Maximum Power Point Tracking algorithms for Photovoltaic arrays under uniform solar irradiation

1. Models of the photovoltaic (PV) cell, PV panel and PV array
2. Maximum Power Point Tracking (MPPT) algorithms

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Table of contents

1. Models of the photovoltaic (PV) cell, PV panel and PV array

1.1. Solar Energy

The solar energy received on Earth’s surface annually sums up to 1,5 x10^{15} kWh, almost 10.000 times the world's annual energy consumption. In estimating the possibilities of using the solar energy we must consider both the advantages and its disadvantages.

The advantages:

- It is an abundant Renewable Energy
- This technology is Omnipresent and it can be captured for conversion on a daily basis
- It is a Non-polluting technology, which means that it does not release green house gases
- It is a Noiseless technology as there are no moving parts involved in energy generation
- This technology requires Low-maintenance because of lack of moving parts
- It can be installed on modular basis and expanded over a period of time
- Most viable alternative for providing electricity in remote rural areas as it can be installed where the energy demand is high and can be expanded on modular basis.

1. Models of the photovoltaic (PV) cell, PV panel and PV array

1.1. Solar Energy

Disadvantages:

- As the technology is in an *evolving stage*, the efficiency levels of conversion from light to electricity is in the range of 10 to 17%, depending on the technology used.
- The initial investment cost of this technology is high. At present the technology is basically surviving because of subsidy schemes available by the government.
- Solar energy is available only during daytime. Most load profiles indicate peak load in the evening/night time. This necessitates *expensive storage devices* like battery, which need to be replaced every 3 to 5 years. Generally, the cost of the Battery is 30 to 40% of the system cost.
- As the efficiency levels are low, the space required is relatively high. For instance, with the existing levels of technologies, the land required for putting up a 1 MW solar PV power plant is between 6 to 9 acres. However, research is going on to increase the efficiency levels of the cell.
- Solar energy is heavily dependent on atmospheric conditions.
- Solar insolation varies from location to location, so there are certain *geographic limitations* in generating solar power.

1.1. Solar Energy

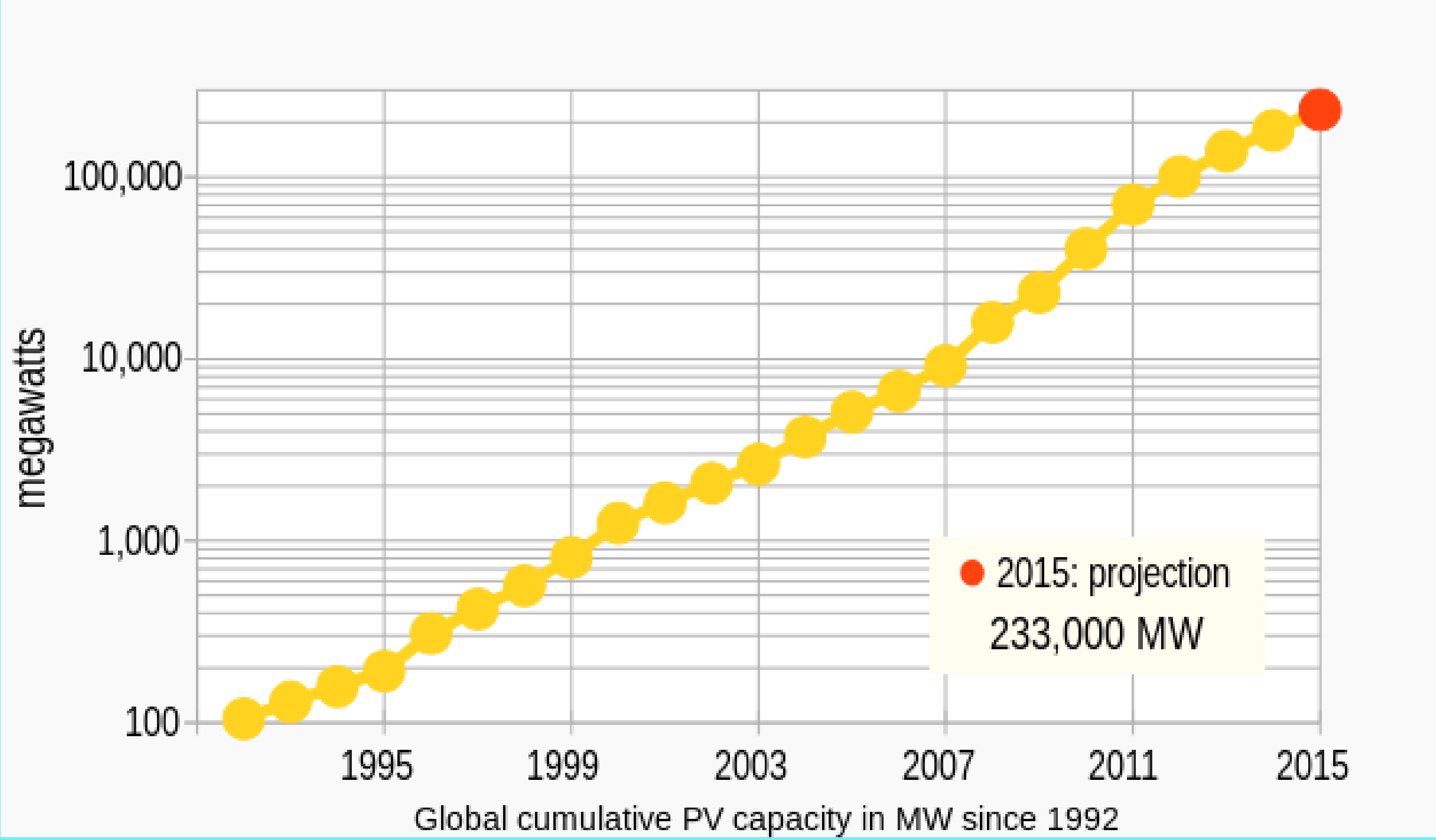
World's largest photovoltaic power stations

Name	Country	Capacity MW_p	Generation GW·h p.a.	Year
Charanka Solar Park	India	600	n.a.	2012
Solar Star (I and II)	United States	579	n.a.	2015
Topaz Solar Farm	United States	550	1,096	2014
Desert Sunlight Solar Farm	United States	550	1,023	2015
Copper Mountain Solar Facility	United States	458	484	2015

https://en.wikipedia.org/wiki/List_of_photovoltaic_power_stations

1.1. Solar Energy

Exponential growth on semi-log chart



In 2014, the cumulative photovoltaic capacity increased by 40.1 GW or 28% and reached at least 178 GW by the end of the year, sufficient to supply 1 percent of the world's total electricity consumption of currently 18,400 TWh. https://en.wikipedia.org/wiki/Growth_of_photovoltaics

1. Models of the photovoltaic (PV) cell, PV panel and PV array

1.1. Solar Energy

Solar Irradiance

The amount of solar power available per unit area is known as **irradiance**. **Irradiance is a radiometric term** for the power of electromagnetic radiation at a surface, per unit area. It is used when the electromagnetic radiation is incident on the surface.

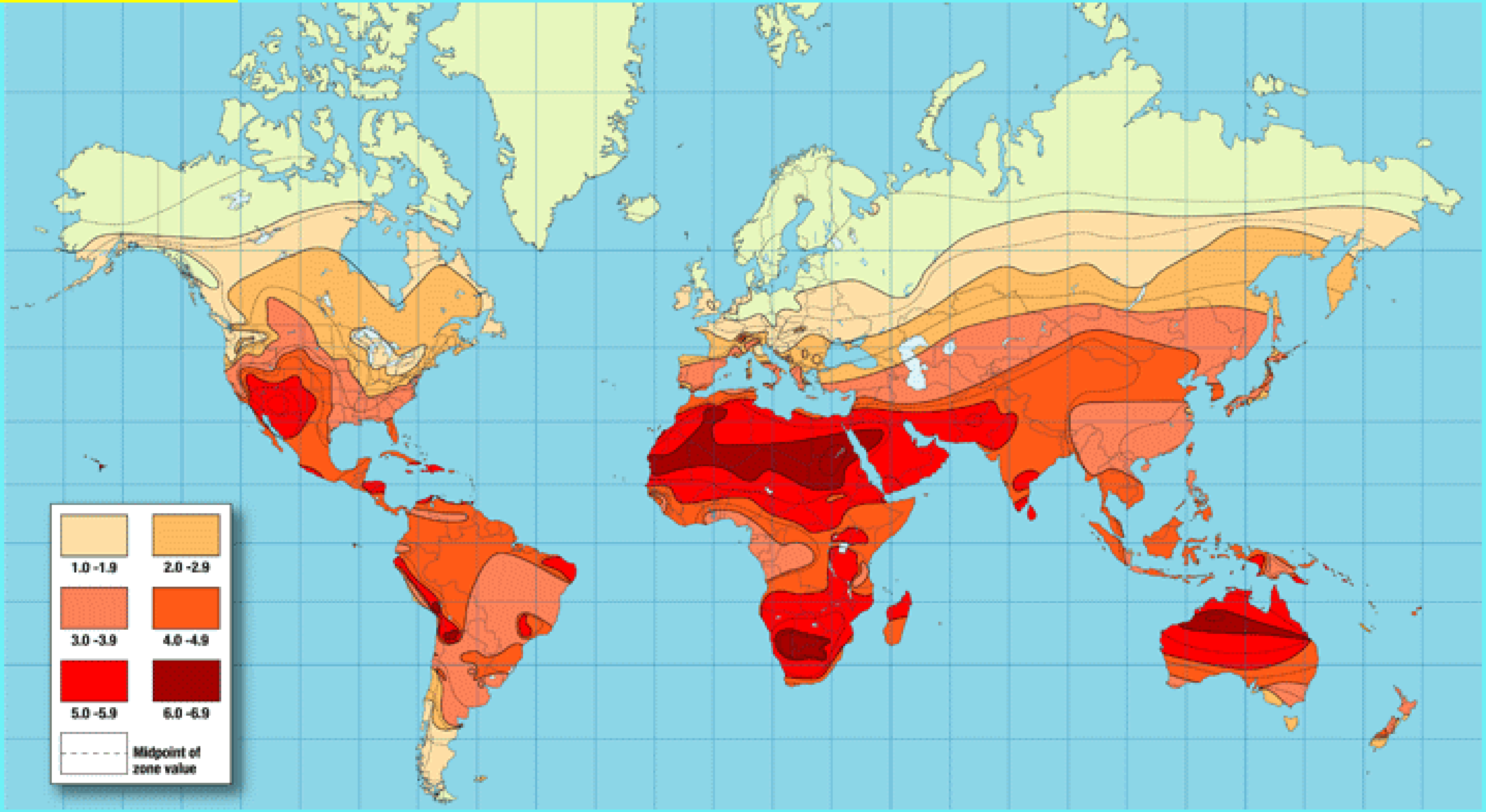
Solar Constant

The solar constant is the amount of incoming solar electromagnetic radiation per unit area, measured on the outer surface of Earth's atmosphere on a plane perpendicular to the rays.

The solar constant includes all types of solar radiation, not just the visible light. It is estimated to be roughly, G_{SC} =1,366 watts per square meter (W/m²).

1. Models of the photovoltaic (PV) cell, PV panel and PV array

1.1. Solar Energy



The map shows the amount of solar energy in hours, received each day on an optimally tilted surface during the worst month of the year. (Based on accumulated worldwide solar insolation data). Source: www.altestore.com

1. Models of the photovoltaic (PV) cell, PV panel and PV array

1.1. Solar Energy

Solar Spectrum

The sun radiates power over a continuous band or spectrum of electromagnetic wavelengths. The power levels of the various wavelengths in the solar spectrum are not the same.

Ultraviolet, Visible and Infrared Radiation

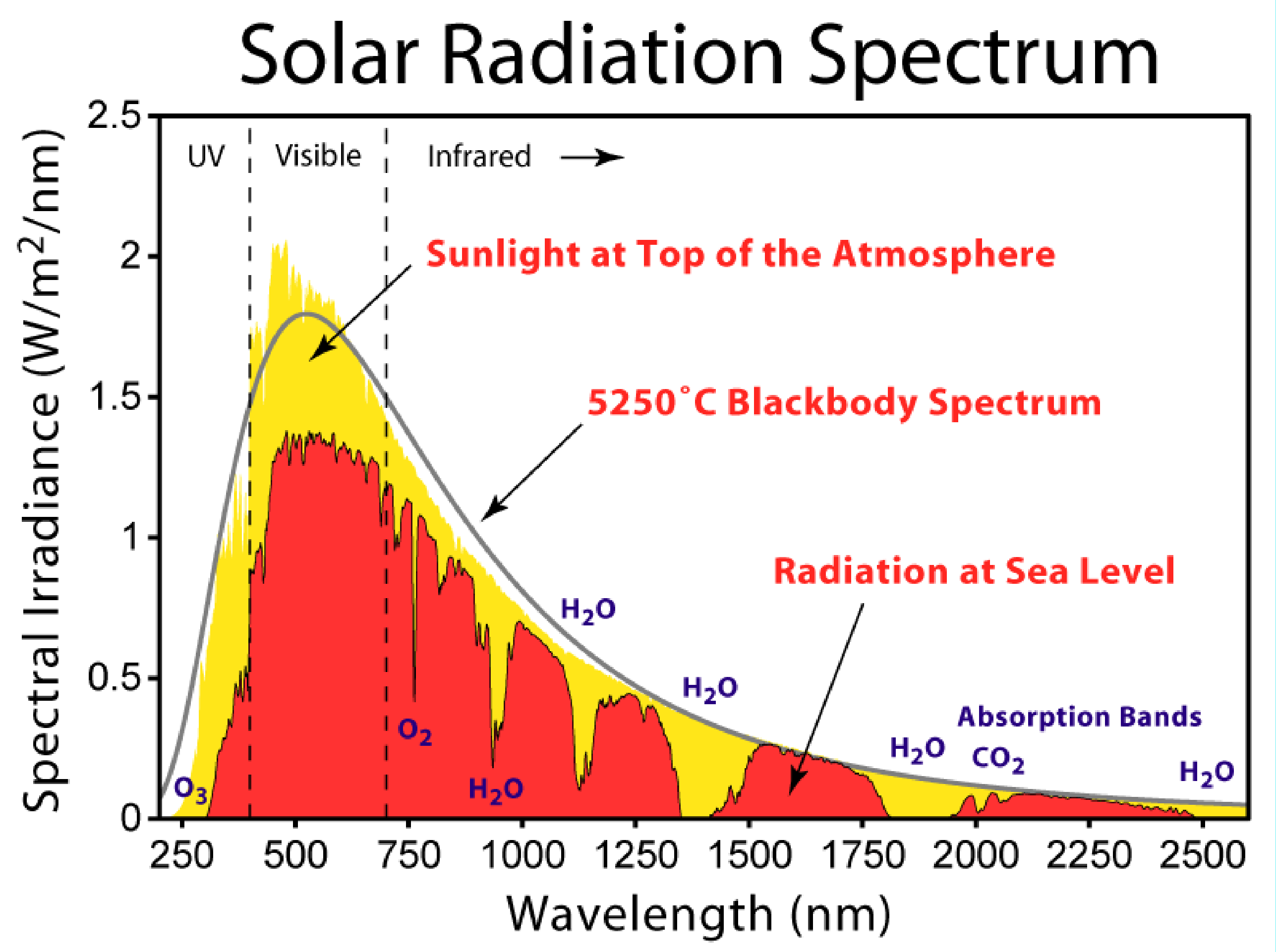
The sun's total energy is composed of:

- 7% ultraviolet radiation ($\lambda<0,38\ \mu m$),
- 47% visible radiation ($0,38\ \mu m < \lambda < 0,78\ \mu m$) and
- 46% infrared (heat) radiation ($\lambda > 0,78\ \mu m$).

Photovoltaic cells primarily use visible radiation.

1. Models of the photovoltaic (PV) cell, PV panel and PV array

1.1. Solar Energy



Solar Spectrum (Source: www.juliantrubin.com)

1. Models of the photovoltaic (PV) cell, PV panel and PV array

1.1. Solar Energy

Solar Insolation

The results of the earth's motion and atmospheric effects at various locations have led to essentially two types of solar insolation data. These are daily and hourly.

Solar irradiance is related to *power per unit area* where as

solar insolation is related to *radiant energy per unit area*. Solar insolation is determined by summing solar irradiance over time, and is usually expressed in units of kWh/m^2 /day.

1.2. Photovoltaic conversion. The photovoltaic effect

In the photovoltaic effect, **the solar energy generates electron-hole pair** in a semiconductor device to produce electricity.

It consist in increasing the electrical conductivity of a semiconductor or dielectric material under the action of light, due to the generation of free charge carriers-electrons and holes.

The photovoltaic effect was discovered in 1839.

Bell Laboratories scientists developed the first viable PV cells in 1954.

One electron-hole pair is created for every incident photon that has an energy,

$$W_f = h\upsilon$$

if

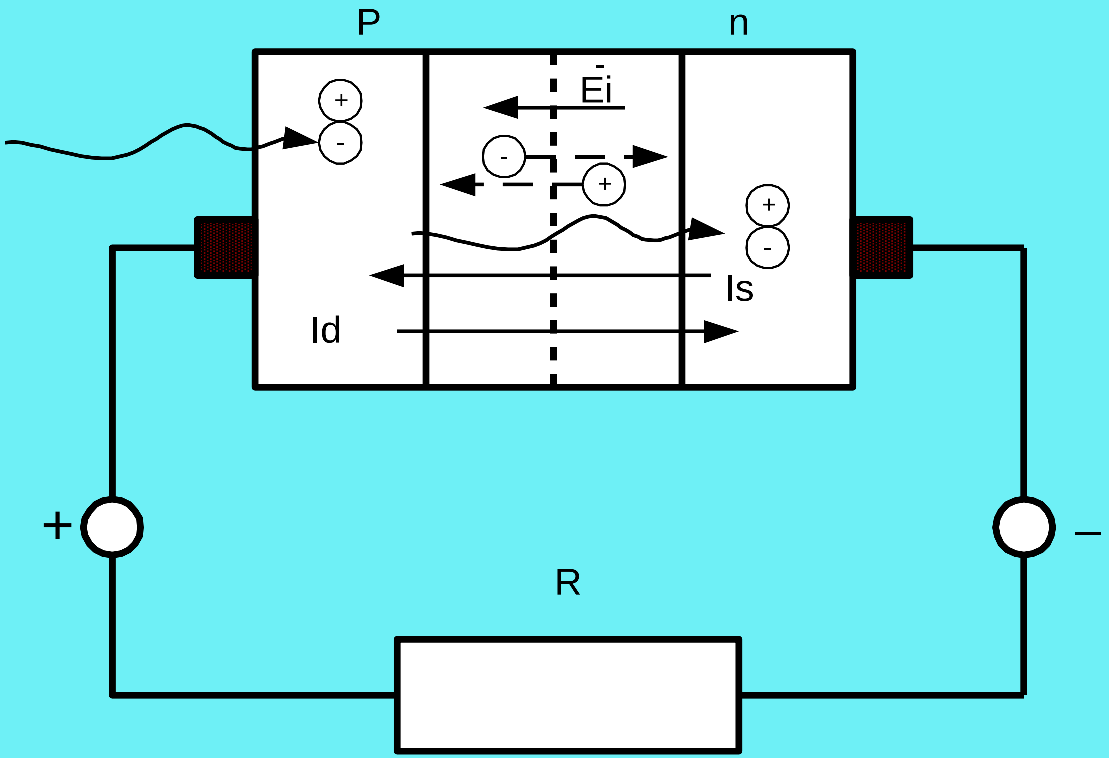
$$W_f > W_g$$

where

h=6,6254·10^{-34}J·s is the Planck's constant,

υ is the frequency of the electromagnetic wave, and

W_g is the band-gap energy.



1.2. Photovoltaic conversion. The photovoltaic effect

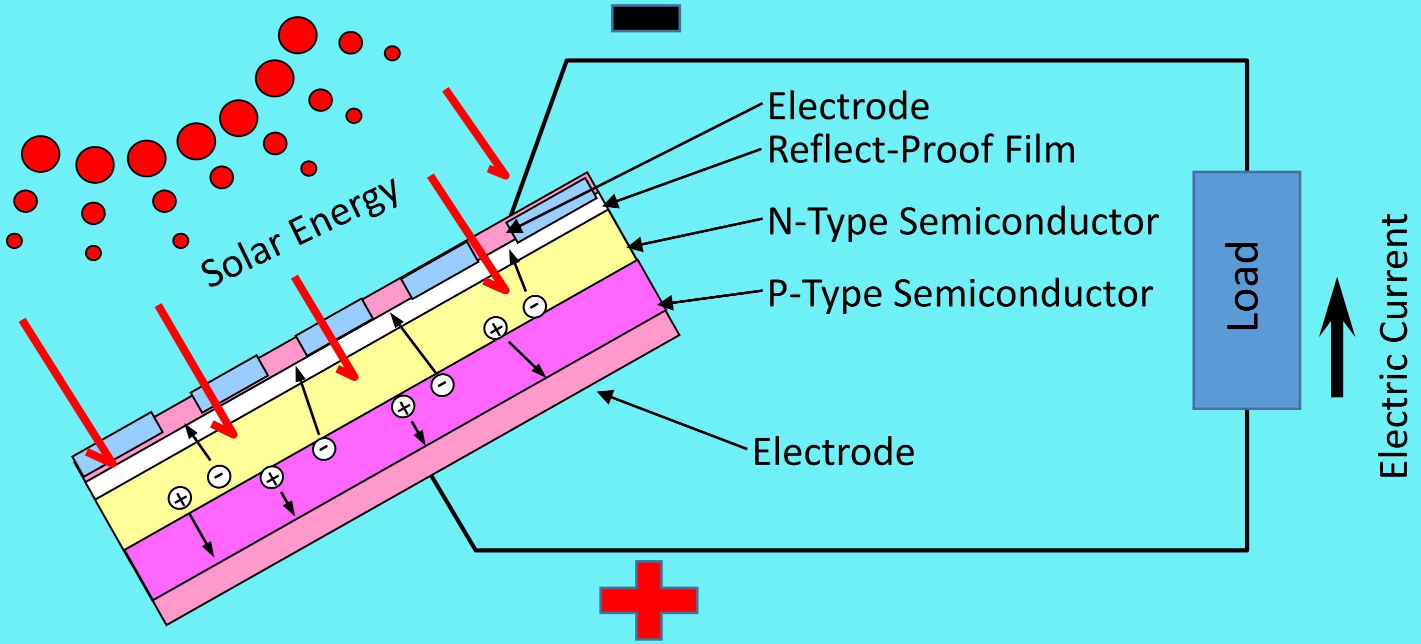
Material	ν_0 (THz)	λ (nm)	W_g (eV)	Region in which transition from transparent to opaque occurs
α-Sn	19.3	15,500	0.08	Far infrared
Ge	162	1850	0.67	Infrared
Si	265	1130	1.10	Infrared
GaAs	326	920	1.35	Near infrared
GaP	540	555	2.24	Visible
C	1300	230	5.40	Ultraviolet

Light Absorption Limits for Some Semiconductors (A da Rosa, **Fundamentals of Renewable Energy Processes,** 2009, Elsevier Inc.)

1.3. Photovoltaic cell. Construction, principle of operation

A Photovoltaic cell is a device that directly converts light into electrical energy based on the photovoltaic effect.

Most of the photovoltaic cells are made from silicon. A PV cell consists of a pn junction, two electrodes, a conductive grid and an anti-reflection coating.

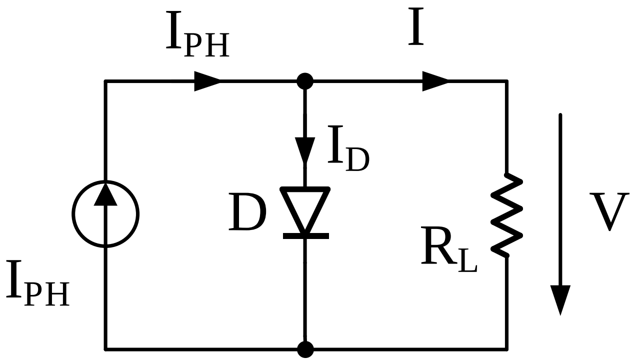


Photovoltaic cell

1.3. Photovoltaic cell. Construction, principle of operation

The operation of the photovoltaic cells can be studied considering the p-n junction in parallel with a constant current source.

The constant current source is modeling the photovoltaic effect.



$$I_{PH} = qA\Phi_g$$

where q is the charge of the elecron,
Φ_g is the flux of photons with energy larger then W_g (band-gap energy), and
A is the active aria of junction

1.4. Types of solar cells

Solar Cell			Conversion Efficiency of Module
Silicon Semiconductor	Crystalline	Single crystal	10 - 17%
		Poly crystalline	10 - 13%
	Non-crystalline	Amorphous	7 - 10%
Compound Semiconductor	Gallium Arsenide (GaAs)		18 - 30%
Organic Semiconductor	Dye-sensitized Type		7 - 8%
	Organic Thin Layer Type		2 - 3%

$$\left(\text{Conversion Efficiency} = \frac{\text{Electric Energy Output}}{\text{Energy of Insolation on cell}} \times 100\% \right)$$

1.5. The efficiency of PV cell

The maximum power produced by a PV cell does not exceed **3W** and the terminal voltage does not exceed the maximum value of 0.6 V at idle.
PV cells can provide power about 160 W / m².
The main factor that defines the quality of a solar cell is the **efficiency**, or the **conversion factor**, which is the ratio of the maximum power delivered by the cell P_M and the incident power P_N.

$$\eta = \frac{P_M}{P_{IN}} = \frac{U_M I_M}{P_{IN}}$$

The ideal efficiency of the PV cell is 43,8% (A da Rosa, **Fundamentals of Renewable Energy Processes,** 2009, Elsevier Inc.). The PV cell made of GaAs is the most efficient (up to 30%).

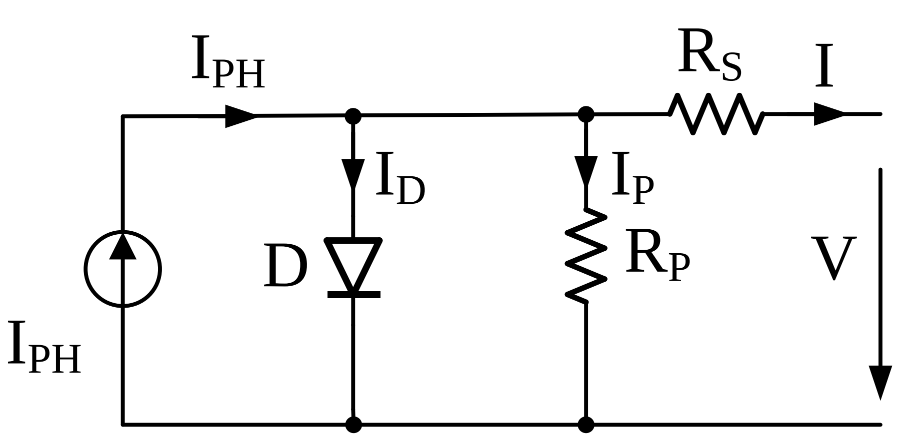
In order to obtain a higher photovoltaic power, the PV cells are connected in series to form a PV panel or a PV module.
The PV modules may be associated in turn in series or in parallel to form fields or PV array.

1.6. The model with a single diode of the PV cell

The PV cell is a non-linear DC source.
There are two models for modeling PV cells: the simple diode model and the double diode model.

The constant current source connected with a semiconductor diode, forms an ideal cell to which a series resistance and a parallel resistance are added.
The current-voltage characteristic of a diode is given by:

$$I_D = I_0\left[exp\left(\frac{qV}{kT}\right) - 1\right]$$



The simple diode model of a PV cell

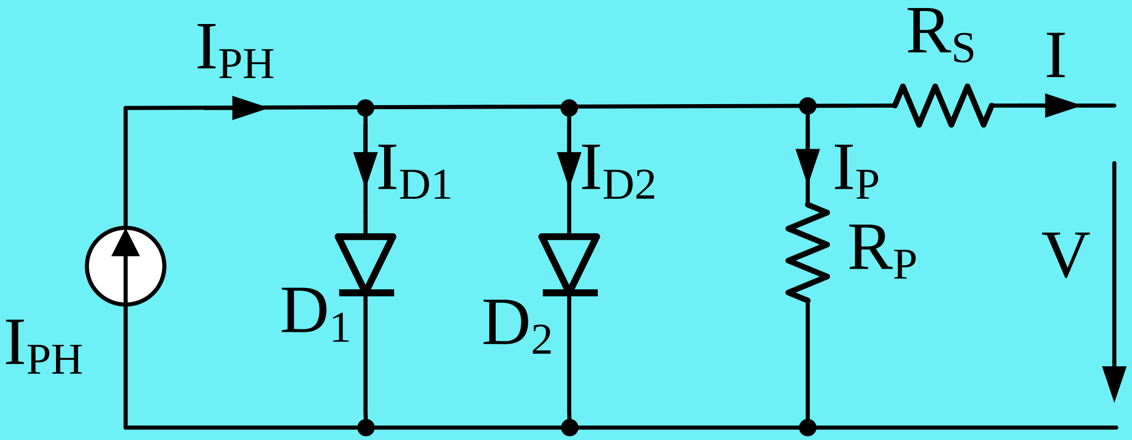
where:
q- electron charge (1.602×10^{-19} C);
k- the Boltzmann constant (1.38×10^{-23} m^2 kg s^{-2} K^{-1});
T- cell temperature;
I_0 - saturation current of the reverse biased junction.

I-V characteristic of a PV cell is given by:

$$I = I_{PH} - I_0\left[exp\left(\frac{q(V + R_S \cdot I)}{kT}\right) - 1\right] - \frac{V + R_S \cdot I}{R_P}$$

1.7. The double diode model of a PV cell

This model takes into account the phenomenon of recombination of the charge carriers in the p-n junction and the variation of the coefficient A of the semiconductor diode with voltage.



The I-U characteristic of a PV cell for double diode model is given by the equation:

$$I = I_{PH} - I_{01}\left[exp\left(\frac{q(V + R_S \cdot I)}{A_1 kT}\right) - 1\right] - I_{02}\left[exp\left(\frac{q(V + R_S \cdot I)}{A_2 kT}\right) - 1\right] - \frac{V + R_S \cdot I}{R_P}$$

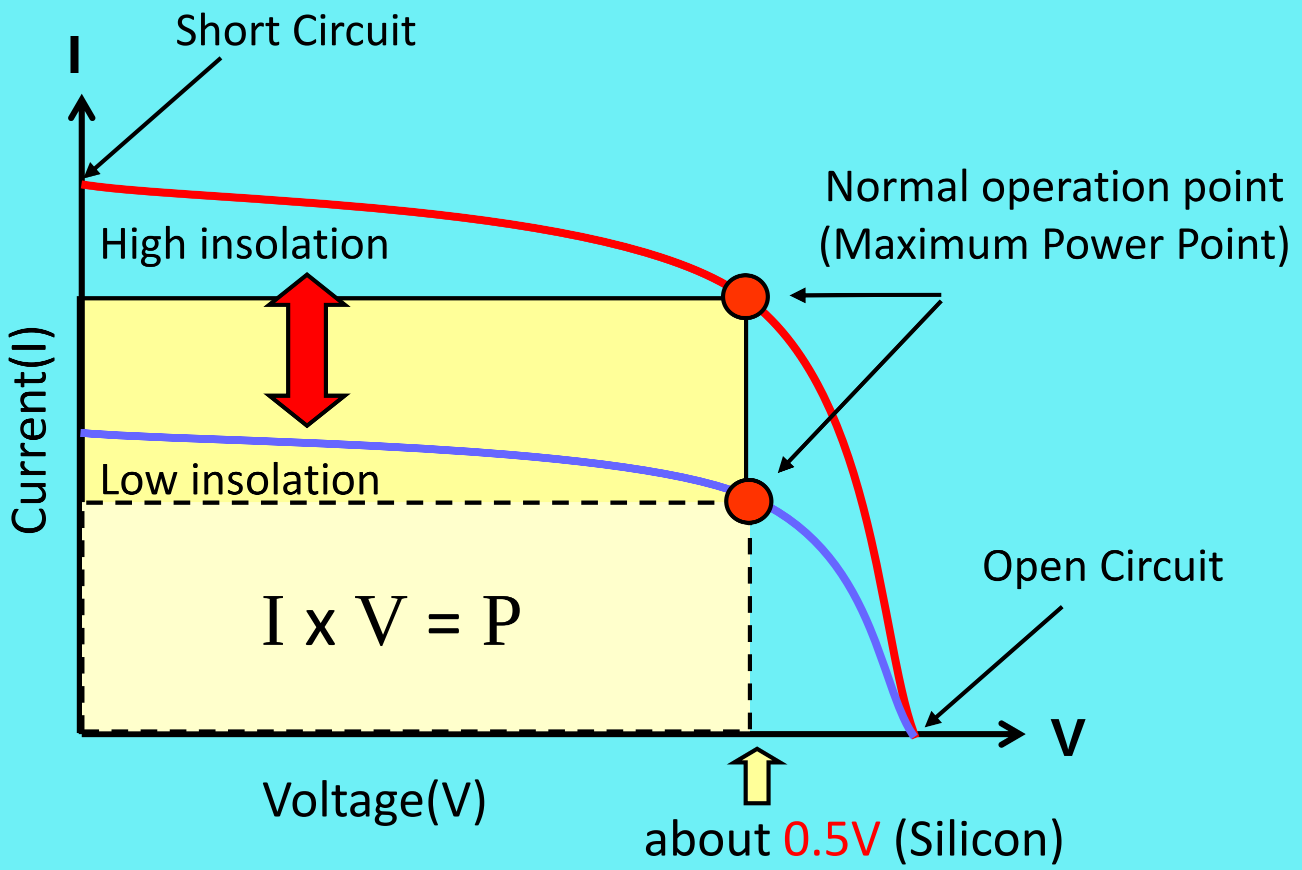
1.8. Characteristic curves of a PV cell

Current-voltage characteristic, I-V

I-V characteristic mainly depends:
- on the intensity of the solar radiation G and;
- on the temperature of the cell.

For an ideal PV cell ($R_S \approx 0$, $R_P \rightarrow \infty$) graph is analytically determined by the relation:

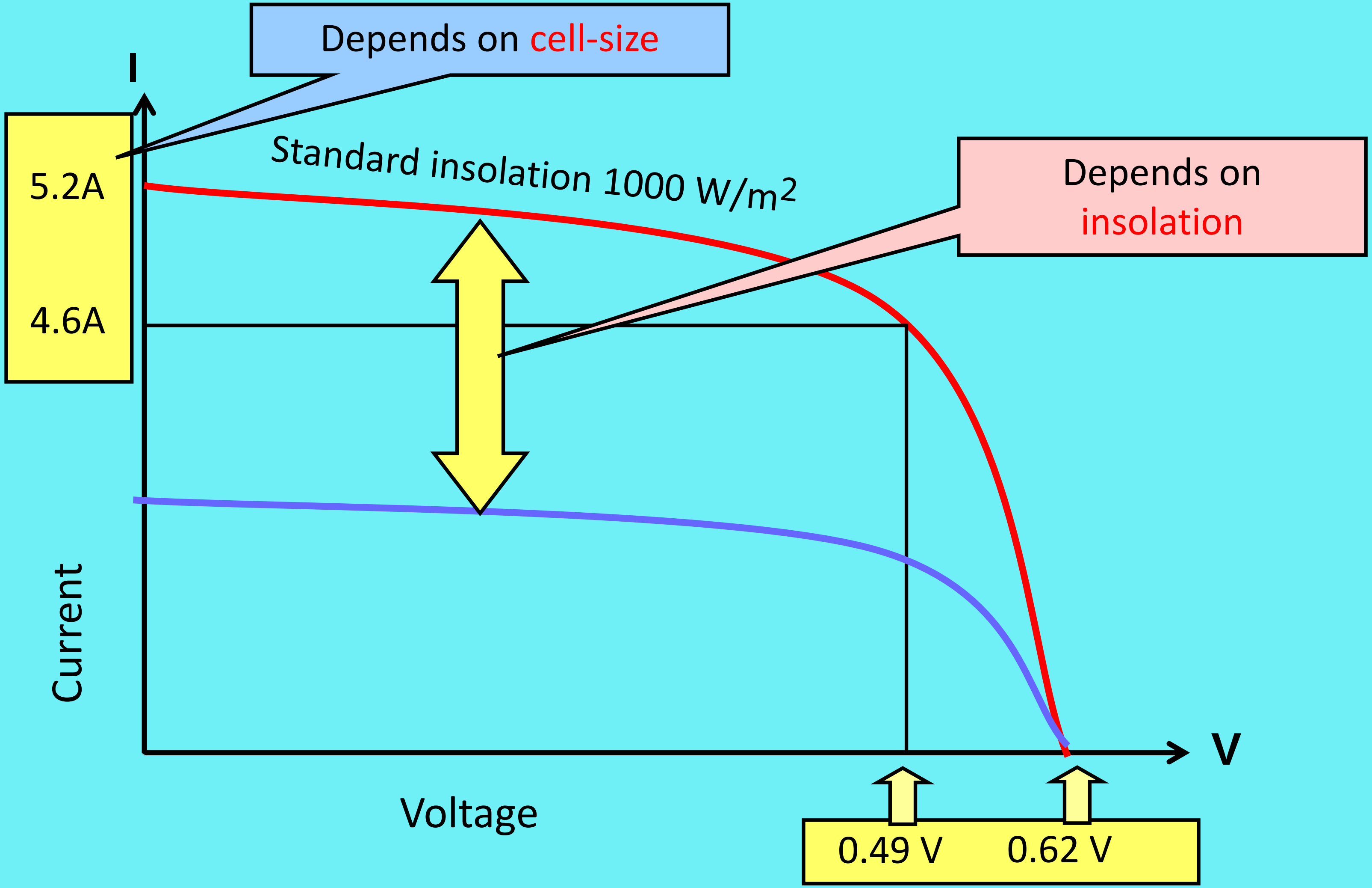
$$I = I_{PH} - I_0 \left[exp\left(\frac{qV}{kT}\right) - 1 \right]$$



•Voltage on normal operation point 0.5V (in case of Silicon PV)

1.8. Characteristic curves of a PV cell

Current-voltage characteristic, I-V



1.8. Characteristic curves of a PV cell

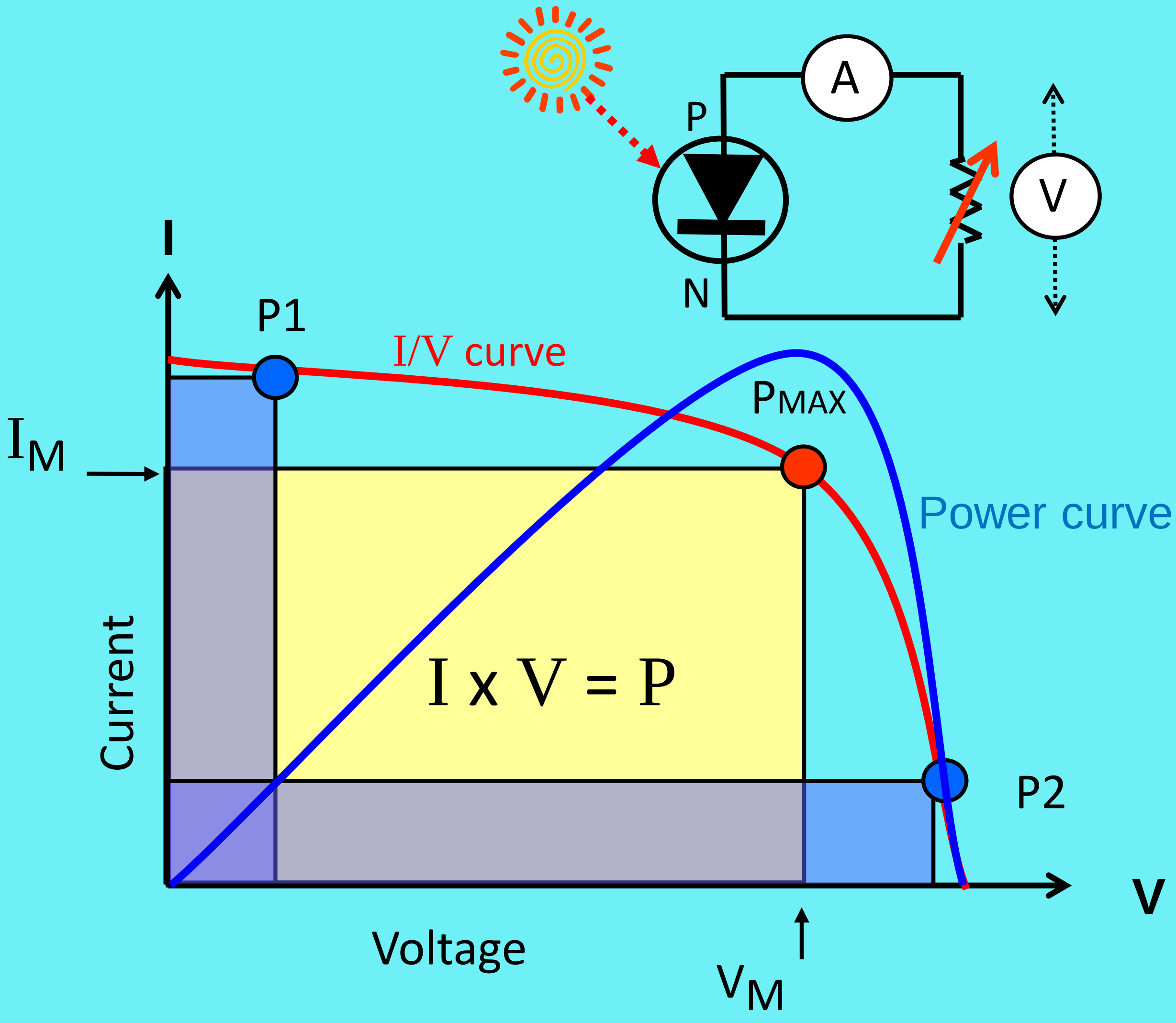
Power-voltage characteristic, P-V

$$P = V \cdot I = V\left\{I_{PH} - I_0\left[exp\left(\frac{qV}{kT}\right) - 1\right]\right\}$$

From the relation $\frac{dP}{dU} = 0$, the coordinates of the maximum power point MPP are obtain.

$$exp\left(\frac{qV_M}{kT}\right)\left[\left(\frac{qV_M}{kT}\right) + 1\right] = \frac{I_{PH} + I_0}{I_0}$$

To obtain the maximum power, the current control (or voltage control) is necessary.



1.8. Characteristic curves of a PV cell

Power-current characteristic, P-I

$$P = I \cdot V = I \cdot V_T \cdot ln\left(1 + \frac{I_{PH} - I}{I_0}\right)$$

where $V_T = \frac{kT}{q}$ is the thermal voltage equivalent.

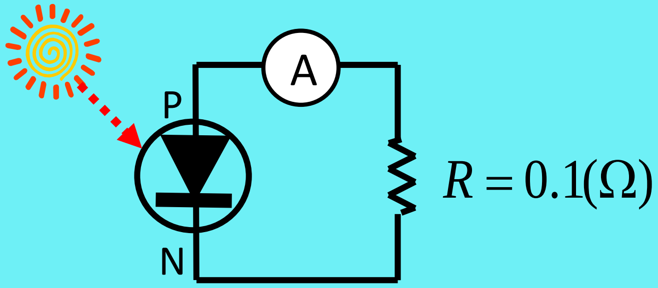
The maximum point is defined by the equations:

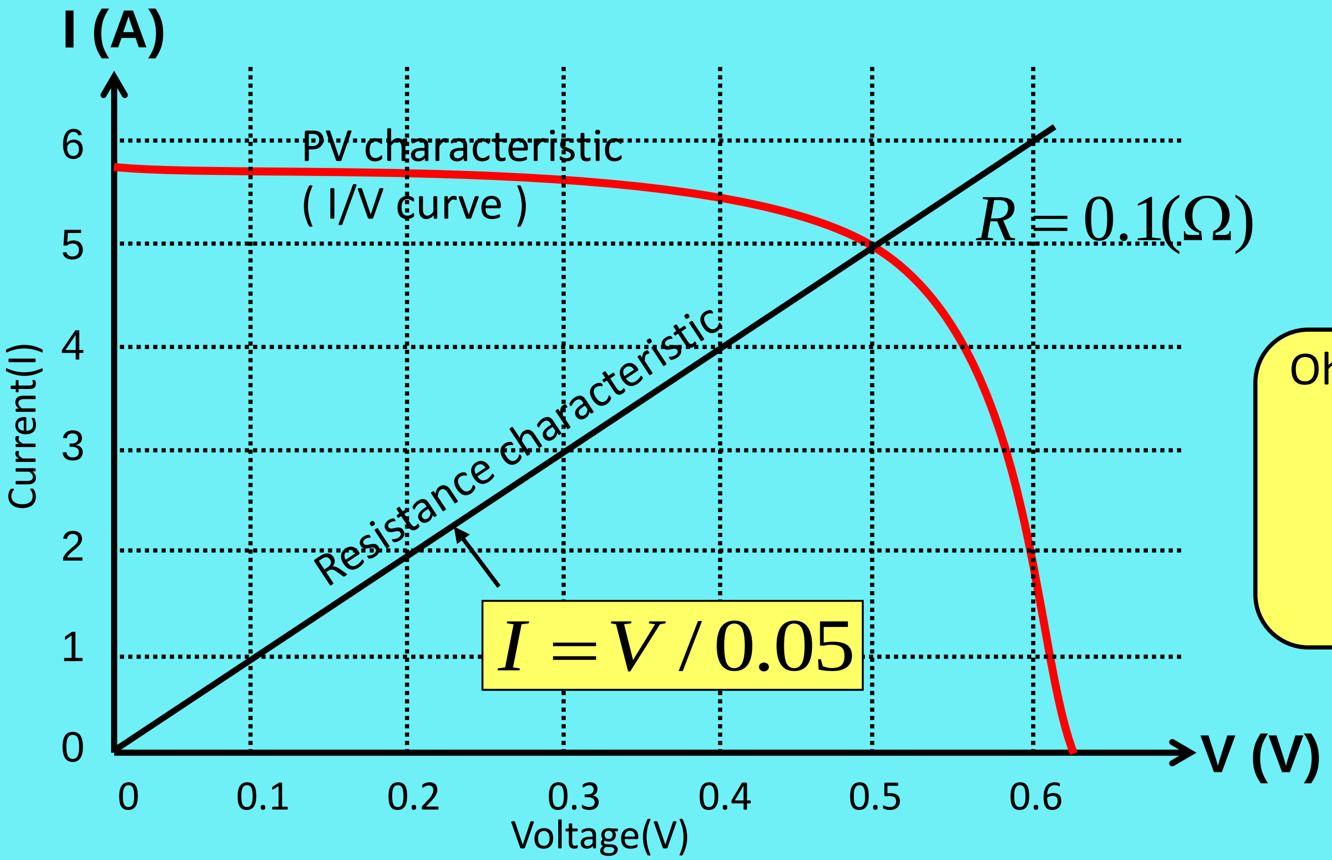
$$V_M = V_0 - V_T ln\left(1 + \frac{V_M}{V_T}\right)$$

$$I_M = I_{PH}\left(1 + \frac{I_0}{I_{PH}}\right)\frac{V_M}{V_M + V_T}$$

1.8. Characteristic curves of a PV cell

Estimate the load power from current-voltage characteristic, I-V

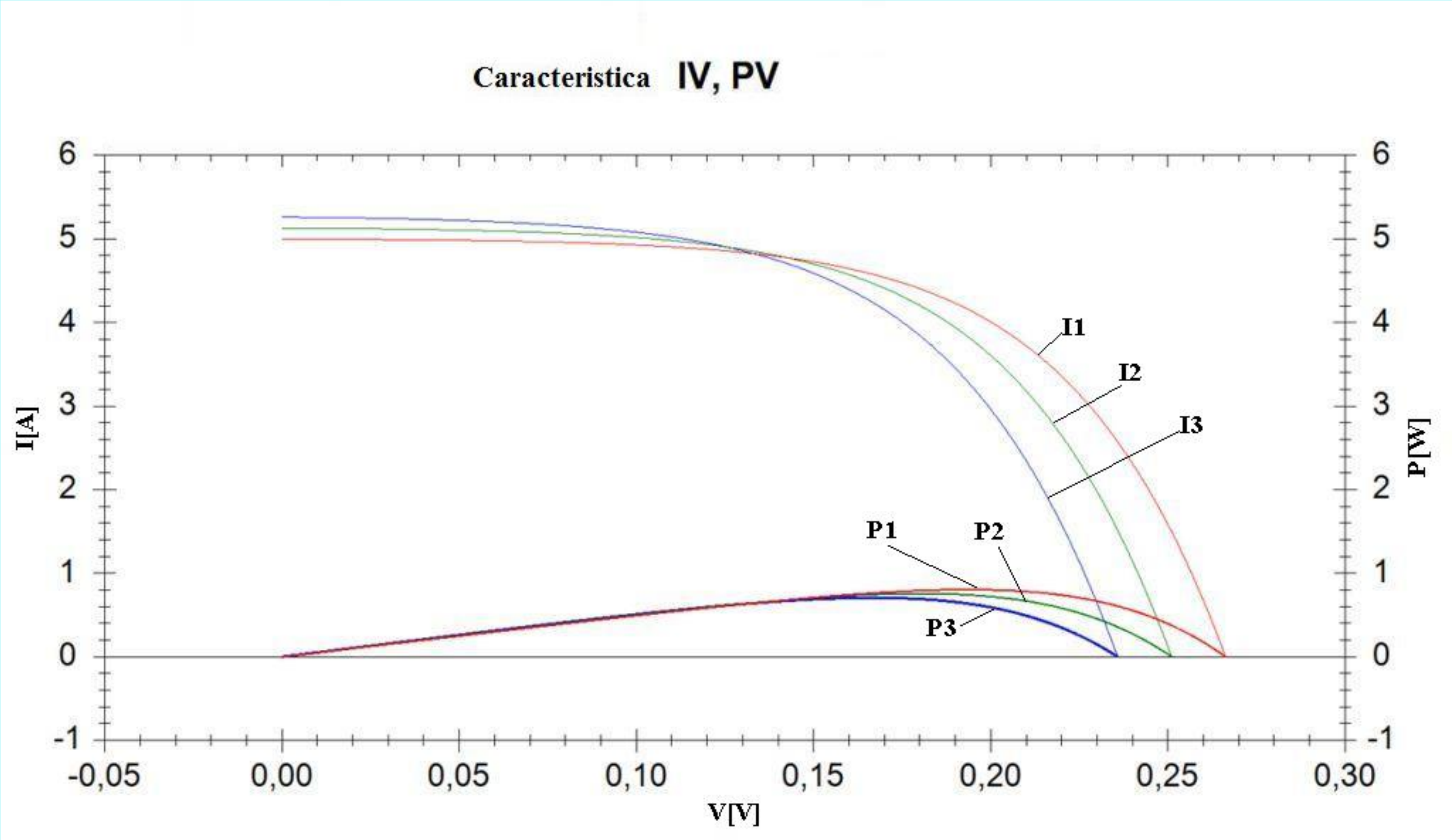




Ohm's low

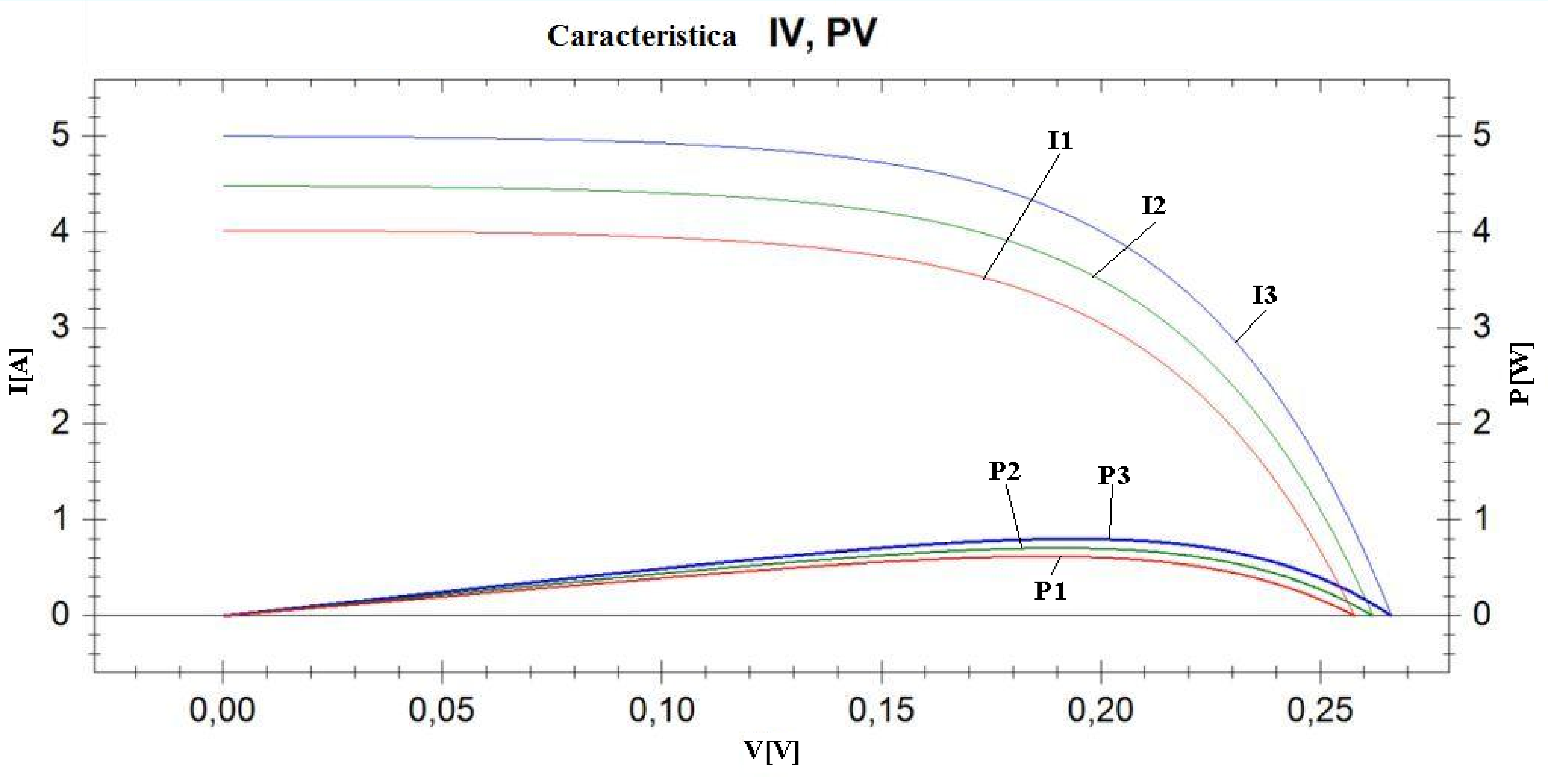
$$I = \frac{V}{R}$$

1.8. Characteristic curves of a PV cell



I-V and P-V characteristics for G=1000 W/m^2, for different values of T
(I_1, P_1 for T = 25^{0}C, I_2, P_2 for T = 30^{0}C, I_2, P_3 for T = 35^{0}C)

1.8. Characteristic curves of a PV cell

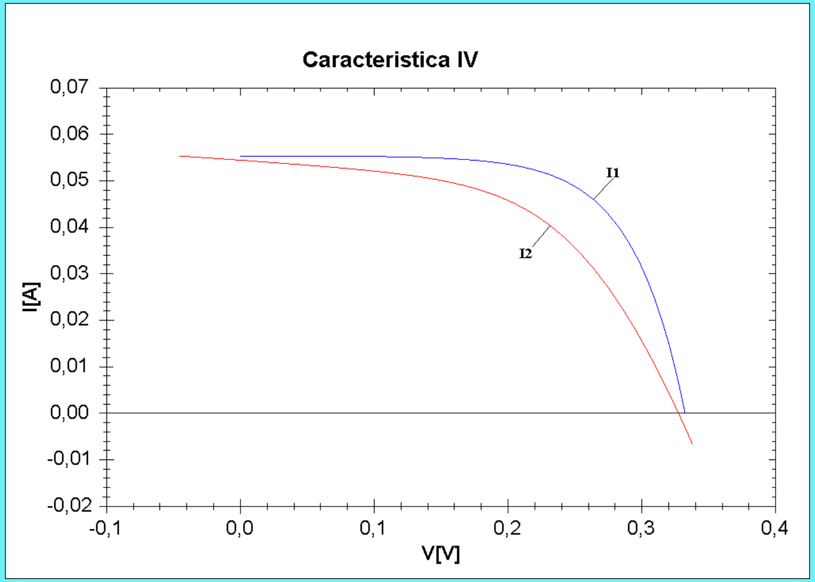


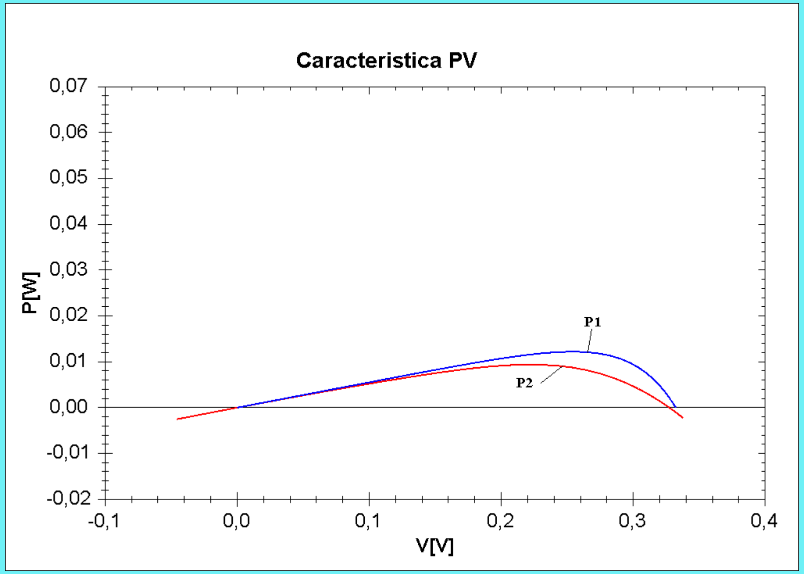
I-V and P-V characteristics for T =25^{0}C , for different values of solar irradiation
(I_1, P_1 for G= 803 W/m^2, I_2, P_2 for G= 896W/m^2, I_3, P_3 for G= 1000W/m^2)

1.8. Characteristic curves of a PV cell

Influence of the Rs and Rp on the characteristics of solar cell

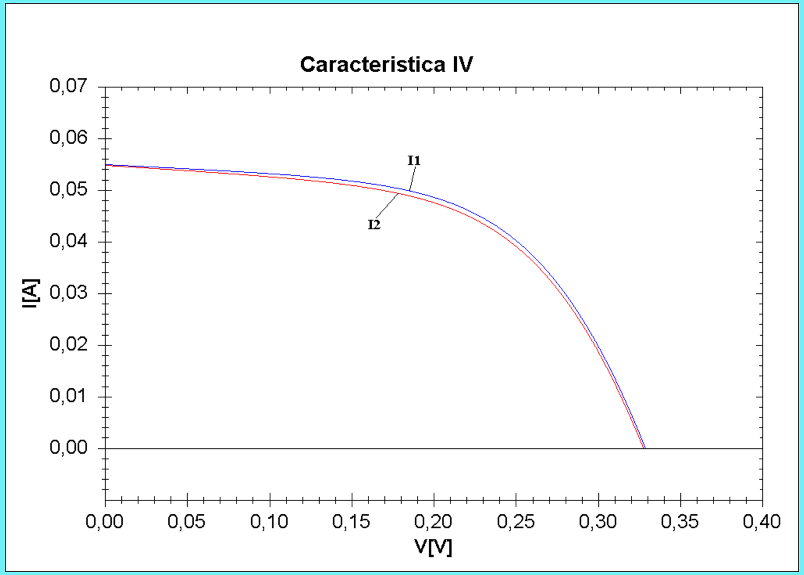
I1 for Rs=0,50Ω;
I2 for Rs=0,83Ω

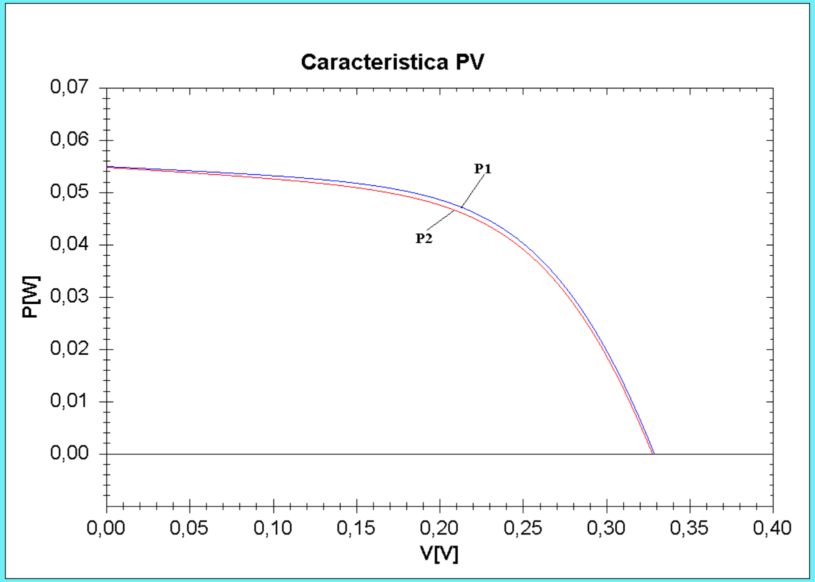




P1 for Rs=0,50Ω;
P2 for Rs=0,83Ω

I1 for Rp=100Ω;
I2 for Rp=50Ω



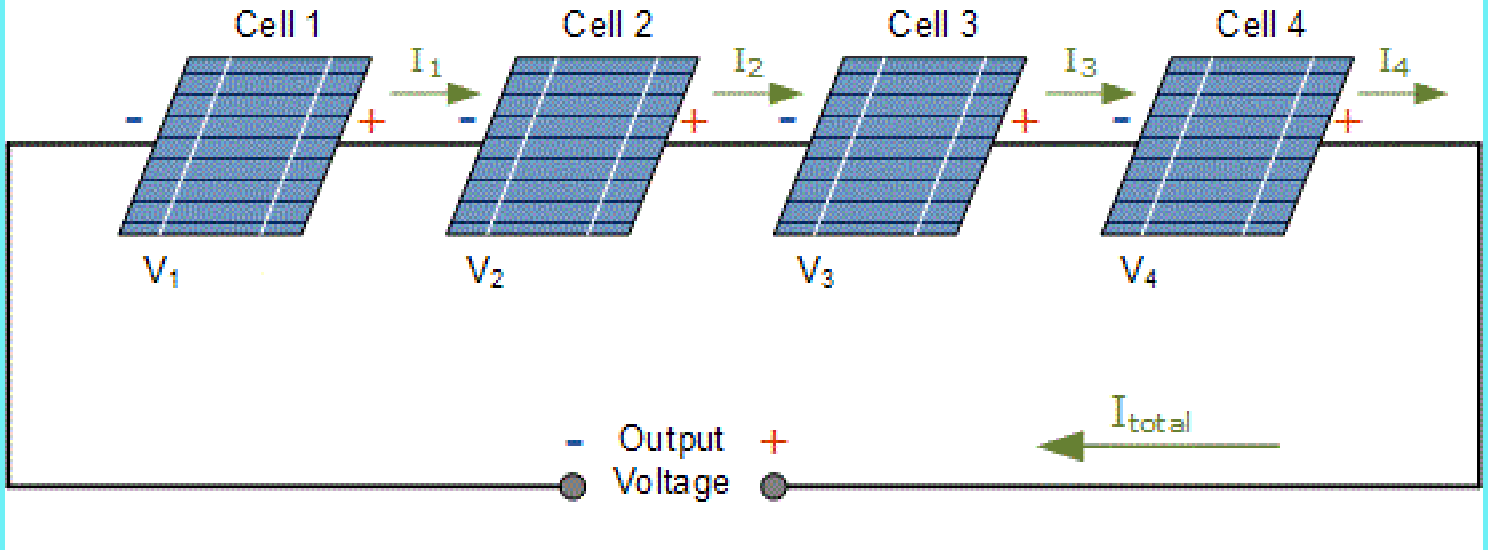


P1 for Rp=100Ω;
P2 for Rp=50Ω

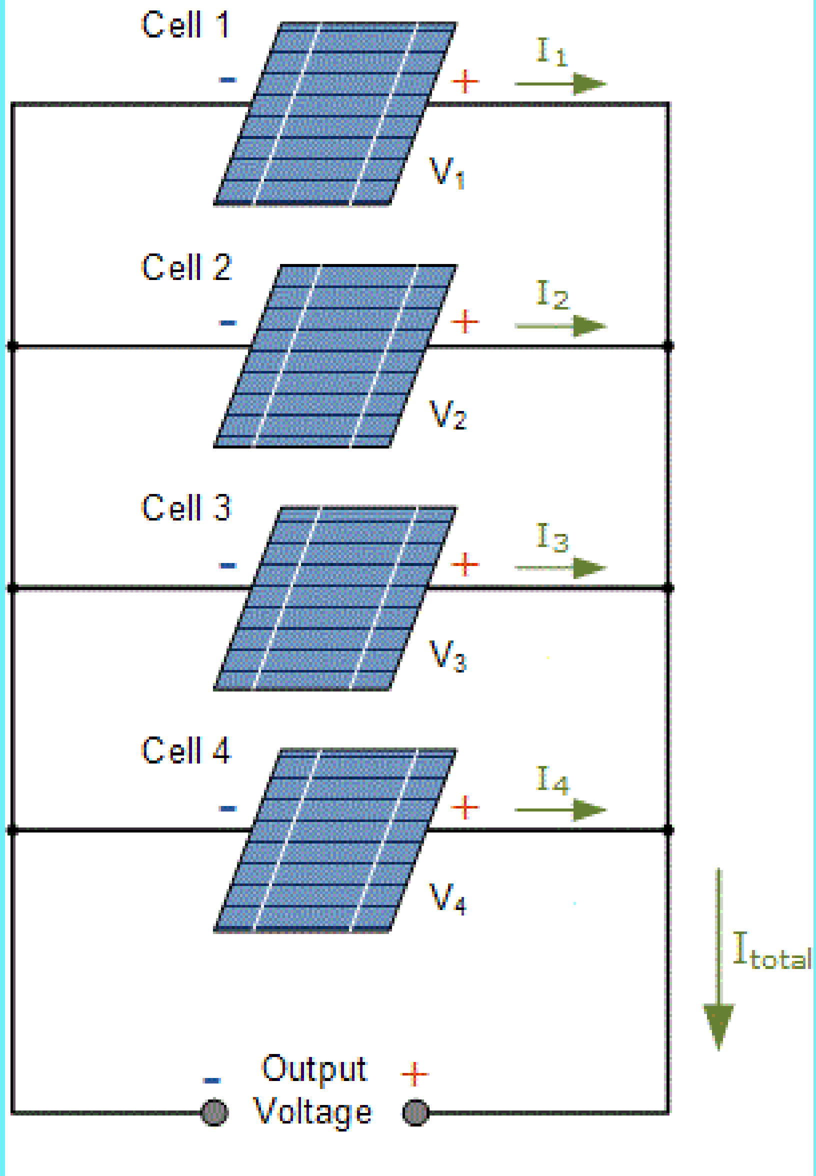
1.9. Solar module model

Connecting PV cells in series

The cells have to be connected in series to increase the total voltage of the module.
(Vout=V1+V2+V3+…).



Connecting PV cells in parallel



The parallel connecting increases the total current generated by the module (Iout=I1+I2+I3+...).

1.9. Solar module model

For N_p cells branches in parallel and N_s cells in series, the total shunt resistances ($R_{sh,module}$) and series resistances ($R_{s,module}$) in module are equal to:

$$R_{p,module} = \left(\frac{N_s}{N_p}\right) \cdot R_p$$

$$R_{s,module} = \left(\frac{N_s}{N_p}\right) \cdot R_s$$

$$I_{SC,module} = N_p \cdot I_{SC}$$

$$V_{OC,module} = N_s \cdot V_{OC}$$

where

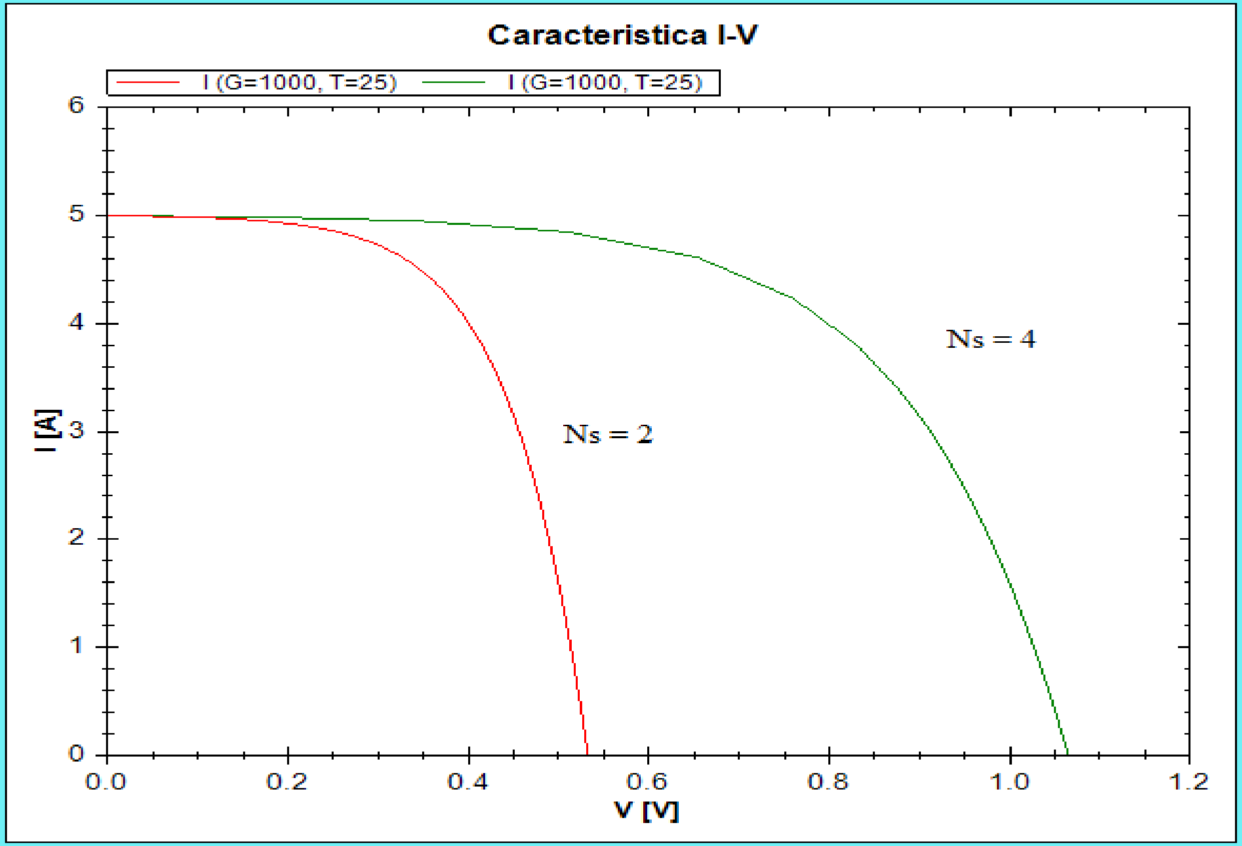
$R_{p,\ module}$: Total shunt resistance in the PV module, Ohm.
$R_{s,\ module}$: Total series resistance in the PV module, Ohm.
R_p: Shunt resistance in one PV cell, Ohm.
R_s: Series resistance in one PV cell, Ohm.
N_s: Number of cells in series
N_p: Number of cells branches in parallel

where

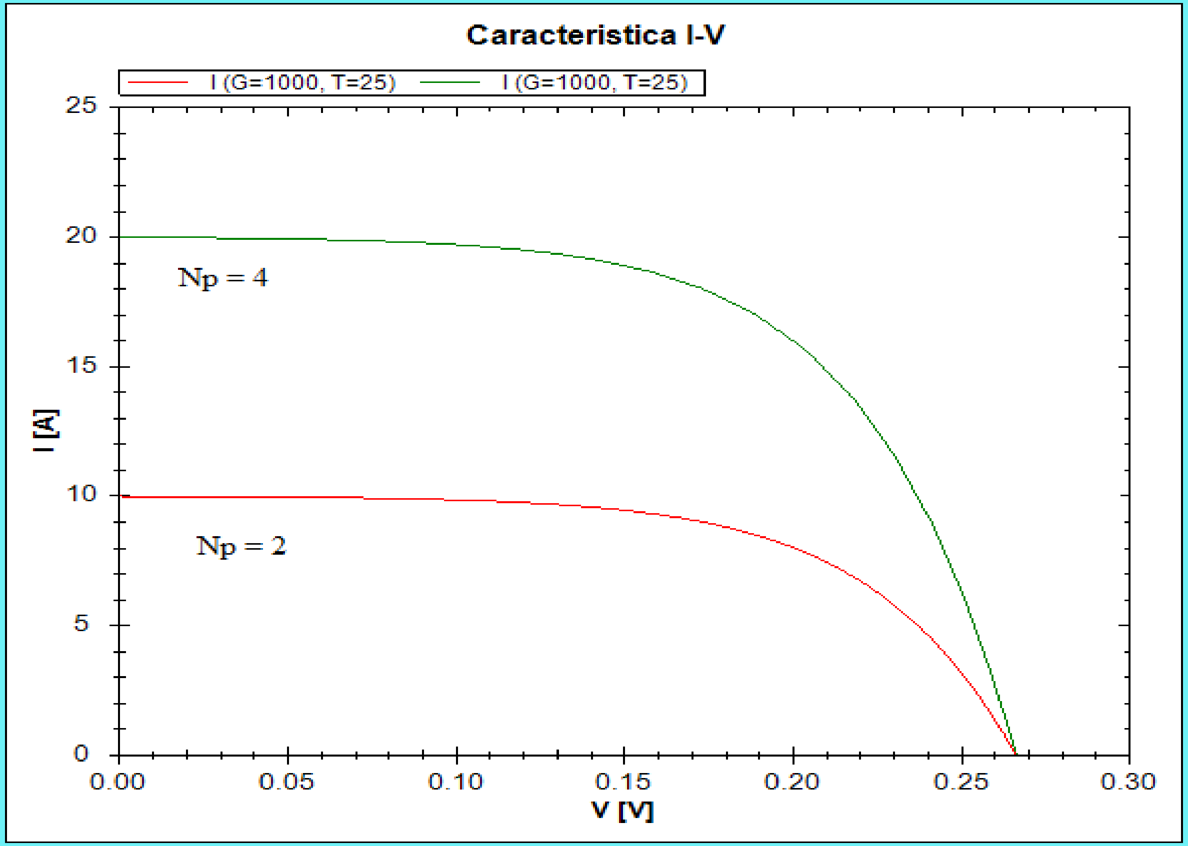
$I_{SC,\ module}$: Total short circuit current of the PV module, A.
$V_{OC,\ module}$: Total open circuit voltage of the PV module, V.
I_{SC}: Short circuit current of one photovoltaic cell
V_{OC}: Open circuit voltage of one photovoltaic cell

1.9. Solar module model

Influence of connected in series / parallel photoelectric cells

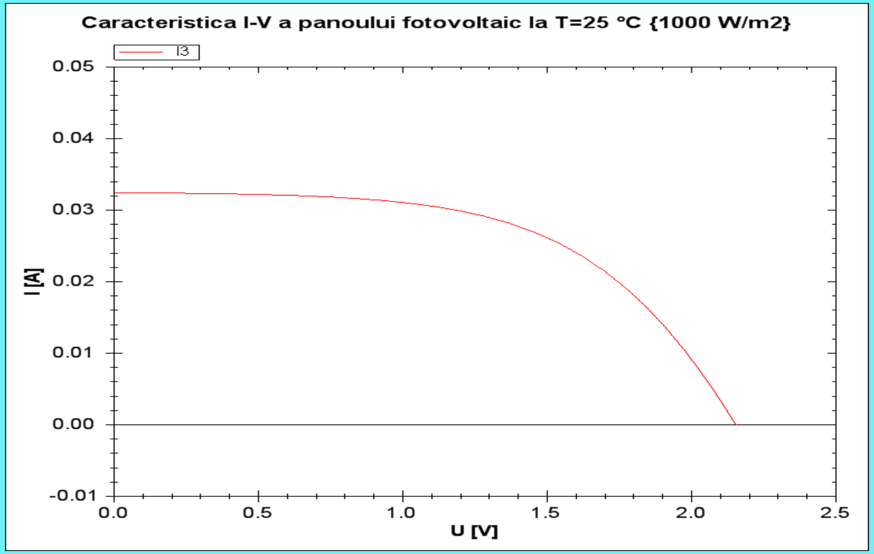


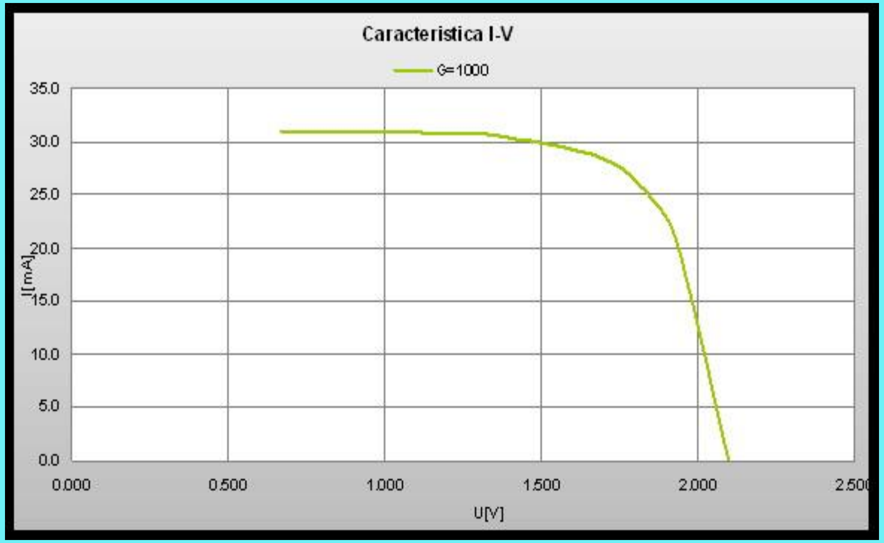
Connected in series



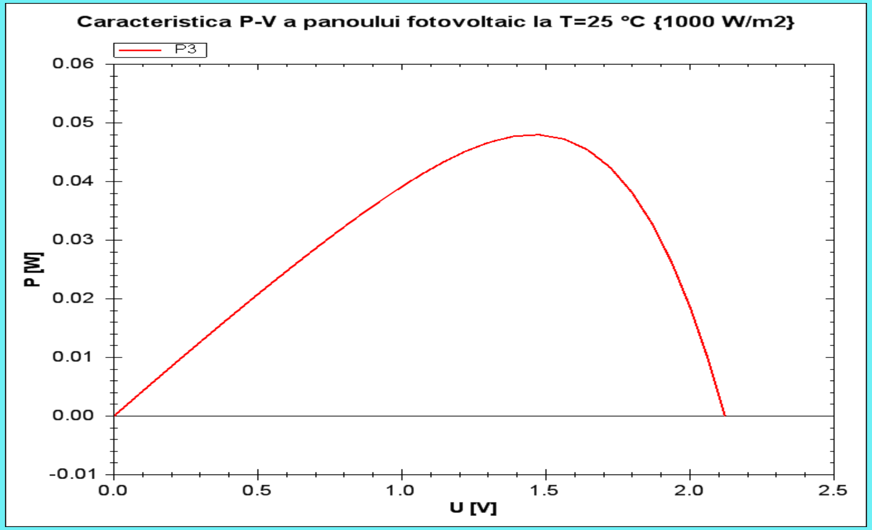
Connected in parallel

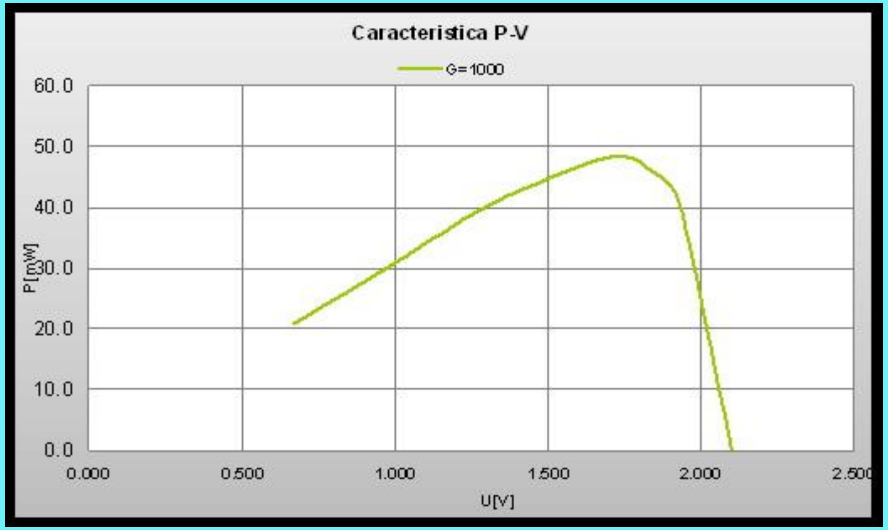
The comparatives results obtained by simulation and measurement





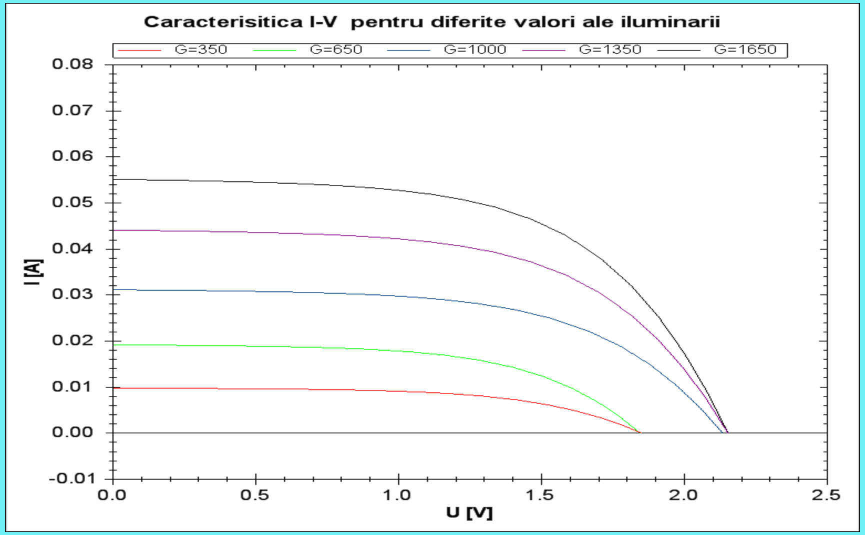
I-V characteristic for constant T=25 °C {1000 W/m2}

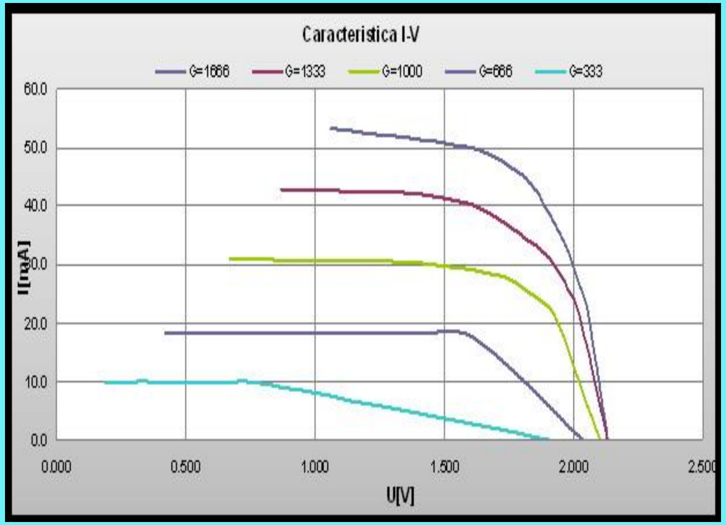




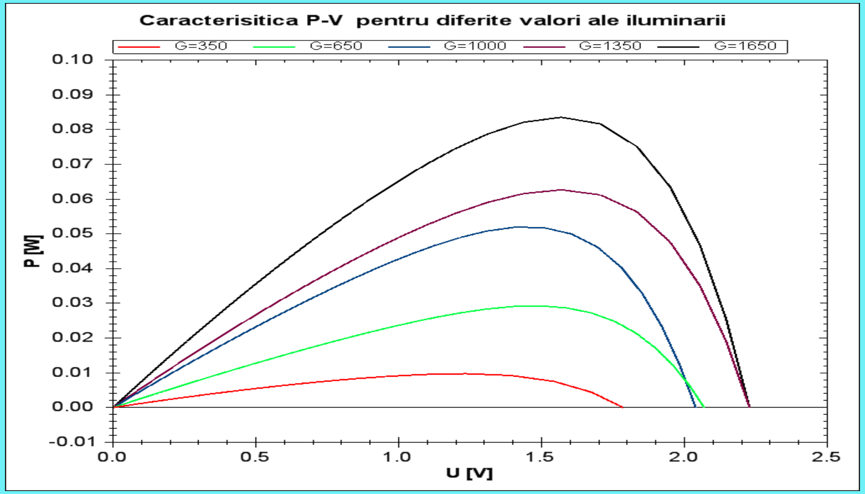
P-V characteristic for T=25 °C {1000 W/m2}

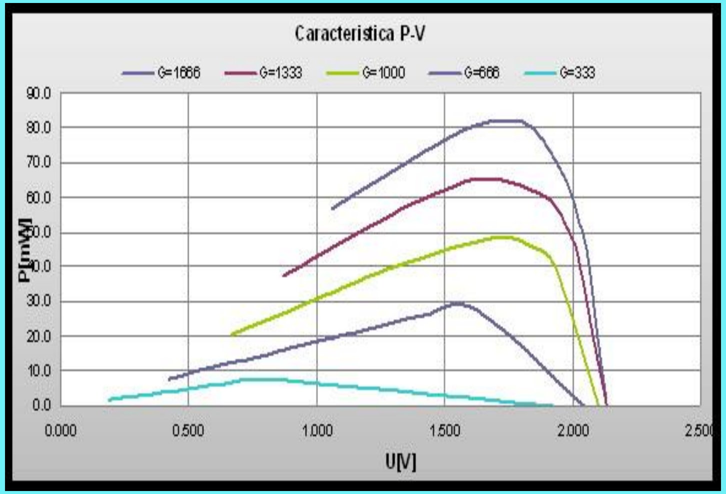
The comparatives results obtained by simulation and measurement





I-V characteristics for different solar irradiation





P-V characteristics for different solar irradiation

1.9. Solar module model

Specifications of Lorentz LC80-12M PV Module at standard test condition (1000 W/m², 25 °C)

Parameter	Variable	Value
Maximum Power	P_m	*80W*
Voltage@ Pm	V_m	*17.2V*
Current @ Pm	I_m	*4.6A*
Short circuit current	I_{SC}	*5A*
Open-circuit voltage	V_{OC}	*22.4V*
Temperature coefficient of open circuit voltage	*ko*	*-(0.35) %/°C*
Temperature coefficient of short circuit current	*ki*	*(0.09) %/°C*
Temperature coefficient of power		*-(0.5) %/°C*

1.10. Solar array model

The modules in a PV system are typically connected in arrays. Considering the case of an array with M_P parallel branches each with M_S modules in series.
The applied voltage at the array's terminals is denoted by V_{ARRAY}, while the total current of the array is denoted by:

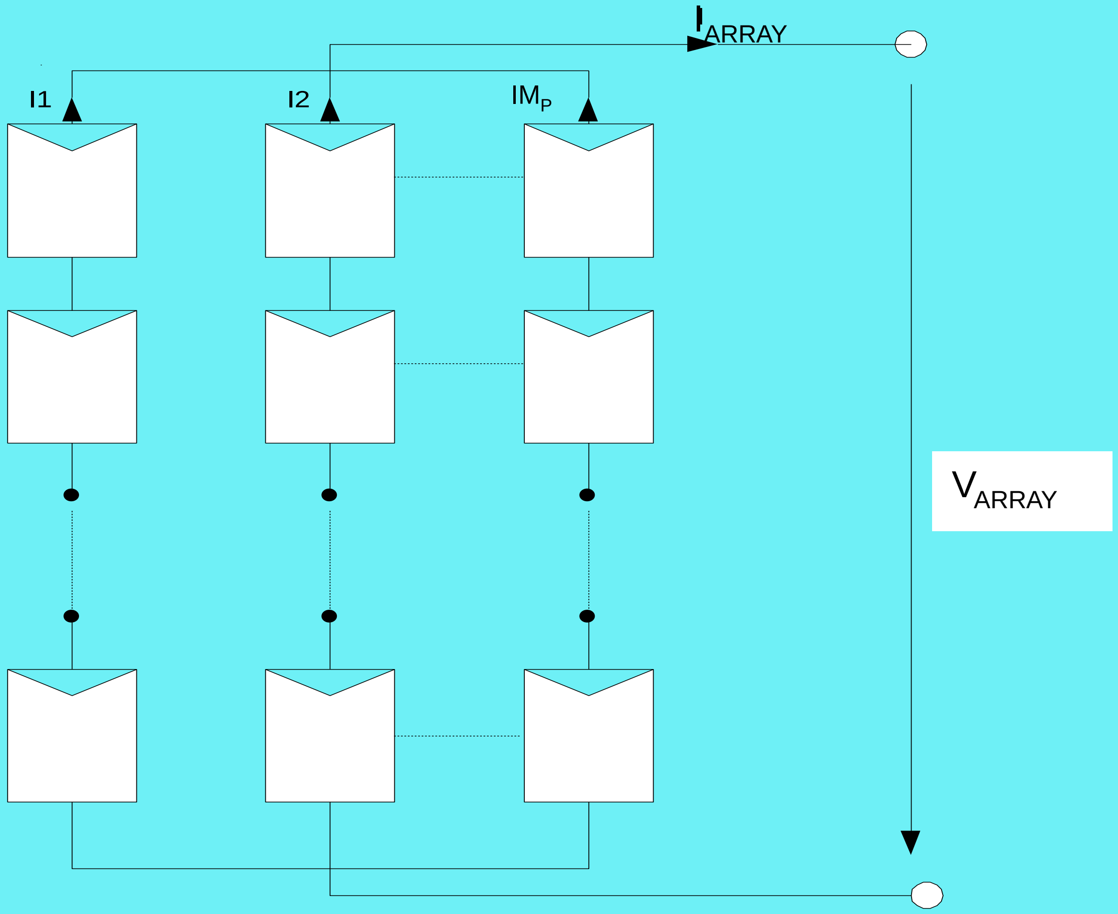
$$I_{ARRAY} = \sum_{i=0}^{M_p} I_i$$

If it is assumed that the modules are identical and the ambient irradiation is the same on all the modules, then the array's current is:

$$I_{ARRAY} = M_p I_{module}$$

And the array's voltage is:

$$V_{ARRAY} = M_s V_{module}$$



1.11. PV architectures

The mixed group of the PV modules is called either: area, field or photovoltaic array.

The main types of configurations of the PV systems are:

- **Centralized configuration**

The modules are grouped in short or long strings, which are connected in parallel to a central inverter.

- **String configuration**

Each PV string is connected to a DC-AC single-phase inverter. When the voltage is low, the presence of a DC-DC boost is necessary.

- **Multistring configuration**

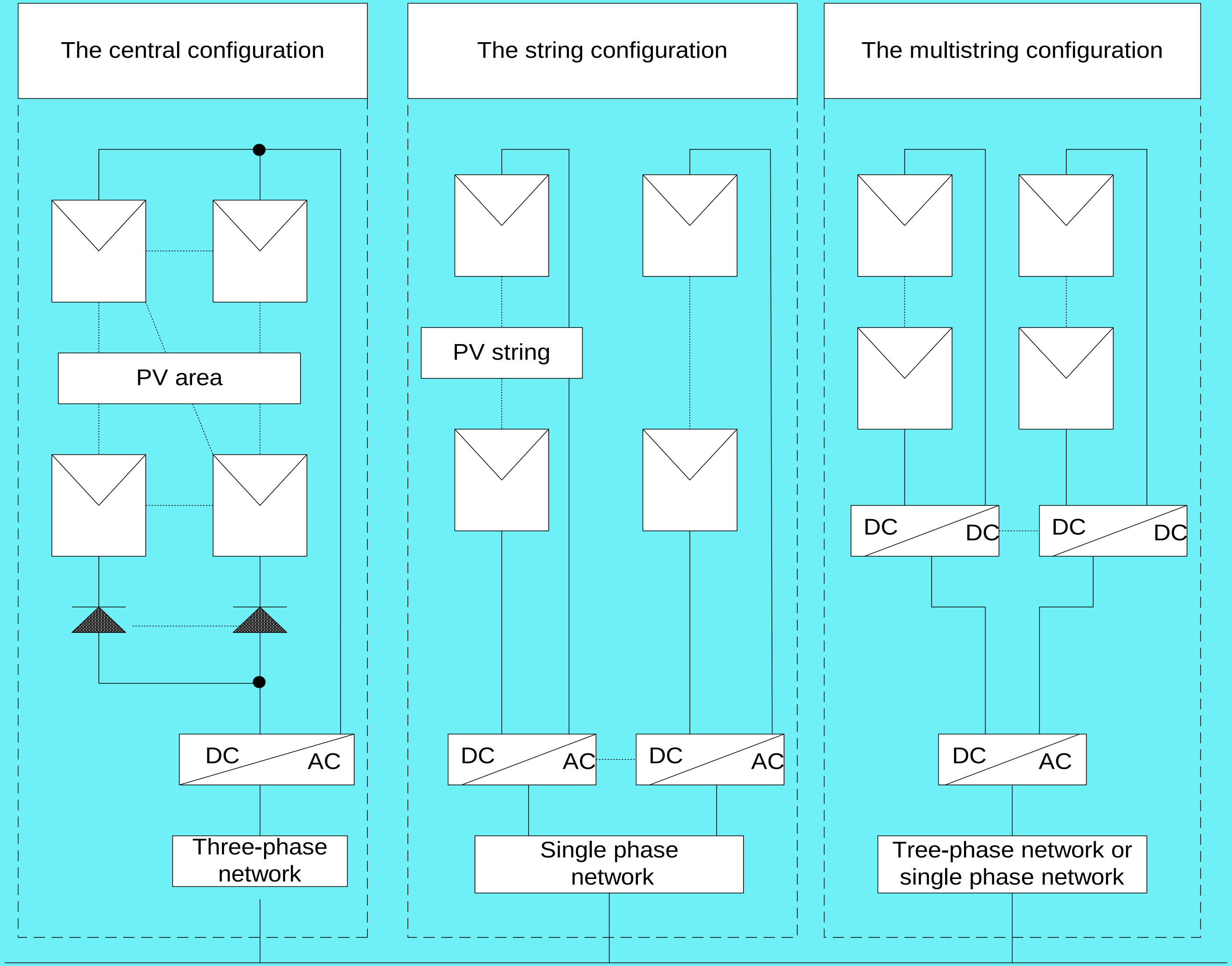
Each string is provided with a DC-DC converter. Each string has implemented its own MPPT using a DC-DC converter.

- **Modular configuration**

It is based on a modular model. It is done with DC-DC converters connected to a common DC bar. Each string is connected to a DC-DC converter which has implemented a MPPT algorithm. To connect the installation to a single-phase network or three-phase, DC-AC inverters are provided.

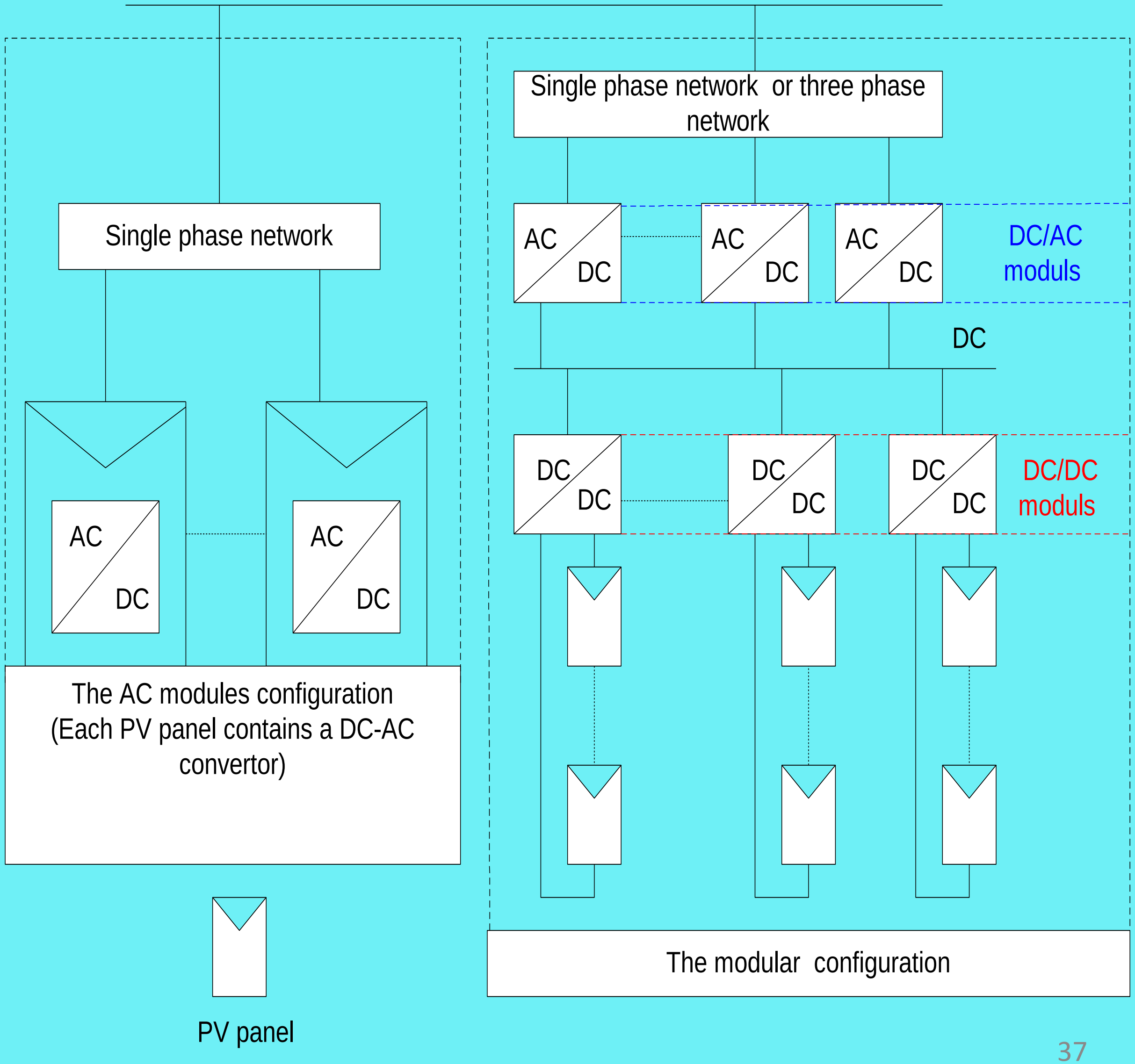
1.11. PV architectures

PV system configurations central inverter, string, multistring



1.11. PV architectures

PV system configurations, modular, with AC modules



1.12. Comparison between the various configuration of the PV system

Number	Type configuration	Advantages	Disadvantages
1.	Central inverter.	- Used at high power P>10kW; price at the installed - Low capacity; - Good results in conditions of partial shading;	- Significant losses of supply in case of inverter failure; - Lower efficiency due to lack MPPT for each string;
2.	String.	- Presents MPPT at level of string; - Allows the building of plant in steps; - It is used at average power of 10-12kW;	- Relatively high price; - Single phase only;
3.	Multistring.	- Each string is equipped with DC-DC converter with its own MPPT;	- High price; - In case of failure of the inverter, the system is shut down;
4.	Modular.	- Are used at high power between 10-30 kW; - Presents MPPT on the string, low loss of power in the event of a fault, being rapidly replaced the module;	- High price; - Requires highly skilled personnel, spare parts in stock;
5.	AC module	- Each PV panel is provided with its own inverter and MPPT algorithm;	- High price; - Low power under 1kW; - Requires high-qualified staff;

2. Maximum Power Point Tracking (MPPT) algorithms

2.1. MPPT systems

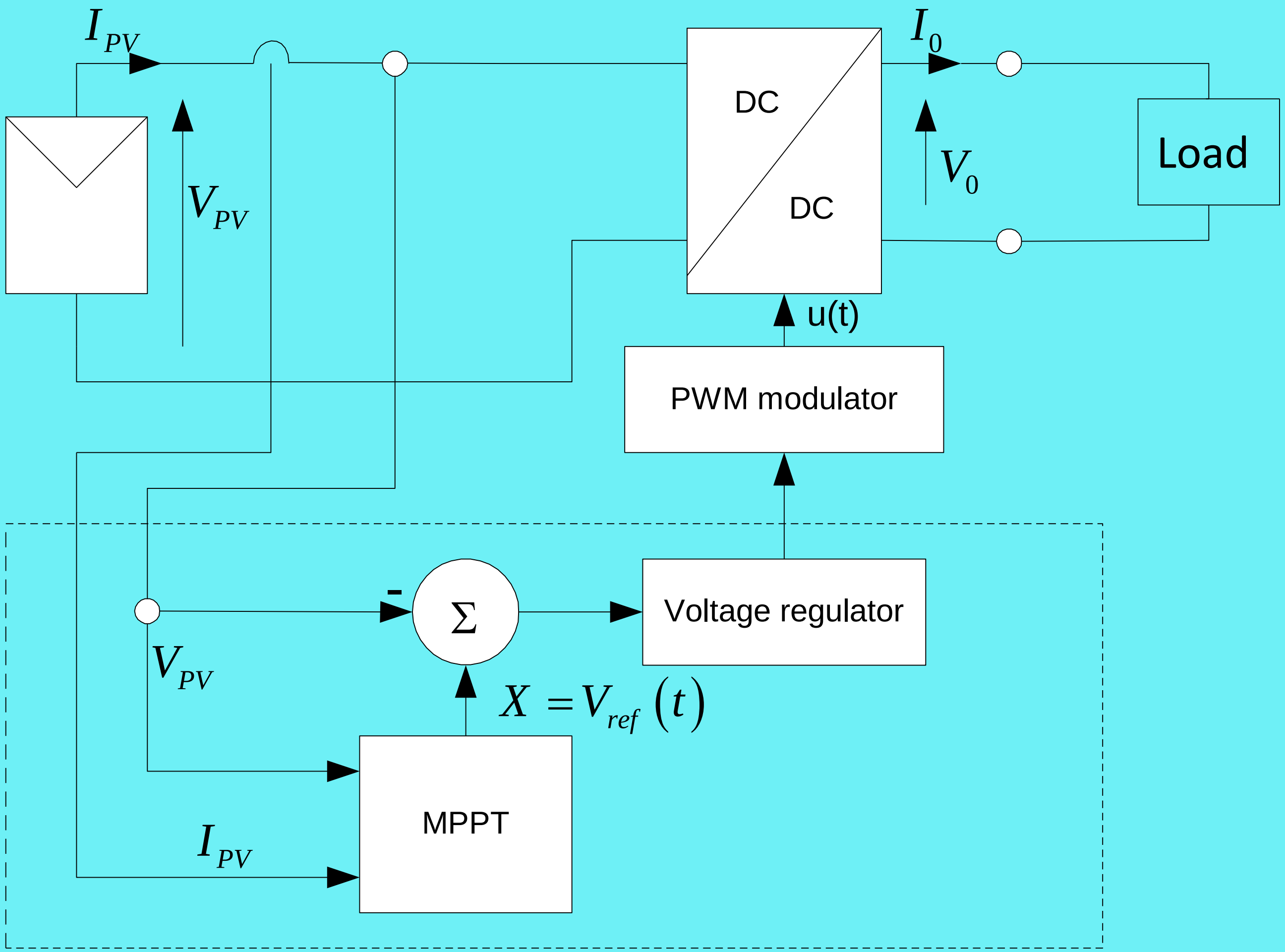
To achieve the **maximum power transfer** between the PV generator and the receiver, the MPPT systems with maximum power point tracking is necessary.

A DC-DC converter is interconnected between the PV generator and the receiver for a continuous adaptation of the load to a PV generator.

A pulse modulated control signal is applied to the gate of a MOSFET.

The converters used in the MPPT systems are DC-DC buck type, and boost.

The maximum power point tracking (MPPT) is done using MPPT algorithms.



2.2. MPPT techniques

The **MPPT techniques are largely classified into three groups:**

- **Indirect techniques (off-line) that use technical data of the PV panels to estimate MPP.**
- **Direct techniques (on-line) that use the measured parameters (U, I) in real time.**
- **Other methods which include a combination of these two methods.**

The MPPT methods that are frequently used in photovoltaic systems are:

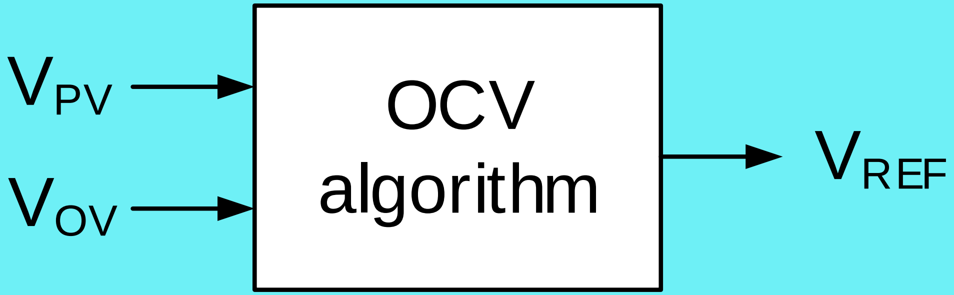
- **Open circuit voltage method (OCV);**
- **Short-circuit current method (SCC);**
- **Perturb and Observe (P & O);**
- **Incremental conductance method (IC);**
- **The method of artificial neural networks (ANN);**
- **Fuzzy logic controller method (FLC).**

2.2.1. Open circuit voltage method

The method is based on a linear relationship between the open circuit voltage (V_{OC}) and the voltage of the maximum power point (V_M).
The temperature and the solar irradiance changes the position of MPP in a range of 2%.

$$V_M \approx kV_{OC}$$

where:
constant k is between 0.73-0.80 and depends on the characteristics of the PV panel.



2.2.2. Short-circuit current method

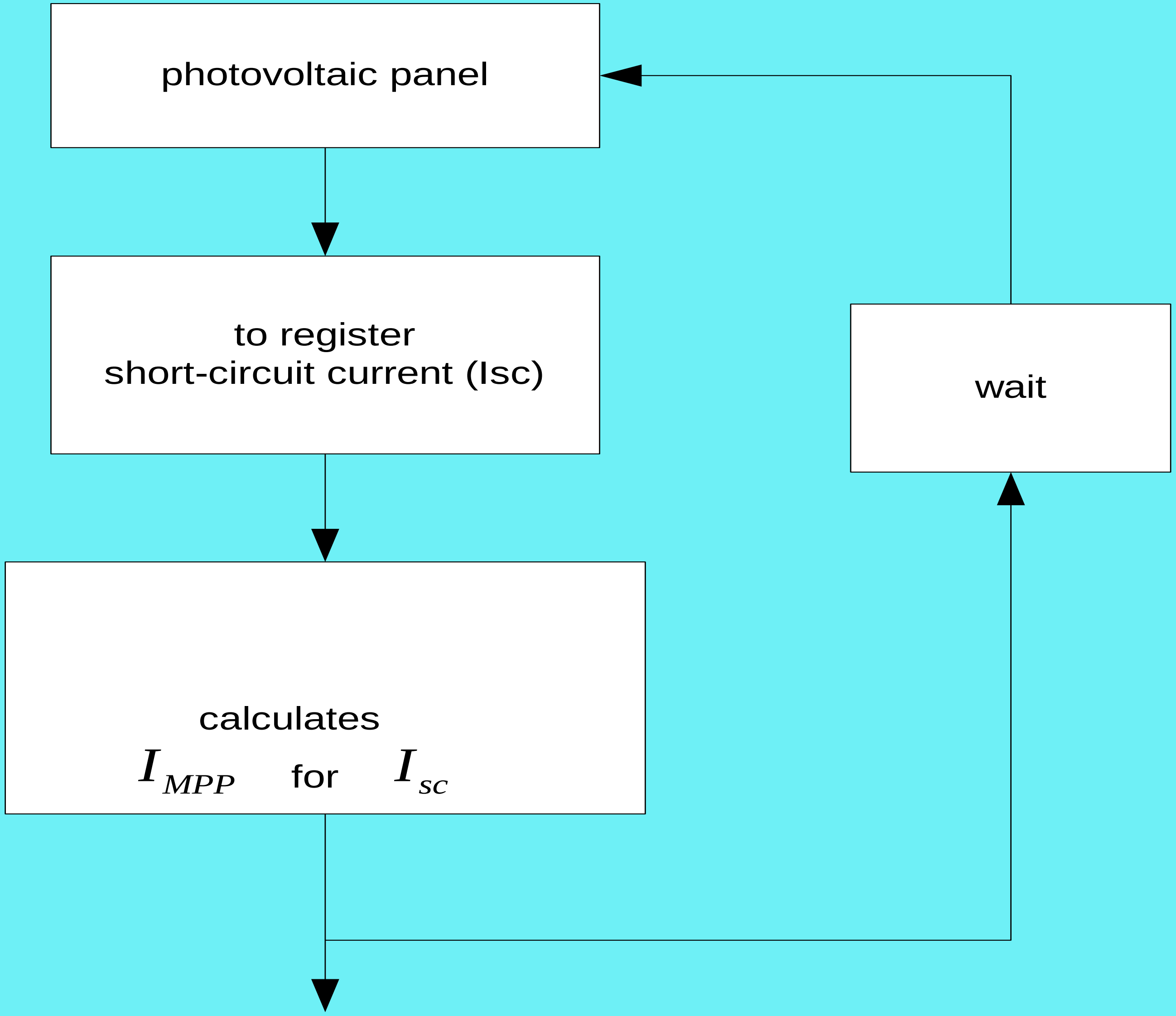
The method is similar to the open-circuit voltage method and assumes a linear relationship between the short-circuit current, I_{SC} and the current of the maximum power point I_M.

$$I_M \approx kI_{SC}$$

The constant k' is between 0.8-0.9 and depends on the characteristics of the PV panel.

Both methods (OCV) and (SCC) are simple to apply, have a low price but fail to transmit the output maximum power for two reasons:

- the interruption of the circuit for the execution the measurement of V_o and $I_{SC;}$
- the maximum power point cannot be followed precisely.



2.2.3. Perturb and observe method

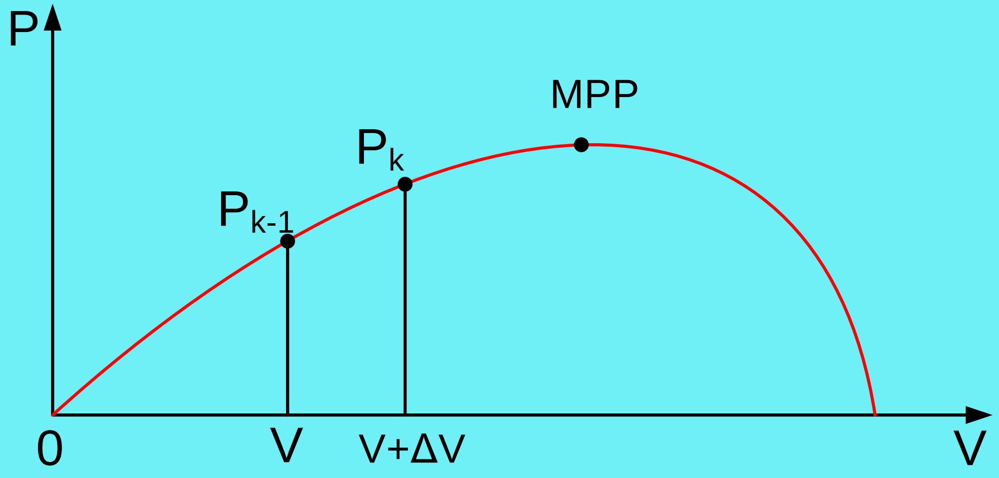
It is one of the simplest direct methods.

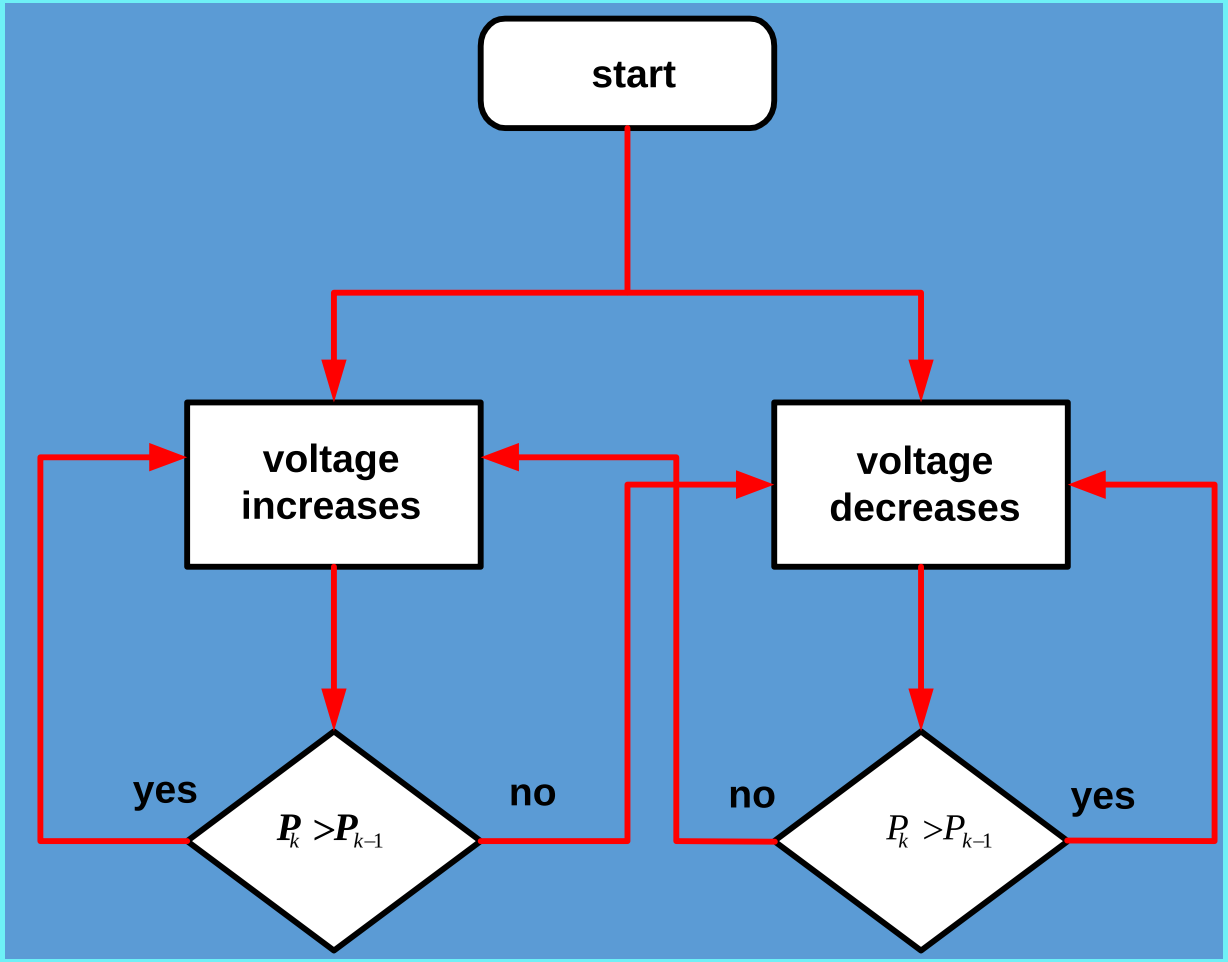
The maximum power point is calculated by successive attempts: the voltage across the PV generator is amended and then the output power is compared with previous power.

The process continues until: $\frac{dP}{dV}$=0.

The method does not require knowledge of the characteristics of the PV panels, but there are oscillations around the MPP in steady state operating as well as sudden changes in solar radiation.

2.2.3. Perturb and observe method





2.2.4. Incremental conductance method

The determination of the MPP is done by monitoring the derived power in relation to the voltage, $\frac{dP}{dV}$

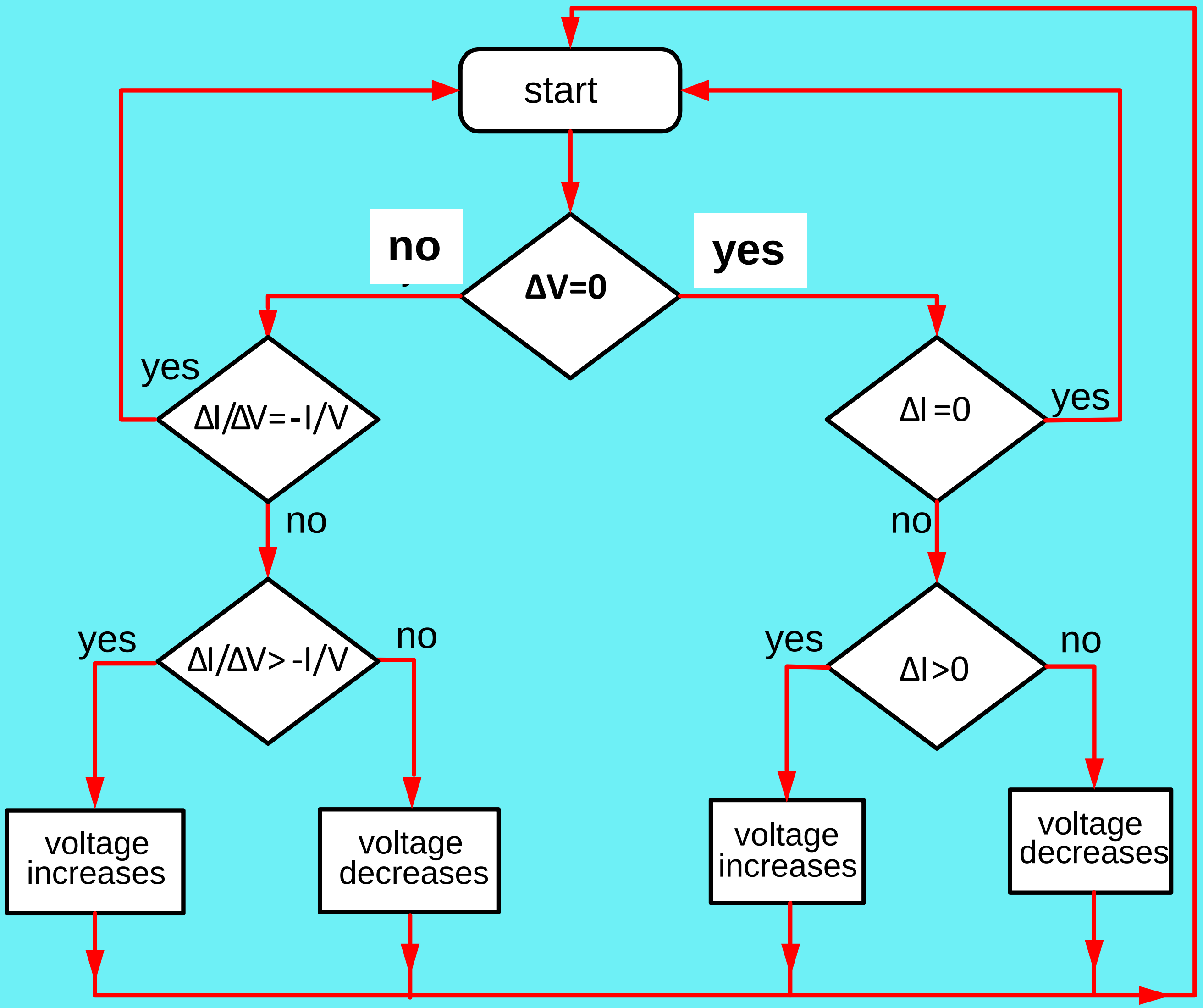
$$\frac{dP}{dV} = \frac{d(V \cdot I)}{dV} = I + V\frac{dI}{dV} = 0$$

$$\frac{I_m}{V_m} = \frac{dI}{dV}\bigg|_{V=V_m}$$

$$\frac{\Delta I}{\Delta V} < 0, \quad if \quad \frac{\Delta I}{\Delta V} \succ -\frac{I}{V} \Rightarrow V < V_m$$

The IC method does not present oscillations in operation, does not provide a wrong tracking direction of the MPP and gives good results in case of partial shading.

Logic diagram for the algorithm incremental conductance



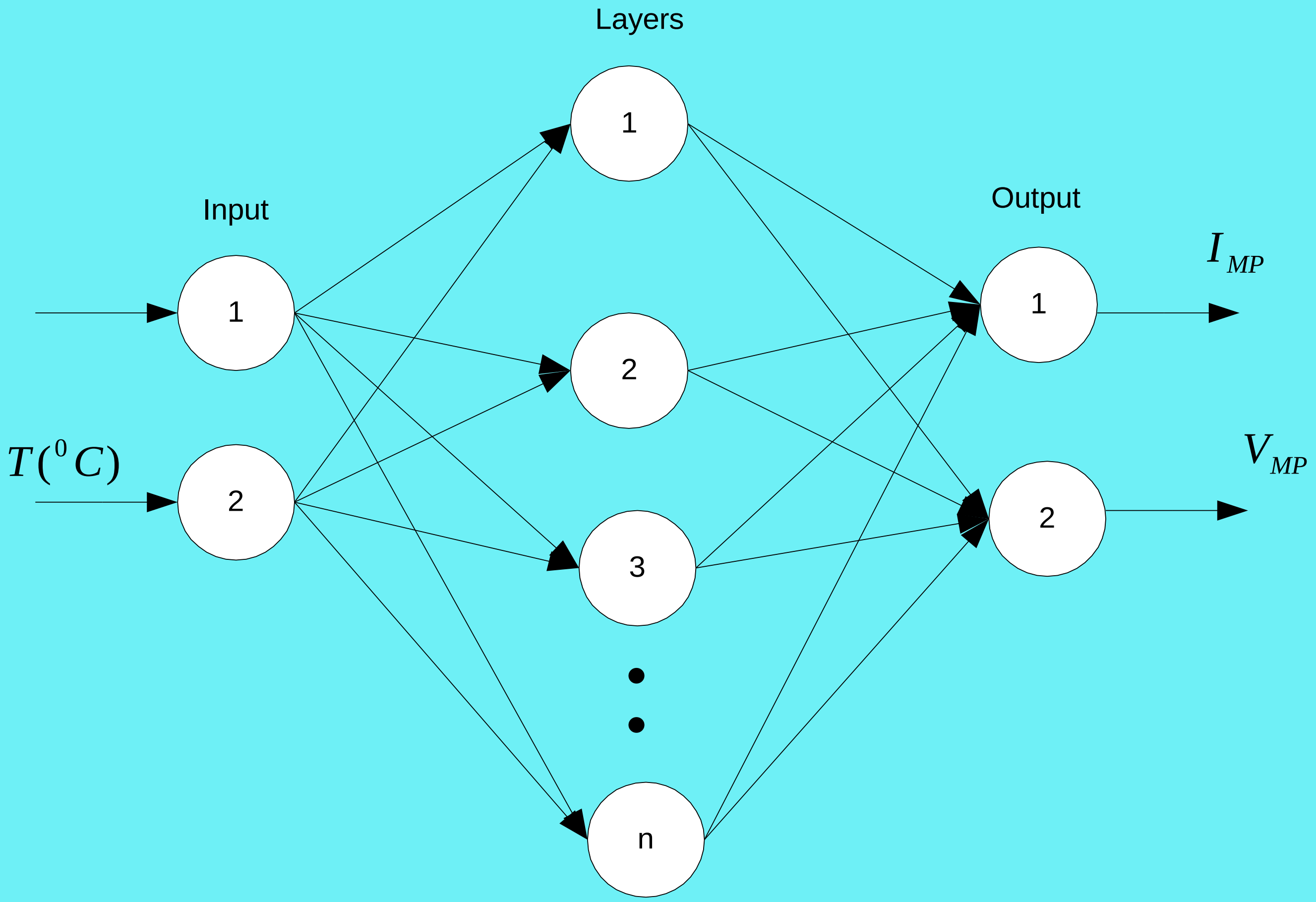
2.2.5. The method of artificial neural networks

The input signal for each neuron is either the signal from a neighbouring neuron or the input variables associated with nonlinear system: V_{OC}, I_{SC} or T.

The output signal is usually a reference signal, which may be voltage or current.

This method determines with precision the MPP without requiring knowledge of PV parameters, but the algorithm must be specifically designed for the PV area to which it will be used.

The structure of an artificial neural network

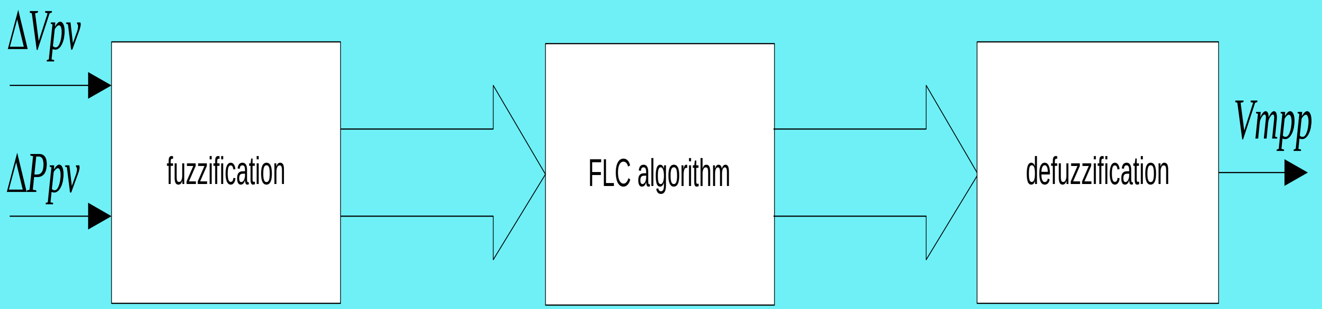


2.2.6. Fuzzy logic controller method

The fuzzy logic controller method is a numerical method to calculate the MPPT system.
It consists of three main blocks:

- fuzzification
- rules inferences
- defuzzification

Block diagram of a system based on FLC method



Fuzzification is designed to convert the numerical values of the input in linguistic variables.

The FLC algorithm transforms the deterministic value in a crowd fuzzy based on if-then rules of fuzzification.

Defuzzification does the reverse operation, which consists in converting fuzzy sets in the deterministic numerical variables.

The method is used in systems that do not have a precise mathematical model.

The technique determines the minimum oscillations around the maximum power point (MPP) and works well for modification of solar radiation intensity.

2.3. Comparison between presented methods

MPPT techniques	Classification	Dependence of the PV area parameters	Sensors	Complexity	Speed tracking	Efficiency at partial shading
OCV	Indirect	Yes	U	Simple	Slow	No
SCC	Indirect	Yes	I	Simple	Slow	No
P&O	Direct	No	U,I	Simple	Average	No
IncCond	Direct	No	U,I	Average	Fast	Yes
ANN	Indirect	No	U,I	Advanced	Fast	Yes
FLC	Indirect	No	U,I	Advanced	Fast	Yes

Conclusions

The photovoltaic cell is the device that directly converts the solar energy into electrical energy. Most solar cells are made of silicon and three main types are distinguished: monocrystalline silicon cells, polycristaline silicon cells and amorphous cells. The PV cells operation can be studied considering a p-n junction in parallel with a constant current source. The PV cell modeling is carried out with two patterns: the simple diode model and the double diode model. Through serial connection of identical PV cells a panel or PV module is obtained. Small power PV generators are built by series connection of several PV modules; high power PV generators are consisting of more strings connected in parallel. To achieve the maximum power transfer between the PV generator and receiver, MPPT systems were used.

There are many techniques to extract the maximum power MPPT: indirect techniques, direct techniques and other methods that include a combination of these two methods.

Indirect methods use the technical data of the PV panels (characteristics, parameters) to calculate the MPP. Direct techniques use parameters (voltages, currents) measured in real time. Direct methods do not require knowledge or measurement of the temperature and the solar radiation intensity. The problems of tracking speed, stability and accuracy can be solved using methods based on numerical calculations: the method of artificial neural networks (ANN), fuzzy logic controller-based method (FLC). These methods are intelligent tracking MPPT methods and have the advantage of working with imprecise sizes and do not require precise mathematical models.