,75E-10	0,8	40,2			23,6240	4,38E+01
		200	1	5	300,79	1,87	1,0	4,02E-10	1,0	40,4			23,2434	4,34E+01
		300	1	6	303,21	1,88	1,5	5,78E-10	1,5	40,8			22,8805	4,31E+01
		400	1	7	305,45	1,90	2,0	8,04E-10	2,0	41,0			22,5511	4,28E+01
		500	1	8	307,39	1,91	2,5	1,07E-09	2,5	41,2			22,2676	4,25E+01
		600	1	9	308,97	1,92	3,0	1,34E-09	3,0	41,3			22,0398	4,23E+01
		800	1	10	310,13	1,93	4,0	1,58E-09	4,0	41,7			21,8748	4,21E+01
		1000	2	12	311,00	1,93	5,0	1,79E-09	5,0	42,0			21,7515	4,20E+01
		TOTAL	11											

Figure 6.1 : Case K / [Get_power_out_with_NR_G_and_T_CHANGES.xls] / "temperature changes"

This temperature value must be moved towards "NR" sheet in the yellow gap. Also the condition of irradiation is introduced in the other yellow gap. Because of all parameters of the SW160 tested were introduced:

SOLAR PANEL	SW 160
Manufacturer data	
Pmáx (W)	160
Voc (V)	43,8
Vmpp (V)	35
Isc (A)	5
Impp (A)	4,58

Figure 6.2: Manufacturer data Case K /[Get_power_out_with_NR_G_and_T_CHANGES.xls]/ "temperature changes"

MAXIMUM POWER WITH NEWTON RAPHSON			
Iph [A]	5,0	G [W/m2]	1000
Is [A]	1,789E-09	Isc [A]	5
alfa	37,28	Go [W/m2]	1000
q [C]	1,6E-19	tau	0,0015
A	1		
k [J/K]	1,38E-23	Eg [eV]	1,1
T [K]	311	Vmpp [V]	36,5
n	72	Iso [A]	2,6301E-10
Vt [V]	0,02682	To [K]	298

Figure 6.3: Maximum Power with Newton Rapshon. Case K /[Get_power_out_with_NR_G_and_T_CHANGES.xls] /"temperature changes"

Afterwards the program gives the ***Vmpp*** (here it takes the 39,5 V of value) when the following iterations are calculated and it looked up the smaller error.

Fn	Fn_p	V(n+1)	deltaV	I	Power	Vn
5,01950E+00	-3,91364E-09	1282564389,6	-1,283E+09	5,0	5,0	1
5,01950E+00	-5,59143E-09	897712512,5	-8,977E+08	5,0	7,5	1,5
5,01950E+00	-7,91905E-09	633851247,6	-6,339E+08	5,0	10,0	2
5,01950E+00	-1,1134E-08	450824906,6	-4,508E+08	5,0	12,5	2,5
5,01950E+00	-1,55576E-08	322640386,6	-3,226E+08	5,0	15,1	3
5,01950E+00	-2,16232E-08	232135247,5	-2,321E+08	5,0	17,6	3,5
5,01950E+00	-2,9915E-08	167791896,7	-1,678E+08	5,0	20,1	4
5,01950E+00	-4,12192E-08	121775719,4	-1,218E+08	5,0	22,6	4,5
5,01950E+00	-5,6592E-08	88696347,6	-8,870E+07	5,0	25,1	5
5,01950E+00	-7,74507E-08	64808992,5	-6,481E+07	5,0	27,6	5,5
5,01950E+00	-1,05695E-07	47490328,4	-4,749E+07	5,0	30,1	6
5,01950E+00	-1,43869E-07	34889336,8	-3,489E+07	5,0	32,6	6,5
5,01950E+00	-1,95375E-07	25691681,0	-2,569E+07	5,0	35,1	7
5,01950E+00	-2,64757E-07	18958914,2	-1,896E+07	5,0	37,6	7,5
5,01950E+00	-3,58084E-07	14017681,3	-1,402E+07	5,0	40,2	8
5,01950E+00	-4,83448E-07	10382720,5	-1,038E+07	5,0	42,7	8,5
5,01950E+00	-6,51634E-07	7702951,5	-7,703E+06	5,0	45,2	9
5,01950E+00	-8,77003E-07	5723477,2	-5,723E+06	5,0	47,7	9,5
5,01950E+00	-1,17866E-06	4258643,7	-4,259E+06	5,0	50,2	10
5,01950E+00	-1,58203E-06	3172839,5	-3,173E+06	5,0	52,7	10,5
5,01950E+00	-2,12085E-06	2366746,2	-2,367E+06	5,0	55,2	11
5,01950E+00	-2,83998E-06	1767450,5	-1,767E+06	5,0	57,7	11,5
5,01949E+00	-3,79892E-06	1321306,0	-1,321E+06	5,0	60,2	12
5,01949E+00	-5,07661E-06	988761,7	-9,887E+05	5,0	62,7	12,5
5,01949E+00	-6,77768E-06	740604,1	-7,406E+05	5,0	65,3	13
5,01948E+00	-9,04079E-06	555217,7	-5,552E+05	5,0	67,8	13,5
5,01948E+00	-1,20496E-05	416583,2	-4,166E+05	5,0	70,3	14
5,01947E+00	-1,60471E-05	312811,0	-3,128E+05	5,0	72,8	14,5
5,01946E+00	-2,1355E-05	235064,0	-2,350E+05	5,0	75,3	15
5,01945E+00	-2,83985E-05	176765,8	-1,768E+05	5,0	77,8	15,5
5,01943E+00	-3,77402E-05	133015,8	-1,330E+05	5,0	80,3	16
5,01941E+00	-5,01229E-05	100158,6	-1,001E+05	5,0	82,8	16,5
5,01938E+00	-6,65283E-05	75464,3	-7,545E+04	5,0	85,3	17
5,01934E+00	-8,82526E-05	56892,3	-5,687E+04	5,0	87,8	17,5
5,01929E+00	-0,000117007	42915,5	-4,290E+04	5,0	90,4	18
5,01923E+00	-0,000155048	32390,6	-3,237E+04	5,0	92,9	18,5
5,01914E+00	-0,000205355	24460,3	-2,444E+04	5,0	95,4	19
5,01902E+00	-0,000271854	18481,7	-1,846E+04	5,0	97,9	19,5
5,01886E+00	-0,000359722	13972,1	-1,395E+04	5,0	100,4	20
5,01865E+00	-0,000475782	10568,7	-1,055E+04	5,0	102,9	20,5
5,01838E+00	-0,000629022	7999,1	-7,978E+03	5,0	105,4	21
5,01802E+00	-0,000831282	6058,0	-6,036E+03	5,0	107,9	21,5
5,01754E+00	-0,001098151	4591,1	-4,569E+03	5,0	110,4	22
5,01690E+00	-0,001450152	3482,1	-3,460E+03	5,0	112,9	22,5
5,01607E+00	-0,001914293	2643,3	-2,620E+03	5,0	115,4	23
5,01497E+00	-0,002526114	2008,7	-1,985E+03	5,0	118,0	23,5
5,01351E+00	-0,003332364	1528,5	-1,504E+03	5,0	120,5	24
5,01159E+00	-0,004394526	1164,9	-1,140E+03	5,0	123,0	24,5
5,00906E+00	-0,005793442	889,6	-8,646E+02	5,0	125,5	25
5,00572E+00	-0,007635385	681,1	-6,556E+02	5,0	128,0	25,5
5,00133E+00	-0,010060029	523,1	-4,971E+02	5,0	130,5	26
4,99554E+00	-0,013250912	403,5	-3,770E+02	5,0	133,0	26,5
4,98791E+00	-0,017449161	312,9	-2,859E+02	5,0	135,5	27
4,97787E+00	-0,022971497	244,2	-2,167E+02	5,0	138,0	27,5
4,96465E+00	-0,030233864	192,2	-1,642E+02	5,0	140,4	28
4,94725E+00	-0,039782406	152,9	-1,244E+02	5,0	142,9	28,5
4,92437E+00	-0,052334101	123,1	-9,409E+01	5,0	145,4	29
4,89426E+00	-0,068830026	100,6	-7,111E+01	5,0	147,8	29,5
4,85468E+00	-0,090505204	83,6	-5,364E+01	5,0	150,3	30
4,80263E+00	-0,118980139	70,9	-4,036E+01	5,0	152,7	30,5
4,73421E+00	-0,156380801	61,3	-3,027E+01	5,0	155,1	31
4,64430E+00	-0,205495848	54,1	-2,260E+01	5,0	157,4	31,5
4,52616E+00	-0,26998264	48,8	-1,676E+01	5,0	159,7	32
4,37096E+00	-0,354637128	44,8	-1,233E+01	5,0	162,0	32,5
4,16712E+00	-0,465747401	41,9	-8,947E+00	5,0	164,1	33
3,89945E+00	-0,61155676	39,9	-6,376E+00	5,0	166,1	33,5

3,54800E+00	-0,802870164	38,4	-4,419E+00	4,9	168,0	34
3,08666E+00	-1,05384836	37,4	-2,929E+00	4,9	169,6	34,5
2,48115E+00	-1,383047665	36,8	-1,794E+00	4,9	171,0	35
1,68656E+00	-1,814781222	36,4	-9,293E-01	4,8	172,1	35,5
6,44024E-01	-2,380900941	36,3	-2,705E-01	4,8	172,7	36
-7,23620E-01	***-3,123129869***	***36,3***	***2,317E-01***	***4,7***	***172,7***	***36,5***
-2,51747E+00	-4,096114719	36,4	6,146E-01	4,6	171,9	37
-4,87000E+00	-5,371420473	36,6	9,067E-01	4,5	170,1	37,5
-7,95474E+00	-7,042757311	36,9	1,129E+00	4,4	166,9	38
-1,19990E+01	-9,232819334	37,2	1,300E+00	4,2	162,0	38,5
-1,73005E+01	-12,10223125	37,6	1,430E+00	4,0	154,7	39
-2,42491E+01	-15,86125165	38,0	1,529E+00	3,7	144,4	39,5
-3,33554E+01	-20,78508083	38,4	1,605E+00	3,3	130,1	40
-4,52878E+01	-27,23388149	38,8	1,663E+00	2,7	110,6	40,5
-6,09212E+01	-35,67896083	39,3	1,707E+00	2,1	84,2	41
-8,14012E+01	-46,73700748	39,8	1,742E+00	1,2	48,8	41,5
-1,08227E+02	-61,21485713	40,2	1,768E+00	0,0	1,7	42
-1,43360E+02	-80,16801996	40,7	1,788E+00	-1,4	-60,8	42,5

Figure 6.4 : Iterations to calculate the Maximum Power with Newton Rapshon. Case K /[Get_power_out_with_NR_G_and_T_CHANGES.xls] / "temperature changes"

The Power and the Current in the maximum power point are taken out from this last Table and a summarize for temperatures and irradiances required are added in the [**POWER CALCULATIONS_AND_COSTS.xls**] where the maximum power points for each temperature and irradiation are showed. It is known:

G	*T*
50	293,58
100	295,84
150	298,29
200	300,79
300	303,21
400	305,45
500	307,39
600	308,97
800	310,13
1000	311,00
SUMMER	

Figure 6.5: G and T in case K

K.-	MPP SUMMER DAY G AND TEMPERATURE CHANGES					
ERROR	G	ERROR abs	I	POWER	V	T
-0,0371	50	0,0371	0,2	7,9	38,9	293,6
0,1088	100	0,1088	0,5	16,3	39,9	295,8
-0,2351	150	0,2351	0,7	24,7	40,2	298,3
0,1455	200	0,1455	0,9	33,1	40,4	300,8
-0,2194	300	0,2194	1,4	50,2	40,8	303,2
0,1058	400	0,1058	1,9	67,3	41,0	305,5
-0,0090	500	0,0090	2,4	84,5	41,2	307,4
-0,1131	600	0,1131	2,9	101,7	41,3	309,0
0,0320	800	0,0320	3,8	137,1	41,7	310,1
-0,2705	1000	0,2705	4,8	172,7	42,0	311,0

alfa	desv	size	confid. Interv
0,05	0,0902	10	0,056

LOW	Promedio	HIGH
-0,11	-0,05	0,01

Figure 6.6: MPP in the K case

The ***error abs*** was described in the Newton Rapshon Algorithm section with the rest of interpretation of these numbers. Now the confidence interval is introduced. This interval uses *alfa* (0,05 means 95 % of probability), *desv* is the standar desviation and the *size* of the sample is 10 data. This function returns a value used to construct a confidence interval for the mean of *error abs* which is the voltage error. This value comes from a normal distribution knowing the standard deviation (*desv*), the mean (*promedio*) and the size of the sample (*size*). It can 95 % percent confident that the error voltage in the maximum power point is within the interval which takes as minimum value *LOW* and as maximum value *HIGH.*

$$[-0'11-0'05,-0'11+0'01]$$
$$[-0'16,-0'10]$$

Therefore the maximum power point voltage in all cases of summer introduced of the Figure would be within:

[Vmpp – 0’16 , Vmmp – 0’10]

In a 95 % of probability. In the case above in *Figure ()* for ***G*** = 1000 W/m2 and the ***T***= 311 K, the *Vmmp* is within the interval *[36’34 , 36’4]*

In the *A* until *H* cases where Temperature is the standard one and constant, one step in the process is avoided (about *“temperature changes*” sheet) and one of the yellow gaps is never changed.

Now is the moment to introduce all Energy data coming from the Integrator of Simplorer. Because of all maximum power points were calculated and they keep constant during one second of the simulation, the next table could be obtained for K.- case:

K)		G	At	t	T	VT	Iph	Is	I	V	Vcarga	Icarga	LN	VT*LN	POWERmmp	Energympp
IRRADIANCE AND TEMPERATURE CHANGES	K.- Clear Sky in High Irradiances	50	1	2	293,6	1,82	0,2	1,32E-10	0,2	38,9			24,3570	4,44E+01	7,9	7,9
		100	1	3	295,8	1,84	0,5	1,88E-10	0,5	39,9			24,0030	4,41E+01	16,3	16,3
		150	1	4	298,3	1,85	0,8	2,75E-10	0,8	40,2			23,6240	4,38E+01	24,7	24,7
		200	1	5	300,8	1,87	1,0	4,02E-10	1,0	40,4			23,2434	4,34E+01	33,1	33,1
		300	1	6	303,2	1,88	1,5	5,78E-10	1,5	40,8			22,8805	4,31E+01	50,2	50,2
		400	1	7	305,4	1,90	2,0	8,04E-10	2,0	41,0			22,5511	4,28E+01	67,3	67,3
		500	1	8	307,4	1,91	2,5	1,07E-09	2,5	41,2			22,2676	4,25E+01	84,5	84,5
		600	1	9	309,0	1,92	3,0	1,34E-09	3,0	41,3			22,0398	4,23E+01	101,7	101,7
		800	1	10	310,1	1,93	4,0	1,58E-09	4,0	41,7			21,8748	4,21E+01	137,1	137,1
		1000	2	12	311,0	1,93	5,0	1,79E-09	5,0	42,0			21,7515	4,20E+01	172,7	345,4
		TOTAL	11										Perdidas	0,2	**63,1**	**868,2**
															Without track	Mean Power
															0,80	**78,9**

PO		NR		InC+CV FLEXIBLE area	
Mean Power tracker	Efficiency	Mean Power tracker	Efficiency	Mean Power tracker	Efficiency
68,7	**87,1**	77,48	**98,2**	69,8	**88,5**

Figure 6.7: Efficiency of the trackers

And all different cases are linked to the next resume table:

	EFFICIENCY		
CASE	PO	NR	FLEX A
A.-	87,1	96,9	88,0
B.-	93,4	96,6	98,2
C.-	96,3	95,5	97,4
D.-	97,4	98,1	96,1
E.-	93,9	97,6	98,0
F.-	98,4	99,9	100,0
G.-	96,5	96,6	97,2
H.-	95,7	96,8	97,4
K.-	87,1	98,2	88,5
M.-	92,3	94,1	96,7
Mean	***93,8***	***97,0***	***95,8***
desv	3,98	1,57	4,10
alfa	0,05	0,05	0,05
size	10	10	10
conf.interv	2,47	0,97	2,54
LOW E	***91,3***	***96,1***	***93,2***
MEAN	***93,8***	***97,0***	***95,8***
HIGH E	***96,3***	***98,0***	***98,3***

Figure 6.8 : Efficiency analysis all cases.

Thus the correct interpretation of all efficiency data is within interval.

PO: ***[91'3 ; 96'3]***

NR: ***[96'1 ; 98]***

FLEX A : [93,2 ; 98,3]

In a clearer way is the next graph **Figure 6.9**:

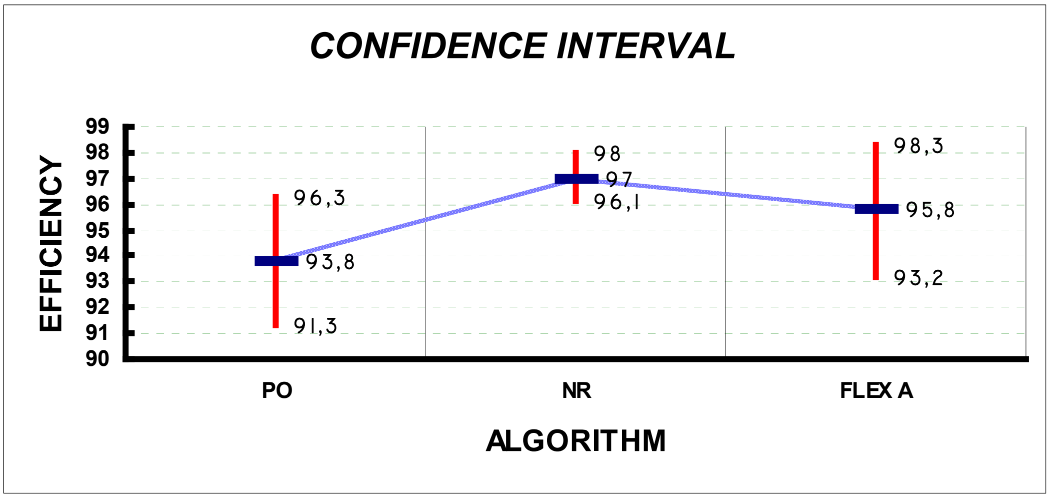


Figure 6.9 : Confidence Interval of Efficiency

It is easy to analyse that the best efficiency is reached by Newton Rapshon algorithm. This one should be the first chosen. It is clear and according to what was expected because the same method was used to implement the simulations in Simplorer and to calculate the maximum power points in excel. It can be observed that the volatility or margin is the narrowest, just less than 2.

The next one that was chosen is the FLEX A, using Incremental Conductance and Constant Voltage concepts, because the volatility is the same comparing with Perturb and Observe (around 5) and the mean efficiency is bigger.

7 ECONOMIC ISSUE

7.1 BACKGROUND

Economic assessment must always be taken into account in Engineering decisions. This section presents an overview on the economical aspects of the implementation of photovoltaic systems. The following analysis will consider how the power efficiency of the solar panel influences in the power production costs.

A basic issue is implicit here, the "time of value of the money" (a interest rate will be fixed).

Concerning phovoltaic generation, two separated cases can be studied:

A) Grid- connected systems
B) Off grid connected systems

This section focus on grid connected systems because PV has an huge off-grid market due to one of its most important characteristics: modular.

The cost trend of grid connected systems and the sales since 1998 approximate is represented in the figure…. It can be observed the great increase in sales and the reducing costs because of continued progress in performance.

7.2 ANALYSIS

7.2.1 ANNUATY FACTOR

If ***I*** is invested at an interest rate of ***i*** percent per year, after ***n*** years without movements in account, the new quantity of money will be:

$$F = I \cdot (1+i)^n \qquad \textbf{[7.1]}$$

Thus, the I of a future quantity of money is:

$$I = F \cdot (1+i)^{-n} \qquad \textbf{[7.2]}$$

If during several years several quantities of money are summed, in the ***n*** year the new value of the money is given by:

$$F = I_y \cdot \left(1 + (1+i) + (1+i)^2 + \ldots + (1+i)^{(n-1)}\right) \rightarrow F = I_y \cdot \frac{\left((1+i)^n - 1\right)}{i} \qquad \textbf{[7.3]}, \textbf{[7.4]}$$

Equation ***[7.4]*** is introduced in ***[7.2]*** and the present value ***I*** of a constant quantitiy of money $\boldsymbol{I_y}$ every year is calculated:

$$I = \frac{I_y \cdot \left((1+i)^n - 1\right)}{\left(i \cdot (1+i)^n\right)} \qquad \textbf{[7.5]}$$

Thus the annuity factor: $\boldsymbol{a_f}$ is calculated as :

$$a_f = \frac{I_y}{I \cdot (1+i)^n} \qquad \textbf{\textit{[7.6]}}$$

Using ***[7.5]***:

$$a_f = \frac{i}{1-(1+i)^{-n}} \qquad \textit{[7.7]}$$

This $\boldsymbol{a_f}$ is enabling the cost to be converted into capital costs that keep up year on year considering time of value of the money. **[11], [13]**

The actual typical interest offered by a bank is 3% and the life of the PV system is around 30 years. Thus the $\boldsymbol{a_f}$ for the actual economic analysis is: 0.05102

It should be commented that $\boldsymbol{a_f}$ does not consider inflation effect. Therefore, why is going to be useful this analysis? Because the purpose is comparing different alternatives system where the inflation affects in the same way.

7.2.2 CASH FLOW

When the Cash Flow, ***CF*** is positive, it means that the benefits are bigger than the costs. In all equations above, ***I*** or ***Iy*** could be positive or negative. If they are positive, they are called benefits (***B)*** and if they are negative, then these values are called costs (***C)***. Therefore the Cash Flow equation can be written in the next two ways:

$$CF = I_{purchase} + I_{electricity} + I_{savings} + I_{repairs} + I_{maintenance} \qquad \textbf{\textit{[7.8]}}$$

It is known that repairs, maintenance and the purchase are costs. The electricity generated and considerable savings are benefits.

$$CF = C_{purchase} + B_{electricity} + B_{savings} + C_{repairs} + C_{maintenance} \qquad \textbf{\textit{[7.9]}}$$

The smaller the costs, the sooner will CF be positive. The following analysis is made considering just Costs. **[11], [13]**

7.2.3 POWER PRODUCTION COSTS

Power production costs (C_{pp} or C_T) are the sum of repairs, maintenance and purchases. This costs are referred by kWh installed.

The cost of the panel, or the purchase value, is considered in this analysis to be 2220 E for 420 kWh maximum installed – around 420 kWh are extracted from 160SW solar panel tested (see [**POWER CALCULATIONS_AND_COSTS.xls]** in electronic format (CD) attached) considering a mean value as hours of sun in Europe- and the efficiency standard without tracker will be considered as 80 %, the last one means 20 % of losses. The maintenance is required each 5 year (depends on size PV system and located place), its costs go around 190 E each time. By the 20th year, 2 repairs are expected to have occurred, each one of them at the cost of 675E –look Table in THIS-. **[11], [13], [14], [24].** In the purchase costs are summed array, controller and the installation. However in the purchase costs it was not considered the MPP tracker cost to avoid making the value up. This will be one hypothesis in the following analysis, costs with or without tracker are the same. In the maintenance costs the annual inspection are assumed and in repairs are included replacement also. [24]. The mean values provided by **[24]** are taken into account after **[11], [13] and [24]** were analysed in ***Table 7.1*** .

Book	kWh inst	TOTAL	E/kWh	Purchase	%	M+R	%	Mainten	%	Repairs	%
[24]	800	9350	11,69	4400	0,47	4950	0,53	2250	0,24	2700	0,29
[11]	800	10000	12,50	7000	0,70	3000	0,30				
[13]	22000	224000	10,18	200000	0,89	24000	0,11	20000	0,09	4000	0,02
THIS	400	4675,00	5,84	2200,00	0,24	2475,00	0,26	1125,00	0,12	1350,00	0,14

Table 7.1: Costs examples

At first the present worth of these costs are calculated. It means that all money is invested already to the same year of the purchase. Taken this assumption, it is desired to determine the Power Production Costs at the end life of the PV system. Therefore n will take 30 years and the annuity factor a_f for the actual economic analysis is: 0.05102 . Finally these equations will be able to compared how much the Power Production Costs are reduced with different trackers. The analysis compares PV systems with different trackers, but with the same purchase values.

In the following ***Table 7.2*** the ***[8.2]*** is used. The ***i*** is 0,03 (3%) and the ***n*** is the corresponding year.

YEAR	COSTS	
	MAINTEN	REPAIRS
5	163,90	
10	141,38	502,26
15	121,95	
20	105,20	373,73
25	90,75	
30	78,28	
TOTAL	**701,45**	**875,99**

Table 7.2 : Costs update to each year.

The ***Table 7.2 : Costs update to each year*** can be seen in [**POWER_CALCULATIONS_AND_COSTS.xls**] in electronic format (CD) attached. The equation used to calculate the present discounted value of future payments in the ***Table 7.2*** is ***[7.2].***

Without tracker the Power Production Costs are:

$$C_{T_{WT}} = C_{PP_{WT}} = \frac{(C_{purchase} + C_{repair} + C_{maintenance}) \cdot a_f \cdot \eta_{Theory_{MAX}}}{Energy_{PV} \cdot \eta_{WT}} \qquad \textbf{[7.10]}$$

Where:

$\eta_{Theory_{MAX}}$ is the theoretical efficiency, the maximum (100%)

η_{WT} is the efficiency without tracker.

η_T is the new efficiency with tracker.

$Energy_{PV}$ is the theoretical energy generated per year by the PV system (the maximum could be extract by the solar panel tested –160SW) given by [**POWER CALCULATIONS_AND_COSTS.xls**] in C16 cell.

$C_{T_{WT}}$ are the total costs without tracker.

$C_{PP_{WT}}$ are the power production costs without tracker

The variables in Equation ***[7.10]*** are calculated for a period of 30 years..

The index ***WT*** means without tracker.

With tracker the Power Production Costs are:

$$C_{T_{Tracker}} = C_{PP_{tracker}} = \frac{(C_{purchase} + C_{repair} + C_{maintenance}) \cdot a_f \cdot \eta_{Theory_{MAX}}}{Energy_{PV} \cdot \eta_{tracker}} \qquad \textbf{[7.11]}$$

$C_{PP_{tracker}}$ are the power production costs with the solar photovoltaic array working with the tracker.

$C_{T_{Tracker}}$ are the total costs with the solar photovoltaic array working with tracker.

$\eta_{tracker}$ is the efficiency of the maximum power point tracker.

Using ***[7.10]*** and ***[7.11]*** the table showed all values.

COSTS	PO	NR	FLEX A
Effficiencies	93,80	97,03	95,75
Without	80	80	80
Cwt [E/kWh]	0,5781	0,5781	0,5781
C [E/kWh]	0,4930	0,4766	0,4830
AC [E/kWh]	0,0851	0,1014	0,0951
%	**14,7**	**17,5**	**16,4**

Table 7.3 : Difference costs comparing a PV working with tracker or without tracker using different algorithms.

The losses in Power are from 20% and 40% **[11],** here it was considered the best case, just 20 % of losses generated means efficiencies without tracker around 80 %. Therefore the data obtained (15 %) are at least the money is saved when MPP trackers are used.

If the same analysis was made in non-renewable alternatives during the same Life Cycle should be favour the renewable ones. An example can be read in **[24]** Because until now just a simple initial cost comparison that not included lifetime energy consumption (zero in renewable and high consumption of fuel, coal…in non-renewable) was made, the non-renewable kept up as favourites. In ***[8.9]*** $C_{maintenance}$ are bigger in non-renewable alternatives, Energy Costs (fuel, coal,…) not included in ***[8.9]*** because of zero value in renewable energy, in non-renewable alternatives is high every year, $B_{savings}$ also is bigger in renewable ones. All of this goes to say that CF in renewable takes zero value before than non-renewable, therefore it can be seen the advantages of renewable. All of this without consider aspects as energy independence, non risk regarding inflation of fuel and sustainability which make the renewable a good choice in Europe on nowadays.

7.2.4 DISCOUNTED PAYBACK PERIOD AND ENERGY PAYBACK TIME

It was explained before that when ***CF*** begins to be positive, that indicates benefits bigger than costs. Discounted Payback Period is the year just when ***CF*** (the sum of costs and benefits) begins to be positive. This economic measure is simple and does not consider the cash flow after recovery of the initial investment. Obviously it considers time of value of money (discounted). According to ***[7.8]***:

$$\sum_{n=0}^{DPB} \frac{I_i}{(1+i)^n} = 0 \qquad \textbf{\textit{[7.12]}}$$

As the analysis here done is concerning costs, not benefits and the time and space is limited, just the equation will be showed.

Similar analysis is taken in Energy Payback Time, which shows the year when the energy already produced by PV system is equal to the energy was that was spent in its production. A considerable amount of energy is consumed in finding and purifying Silizium, making steel, plastic, transporting, among others. After that energy is then produced by the PV systems. The smaller the Energy Payback Time, the least environmental impact would be produced. This energy payback is smaller in countries with high irradiances and in countries where recycling is more commonly practiced (EPT could be reduced 20 % with this last measure). **[11], [13]**

8 CONCLUSIONS AND PROPOSALS

The efficiency of the solar panel is deeply connected with its ability to track the maximum power point. The main conclusions were written in MPP TRACKERS section, in EFFICIENCY ANALYSIS and in ECONOMIC ISSUE.

In MPP trackers section all advantages and disadvantages were specified. The most significant ones are shown in T***able [8.1]***.

After an efficiency analysis was made, the results show that the best efficiencies are reached with Newton Rapshon algorithm (NR: [96'1 , 98]) in comparison with Perturb and Observe method (PO: [91'3, 96'3]) or the Flexible Area method–using Incremental Conductance and Constant Voltage –(FLEX A : [93,2 ; 98,3]). Therefore the Newton Algorithm is suggested to implement in DSP. Also the mean value of efficiency is more centered that in the other ones. . However in the following Proposals if the Flexible Area is improved, its variability could be reduced and the best interval of efficiency would be reached, because the maximum eficiency corresponds to it.

In the economic issue to point out the most significant is 15 % of the power production costs are at least the money is saved when MPP trackers are used ***Table 7.3***.

One of the proposal is the improvement in the Constant Voltage algorithm and the consequently improvement in the Flexible Area algorithm. The ratio ***Vmpp/Voc*** is usually fixed as 0,76 **[30]** and **[2]** in Constant Voltage Algorithm. An improvement was explained in Flexible Area considering a function between open circuit voltage and maximum power point voltage when the temperature changes and other when temperature changes to each solar panel. However just the aproximation ***ΔVoc = ΔVmpp*** was made. Therefore this function **[5.16]** and **[5.17]** can be found.

Other proposal is concerning the Constant Voltage algorithm and the consequently one in Flexible Area algorithm. To fix the ratio ***Vmpp/Voc*** or to make ***ΔVoc = ΔVmpp*** is necessary to measure the open circuit voltage and some Power losses appear. The manufacturers provides the thermal characteristics (%/K) of the short circuit and the (%/K) of the open circuit voltage. Therefore, implementing the measurement of temperature could avoid losses of Power in these 2 algorithms (Constant Voltage and Flexible Area Algorithm).

In this work the crystalline cell was analysed, because by now there is not an equivalent circuit made of the thin film technology. The less clearly marked MPP demands better control technology of inverter and the MPP controller. So it is also suggested to compare these simulations with the thin film ones making all new equations and the equivalent circuit.

The last proposal is made in Perturb and Observe Algorithm and concerns the response of the algorithm when a big variation is produced. It is suggested that this perturbation stage could be bypassed and other algorithm could enter in action.

ALGORITHM	**ADVANTAGES**	**DISADVANTAGES**
Constant Voltage	Easy to implement in circuitry	Power losses when charge is disconnected
Incremental Conductance	Good performance under rapidly changing atmospheric conditions	The condition **dP/dV=0** is seldom occurred. It can be solved with marginal errors (**E**) in the conditions.
		Power losses are unavoidable.
Flexible Area Algorithm	Simplicity and the area where the maximum power point is located is fixed quickly. (Figure 5.33)	Peaks of current could happen if the Voc is measured at the same time that the increase of Power. (Figure 5.34 and Figure 5.35).
NR	Irradiation and temperature effects are considered correctly together **Figure 5.20**	Small changes in high irradiation like in **Figure 5.21** can not imply a movement because of the step voltage.
	The proportion of the jump in irradiation can be seen. (Figure 5.18)	In low irradiances, the algorithm cannot see the changes perfectly (**Figure 5.21)**
	Maximizes the power from the solar array in the most of the cases	
Perturb and Observe	Robustness and simplicity	It does not consider correctly irradiation and temperature effect together (**Figure 5.11**).
		It can see the irradiation change but it can not appreciate the proportion of this change (**Figure 5.8 and Figure 5.10**).
		Doesn´t work so good when the radiation varies quickly, for example, under rapidly changing atmospheric conditions (**Figure 5.10**)
		Power losses when the algorithm is moving continually around MPP without settling down on it.

Table 8.1: General Advantages and Disadvantages of the MPP trackers

C APPENDIXES

C.1 SIMULATIONS

C.1.1 P&O SIMULATION

The following section shows the implementation of the Perturb and Observe algorithm in Simplorer. At the first just irradiation changes will be simulated. It will be processed with the same conditions that have explained in 5.- WEATHER CONDITIONS.

The Solar Panel Equivalent Circuit corresponds to ***Figure 4.1***

The resistance is calculated according to the equations ***[4.1]*** and ***[4.2]***

The thermal voltage in the diode is calculating as ***[4.12]***

Cause just irradiation changes, Photocurrent is given by ***[4.9]*** and the saturation current of the diode by ***[4.13]***

Cause irradiation and temperature changes, Photocurrent is obtained from ***[4.10]*** and ***[4.11]*** after introducing saturation current in STC ***[4.13]*** in it, will be used to saturation current of the diode in different temperatures.

The equation are going to be used are ***[3.1]*** and ***[3.2]*** to calculate the resistance.

The voltage out initial is set up in stable state when the algorithm is starting. The delay time will be enough to make the parameters stable also. Sampling frequency can be changed also.

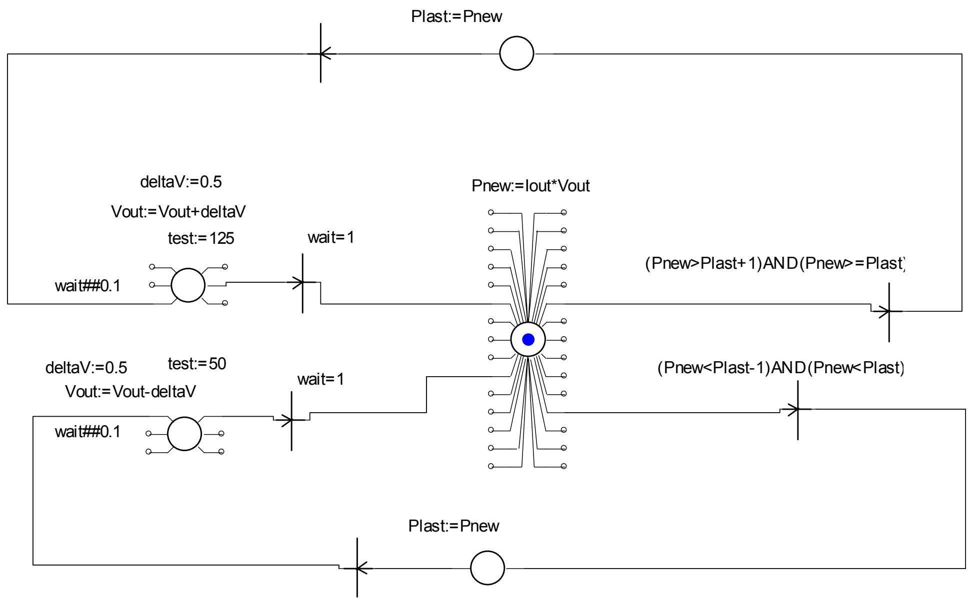


Figure C.1.1: Perturb and Observe implementation in Simplorer

INITIAL CONDITIONS.

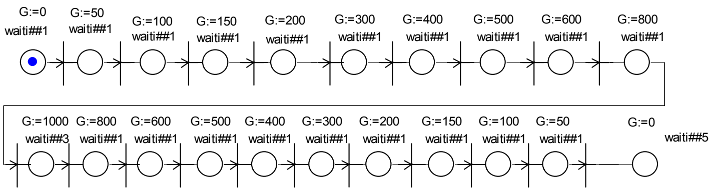
EQU	ICA:
Iout:=AM3.I	Vout:=31
Iph:=G*5/1000	Pnew:=0
deltaV:=0.5	G:=0
	deltaV:=0.5
	Plast:=0

All under it is tracking around 5 min.

<u>C.1.1.1 P&O RADIATION CHANGES</u>

A CLEAR SKY IN HIGH IRRADIATION (summer day)

Congratulation1_jccb_finish.ssh



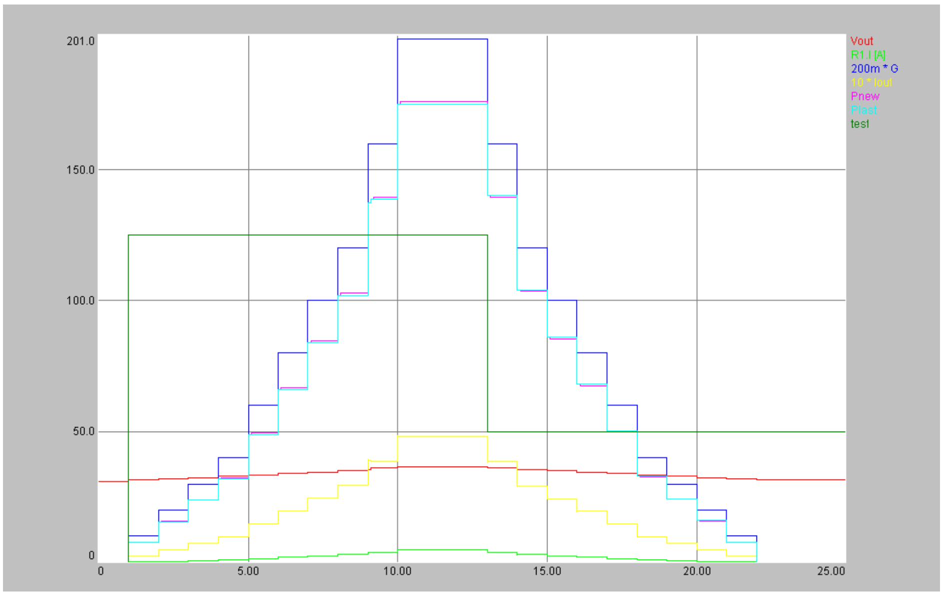


Figure C.1.2: PO Clear Sky in High irradiation

STC→ 36,4 V maximum power. Maximum power→175,9 W. Vout varies between:31,5 – 36,4 V. TOTAL: 1576,1/22=71,64 W (mean power)

A.1 PARABOLIC IRRADIANCE REPRESENTATION

Congratulation1_jccb_finish_proof.ssh

To understand how the algorithm works during soft irradiance changes the Figure is presented. The Initial condition are write them down and the equations also

EQU	ICA:
Iout:=AM3.I	Vout:=31
Iph:=G*5/1000	Pnew:=0
deltaV:=0.5	G:=0
G:=-6.94*(t^2)+166.66*t	deltaV:=0.5
	Plast:=0

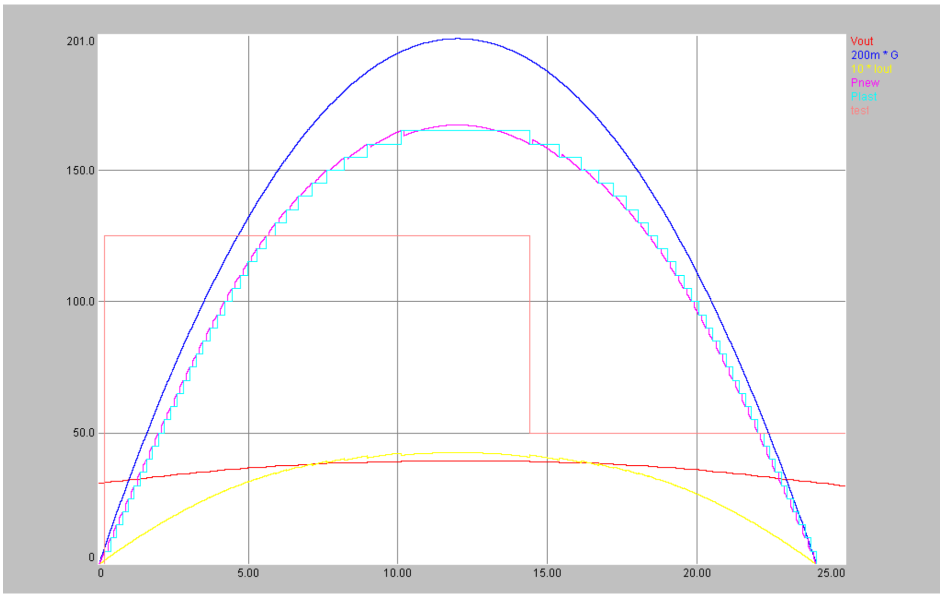


Figure C.1.3: PO Clear Sky in High Irradiation. Parabolic representation

The Vout goes since 30,9 at first, close to STC 39,2 V and then, when irradiance is 0, Vout take 30 V .The maximum power is around 167,21 W

B CLEAR SKY WITH SOME CLOUDS IN HIGH IRRADIANCES

Congratulation1_jccb_finish_cschi.ssh

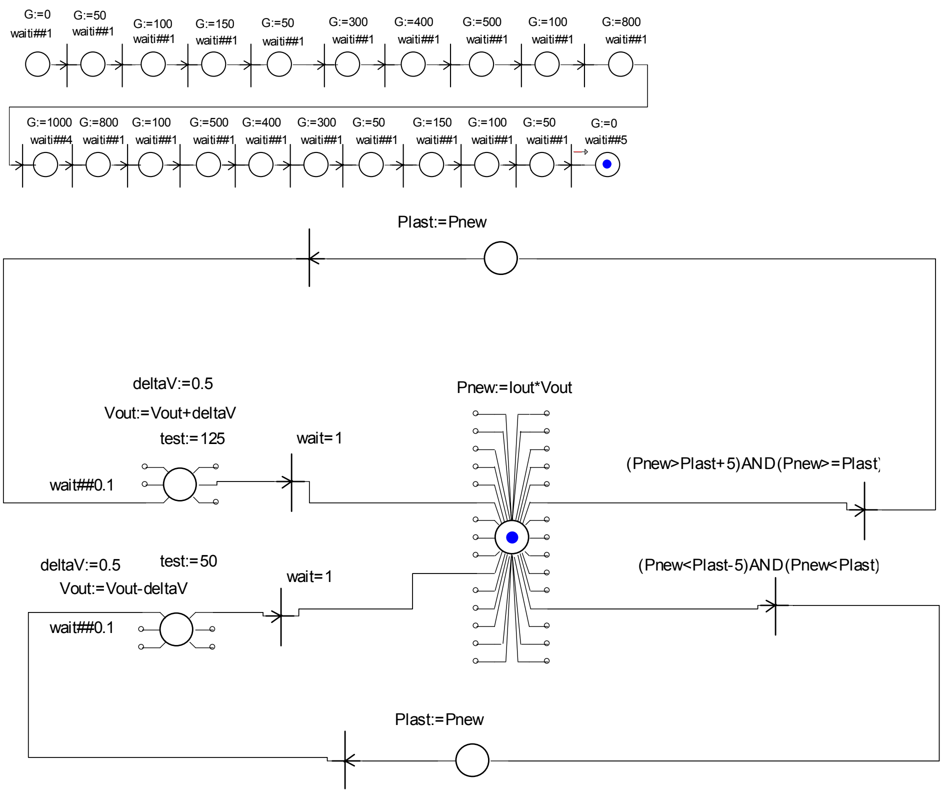


Figure C.1.4: Perturb and Observe implementation in Simplorer case B

An adjustment is made here. Just the margin is changed. When the differences of the power is bigger than 5, Plast = Pnew and the voltage is increased again. Until this tolerance is not reached, Pnew continues calculating on its own. It is closer to the reality because 1 W of Power differences is so little bit. Accurate equipment is necessary to measure these values. Here the sampling frequency is 200 micro seconds. It is enough to get accurate values. The delay to wait is approximately 3 minutes. And before the next alteration is kept constant the irradiation during 20 minutes.

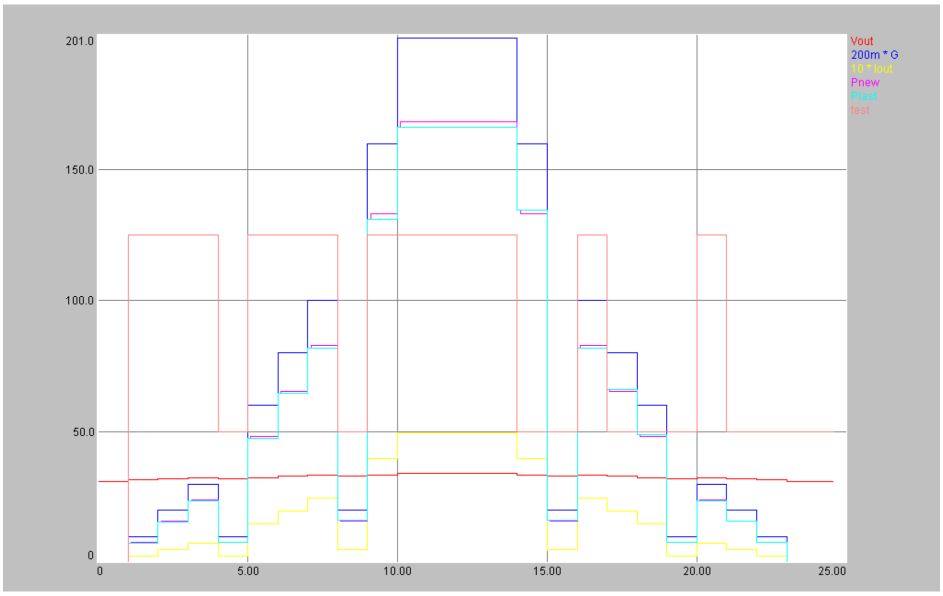
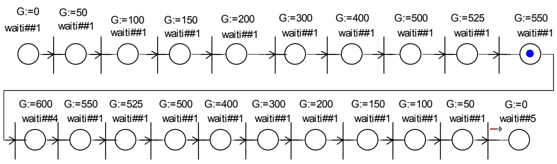


Figure C.1.5: PO Clear Sky in High Irradiances with some clouds.

In STC→ 34 V. The falls implied a delay. It see a change but not the proportion of the change the voltage varies between 31 V and 34 V the maximum power can be found in 14 s with 168,3 W . TOTAL: 1473/22=66,95 W (mean power)

D CLEAR SKY LOW IRRADIANCES (or covered sky in high irradiation)

Congratulation1_jccb_finish_csli.ssh



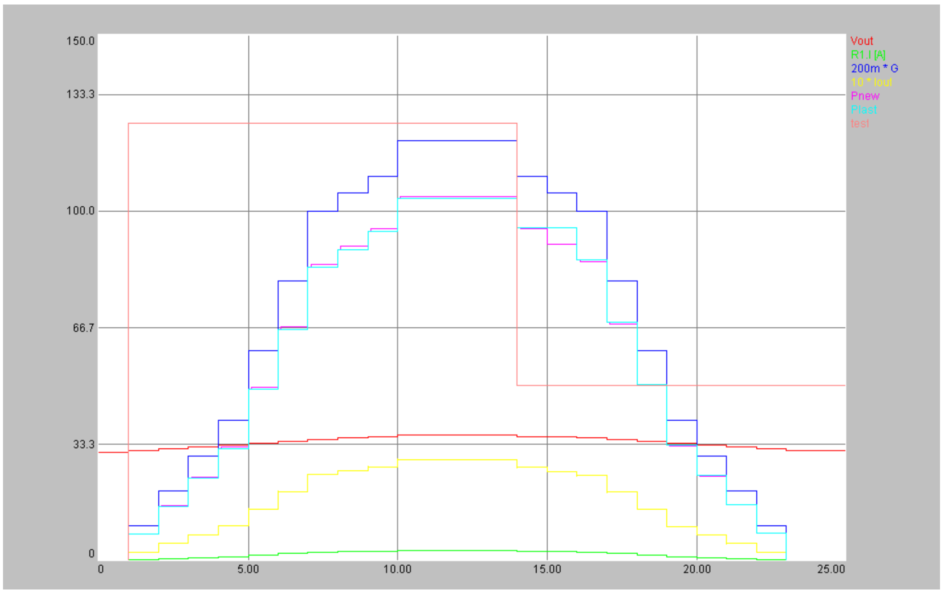
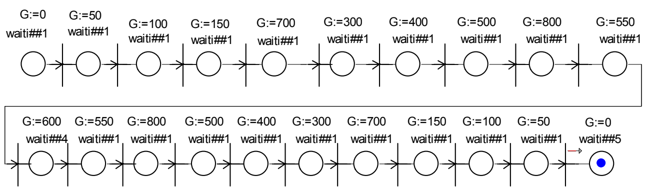


Figure C.1.6: PO Clear Sky in Low Irradiances.

Voltage varies between 36 and 30,9 V. Maximum power is 104,1 W. 600 W/m2→ 36 V. TOTAL: 1350/22=61,36 W (mean power)

E COVERED SKY WITH SOME CLEARS LOW IRRADIANCES

Congratulation1_jccb_finish_csCli.ssh



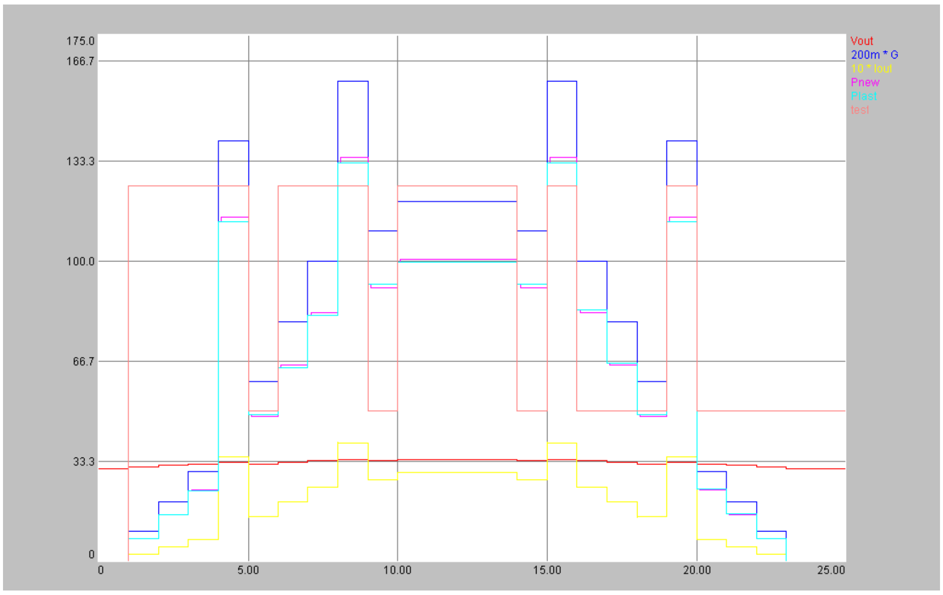
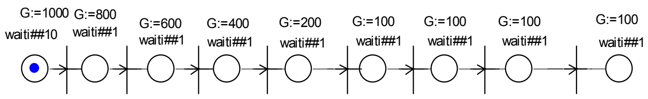


Figure C.1.7: PO Covered Sky with some Clears in Low Irradiances

Voltage is 34 V during constant 600 W/m2.The climbs are followed with delay.(depends of the sampling frequency)--> in the climb until 800W/m2 (when the irradiation is increasing) the power is around 134,5 W, however can be compared with the power in 800 W/m2 of irradiation when the sky is clear in high irradiation is bigger, therefore some losses are reached. TOTAL: 1570/22=71,36 W (mean power)

F CHANGES IN HIGH IRRADIATION

Congratulation1_jccb_finish_chHI.ssh



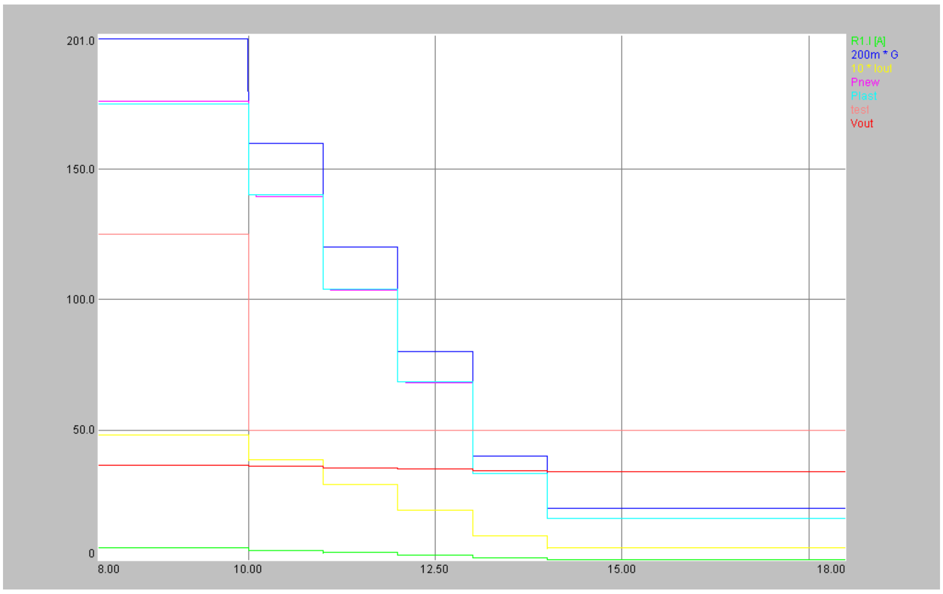
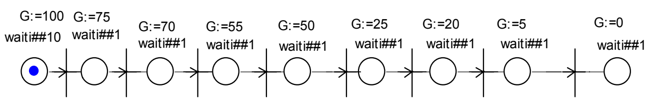


Figure C.1.8: PO Changes in High Irradiation

In STC→ 1000 W/m2 : the power is around 175,9 W and the Vout is around 36,4 V.And 34 V when irradiation is 100 W/m2. It is important to know that this algorithm depends of the configured voltage step, here the step is V= 0.5 V. TOTAL: 2105,3/15= 140,35 W (mean power)

G CHANGES IN LOW RADIATION

Congratulation1_jccb_finish_chLI.ssh



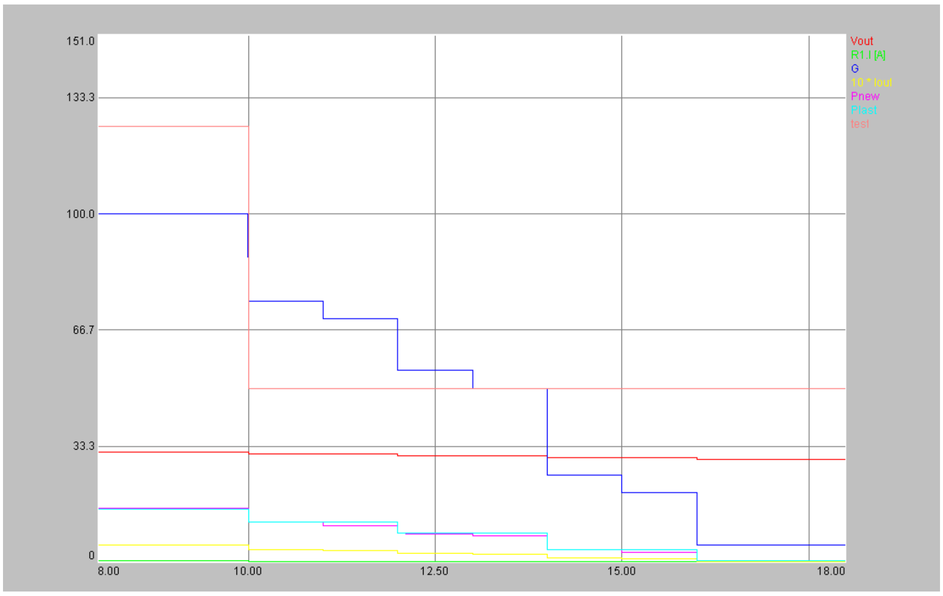
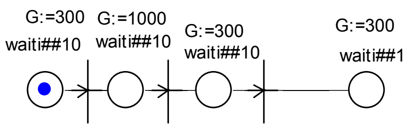


Figure C.1.9:PO Changes in Low Irradiation

The Vout goes since 31,5 to 29,5 V.It is point down that if the Pnew is smaller than Pnew (twice) but the difference is not so high (implementation must be 1 W of difference), thereby no Vout jumps are obtained.This configuration should be the same if the small jumps are avoided. The Power maximum is around 15,5 W. TOTAL: 179,2/15=11,94 W (mean power)

H BIG IRRADIATION VARIATION

Congratulation1_jccb_finish_proof_BIGvariat.ssh



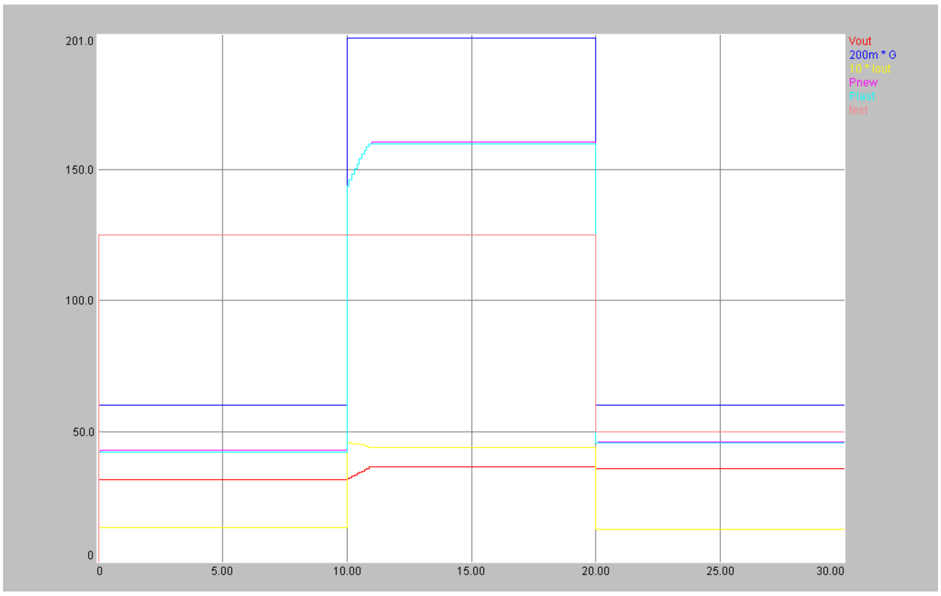


Figure C.1.10: PO Big Irradiation Variation

Vout at first:31,4 V; then 36,4 V and at last 36 V. Pmax = 175,9 W. Logically at the first change, the voltage out is increasing several times because of it is no located around the maximum power point area. Later at the drop, the voltage moves down just once because it is located close to the maximum power point. TOTAL: 2916,9/34=85,79 W (mean power)

G SMALL IRRADIATION VARIATION

Congratulation1_jccb_finish_proof_SMALLvariat.ssh

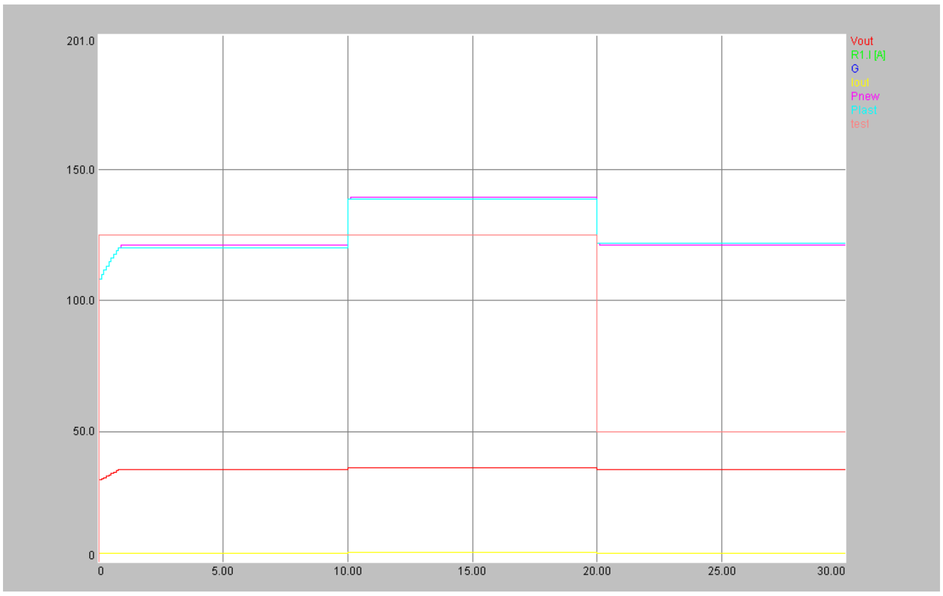


Figure C.1.11: PO Small Irradiation Variation

Vout: 35,4 V→36V→35,4 V. Pmax= 139,6 W (800 W/m2). TOTAL: 4282,3/34=125,95 W. (mean power)

<u>C.1.1.2 P&O RADIATION AND TEMPERATURE CHANGES</u>

K CLEAR SKY IN HIGH IRRADIANCES

Congratulation1_jccb_finish_temperature_summer.ssh

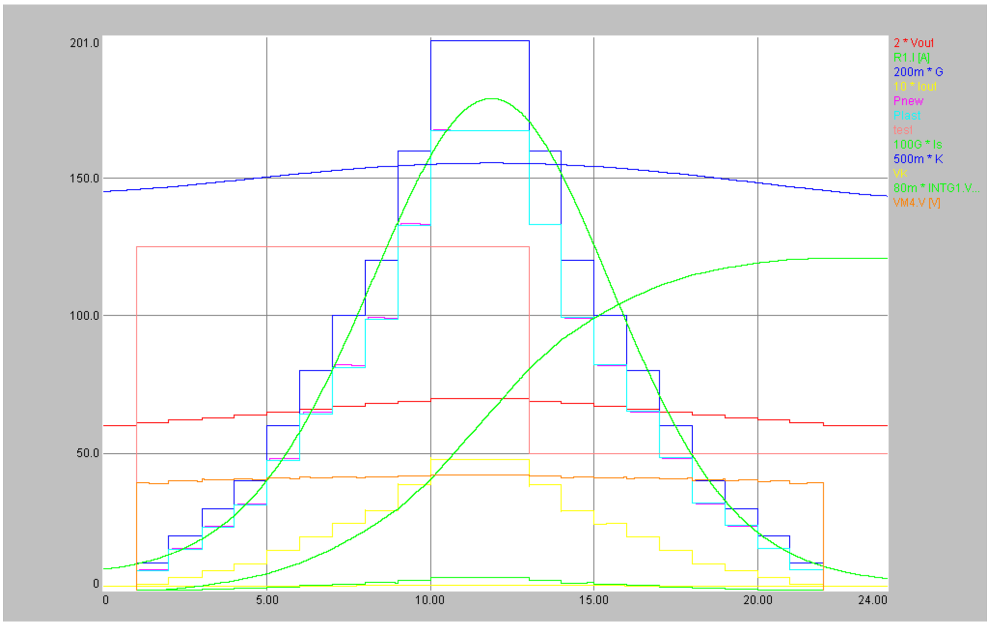


Figure C.1.12: PO Clear Sky in High Irradiation with temperature changes.

Vout: 30V →35 V→30V. Pmaxima= 167,1 W. Energy=1512 J and Power= 1512J/22s =68,72 W (mean values). Voc=41,9 V. Is=1,32E-10 → 1,79E-9 A. TOTAL: Energy=1512 J and Power= 1512J/22s =68,72 W (mean values)

M CLEAR SKY IN LOW IRRADIANCES

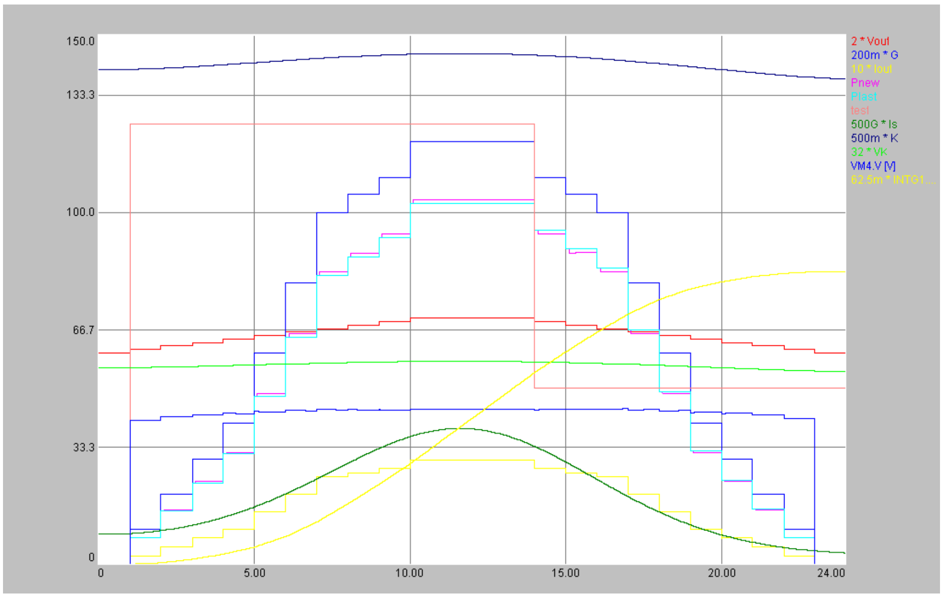


Figure C.1.13: PO Clear Sky in Low Irradiances with temperature changes.

Energy: 1329,2 J → Power:1329,2/22= 60,42 W (mean values). Vout:30→35→30 V. Power max: 103,7 W. Voc:40,7 →43,9→40,7 V

C.1.2 NR SIMULATION

The following section shows the implementation of the Newton and Raphson algorithm in Simplorer. At the first just irradiation changes will be simulated. It will be processed with the same conditions that have explained in 5.- WEATHER CONDITIONS.

The Solar Panel Equivalent Circuit corresponds to ***Figure 4.1***

The resistance is calculated according to the equations ***[4.1]*** and ***[4.2]***

The thermal voltage in the diode is calculating as ***[4.12]***

Cause just irradiation changes (6.3.2.1), Photocurrent is given by ***[4.9]*** and the saturation current of the diode by ***[4.13]***

Cause irradiation and temperature changes (6.3.2.2), Photocurrent is obtained from ***[4.10]*** and ***[4.11]*** after introducing saturation current in STC ***[4.13]*** in it, will be used to saturation current of the diode in different temperatures.

The equation are going to be used are ***[3.1]*** and ***[3.2]*** to calculate the resistance.

The voltage out initial is set up in stable state when the algorithm is starting. The delay time will be enough to make the parameters stable also. Sampling frequency can be changed also.

The simulation in Simplorer is as:

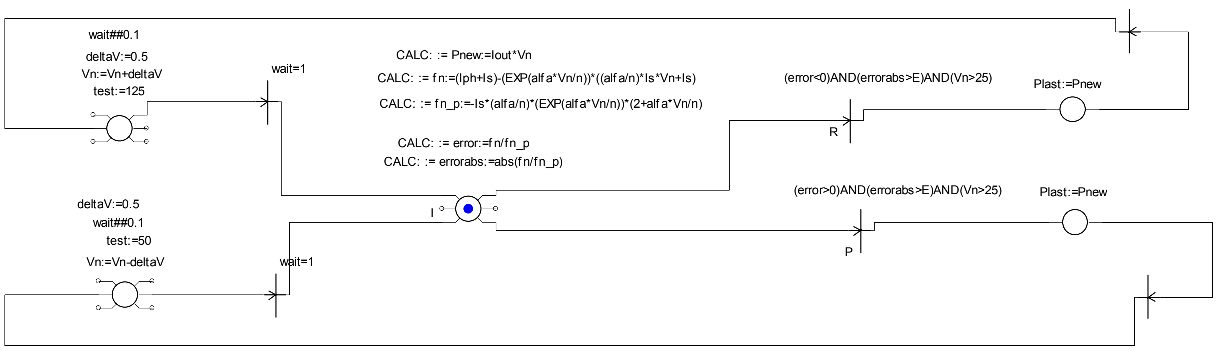


Figure C.1.14: Newton Raphson Implementation in Simplorer

INITIAL CONDITIONS.

Vn:=31
Ta:=298
q:=1.6E-19
k:=1.38E-23
A:=1
ICA:

deltaV:=0.5
Vt:=0.0257025
n:=72
Voc:=43.8
G:=50
E:=0.5
ICA:

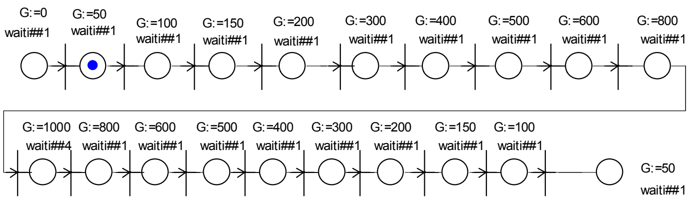
EQU
Iout:=AM1.
alfa:=q/(A*k*Ta

EQU
Iph:=G*5/1000
Is:=5/EXP(43.8/(Vt*n)

C.1.2.1 NR RADIATION CHANGES.

A CLEAR SKY IN HIGH IRRADIATION (summer day)

Newton_raph_sar.ssh



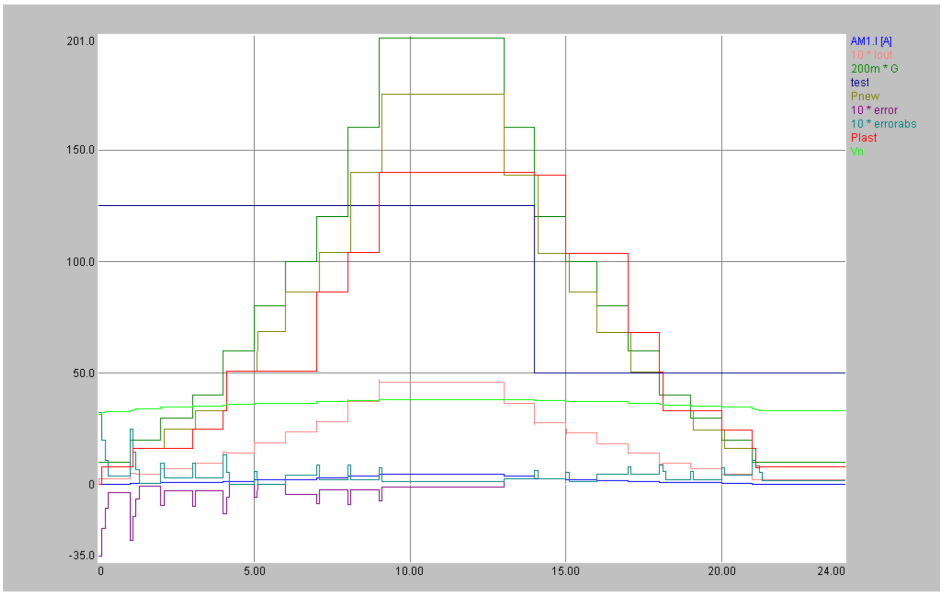


Figure C.1.15: NR Clear Sky in High Irradiation

STC→ 37,9 V. Maximum power→174,97 W. Vout varies between:31,5 – 37,9 V – 32,9V. TOTAL: 1753,5/22=79,70 (mean power)

A.1 PARABOLIC IRRADIANCE REPRESENTATION

Newton_raphs_sar_sinusoidal_proof.ssh

To understand how the algorithm works during soft irradiances changes, the ***Figure C.1.16*** is presented. The Initial conditions and the equations are shown bellow also.

Vn:=31
Ta:=298
q:=1.6E-19
k:=1.38E-23
A:=1
ICA:

deltaV:=0.5
Vt:=0.0257025
n:=72
Voc:=43.8
G:=50
E:=0.5
ICA:

EQU
Iout:=AM1.
alfa:=q/(A*k*Ta
G:=-6.94*(t^2)+166.66*t

EQU
Iph:=G*5/1000
Is:=5/EXP(43.8/(Vt*n))

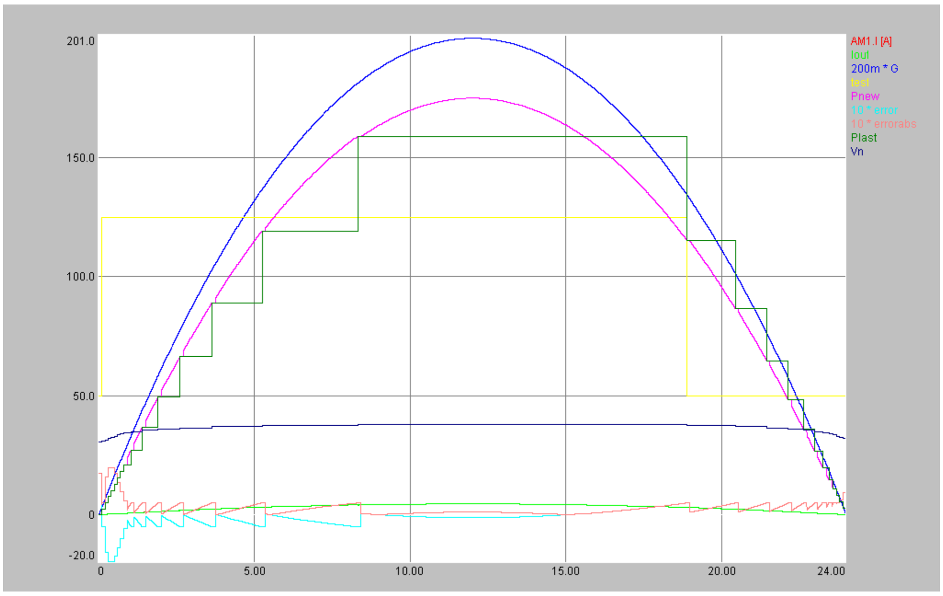
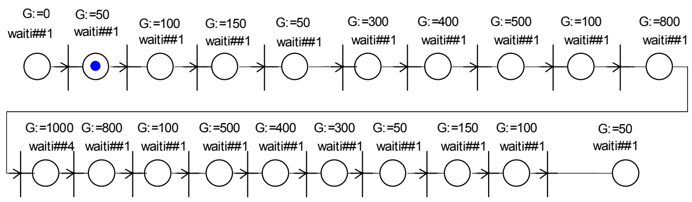


Figure C.1.16: NR Parabolic Representation Clear sky in High irradiances

The maximum power takes the 174,9 W value and in that point the voltage out is around 37.9 V. The voltage out moves from 31.5 V until 37.9 V. When the irradiation is increasing the voltage out can take, when the irradiation is approximately 675 W/m2, the value of Vout is 36,9 V (just in 5s). It marks this, because in the same situation when the irradiation is decreasing (just 18 s), the value of Vout is 37,9. This difference, how it checks above in other graphs is caused because until the MPP is reached, the Newton Rapshon algorithm takes longer (more time) to reach the root.

B CLEAR SKY WITH SOME CLOUDS IN HIGH IRRADIANCES

Newton_Raph_sar_HisC.ssh



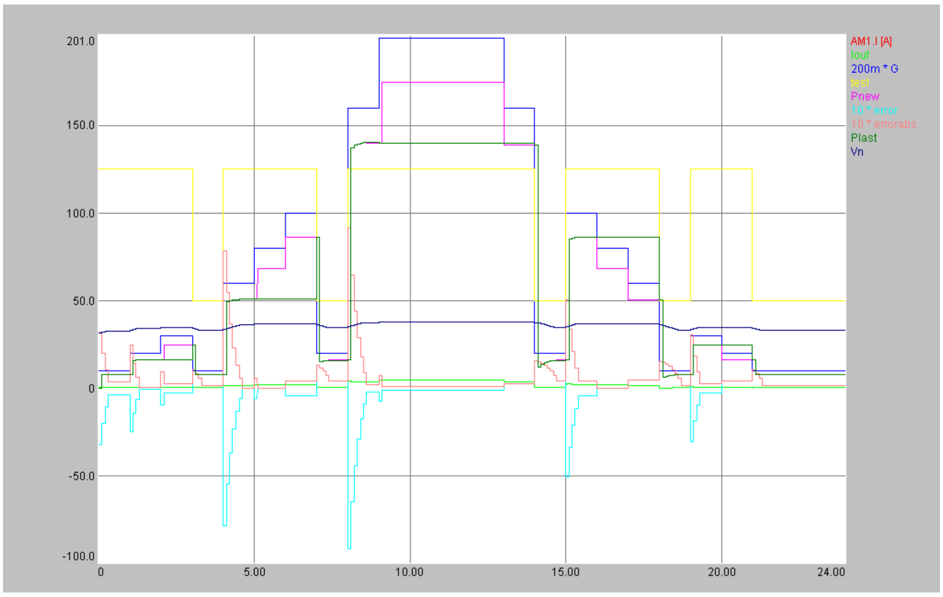
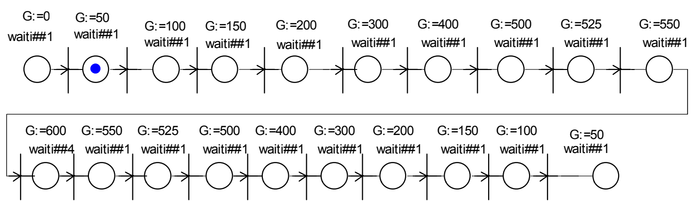


Figure C.1.17: NR Clear Sky with some clouds in High Irradiation

STC→ 37,9 V. The falls implied a delay. Quickly the correct voltage is reached. The second fall when the irradiance is increasing implies a error around –92. The voltage varies between 31,5 V → 37,9 V and 33 V. The maximum power can be founded since 9 s and take the value of 174,8 W. TOTAL: 1523,2/22=69,23 W (mean power)

D CLEAR SKY LOW IRRADIANCES (covered sky)

Newton_raph_sar_csLI.ssh



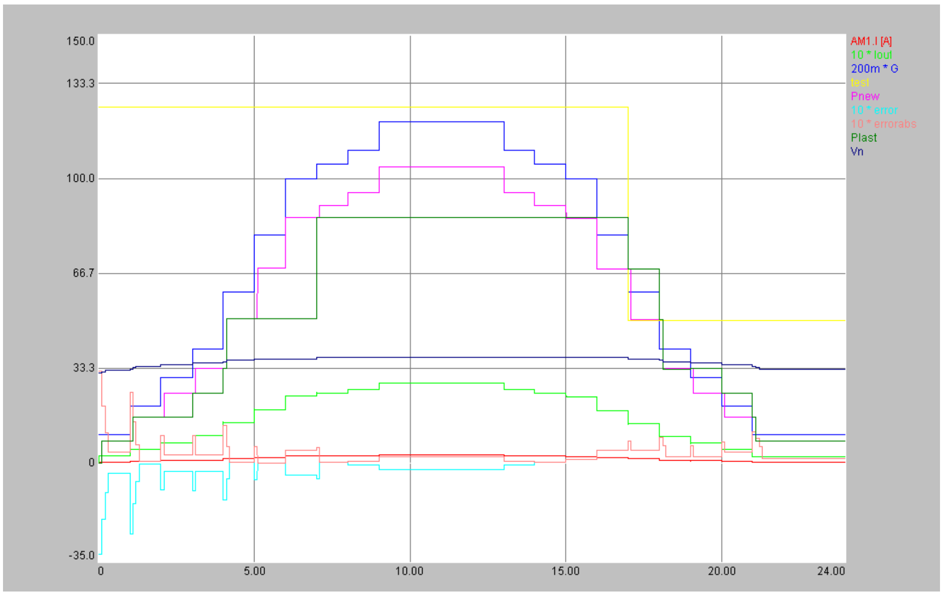
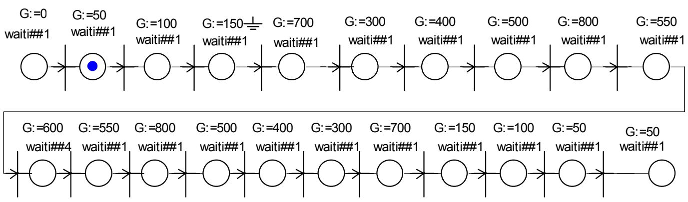


Figure C.1.18: NR Clear Sky in Low Irradiances

Voltage varies between 31,5V → 36,9 →33V.Maximum power is 104,1W.600 W/m2→ 36,9 V. TOTAL: 1359,7/22= 61,78 W (mean power)

E COVERED SKY WITH SOME CLEARS LOW IRRADIANCES

Newton_raph_sar_csCLI.ssh



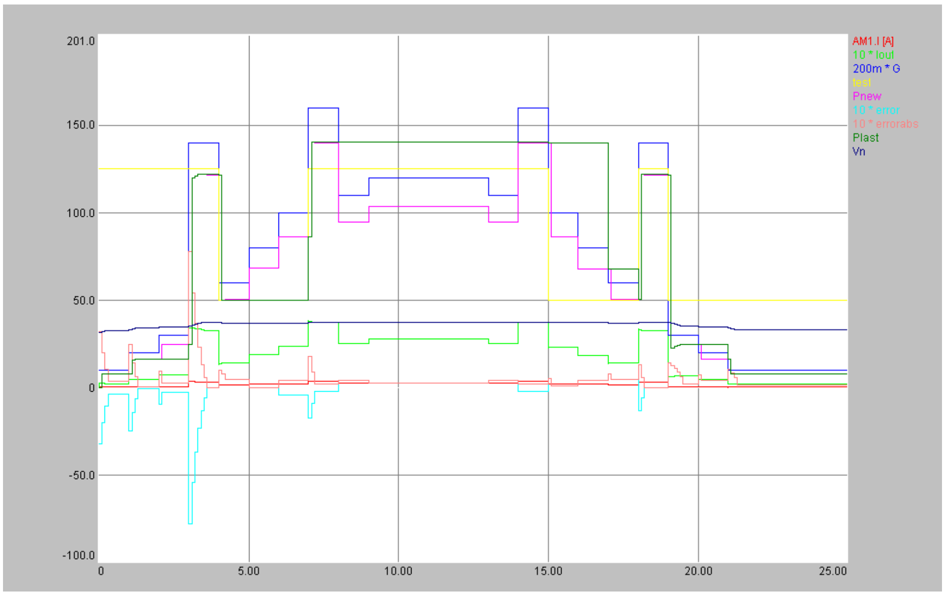
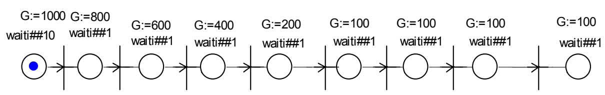


Figure C.1.19:NR Covered Sky with some Clears in Low Irradiances

Voltage varies between 31,5 V – 37,5 V –33V .Vout is 37,5 V during 600 W/m2 and P = 103,5 W. The climbs are followed with delay (depends of the sampling frequency)--> in the climb until 800W/m2 (when the irradiation is increasing) the power is around 139,7 W, however can compare with the power in 800 W/m2 of irradiation when the sky is clear in high irradiation is lower because of some losses are reached. And here the error takes -72. It can be explained why this mistake is bigger than the rest of them because of at first not MPP is reached, the Vout is not located around the voltage is expected to be (35 V until 38 V). Which variation is produced here will imply a significant error. TOTAL: 1631,5/22=74,15 W (mean power)

C CHANGES IN HIGH RADIATION

Newton_raph_sar_Chhi.ssh



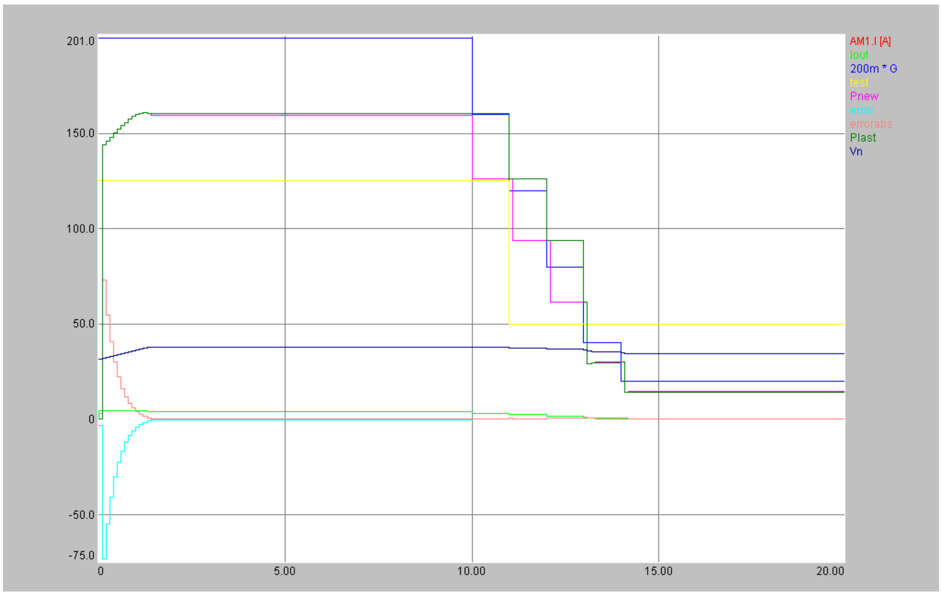
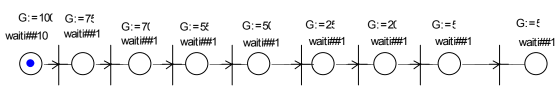


Figure C.1.20: NR Changes in High Irradiation

STC→ 1000 W/m2 : the power is around 176,2 W just when 1000W/m2 is got it, however the Vout is stablish later in 38 V and the power is 174,7 W during 1000W/m2 continues. And 34,4 V when irradiation is 100 W/m2. It is important to know that this algorithm depends about the step configured, here the step is V= 0.5 V. TOTAL:2092,8/15=139,2 W

D CHANGES IN LOW IRRADIANCES

Newton_raph_sar_Chli.ssh



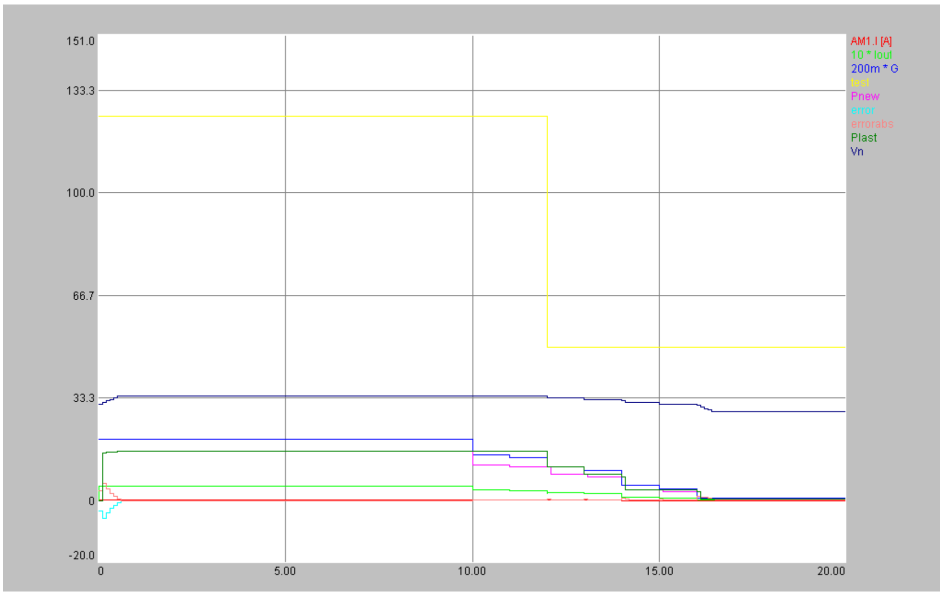
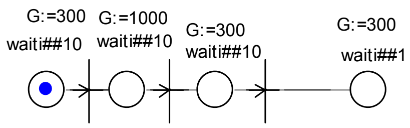


Figure C.1.21: NR Changes in Low Irradiances.

The Vout goes since 34 V to 28,9 V when the G drop to 5 W/m2 (approximatly = 0 W/m2) .The Pmax reached is 16,08 W. TOTAL: 182,10/15=12,13 (mean power)

H BIG IRRADIATION VARIATION

Newton_raphs_BIG_variation.ssh



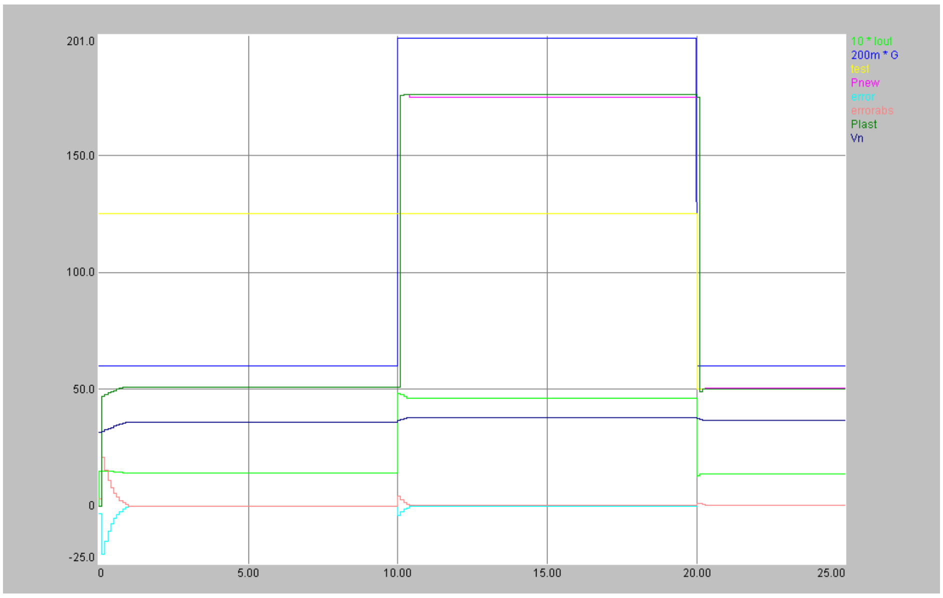
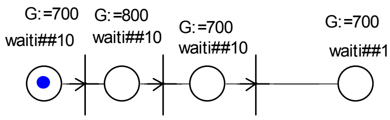


Figure C.1.22:NR Big Irradiation Variation

Vout at first:35,9 V; then 37,9 V and at last 36,4 V. The Vout is got in less than 0.4 s. Pmax=176,21 W. TOTAL: 2951,5/34 = 86,80 W. (mean power)

G SMALL IRRADIATION VARIATION

Newton_Raphson_sar_SMALLvariation.ssh



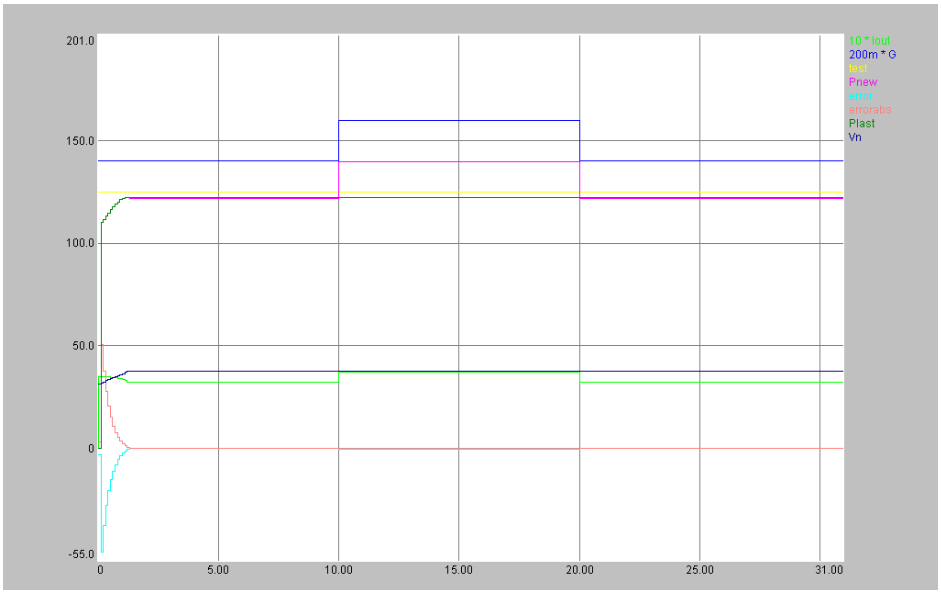
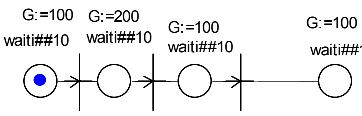


Figure C.1.23: NR Small Irradiation Variation in High Irradiances

Vout: 31,5 V→37,4 V and later keeps constant all the time. The algorithm does not move when a small irradiation change is done. TOTAL: 4286,1/34=126,06 W (mean power)

G.1 SMALL IRRADIATION VARIATION 2

Newton_Raphson_sar_SMALLvariation2.ssh



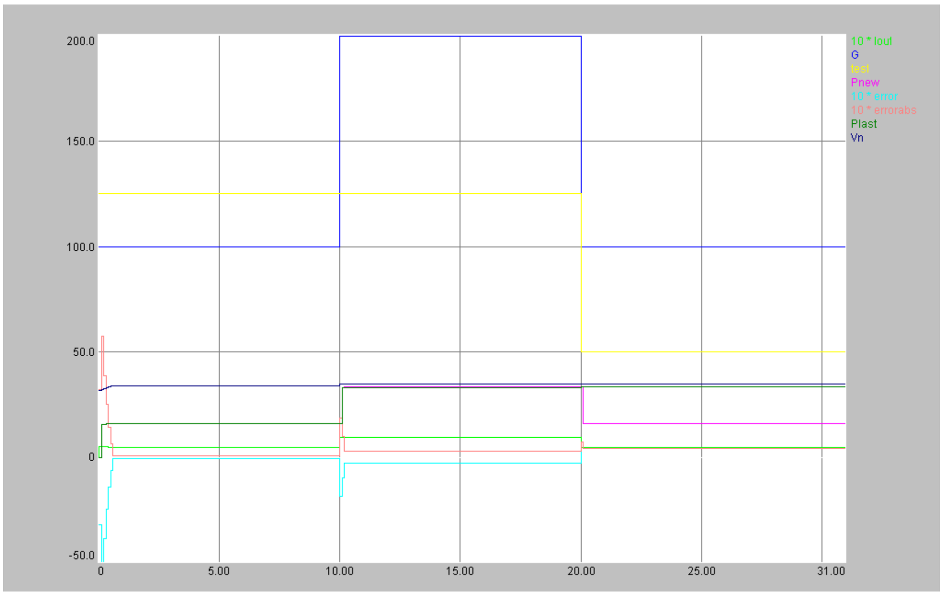


Figure C.1.24: NR Small Irradiation Variation in Low Irradiances

When the small variation is produced in low irradiances, the algorithm can see the change perfectly. However it notices that when it is the drop only one step down in V is made, differently that when irradiation increases. That is because of explained before, when the MPP in a high position is reached, a slight movement is done to reach the next one in a drop. Let us think about right side of the curve I vs V. So, also in low irradiances the curve is flatter than is high irradiances. Therefore the algorithm is expected to move a little more the voltage than when in high irradiations are trying to find out. Vout: 33,9 V→34,9 V→34,5V and later keeps constant all the time and Pmpp=33,2 W. TOTAL:714,5/34=21,014W (mean power)

<u>C.1.2.2 NR RADIATION AND TEMPERATURE CHANGES</u>

K CLEAR SKY IN HIGH IRRADIANCES

Newton_raph_sar_temperature_summer.ssh

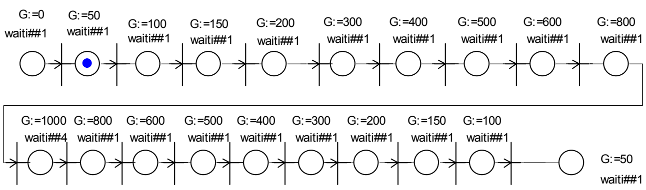
Initial Conditions and equations

Vn:=30
Ta:=298
q:=1.6E-19
k:=1.38E-23
A:=1
ICA:

deltaV:=0.5
Vt:=0.0257025
n:=72
Voc:=43.8
G:=50
E:=0.5
ICA:

EQU
Iph:=(G/1000)*(5+0.0015*(K-298))
Is:=5/EXP(43.8/(Vt*n)

EQU
Iout:=AM1.
alfa:=q/(A*k*Ta
VK:=((1.38E-23)*K/(1.6E-19))*72
K:=(2E-15)*(t^5)+0.0007*(t^4)-0.0341*(t^3)+0.3666*(t^2)+1.0239*t+290.33
Is:=(2.63013E-10)*((K/298)^(3/72))*EXP((-177.133655)*((1/K)-(1/298)))



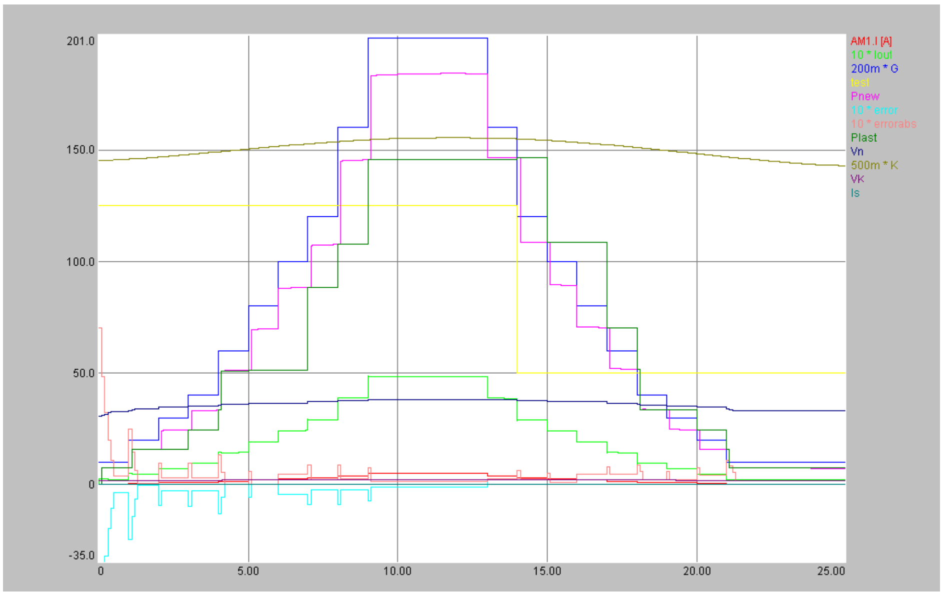


Figure C.1.25: NR Clear Sky in High Irradiances with Temperature Changes

Vout → 30,5 → 35 V → 30,5 V. Voc → 39,4 → 42 V. Pmax: 167,2 W. Energy : 1704,6 J → Potencia media : 1704,6/22=77,48 W (mean power)

M CLEAR SKY IN LOW IRRADIANCES

Newton_raphson_sar_csLI_temperature_winter.ssh

Initial conditions and equations

deltaV:=0.5

Vn:=31

Vt:=0.0257025

Ta:=298

n:=72

q:=1.6E-19

Voc:=43.8

k:=1.38E-23

G:=50

A:=1

E:=0.5

ICA:

ICA:

EQU

EQU

Iout:=AM1.

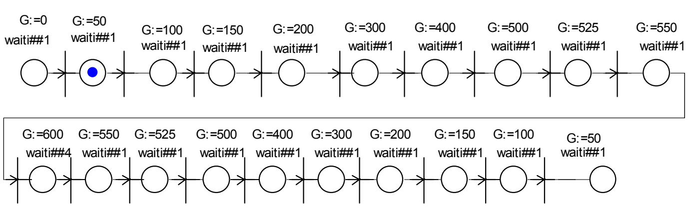
Iph:=(G/1000)*(5+0.0015*(K-298))

alfa:=q/(A*k*Ta

VK:=((1.38E-23)*K/(1.6E-19))*72

K:=(2E-15)*(t^5)+0.0007*(t^4)-0.0341*(t^3)+0.3666*(t^2)+1.0239*t+290.33

Is:=(2.63013E-10)*((K/298)^(3/72))*EXP((-177.133655)*((1/K)-(1/298)))



Here it is distinguished that when the temperature is increasing the current increase a little enough to make the power bigger because the margin of the voltage is the same.

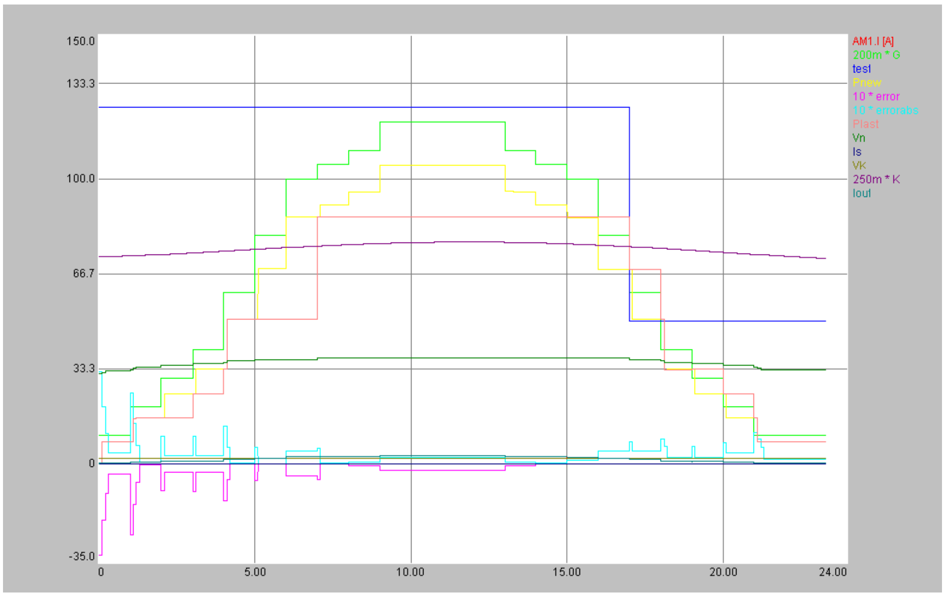
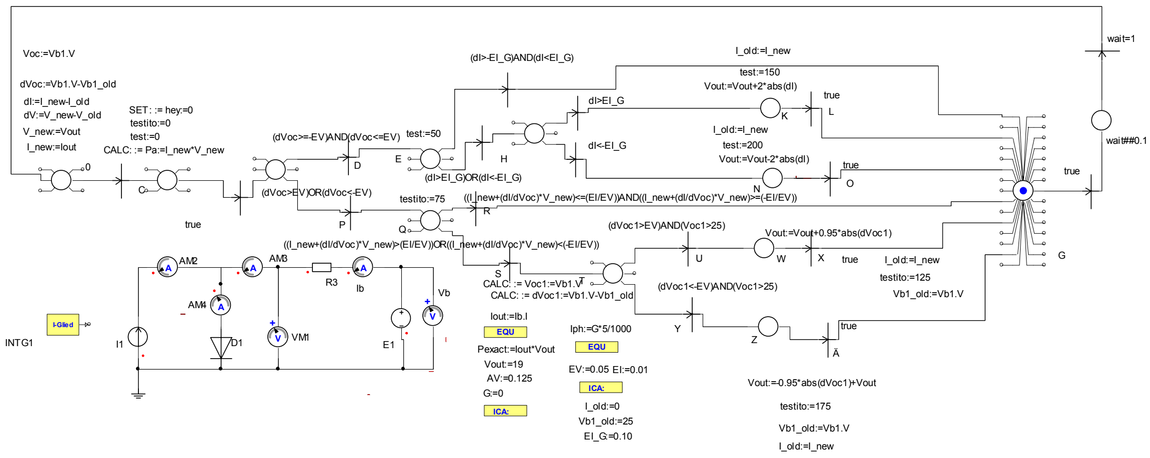


Figure C.1.26: NR Clear Sky in Low Irradiances with temperature changes.

Vout: 36 → 39,5 V. Pmax =104,24 W. Energia =1355,51/22=61,62 W (mean power). Voc: 40,84 →44,17 V

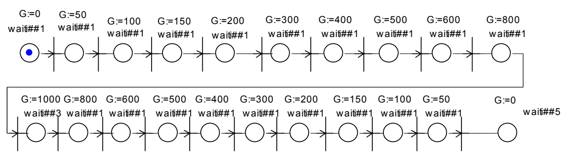
C.1.3 FLEX A SIMULATIONS



C.1.3.1 FLEX A RADIATION CHANGES

A CLEAR SKY HIGH IRRADIATION (summer day)

JCCB_clear_sky_HI_A.ssh



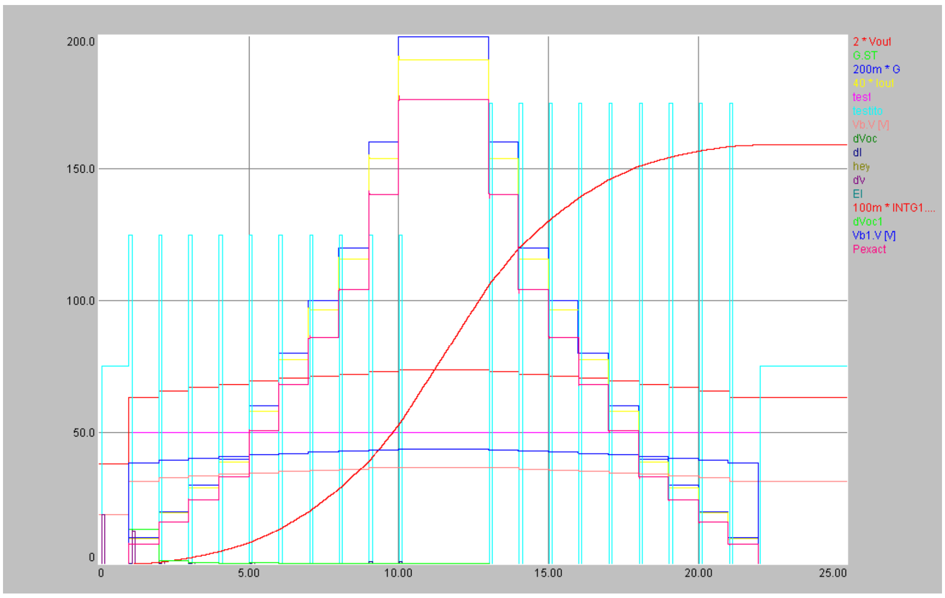


Figure C.1.27: FA Clear Sky High Irradiation

STC→ 36,9 V. Pmax = 176,2 W. Vout→ 31,6 → 36,9 V. Energy 1591,23 J /22s = 72,33 W. (mean power)

A.1 PARABOLIC IRRADIANCE REPRESENTATION

JCCB_clear_sky_HI_parabolic_A1.ssh

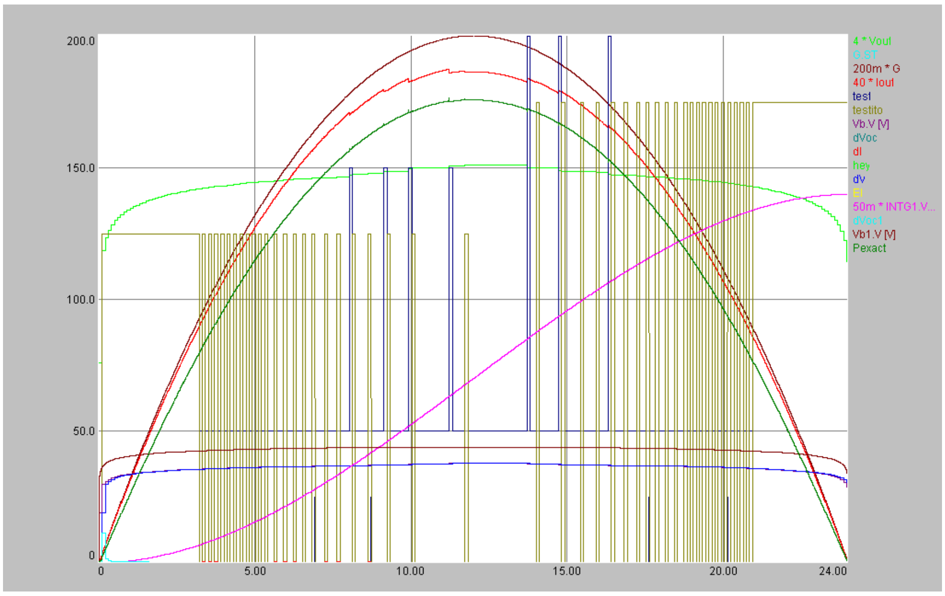


Figure C.1.28 : FA Parabolic representation of a clear sky in High Irradiation

Vout : 29,6 → 37,7 V. Maximum Power is around : 176,40 W. Energy: 2797,24 J/24 s= 116,55 W (mean value)

B CLEAR SKY WITH SOME CLOUDS IN HIGH IRRADIANCES

JCCB_clear_sky_sClouds_HI_B.ssh

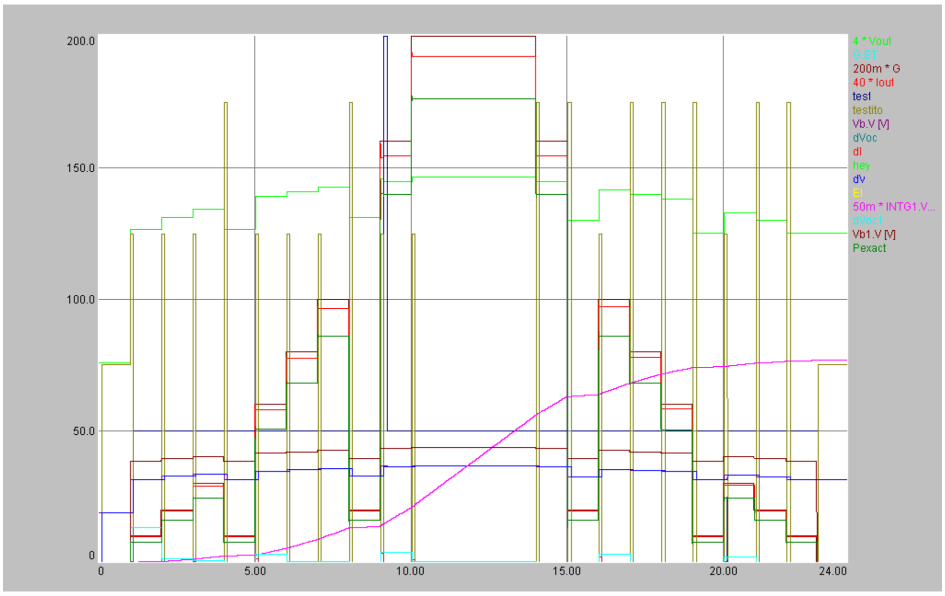


Figure C.1.29: FA Clear Sky with some clouds in High Irradiances

Vout: 31,6 V→ 36,6 V. Pmasx:=177,33 W. Energy: 1536,05/22s = 69,82 W (mean power)

D CLEAR SKY LOW IRRADIANCES

JCCB_clear_sky_LI_D.ssh

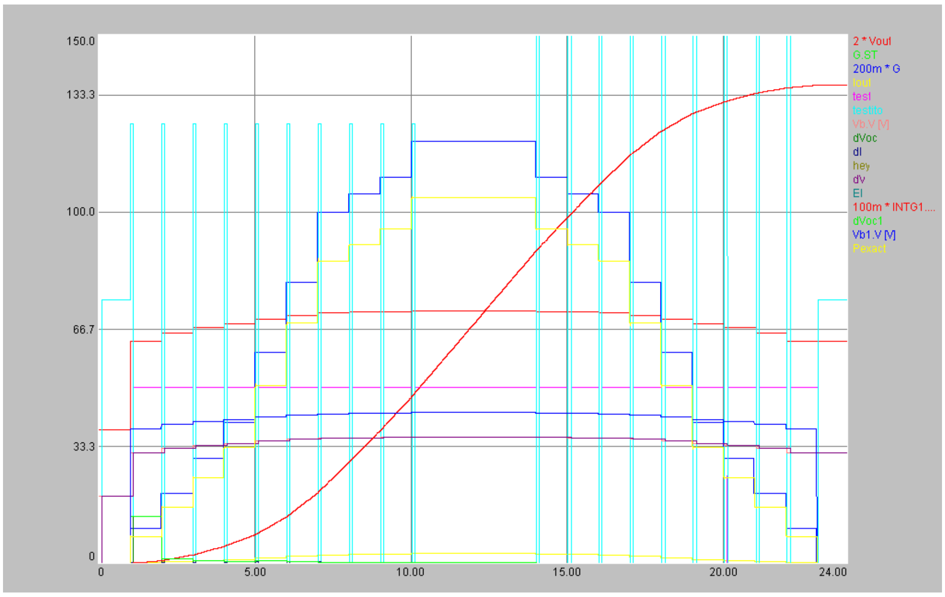


Figure C.1.30: FA Clear Sky in Low Irradiances

Vout= 31,6 V → 35,9 V. Maximum Power: 104,41 W. Energy: 1360,42 J /22s = 61,84 W(mean power)

E COVERED SKY WITH SOME CLEARS LOW IRRADIANCES

JCCB_clear_sky_CsCLI_E.ssh

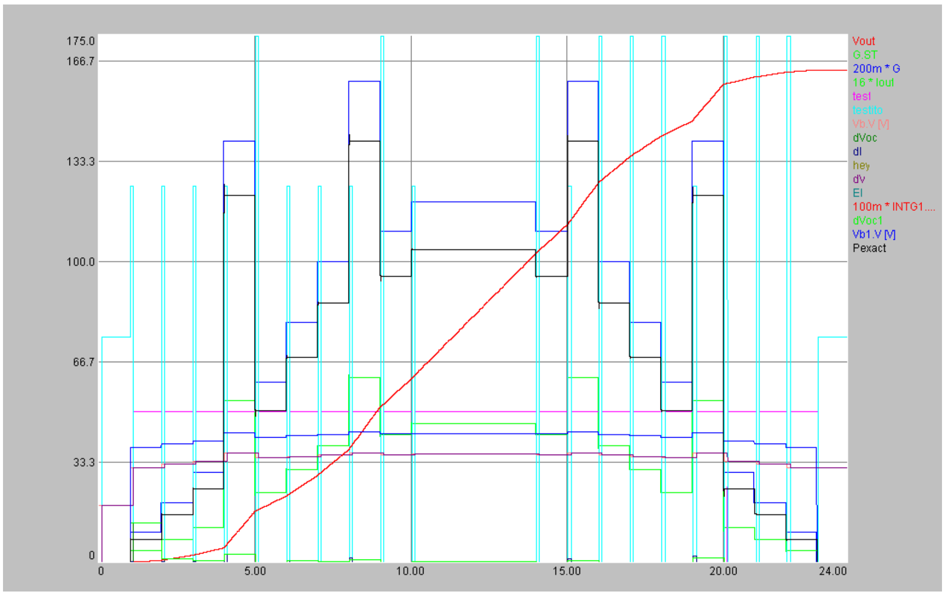


Figure C.1.31: FA Covered Sky with some Clears in Low Irradiances.

Vout: 31,5 → 35,9 V. P (600 W/m2) : 104 W. Energy : 1637,54/22 s = 74,43 W (mean power)

C CHANGES IN HIGH RADIATION

JCCB_ChHI.ssh

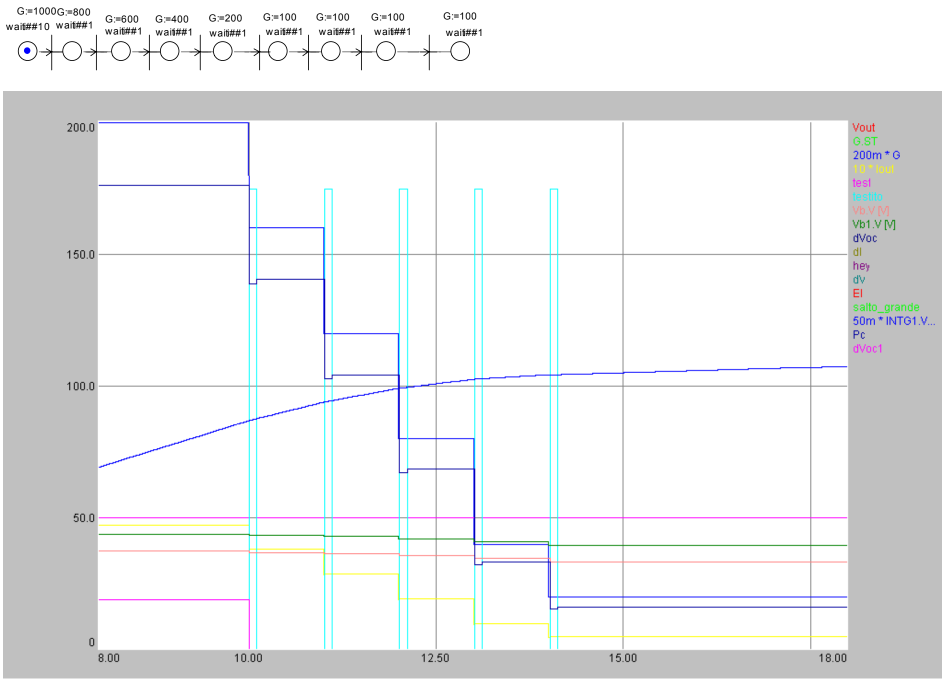


Figure C.1.32: FA Changes in High Irradiation

STC→ 1000 W/m2 : the power is around 176,1 W y Vout 37,3 V. Vout is 33,2 V when irradiation is 100 W/m2. Energy: 2101,38/15= 140,092 W (mean power)

F CHANGES IN LOW RADIATION

JCCB_ChLi.ssh

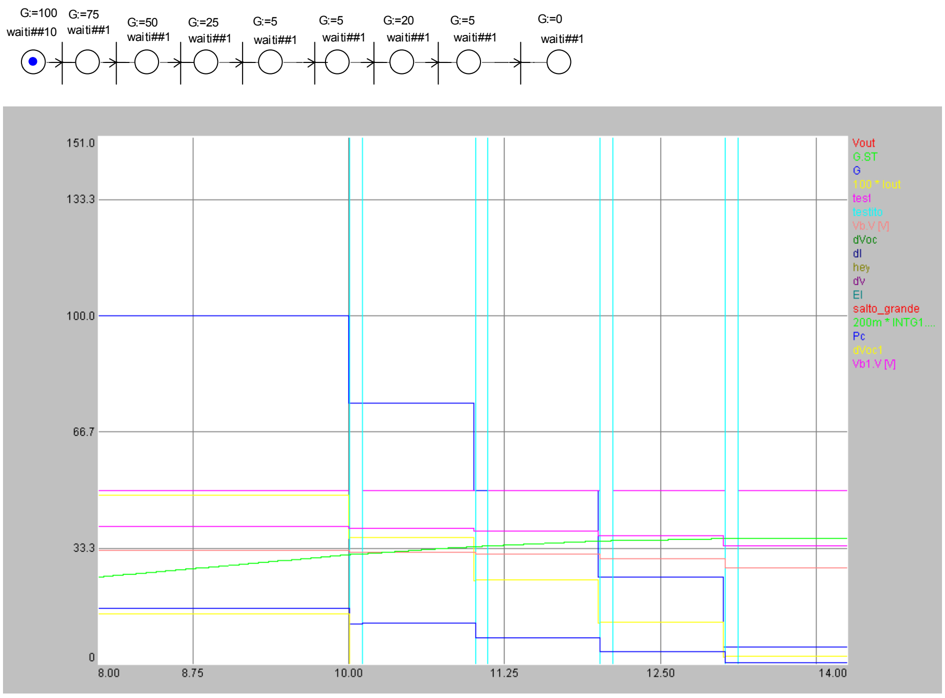
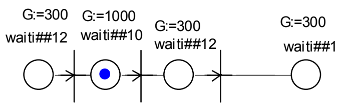


Figure C.1.33: FA Changes in Low Irradiation.

The Maximum Power is around: 16,41 W. The Vout goes since 32,8 to 27,5V. Energy:182,085/15=12,14 W (mean power)

H BIG IRRADIATION VARIATION

JCCB_BIGvariat.ssh



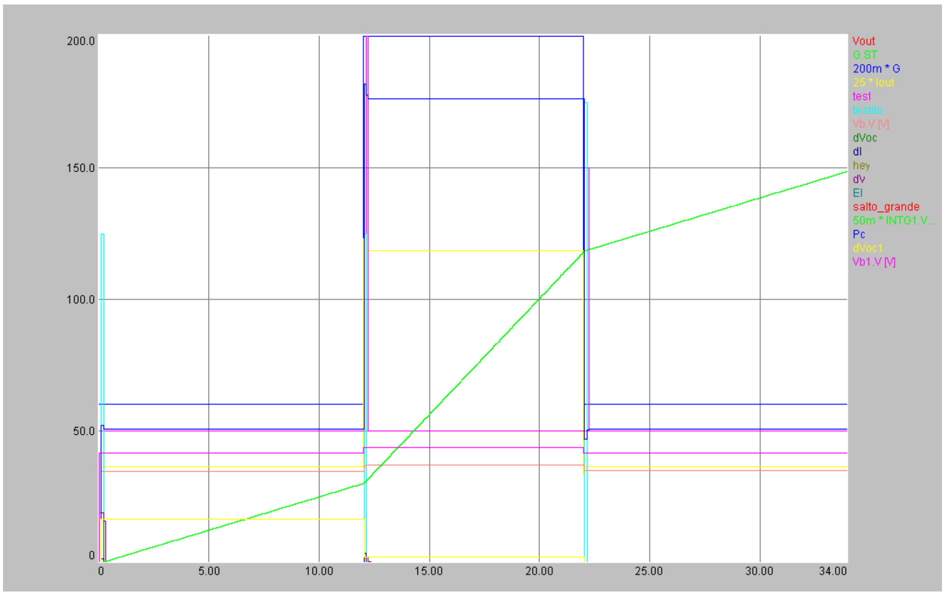


Figure C.1.34: FA Big Irradiation Variation

Vout: 34,7 V→ 37,1 V. Pmax: 176,2 W. It can be apreciated one wrong way of increasing or decreasing voltage are working. Bellow there is a zoom of this area affected:

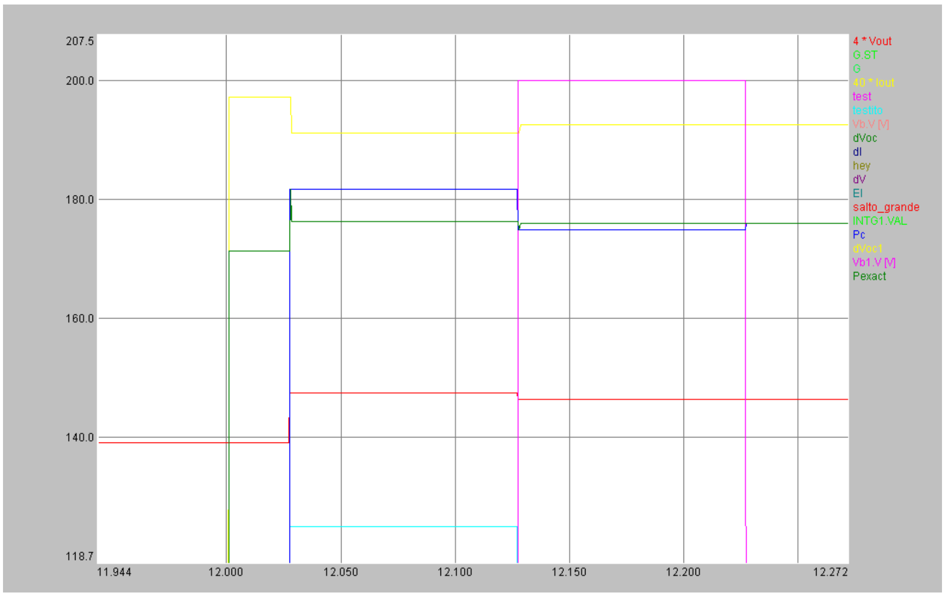


Figure C.1.35: FA Big Irradiation Variation Zoom

Increase Vout should be bypassed when dI is so small. 0,2 W losses. If it is bypassed:

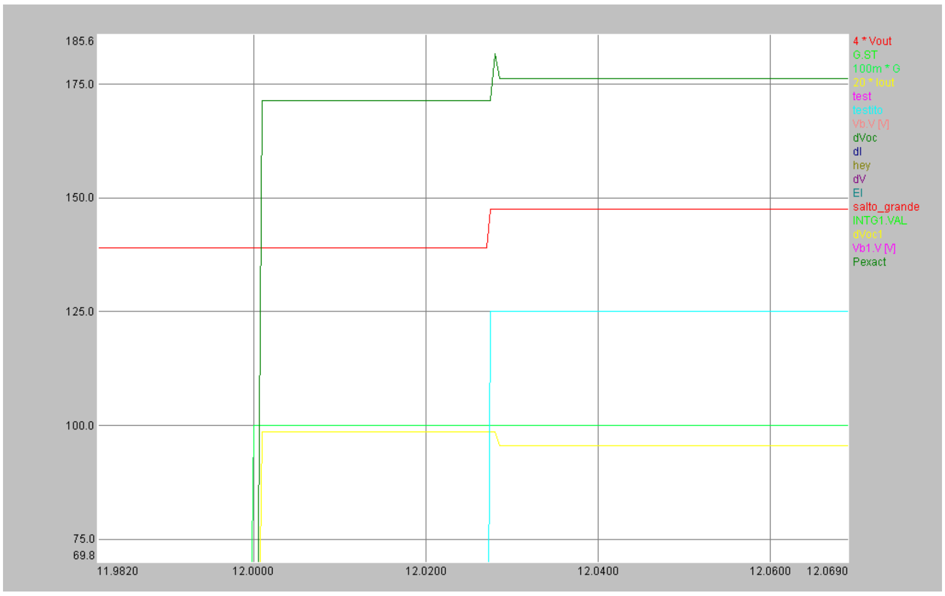


Figure C.1.36: FA Big Irradiation Variation Bypassed.

Energy: 2971,68 J/ 34s → 87,40 W (mean power)

I SMALL VARIATION

JCCB_SMALLvariat.ssh

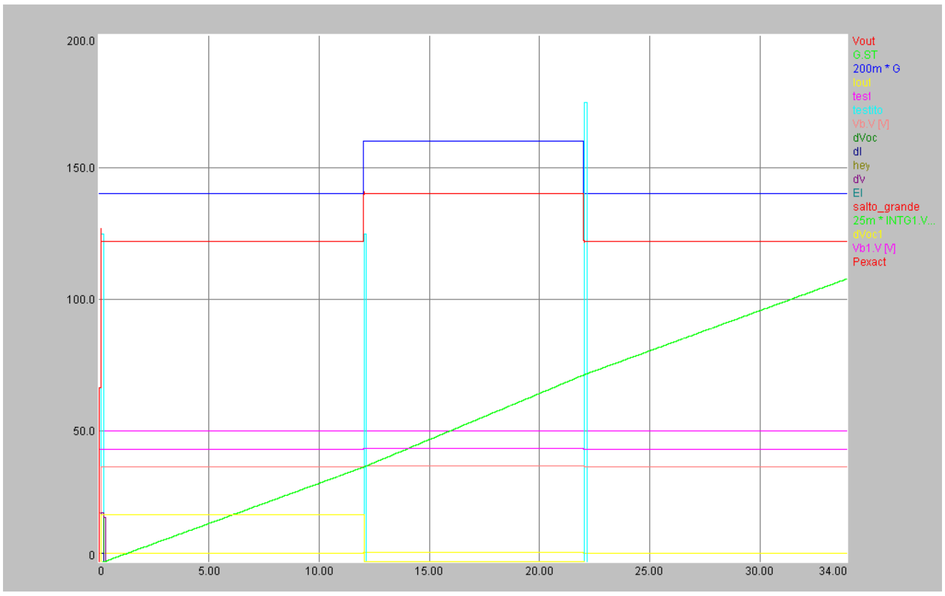


Figure C.1.37:FA Small Irradiation Variation in High Irradiances.

Vout: 36,1→ 36,5 V. Pmax→140,1 W. Energy:4315,51 J/34s → 126,93 W (mean power)

G.1 SMALL VARIATION 2

In low irradiances

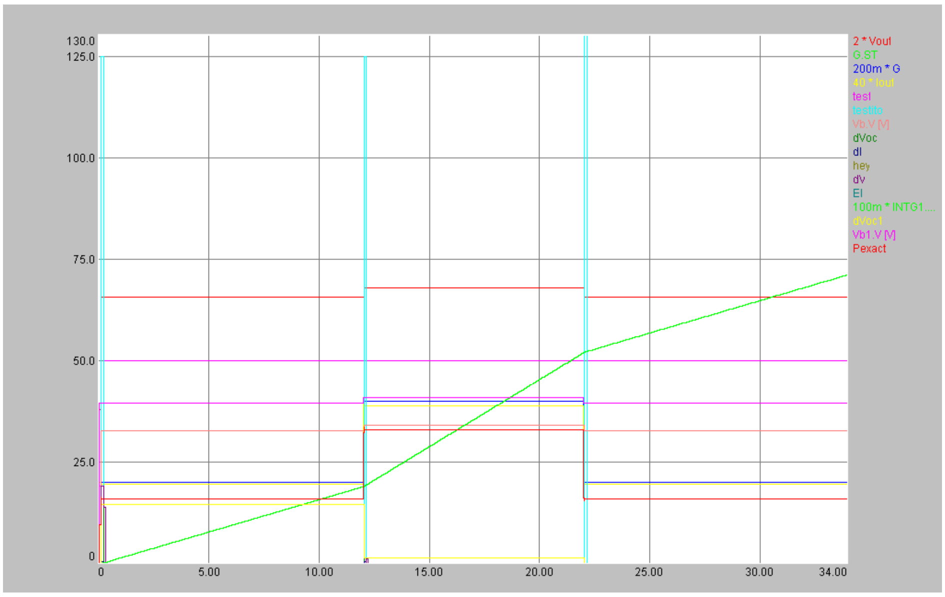


Figure C.1.38:FA Small Irradiation Variation in Low Irradiances

Vout: 32,8 V → 34 V. Pmax: 33 W. Good behaviour it is observed also. Energy: 711,51 J / 34s =20,93 W. (mean power) And in the following temperature and radiation changes together. The characteristics in the diode are:

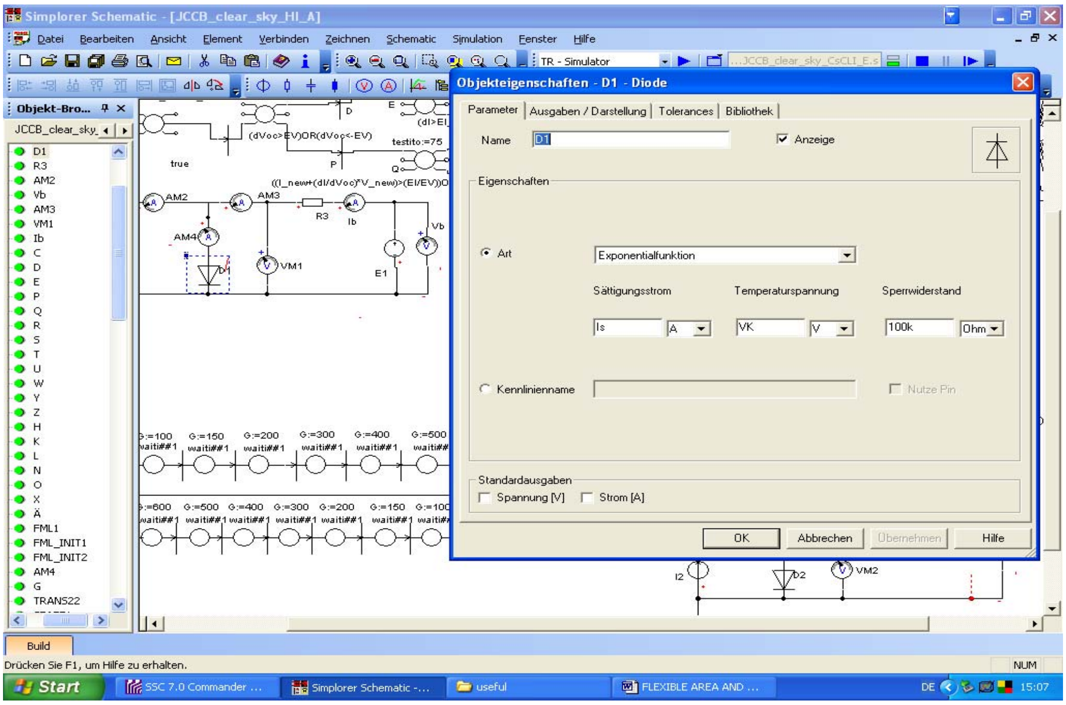


Figure C.1.39:FA Characteristics in the diode when Temperature Changes are produced. Where VK ans Is:

VK:=((1.38E-23)*K/(1.6E-19))*72

EQU

Iout:=AM3.I

Iph:=(G/1000)*(5+0.0015*(K-298))

deltaV:=0.4

Is:=(2.63013E-10)*((K/298)^(3/1))*EXP((-1.27536E+4)*((1/K)-(1/298)))

C.1.3.2 FLEX A RADIATION AND TEMPERATURE CHANGES

K CLEAR SKY IN HIGH IRRADIANCES

JCCB_clear_sky_HI_G_and_T_changes_K.ssh

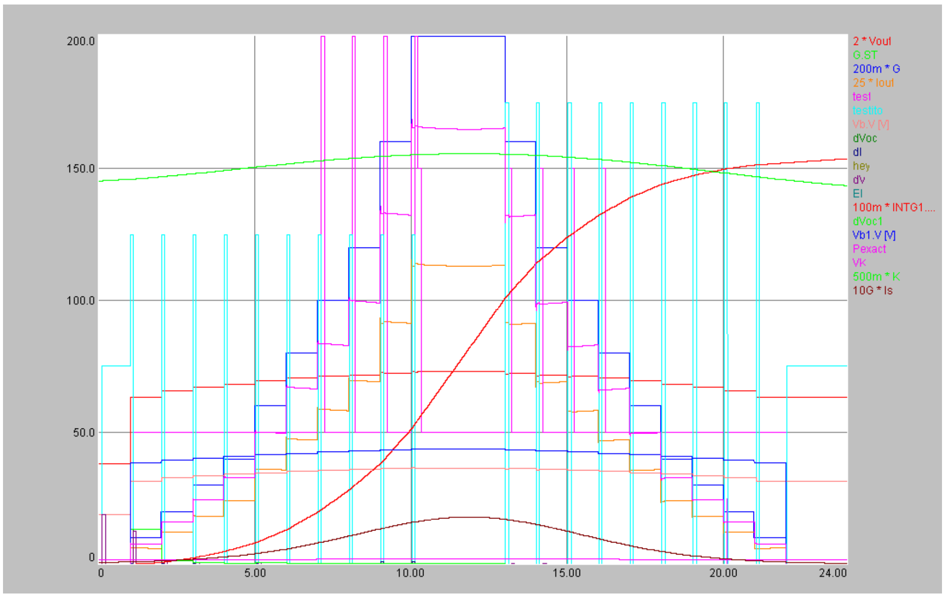


Figure C.1.40:FA Clear Sky in High Irradiances with Temperature changes

Vout: 31,6 V → 36,4 V. Pmax: 168,64 W. Energy: 1536,00 J and Power =1536/22=69,82 W. (mean power). Voc: 43,6 V. Is: It is increasing correctly

M CLEAR SKY IN LOW IRRADIANCES

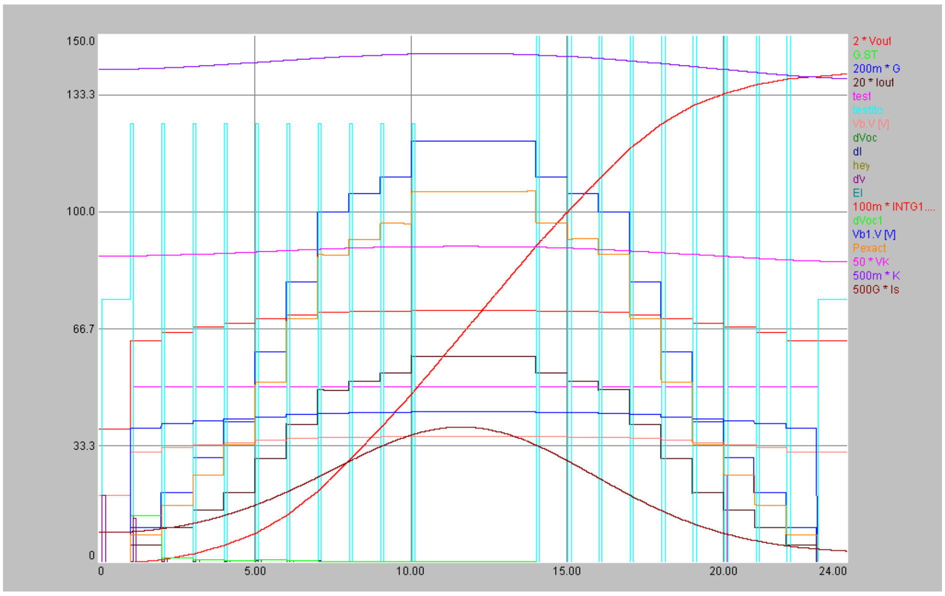


Figure C.1.41: FA Clear Sky in Low Irradiances with Temperature Changes

Vout: 31,6 V → 35,9 V. Energy =1392,85 J → Power: 1392,85/22 = 63,31 W (mean power) Power max:105,94 W. Voc:38,3 → 43 V

C.2 BROCHURES

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