Photovoltaic Modelling Introduction

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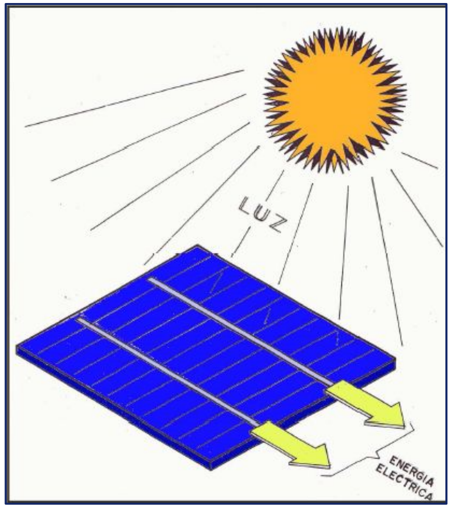
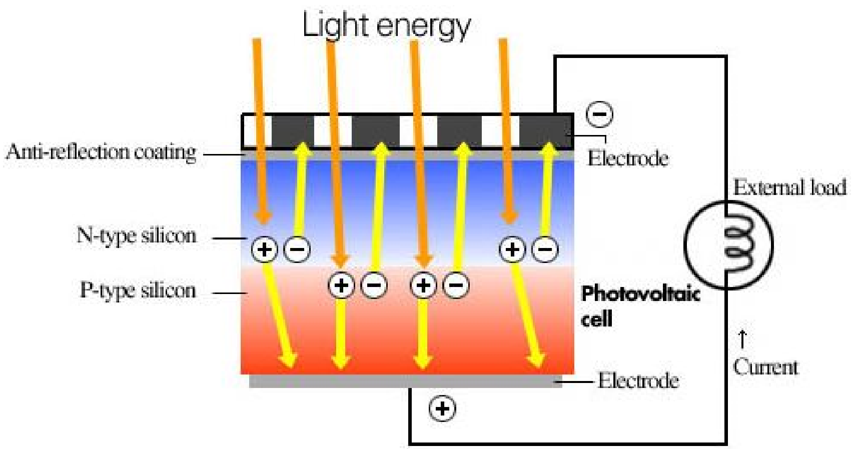
2 Photovoltaic Panel

3 Photovoltaic System

Photovoltaic effect

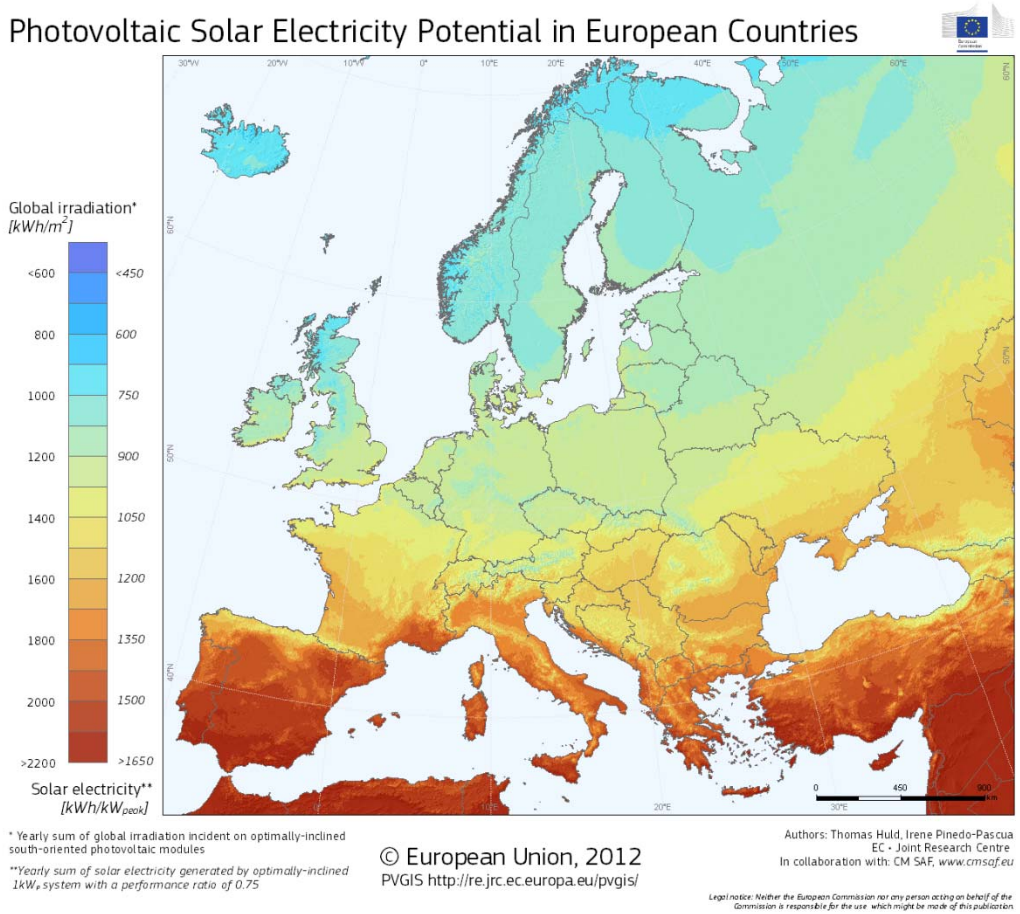
- *Sunlight striking a semiconductor and causing electrons to be excited due to energy in the sunlight (photons).*





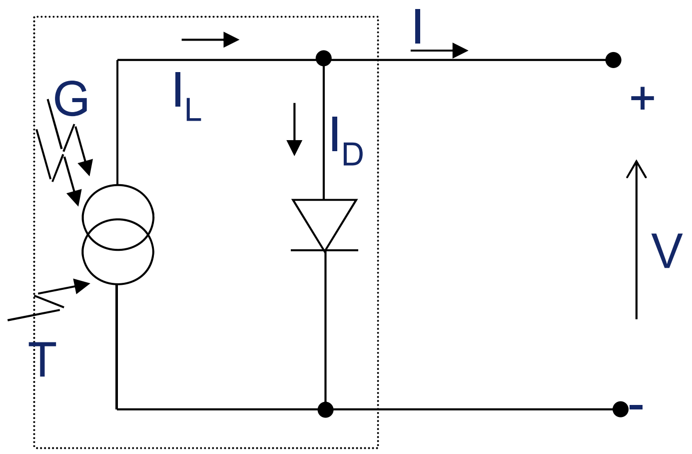
Several important magnitudes must be used:

- *Irradiance*
- *Temperature*
- *Current*
- *Voltage*



Ideal Cell

Ideal Cell



$$I = I_L - I_D \qquad (1)$$

- Total current in the diode

$$I_D = I_0 \left[e^{\frac{qV}{aKT_C}} - 1 \right] \qquad (2)$$

- The Current I_0: appears with reverse polarity and relatively high negative tensions.

$$I = I_L - I_0 \left[e^{\frac{Vq}{aKT_C}} - 1 \right] \qquad (3)$$

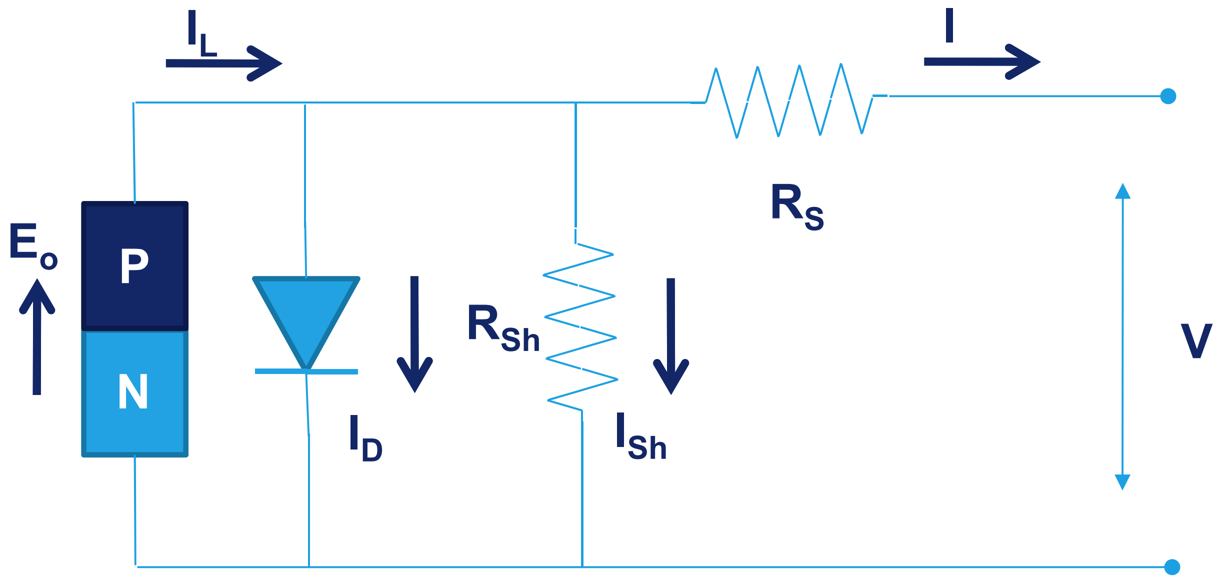
Photovoltaic effect

- Other characteristics or data

$$I = I_L - I_0\left[e^{\frac{Vq}{aKT_C}} - 1\right]$$

  - I_D: Diode current (A)
  - I_0: Saturation current of the diode (A)
  - q: Electron charge, 1.6 10^{-19} (C)
  - a: Diode ideality factor.
  - K: Boltzmann's Constant, 1.38 10^{-23} J/K
  - T_C: Cell Temperature (ºK)
  - V: Voltage on the photovoltaic module (V)
  - I: Current photovoltaic module (A)

Equivalent circuit of a photovoltaic cell



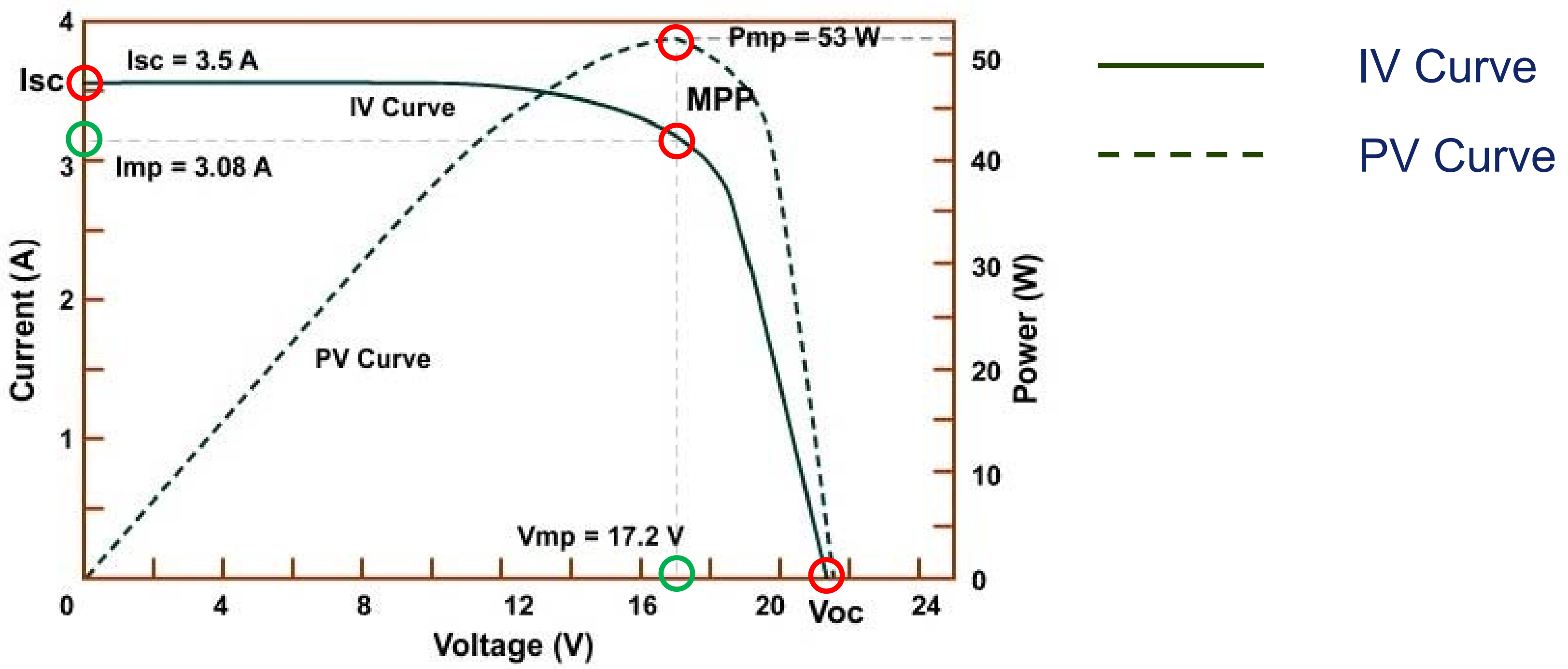
$$\boxed{I = I_L - I_D - I_{Sh}} = I_L - I_d\left[e^{\frac{q(V+R_s I)}{aKT}} - 1\right] - I_{Sh}$$

$$\mathrm{I} = \mathrm{I_L} - \mathrm{I_0} \cdot \left(e^{\frac{q(\mathrm{V}+\mathrm{I}\,\mathrm{R_s})}{aK\mathrm{T}}} - 1\right) - \frac{(\mathrm{V}+\mathrm{I}\,\mathrm{R_s})}{\mathrm{R_{sh}}}$$

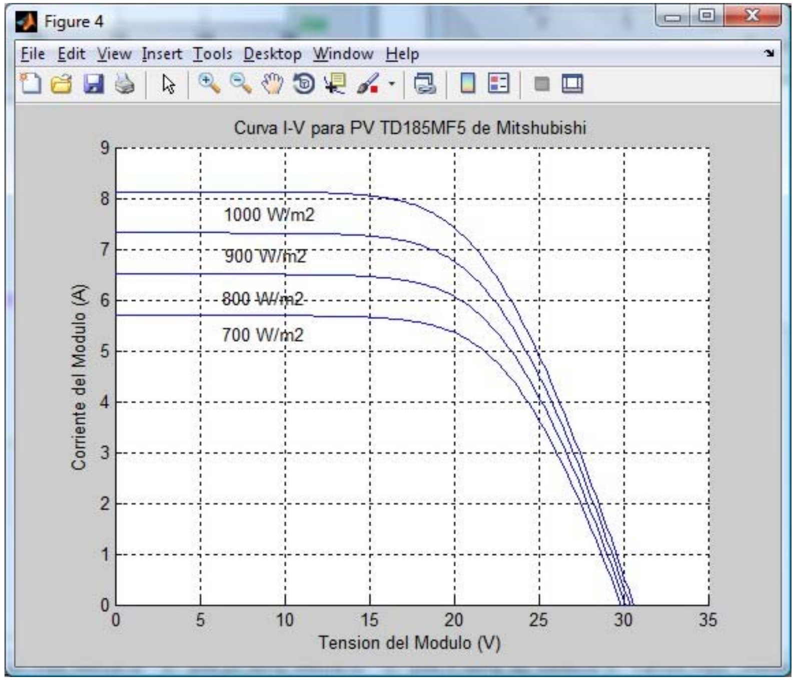
The fundamental electrical parameters:

- **Short circuit current (I_{sc})** is the current through the solar cell when the voltage across the solar cell is zero
- **Open circuit voltage (V_{oc})** is the difference of electrical potential between two terminals of a device when disconnected from any circuit. There is no external load
- **Maximum current (I_{max})** current at the maximum power point
- **Maximum voltage (V_{max})** current at the maximum power point
- **Maximum power (P_{max})**

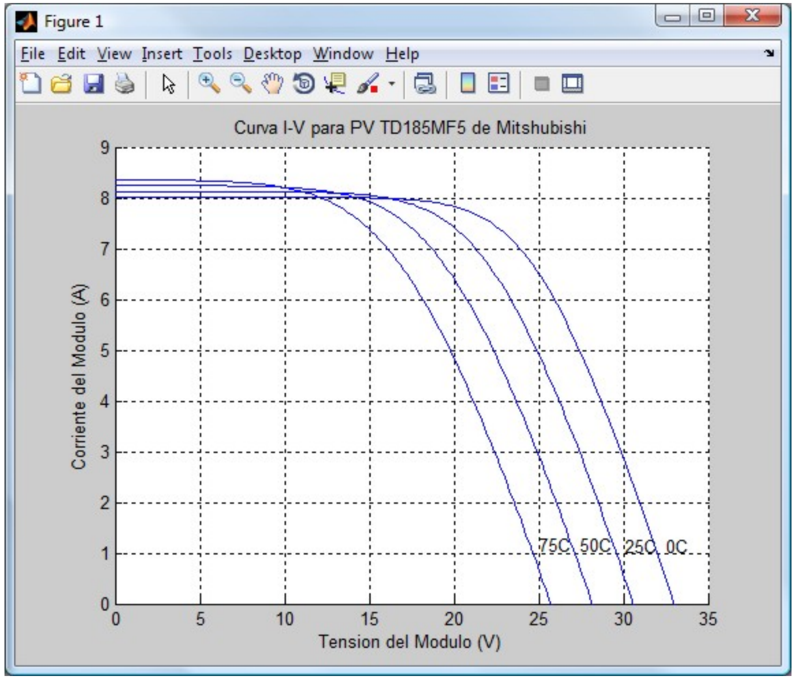
Characteristic curves (IV) and (PV)



Types of IV characteristic curves:

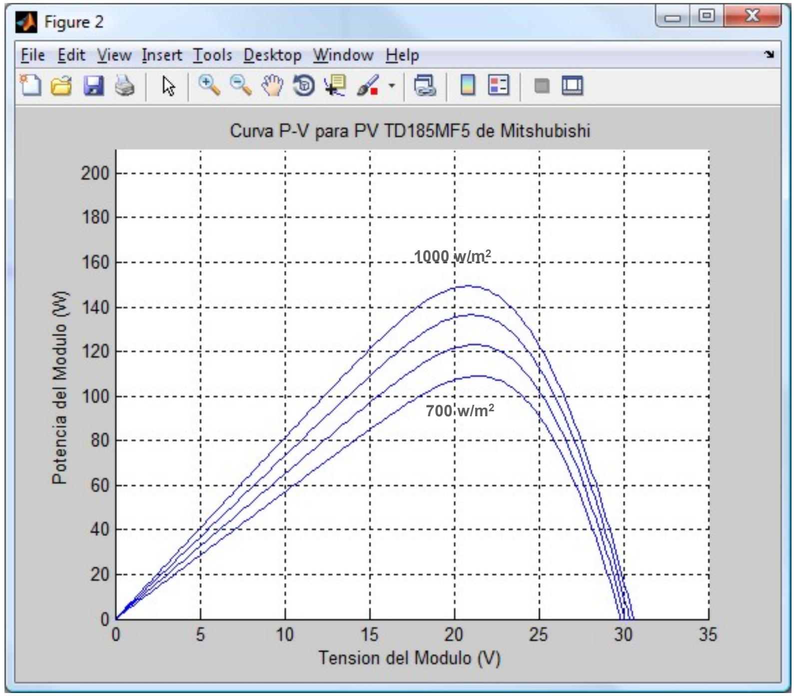


IV curve for constant Tª 25ºC

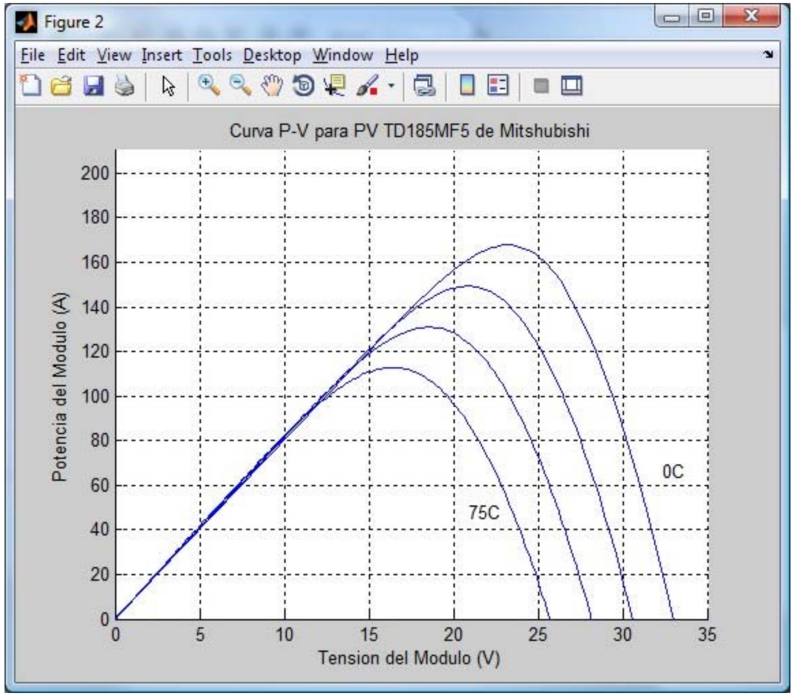


IV curve for constant G (Irradiance) 1000 W/m²

Types of PV characteristic curves:



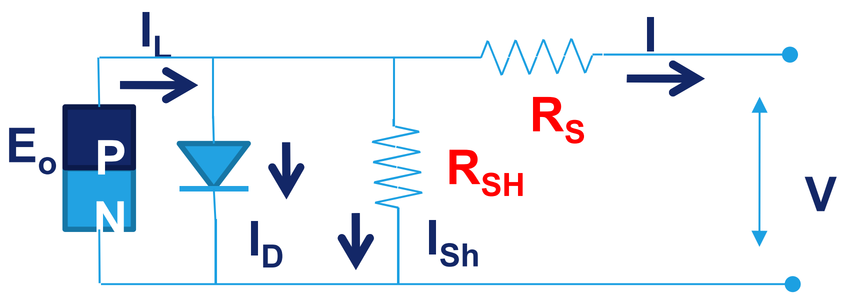
PV curve for constant Tª 25ºC



PV curve for constant G (Irradiance) 1000 W/m²

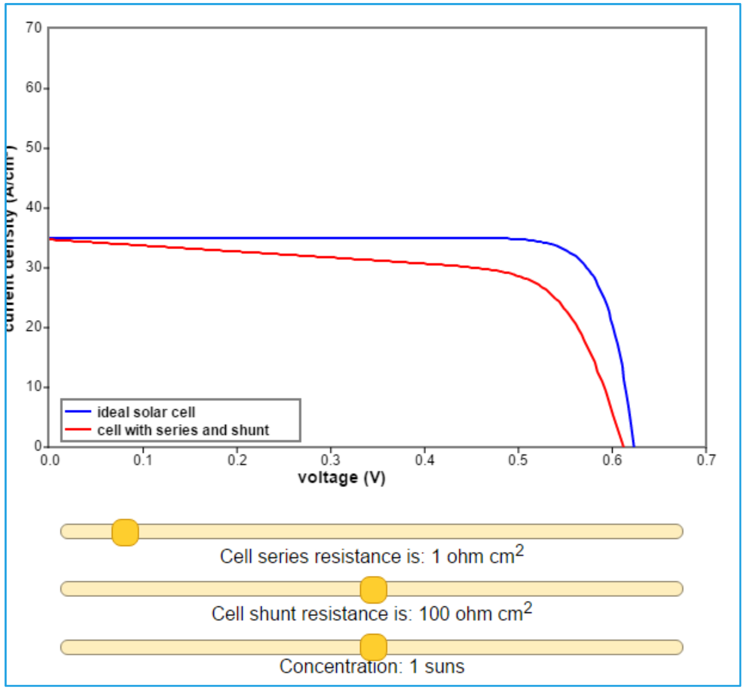
Series and shunt resitances:

- **R_s**: A function of the impurities and contact resistance.
- **R_{sh}**: Inversely proportional to the leakage current to earth.
- **<u>Ideal photovoltaic cell</u>**: $R_S = 0$ and $R_{sh} = \infty$.
- **Silicon cells**: $R_s = 0{,}05–0{,}1\Omega$ and $R_{sh} = 200–300\ \Omega \Rightarrow I_{sh} \approx 0$.
- The PV conversion efficiency is very sensitive to small variations in R_s, but insensitive to variations in R_{sh}



Series and shunt resitances:

- **Influence of the R_S and R_{SH} on the curve caracteristics**



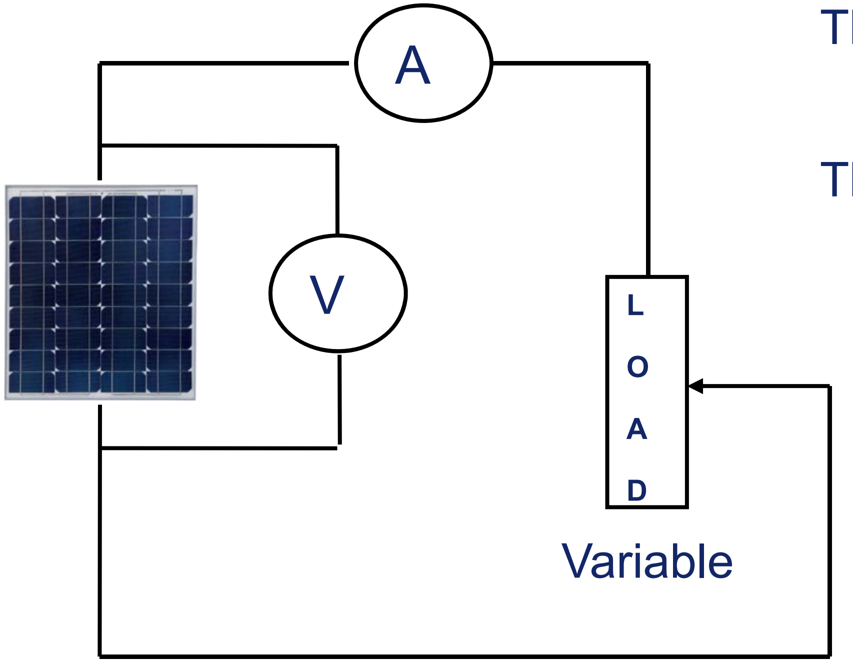
❖ Measurement conditions of a photovoltaic cell

- Standard Test Conditions, STC
  - Solar irradiance : 1 kW/m^2.
  - Air mass : PM 1,5.
  - Cell temperature : 25 ºC.

The **air mass coefficient** defines the direct optical path length through the Earth's atmosphere, expressed as a ratio relative to the path length vertically upwards, i.e. at the zenith.

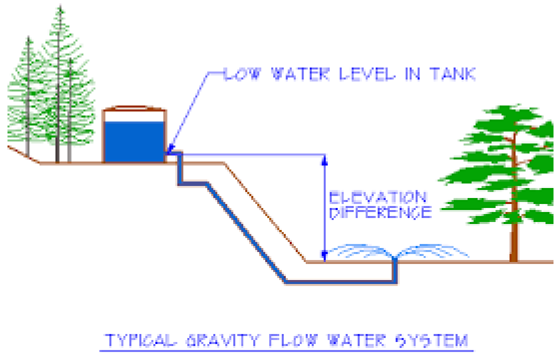
- Condiciones de operación estándar, SOC
  - Solar irradiance : 0,8 kW/m^2.
  - Wind speed : 1 m/s.
  - Environment temperature : 20º C.
- Nominal operating temperature of cells, NOCT. (Open circuit).

Data gathering for IV or PV curve building



The current is similar to measure flow of a river

The voltage is similar to measure slope of a river

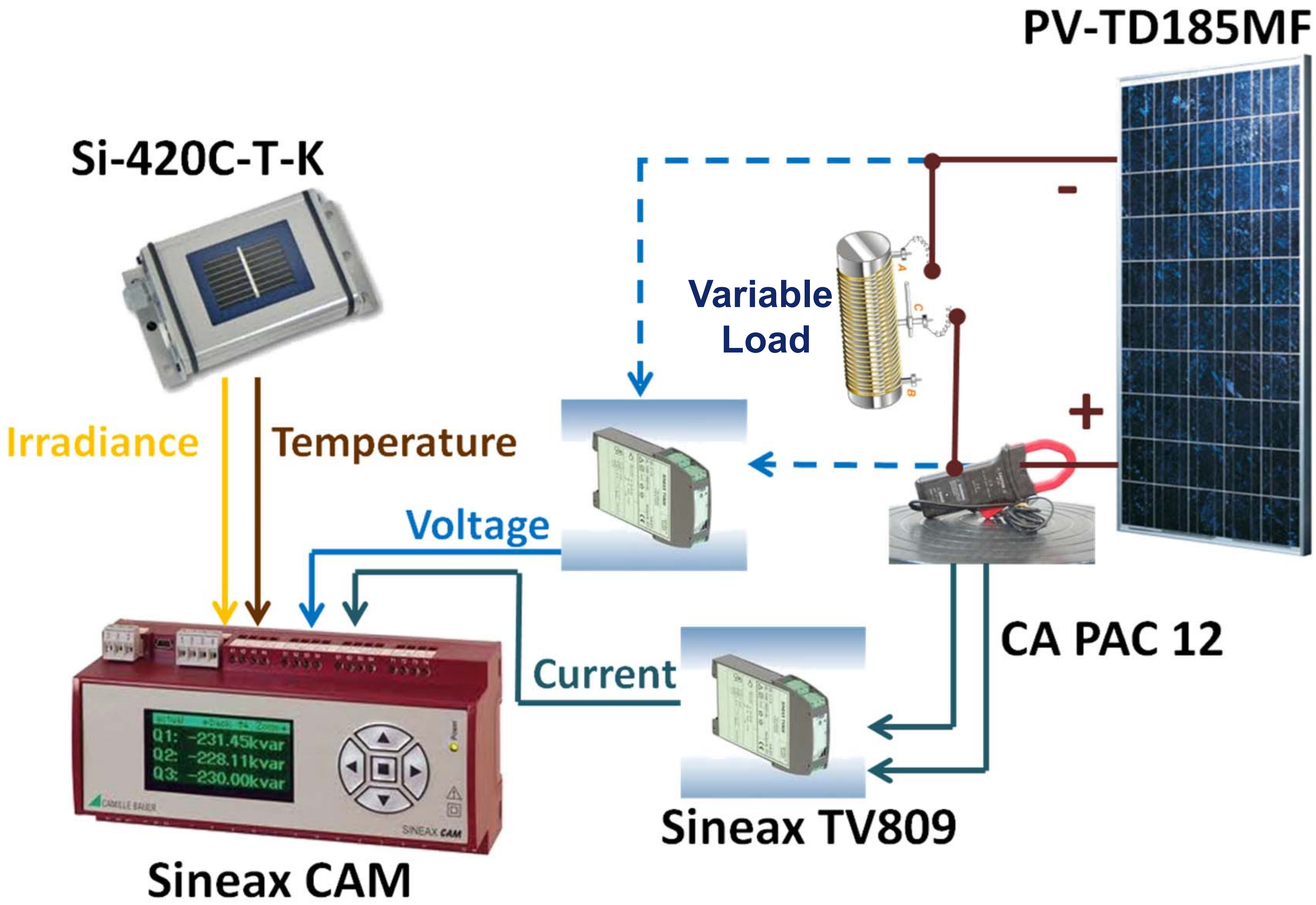


Data gathering for IV or PV curve building

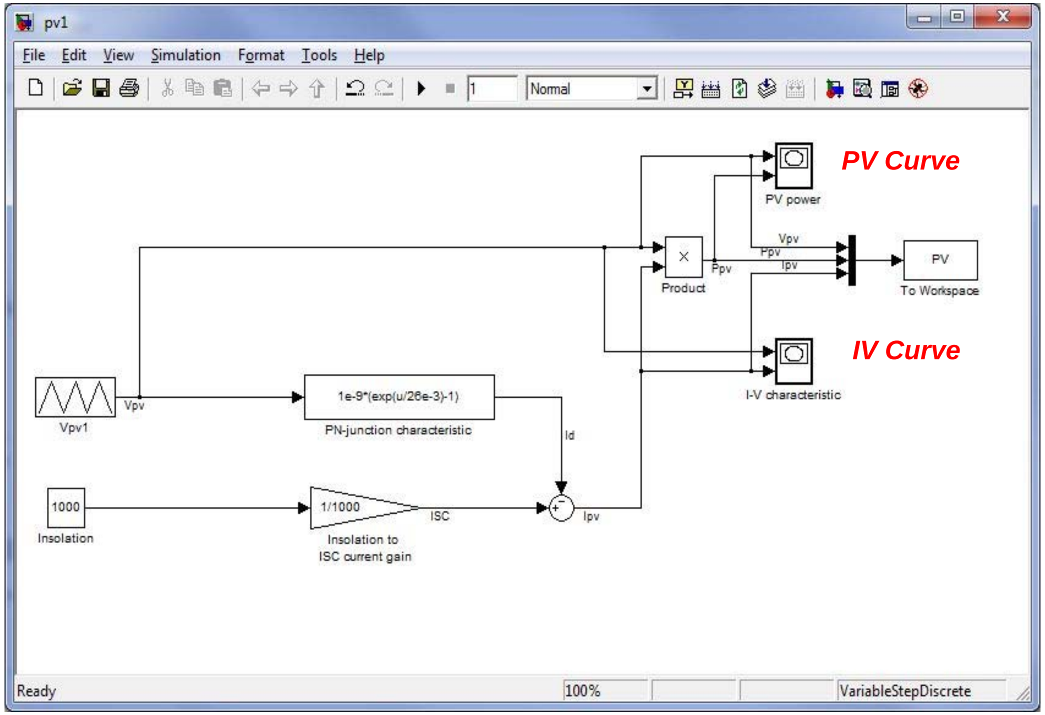
The elements used for measurements are:

- **Sineax CAM** 

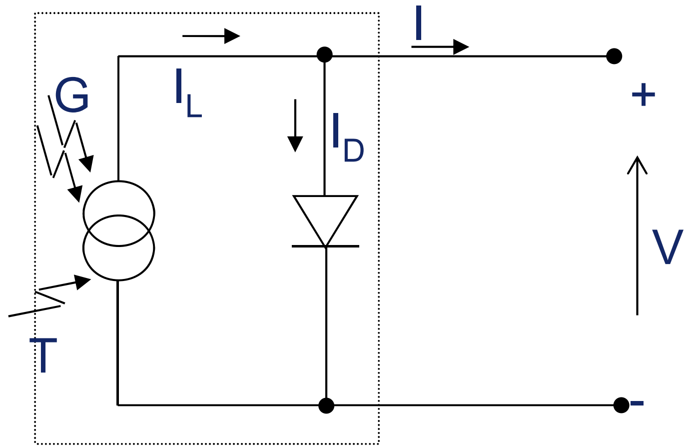
- **TV809** 
- **Irradiance sensor (Si-420TC-T-K)** 
- **Current clamps: Chauvin Arnoux PAC12: The PAC12**


PV-TD185MF
Si-420C-T-K
Variable
Load
-
+
Irradiance
Temperature
Voltage
Current
CA PAC 12
Sineax TV809
Sineax CAM
Q1: -231.45kvar
Q2: -228.11kvar
Q3: -230.00kvar

Mathematical Models of the photovoltaic cell:



Ideal Cell

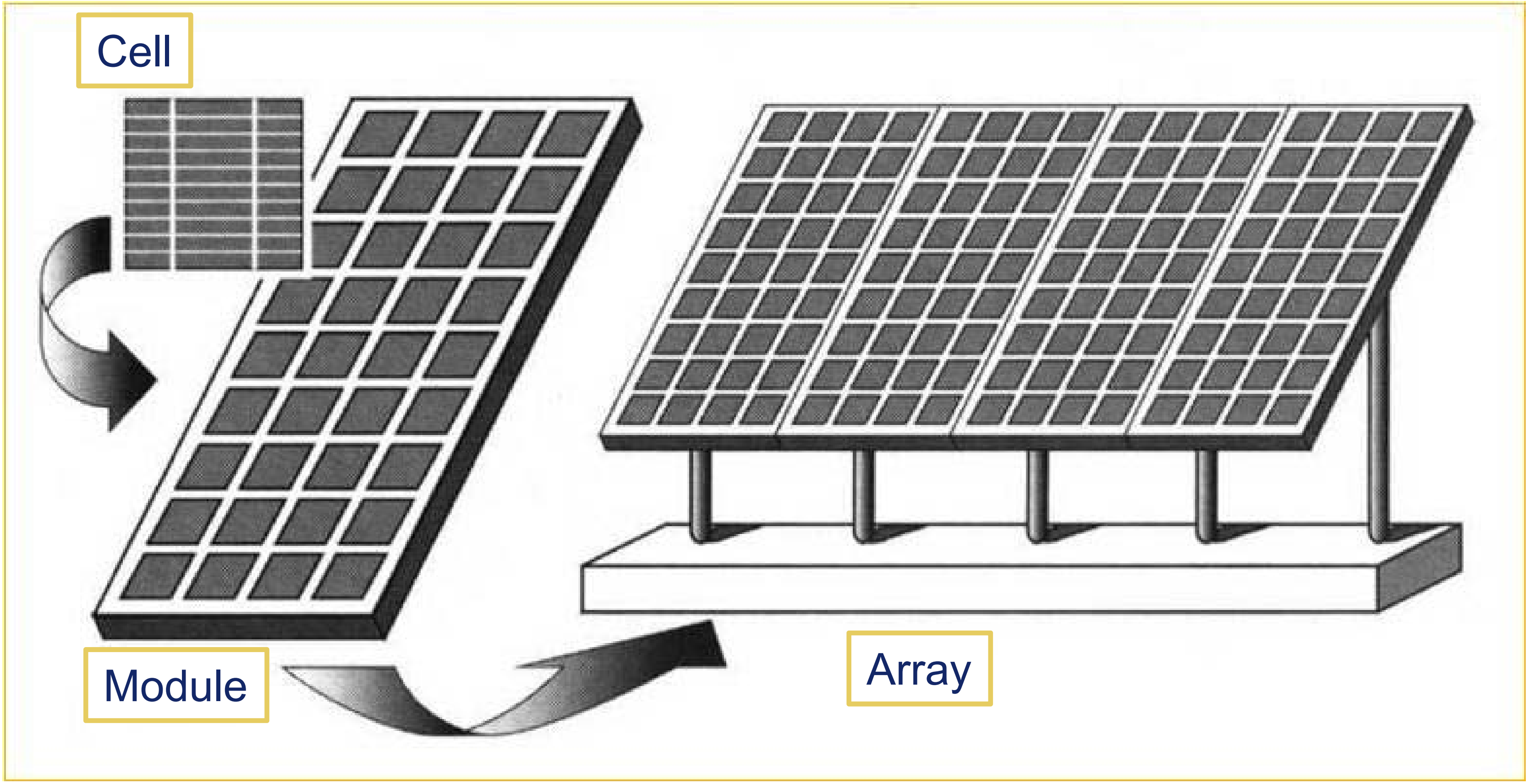


$$I_{PV} = I_L - I_0 \left[e^{\frac{Vq}{aKT_C}} - 1 \right]$$

Basic Models

Complex Models

Photovoltaic Panel



Key specifications of the PV Panel

- I_{sc} : Short Circuit Current
- V_{oc} : Open Circuit Voltage
- N_S: Number of cells in series
- P_{max}: Maximum power
- I_{mp}: Maximum power current
- V_{mp}: Maximum power voltage
- Normal operating cell temperature (NOCT)
- α_{Isc}: Temperature coefficient of I_{sc}
- β_{Voc}: Temperature coefficient of V_{oc}

Basic Models

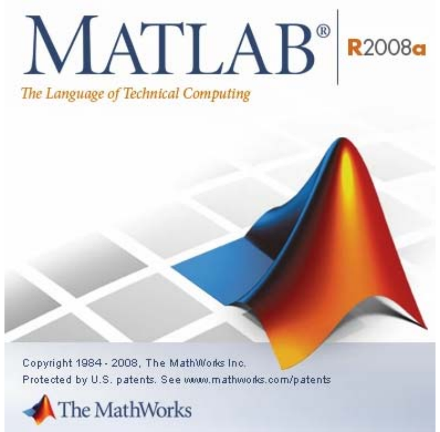
- **Matlab Tools**
- **Basic Model in Simulink**
- **Simulink model with Tags**
- **Physical component model**
- **Model advanced component library**
- **Model with real data**

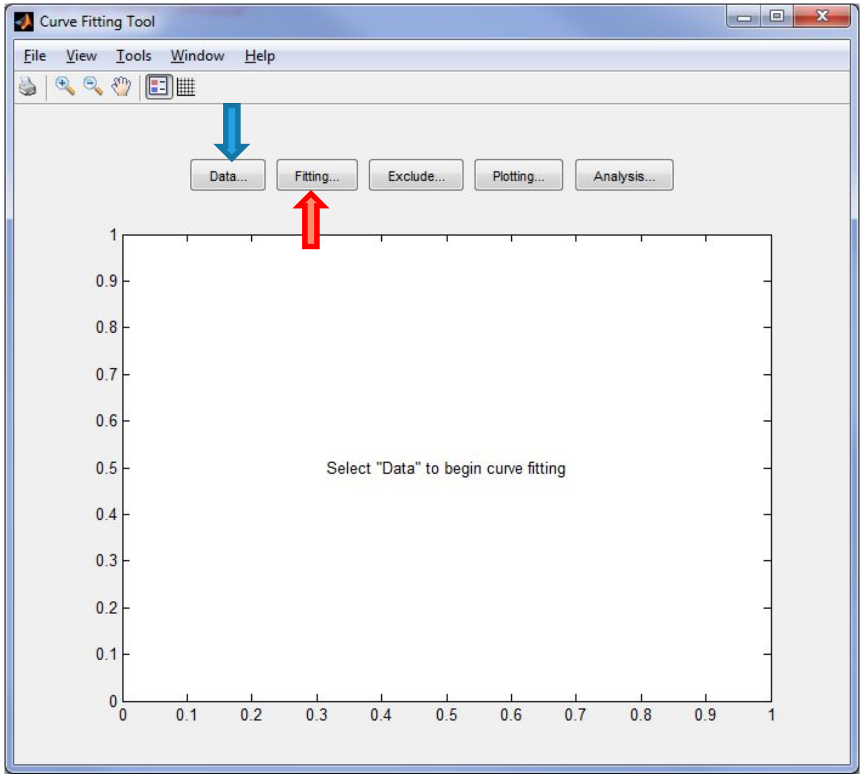
Matlab Tools

- **Curve Fitting Toolbox**

  >>cftool

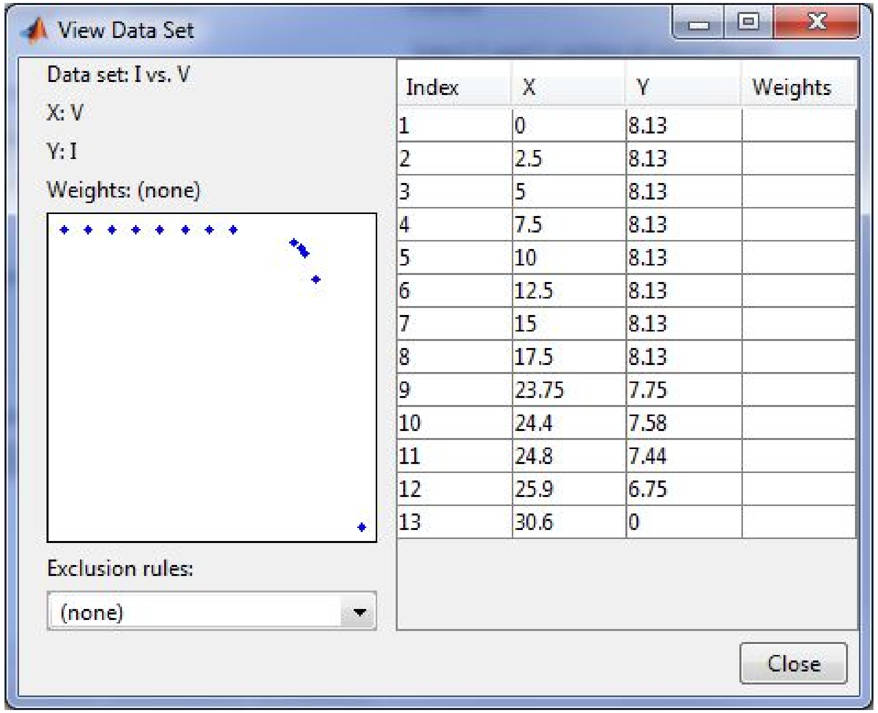
  >>cftool(V,I)





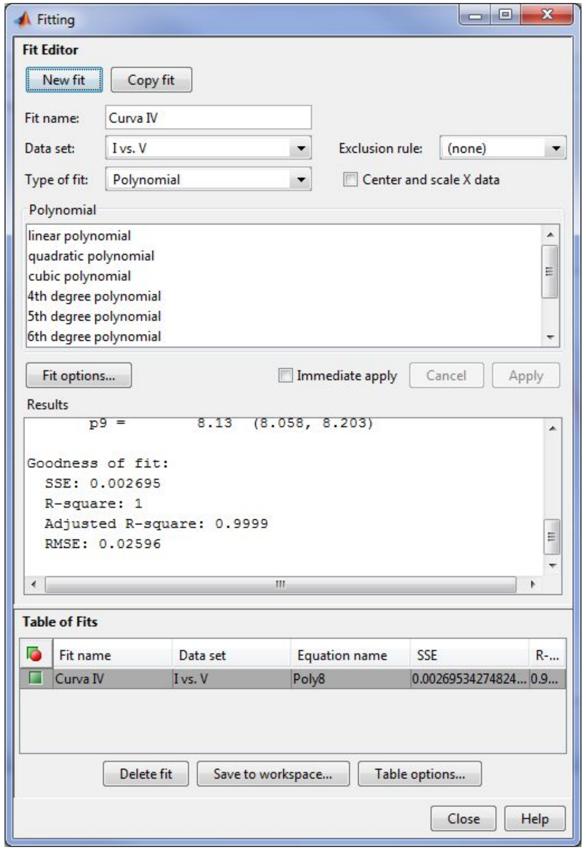
Matlab Tools: Curve Fitting Toolbox

Data Tab



Index	X	Y	Weights
1	0	8.13	
2	2.5	8.13	
3	5	8.13	
4	7.5	8.13	
5	10	8.13	
6	12.5	8.13	
7	15	8.13	
8	17.5	8.13	
9	23.75	7.75	
10	24.4	7.58	
11	24.8	7.44	
12	25.9	6.75	
13	30.6	0	

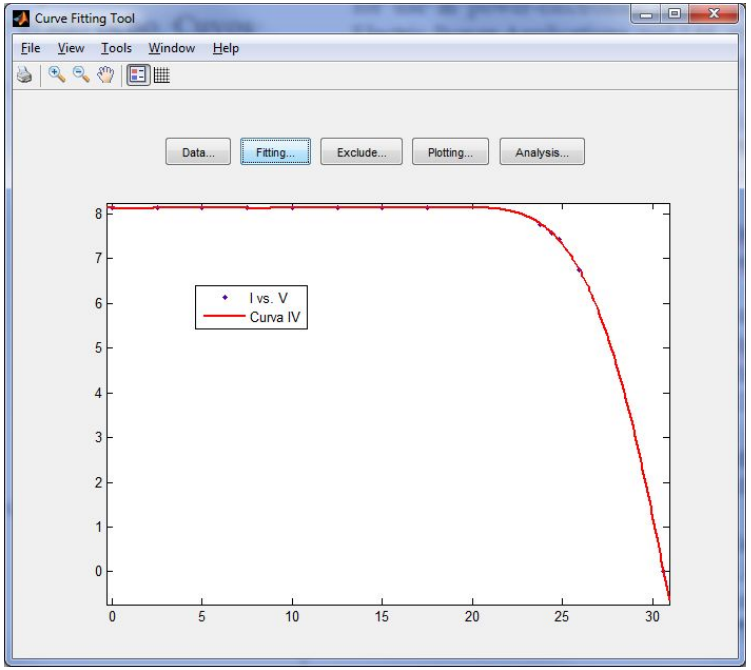
Fitting Tab



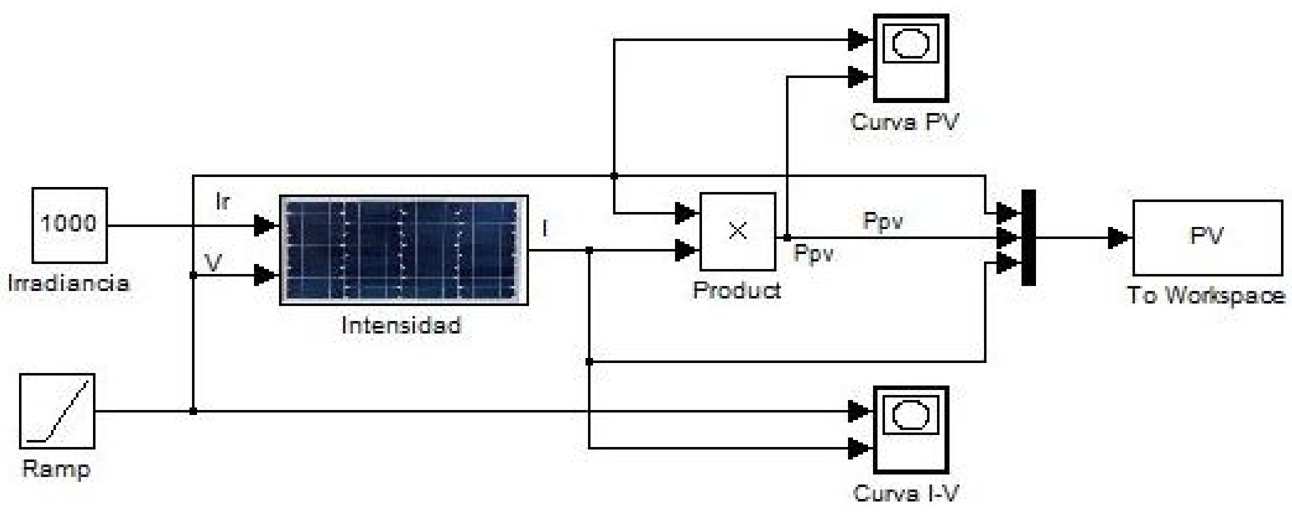
Matlab Tools: Curve Fitting Toolbox

$f(x) = p_1*x^8 + p_2*x^7 + p_3*x^6 + p_4*x^5 + p_5*x^4 + p_6*x^3 + p_7*x^2 + p_8*x + p_9$

- $p_1 = 1.536e\text{-}009$
- $p_2 = -1.699e\text{-}007$
- $p_3 = 7.451e\text{-}006$
- $p_4 = -0.0001679$
- $p_5 = 0.002085$
- $p_6 = -0.01407$
- $p_7 = 0.04677$
- $p_8 = -0.05706$
- $p_9 = 8.13$

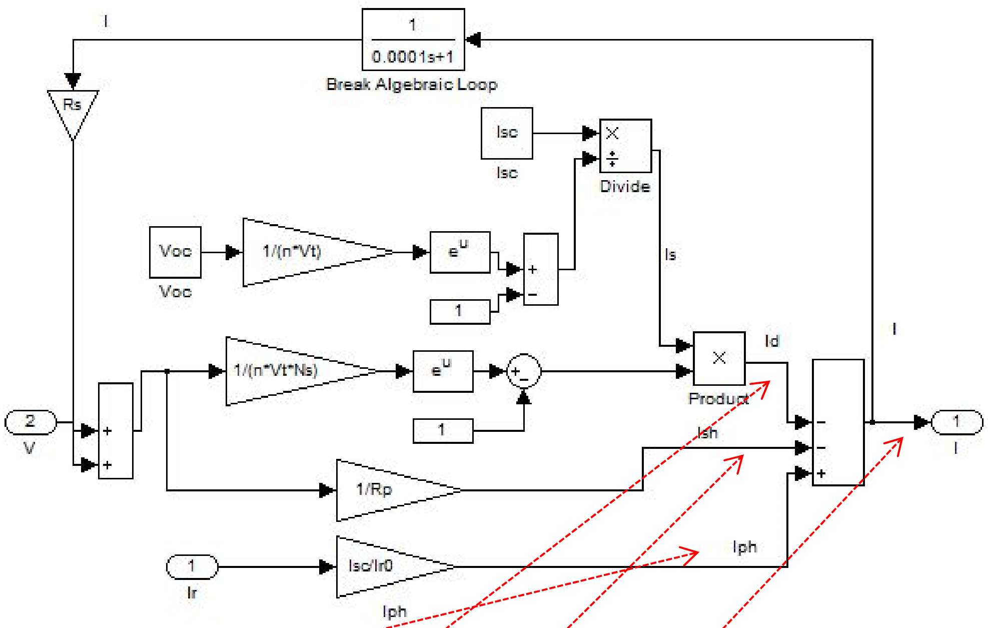


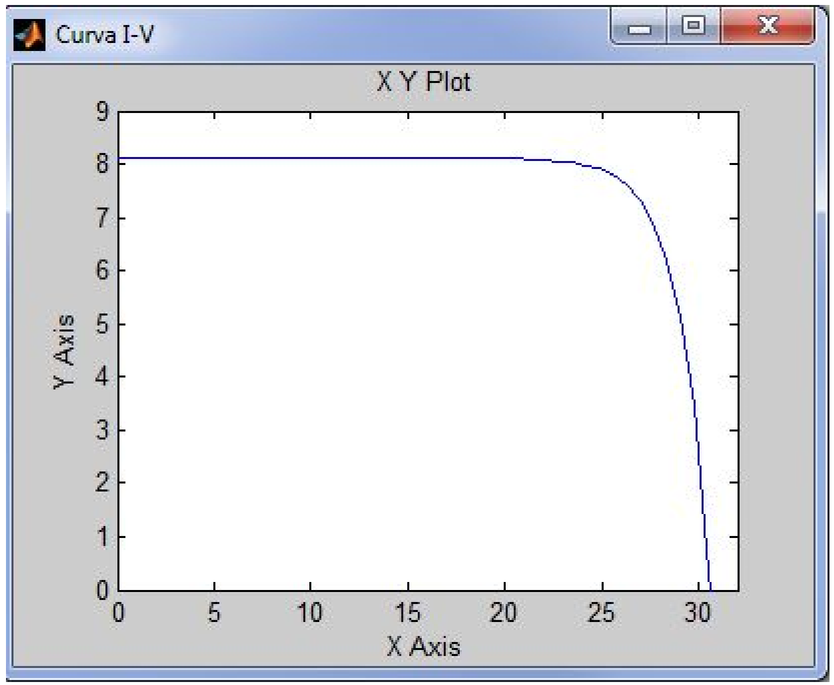
Basic Model in Simulink



Basic Model in Simulink

$$I = I_{ph} - I_s * (e^{(V+I*R_s)/N*V_t} - 1) - (V+I*R_s)/R_p$$

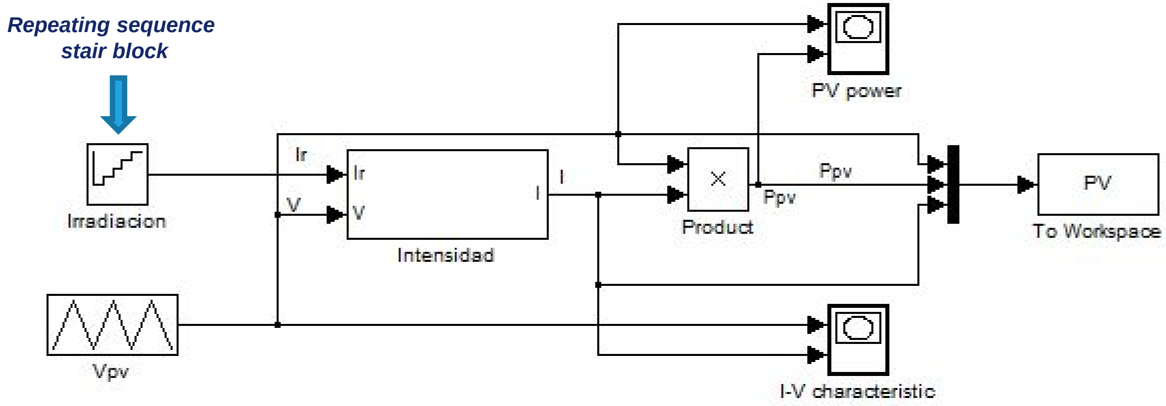


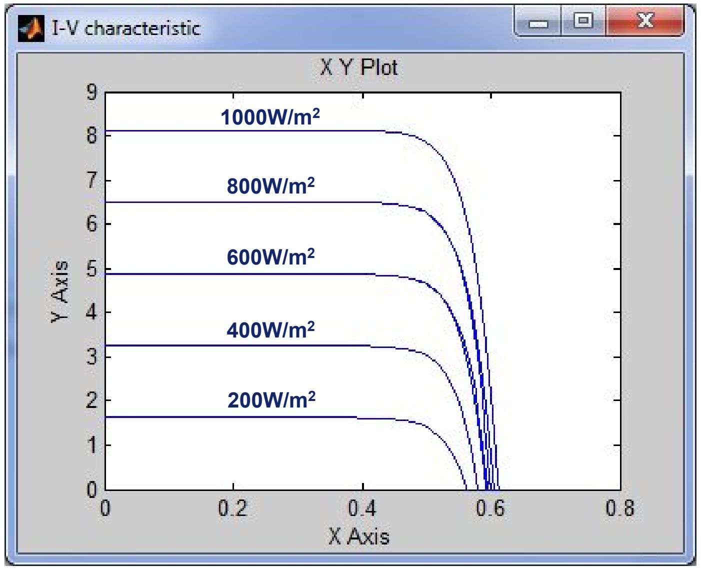


$$I_{ph} - I_d - I_{sh} = I$$

Basic Model in Simulink

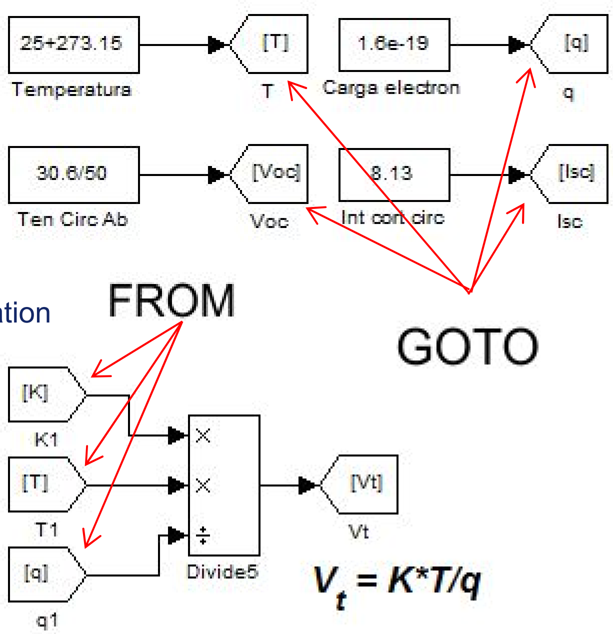
$$I = I_{ph} - I_s * (e^{(V + I * R_s) / N * V_t} - 1) - (V + I * R_s) / R_p$$





Simulink model with Tags

Initial conditions



Initialization


Title: From :: Blocks (Simulink®)

Simulink®

Provide feedback about this page

From

Accept input from Goto block

Library

Signal Routing

Description

The From block accepts a signal from a corresponding Goto block, then passes it as output. The data type of the output is the same as that of the input from the Goto block. From and Goto blocks allow you to pass a signal from one block to another without actually connecting them. To associate a Goto block with a From block, enter the Goto block's tag in the **Goto Tag** parameter.


Title: Goto :: Blocks (Simulink®)

Simulink®

Provide feedback about this page

Goto

Pass block input to From blocks

Library

Signal Routing

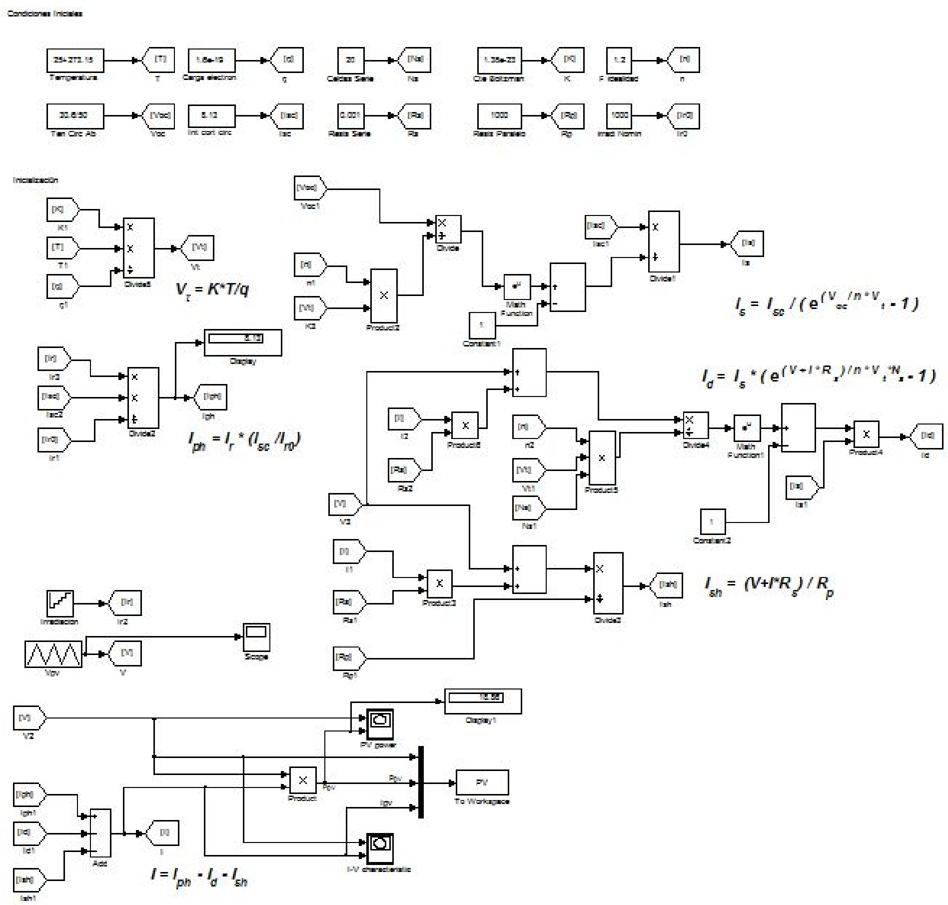
Description

The Goto block passes its input to its corresponding From blocks. The input can be a real- or complex-valued signal or vector of any data type. From and Goto blocks allow you to pass a signal from one block to another without actually connecting them.

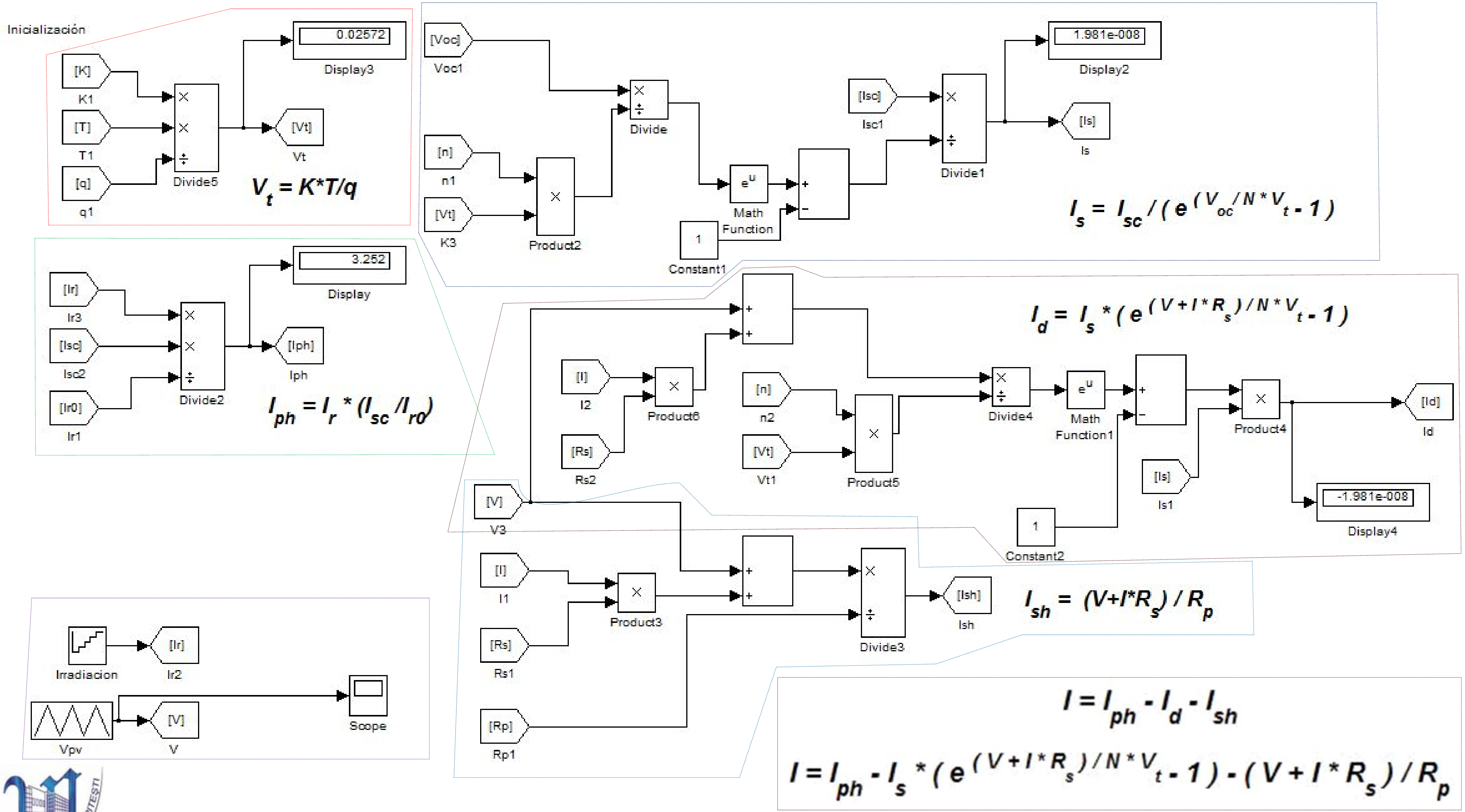
Simulink model with Tags

$$I = I_{ph} - I_d - I_{sh}$$

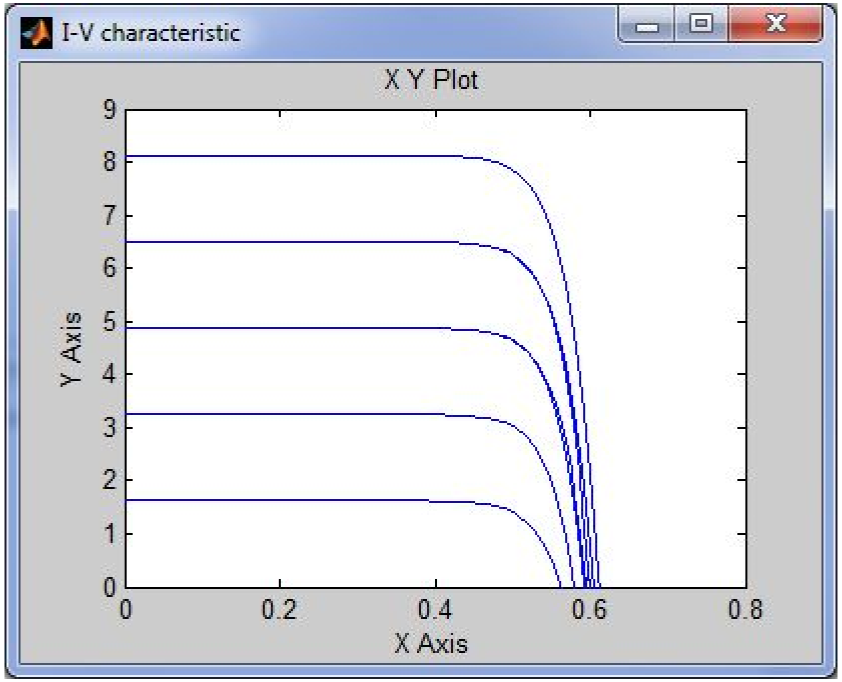
$$I = I_{ph} - I_s * (e^{(V+I*R_s)/n*V_t*N_s} - 1) - (V + I*R_s)/R_p$$



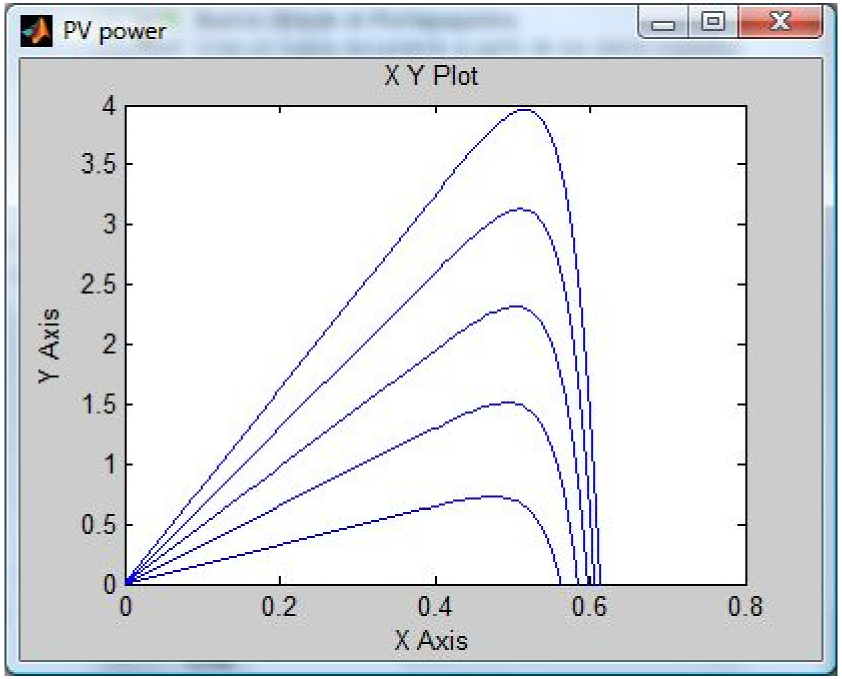
Photovoltaic Panel



Photovoltaic Panel



IV characteristic curves

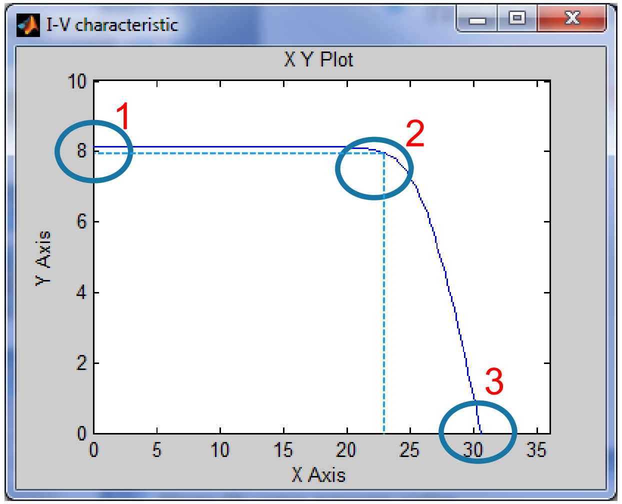


PV characteristic curves

Photovoltaic Panel

General equation :

$$I = I_L - I_0 \cdot \left(e^{\frac{(V + I R_s) q}{a k T_{cK}}} - 1 \right) - \frac{(V + I R_s)}{R_{sh}}$$



We always know three points :

1. Short Circuit Current: $I = I_{sc}$, $V = 0$
2. Open Circuit Voltage: $I = 0$, $V = V_{oc}$
3. The maximum power point: $I = I_{mp}$, $V = V_{mp}$

Complex Mathematical Models

- ***I_L : Photocurrent,.***
- ***I_0 : Reverse saturation current of the diode,***
- ***R_S: Series resistance,***
- ***R_P : Shunt resistance,***
- ***a: A parameter curve fit***

- Model of three parameters
  - R_s, $(R_{sh} \rightarrow \propto)$, a, $(I_L = I_{sc})$ e I_0.
- Model of four parameters
  - R_s, $(R_{sh} \rightarrow \propto)$, a, I_L e I_0.
- Model of three parameters
  - R_s, R_{sh}, a, I_L e I_0.

❖Model of three parameters

Unknowns : R_s, ($R_{sh} \rightarrow \infty$), a, ($I_L = I_{sc}$) e I_0.

General Equation:

$$\boxed{I = I_L - I_o\left(e^{\frac{V+IR_S}{a}} - 1\right)}$$

$$I_0 = \frac{I_{sc}}{e^{\frac{V_{oc}}{V_T}}}$$

$$R_s = \frac{V_{oc} - V_{mp} + V_T . \ln\left(\frac{I_{sc} - I_{mp}}{I_{sc}}\right)}{I_{mp}}$$

$$a = \frac{\beta_{V_{oc}} T_c - V_{oc} + \varepsilon N_s}{\frac{\alpha_{I_{sc}} T_c}{I_L} - 3}$$

Model of four parameters

Incógnitas: R_s, $(R_{sh} \rightarrow \propto)$, a, I_L e I_0

General Equation: $$\boxed{I = I_L - I_o\left(e^{\frac{V+IR_s}{a}} - 1\right)}$$

$I = I_{sc}$ y V= 0 $$I_{sc} = I_L - I_o\left(e^{\frac{I_{sc}R_s}{a}} - 1\right)$$

I = 0 y V= V_{oc} $$0 = I_L - I_o\left(e^{\frac{V_{oc}}{a}} - 1\right)$$

$I = I_{mpp}$ y V= V_{mpp} $$I_{mp} = I_L - I_o\left(e^{\frac{V_{mp}+I_{mp}R_s}{a}} - 1\right)$$

According to Townsend $$a = \frac{\beta_{V_{oc}}T_c - V_{oc} + \varepsilon N_s}{\frac{\alpha_{I_{sc}}T_c}{I_L} - 3}$$

❖Model of five parameters

$$I = I_L - I_0 \cdot \left(e^{\frac{(V + I R_s) q}{a k T_{cK}}} - 1 \right) - \frac{(V + I R_s)}{R_{sh}}$$

- Short circuit current : $I = I_{sc}$, $V = 0$
- Open circuit voltage : $I = 0$, $V = V_{oc}$
- At the point of maximum power : $I = I_{mp}$, $V = V_{mp}$
- At the point of maximum power : $dP/dV_{mp} = 0$
- In short circuit: $dI_{sc} / dV = -1/Rsh$

❖Model of five parameters

$$I = I_L - I_0 \cdot \left(e^{\frac{(V + I R_s) q}{a k T_{cK}}} - 1 \right) - \frac{(V + I R_s)}{R_{sh}}$$

(1) $$I_{sc} = I_{ph} - I_0 e^{\frac{I_{sc} R_s}{n_s V_T}} - \frac{I_{sc} R_s}{R_{sh}}$$ $P(0, I_{sc})$

(2) $$I_{oc} = 0 = I_{ph} - I_0 e^{\frac{V_{oc}}{n_s V_T}} - \frac{V_{oc}}{R_{sh}}$$ $P(V_{oc}, 0)$

(3) $$I_{mpp} = I_{ph} - I_0 e^{\frac{V_{mpp} + I_{mpp} R_s}{n_s V_T}} - \frac{V_{mpp} + I_{mpp} R_s}{R_{sh}}$$ $P(V_{mp}, I_{mp})$

❖Model of five parameters

(4)

$$\left.\frac{dP}{dV}\right|_{I=I_{mpp}} = I_{mpp} + V_{mpp}\frac{-\frac{(I_{sc}R_{sh}-V_{oc}+I_{sc}R_s)e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{n_sV_T}}}{n_sV_TR_{sh}}-\frac{1}{R_{sh}}}{1+\frac{(I_{sc}R_{sh}-V_{oc}+I_{sc}R_s)e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{n_sV_T}}}{n_sV_TR_{sh}}+\frac{R_s}{R_{sh}}}$$

$dI_{sc} / dV = -1/Rsh$

$dP/dV_{mp} = 0$

(5)

$$-\left.\frac{1}{R_{sh}}\right|_{I=I_{sc}} = \frac{-\frac{(I_{sc}R_{sh}-V_{oc}+I_{sc}R_s)e^{\frac{I_{sc}R_s-V_{oc}}{n_sV_T}}}{n_sV_TR_{sh}}-\frac{1}{R_{sh}}}{1+\frac{(I_{sc}R_{sh}-V_{oc}+I_{sc}R_s)e^{\frac{I_{sc}R_s-V_{oc}}{n_sV_T}}}{n_sV_TR_{sh}}+\frac{R_s}{R_{sh}}}$$

$dI_{sc} / dV = -1/Rsh$

❖Full model

$$I = I_L - I_0 \cdot \left(e^{\frac{(V + I R_s) q}{a k T_{cK}}} - 1 \right) - \frac{(V + I R_s)}{R_{sh}}$$

$$I_{sc,ref} = I_{L,ref} - I_{0,ref}\left(e^{\frac{I_{sc,ref} R_{s,ref}}{a_{ref}}} - 1 \right) - \frac{I_{sc,ref} R_{s,ref}}{R_{sh,ref}}$$

$$0 = I_{L,ref} - I_{0,ref}\left(e^{\frac{V_{oc,ref}}{a_{ref}}} - 1 \right) - \frac{V_{oc,ref}}{R_{sh,ref}}$$

❖Full model

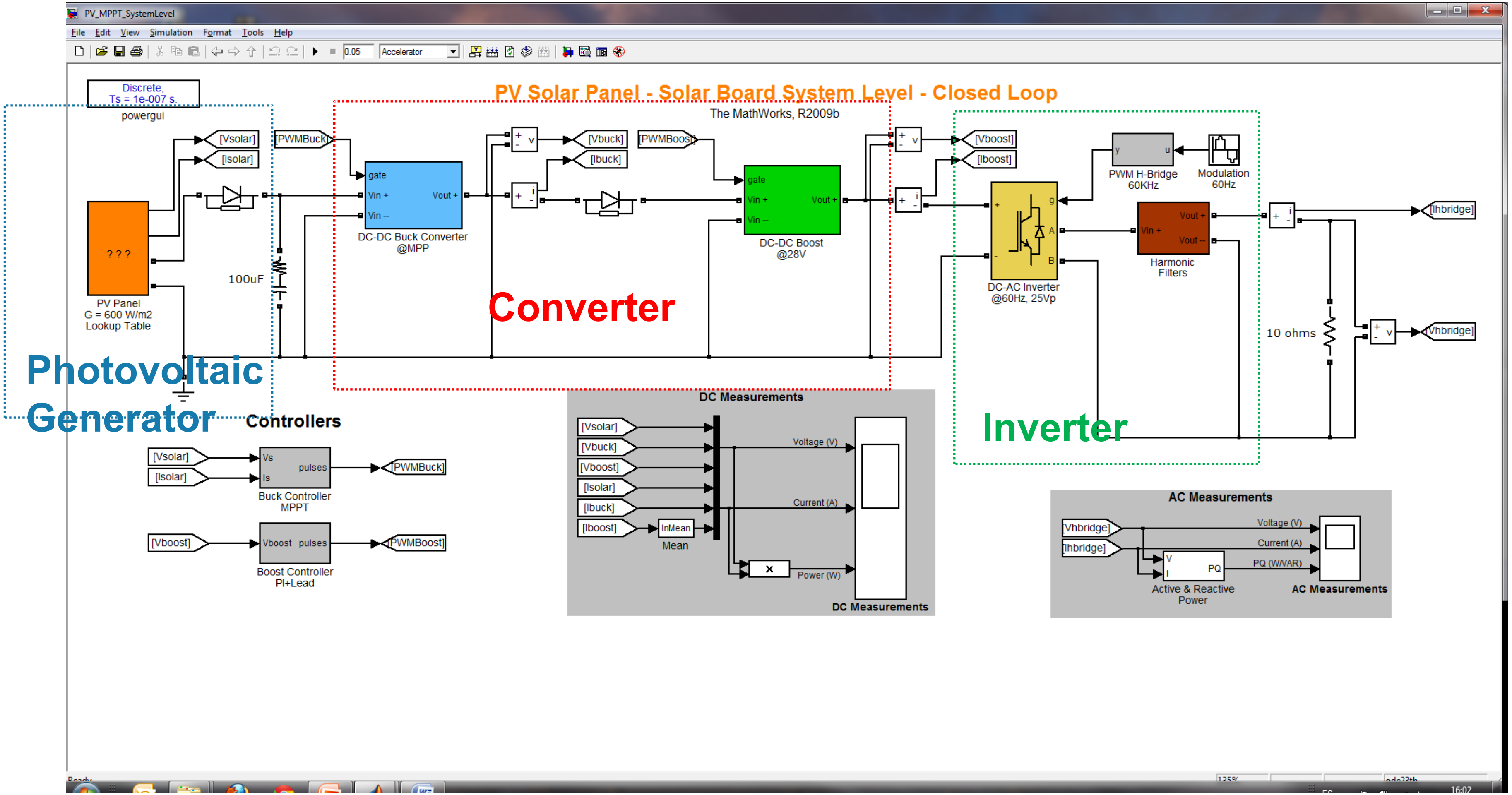
$$I_{mp,ref} = I_{L,ref} - I_{0,ref}\left(e^{\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{a_{ref}}} - 1\right) - \frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{R_{sh,ref}}$$

$$\left.\frac{d(IV)}{dV}\right|_{mp} = I_{mp} - V_{mp}\left.\frac{dI}{dV}\right|_{mp} = 0$$

$$\left.\frac{dI}{dV}\right|_{mp} = \frac{\frac{-I_0}{a}e^{\frac{V_{mp}+I_{mp}R_s}{a}} - \frac{1}{R_{sh}}}{1 + \frac{I_0 R_s}{a}e^{\frac{V_{mp}+I_{mp}R_s}{a}} + \frac{R_s}{R_{sh}}}$$

$$\beta_{V_{oc}} = \left.\frac{\partial V}{\partial T}\right|_{I=0} \approx \frac{V_{oc,ref} - V_{oc,T_c}}{T_{ref} - T_c}$$

Photovoltaic System

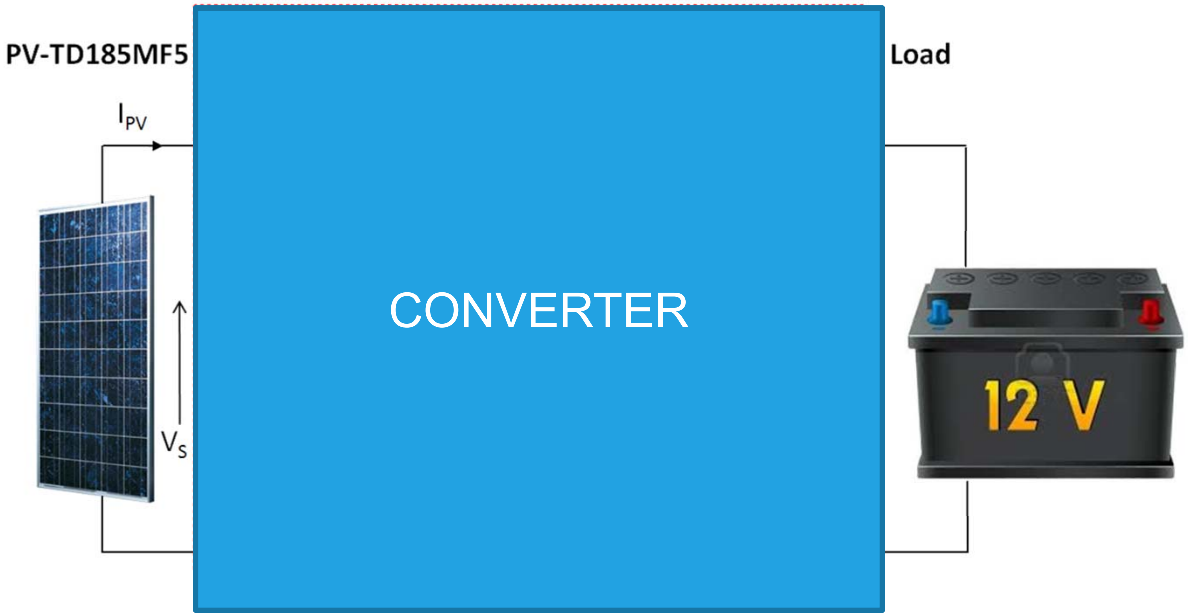


❖ Types of DC / DC converters basic

- **Boost converter: $V_{Load} > V_{Module}$**
- **Buck converter: $V_{Load} < V_{Module}$**
- **Buck-Boost converter: $V_{Load} > V_{Module}$ or $V_{Load} < V_{Module}$**

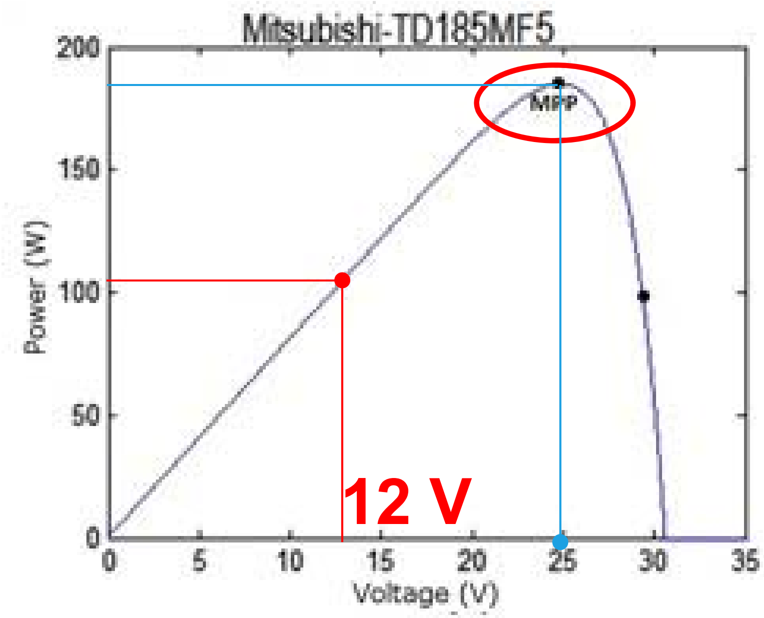
Photovoltaic System

❖Why do we need to put a converter, for example between the photovoltaic module and battery? For example.



Photovoltaic System

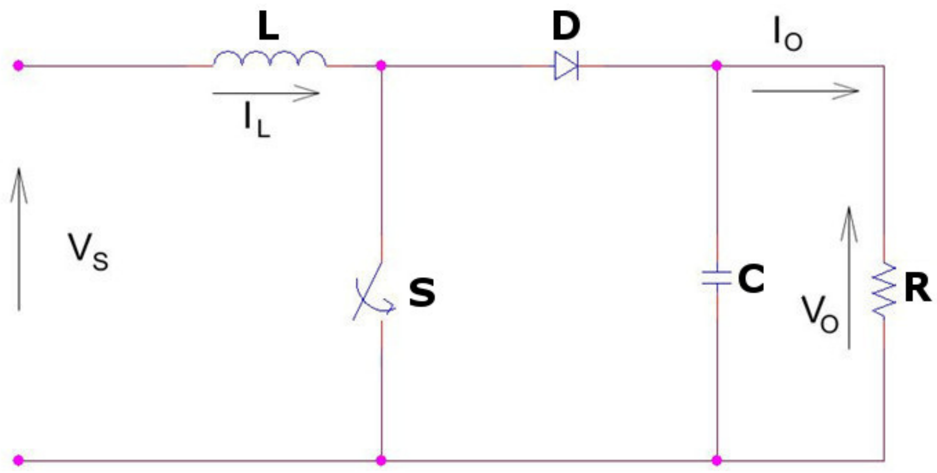
❖ Why do we need to put a converter, for example between the photovoltaic module and battery?



For G = 1000 W/m^2
T = 25 ºc

Our efficiency is poor. We need to work near the MPP

❖Types of DC / DC converters basic



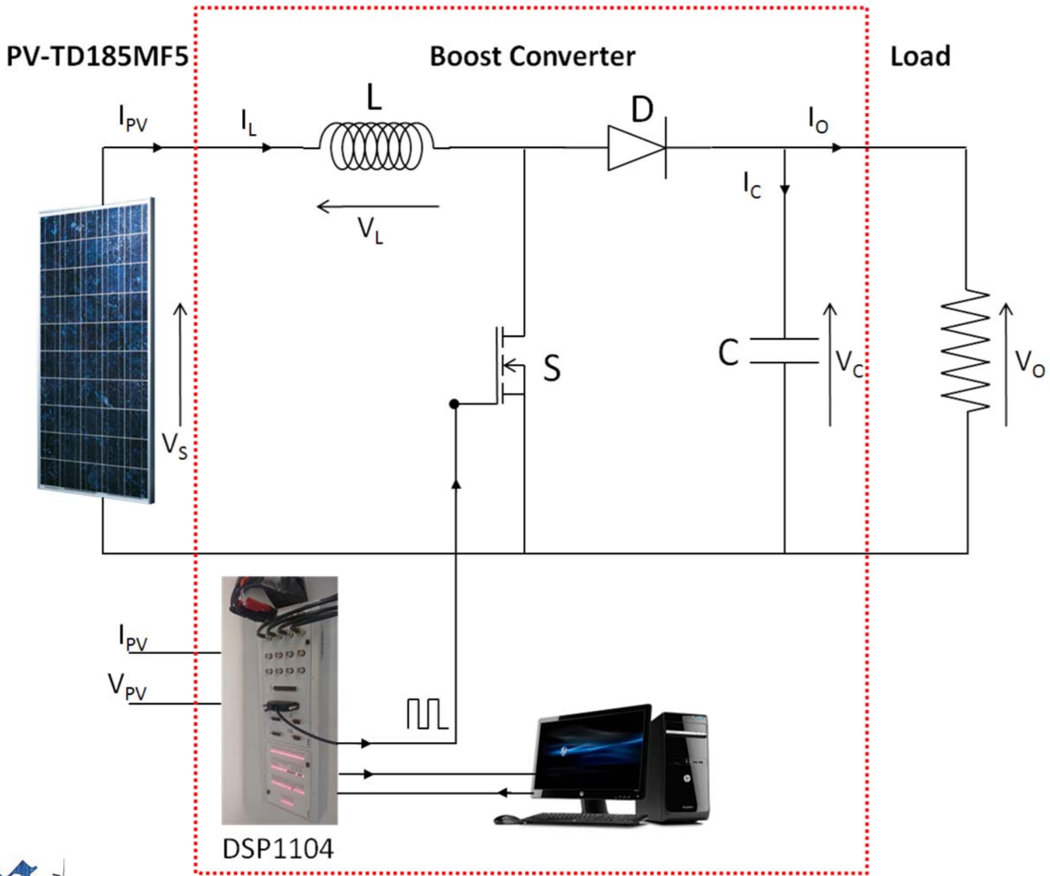
Boost converter

In the case of a Boost converter in continuous driving operating mode, the relations between the input (V_S and output (V_O) variables are given by Equations

$$V_{Load} > V_{Module}$$

$$V_O = \frac{V_S}{(1 - \delta)}$$

❖How do we do it:



$$V_O = \frac{V_S}{(1 - \delta)}$$

With de MPPT look for δ

$$\delta = 1 - \frac{V_S}{V_O}$$