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A P P U N T I

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MATERIA: Power Generation from renewalbe sources (6CFU) - Prof. Spertino

STATE OF THE ART IN PHOTOVOLTAICS, PROS ⊕ and CONS ⊖ of PV (photovoltaic)

LEZ 1

The solar energy is
- several orders of magnitude greater than the consumption linked to the human activities ⊕
- It's very distributed around the world, unlike fossil energy ⊕
- it's renewable, and almost costant on yearly basis ⊕
- the power density is lower than other energy sources ⊖

The silicon (Si) is one of the most abundant source / material on the Earth, it's inexaustible. ⊕

The increasing of temperature causes a decreasing of the efficiency ⊖

It isn't required a ~~coolant~~ cooling system → NO use of water ⊕
There isn't combustion ⊕
It's a direct converter of energy, there isn't a turbine as in power plants ⊕, → NO maintenance due to consumption → long lasting ⊕
It doesn't contribute to the global warming ⊕

Type of Si and other materials used for PV models

Technology	Efficiency
m-Si ; m-Si/a-Si	~~13-20 %~~ 15 - 21%
p-Si	~~12-14 %~~ 14 - 16%
a-Si ; a-Si/μc	~~5-9 %~~ 6 - 10%
CIS/CIGS	~~10-11 %~~ 11 - 13%
CdTe/CdS	~~9-10 %~~ 13 - 15%

m-Si : mono crystalline Silicon
higher efficiency, higher cost, darker color

p-Si : poli crystalline / multi crystalline Silicon, medium efficiency, medium cost, blue color
→ most used technology because it's a good compromise between cost and efficiency

The Si used for these technologies is very pure, about 99,9999 % of Si ⊖, it's difficult to purify

a-Si : amorphus Silicon, low efficiency, low cost

CIS / CIGS : Copper - Indium - Selenium / Copper - Indium - Gallium - Selenium, but Indium and Gallium are rare on the Earth

CdTe / CdS : Cadmium - Telluride / Cadmium - Sulfite

THIN FILMS technologies, Silicon technologies are thicker

The source is the sunlight, the device is a static direct converter and it's near to the consumers → low transmissions losses ⊕. It's recyclable (for info www.pvcycle.org) ⊕

High cost of the electricity energy about 0,20 € / kWh ⊖

Drawbacks:
- the device operate in DC, so we need another component to convert to AC → INVERTER ⊖, or to storage in batteries
- intermittent power production ⊖
- the installation cost is higher than ~~of~~ other sources (about 1000 ÷ 2000 € / kWh_p) ⊖
  ↳ peak

The EPBT (energy payback time) is less than 3 years ⊕

Hypothetically, if we want to satisfy the yearly electricity consumption with PV, which surface would be necessary?

The productivity of a PV plant is 1200 [GWh/GW] in a year
In Italy the electric consumption is 330 [TWh], so we would need to install 275 [GW] of power in PV plants
To obtain 1 [GW] we need to cover with photovoltaic modules 10 [km²] of surface, so to satisfy the consumption we have to cover 2750 [km²], remembering that the Italian surface is 301278 [km²], it's the 0,91% of the italian surface.

A suitable site / software is the PV GIS of JRC

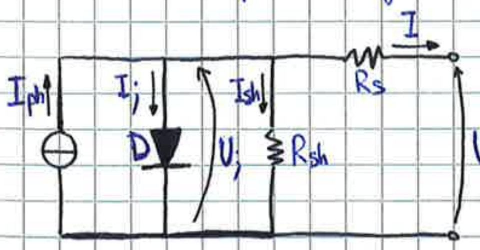
Some typical parameters of PV modules are:
- the cell technology
- the rated power tollerance (rated stands for "peak") (± 3÷5 % /°C)
- the cell size and dimensions (156.25 cm², 243.36 cm²)
- the thermal power coefficient (γ_p) (− 0,2 ÷ 0,5 % /°C)
- the Normal Operating Cell Temperature (NOCT) (45-50°C)
- the voltage of the system (600-800-1000 V)
- the weight

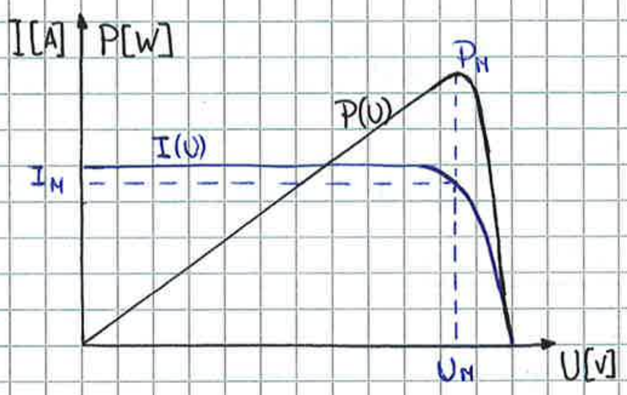
The flash tests indicates measured data without uncertainty, obtained with sun simulators

Some typical values for a crystalline silicon technology at Standard Test Conditions (STC) ($G = 1\,kW/m^2$, $T_{cell} = 25°C$)

1 cell: $P_{nom} = 2{,}5 - 4\ W$, $U_{nom} = 0{,}5\ V$, $U_{oc} = 0{,}6\ V$, $J = 27\text{-}33\ mA/cm^2$, $S = 100\text{-}400\ cm^2$
1 module with 60 cells: $P_{nom} = 150 - 240\ W$, $U_{nom} = 30\ V$, $U_{oc} = 36\ V$
1 model with 72 cells: $P_{nom} = (180 - 260\ W)$, $U_{nom} = 36\ V$, $U_{oc} = 43{,}2\ V$

Just an anticipation of the equivalent circuit of a solar cell and the I-V curve





Current source $I_{ph} = k \cdot S \cdot G$
irradiance

Junction current $I_j = I_0 \cdot (e^{A^+ U_j} - 1)$

Current balance $I = I_{ph} - I_j - U_j / R_{sh}$

Voltage balance $U = U_j - R_s \cdot I$

$$A^+ = \frac{q}{m\, k_B T}$$

mc-Si its production techniques are more simple and cheaper, obviously the quality is lower due to the presence of grain boundaries: these reduce solar cell performance by blocking carrier flows and providing shunting paths for current flow across the p-n junction

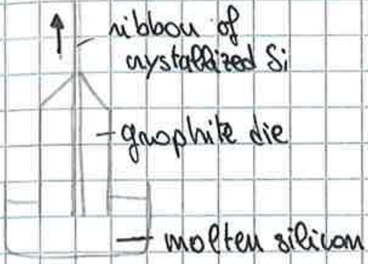
WAFER SLICING

The ingot of silicon are very big, so they need to be cut into wafers

The ingot is sliced into bricks and then cut by a rotating wire saw into wafers

EDGE DEFINED FILM FED GROWTH (EFG)

It's a process in which the slicing procedure is not needed



(matrice, stampo)
The EFG techniques uses a die to define thickness of a sheet of silicon. Careful adjustement of the temperature profile of the graphite die causes the sheets of silicon to crystallize with large grains

For the production of p-Si technology it's used the "block casting" procedure in which silicon, through electricity, is fused in a graphite crucible, then is performed a directional crystallization. The ingot is now cut through a slice in a parallelepiped square-based ingots with a side of 15.6 cm.

Now the top and tail of the ingot are cut because of the impurity. Finally ingot are cut into wafers with a multi-wire diamond saws (0.2-0.3 mm of thickness).

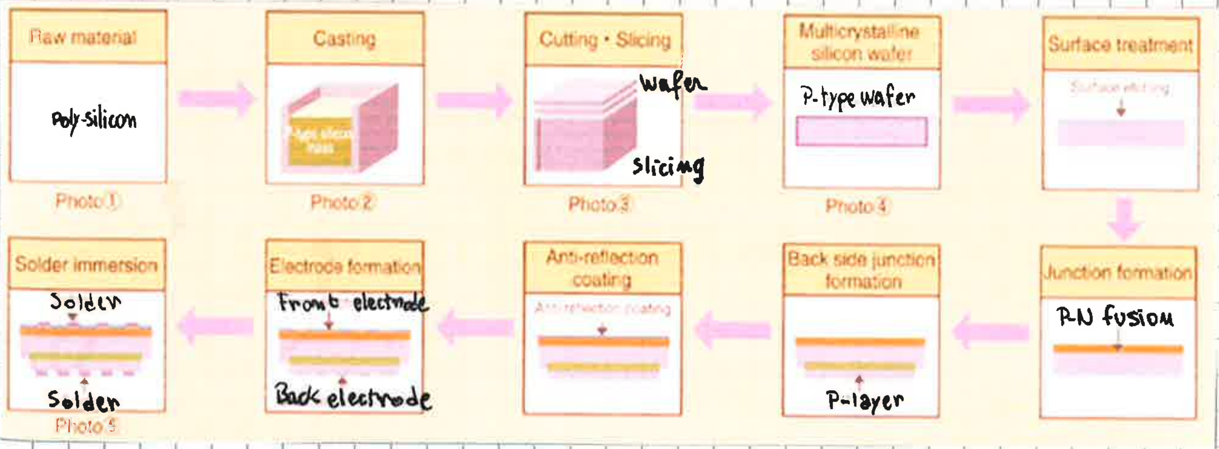
Unfortunately 80-80% of the material is lost.

During this process the silicon is p-doped (~~proton~~) with Boron.

After slicing the wafer has to be transformed in junction with a gaseous diffusion with Phosphorus in order to obtain a n-type (~~neutron~~) on one side: this doped layer is about 1 µm thick.

In order to reduce the reflection it's disposed an anti-reflection layer (Si nitride or Tioxide)

Finally electrodes are produced: on the frontal side exposed to the sunlight is connected an electrode with serigraphy, in order to obtain an continuate contact with the n-layer. On the other side a plate aluminium electrode is connected



DOPING

p -> positive (~~proton~~) (hole)
n -> negative ([illegible]) (electron)
i -> intrinsic: no doping

The Staebler-Wronski effect: it causes the reduction of the efficiency during the life of the cell

(ex. for a-Si $\eta = 8\%$ but after 2 years $\eta = 6.5\%$: -20% of efficiency)

For thin films this effect ~~is higher~~ causes bigger degradation that for the c-Si, instead CIS and CdTe don't present this degradation

CPV systems (concentrated photovoltaic)

This technology needs DESERT condition: more than 200 days of very sunny conditions → it uses only direct irradiation

For this point it needs also a sun-tracking system*: it comports high cost of maintenance, because it must be very accurate, the sunbeam must be perpendicular

For the high CPV are used the MULTI-JUNCTION cells:

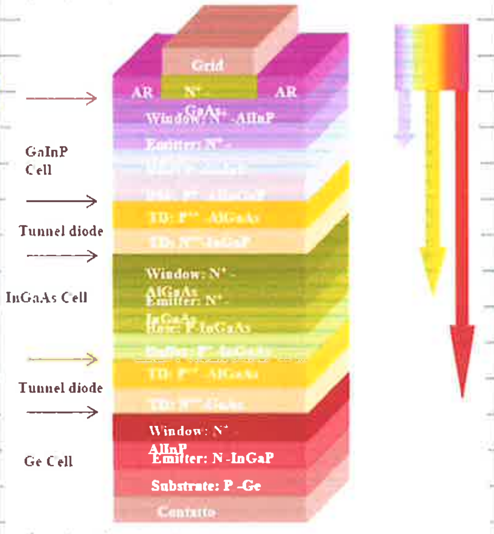
These are composed of different deposition layers of semiconductor material. They have 3 overlapping solar cells that are sensible to different λ

The interfaces between cells are made using tunnel diodes

The cells are in series to achieve more V with the same I

$$V_{oc}(\text{multi}_j) = 2.5\,V \qquad I(\text{multi}_j) = \frac{1}{2} I(c\text{-}Si)$$
$$V_{oc}(c\text{-}Si) = 0.66\,V$$

$$P(m_j) = 2P(c\text{-}Si)$$



The best efficiency reached is 45%, but the theoretical limit is about 70%

* it has two axes tracking: AZIMUT and TILT ANGLE

Generally the total of P_p (PCU) is lower than P_p (PV) because of the thermal losses (Joule effect)

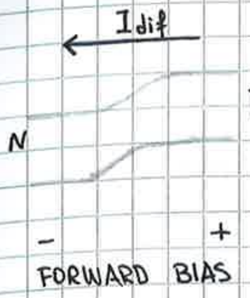
During the sunrise we can connect step-by-step every slave till the noon, and in the afternoon we disconnect every slave till the sunset

Required tasks for the grid-connected inverter:

- maximum power point tracker (MPPT)
- active and reactive power control ($\cos \varphi = 1$)
- grid interface protection

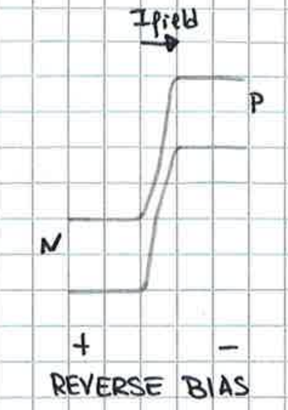
The grid connection takes place:

- with or without transformers (transformerless)
- at high (100 kHz) or low (50 Hz) frequency transformer



positive potential ⊕ applied to
the P layer
↓
reduction of electric field

positive potential ⊕ applied to the
N layer → growth of the electric field



(The arrow represents the direction of the flow of the positive charges)

The junction works as a rectifier and his IV characteristic is given by:

$$I = I_0 \left(\exp\left(\frac{qU}{mKT}\right) - 1\right)$$

where I_0: saturation current
q: electron charge
U: voltage
m: quality factor of the junction
k: Boltzmann costant
T: temperature

THE PHOTOVOLTAIC EFFECT

The radiation is able to reach the p-N junction (depletion region) because the N layer is very thin (~1 μm).
The diffusion causes the very high electric field (1 V/μm ; 1 MV/m)

The photovoltaic conversion of the solar energy is based on the quantic nature of the light, seen as a flux of photons which transport the energy

$E_{ph}(\lambda) = hc/\lambda$ h: Planck costant   c: light speed λ: wavelenght

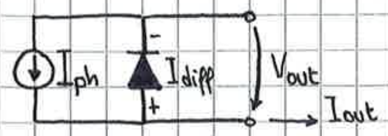
In a sunny day about $4{,}4 \cdot 10^{-7}$ photons invest every second a square centimeter of the Earth.

Only the photons with energy $E_{ph} > E_{gap}$ (energy jump between valence band and conduction band) are converted into electricity. When one of these photons joins the semiconductor it can be absorbed and can promote an electron from the valence band to the conduction one. This process creates ELECTRON/HOLES PAIRS, because in the valence band is formed a hole.

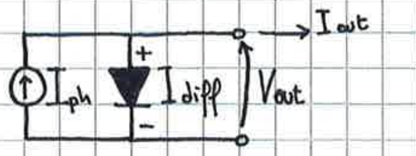
Every semiconductor converts only a part of the solar spectre: a portion of the energy of the photons is lost in the absorption process. It has been observed that every electron-hole pair has an excess of energy with respect to the Energy gap. Immediatly after the emission, the electron decades (in terms of energy) near the borders of the respective band.
The energy in excess is lost as heat and it can't be converted in power.
This is one of the mechanism of losses

THE CURRENT-VOLTAGE CHARACTERISTIC

A solar cell under the G action can be represented by these equivalent circuit (with active sign convention, because is a source)



or

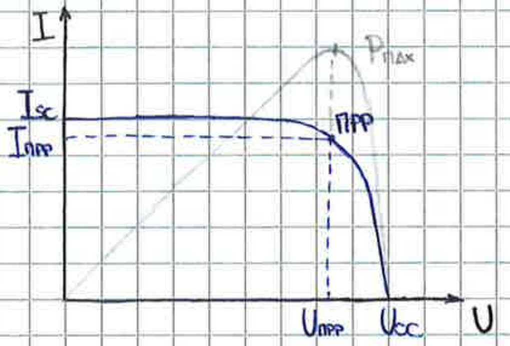


MOST USED

The connection of the diode is in FORWARD BIAS

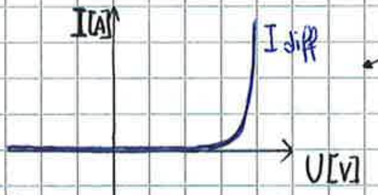
In a solar cell the photovoltaic current I_{ph} is produced and it's proportional to G and the diode current is substracted, due to the diffusion, which increases with voltage up to the balance value U_{oc} in open circuit condition

$I_{out} = I_{ph} - I_{dif}$



The current-voltage characteristic of an irradiated cell is non-linear and is defined by:

- I_{MPP} : maximum power point current
- U_{MPP} : maximum power point voltage
- I_{sc} : short circuit current
- U_{oc} : open circuit voltage

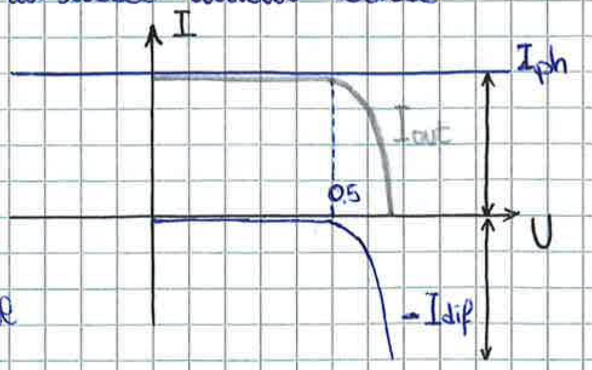


I-V curve of a diode (experimental test)

REVERSE BIAS negligible current

FORWARD BIAS current = 0 until a threshold voltage

The I-V curve of a solar cell is given by $I_{out} = I_{ph} - I_{dif}$ where I_{ph} is seen as an ideal current source



In the solar cell the threshold voltage is about 0.5 V

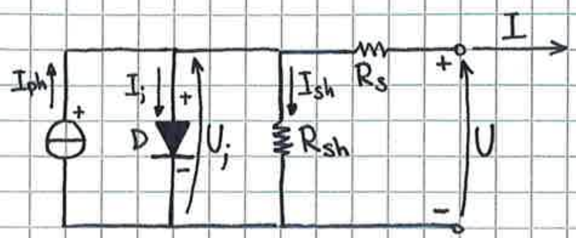
When the two lenghts ↕ are equal

→ we have open circuit current → $I_{out} = 0$

and open circuit voltage V_{oc}

When $I_{out} = I_{sc}$ or $V_{out} = V_{oc}$ → $P = 0$

THE EQUIVALENT CIRCUIT

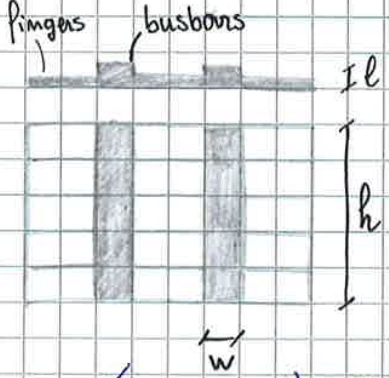


This equivalent circuit is a good compromise between accuracy and simplicity

The ideal current source and the diode represent the solar cell

The shunt resistance Rsh represents the current losses by the cell with the lateral plate. It can be increased increasing the isolation of the lateral surfaces.

The series resistance Rs represents the resistance of the frontal electrode. It can be decreased increasing the numbers of busbars on the front contact.



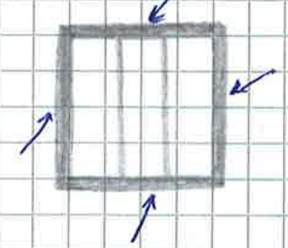
$R_{bar} = \rho \frac{l}{S}$

where $S = h \cdot w$

$R_s = \frac{R_{bar}}{2}$ or $\frac{R_{bar}}{3}$

with 2 or 3 busbars

Rs ~~eq~~ is given by the busbars and the fingers, the most important is the busbar contribution



Usually are used ~~for~~ big surfaces -> more busbars (2 or 3) but this increase the lateral surface -> we need more isolation, because it's necessary to isolate the 4 lateral surfaces of the solar cell

With isolation the shunt resistance Rsh increase and the leakage current Ish decrease

Rs should be as low as possible ($1 \div 100\ m\Omega$)

Rsh should be as high as possible ($1 \div 100\ \Omega$)

EQUATIONS

q: electron charge
m: quality factor
k_B: Boltzmann constant

JUNCTION CURRENT $I_j = \underbrace{I_0 \exp\left(\frac{qU_j}{m k_B T}\right)}_{I_{dif}} - \underbrace{I_0}_{\text{reverse saturation current}}$

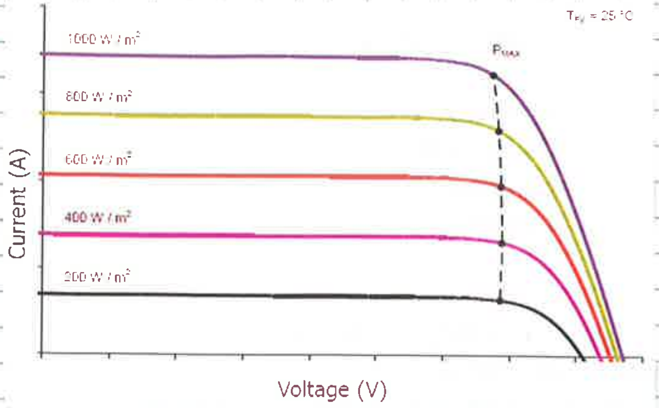
$I_j = I_0 \left(e^{\frac{qU_j}{m k_B T}} - 1\right)$

$I = I_{ph} - I_j - \frac{U_j}{R_{sh}}$

$I_{ph} = k_{mat} \cdot G \cdot A$ A = surface of the cell

$U = U_j - R_s \cdot I$

The I-V curve changes with the irradiance and with the temperature



If G decreases I_{sc} decreases proportionally, while V_{oc} decreases with a logarithmic behaviour

$$I_{ph} = k_{mat} \cdot G \cdot A$$

$$I_{sc} \approx I_{ph} \qquad I_{sc} = \frac{R_{sh}}{R_{sh}+R_s} I_{ph}$$

but $R_s \ll R_{sh}$

and I_{dif} is negligible in forward bias

What's the dependence of V_{oc} with G? To see it let's look at the open circuit condition, we can neglect the R_{sh}

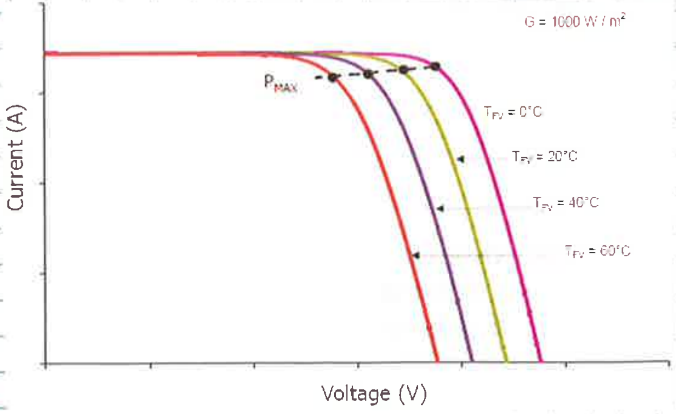
$$I_{ph} - I_0 \exp\left(\frac{q V_{oc}}{m k_B T}\right) + I_0 = 0 \qquad \frac{I_{ph}+I_0}{I_0} = \exp\left(\frac{q V_{oc}}{m k_B T}\right)$$

$$\frac{q V_{oc}}{m k_B T} = \ln\left(\frac{I_{ph}+I_0}{I_0}\right) \qquad V_{oc} = \underbrace{\frac{m k_B T}{q}}_{V_{th}} \ln\left(\frac{I_{ph}+I_0}{I_0}\right)$$

V_{th} is called equivalent thermal voltage

$$I_{ph} = 5 \div 8\,A \qquad I_0 \simeq \mu A \rightarrow V_{oc} \approx V_{th} \ln\left(\frac{I_{ph}}{I_0}\right)$$

This figure focuses also on the MPPs (black points), it's almost a vertical line so V_{oc} it's almost constant for G variation



temperature of the cell

If T_c increases:

- I_{sc} has a slight increment, due to the reduction of the energy gap
- an increase of I_0 in the diode and a consequent reduction of the V_{oc}

These variations cause a global decrement of the P_{MAX}

$$\alpha_{J_{sc}} = \frac{dJ_{sc}}{dT} = +10 \frac{\mu A}{cm^2\,°C}$$

$$\beta_{V_{oc}} = \frac{dV_{oc}}{dT} = -2{,}2 \frac{mV}{°C}$$

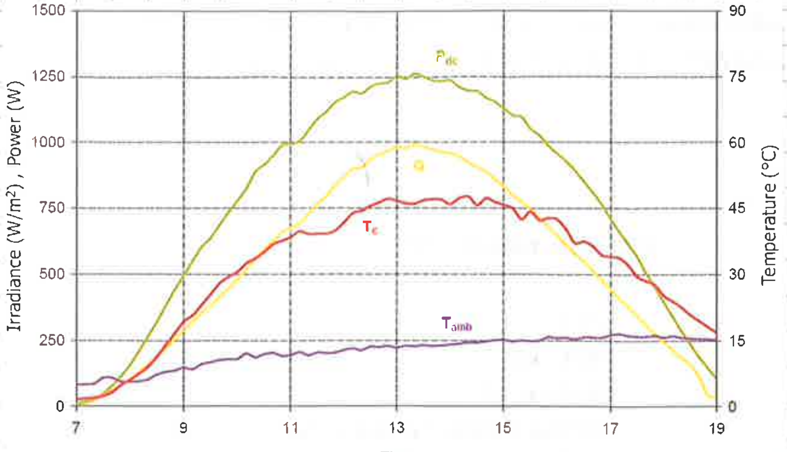
$$\gamma = \frac{dP_n}{P_n\,dT} = \frac{-0{,}45\%}{°C}$$

from STC

$T = 25°C$

In the applications, often, it's believed that I_{sc} depends only from G, and that V_{oc} depends only from T.

SIMULTANEOUS VARIATIONS of G and T in a day



In this example

T_c is measured behind the module

The max(T_c) is near the max(G)

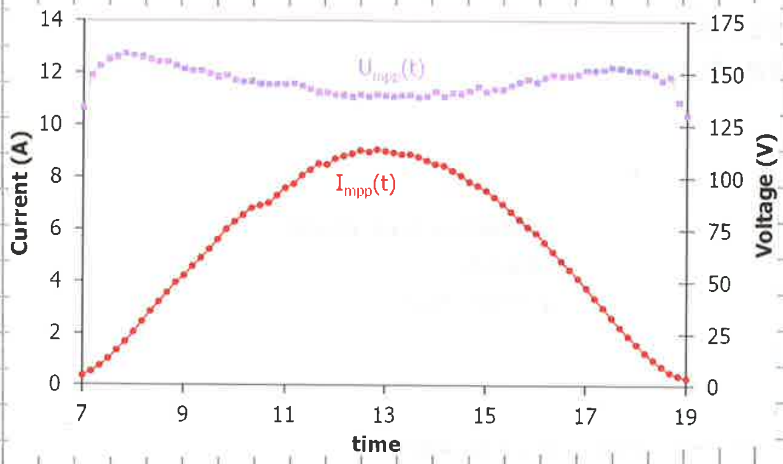
The evolution of P_{MAX} is similar to the evolution of G

but,

$P_{rated} = P_{peak} \simeq 1.5$ kW (STC),

max(P_{dc}) $\simeq$ 1.25 kW

This difference is caused by the thermal losses due to the T_c



To have the max(U) is necessary only a little G

MISMATCHING

Every c-Si solar cell, with rated irradiance, supplies voltage of 0.5 - 0.6V and a current, proportional to the surface, with current density $J_{sc} = 25\text{-}35\ mA/cm^2$ (for a cell with a side = 15,6 cm $\rightarrow I_{sc} = 6\text{-}8{,}5A$)

However the loads usually used require voltage and current higher then those given by a single cell; to achieve the required power, it's necessary to connect severall cells in series and in parallel

The ~~most~~ mismatch occurs when one or more cells supply a fewer current with respect to the others. (MISMATCH of the different I-V curves)

The most common causes of mismatch of I-V curves of a group of solar cells are:

1) manufacturing tolerance } these two are always present
2) manufacturing defects }
3) partial shading

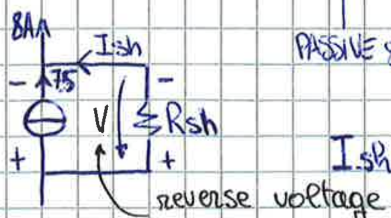
Let's consider the case in which Ns-1 solar cells in series supply 8A and only 1 (the weckest) supplies only 7.5 A.

the first Ns-1 current source are connected with the ACTIVE sign convention

But the last, supplying only 7.5A, $\underbrace{\text{becomes a load}}$, and the difference (0.5 A) is the current in the resistance.

PASSIVE sign convention

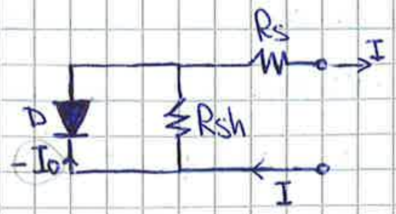
→ this resistance is the shunt resistance



$I_{sh} = 0.5 A$

Consequences:
- Output power decreases (as we can see in the next figure)
- The last power becomes a load, → heat it's possible that the cell exceed the thermal limit, if it lasts for a long time

For a shaded cell the equivalent circuit is almost this:



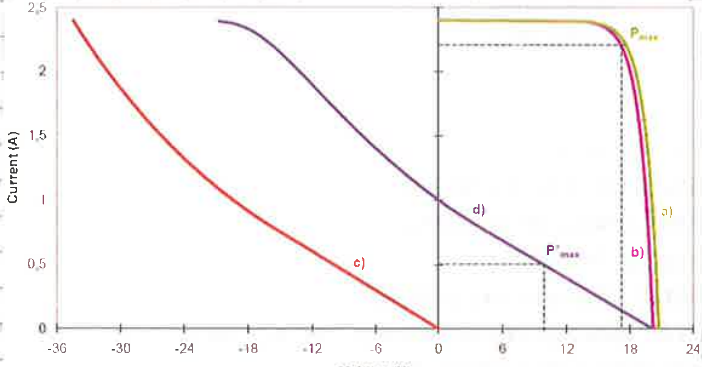
so we can represent it only with ~~[illegible]~~ Rsh, because I_D is negligible and $R_{sh} \gg R_s$

in a diode $I_D = I_0\left(\exp\left(\frac{qU}{mkT}\right) - 1\right)$

The voltage drop is linear with $R_{sh} \cdot I$

(In the figure in the previous page we can see the different "shaded cell" behaviour of different technologies (m-Si, p-Si, a-Si). Summing these with the "not-shaded" cells we can see that for m-Si we will have more losses than p-Si and a-Si)

NUMERICAL EXAMPLE 36 p-Si cells, 1 shaded



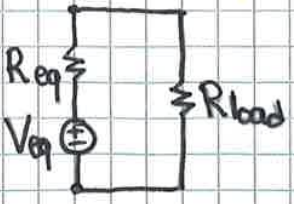
c) is the shaded cell

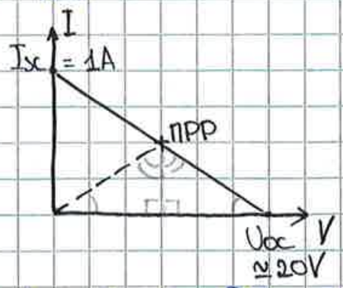
b) Ns-1 normal irradiated cells

d) resulting curve

a) Ns normal irradiated cells (NO SHADE)

The behaviour of the resulting curve is a Thevenin equivalent circuit, so it's easy to find MPP





$R_{eq} = \frac{20V}{1A} = 20\ \Omega$ (not so high for a Rsh)

The MPP is found when $R_{load} = R_{eq}$ (when the two triangles are equal)

so $U_{MPP} = 10V$ $I_{MPP} = 0.5A$ $P_{MAX} = 5W$

In shaded condition m-Si $P = 0$ W

p-Si $P \neq 0 \cong 5$ W

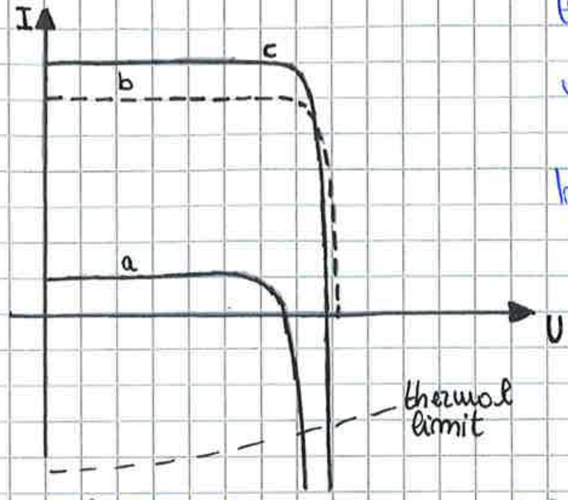
$P_{MAX} = U_{MPP} \cdot I_{MPP} = \frac{1}{2} I_{sc} \cdot \frac{1}{2} U_{oc} =$

$= 0.25 \cdot (U_{oc} - I_{sc})$

FF = 25% ↵

MISMATCH in parallel connection

Likewise in series connection, with N_p parallel connected cells if one cell has a defective IV curve the resulting curve (c) is given by the sum of the $N_p - 1$ currents of the normal cells (b) with the one of the shaded (a)



In parallel the risk of the shadow effect is not in terms of reverse voltage, but a generation of reverse current → 4th quadrant: there isn't the breakdown voltage risk, only HOTSPOT can occur.

The reverse current can flow in Rsh and in D_p, as a diffusion current.

For example it can occurs when a module has less U_{oc} (12 against 13), the reverse current flows in the defective one.
The resulting curve will have
$$U_{oc} = (U_{oc})_{min} \rightarrow 12V$$
$$I_{sc} = \sum_{i=1}^{N_p} I_{sc_i}$$

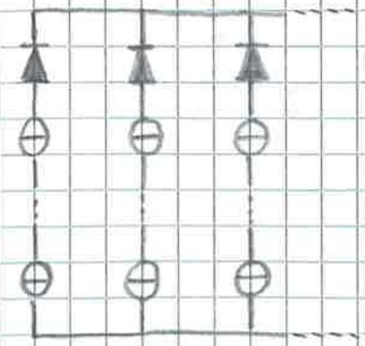
The worst condition is in open circuit, because the shaded cell must absorb the current of the irradiated cells.

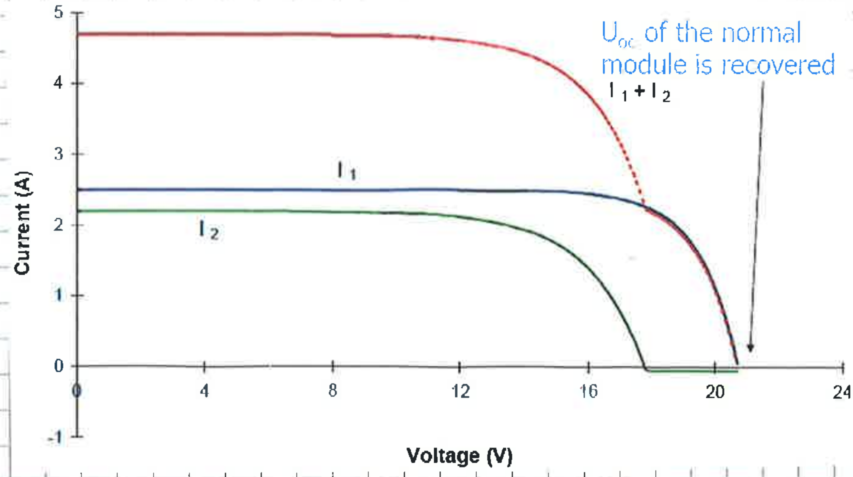
It can occur that it works the 4th quadrant reaching the hotspot point, after that the cell fails and the module works without it

To prevent this reverse current we can connect in series a BLOCKING DIODE Ds with the direction of the PV current

This diode can avoid that the defective cell operates as a load.

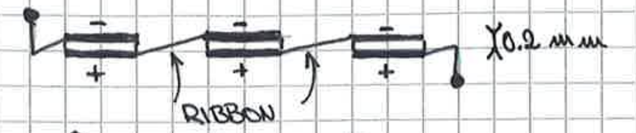
As for the by-pass diode it's impossible to connect at each cell a blocking diode; so generally a diode is connected at every series of cells.





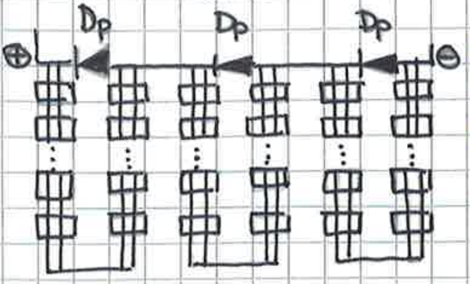
STRUCTURE and SPECIFICATIONS of PV

A PV module is composed of a number of solar cells connected in series or in parallel (for example 36 or 72)



The ribbon is the connection of the bus bars of the previous cell back contact with the next cell front bus bar

It's necessary to protect these ribbons by many agents
- sun beams
- rain
- snow
- wind
- humidity



with 3 by-pass diode Dp

This is the most popular configuration

The typical structure of a PV module is the following:

To protect the module we put up and down an EVA polymeric layer (Ethylene Vinyl Acetate) against the humidity (it's similar to a glue)

The glass is very trasparent to the light

A frame in aluminium is useful to fix the module to a structure; if the PV module is integrated there isn't the frame

The sealant gasket is used to avoid water touching the cells

The building integrated PV (BIPV) has 2/(3) glasses (1 top - 2 bottom) to better isolate the module, but 3 it's very rare (they contains also Argon)

On the bottom there is a polymeric layer of TEDLAR, not trasparent material.

The Nominal Operating Cell Temperature (NOCT) is the equilibrium temperature of a solar cell in a module, placed at the sun, in standardized conditions:
- irradiance $G = 800\ W/m^2$ (AM = 1.5)
- ambient temperature $T_a = 20°C$
- wind speed $v = 1\ m/s$

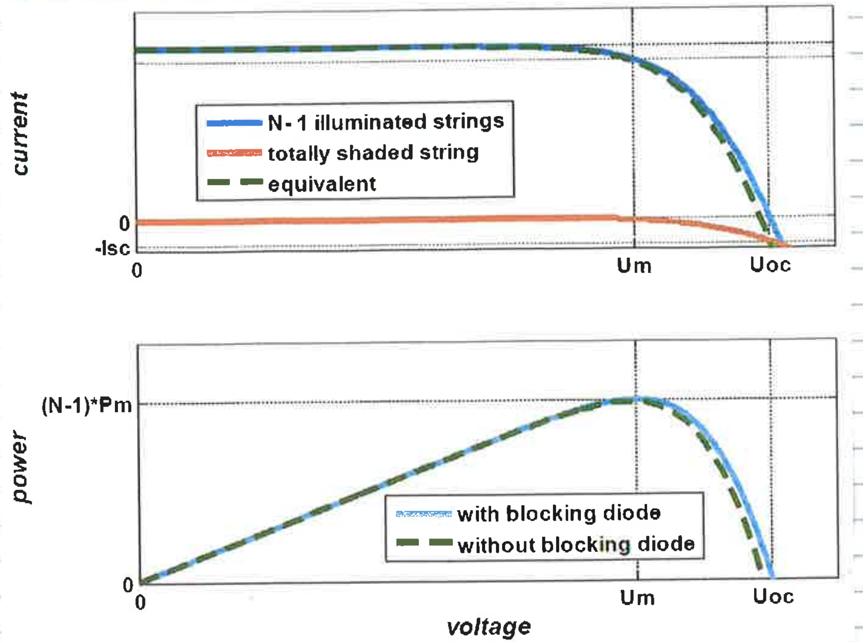
typical values, with this definition, are 43 - 50 °C

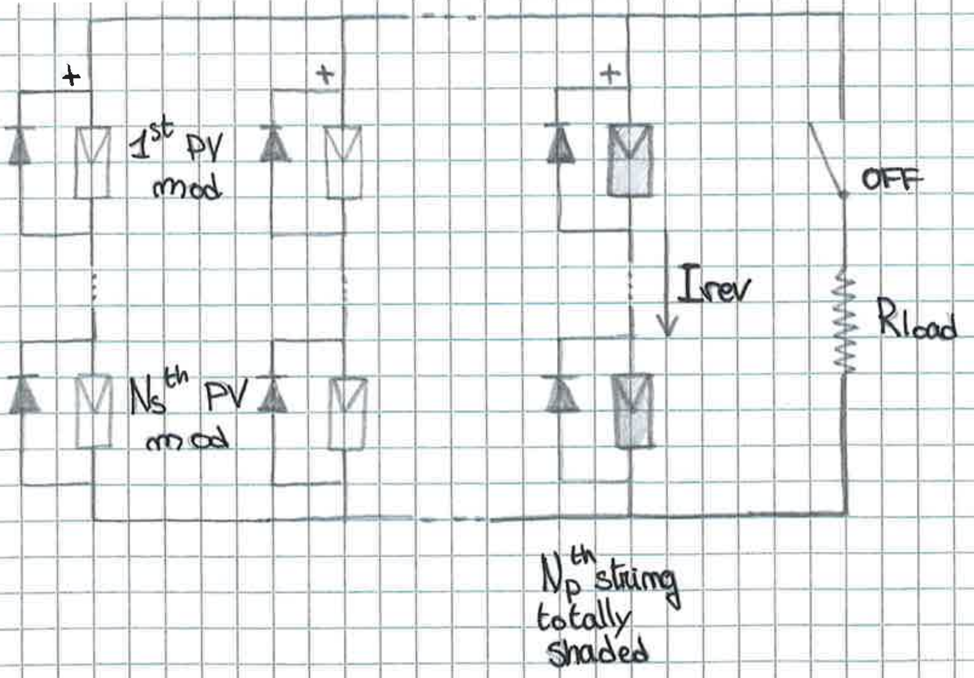
This definition is for a free-standing installation, in the future we will need a new definition of NOCT for BIPV, because it will be higher of several degrees.

$$T_c = T_a + \frac{NOCT - 20°C}{800\ W/m^2} \cdot G\,[W/m^2]$$

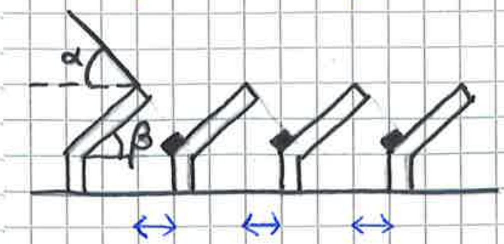
It's possible to avoid the blocking diode, because the installation causes losses?

In absence of Ds a shaded string will work passively and absorbs a reverse current.
The Irev becomes max during the no load operation.
The power losses by a complete shaded string during the normal running at MPP are negligible: this assumption is valid if there aren't short circuit failures between the modules.



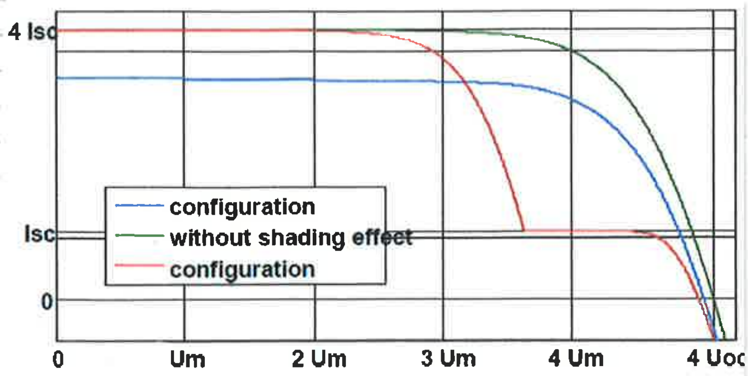


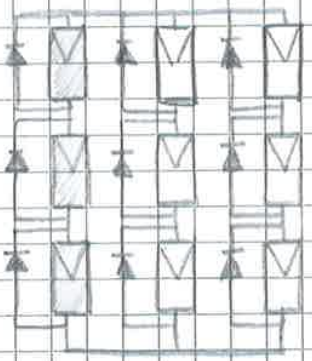
It maybe that also for a common configuration as for a flat roof ground level the shading effect occurs.



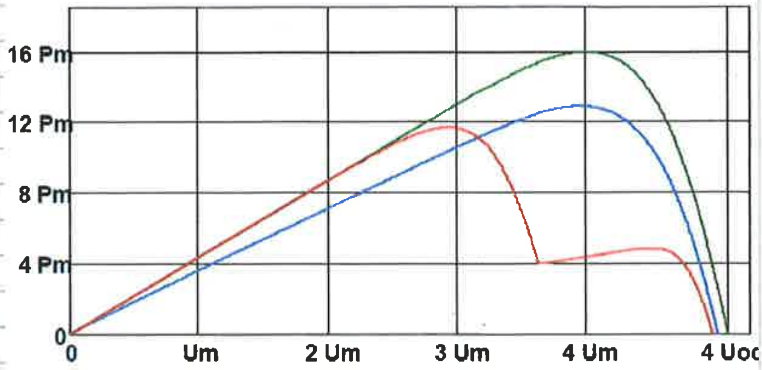
May be that the distance between the modules is not sufficient to avoid the shading effect.

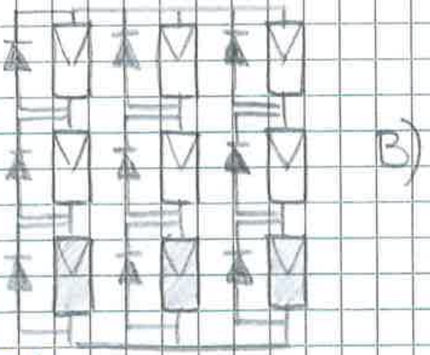
This figure shows the difference between the case in which is shaded a string or a module for each string.





A) in this configuration isnot necessary the Ds





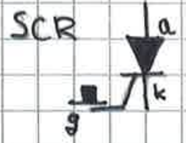
As we can see the case A) has the V_{mpp} equal to (4·V_{mpp}) the ideal condition, while the B) has the V_{mpp} very different from the normal condition c) ~ 3·V_{mpp}

The configuration A) provides more Power

THE OPERATING PRINCIPLE of INVERTER and MPPT

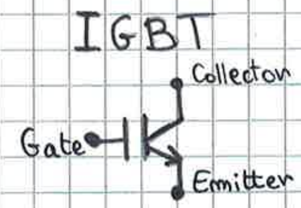
Older inverters were based on SCR silicon controlled rectifiers (or thyristors).

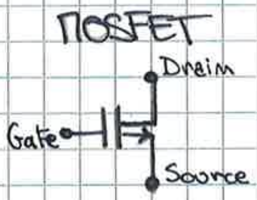
They were able to transfer the power from DC side to the AC side only with the line voltage (line commutated)
Thyristors in forward bias switch ON themselves only after a delay with respect to the reference signal: the reactive power is absorbed from the network; in addition these can't be controlled in the opening, but they are switched off only after the natural zero crossing of current.



Newer inverters uses the transistors.
They permit to generate the alternating waveforms and transfer power from DC side to AC side in absence of line voltage (SELF-COMMUTATED)

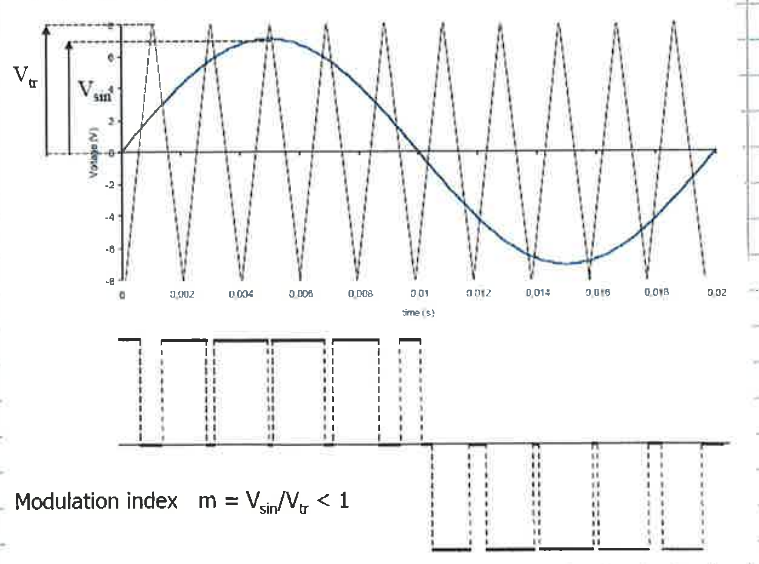
The power transistors (MOSFET and IGBT) are electronic switches, closing and opening controlled, with lead and lag angles in regards to a reference signal generated by a "clock" signal inside the converter. It's possible to have reactive power, INDUCTIVE or CAPACITIVE, with low armonic content waveforms





The transistors have low losses ($I_{GATE} \approx 0$) and the conduction losses
IGBT) $V_{C-E} \cdot i_C$
MOSFET) $R_{D-S} \cdot i_D^2$

Often the transistor ON/OFF mode is in accordance with the PWM technique (PULSE WIDTH MODULATION)
A comparison between a triangular waveform generated with a quartz clock (the carrier) and a sinusoidal waveform (the modulating) is implemented.



Modulation index $m = V_{sin}/V_{tr} < 1$

The carrier waveform has high frequency (1-100 kHz) while the modulating has 50 or 60 Hz.

Control parameters are the modulation index $m \leq 1$ and the phase angle of the modulating waveform.

If $m > 1$ (overmodulation) the conversion is irregular

The galvanic separation is obtained only with LF transformer (it's the electrical isolation between primary and secondary circuit).

The HF transformer has parasitic capacitance parameters between primary and secondary and they don't ensure the galvanic isolation

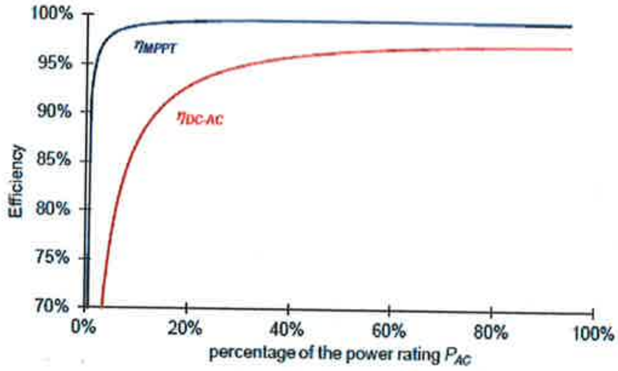
Typical specifications for grid-connected inverter:

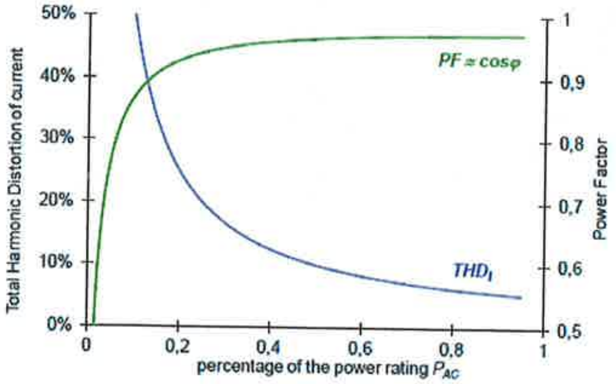
- high conversion efficiency ($\eta > 90\%$) and low noload losses
- power factor $PF = \cos\varphi > 0.9$
- low harmonic distortion ($THD < 5\%$)
- maximum-power-point tracking with high accuracy
- ability to limit the input power from PV generator shifting the operating point away from the MPP
- low ripple on the DC voltage
- automatic turn ON turn OFF with low irradiance thresholds.

The inverter with transistors is able to provide the active and reactive power in absence of line voltage

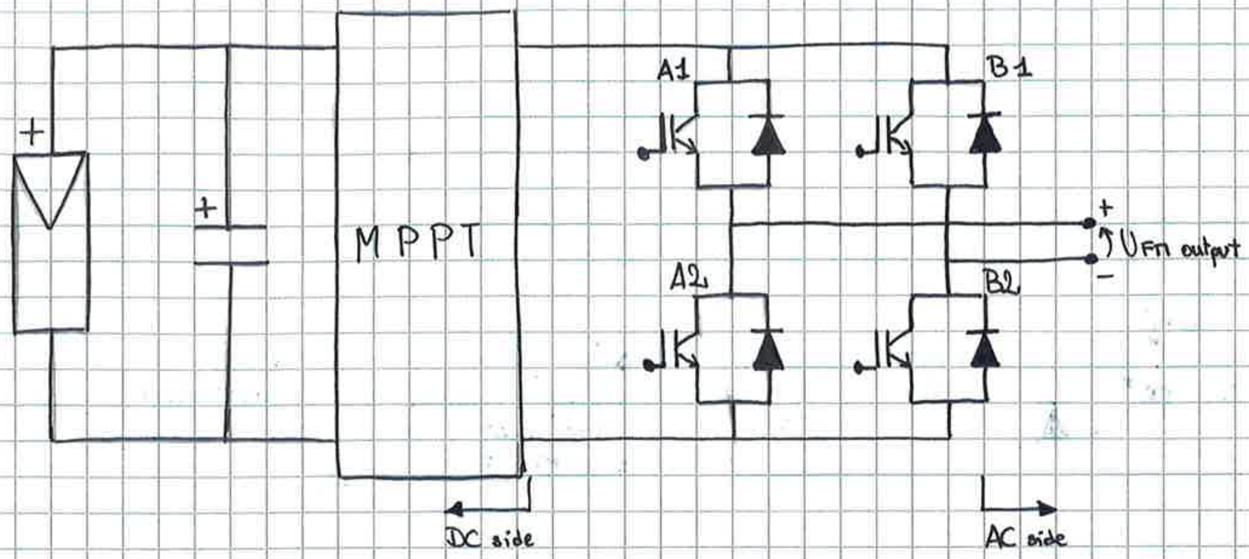
If the network is disconnected the inverter with MPPT, working at PF ≈ 1, is unable to provide the flow of active/reactive power required by the load. Voltage variations are induced.

These voltages disturbances are timely detected by the interface relay that turns OFF the inverter.





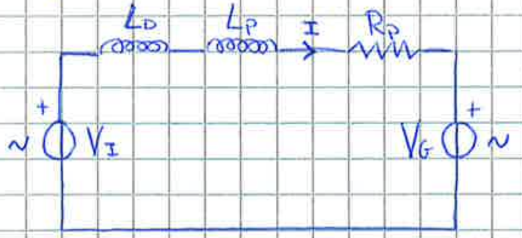
let's consider



if $V_{F\Pi} > 0$: A1 and B2 are connected to the output, without the diodes
$V_{F\Pi} = 0$: A1 without diode, B1 with diode
$V_{F\Pi} < 0$: B1 and A2 without diodes
$V_{F\Pi} = 0$: B1 without diode, A1 with diode
or B2 with diode, A2 without diode

$P_{AC} = \underbrace{V_{AC}}_{\text{grid voltage}} \cdot I_{AC} \cdot \cos\varphi$

L_P and R_P are parasitic parameters



The load angle β of the phasor $\bar{V}_I$ to ensure that the current phasor $\bar{I}$ is in phase with the voltage ~~value of~~ phasor $\bar{V}_G$

L_D is chosen on the design stage

$V_I I \cos\beta = V_G I + R_P I^2$

$V_I I \sin\beta = X_L \cdot I^2$

β: is the load angle between $V_{Inverter}$ and V_{Grid}, not φ (between V_G and I_G)

$P_I = V_I \cdot I_{AC} \cdot \cos\beta = P_{Grid} + R_P I_{AC}^2$

$P_I = \eta_{MPPT} \cdot P_{max} = V_G \cdot I_{AC} + R_P I_{AC}^2$

$Q_I = V_I I_{AC} \sin\beta = X_L \cdot I_{AC}^2$ $\qquad L_D \gg L_P \qquad X_L = \omega(L_D + L_P)$

$tg\beta = \frac{Q_I}{P_I} \qquad \beta = tg^{-1}\left(\frac{Q_I}{P_I}\right)$

HOW TO EVALUATE THE ENERGY

Therefore, a new meaning of symbols in the productivity formula is proposed.
The new procedure aims to reduce uncertainties in the energy assessment and includes two phases:
- two experimental tests;
- development of the environmental variables database;

As for the equivalent hour h_{eq} parameter the local agency for environmental protection (ARPA) provides the irradiance and the ambient temperature data

In order to evaluate the irradiance value at the tilt angle and the over-temperature losses in terms of a certain $K_{TEMP} = 1 + \gamma_p (T_c - 25°C)$ factor, a simple calculation can be performed

$$E_{AC} = P_n \cdot h_{eq} \cdot K_{TEMP} \cdot \eta_{PCU}$$

AUTOMATIC DATA ACQUISITION SYSTEM (ADAS)

ADAS is based on a DAQ board with 16-bit resolution, 8 differential channels, 50 kSample/s sampling rate per channel.
It's checked in the POLITO calibration laboratory.
ADAS is suitable for DC/AC measurements (DFT up to the 50th harmonic)
The ranges are extended to 1000 V_{pk} and 2000 A_{pk} with typical values of uncertainty

±0.1% for V
±0.5-1% for A
±0.6-1.1% for P
±2.5% for G

Experimental results and measurements

A calibrated solar cell is used as irradiance sensor. In order to determine the rated power P_n in operating conditions, measured IV curves are extrapolated to the STC

$$V_2 = V_1 - R_s (I_2 - I_1) - k I_2 (T_2 - T_1) + \beta (T_2 - T_1)$$

$$I_2 = I_1 + I_{sc1} \left(\frac{G_2}{G_1} - 1 \right) + \alpha (T_2 - T_1)$$

1) means measuring conditions
2) means STC

From the measurement $P_n \cong 18\ kW_p$, from the manufacturer $P_n \cong 20\ kW_p$

Some losses are yet contained in the measurement for example mismatch or losses in the cables

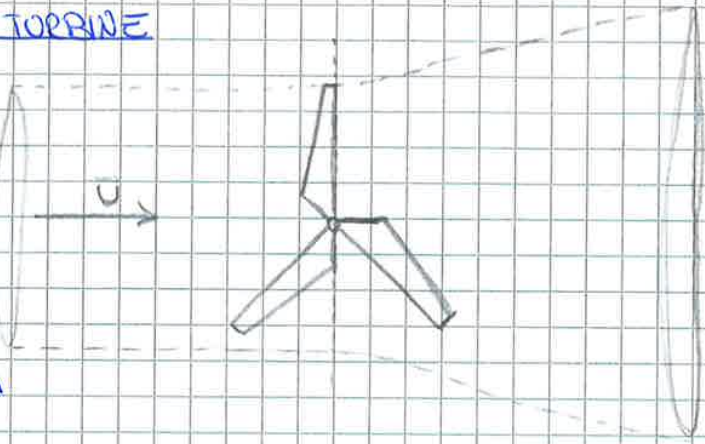
The expected power normally is $P_{EXP} = 92\% P_N$ if $P_n < P_{EXP}$ the experimentation isn't acceptable

WIND POWER

ENERGY CONVERSION in a WIND TURBINE

Regarding a horizontal-axis wind turbine, these phenomena occur in a stream tube with stationary flow:

1. surface expansion
2. kinetic energy ~~production~~ reduction
3. pressure increments before and after the blades



By applying Bernoulli's principle

$$\text{Energy} = \frac{1}{2} m u^2 + m g h + p \cdot Vol$$

m = mass
u = windspeed
g = gravitational acceleration
h = heigth
p = pressure
Vol = volume

$$\text{useful work} \approx \frac{1}{2} m u_1^2 - \frac{1}{2} m u_2^2$$

Continuity equation for mass $\dot{m} = cost = \rho \cdot u \cdot A = const$

An air mass, with density $\rho = 1,225\ kg/m^3$ (at sea level with 15°C), speed u through a cross section of area A has a Power density

$$\frac{P}{A} = \frac{1}{2} \rho u^3 \quad [W/m^2]$$

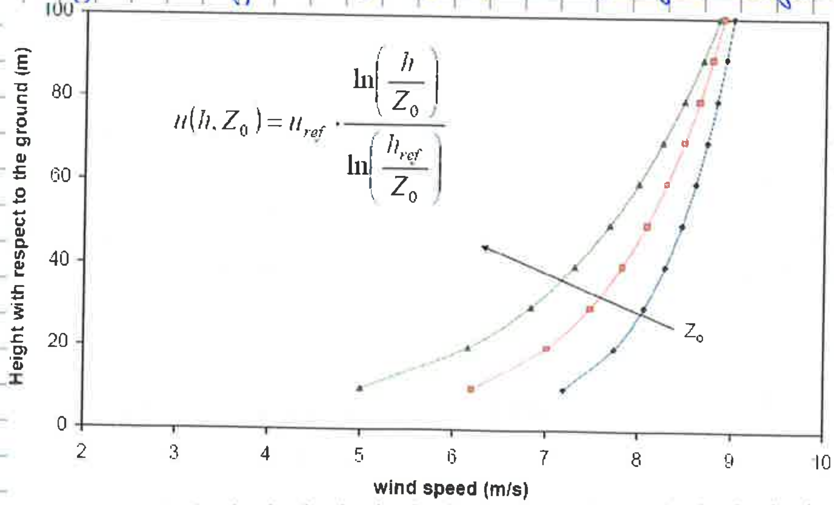
The air density is function of temperature T and pressure p; it decreases with rises in height with respect to the ground

$$\rho = \frac{p}{R_0 \cdot T}$$

$R_0 = 287,05\ \frac{J}{kg\,K}$ is the gas constant for dry air

The wind parameters are speed and directions; it's important to collect these datas and store it.

The data are transferred at the hub height, since wind speed depends on height, with positive increment (wind shear), and on terrain roughness (roughness height Z_0, low value for flat surfaces)



The maximum mechanical power of a HAWT horizontal axis wind turbine is imposed by the BETZ LIMIT

Before and after the blades the wind must conserve the q_m

$$\rho V_1 A_1 = \rho V_2 A_2$$

The force given to the rotor it's equal to the variation of q_m between before and after

$$F \cdot t = m \cdot (V_1 - V_2) \qquad F = \frac{m}{t}(V_1 - V_2) = q_m (V_1 - V_2)$$

where F is the horizontal force expressed by the wind to the blades, and so to the tower. The rotor power is

$P = F \cdot V = q_m \cdot V (V_1 - V_2)$ and doing the balance of the kinetic energy we found

$$P = q_m \left(\frac{V_1^2 - V_2^2}{2} \right) \quad \Rightarrow \quad V = \frac{V_1 + V_2}{2}$$

We can define an interference coefficient (of the rotor on the wind)

$a = 1 - \frac{V}{V_1}$ $\quad V = V_1(1-a)$ it's an index of how much the wind speed decreased passing through the blades.

$$V_2 = V_1 (1 - 2a)$$

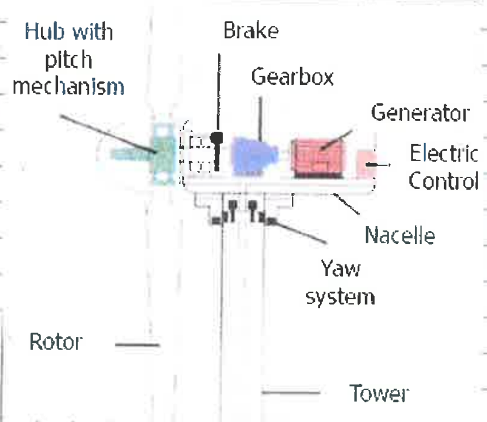
We can write

$$P = \rho A V_1 (1-a) \left(\frac{V_1^2 - V_1^2 (1-2a)^2}{2} \right) = \rho A V_1^3 \, 2a (1-a)^2$$

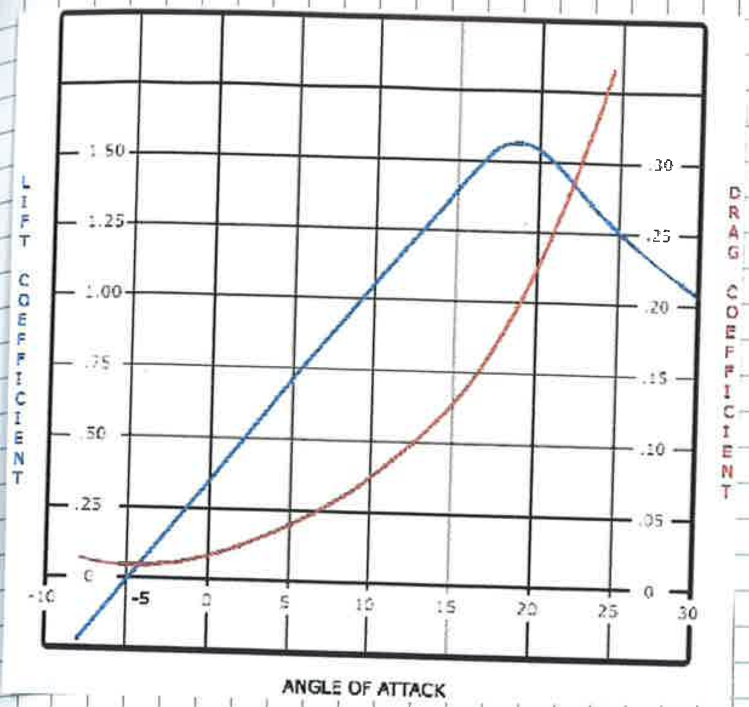
Searching for the maximum we find two values $a = 1$ (it means NO power) and $a = \frac{1}{3}$. After substitution of a $P = \frac{8}{27} \rho A V_1^3$, that is about $\frac{16}{27}$ of the theoric power ($\sim 59\%$)

Turbines are placed at heights up to 100 m with respect to the ground by TOWERS. The blades of fiberglass or carbon-fiber (with diameters 30-100 m) are designed so as to maximize the lift. The hub has to rotate the low-speed shaft (10-30 rpm) the gearbox must rotate the high speed shaft (1000-1500 rpm)

The high-speed shaft provides the torque to the electric generator. All the components are into the NACELLE.



Typical mechanicals regulations are: pitch control of the blades and yaw control. The pitch control can be towards the stall or the feather. The yaw control allows to follow the wind direction.

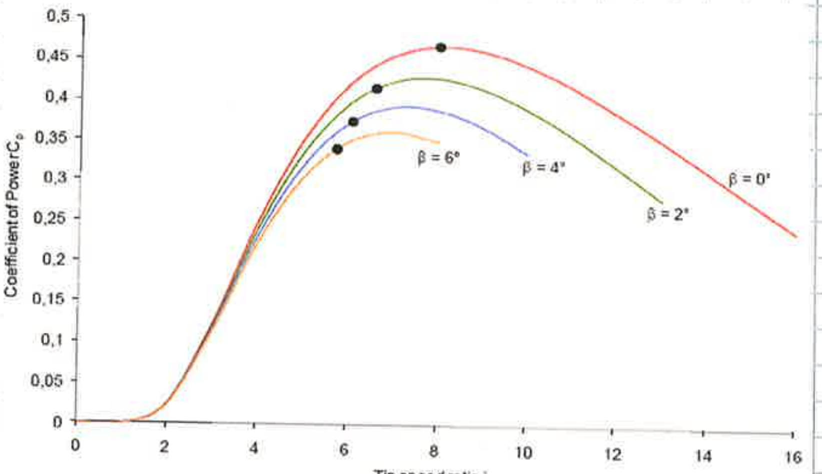


Now we have to define a relation between efficiency and the tip speed ratio: the COEFFICIENT OF POWER $C_p(\lambda)$

$$C_p = \frac{P_{mec}}{P_{wind}}$$

$$P_{wind} = \frac{1}{2}\rho A v^3$$

For $\alpha > 20°$ there are stall phenomenon



With wind at low-medium level it's better to optimize the efficiency, instead for increasing wind speed it's better to increase the torque

We can assume that $V = \omega r$ is constant, because ω is fixed due to the electric frequency of the grid (for a fixed-speed wind turbine)

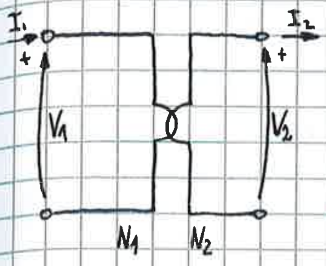
If we assume β constant (NO PITCH CONTROL), V constant and v increasing obviously also α increase; with high α there's STALL

ELECTRICAL ASPECTS

The electric machine is an induction generator with a squirrel cage rotor

The magnetic flux is $B \cdot S$ (induction · surface)

The equivalent circuit is similar to that of the triphase transformer



Ideal transformer

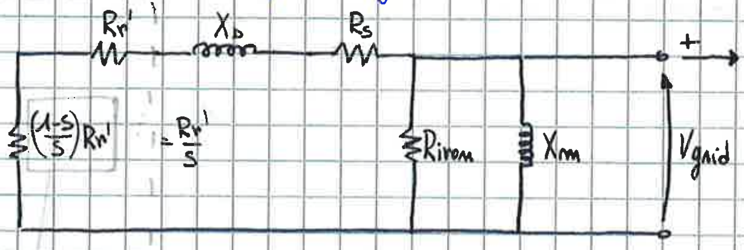
$t = \frac{N_1}{N_2}$ | $\frac{V_1}{V_2} = t$ $\frac{I_2}{I_1} = t$ $V_1 I_1 = V_2 I_2$

$\vec{B} = \mu \vec{H}$

$\vec{B}$: induction, $\vec{H}$: magnetic field

An induction machine is characterized by different causes of losses and non-idealities:

- Joule losses in the stator and rotor windings (can be represented by a resistance in series)
- leakage fluxes (inductive reactance in series)
- Iron losses due hysteresis and eddy currents (resistance in parallel)
- Remarkable magnetizing current (inductive reactance in parallel)



This is the simplified single phase equivalent circuit of an INDUCTION MACHINE

* this is a resistance that represents the resistance to the conversion

The iron losses and the magnetizing current are negligible

$$P_{iron} = 3 \frac{V_{grid}^2}{R_{iron}} \cong 0 \longrightarrow R_{iron} \cong \infty$$

$$I_m = \frac{V_{grid}}{X_m} \cong 0 \longrightarrow X_m \cong \infty$$

S is the SLIP

it measures the deviation of magnetic-field speed (Ω_0/p) with respect to the rotor speed (ω_{mec})

$$s = \frac{\frac{\Omega_0}{p} - \omega_{mec}}{\frac{\Omega_0}{p}}$$

where $\Omega_0 = 3000$ rpm

and p = pole pairs

p	Ω_0/p [rpm]
1	3000
2	1500
3	1000
4	750
5	600
6	500

If the induction machine is operating as a motor the slip range is from 0 to 1

$s=0$ means $\omega_{mec} = \frac{\Omega_0}{p}$ → NO load operation, NO TORQUE

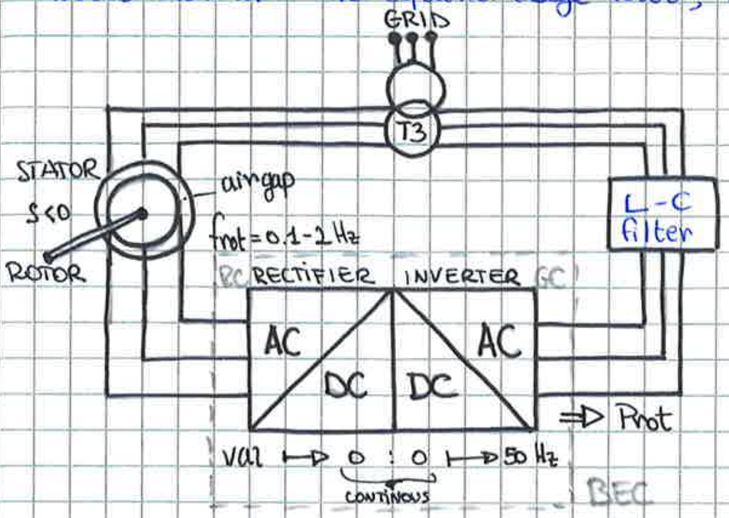
$s=1$ means $\omega_{mec} = 0$ → LOCKED ROTOR, starting condition

If it's operating as a generator the slip is less than 0 → super-synchronous operation

DOUBLY FED INDUCTION GENERATOR (DFIG)

Is the solution for the variable speed wind turbine

It works not with the squirrel cage rotor, but with a wound rotor (cost ⊕)



Both rotor and stator are connected to the grid (3-phase)

There are brushes to connect the rotor windings with the stator windings

f_{rot} is proportional to $\Omega s/p - \omega_{mec}$

We can have different slip but it's better to have slip close to 0

Higher Prot with negative slip

With this solution we have to add an APPARENT RESISTANCE to take into account the use of double converter

$$I_T = \frac{V_{fn}}{\sqrt{\left(R_s + \frac{R_r'}{s} + \frac{R_{app}'}{s}\right)^2 + X_D^2}}$$

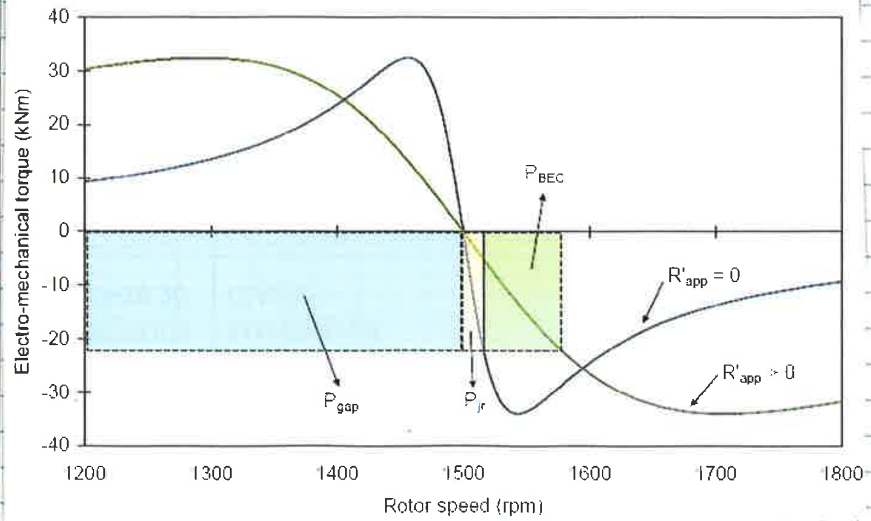
V_{fn} means phase-to-neutral $V_{ll} = \sqrt{3}\,V_{fn}$

but now

$$P_{gap} = 3\,\frac{R_r' + R_{app}'}{s}\,I_T^2$$

$$P_{mech} = 3\,\frac{1-s}{s}\,(R_r' + R_{app}')\,I_T^2$$

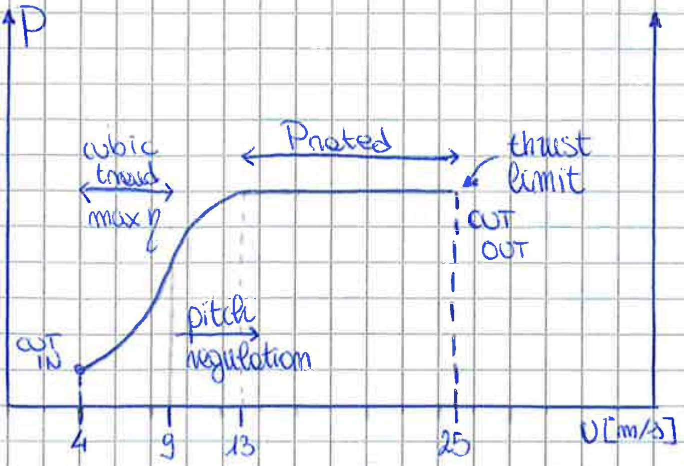
$$P_{BEC} = 3\,R_{app}'\,I_T^2$$

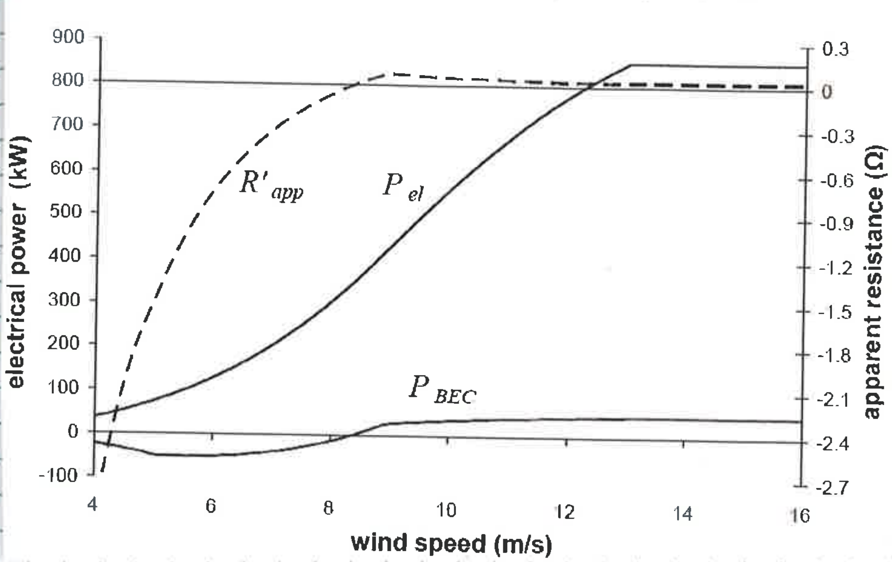


Increasing the resistance the stable region has a lower slope

The P_{BEC} is a power recovery into the grid

There's also another limit at about 25 m/s, the thrust limit, in which we have the max load for the tower



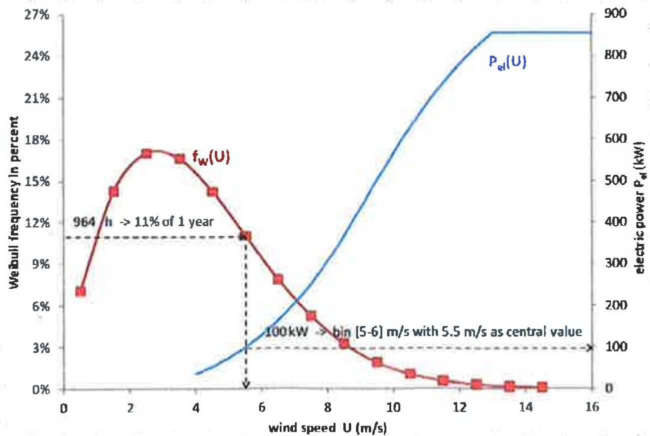


← The suitable BEC control by the apparent resistance for achieving the desired electrical power.

CALCULATION OF THE ENERGY PRODUCTION

$$E_{AC} \propto \sum_{k=4}^{25} P_k(U)$$ for every wind speed U

The turbulence of the wind causes a little loss in the Pmec, so the manufacturer provides a curve (for Pmec) that's calculated with a value of turbulence



$$E_{AC} = \underset{[h/y]}{8760} \cdot \sum_{k=4}^{25} P_k(U) \cdot f_w(U)$$

↳ Weibull distribution, it's the wind frequency

$$Y_{final} = \frac{E_{AC}}{P_{rated}}$$ it's a sort of equivalent hours of work at Pmax

$$CF = \frac{Y_{final}}{8760}$$ it's the capacity factor

to have a return on investment we need a CF > 15%

The calculation of energy production is performed by the product, for every wind speed, of the electric power and the wind frequency curve