Microrredes Eléctricas

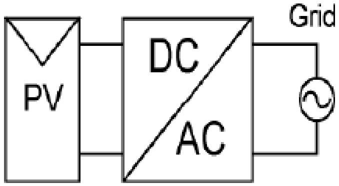
Distributed Energy Resources

1. PV Systems.
2. WT Generation
3. Battery Based Energy Storage Systems

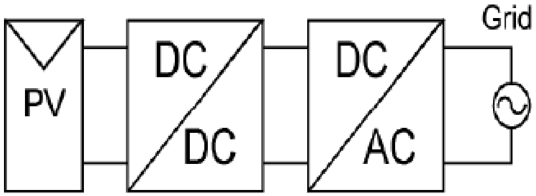
1. PV Systems

1. PV Systems

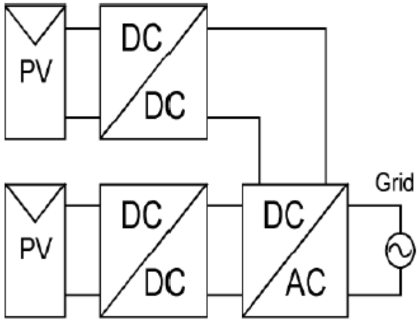
Clasification by number of Power Stages



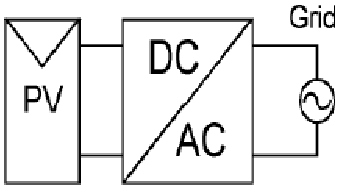
Single Stage Inverter



Two Stage Inverter

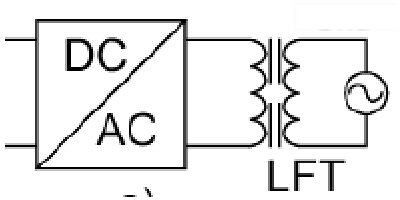


Multi String Inverter

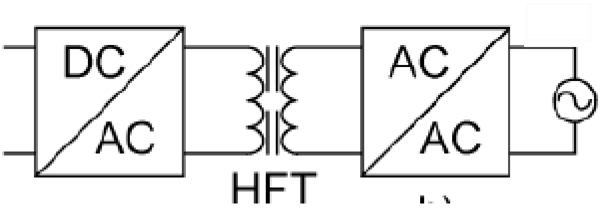


Transformerless

Transformer based



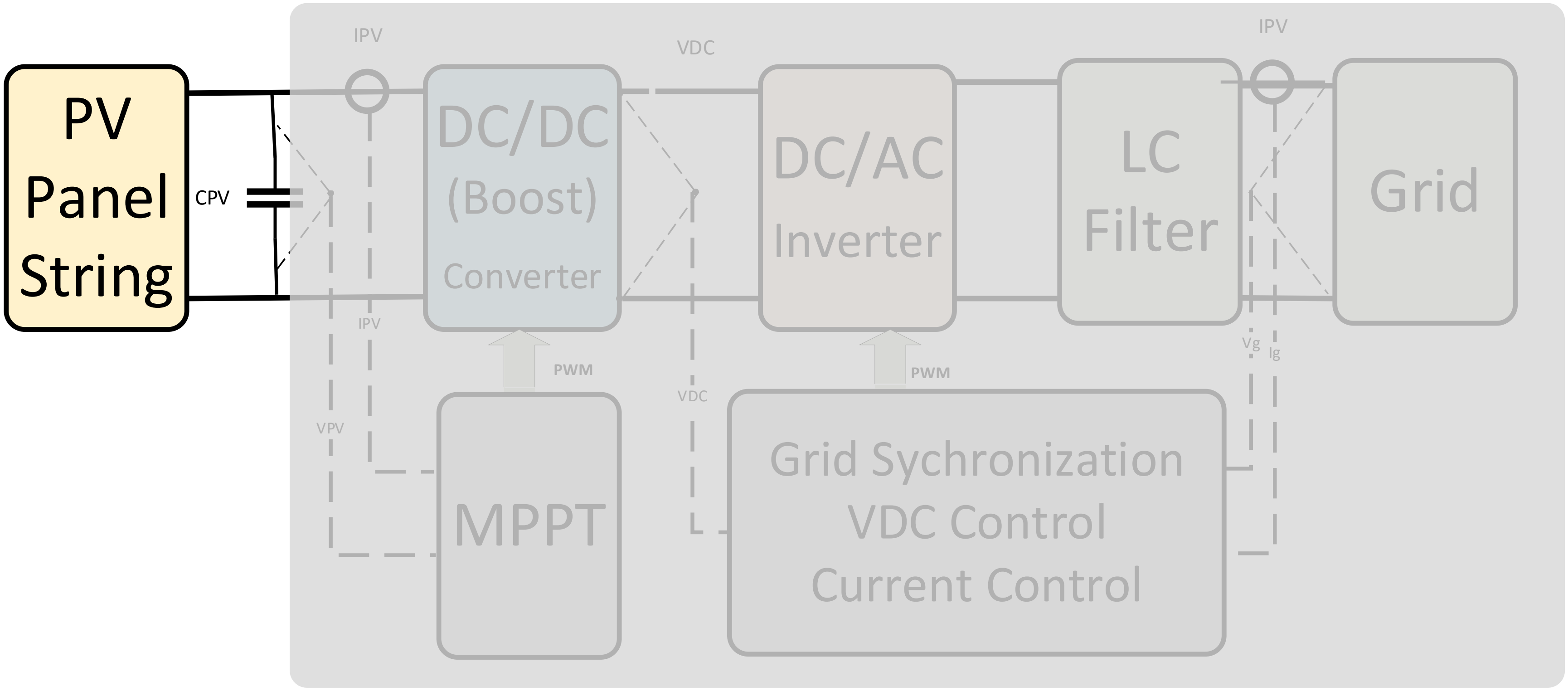
Low Frequency Transformer



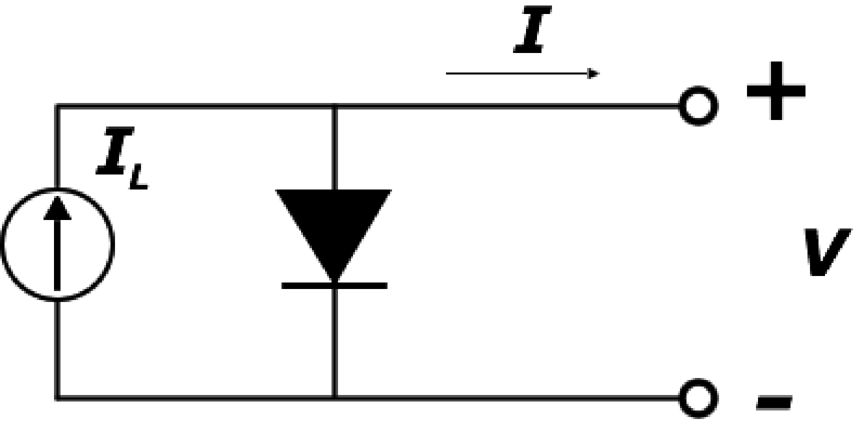
High Frequency Transformer

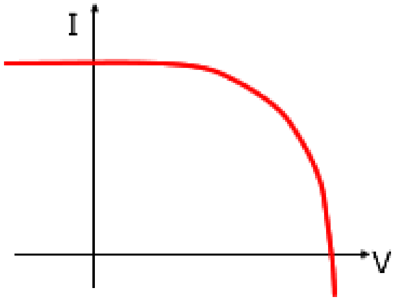
Figures from [1]

General Structure of a PV Inverter.



Model of a PV Cell.





$$I = I_L - I_O\left[\exp\frac{eV}{KT_C} - 1\right]$$

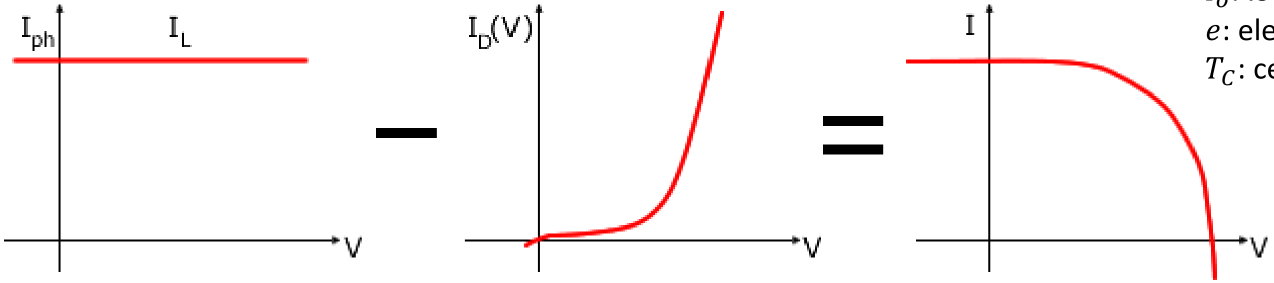
$I_L = I_{ph}$: Photons current.

K: Boltzmann's constant (1.3806503 × 10-23 J/K),

I_o: is the saturatuion current of the diode.

e: electron charge (1.60217646 × 10-19 C).

T_C: cell's operating temperature in degree Kelvin.

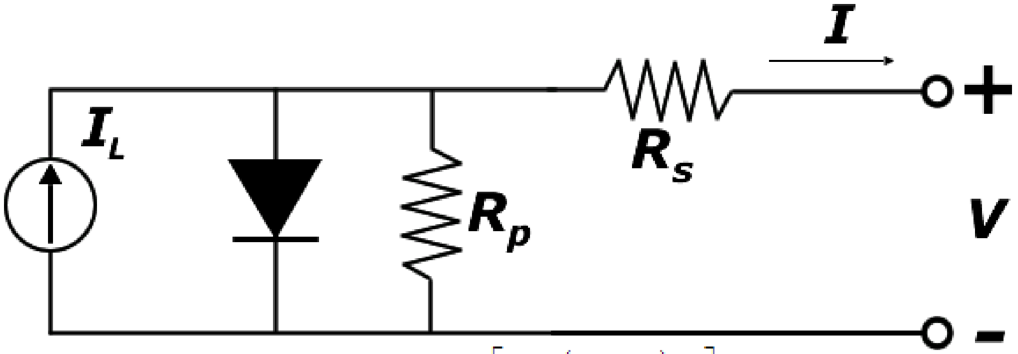


$$I_{ph} = I_L$$

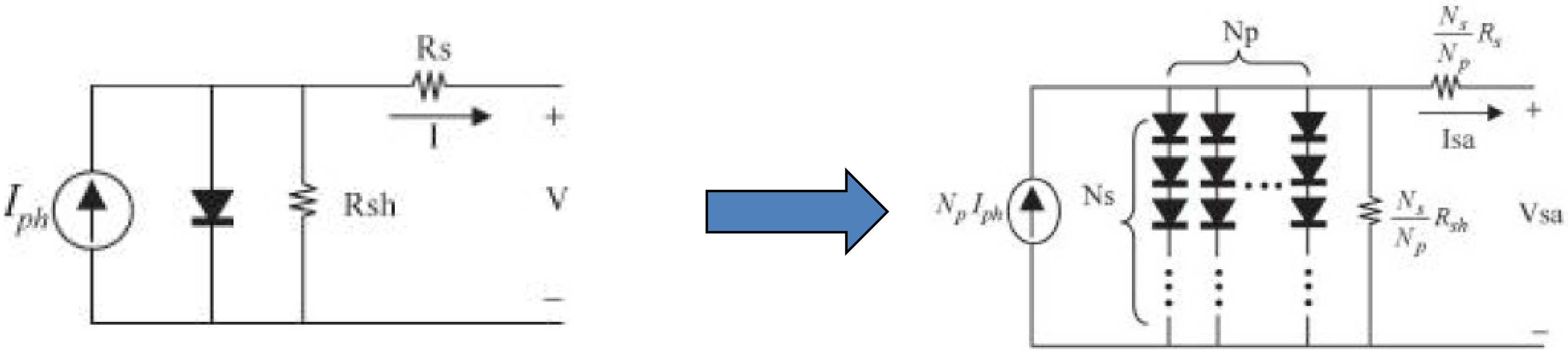
$$I_D(V) = I_O\left[\exp\frac{eV}{KT_C} - 1\right]$$

$$I = I_L - I_O\left[\exp\frac{eV}{KT_C} - 1\right]$$

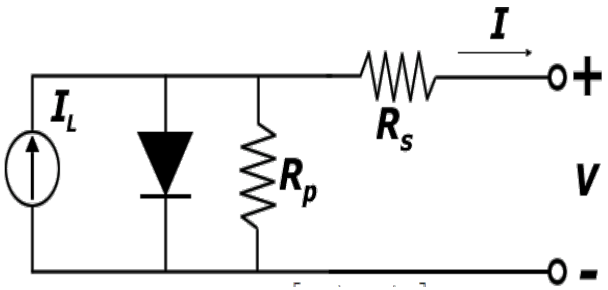
Model of a PV panel, and a PV panel Array.

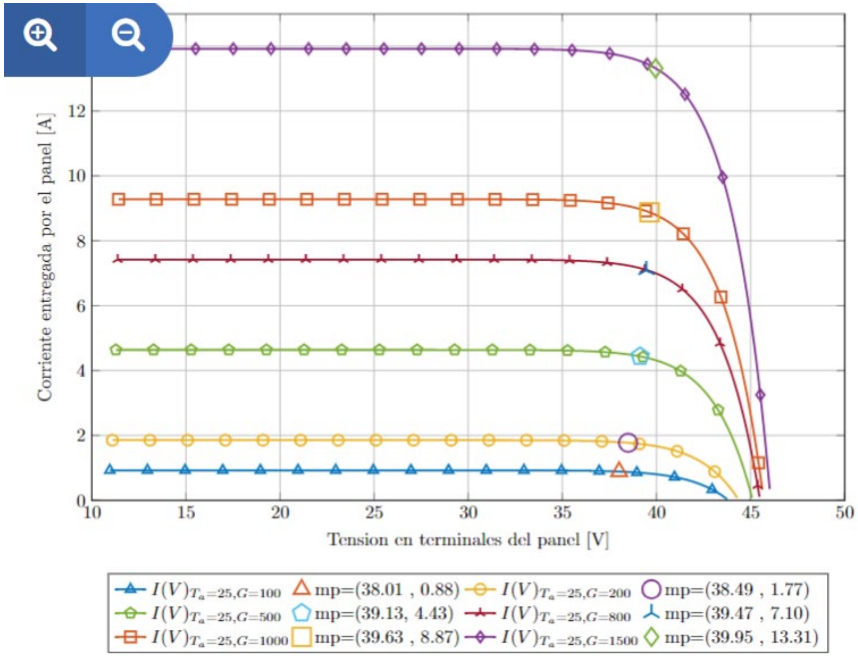


$$I = I_L - I_O\left[\exp\frac{e(V+IR_S)}{KT_C} - 1\right] - \frac{V+IR_S}{R_P}$$



Hands-on 1: Model of a PV Panel.





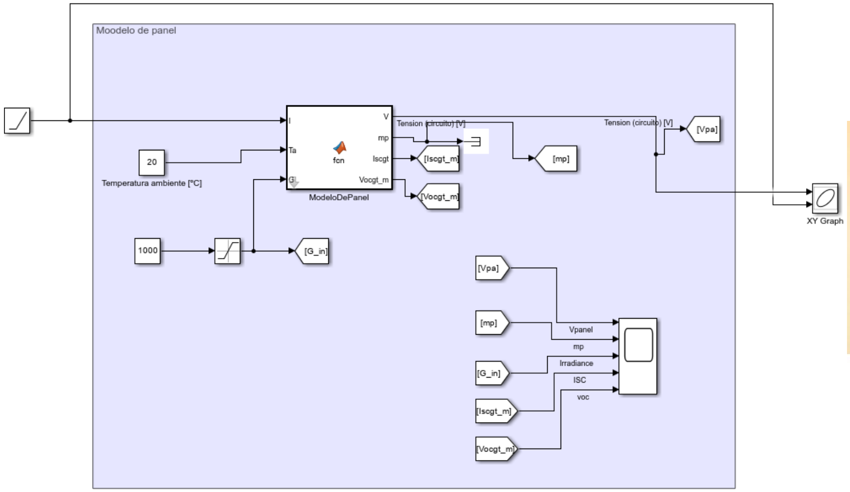
Explicit model proposed in [2].

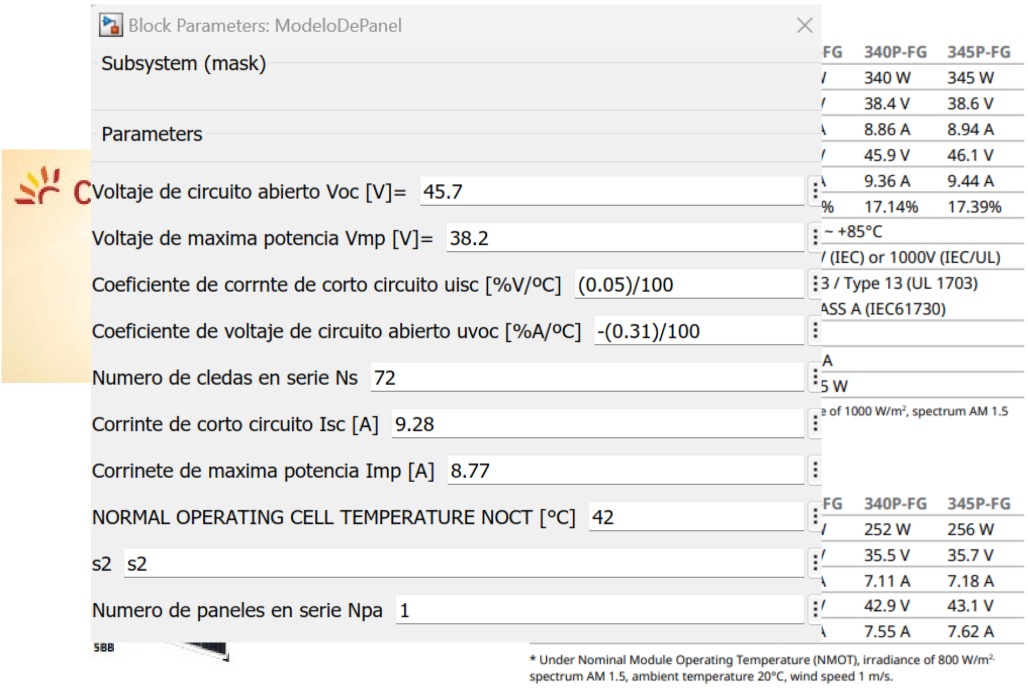
$$V = V_{oc}(T,G)\left(1 - \frac{I}{I_{sc}(T,G)}\right)^{1/s}$$

Hands-on 1 Model of a PV Panel.

KuDymond

CS3U-335|340|345P-FG





Block Parameters: ModeloDePanel

Subsystem (mask)

Parameters

Voltaje de circuito abierto Voc [V]= 45.7

Voltaje de maxima potencia Vmp [V]= 38.2

Coeficiente de corrnte de corto circuito uisc [%V/ºC] (0.05)/100

Coeficiente de voltaje de circuito abierto uvoc [%A/ºC] -(0.31)/100

Numero de cledas en serie Ns 72

Corrinte de corto circuito Isc [A] 9.28

Corrinete de maxima potencia Imp [A] 8.77

NORMAL OPERATING CELL TEMPERATURE NOCT [°C] 42

s2 s2

Numero de paneles en serie Npa 1

FG	340P-FG	345P-FG
/	340 W	345 W
/	38.4 V	38.6 V
\	8.86 A	8.94 A
/	45.9 V	46.1 V
\	9.36 A	9.44 A
%	17.14%	17.39%

~ +85°C

/ (IEC) or 1000V (IEC/UL)

3 / Type 13 (UL 1703)

ASS A (IEC61730)

A

5 W

e of 1000 W/m², spectrum AM 1.5

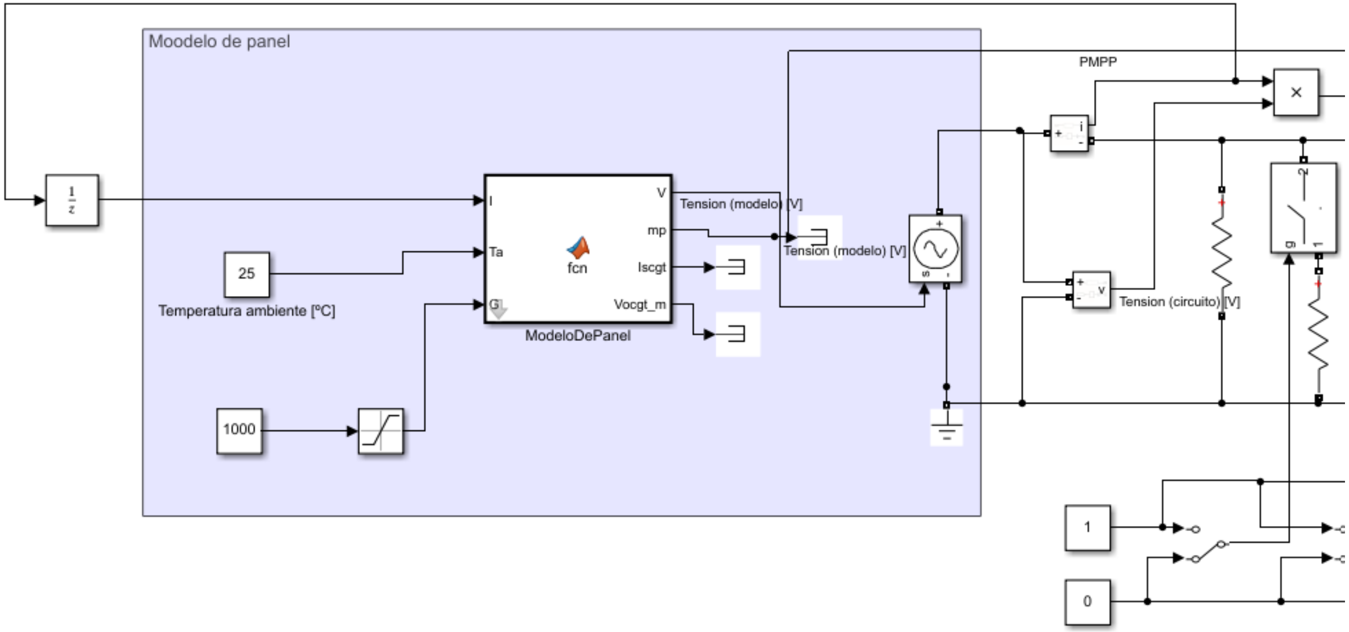
FG	340P-FG	345P-FG
/	252 W	256 W
/	35.5 V	35.7 V
\	7.11 A	7.18 A
/	42.9 V	43.1 V
\	7.55 A	7.62 A

5BB

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

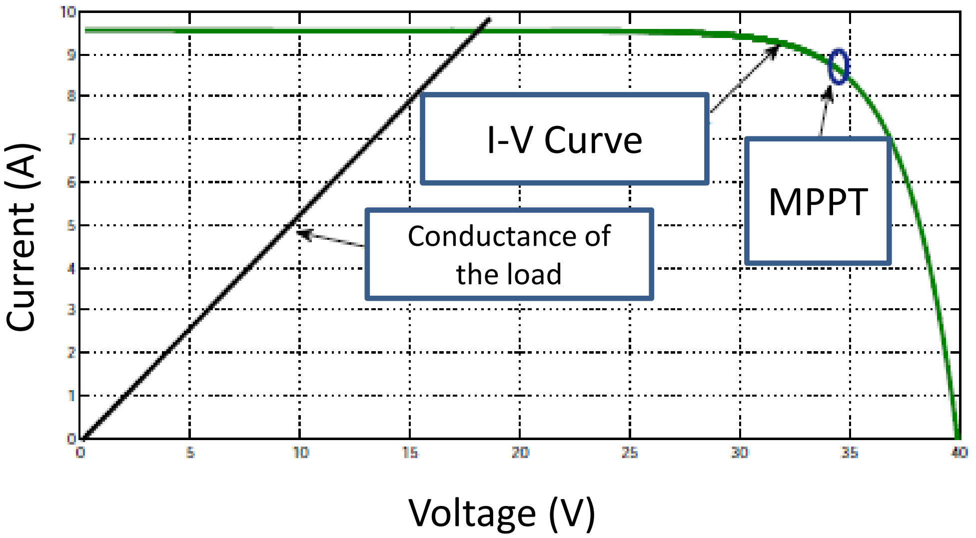
Simulation1 File.

Hands on Simulation 2.



Simulation2 File.

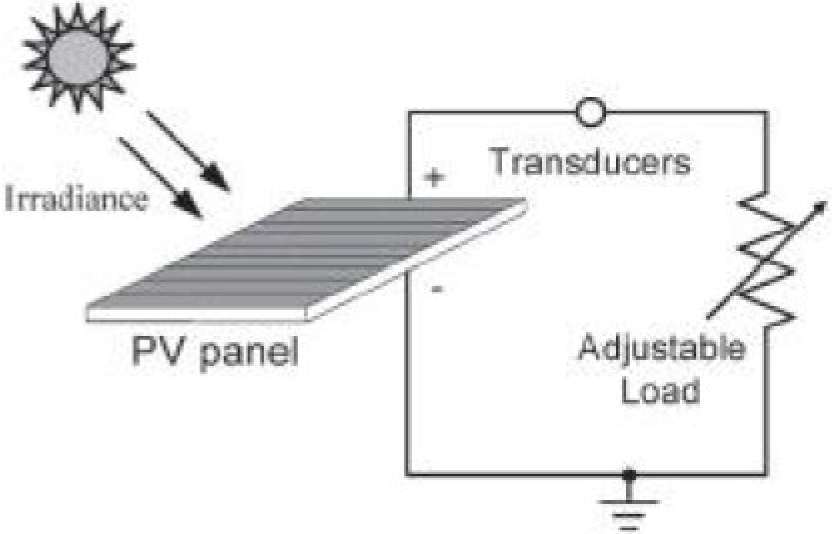
Hands-on PV panel connected to a load.



I-V Curve

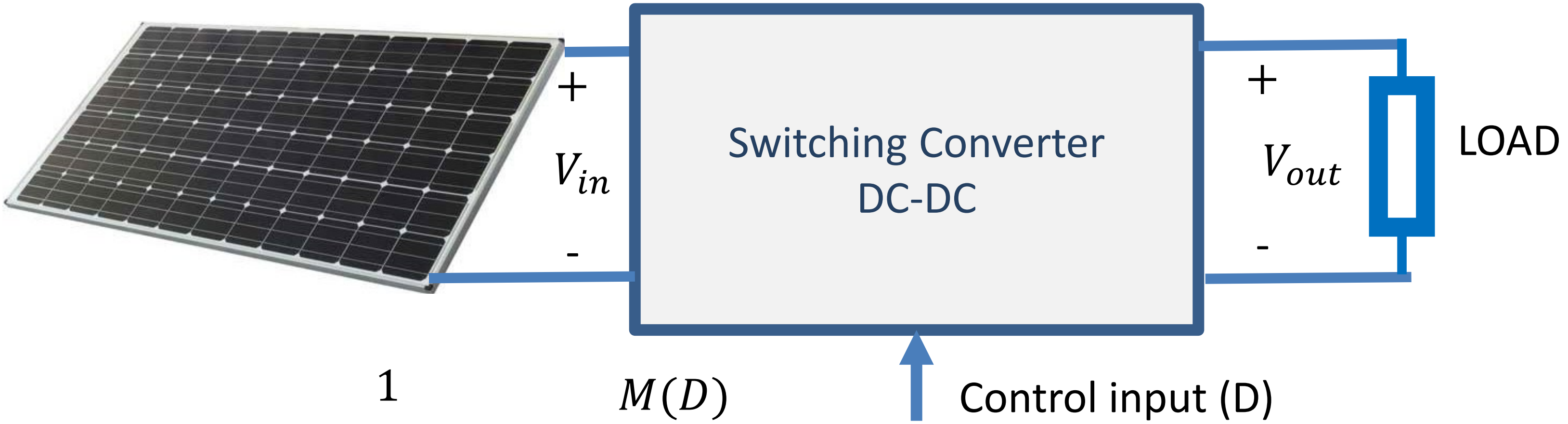
Conductance of the load

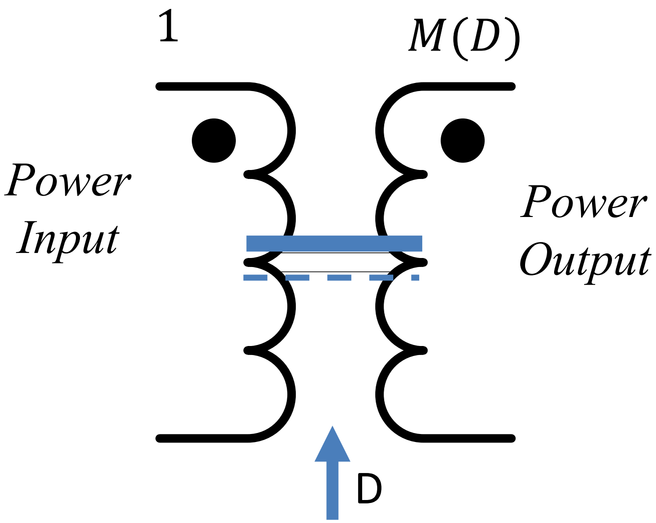
MPPT



PV panel – Load Coupling.

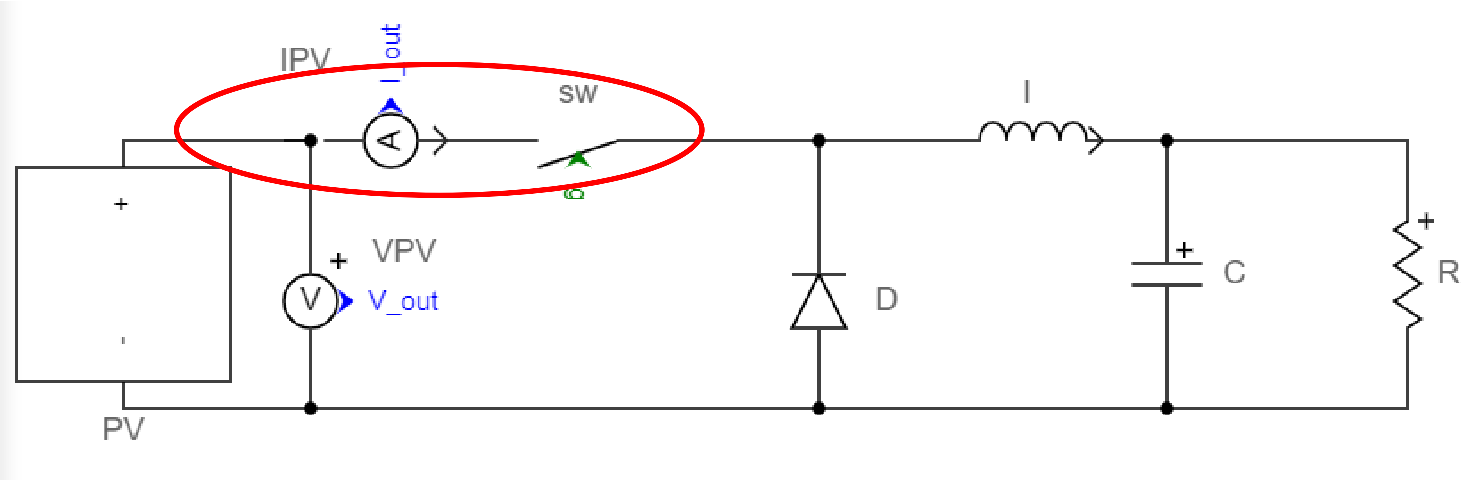
$$V_{out} = M(D)V_{in}$$



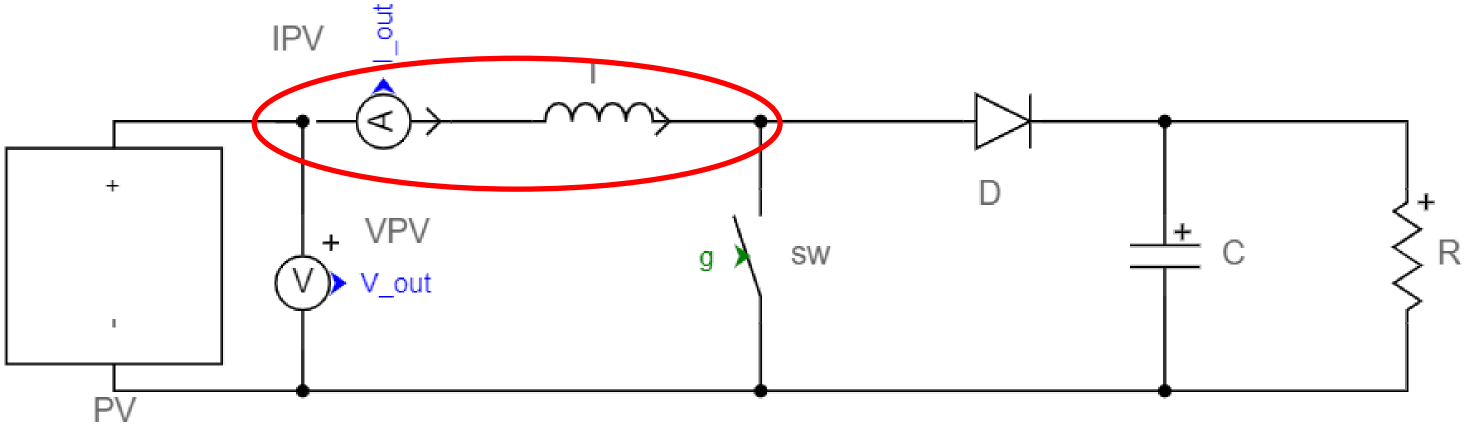


DC/DC Converters Topologies.

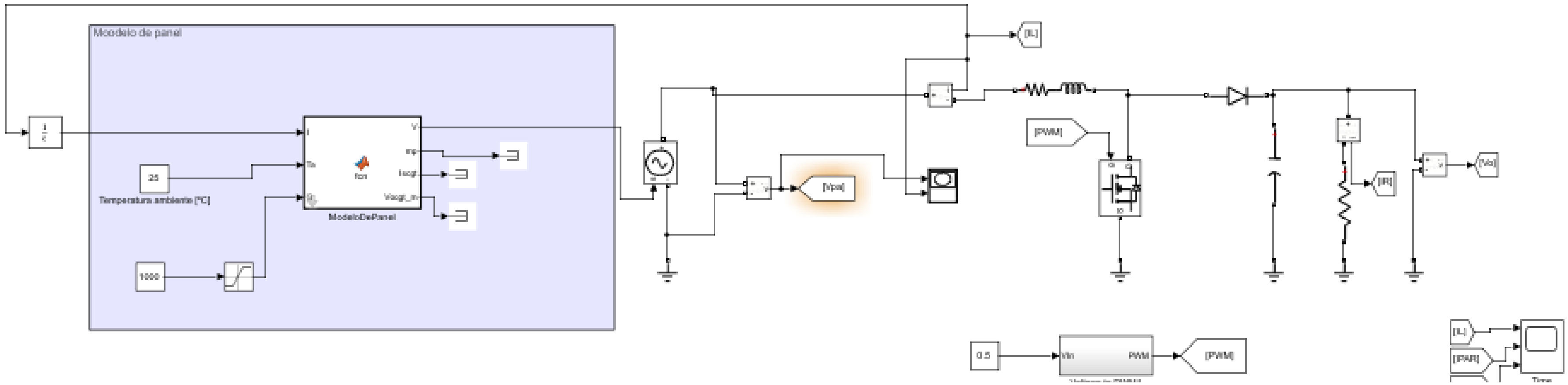
Buck



Boost

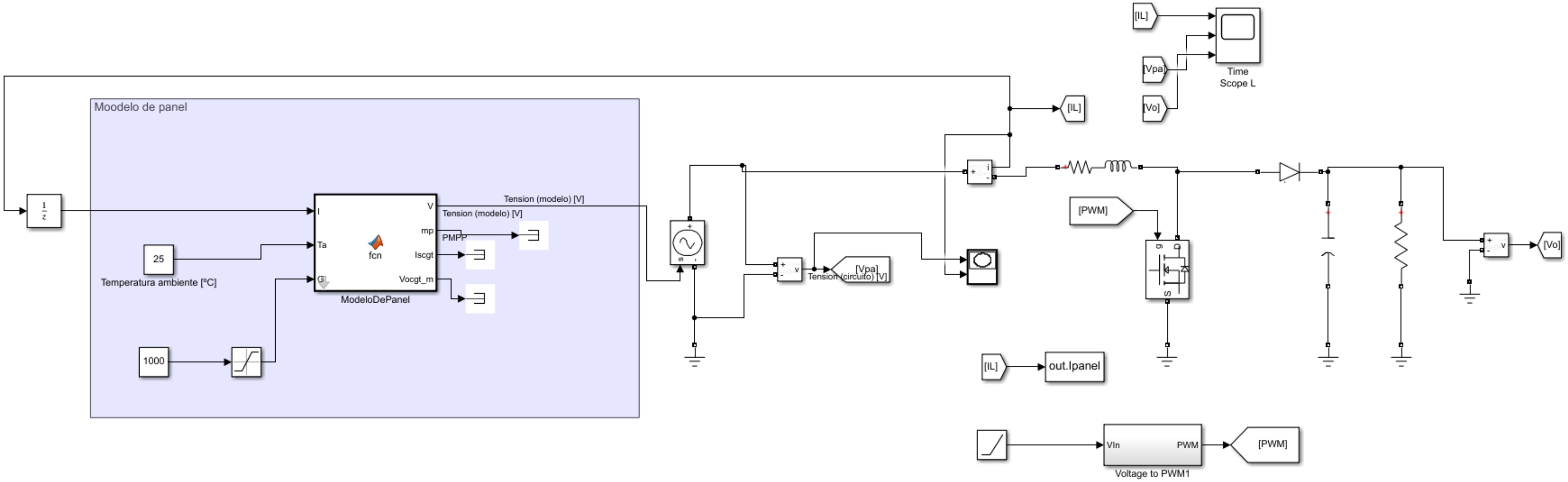


Hands-on Simulation 3.



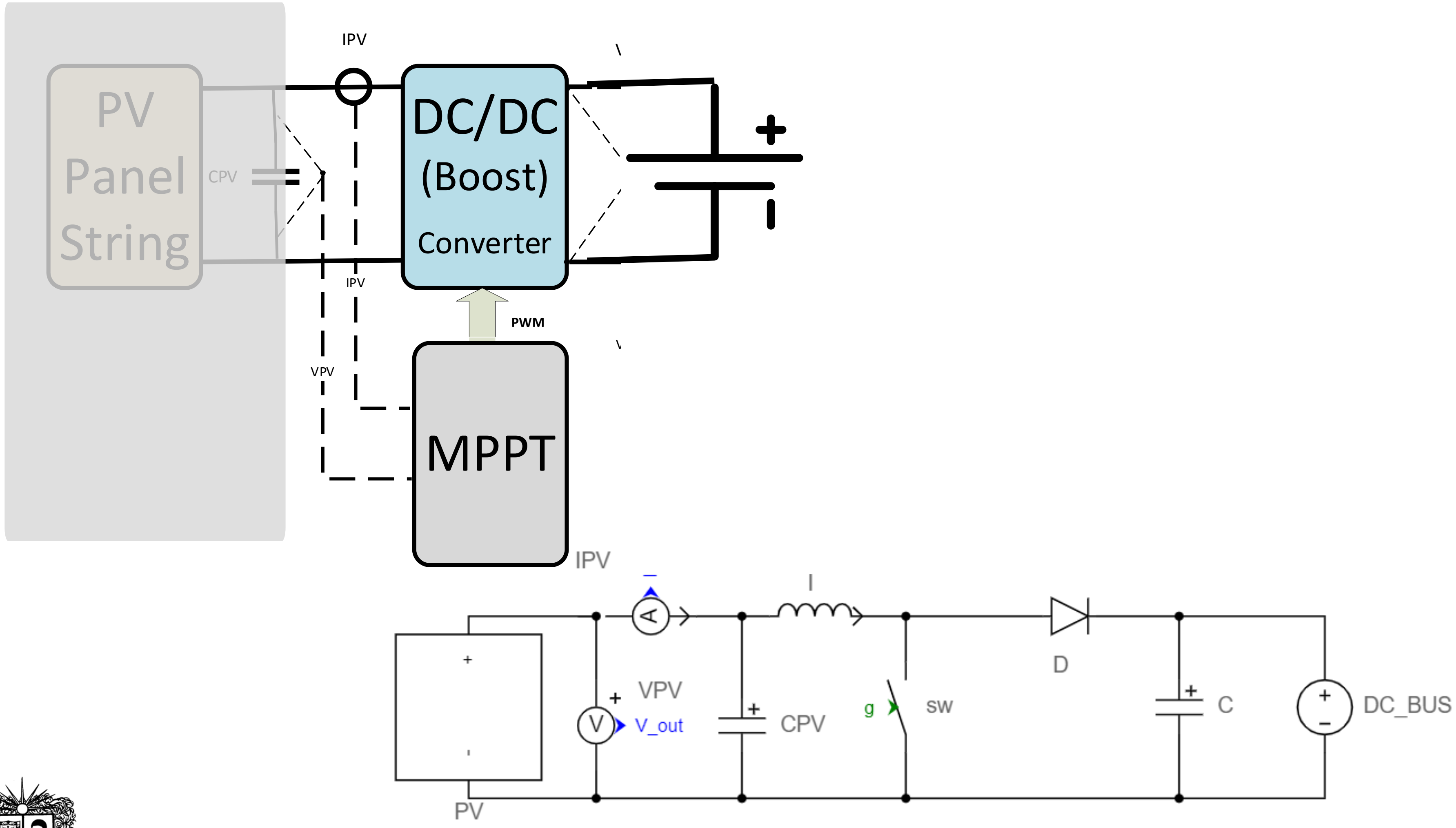
Simulation3 File.

Hands-on Simulation 4.

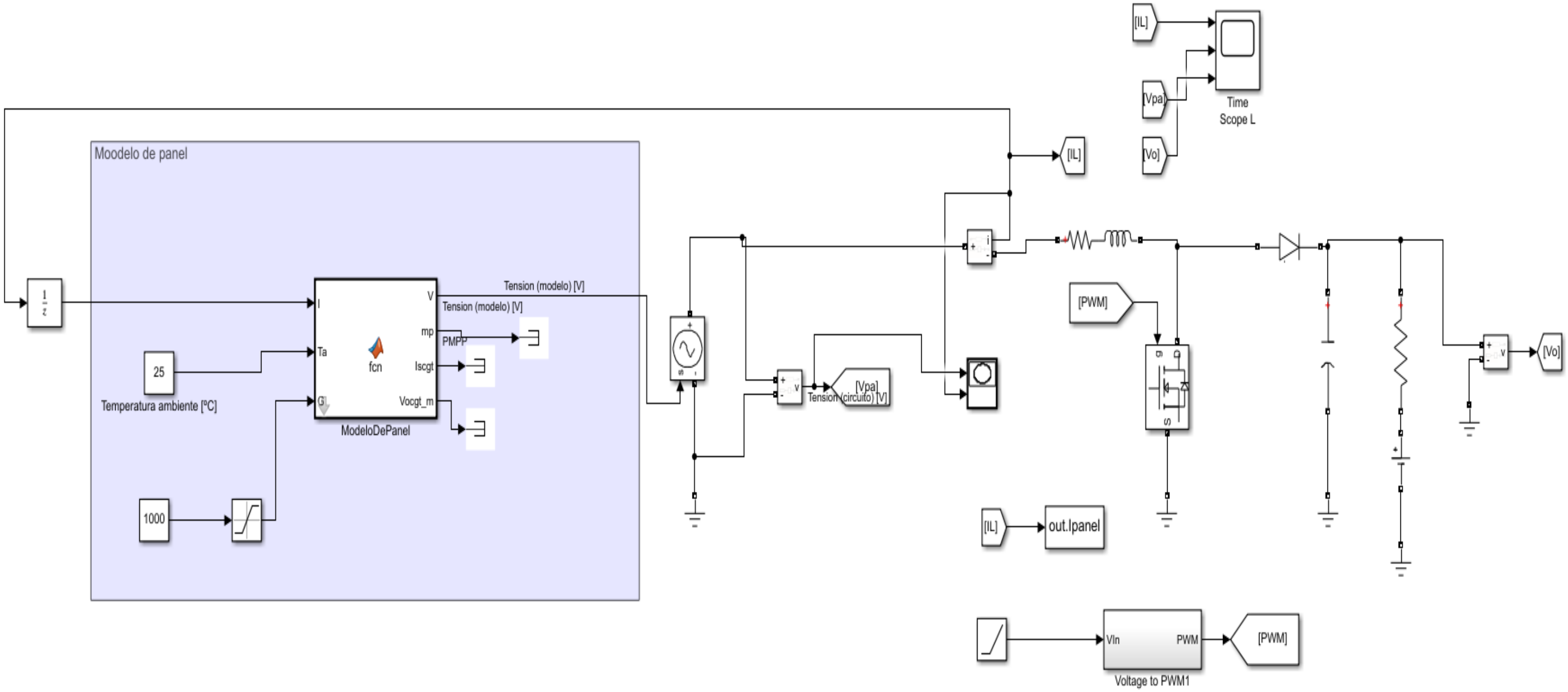


Simulation4 File.

General Structure of a Typical PV Inverter.

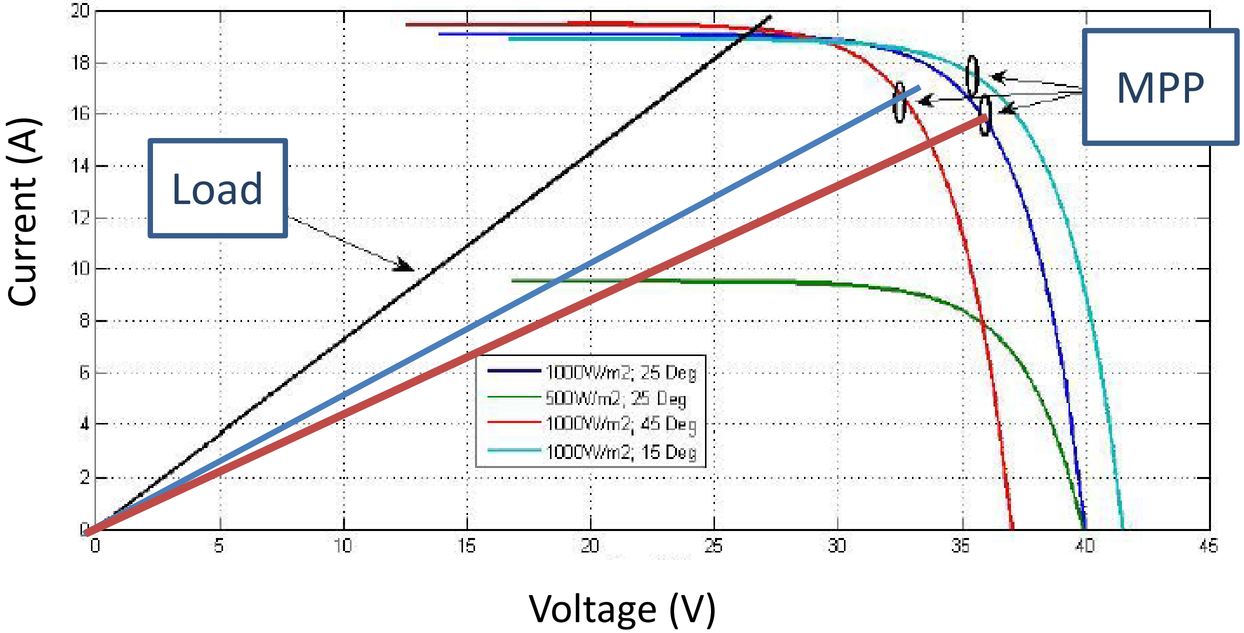


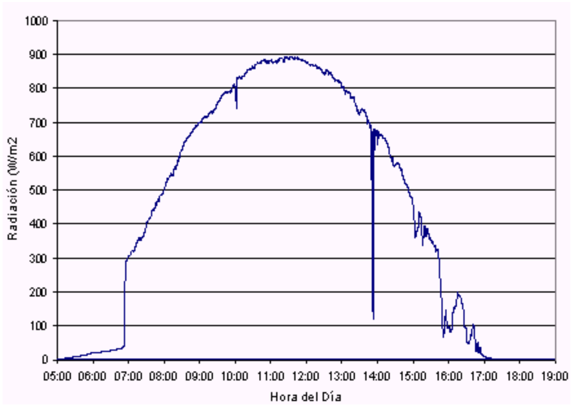
Hands-on Simulation 4B.

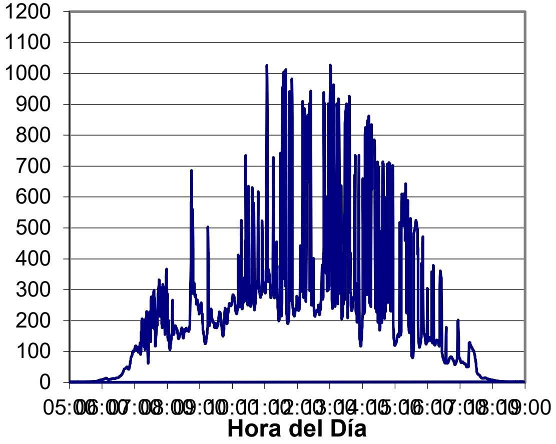


Simulation4B File.

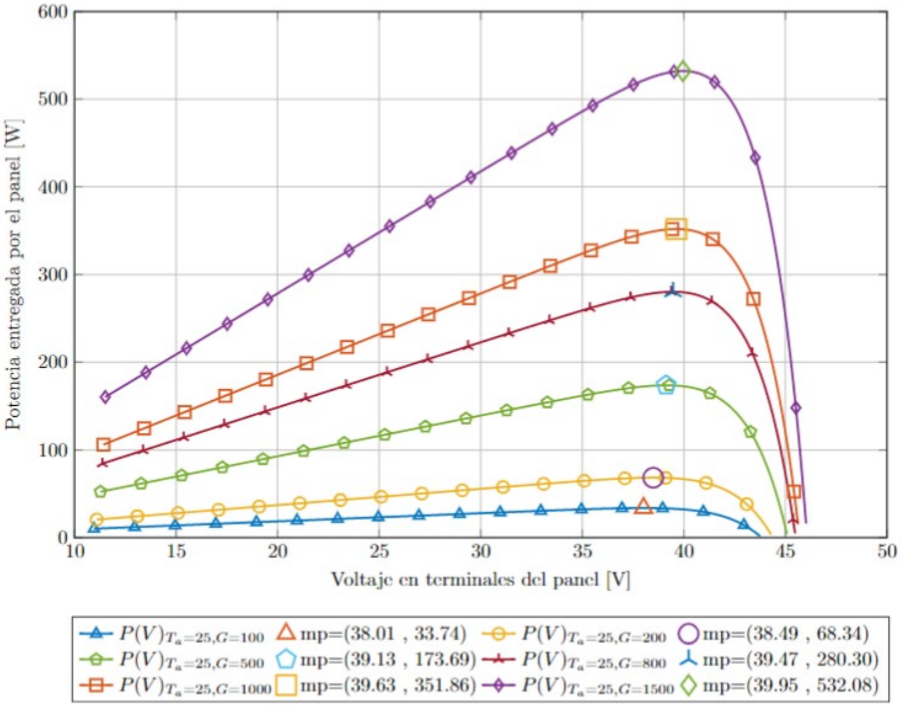
Maximum Power Point Tracking





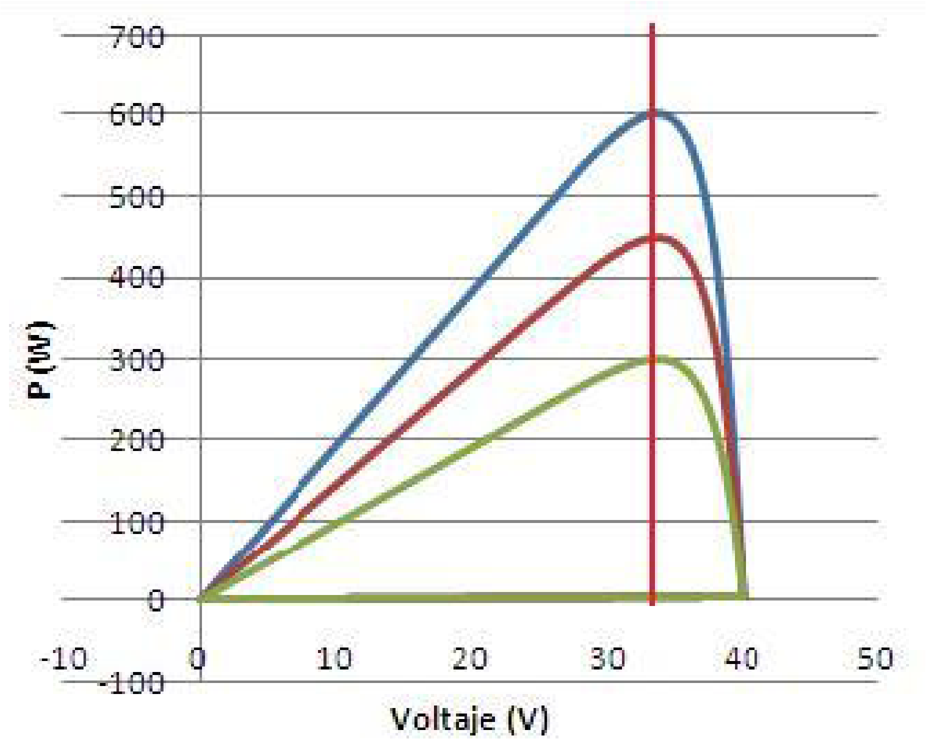


Maximum Power Point Tracking MPPT



Seeking Algorithms
Perturbation and Observation
(P&O)

Maximum Power Point Tracking

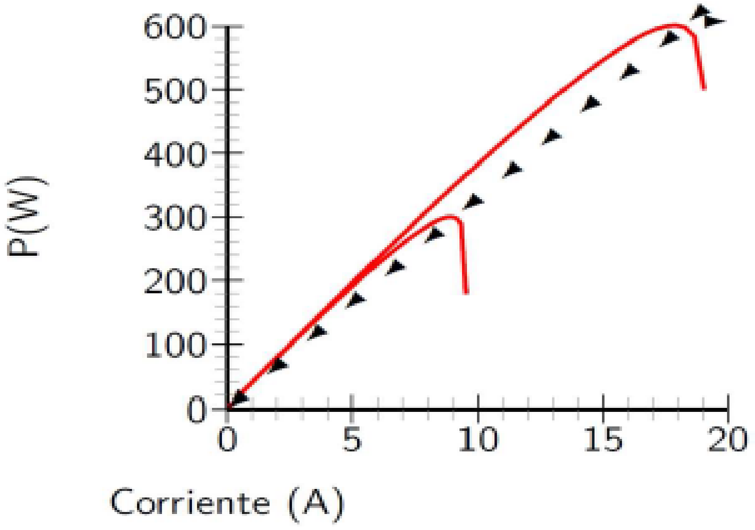


Fractional Open-Circuit Voltage (FOCV) Technique In this technique, can be calculated from the empirical relationship

$$V_{PMP} = kV_{oc}; \quad k < 1$$

The value of k varies between 0.78 and 0.92.

Maximum Power Point Tracking



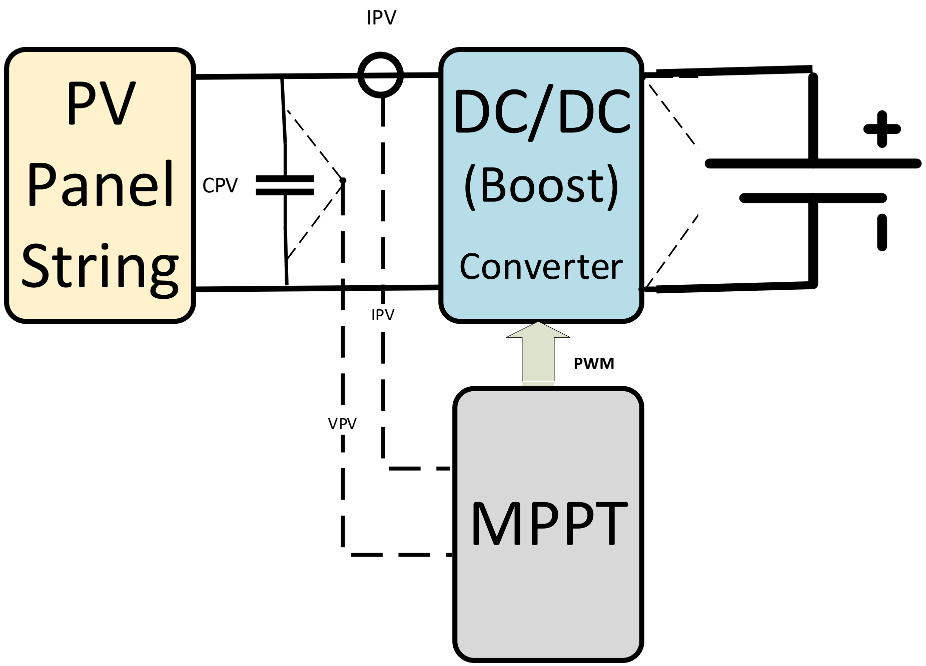
Fractional Short-Circuit Current (FSCI) Technique In this technique, can be calculated from the empirical relationship

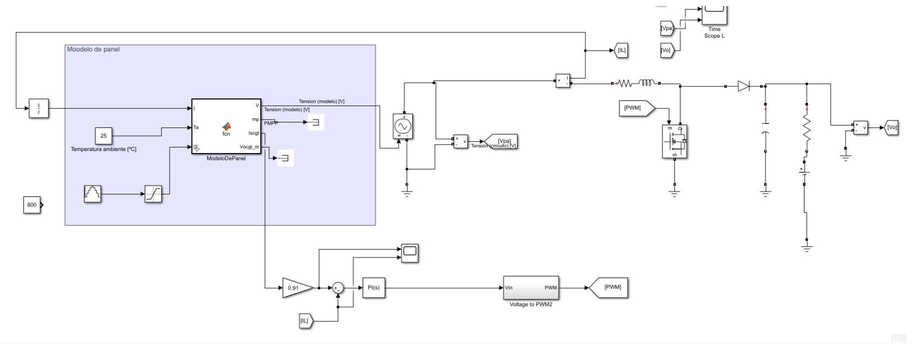
$$I_{PMP} = kI_{SC};\quad k < 1$$

The value of k varies between 0.8 and 0.96

More details in [3]

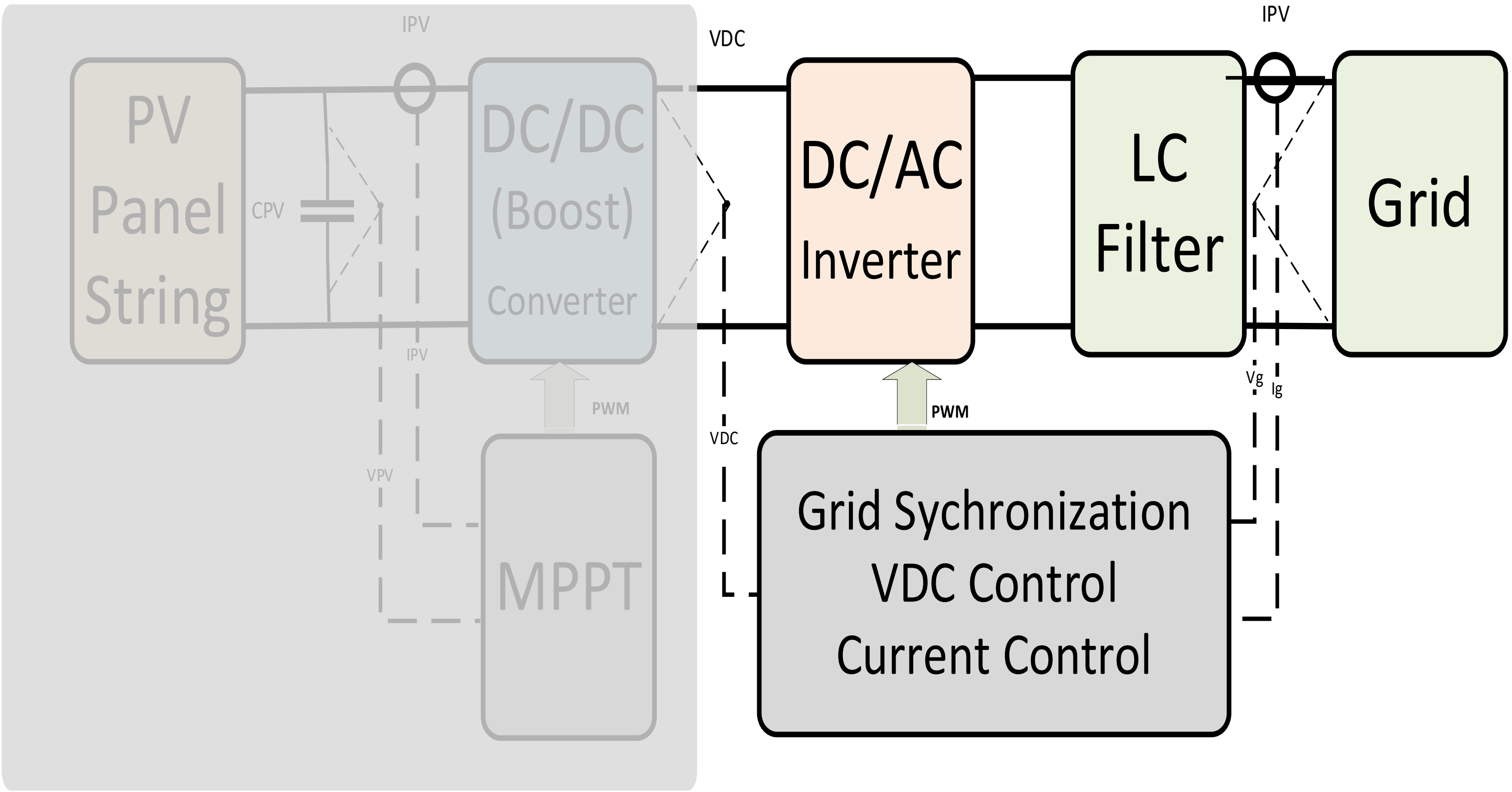
Hands-on Simulation.





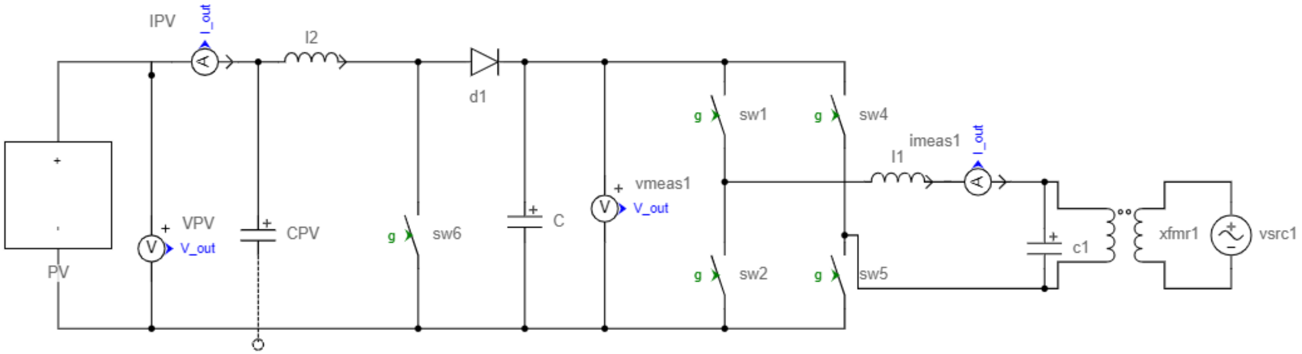
Simulation5 File.

General Structure of a PV Inverter. (DC/AC Side)

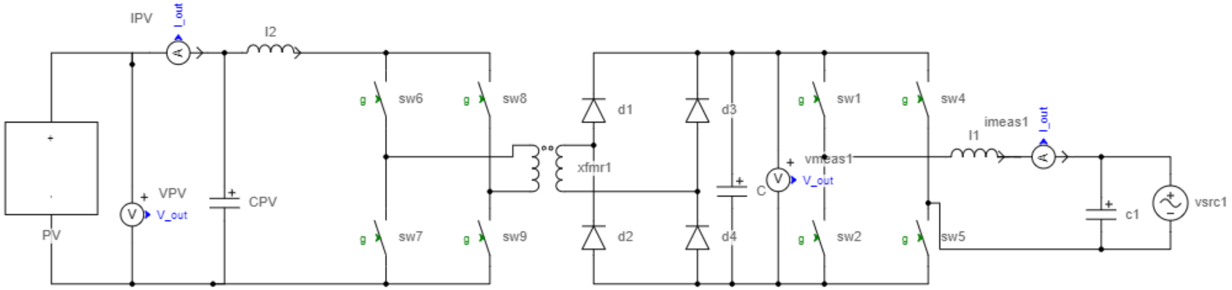


Typical Trasformer based PV Inverter Structures.

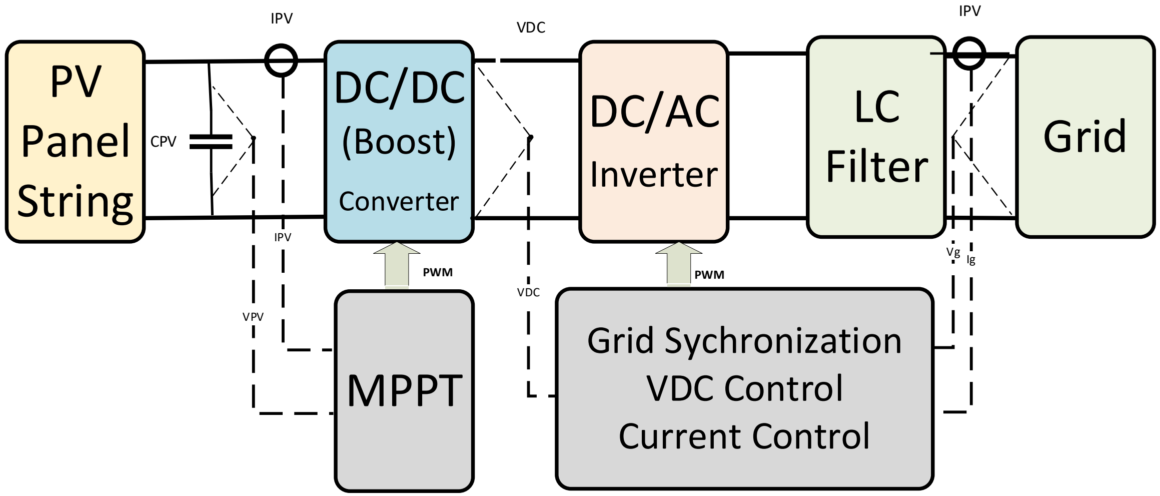
H-Bridge Based Boosting PV Inverter with Low-Frequency Transformer



H-Bridge Based Boosting PV Inverter with High-Frequency Transformer



General Structure of a PV Inverter.



PV Panel String

DC/DC (Boost) Converter

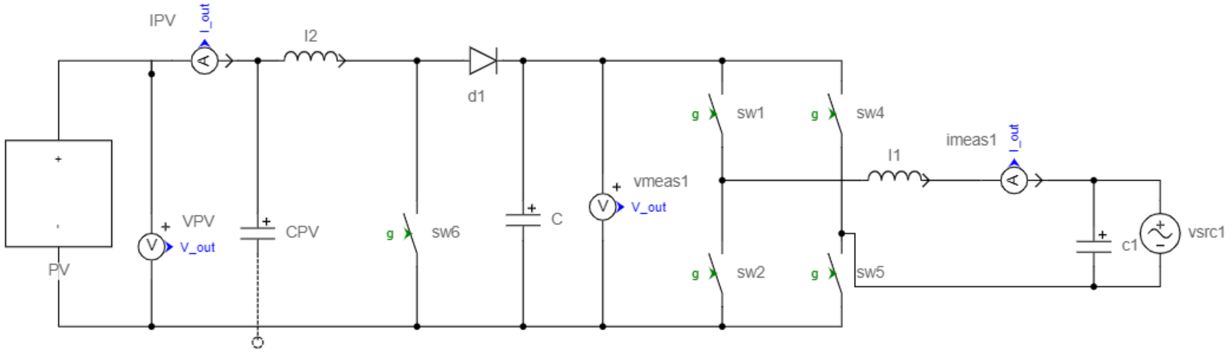
DC/AC Inverter

LC Filter

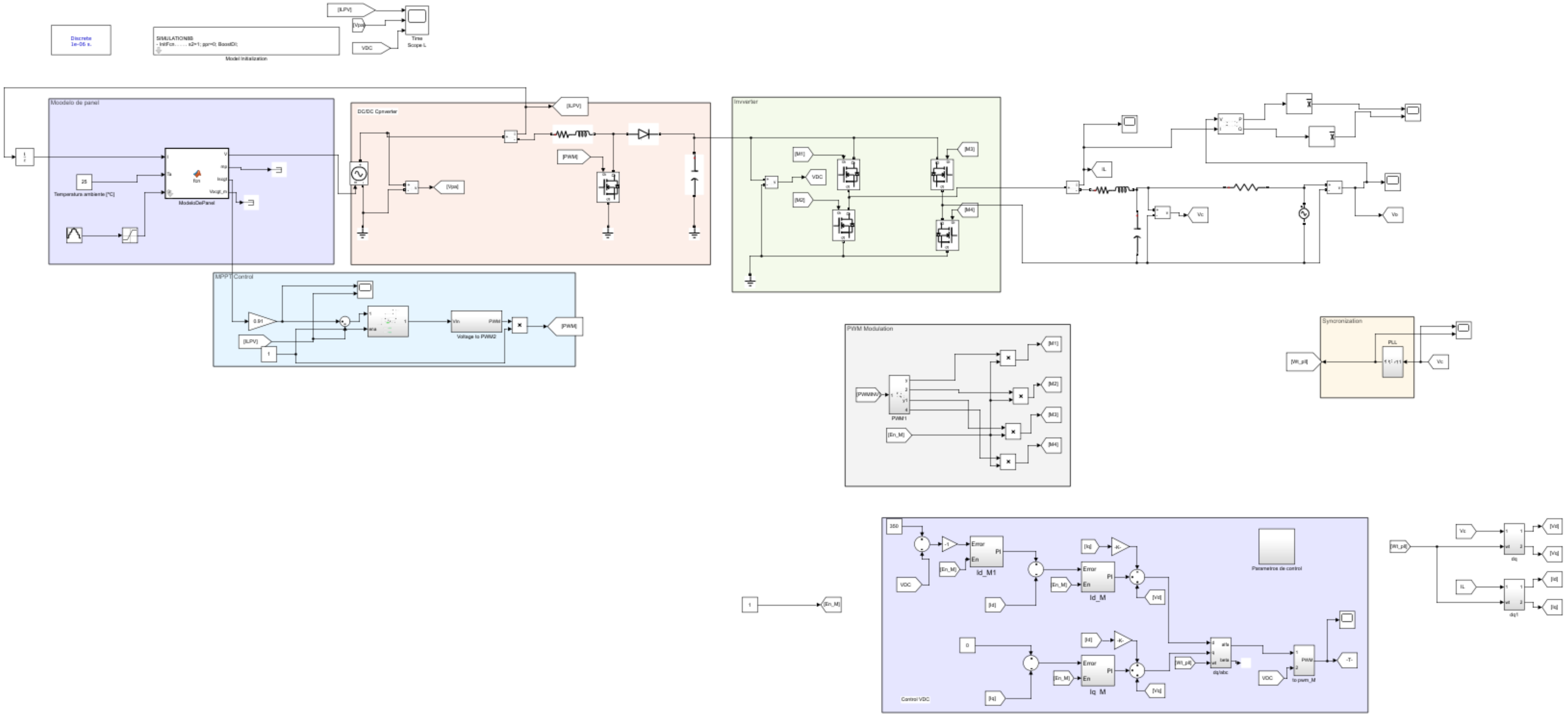
Grid

MPPT

Grid Sychronization
VDC Control
Current Control



Hands-on Simulation Complete Grid Connected PV System.



Simulation8B File.

Simulation10 File.

References.

[1]. S. B. Kjaer, J. K. Pedersen and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," in IEEE Transactions on Industry Applications, vol. 41, no. 5, pp. 1292-1306, Sept.-Oct. 2005.

[2]. N. Boutana, A. Mellit, S. Haddad, A. Rabhi, A. M. Pavan, An explicit I-V model for photovoltaic module technologies, Energy Conversion and Management 138 (2017) 400– 412. doi:10.1016/j.enconman.2017.02.016.

[3]. B. Subudhi and R. Pradhan, "A Comparative Study on Maximum Power Point Tracking Techniques for Photovoltaic Power Systems," in IEEE Transactions on Sustainable Energy, vol. 4, no. 1, pp. 89-98, Jan. 2013, doi: 10.1109/TSTE.2012.2202294.

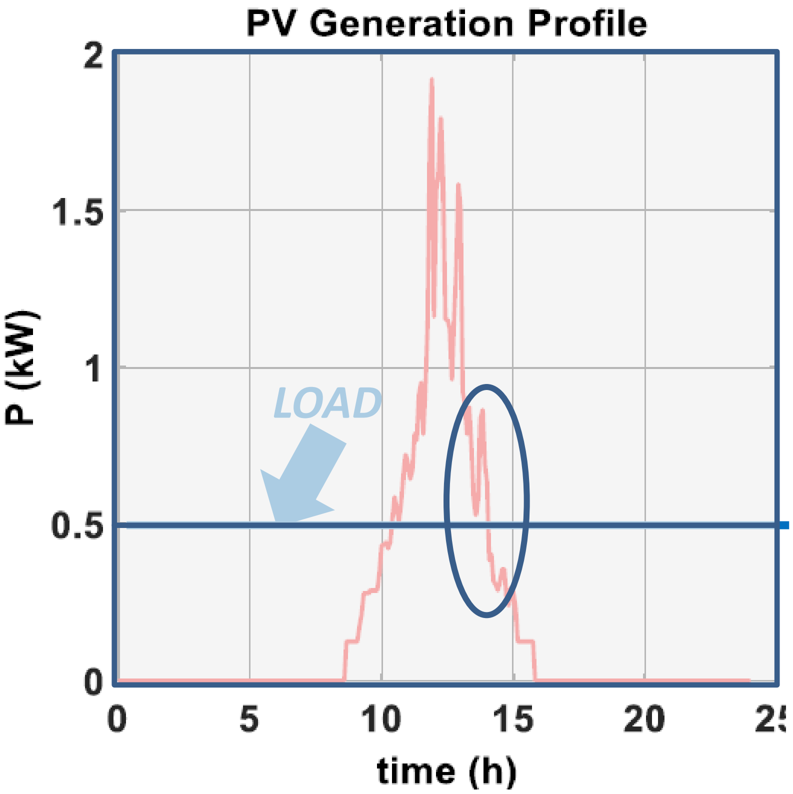
[4]. Madasamy, P.; Suresh Kumar, V.; Sanjeevikumar, P.; Holm-Nielsen, J.B.; Hosain, E.; Bharatiraja, C. A Three-Phase Transformerless T-Type- NPC-MLI for Grid Connected PV Systems with Common-Mode Leakage Current Mitigation. Energies 2019, 12, 2434. https://doi.org/10.3390/en12122434.

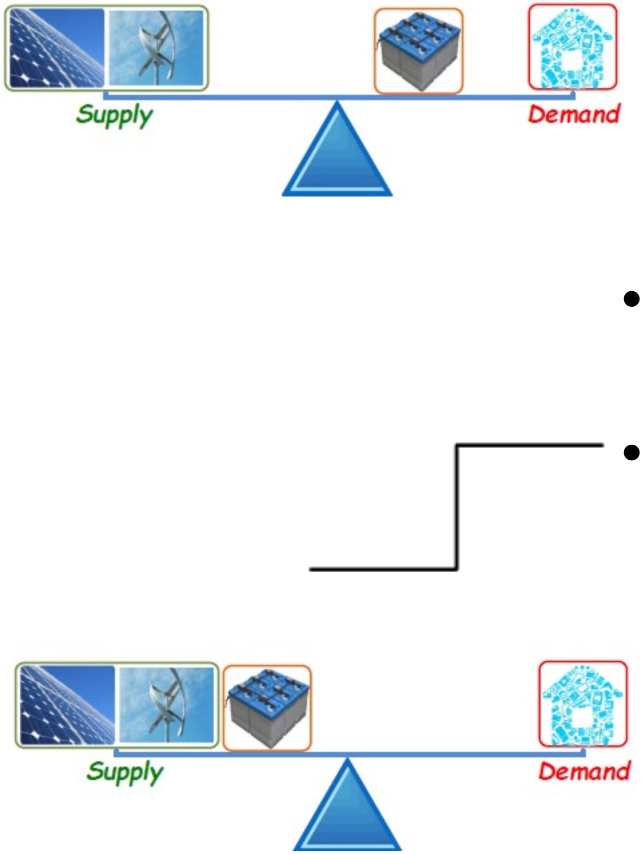
[5]. Remus Teodorescu; Marco Liserre; Pedro Rodriguez, "Grid Converters for Photovoltaic and Wind Power Systems" in Wiley-IEEE Press, 2007, pp.i-xvii, doi: 10.1002/9780470667057.fmatter.

[6]. I. . -S. Kim, M. . -B. Kim and M. . -J. Youn, "New Maximum Power Point Tracker Using Sliding-Mode Observer for Estimation of Solar Array Current in the Grid-Connected Photovoltaic System," in IEEE Transactions on Industrial Electronics, vol. 53, no. 4, pp. 1027-1035, June 2006, doi: 10.1109/TIE.2006.878331.

3. Battery Based Energy Storage Systems

Why do we need energy storage for renewable energy?

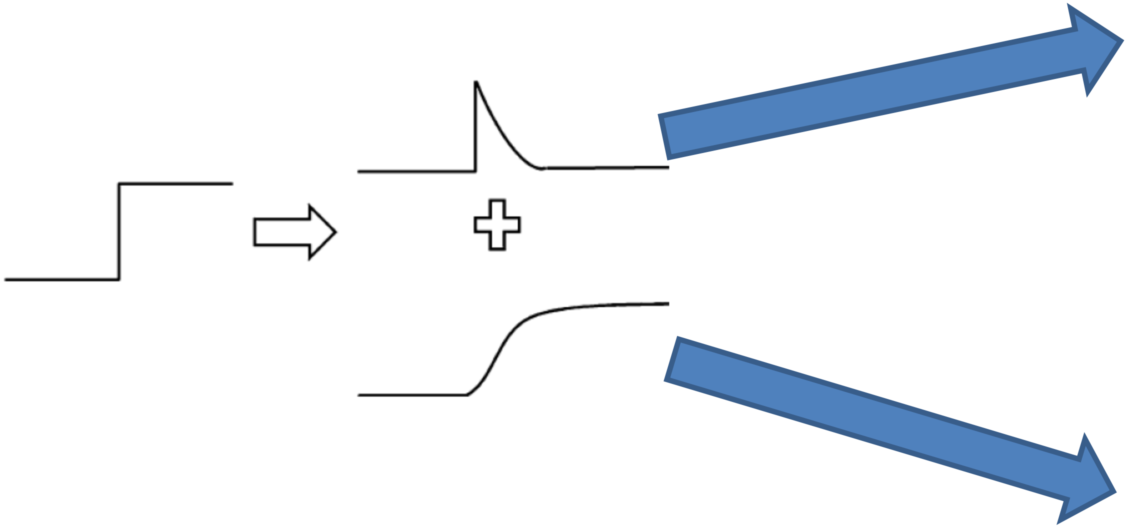




There is not a Single device with both capabilities.

- Fast Response.
- Long-term Availability for Energy Storage and Supply

3. ESS



High Power Density (**HPD**) Devices.

- Supercapacitors.
- Flywheels.
- SMES.

High Energy Density (**HED**) Devices.

- Batteries

$$P_{ESS} = P_{HPD} + P_{HED}$$

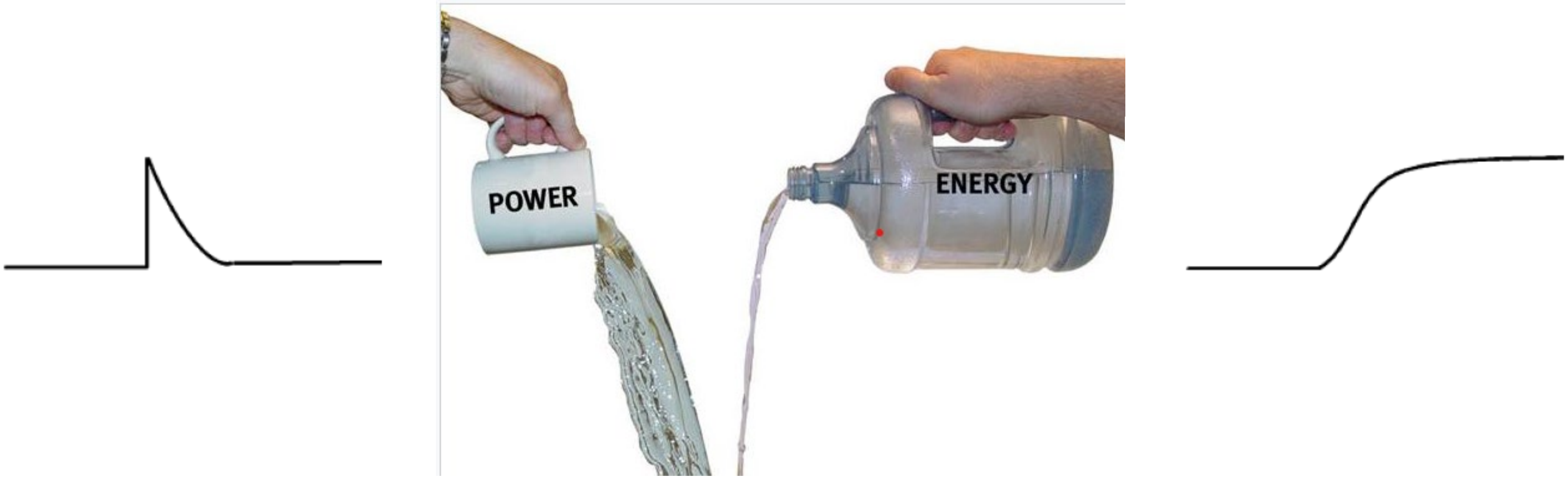
3. ESS

Power Density

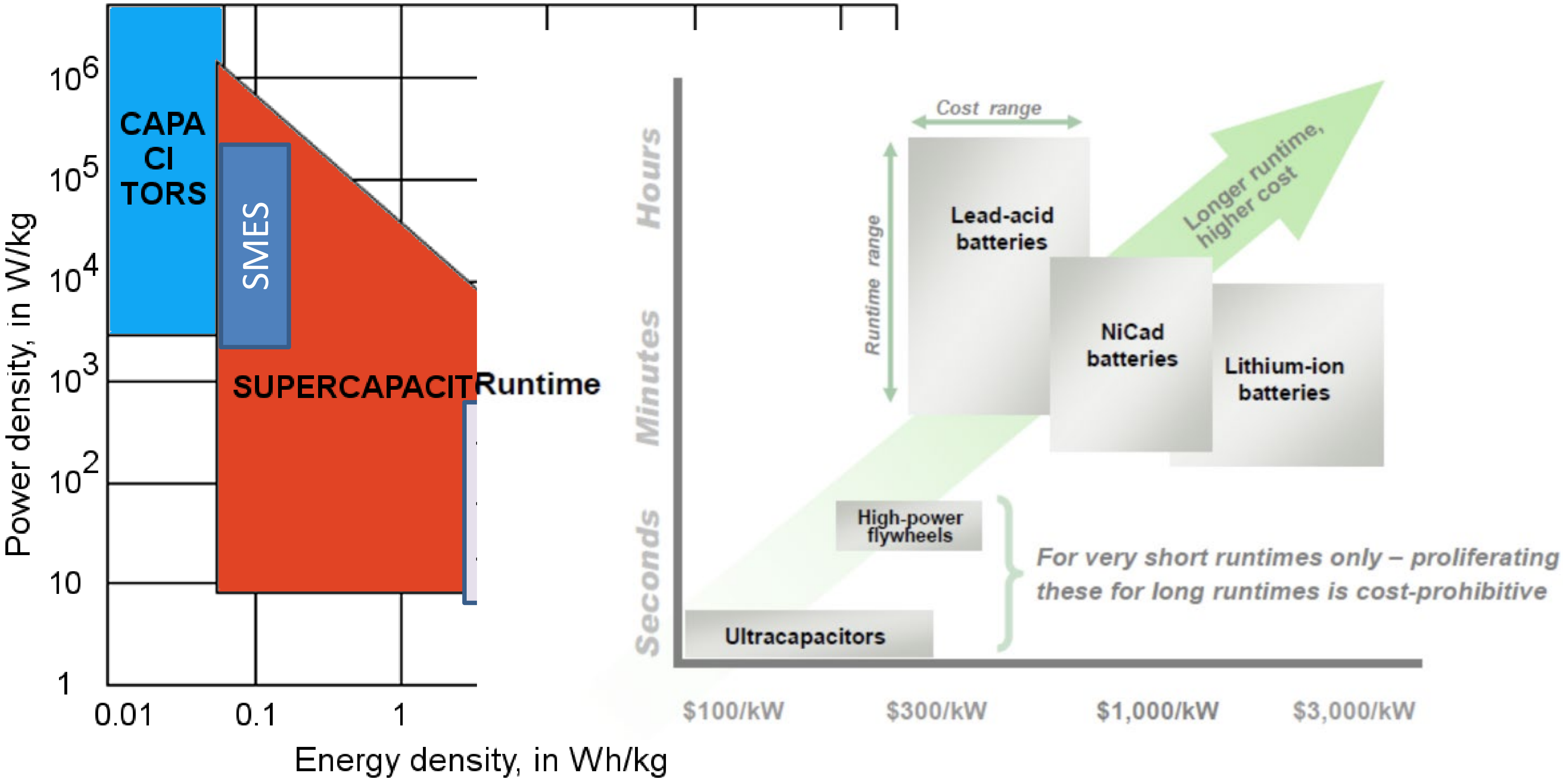
Is the amount of **power** (time rate of energy transfer) per unit **volume**. expressed as (W/L, W/m^3).

- ***Energy Density***

Is the amount of **energy** stored in a given system or region of space per unit **volume**. expressed as (Wh/L, Wh/m^3)

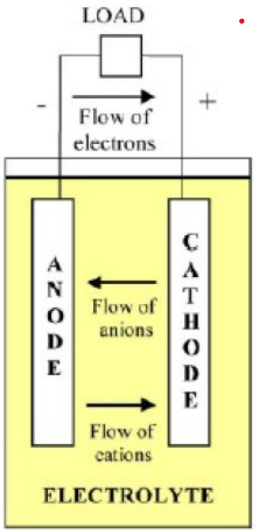


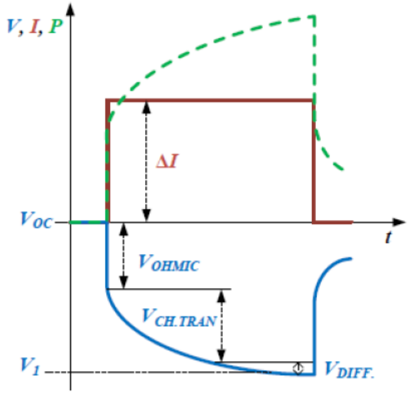
Comparison between Energy Storage Devices

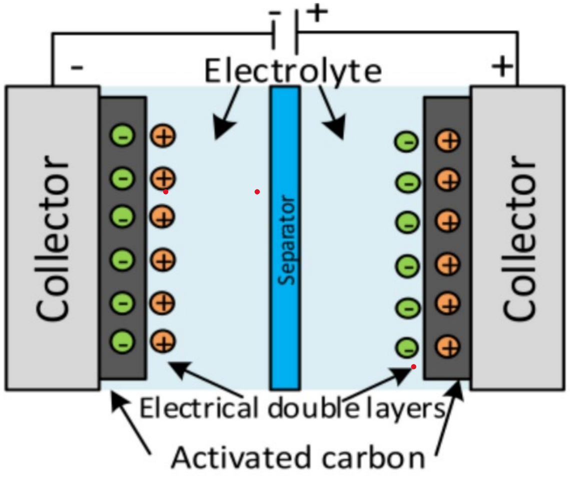


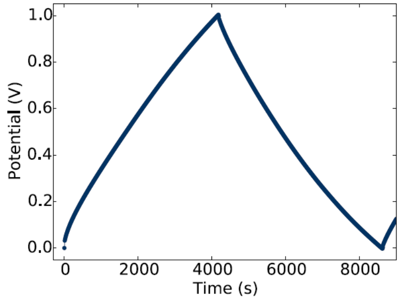
For very short runtimes only – proliferating these for long runtimes is cost-prohibitive

Battery and Supercapacitor.









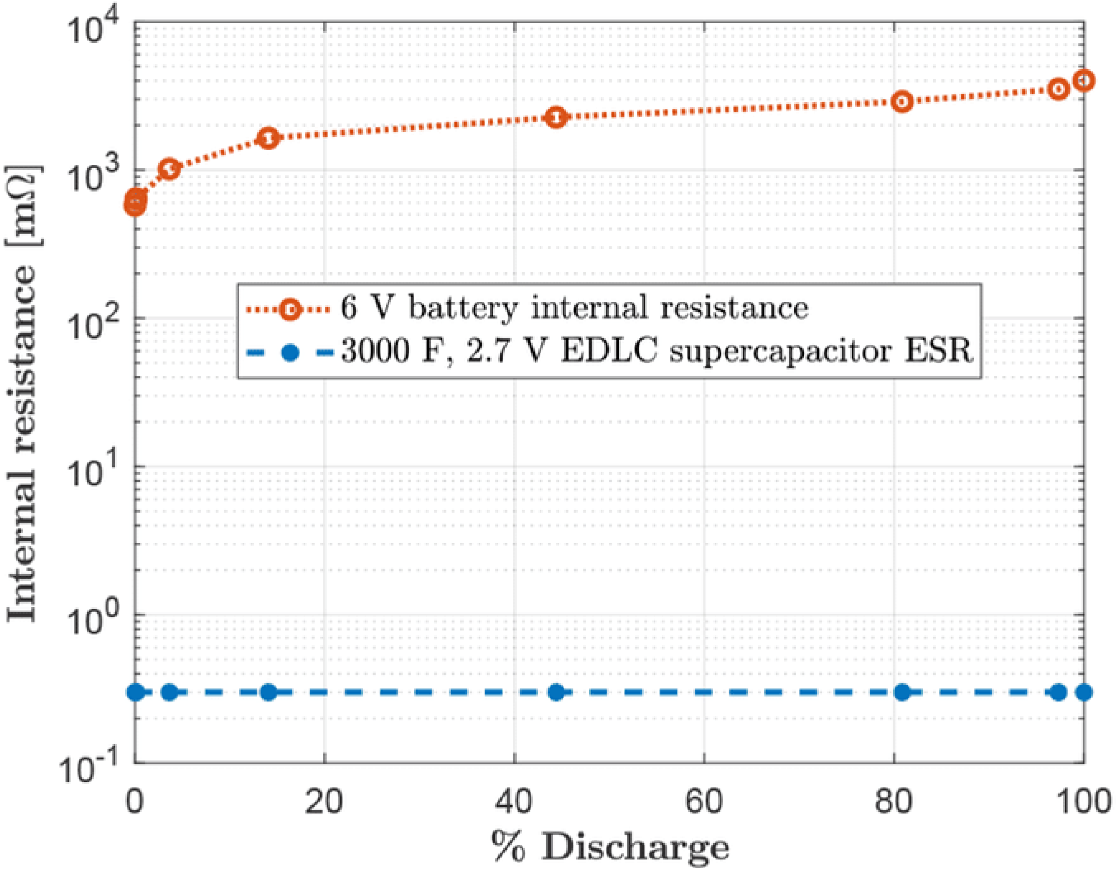
Electrochemical Reaction (REDOX)

Electrostatic Processes

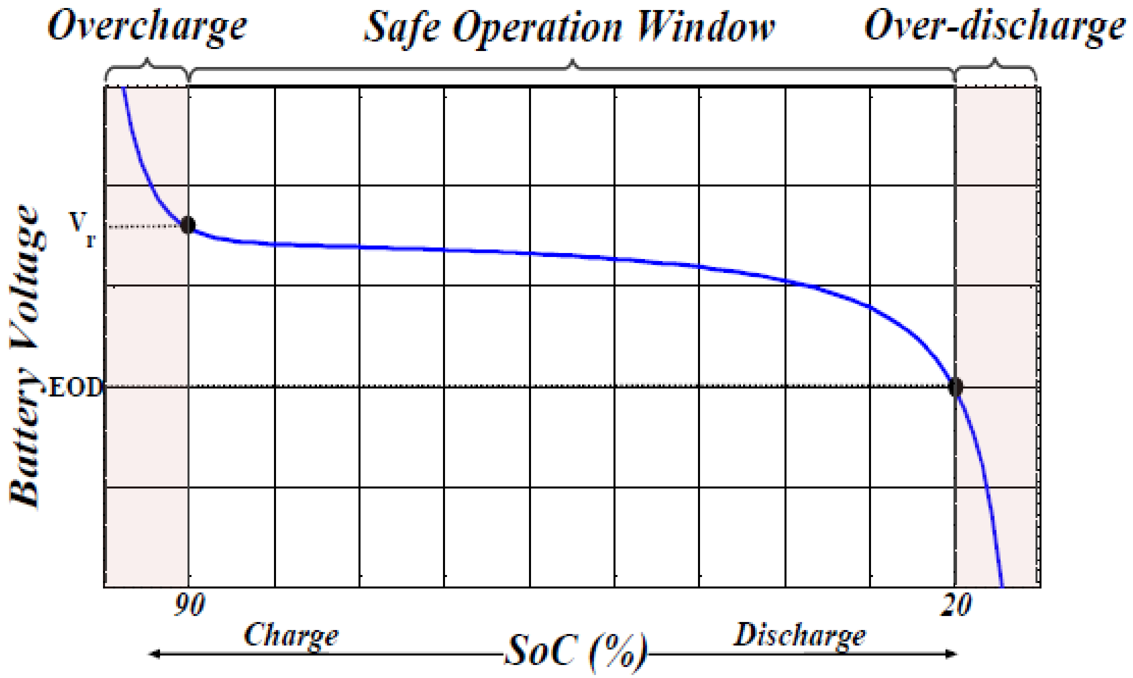
Low internal cell resistance is the key to high-rate capability.

[3]

Battery and Supercapacitor



Battery

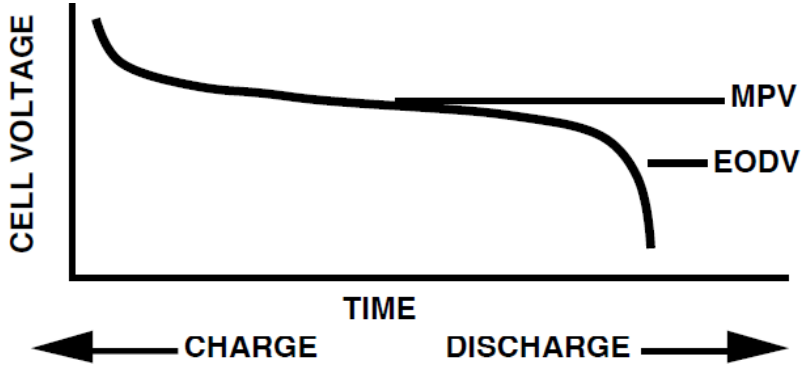


	Charge Cut-off Voltage	Cell Voltage Nominal	Discharge Cut-off Voltage
Lead-acid	2.4 V	2 V	1.75 V
Li-Ion	4.20 V	4 ¯ V	2.5-3.0 V

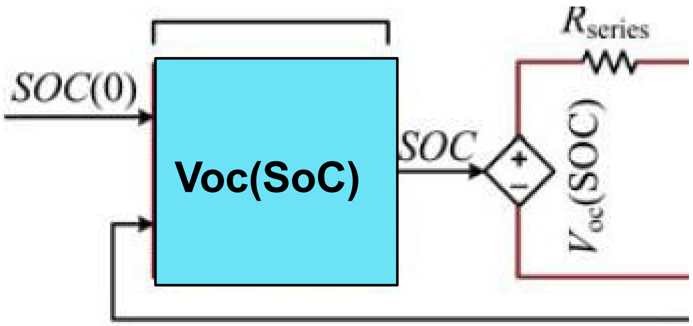
Battery Model

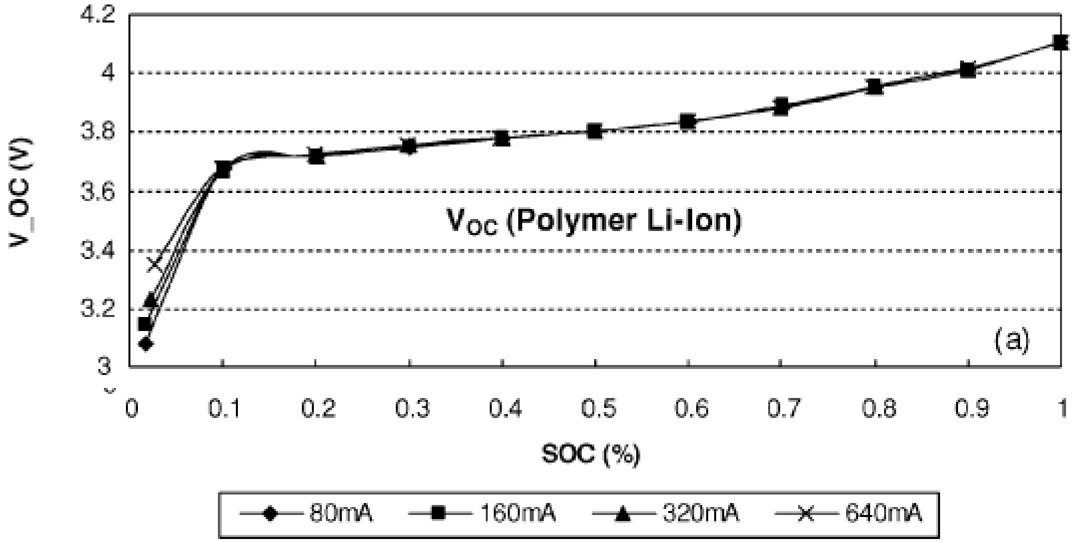
Model Requirements.

- Consider internal resistance, such that under load conditions, the voltage increases, and under discharge conditions, the voltage decreases.
- Generate voltage variation curves based on the state of charge.
- Replicate dynamics in response to variations in load current.



3. ESS



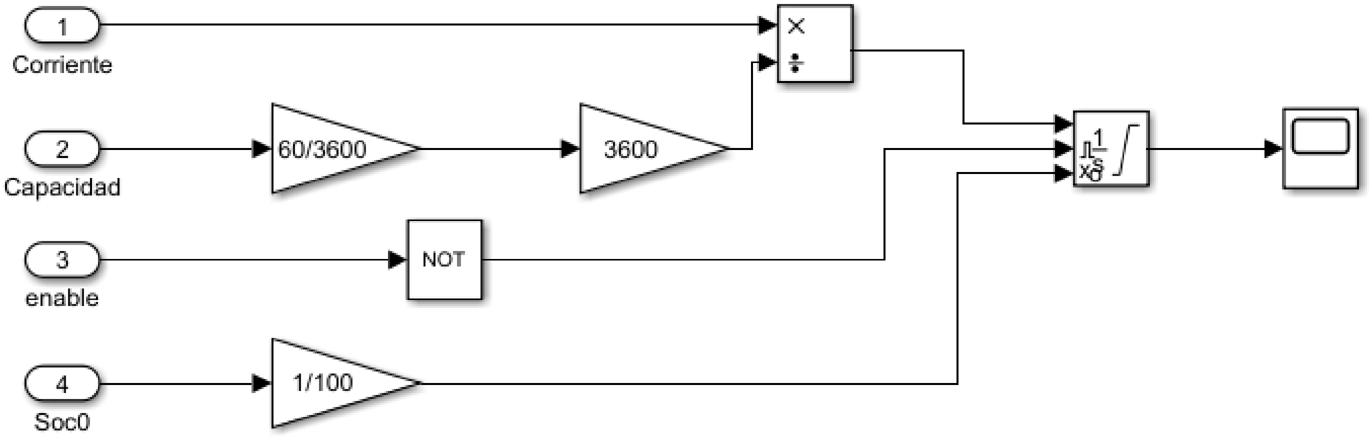


$$V[SoC(t)] = a_0 e^{-a_1 SoC(t)} + a_2 + a_3 SoC\,(t) - a_4 SoC\,(t)^2 + a_4 SoC\,(t)^3$$

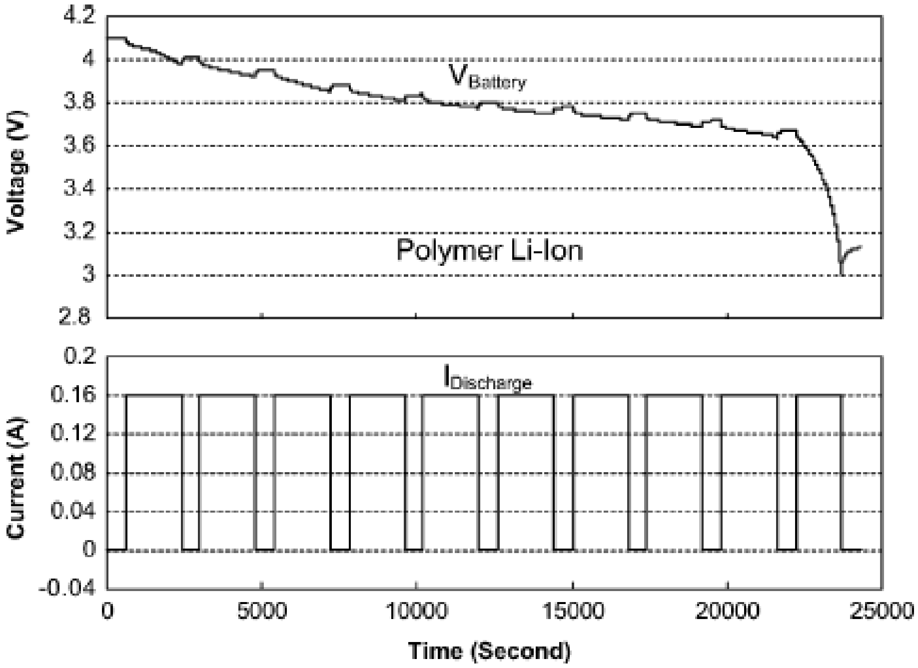
Taesic Kim, and Wei Qiao, "A Hybrid Battery Model Capable of Capturing Dynamic Circuit Characteristics and Nonlinear Capacity Effects"
Min Chen, and Gabriel A. Rincón-Mora, "Accurate Electrical Battery Model Capable of Predicting Runtime and *I*–*V* Performance "

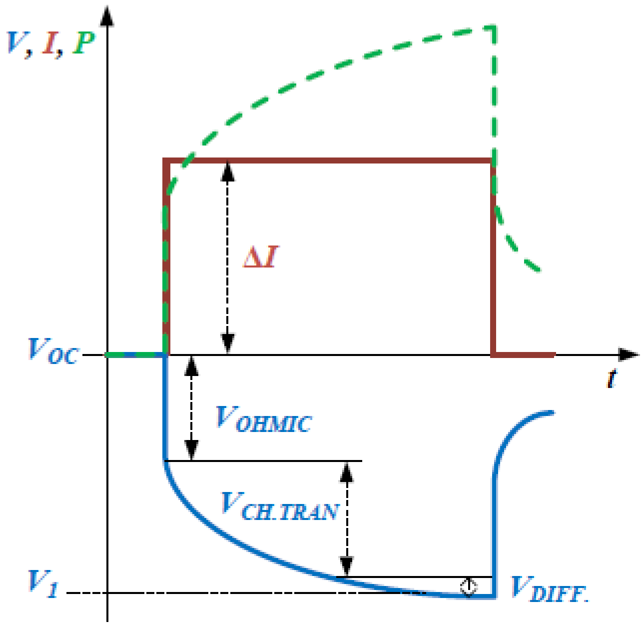
SoC

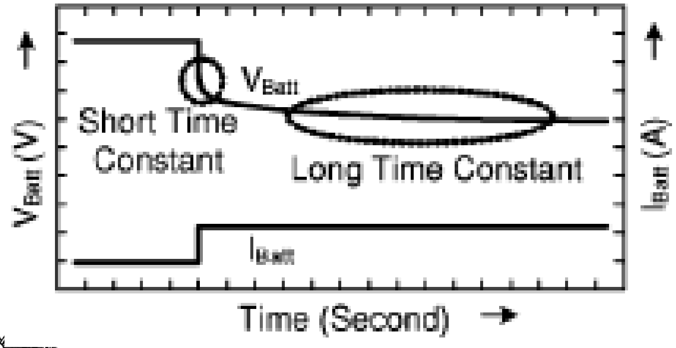
$$SoC(\Delta t)_{Bat(i)} = SoC(0)_{Bat(i)} - \int_0^{\Delta t} \eta_{Bat(i)} \frac{I_{Bat(i)}(\tau)}{C_{Bat(i)}} d\tau;$$



3. ESS





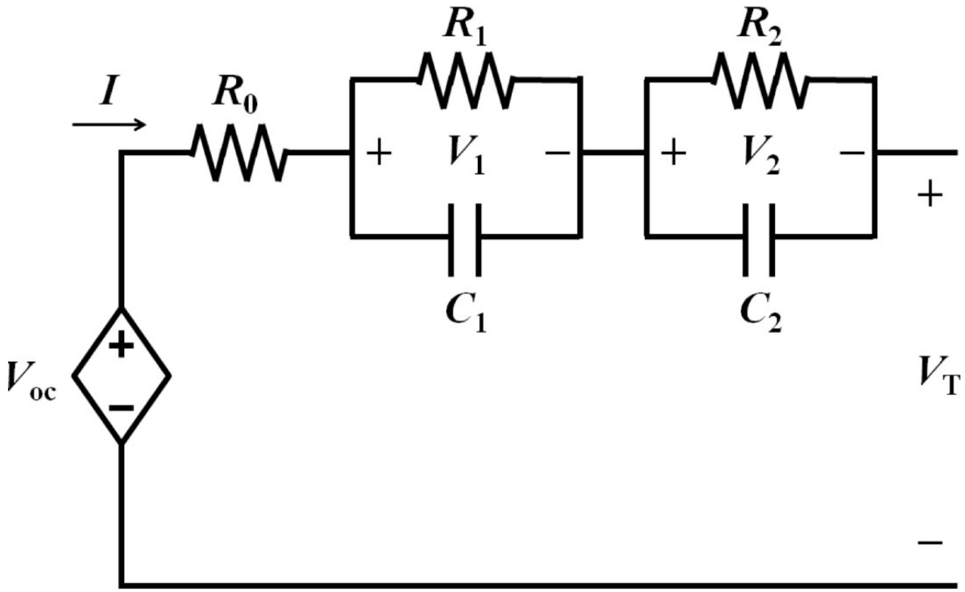


$$R_{OHMIC} = \frac{U_2 - U_1}{I_2 - I_1}$$

Min Chen, and Gabriel A. Rincón-Mora, "Accurate Electrical Battery Model Capable of Predicting Runtime and *I–V* Performance ‟

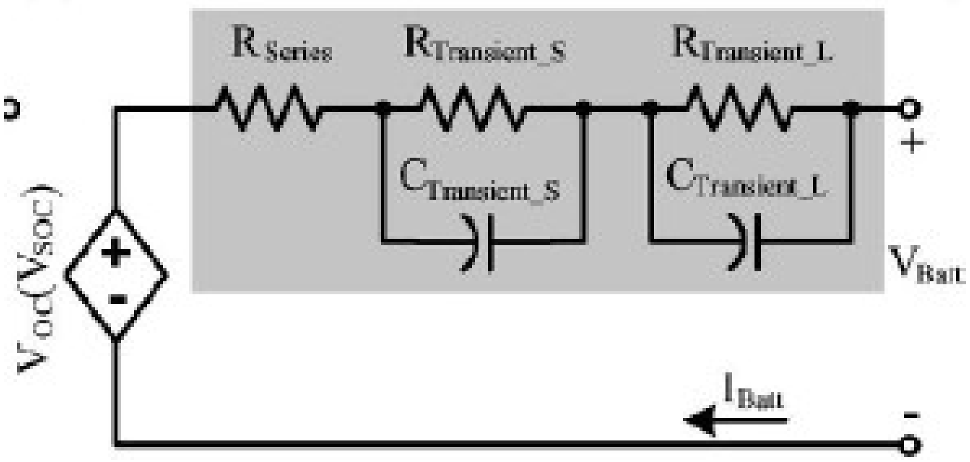
3. ESS

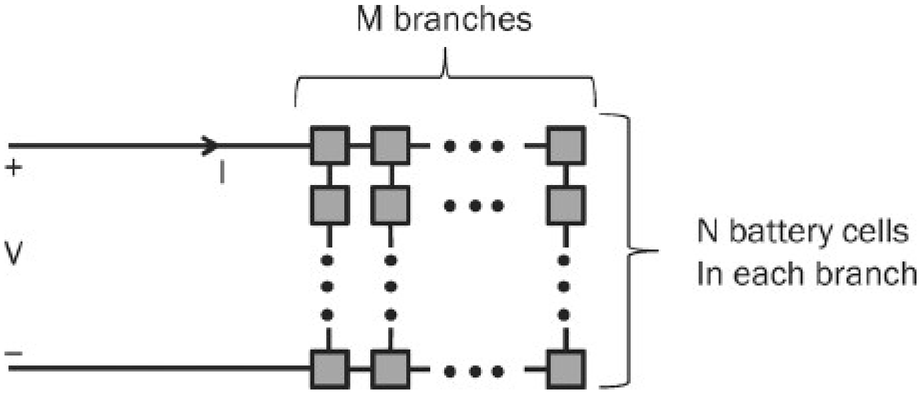
This dynamics can be approximated by circuits using one or more subcircuits of resistors in parallel with capacitors.

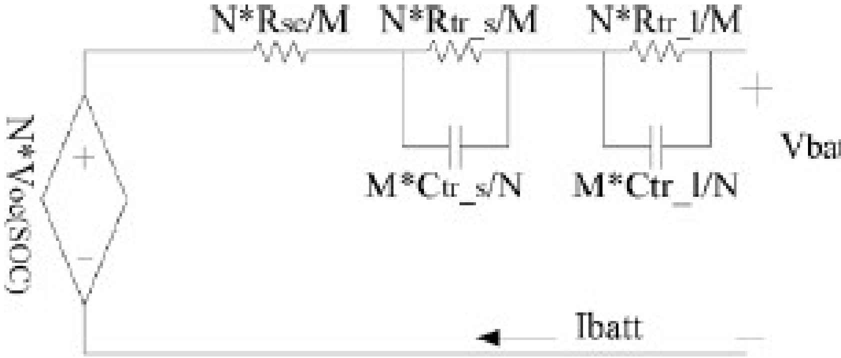


This model is known as the Second Order Randles Model.

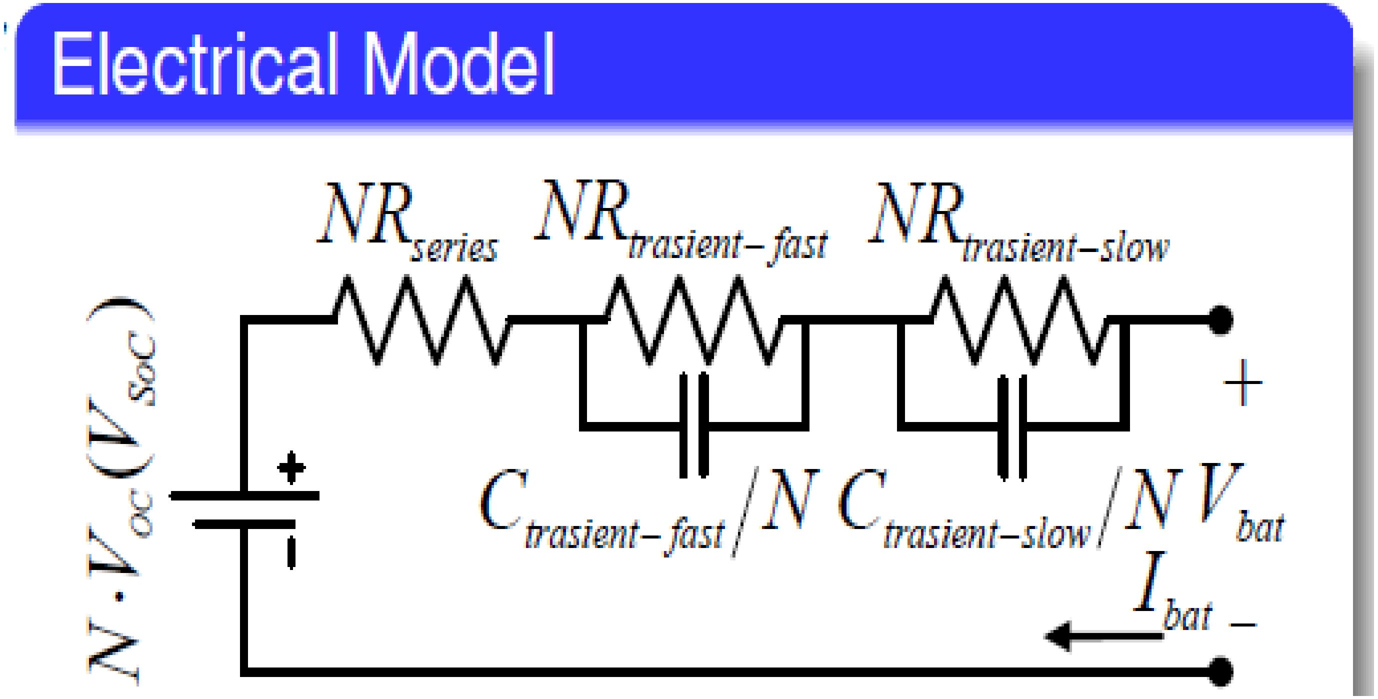
3. ESS


R Series
R Transient_S
R Transient_L
C Transient_S
C Transient_L
+
-
V OC(V SOC)
+
V Batt
I Batt
-

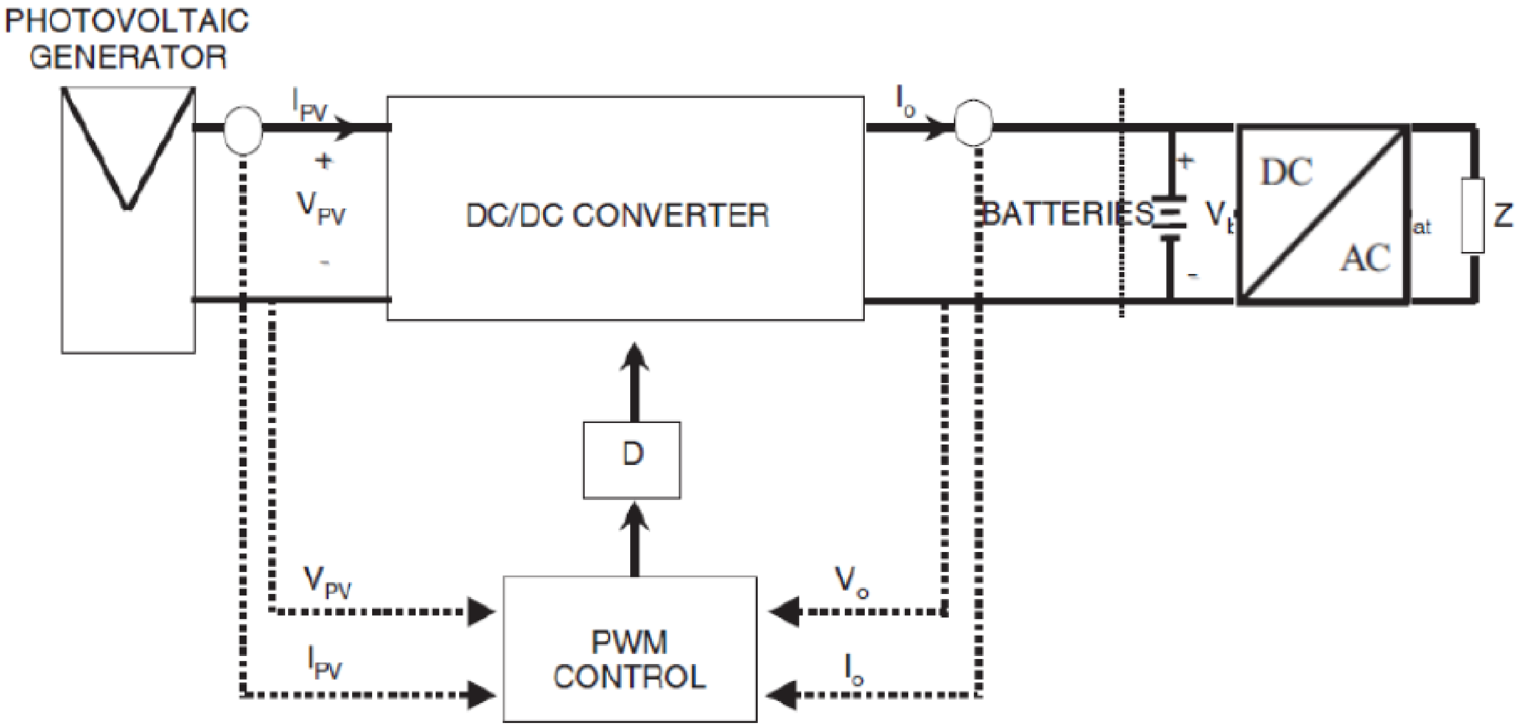

M branches
+
I
V
–
N battery cells
In each branch


N*Rsc/M
N*Rtr_s/M
N*Rtr_l/M
N*Voc(SOC)
+
–
M*Ctr_s/N
M*Ctr_l/N
+
Vbat
Ibatt
–

3. ESS


Electrical Model
NR_{series}
$NR_{trasient-fast}$
$NR_{trasient-slow}$
$N \cdot V_{oc}(V_{SoC})$
+
−
$C_{trasient-fast}/N$
$C_{trasient-slow}/N$
V_{bat}
I_{bat}
+
−

General Structure of a Autonomous PV Inverter.

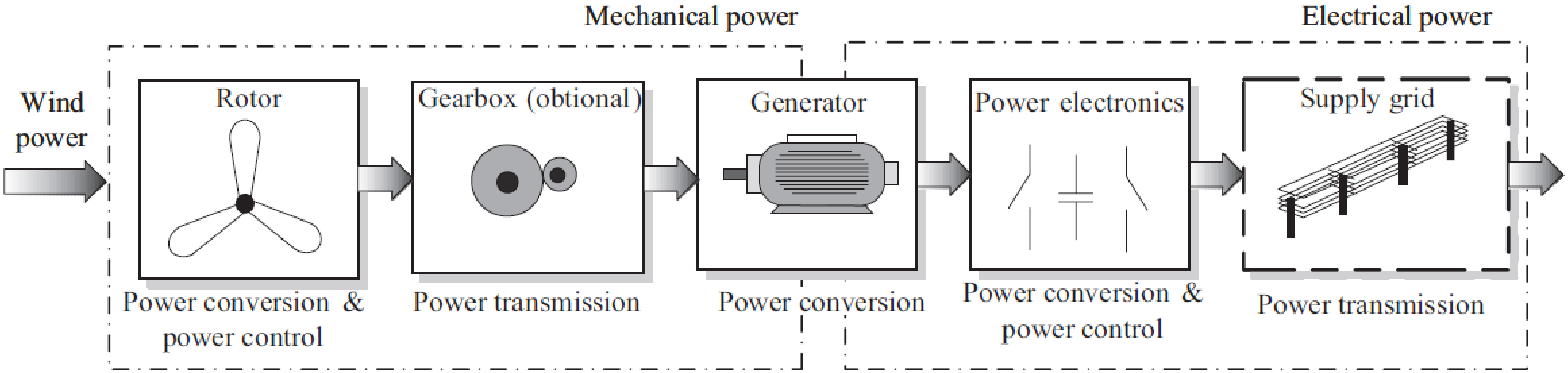


Simulation6 File.

2. WT Generation

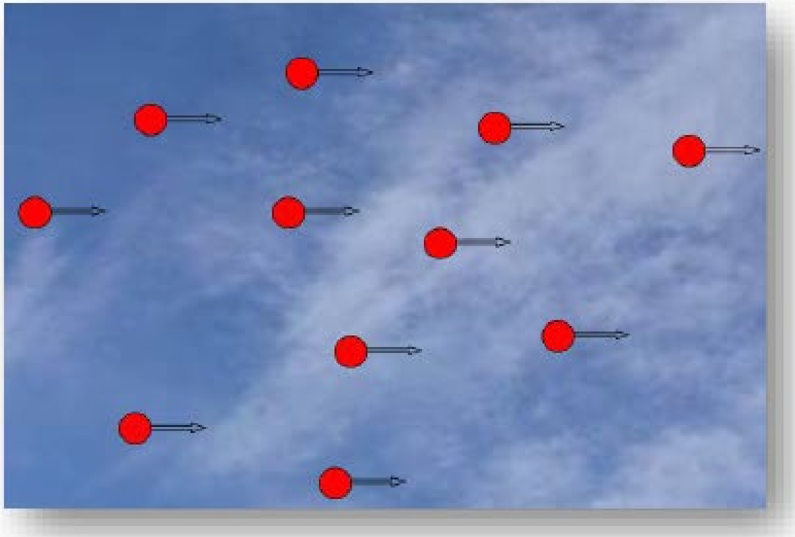
2. WT Generation

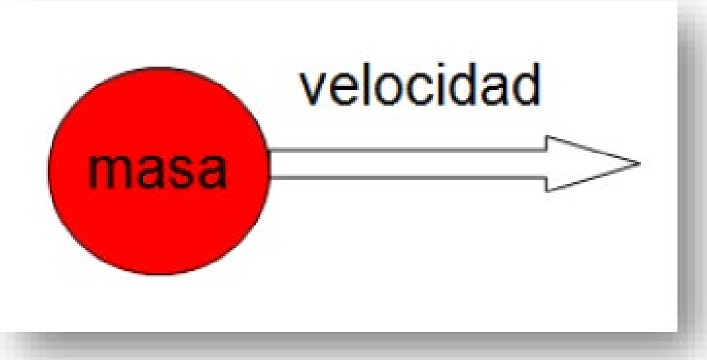
- General Scheme for WT Generation



Wind Power

Kinetic Energy





$$E_k = \frac{1}{2} . m . v^2$$

E_k = energía cinética (J)
m = masa (kg)
v = velocidad (m/s)

Wind Powe

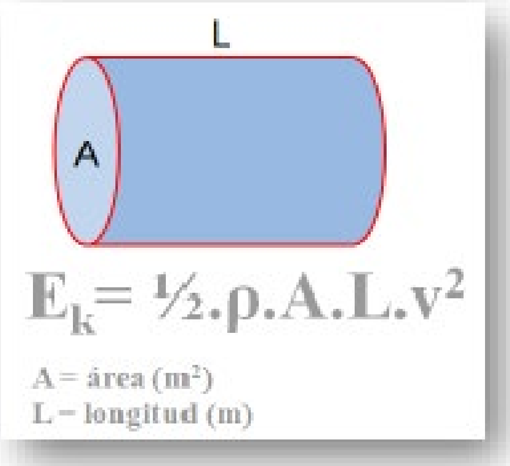
Wind moves horizontaly dh=0. The Energy that can be extracted from wind is Kinetic Energy

$$E_k = \frac{1}{2} m V^2$$

$$E_k = \frac{1}{2} \rho V ol * V^2$$

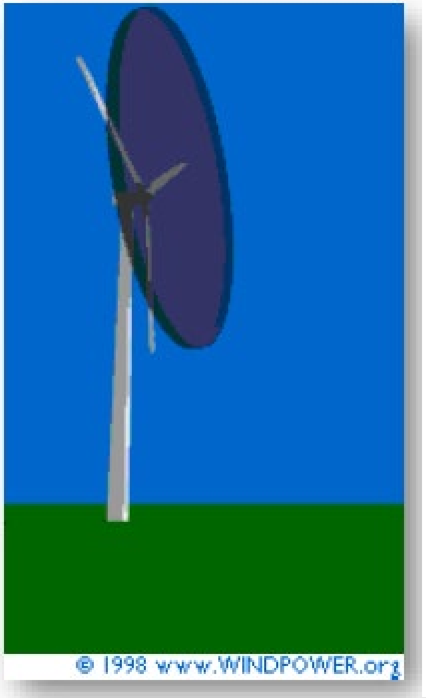
The mass m of the wind can be estimated by the product of its density ρ and volume Vol

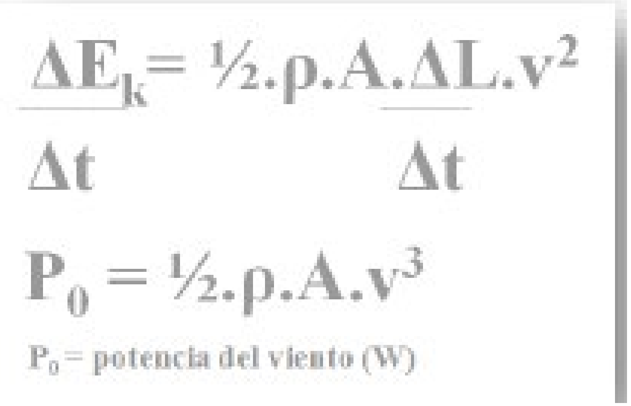
$$m = \rho \mathrm{Vol}$$



$$E_k = ½.\rho.A.L.v^2$$

A = área (m^2)
L = longitud (m)


© 1998 www.WINDPOWER.org



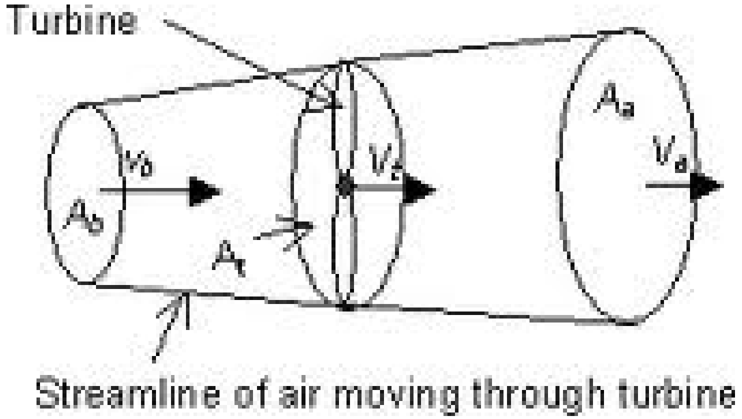
$$\frac{\Delta E_k}{\Delta t} = ½.\rho.A.\frac{\Delta L}{\Delta t}.v^2$$

$$P_0 = ½.\rho.A.v^3$$

P_0 = potencia del viento (W)

Wind Power

Assuming that the air is incompressible (ρ = constant) the flow is constant in each section.

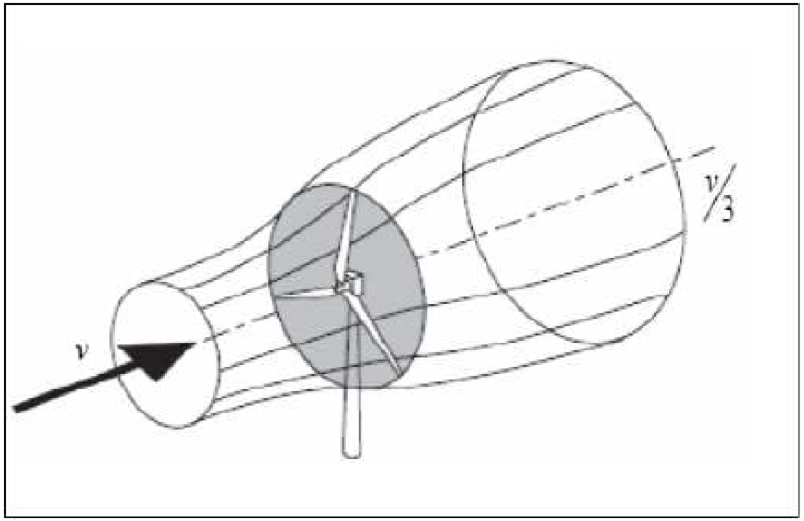


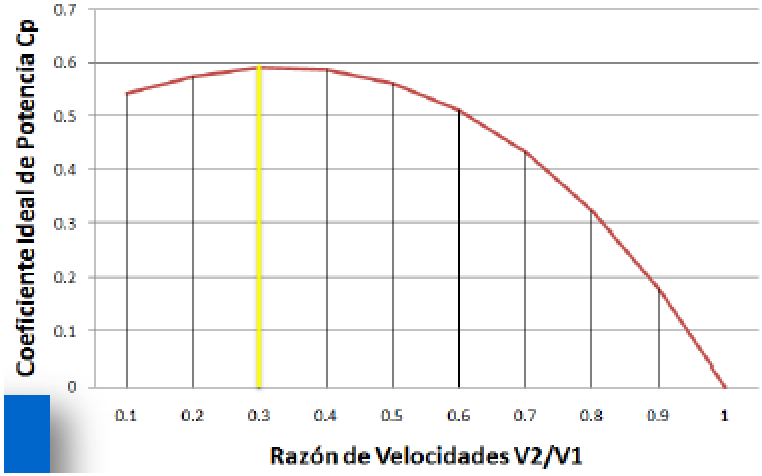
Continuity theorem:

$$A_0 V_0 = A_t V_t = A_a V_a$$

Generated Power.

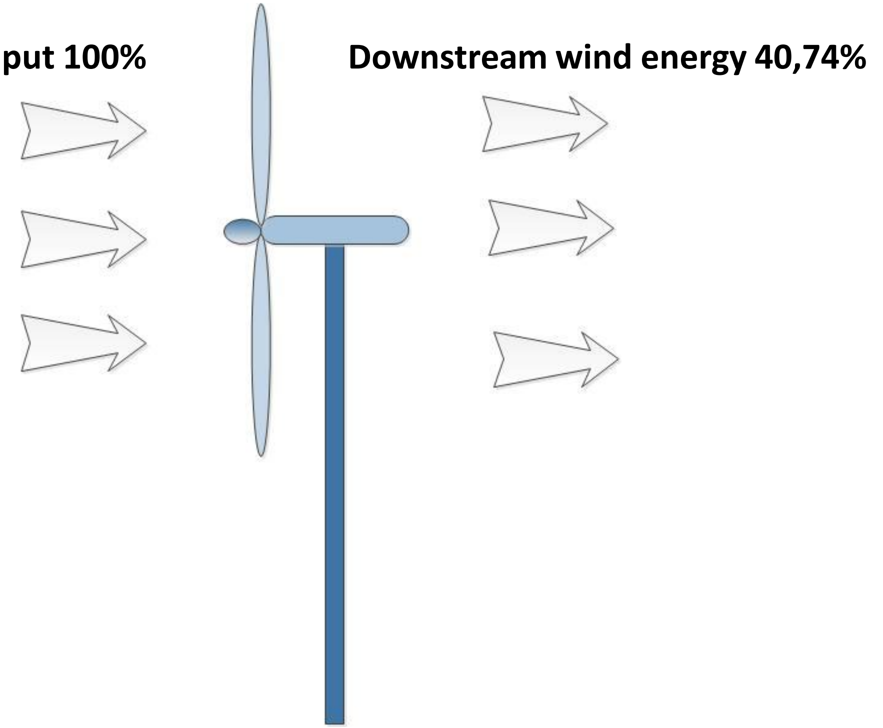
- In 1918 the German physicist Albert Betz published a theory in which he showed that the maximum kinetic energy extractable from the wind by a wind turbine is equal to 16/27 (59.26%).





Generated Power.

- Betz Limit



Upstream Energy Input 100%

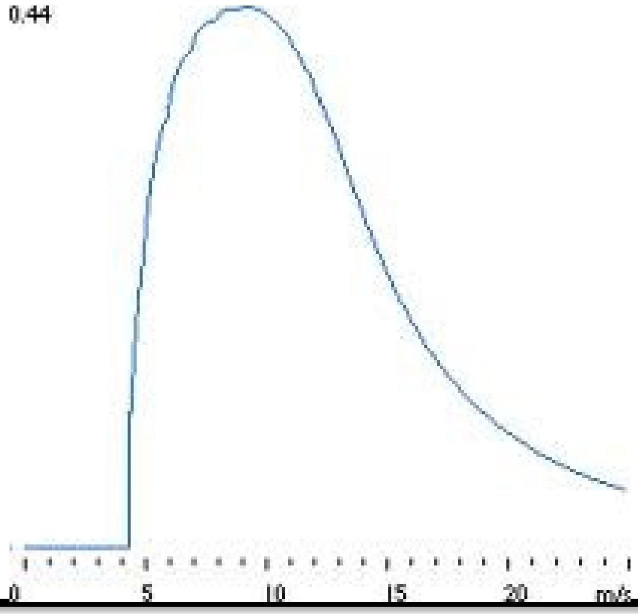
Downstream wind energy 40,74%

Generated Power.

- No rotor operates with a mechanical efficiency of 100%, so the Betz limit indicates the maximum extractable power, but in reality the power will be the result of the efficiency multiplied by the Betz limit, this factor is the power coefficient.

$$P = \frac{1}{2} C_p \rho A V^3 [W]$$

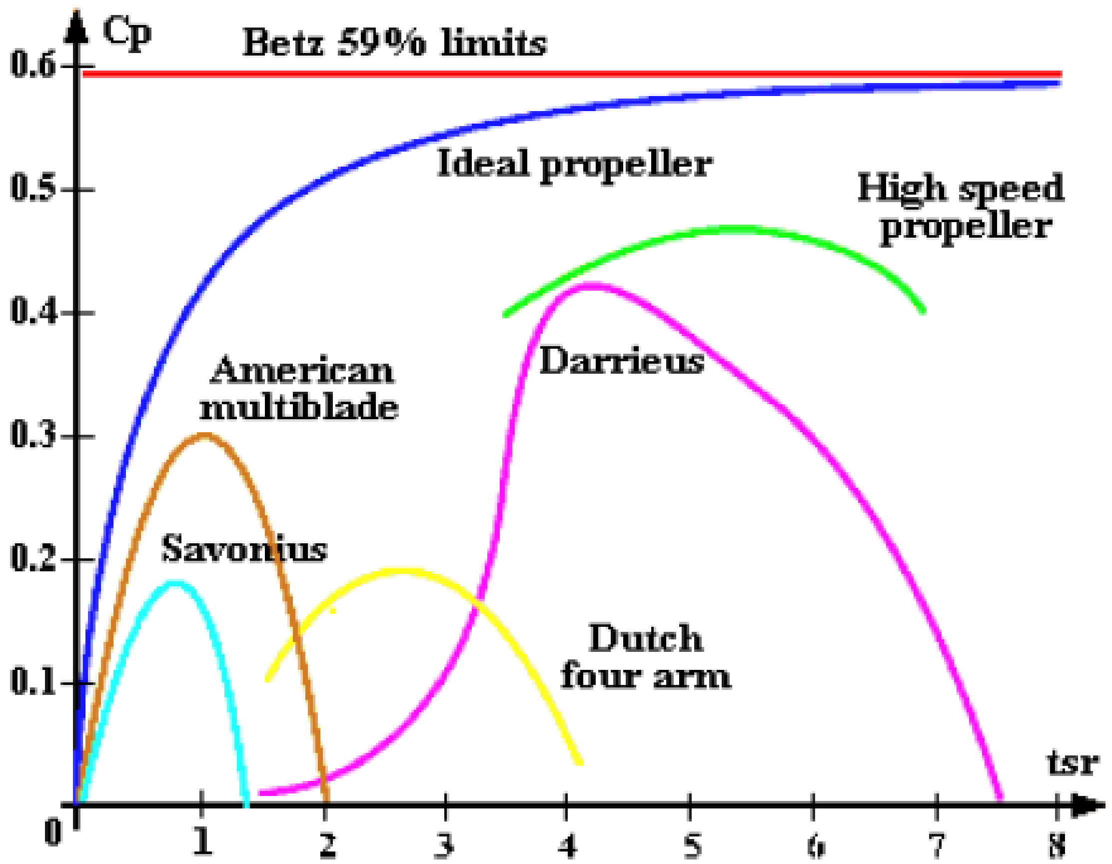
$$C_p \ varía \ con \ V$$



http://www.reysapo.com.uy/vientos-termicos-brisas-marinas/

http://www.bvsde.paho.org/cursoa_meteoro/lecc3/lecc3_7.html

2. WT Generation



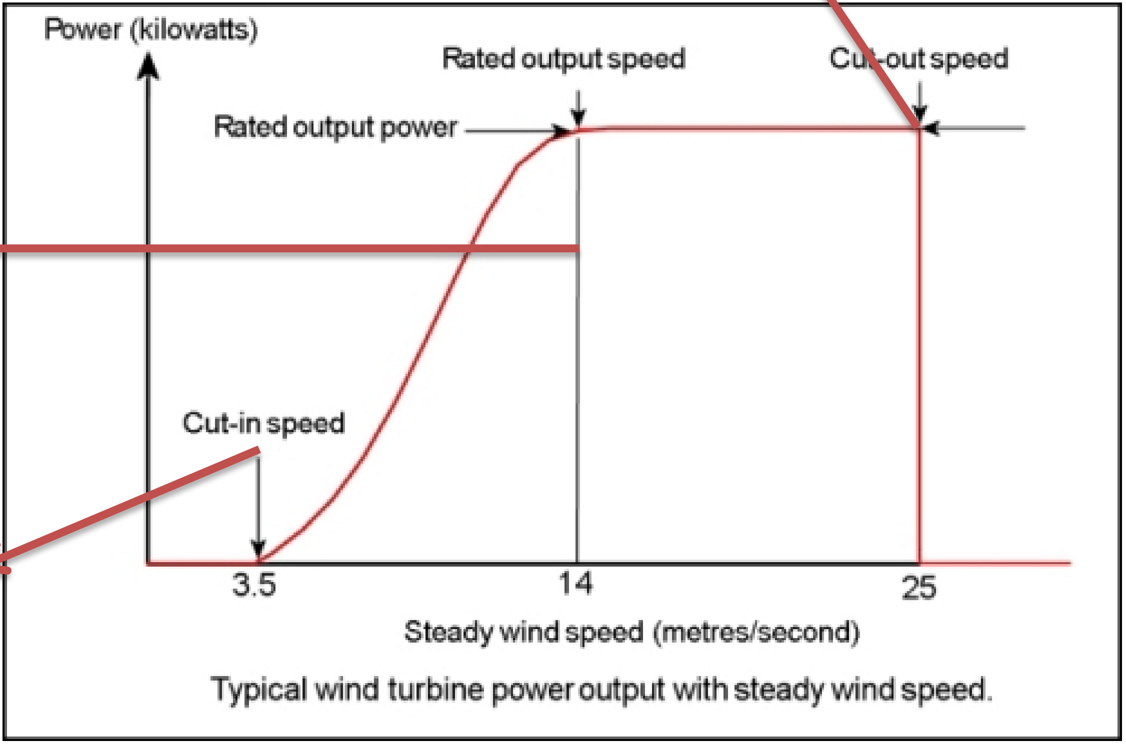
2. WT Generation

Parameters

Cut-off Speed
V_p = maximum speed before the rotor stops

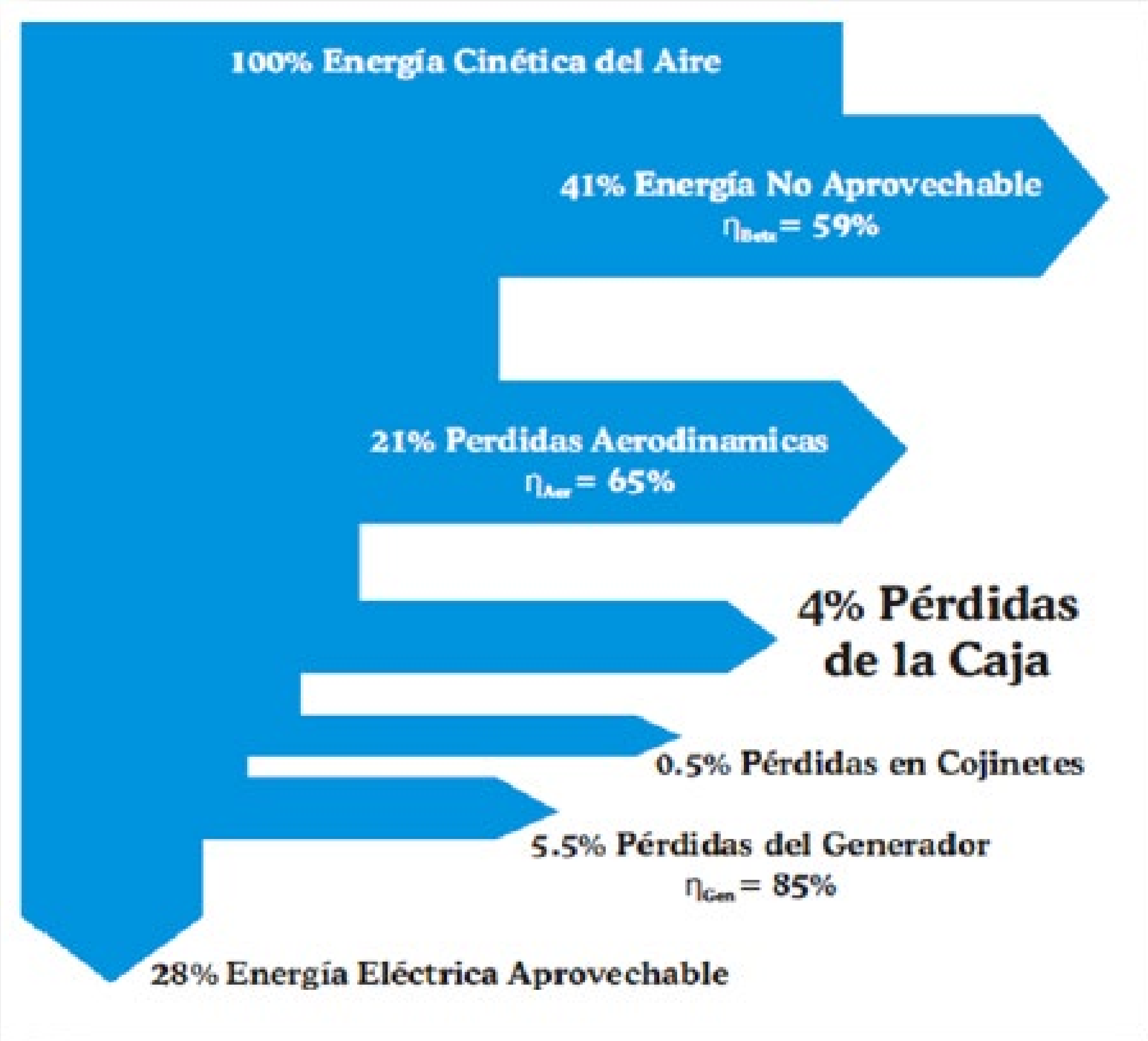
Rated Output Speed
V_n = design speed to generate rated power
C_p =max

Cut-In Speer
V_a = minimum speed required for the rotor to start rotating

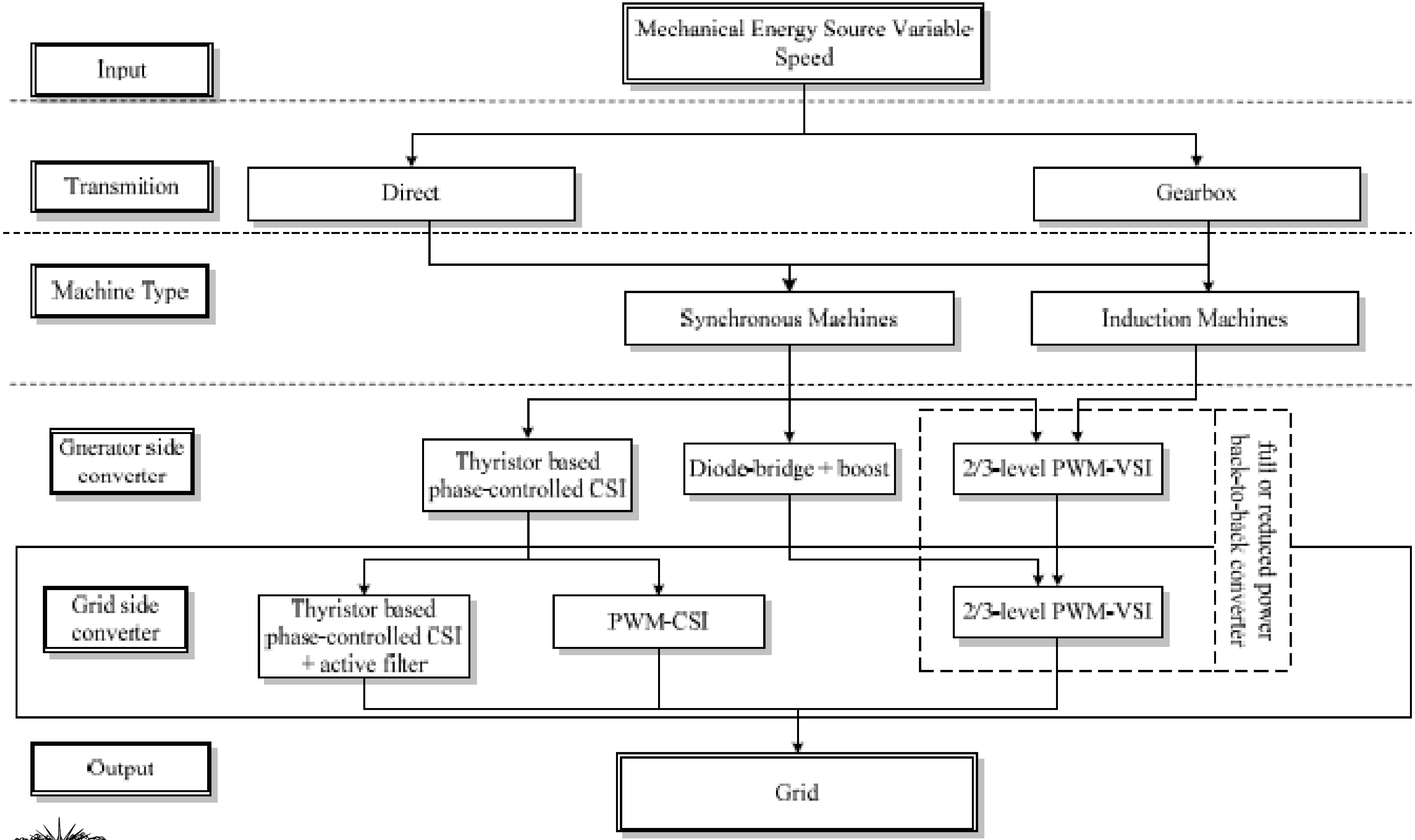


Typical wind turbine power output with steady wind speed.

Efficiency


100% Energía Cinética del Aire
41% Energía No Aprovechable
η_{Betz} = 59%
21% Perdidas Aerodinamicas
η_{Aer} = 65%
4% Pérdidas de la Caja
0.5% Pérdidas en Cojinetes
5.5% Pérdidas del Generador
η_{Gen} = 85%
28% Energía Eléctrica Aprovechable

2. WT Generation



Input

Mechanical Energy Source Variable Speed

Transmition

Direct

Gearbox

Machine Type

Synchronous Machines

Induction Machines

Gnerator side converter

Thyristor based phase-controlled CSI

Diode-bridge + boost

2/3-level PWM-VSI

full or reduced power back-to-back converter

Grid side converter

Thyristor based phase-controlled CSI + active filter

PWM-CSI

2/3-level PWM-VSI

Output

Grid

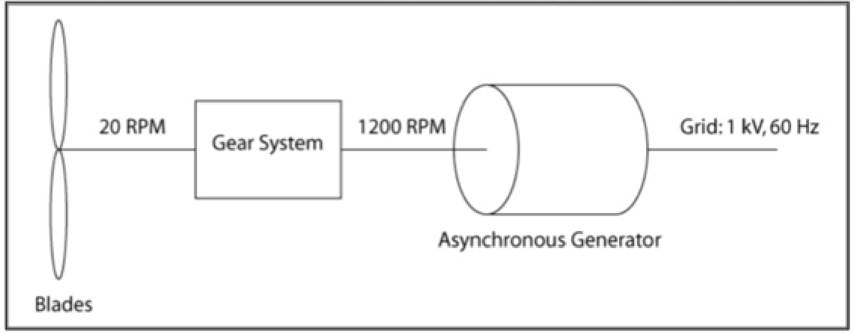
Clasification based on the Machine

- **Syncrhonous Machine**
    - Permanent Magnet Generator(PMG).
    - Externaly exited (Sync Generator).
    - Multipole.
- **Asyncrhonous (Induction).**
    - Wound rotor Induction generator(WRIG).
    - Squirrel cage induction generator (SCIG).

Clasification based on Machine and Convertion Processes

- **Type (A)**
  - (Fixed Speed FS-WT).
- **Type (B)**
  - Limited Variable Speed.
- **Type (C)**
  - Variable Speed. (IM)
- **Type (D)**
  - Variable Speed. (SM)

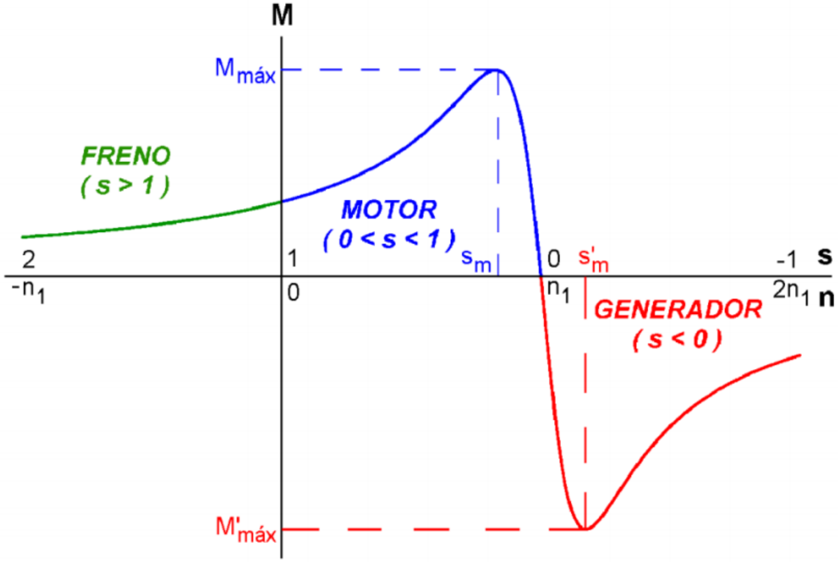
(Type A) Fixed Speed WTG



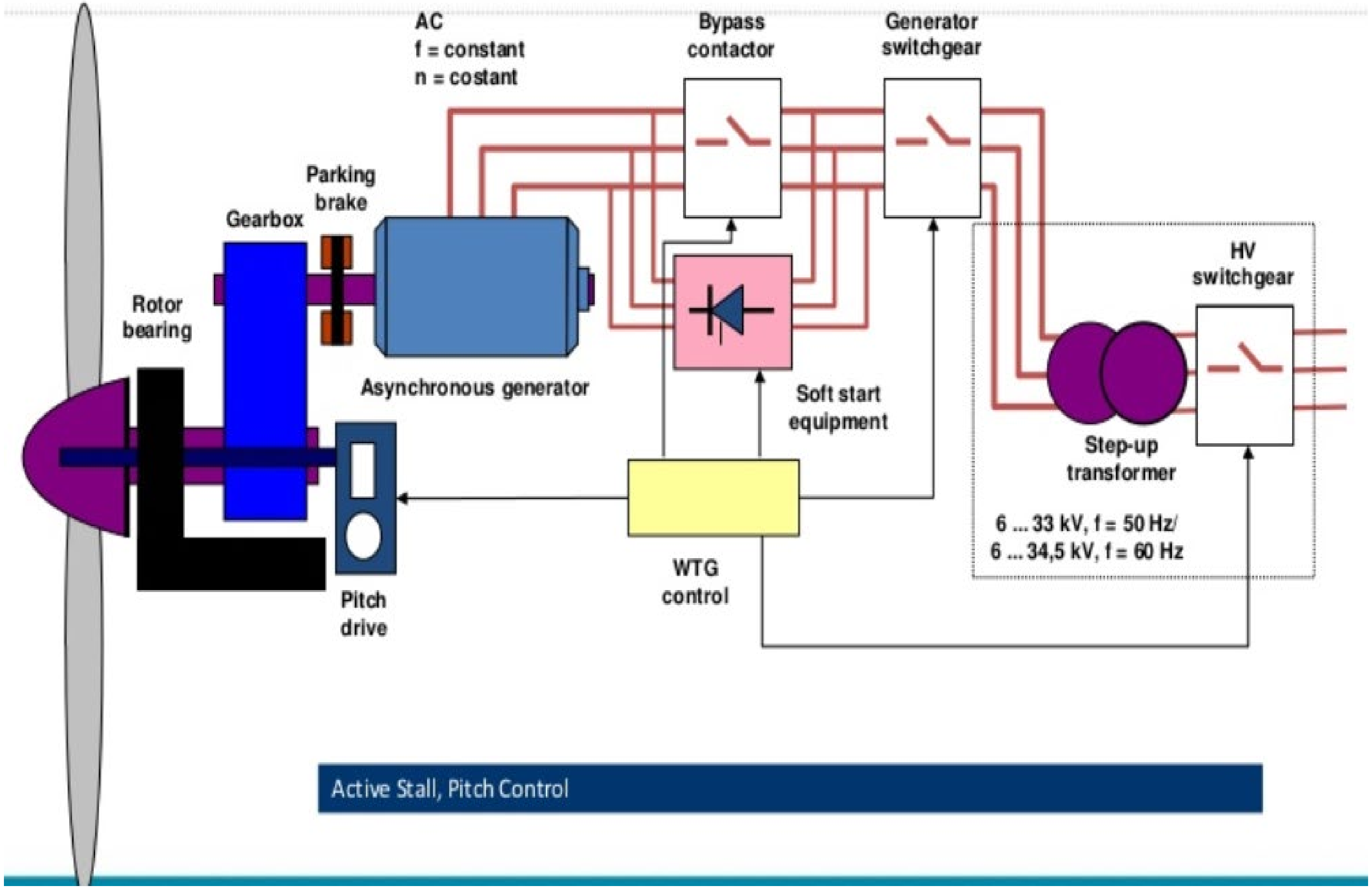
- To operate as a Generator, it must ensure speeds greater than the synchronous speed.

$$s = \frac{n_s - n}{n_s} = \frac{\omega_s - \omega}{\omega}$$

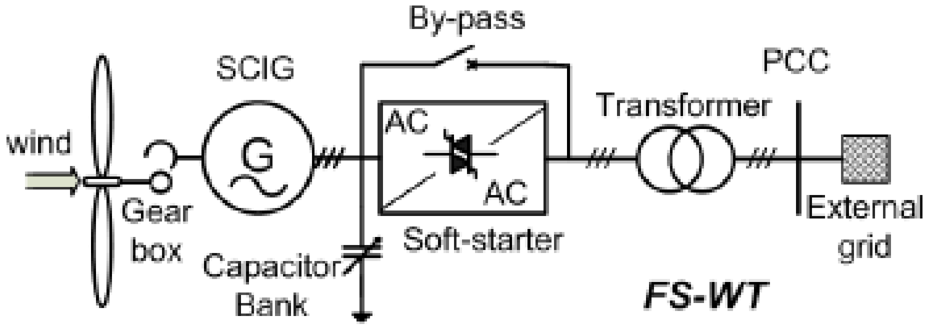
s = deslizamiento
n = velocidad del rotor
ω velocidad angular del rotor



(Type A) Fixed Speed WTG



Type A Fixed Speed WTG



Advantages.

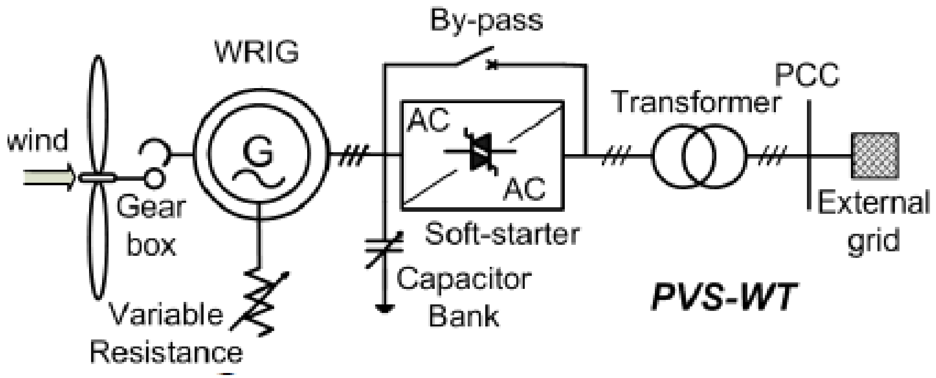
- Economic.
- Robust.

Disadvantages

- It requires a strong and stable network.
- Requires gear box and/or multi-pole motor.
- It consumes reactive power.

- Commonly use SCIG.It
- requires a capacitor bank to compensate the reactive power consumed by the machine.
- Speeds higher than the synchronous speed must be ensured on the high-speed axis.
- It requires the network to magnetize and start.
- Requires an electronic drive circuit for soft start

Type (B) Limited Variable Speed WTG



Advantages.

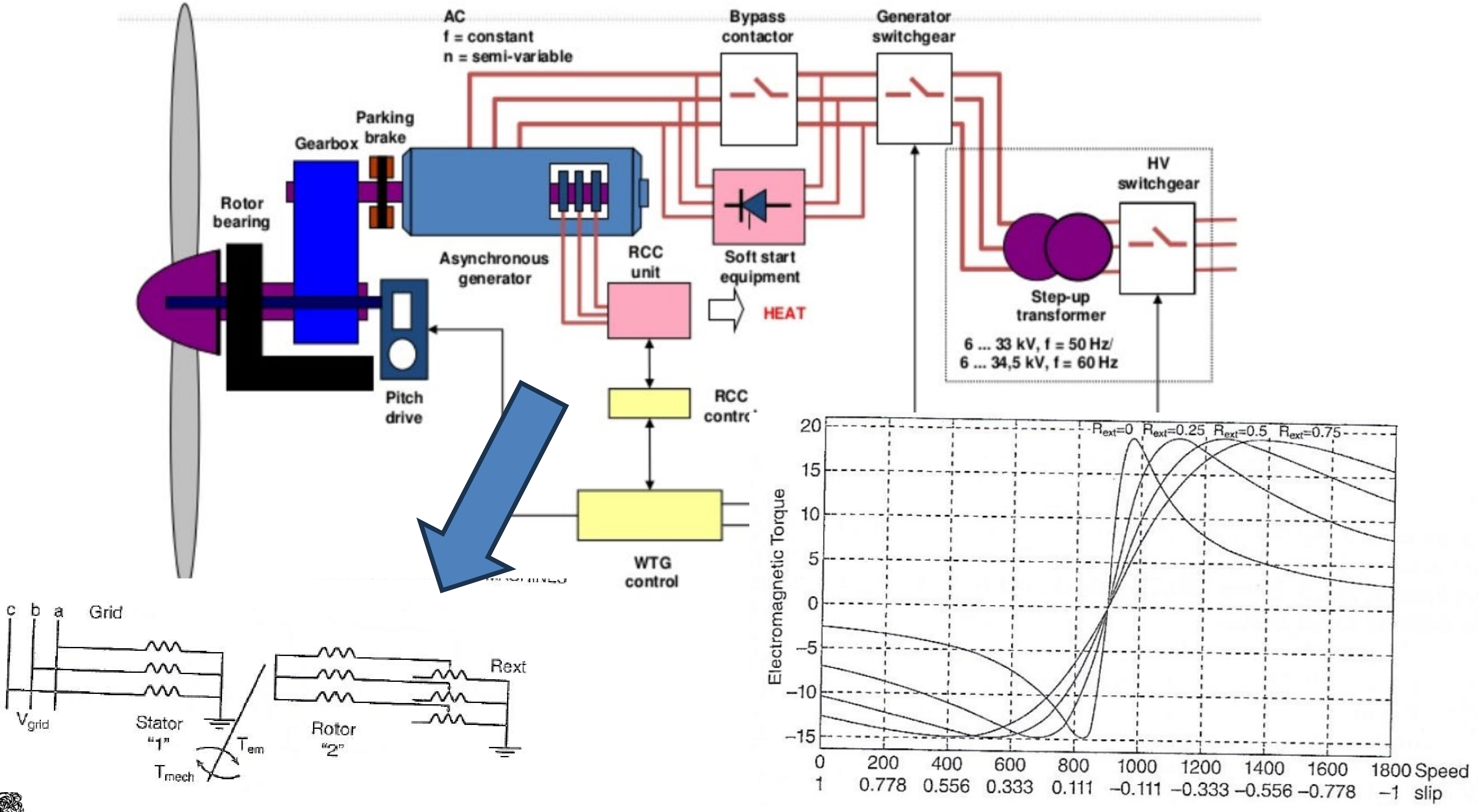
- Variable speed up to +10% of the synchronous speed..

Disadvantages.

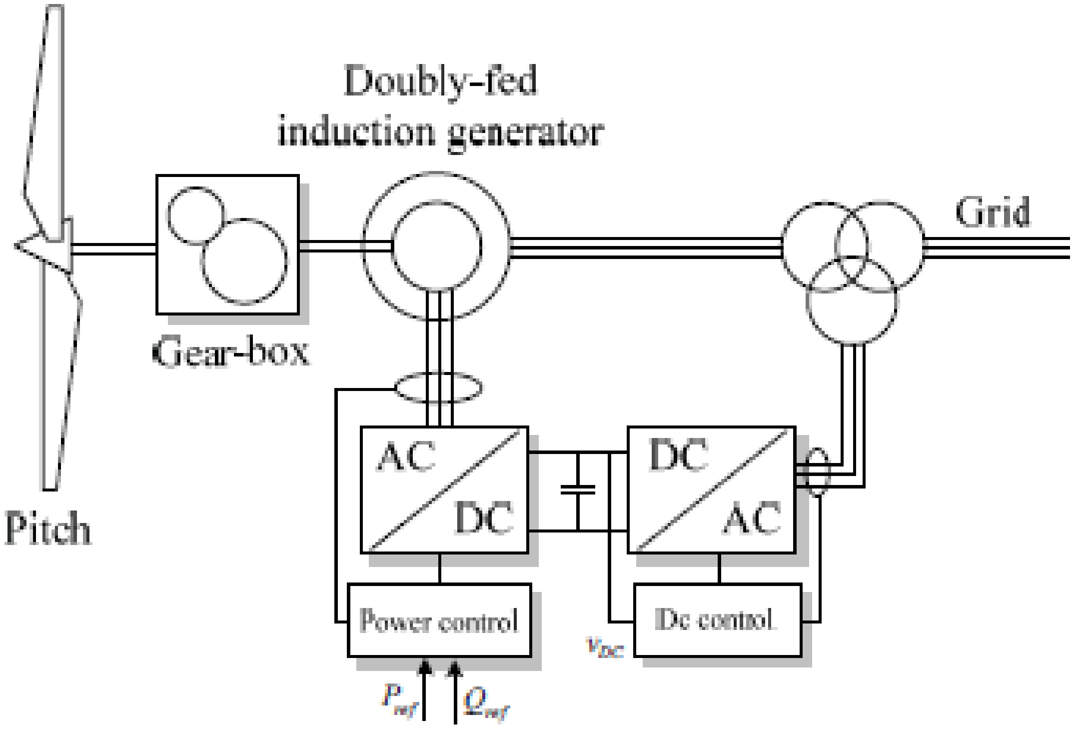
- Losses
- Maintenance.
- It consumes reactive power.

- Use WRIG.
- It requires a capacitor bank to compensate the reactive power consumed by the machine.
- Speeds higher than the synchronous speed must be ensured on the high-speed axis.
- It requires the network to magnetize and start.
- Requires an electronic drive circuit for soft start.
- It uses variable resistors connected to the rotor circuit.
- Requires gearbox

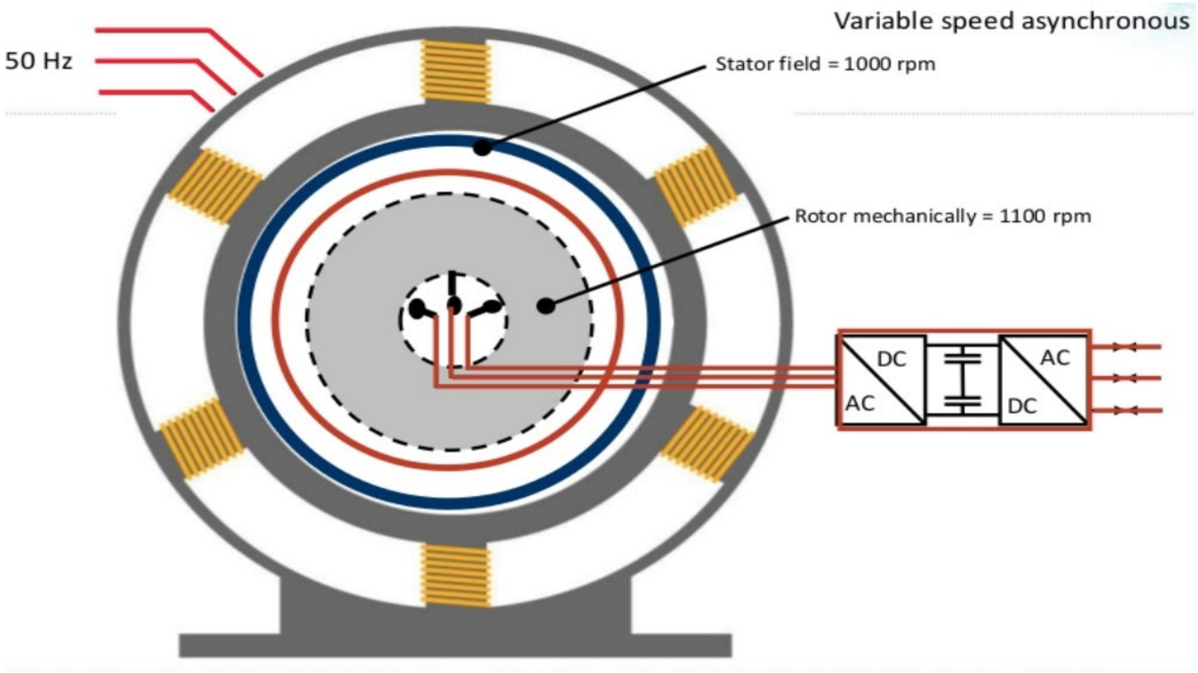
(Type B) Limited Variable Speed WTG



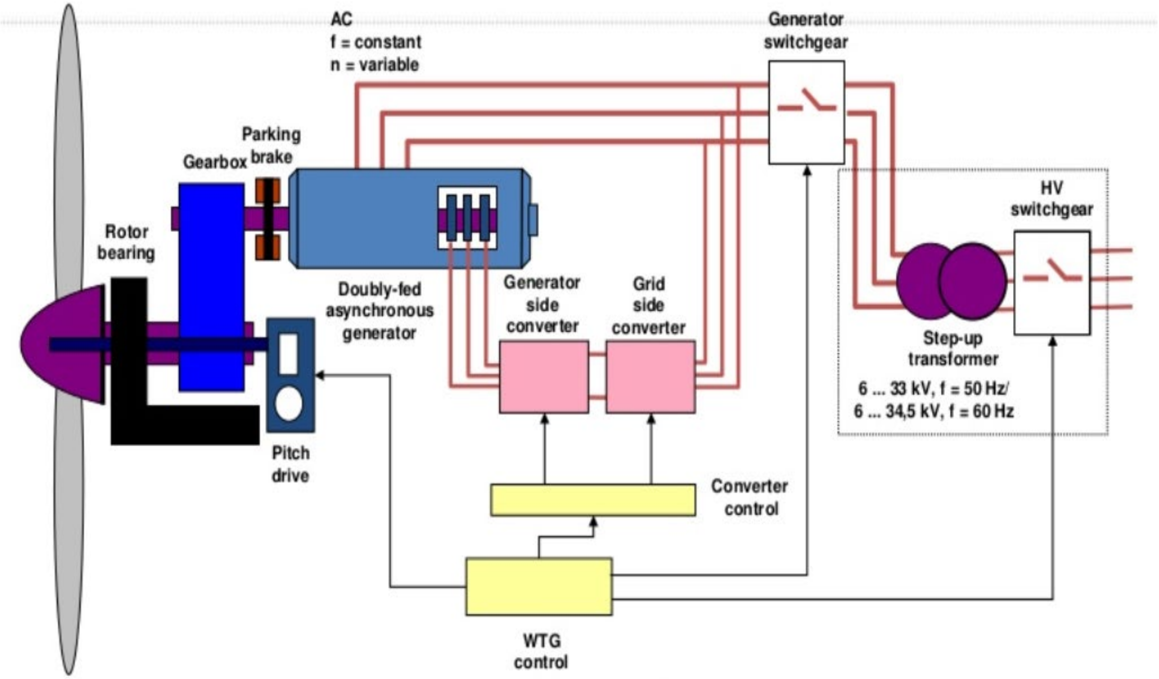
(Type C) Doubly-Fed Wound Inductor Generator



(Type C) Doubly-Fed Wound Induction Generator

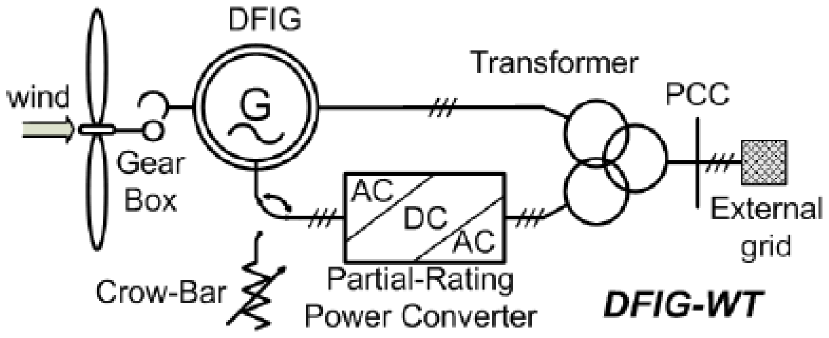


(Type C) Doubly-Fed Wound Induction Generator



2. WT Generation

(Tipo C) Doubly-Fed Wound Induction Generator. (Variable Speed)



Advantages.

- Smooth control of reactive power.
- It allows speed variations of up to 30% of the synchronous speed.
- Better efficiency as both rotor and generator can provide power

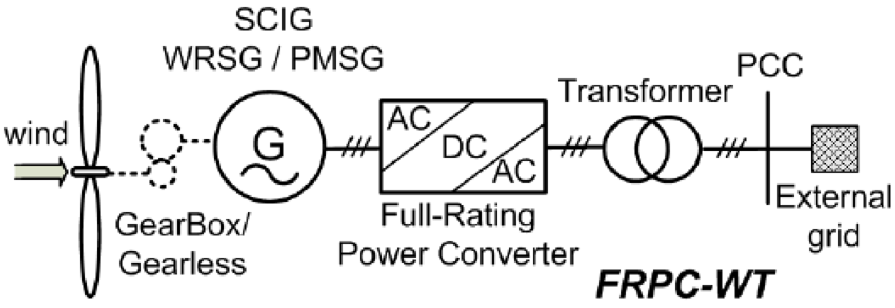
Disadvantages

- It requires high maintenance.
- Depends on the reliability of the converter

- Use WRIG.
- It uses an AC/DC-DC/AC double conversion stage connected to the rotor terminals.
- Speeds higher than the synchronous speed must be ensured on the high-speed axis.
- It requires the network to magnetize and start.
- It does not require a drive circuit with the network.
- Decoupling in the control of active and reactive power (rotor current).

2. WT Generation

(Type D) Variable Speed.



- Use WRIG, SCIG, SG, PMSG.
- It uses an AC/DC-DC/AC double conversion stage as the interface between grid and stator.
- Generates active or reactive power flow decoupling.
- The sync speed can be adjusted.
- It requires the network to magnetize and start.
- Variable speed in a wide range.
- It does not require a connection box or multipole motor.

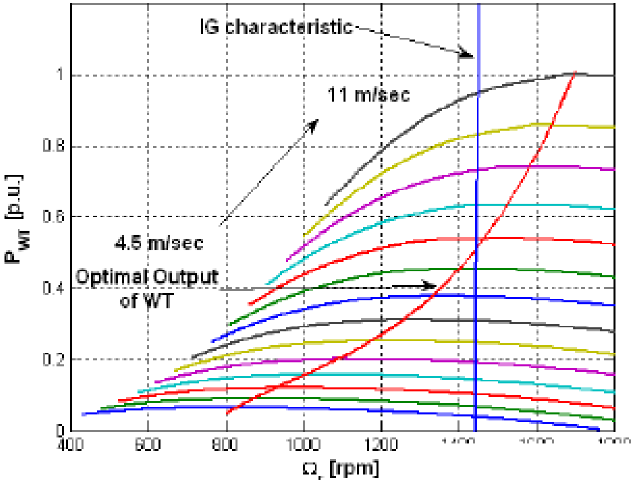
Advantages.

- Full speed control.Frequency mismatch.Independent control of P/Q.

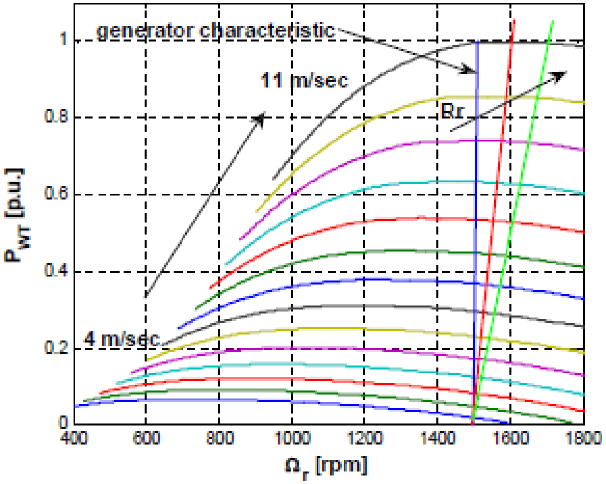
Disadvantages

- Higher cost.
- No inertia.

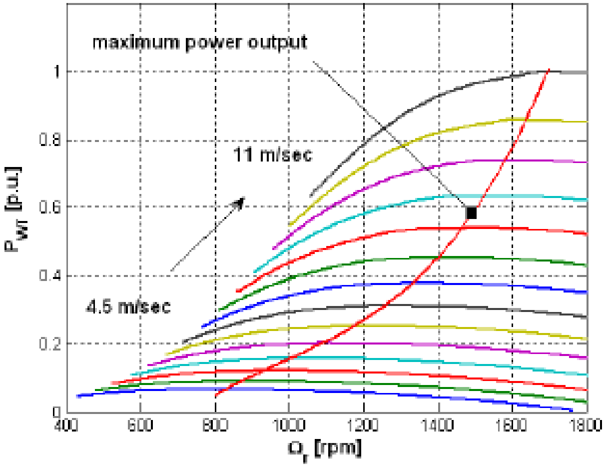
Seguimiento de MPPT.



Type A

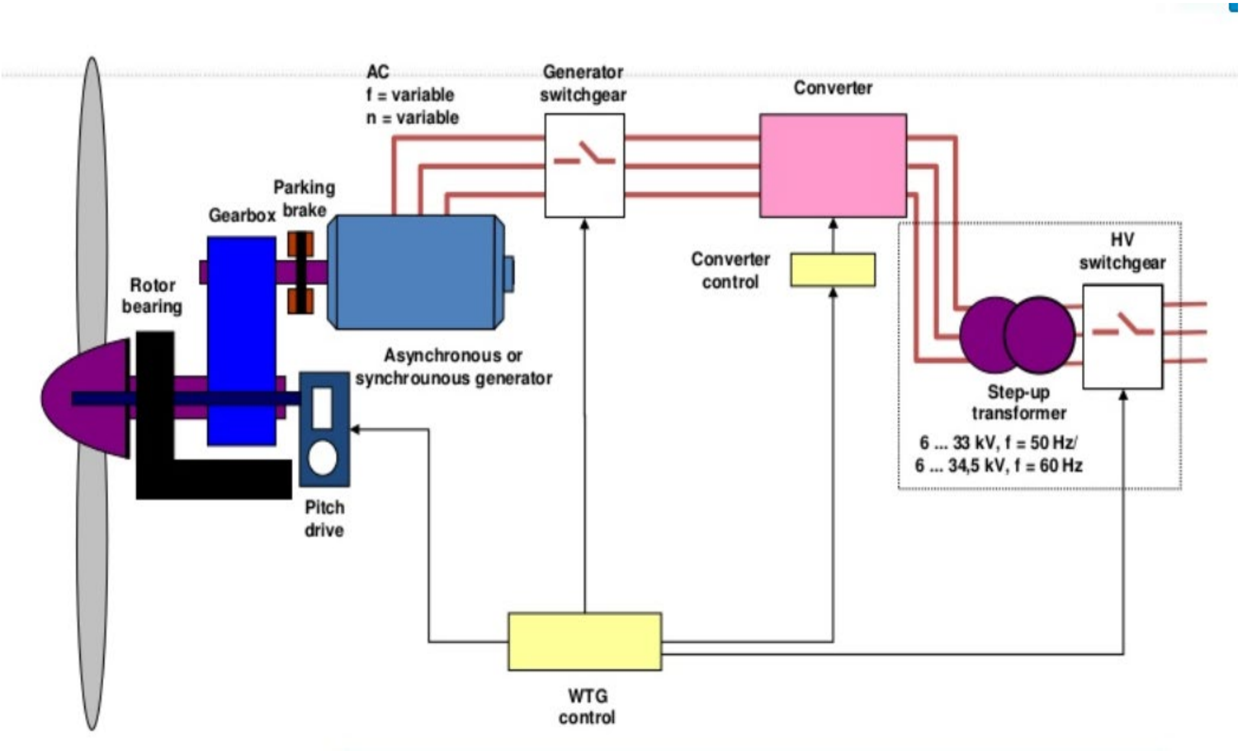


Type B

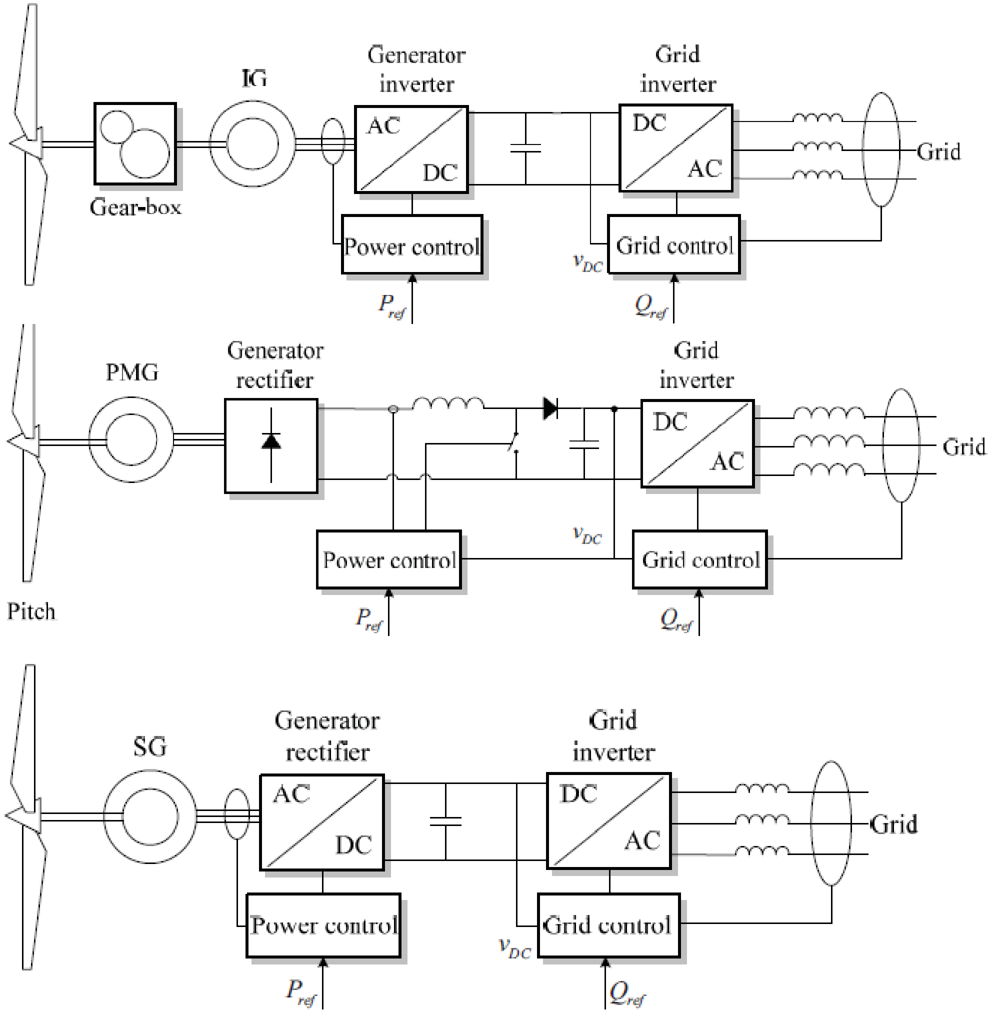


Type C&D

(Type D) Variable Speed.



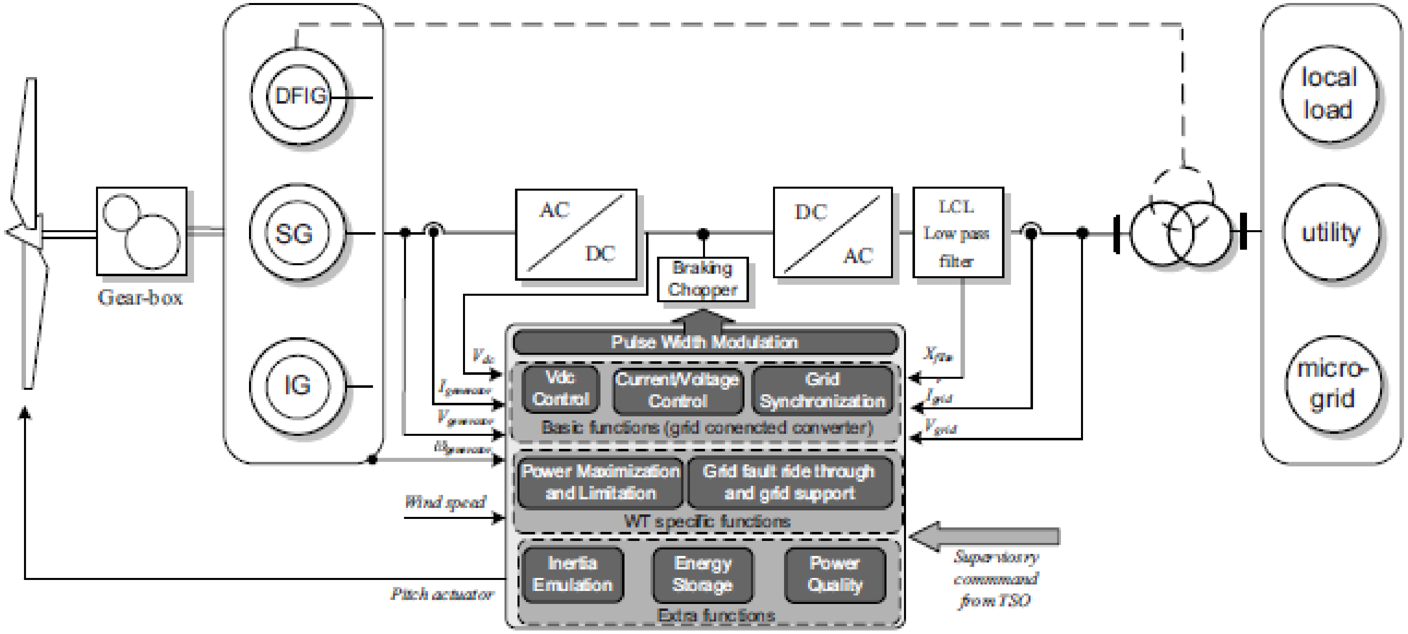
(Type D) Variable Speed.



2. WT Generation

(Tipe D) Variable Speed.

Wind turbine control structure:

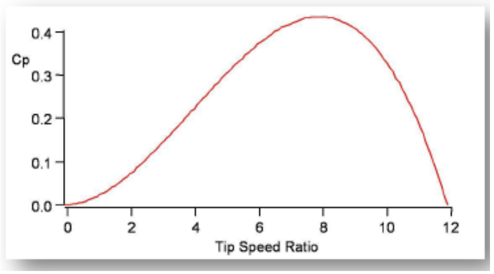


TRS (Tip Speed Ratio)

- **TRS (Tip-Speed ratio)**. Es la relación de la velocidad en punta de pala y la velocidad de viento incidente.

$$\lambda = \omega_r R \; / \; v_w$$

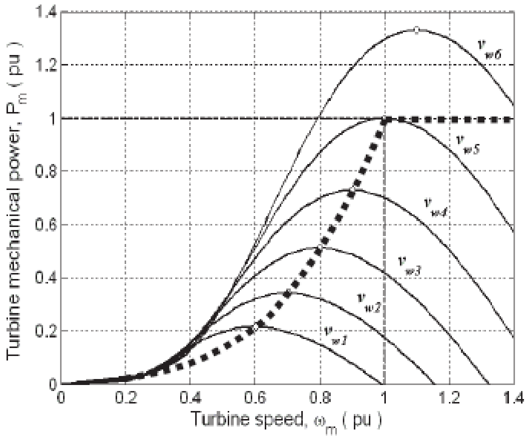
- **Cp** Depende directamente del TRS y de el ángulo de paso (Pitch)



$$P_m = 0.5\pi\rho C_p(\lambda,\beta) R^2 v_w^3$$

2. WT Generation

MPPT



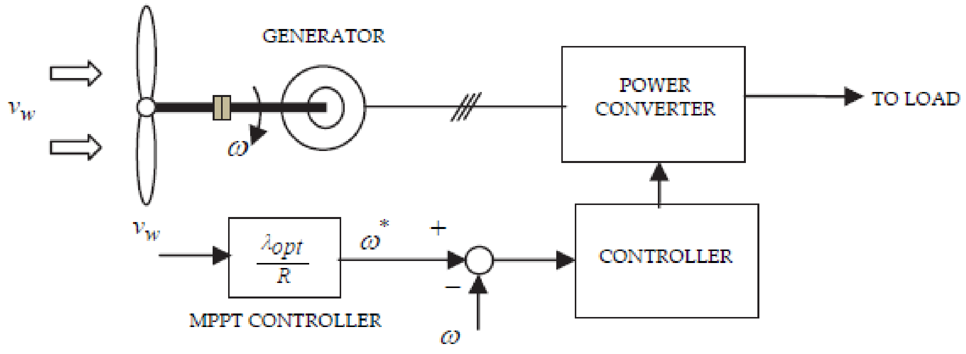
- La potencia de una determinada turbina es máxima en cierto valor de velocidad de rotor llamado **Velocidad Optima de Rotor**.

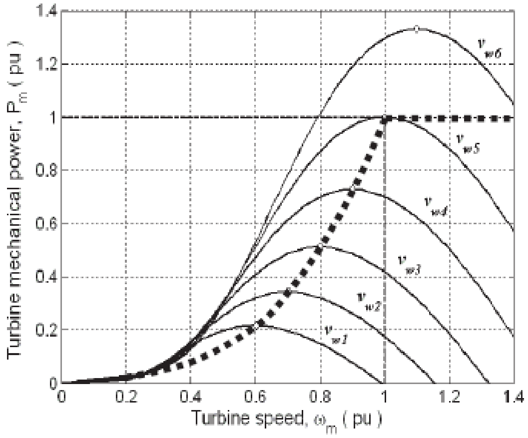
$$\omega_{opt} = \frac{\lambda_{opt} v_w}{R}$$

- Esta velocidad corresponde a un valor optimo del TRS. Entonces a este valor debe operar la turbina para asegurar MPPT.

2. WT Generation

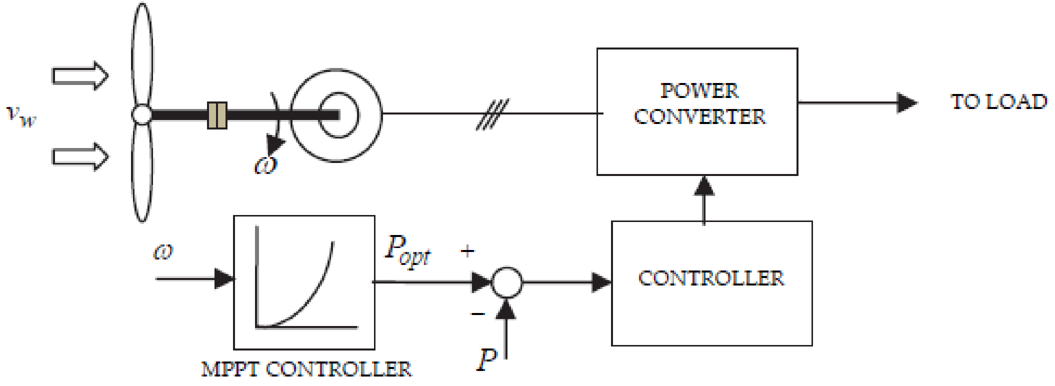
MPPT

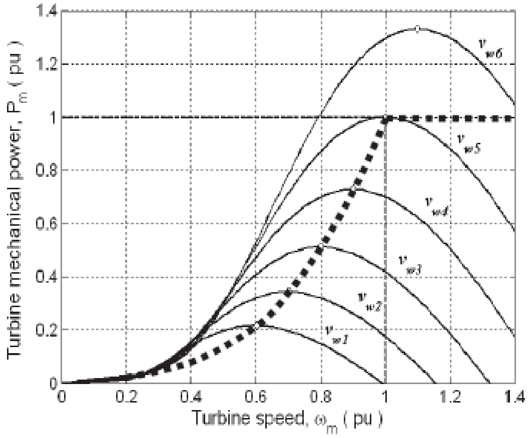




2. WT Generation

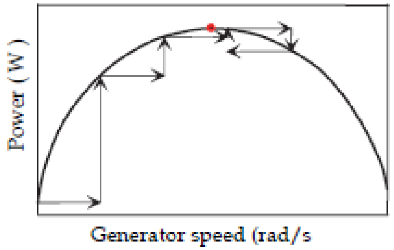
MPPT

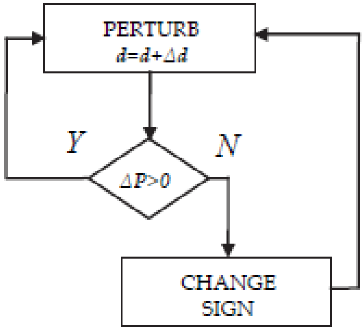




2. WT Generation

MPPT



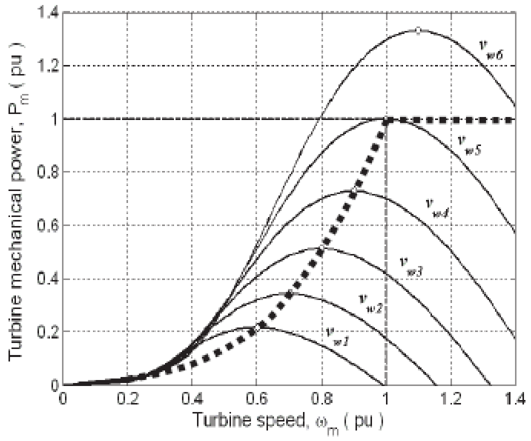

PERTURB
$d = d + \Delta d$

Y

N

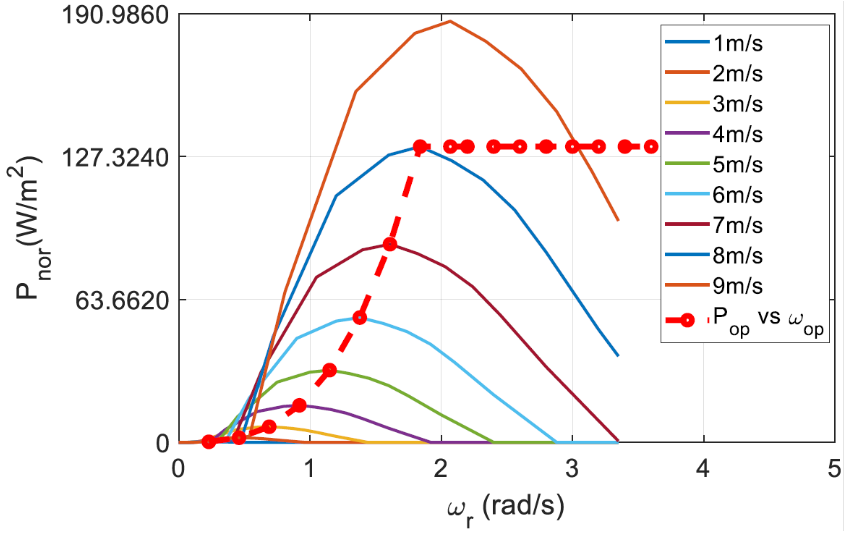
$\Delta P > 0$

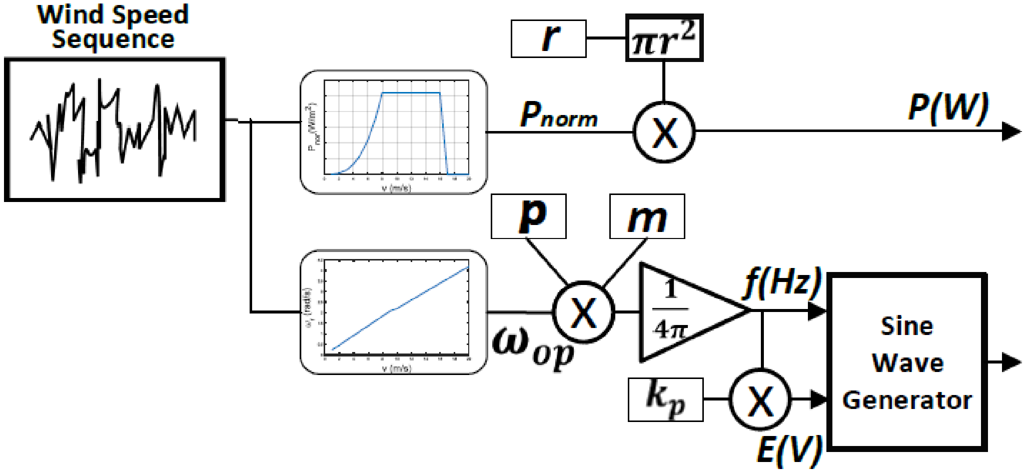
CHANGE
SIGN



Modelling of the Wind Turbine Generation.

optimal generation curve.

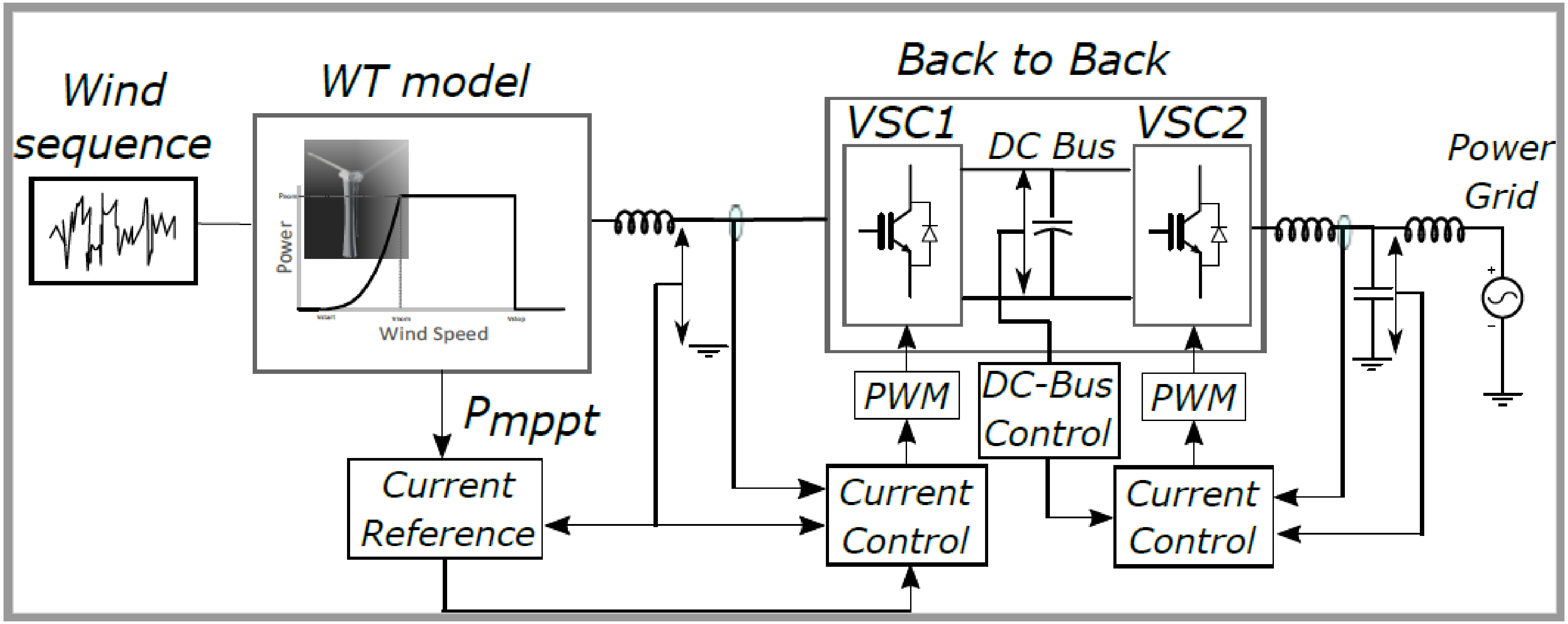




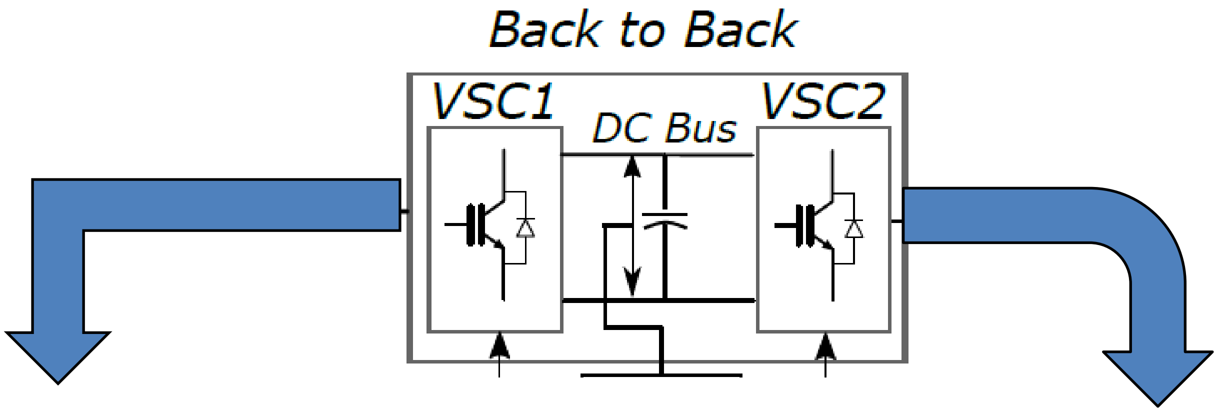
$$f = \frac{\omega_r * p * m}{240 * \pi}$$

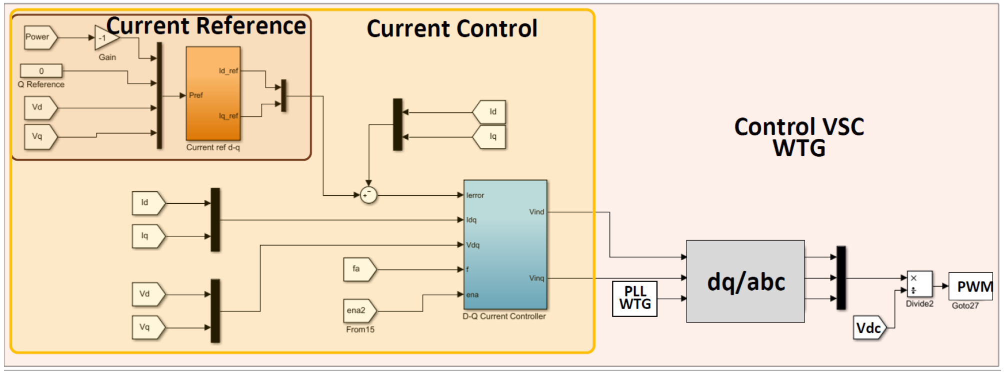
$$E = k_p * f$$

Convertion Stage

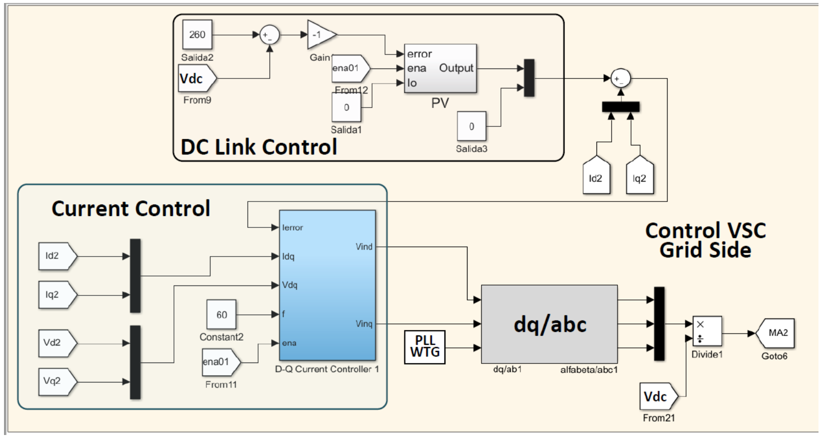


Convertion Stage





Power Control loop.



DC Voltage control loop.

Simulation10 File.