International Solar Alliance Expert Training Course

Solar PV Inverters

In partnership with the Clean Energy Solutions Center (CESC)

Professor Oriol Gomis-Bellmunt

September 2019

Supporters of this Expert Training Series

INTERNATIONAL SOLAR ALLIANCE

CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY
An Initiative of the Clean Energy Ministerial

CARBON TRUST

Expert Trainer: Prof Oriol Gomis-Bellmunt

- Professor in the Electrical Power Department of Technical University of Catalonia (UPC)
- Directive board member of the research group CITCEA-UPC, where he leads the group of power systems dominated by power electronics, including renewable energy (PV and wind), HVDC transmission systems and other power converter based systems (energy storage, EV chargers)
- 20+ years of experience in the fields of renewable energy, power electronics and power systems. Involved in a number of research projects and contracts of technology transfer to industry.
- Coauthor of 3 books, 7 patents and > 100 journal publications, mainly in the field of power electronics in power systems and grid integration of renewables.
- Supervision of 18 doctoral theses and >60 Bachelor and Master theses.

4. Technical Integration of Solar	Introduction to Technical Integration of Solar PV
	Smart grids and PV Integration
	Solar PV Inverters
	PV power plants layouts
	Grid support to the grid from PV power plants - Grid codes
	Power plant controllers
	Planning - Distribution network with distributed PV
	Planning - Transmission network with large scale PV power plants

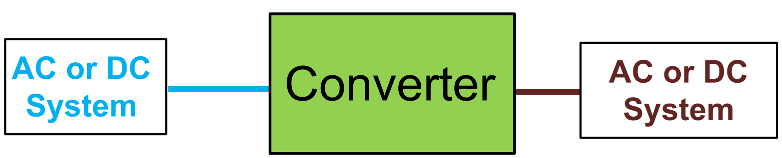
Outline

- Basics of converters
- Electric circuits fundamentals
- Solar inverters functionalities
- I-V and P-V characteristics
- Maximum power point tracking
- Control principles
- Single / two stage inverters
- Galvanic isolation / Anti-islanding detection
- Inverter technologies

Power electronics converters

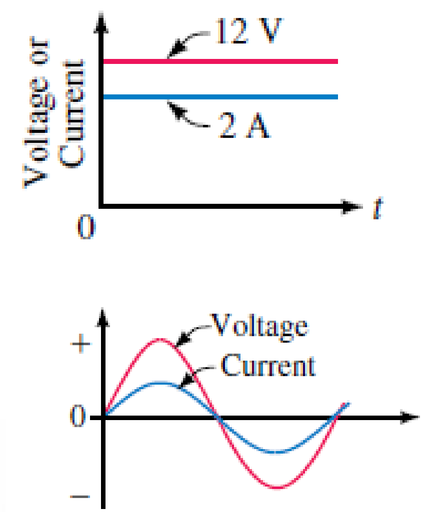
- Power electronics converters are used to exchange power in a controllable way between two electrical systems (electrical power source and sink).

- The two systems can be divided into
  - Direct current systems (DC)
    - Monopolar / Bipolar
  - Alternating current systems (AC)
    - AC frequency (typically 50 or 60 Hz)
    - Single phase / three phase



Fronius

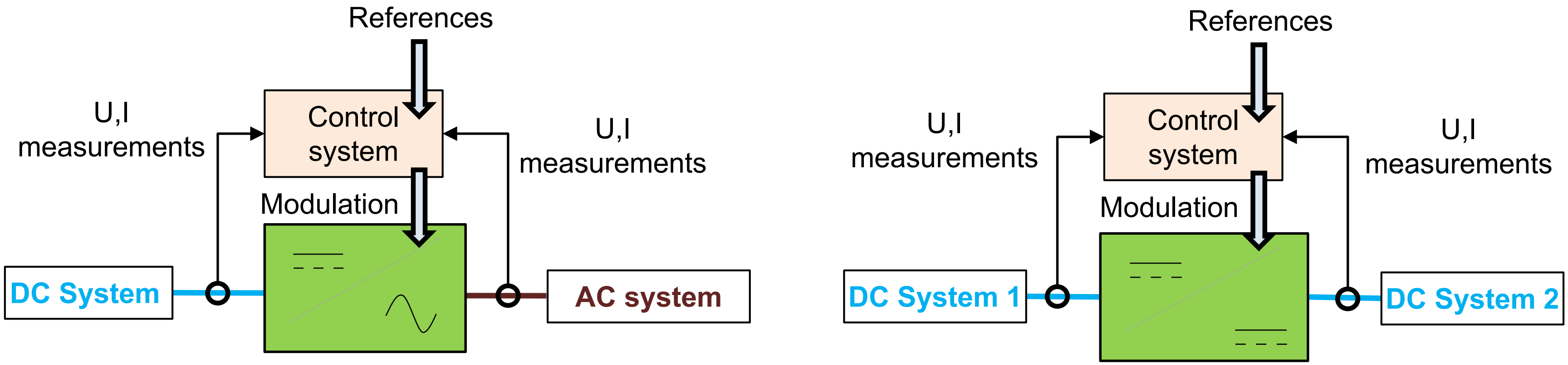
Solar Edge



Robins & Miller "Circuit analysis theory and practice"

Power electronics converters

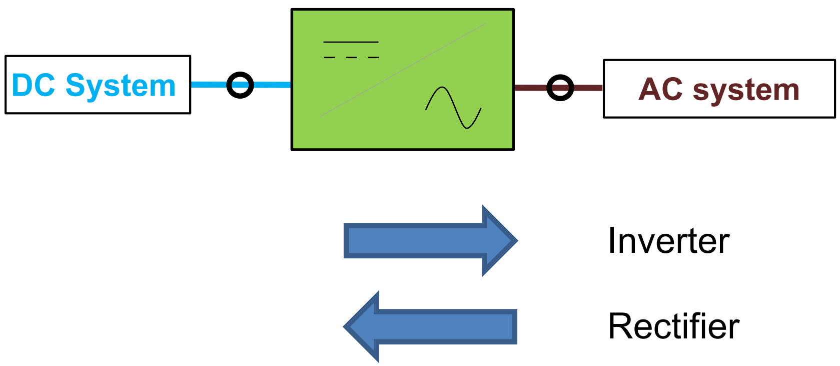
- Power converters can be AC-DC (or DC-AC), DC-DC or AC-AC

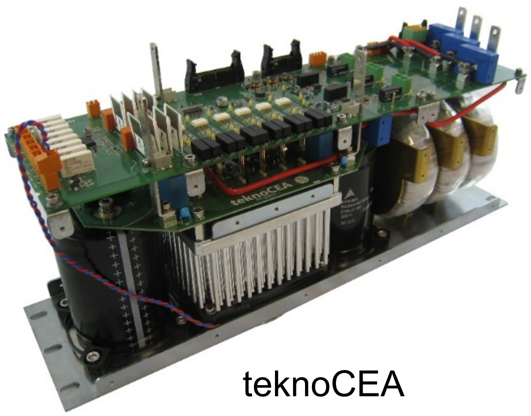


- The converter controls
  - measures the relevant voltages and currents
  - implements the control algorithms to track references
  - applies the appropriate modulation in the converter

AC-DC converters

- AC/DC Converters can be:
  - Rectifiers – Power flows from the AC side to the DC side
    - Example: Electrical vehicle charger
  - Inverters – Power flows from the DC side to the AC side
    - Example: Solar inverter
  - Bidirectional- Operates on both modes depending on conditions
    - Example: Battery converter in microgrid applications

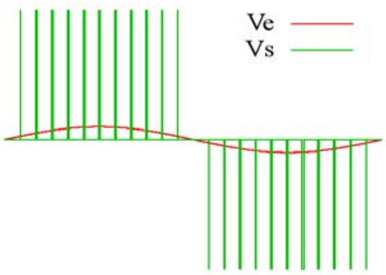




teknoCEA

Voltage source converters (VSC)

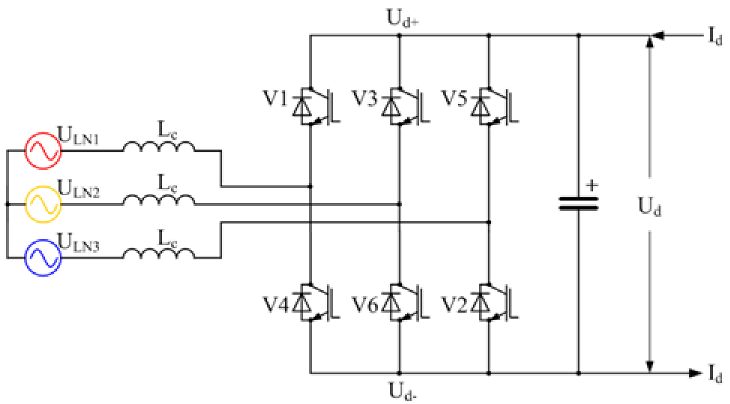
- Voltage source converters (VSC) are typically employed in AC-DC converters applications
- VSC are bidirectional and can potentially operate as rectifiers or inverters
- VSC can independently control active and reactive exchanges with the AC system.
- VSC can apply the desired AC voltage, by modulating the existing DC voltage in the AC side

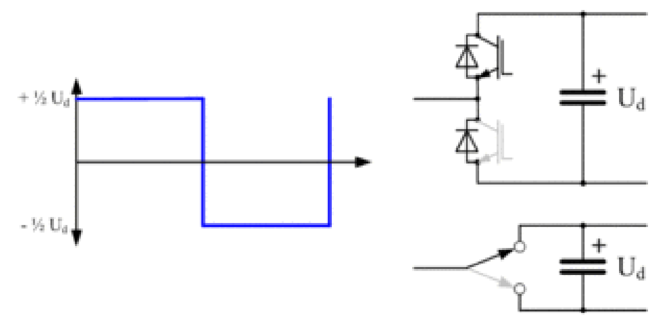


teknoCEA

2-level VSC

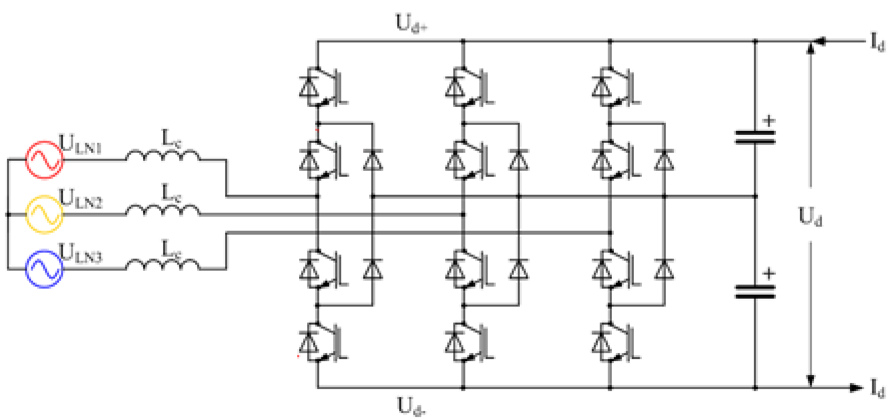
- Two level converters can modulate the voltage with two possible levels (positive and negative voltages)
- They are used for low power applications.
- To have good quality on the waveforms, high switching frequency is needed. Losses increase with switching frequency → Trade-off between power quality and losses.

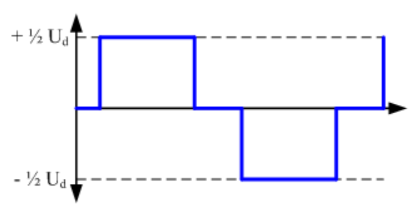


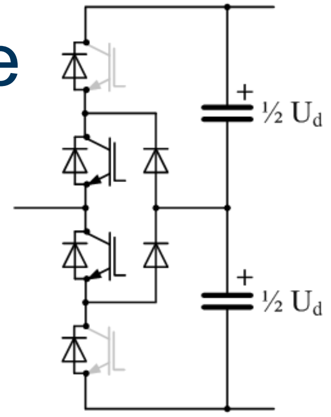


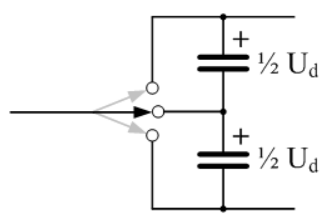
3-level VSC

- Three level converters can modulate the voltage with three possible levels (positive, zero and negative voltages)
- They are used for higher power applications
- The three-level converter allows to reduce switching frequency and losses



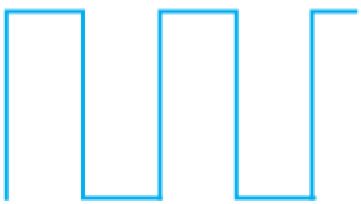




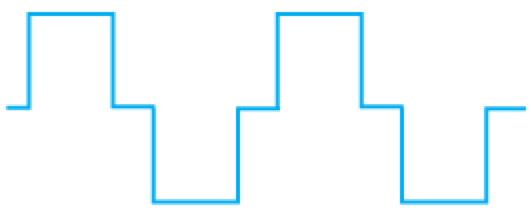


Comparing two-three level

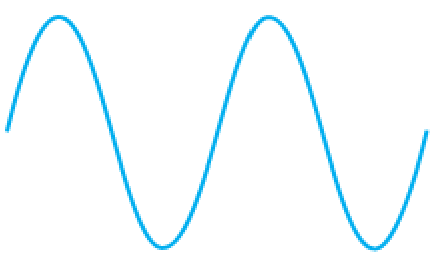
- The square waveform has a THD (Total Harmonic Distortion) of about 45 %.
- With the so-called modified sine wave (three level square wave) it can be reduced to 24 %
- In both cases, pulse width modulation can allow to have very good power quality, but with associated losses.



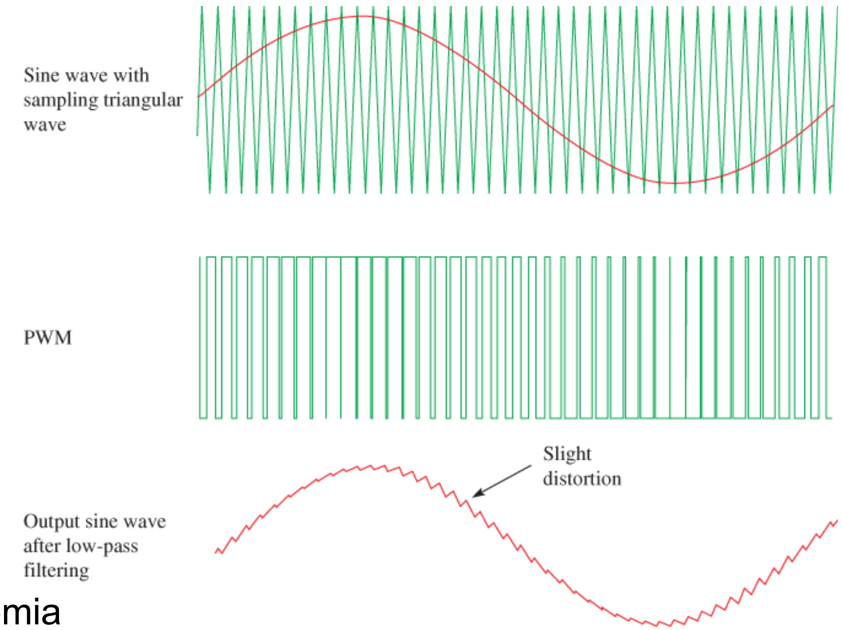
(b) Square wave



(c) Modified sine wave



(a) Sine wave



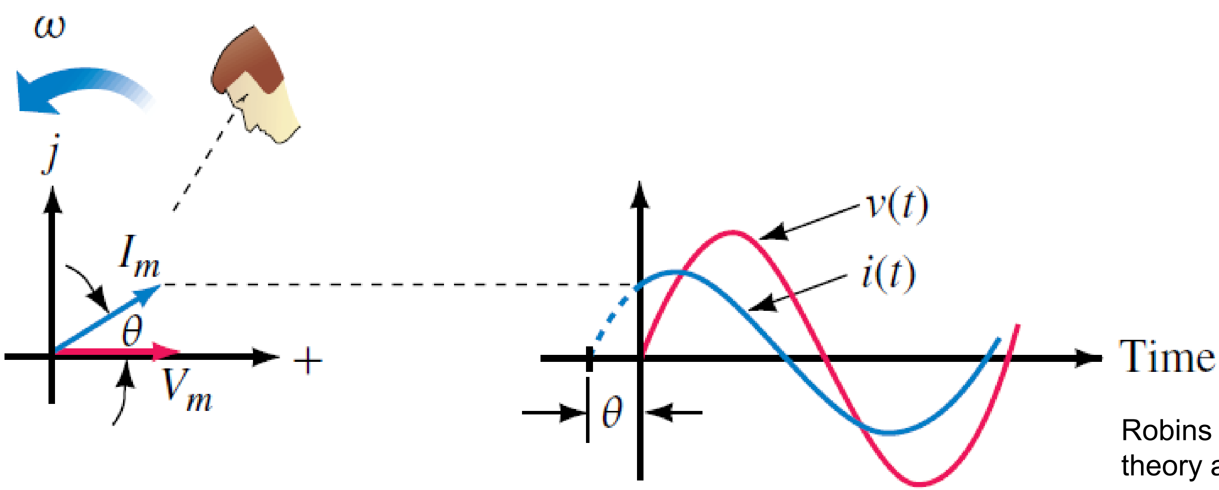
Ahmed Faizan, Electrical academia

AC systems basics

- Voltages and currents can be defined by phasors

$$x(t) = \sqrt{2} \cdot X \cos(\omega t + \alpha)$$

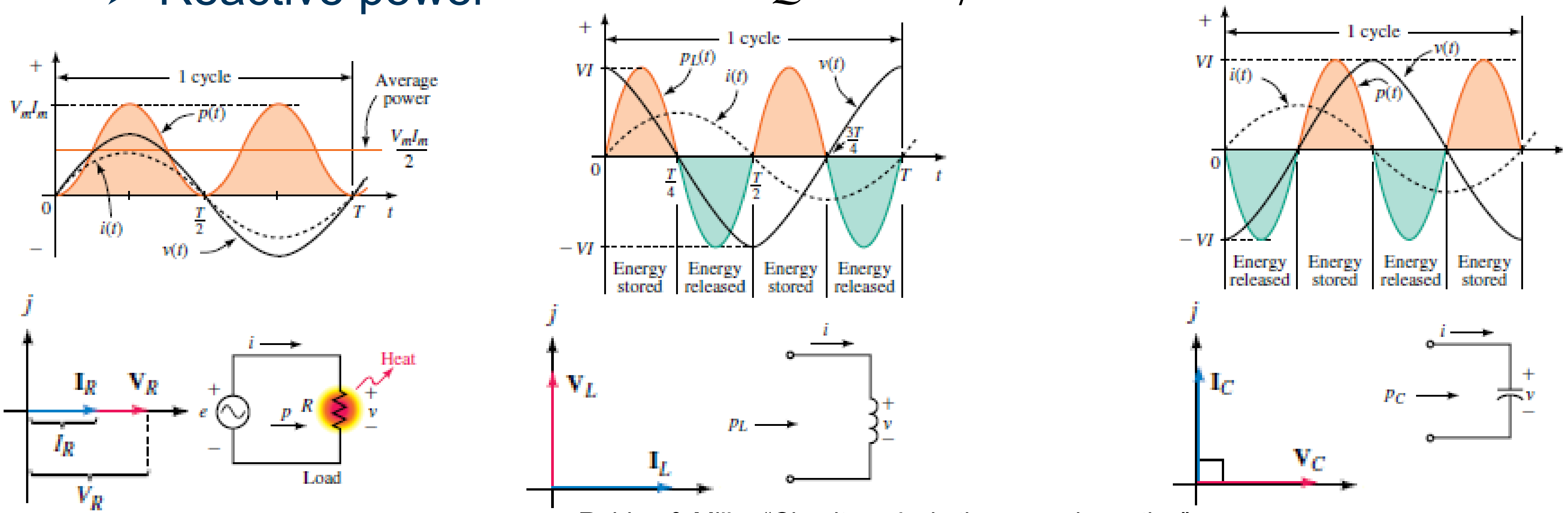
$$\underline{X} = X_{\angle\alpha} = Xe^{j\alpha} = a + jb = \underbrace{X\cos\alpha}_{a} + j\underbrace{X\sin\alpha}_{b}$$



Robins & Miller “Circuit analysis theory and practice”

Power in AC systems

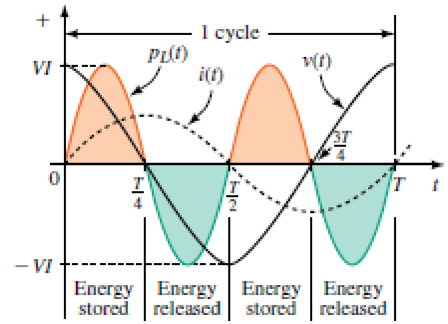
- Real power is oscillating for single phase AC systems but constant for three phase balanced systems.
  - Apparent complex power $\underline{S} = P + jQ = \underline{U}\,\underline{I}^*$
  - Apparent power $S = VI$
  - Active (real) power $P = S\cos\varphi$
  - Reactive power $Q = S\sin\varphi$

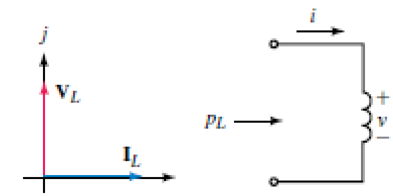


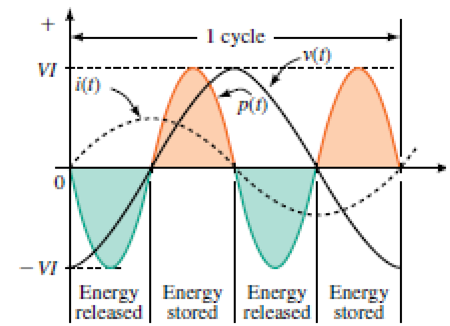
Robins & Miller “Circuit analysis theory and practice”

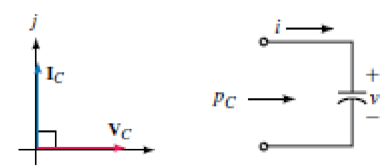
What is reactive power?

- In AC systems, there can be currents with associated average power of 0 (considering ideal inductances or capacitors for example). The current flows but no active power is exchanged. There is power coming back and forth from the grid at double the grid frequency, but the average is 0.
- Reactive power helps us to quantify this phenomenon.
- Reactive power leads to additional losses in the system (associated to the so-called reactive currents) and need for oversizing equipment. Compensation equipment will be used in many applications.
- Reactive power is used for voltage control in transmission and distribution systems. This will be shown in the next slides.









Robins & Miller "Circuit analysis theory and practice"

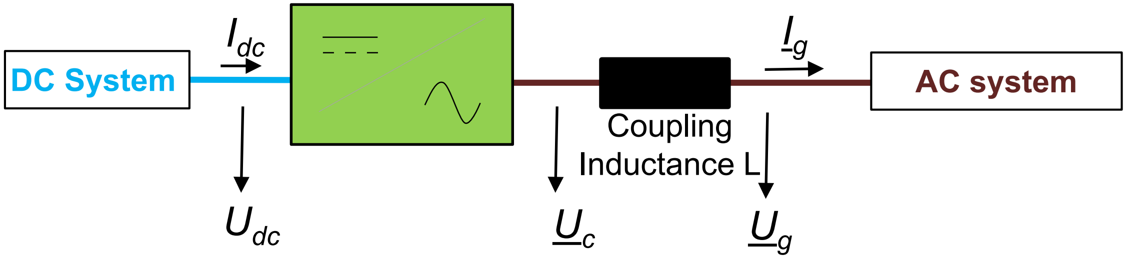
VSC operation principle

- The converter references set the **active** and **reactive power** to be exchanged with the grid
- Referencing the system to $\underline{U}_g = U_g + 0j$, the current to be injected to the grid can be calculated

$$\underline{S} = P + jQ = \underline{U}_g \underline{I}_g^* \rightarrow \underline{I}_g = \frac{(P+jQ)^*}{\underline{U}_g^*} = \frac{P - jQ}{U_g}$$

- This current can be obtained adjusting the converter voltage as (which can be modulated by the VSC)

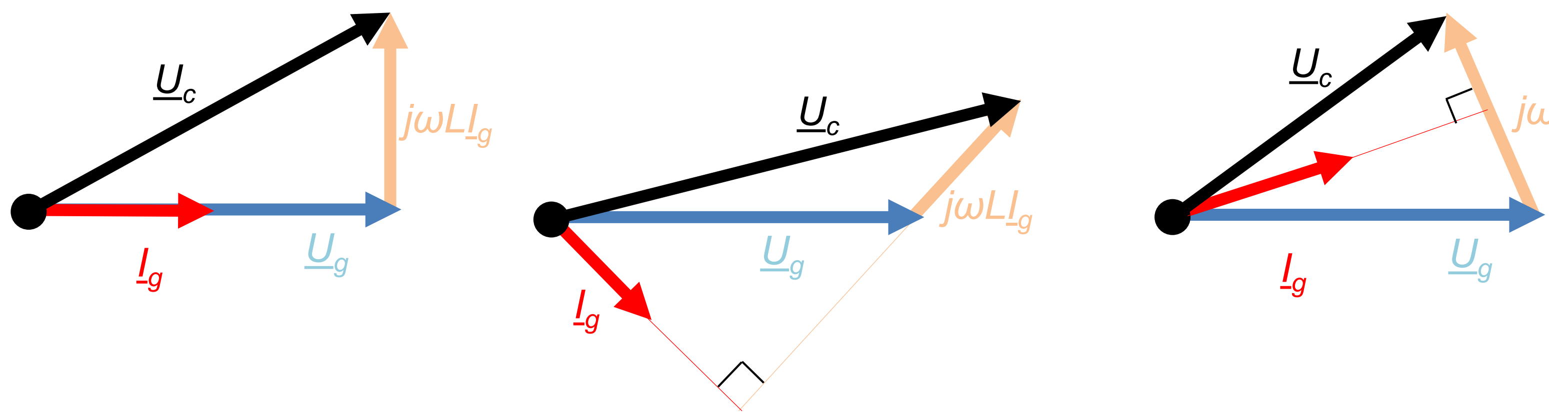
$$\underline{U}_c = \underline{U}_g + j\omega L \underline{I}_g$$

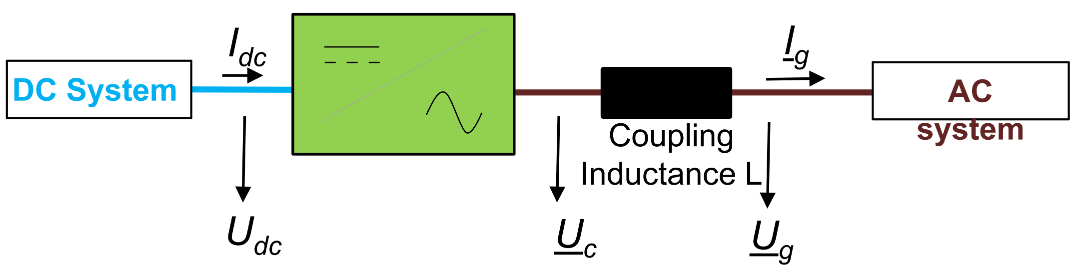


VSC operation principle

$$\underline{S} = P + jQ = \underline{U}_g \underline{I}_g^* \rightarrow \underline{I}_g = \frac{(P + jQ)^*}{\underline{U}_g^*} = \frac{P - jQ}{U_g}$$

$$\underline{U}_c = \underline{U}_g + j\omega L \underline{I}_g$$





Solar PV Inverters

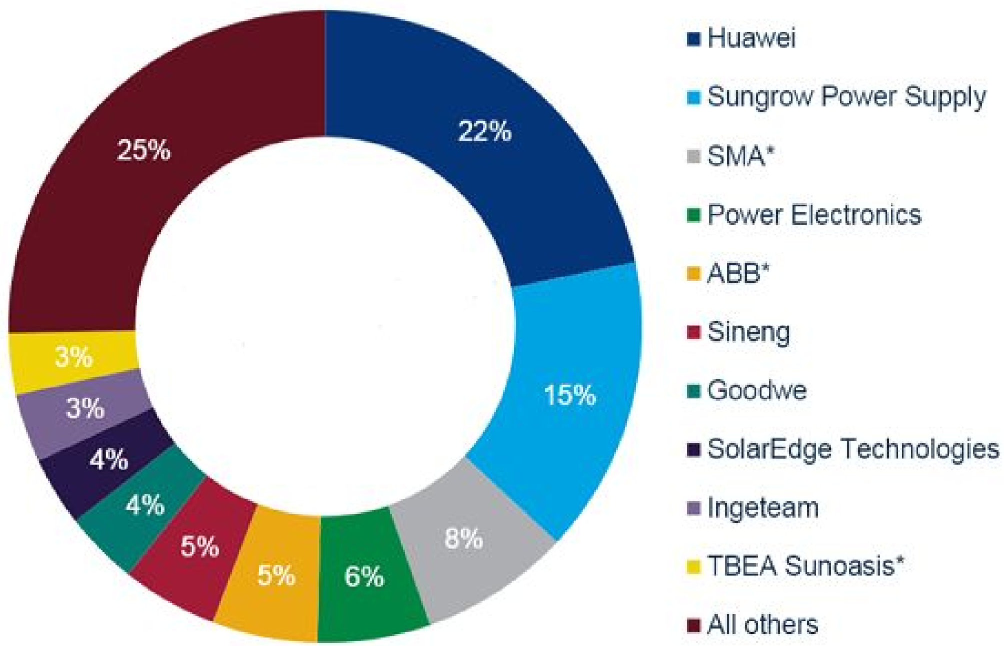
Solar PV Inverters convert the DC output of photovoltaic (PV) solar panels or strings of panel into a AC current which is injected to the grid (or load).

Solar PV inverters have the following functions :

- DC/AC conversion and voltage adaptation
- Maximum power point tracking
- Anti-islanding protection
- Synchronization with the grid
- Support to the grid where the PV system is connected

PV inverters market

Global PV inverter market shares by shipments for full-year 2018 (MWac)***



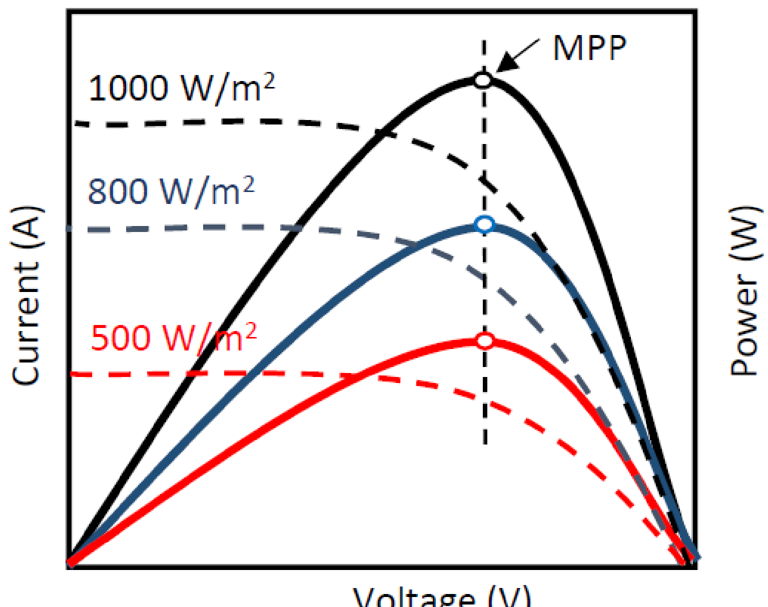
*Estimate
**"All others" includes vendors that rank below the top 10 in market share
***Vendor market shares are accurately represented, but the total pie chart may not equal 100% due to rounding

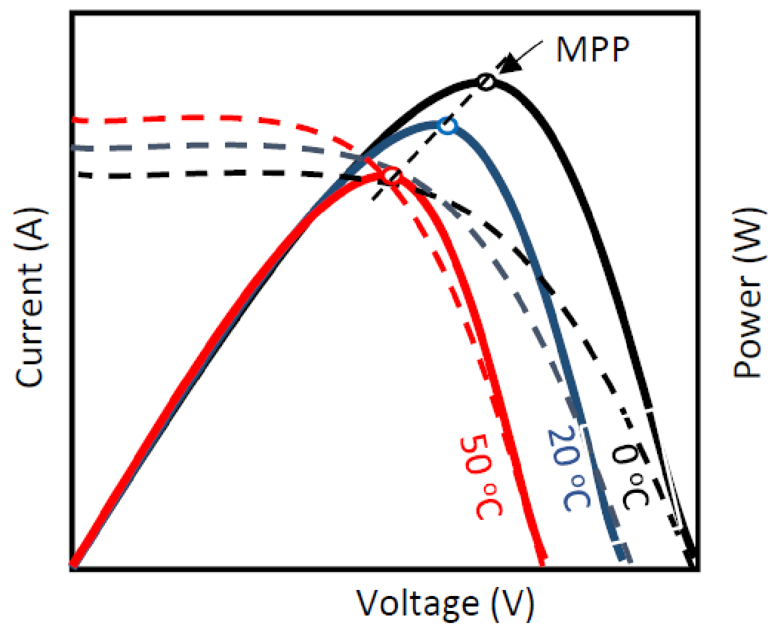
Source: Wood Mackenzie Power & Renewables

PV magazine

I-V and P-V characteristics

- I-V and P-V change for different radiations and temperatures.
- The voltage that maximizes power productions changes and needs to be tracked.





Ana Cabrera, doctoral thesis, UPC 2017

Maximum power point tracking (MPPT)

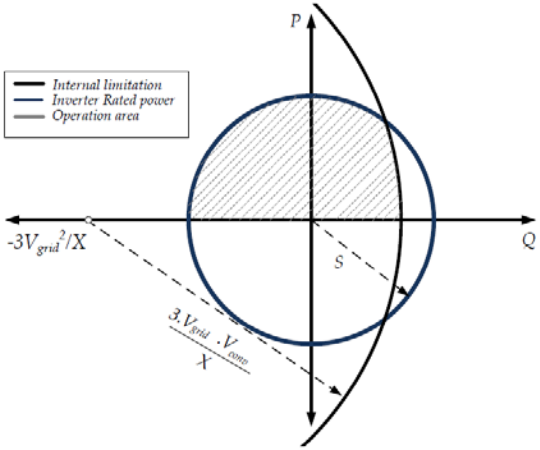
The converter can modify the DC voltage to track the maximum power.

Different methods can be used:

- Constant voltage method
- Short-Current Pulse Method
- Open Voltage Method
- Perturb and Observe Methods
- Incremental Conductance Methods
- Temperature Methods

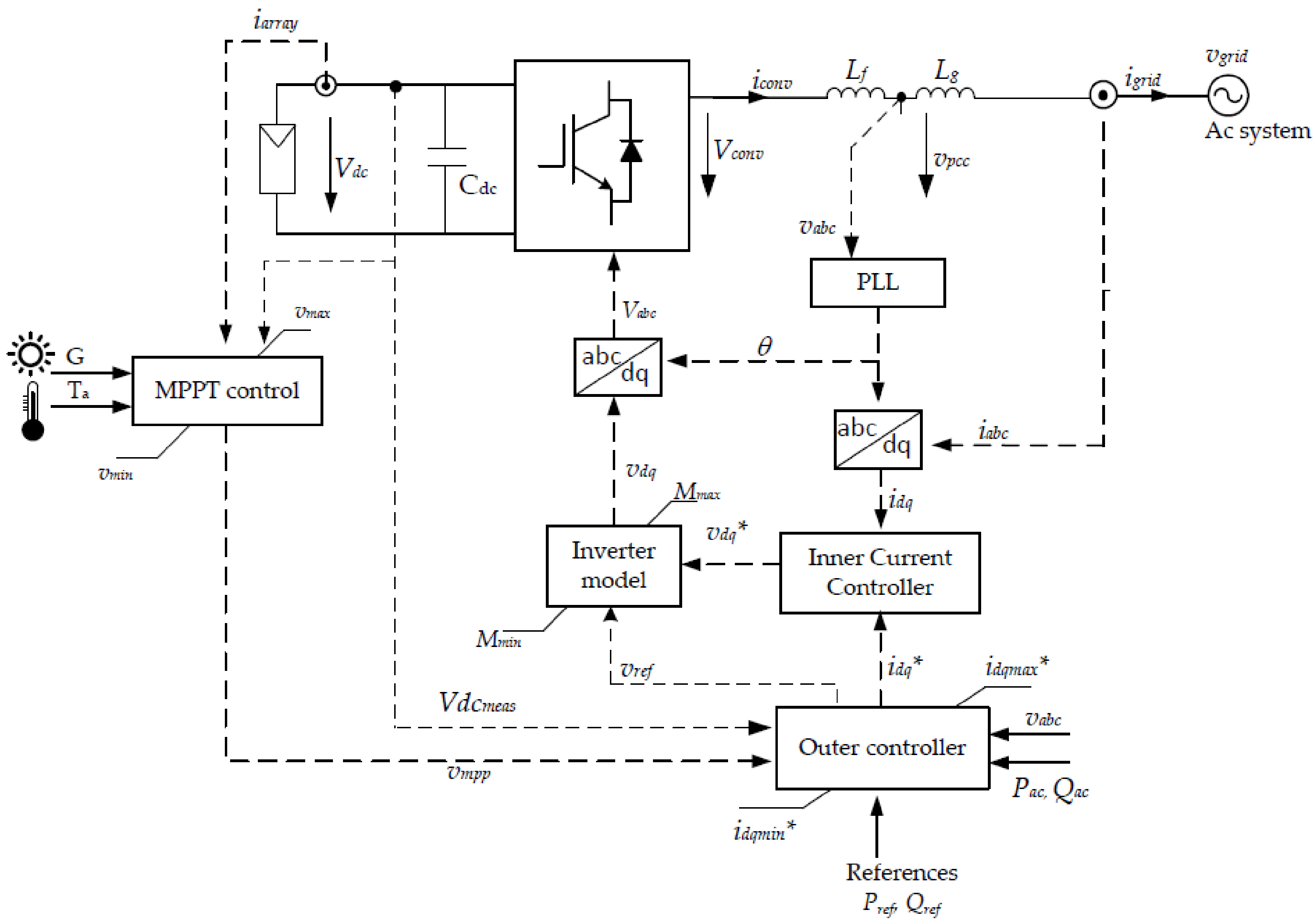
Solar inverter control principles

- The converter can control the active and reactive currents:
  - Active current is used to control active power (to curtail the maximum power available in the panels) or the DC voltage (to do the MPPT).
  - Reactive current can be adjusted to the desired reference considering the converter limits (capability curves)



Ana Cabrera, doctoral thesis, UPC 2017

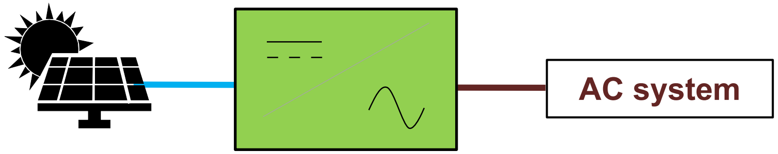
Solar inverter control



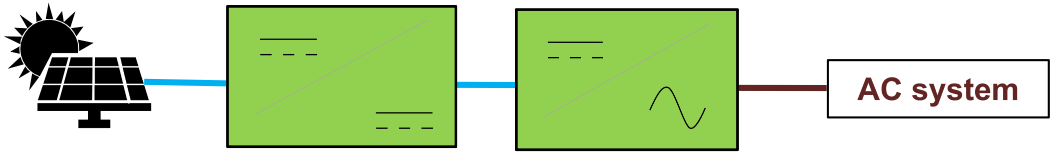
Ana Cabrera, doctoral thesis, UPC 2017

PV Inverters with 1 or 2 stages

- 1 stage converters, directly convert the output DC voltage from the panels to AC current. During MPP tacking, there may be limitations in the AC voltage, the converters can modulate and provide reactive power capability.

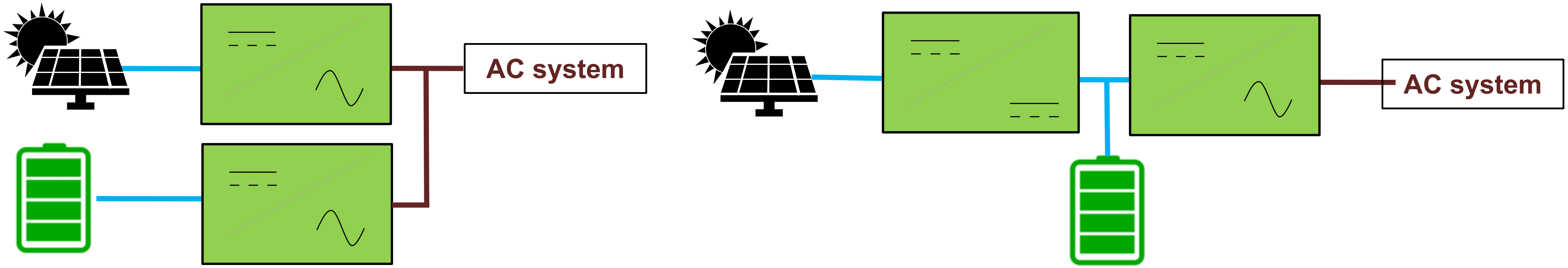


- 2 stage converters, convert the DC output from the panels to a constant DC voltage. In a second stage they convert the DC voltage to ac voltage.



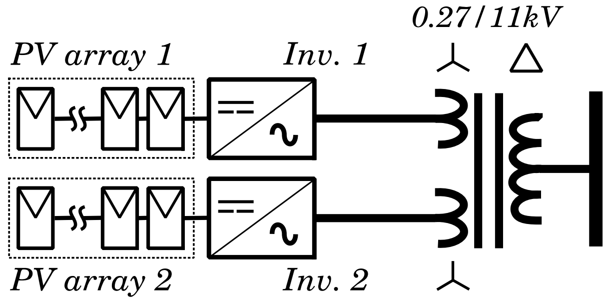
Integration with storage

- Storage systems can be used and connected to the AC or DC side.
- PV Inverters with two stages allow a better integration of the energy storage system, which in some cases can be directly connected to the DC bus.



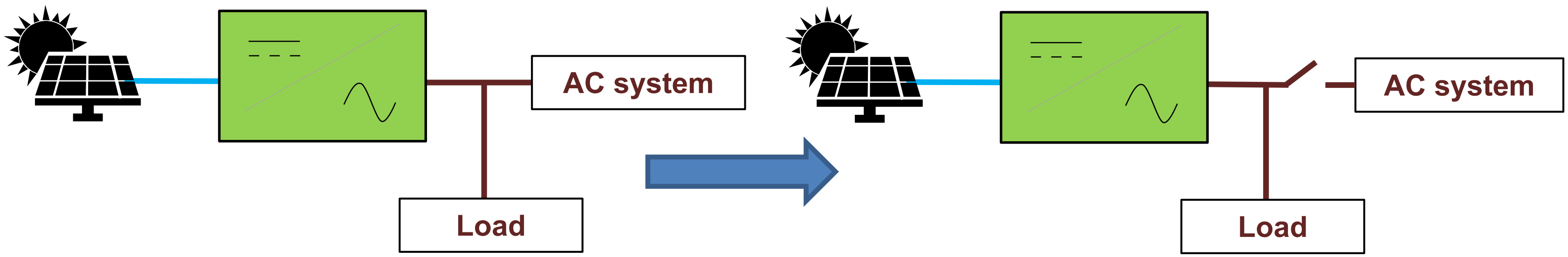
Galvanic isolation

- Galvanic isolation is a protection principle in electrical systems, based on ensuring that there is no direct electrical connection between two sub-systems which are electrically isolated. In this case, power can be exchanged with magnetic fluxes ensuring no electrical connection.
- **Galvanic isolation** between the panels and the grid is typically needed. It can be provided by
  - A typical 50 or 60 Hz transformer connected at the grid side
  - Using a medium/high frequency transformer in the DC-DC converter of the 1st stage of a two stage system.

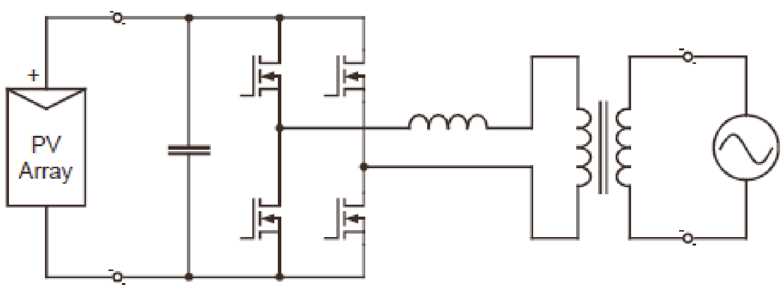


Anti-islanding

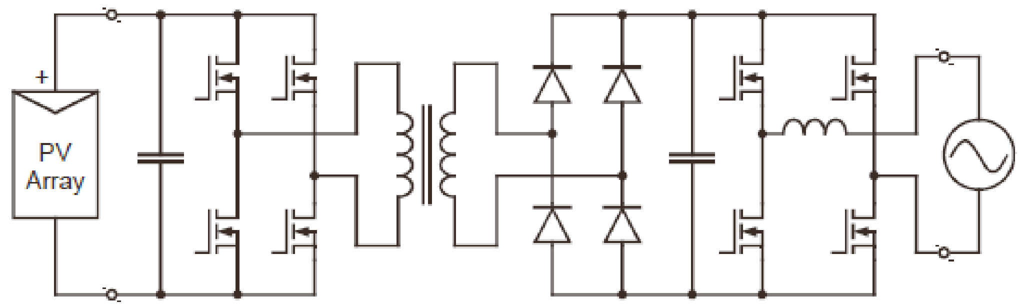
- When the AC grid is lost, the inverter has to detect it, block the inverter and ensure the grid is not energized by the inverter.
- The detection is done by monitoring the grid voltage and frequency and actuating when an anomaly is detected.
- The problem can be challenging in some specific conditions when resonance occurs at the grid frequency (RLC load with LC resonance at grid frequency). In this case, active islanding detection techniques are used.



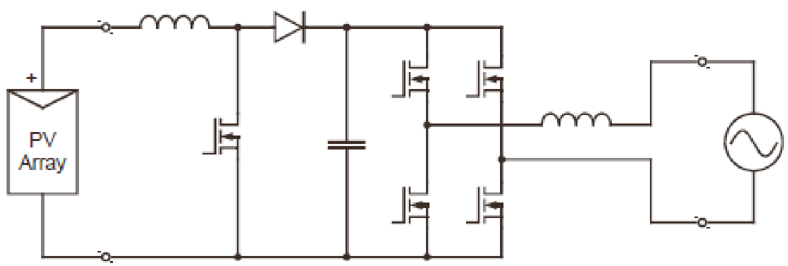
PV power electronics



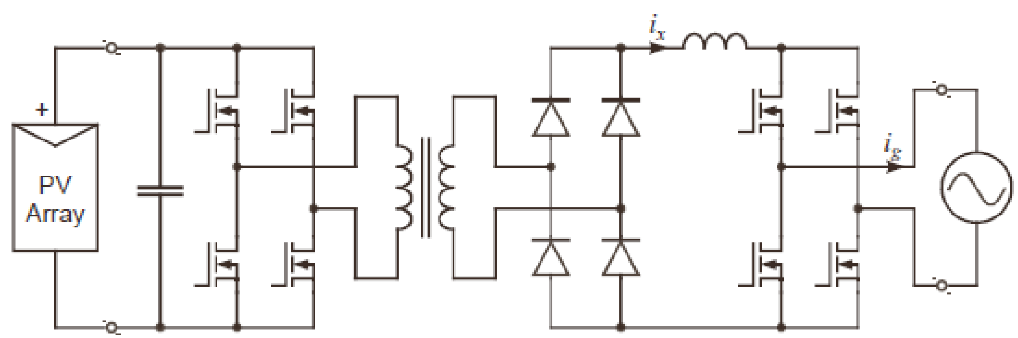
1 stage
(isolation low frequency)



2 stage with isolation (high frequency)



2 stage without isolation



2 stage with isolation (high frequency)

Renewable Energy in Power Systems, Freires , Infield (2008) Wiley

PV inverters efficiency

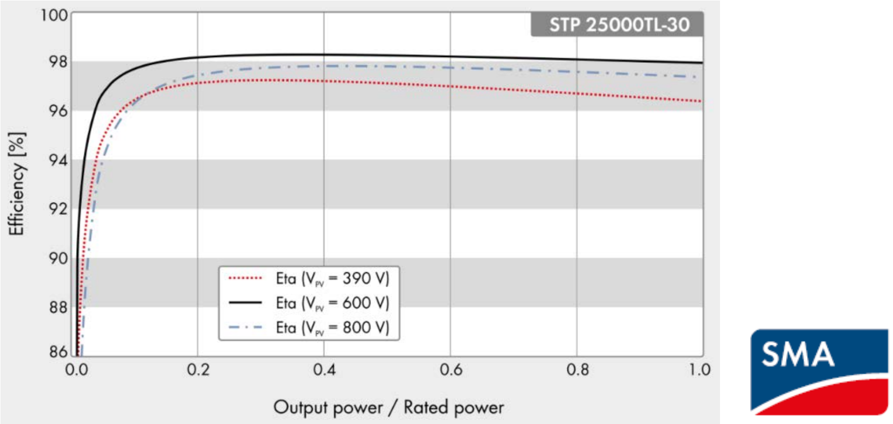
The efficiency of the converter is not constant for different operating points.

Denoting "Exx" the efficiency at xx % of rated power, the European efficiency is calculated as:

Euro Efficiency = 0.03 E5 + 0.06 E10 + 0.13 E20 + 0.1 x E30 + 0.48 E50 + 0.2 E100

The California Energy Commission (CEC) has proposed another formula, which is now common in the US:

CEC Efficiency = 0.04 E10 + 0.05 E20 + 0.12 E30 + 0.21 E50 + 0.53 E75 + 0.05 E100



Example datasheet (single phase)

Type code Input (DC)

Nominal PV-power (P_{PV})	3400 W
Maximum PV-power (P_{PV},max)	3700 W
DC voltage range, mpp (U_{DC})	335 to 800 V
Max DC voltage (U_{DC}, max)	900 V
Nominal DC voltage, (U_N)	480 V
Max DC current (I_{DC}, max)	10.5 A
Number of DC inputs (parallel)	4

Output (AC)

Nominal AC output power (P_{AC})	3300 W
Nominal AC current (I_{AC}, nom)	14.3 A
Nominal voltage (V_{AC}, nom)	230 V
Operating range, grid voltage	180 to 276 V
Operating range, grid frequency (f_{AC})	47 to 63 Hz
Harmonic distortion of grid current	< 3%
Power factor (cos phi)	1
Grid connection Single phase:	L, N and PE
Transformer	No

Efficiency

Max efficiency (P_{ACmax})	97.1%
Euro-eta	96.0%

Power consumption

In standby operation ($P_{standby}$)	< 12 W
Night consumption (P_{night})	< 1 W

Environmental limits

Degree of protection	IP55
Permissible temperature range	-25 C° to +60 C°
Nominal power up to	+50 C°
Relative humidity, not condensing	0 to 100%
Max. altitude (above sea level)	2000 m
Acoustic noise level	<45 dBA

Protections:

Ground fault monitoring
Anti-islanding
Residual current detection (RCD)
DC power switch
DC string fuses
DC reverse polarity
AC short circuit
Overload
Over temperature
Surge protection device
Overvoltage

Data from ABB

Example datasheet (1 phase inv ABB)

Technical data and types

Type code	PVS300-TL-3300W-2	PVS300-TL-4000W-2	PVS300-TL-4600W-2	PVS300-TL-6000W-2	PVS300-TL-8000W-2
	3.3 kW	4.0 kW	4.6 kW	6.0 kW	8.0 kW
Input (DC)					
Nominal PV-power (P_{PV})	3400 W	4100 W	4700 W	6100 W	8100 W
Maximum PV-power ($P_{PV,max}$)	3700 W	4500 W	5200 W	6700 W	8900 W
DC voltage range, mpp (U_{DC})	335 to 800 V				
Max DC voltage ($U_{DC,max}$)	900 V				
Nominal DC voltage, (U_N)	480 V				
Max DC current ($I_{DC,max}$)	10.5 A	12.7 A	14.6 A	19.0 A	25.4 A
Number of DC inputs (parallel)	4, with MC4 quick connectors				
Output (AC)					
Nominal AC output power (P_{AC})	3300 W	4000 W	4600 W	6000 W	8000 W
Nominal AC current ($I_{AC,nom}$)	14.3 A	17.4 A	20.0 A	26.1 A	34.8 A
Nominal voltage ($V_{AC,nom}$)	230 V				
Operating range, grid voltage [1]	180 to 276 V				
Operating range, grid frequency (f_{AC}) [2]	47 to 63 Hz				
Harmonic distortion of grid current (K_{IAC})	< 3%				
Power factor (cosfii)	1				
Grid connection	Single phase: L, N and PE				
Transformer	No				
Efficiency					
Max efficiency (P_{ACmax})	97.1%				
Euro-eta	96.0%	96.3%	96.3%	96.6%	96.6%
Power consumption					
In standby operation ($P_{standby}$)	< 12 W				
Night consumption (P_{night})	< 1 W				
Environmental limits					
Degree of protection	IP55				
Permissible ambient temperature range	-25 C° to +60 C°				
Nominal power up to	+50 C°				
Relative humidity, not condensing	0 to 100%				
Max. altitude (above sea level) [3]	2000 m				
Acoustic noise level	<45dBA				

ABB

Example datasheet (large inverter)

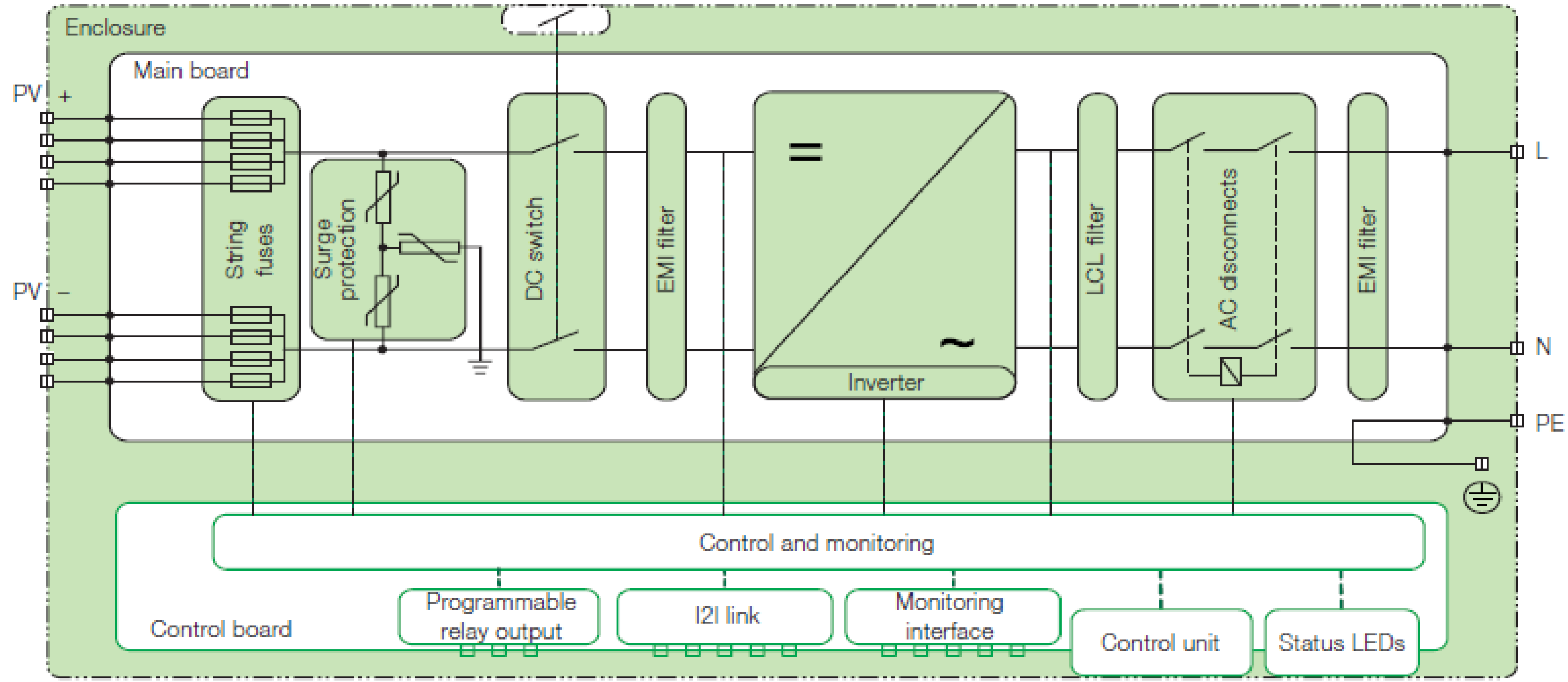
SUNNY CENTRAL 1500 V

SMA

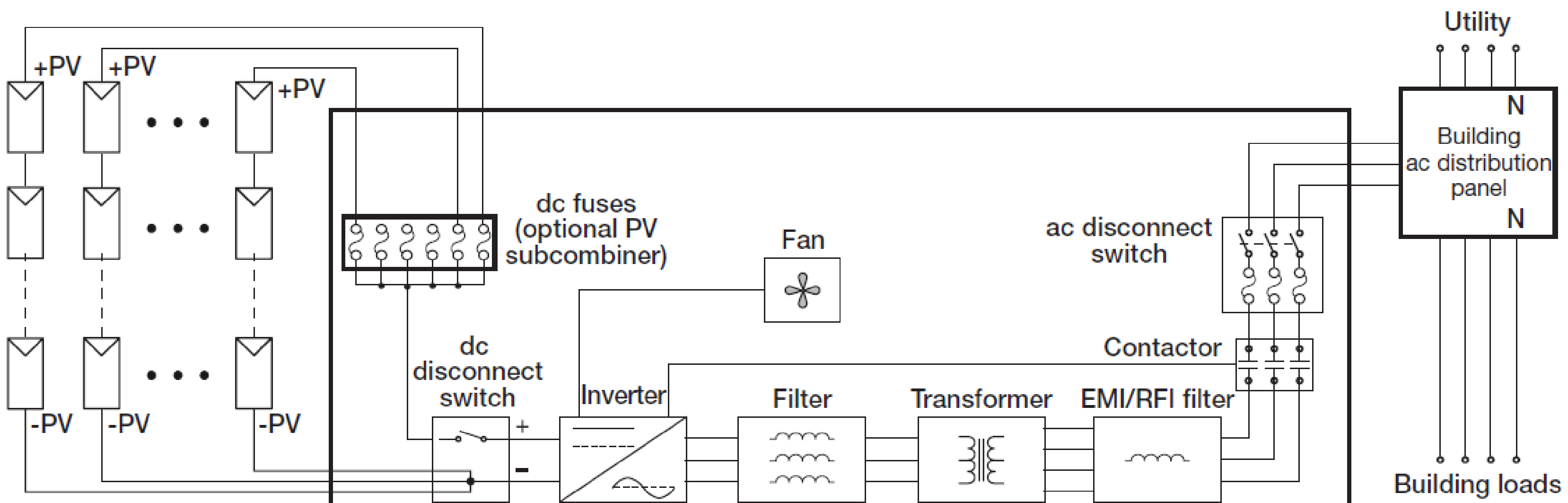
Technical Data	Sunny Central 2500-EV	Sunny Central 2750-EV	Sunny Central 3000-EV
Input (DC)			
MPP voltage range V_{DC} (at 25 °C / at 35 °C / at 50 °C)	850 V to 1425 V / 1200 V / 1200 V	875 V to 1425 V / 1200 V / 1200 V	956 V to 1425 V / 1200 V / 1200 V
Min. input voltage $V_{DC, min}$ / Start voltage $V_{DC, Start}$	778 V / 928 V	849 V / 999 V	927 V / 1077 V
Max. input voltage $V_{DC, max}$	1500 V	1500 V	1500 V
Max. input current $I_{DC, max}$ (at 35 °C / at 50 °C)	3200 A / 2956 A	3200 A / 2956 A	3200 A / 2970 A
Max. short-circuit current rating	6400 A	6400 A	6400 A
Number of DC inputs	24 double pole fused (32 single pole fused) for PV		
Number of DC inputs with optional DC battery coupling	18 double pole fused (36 single pole fused) for PV and 6 double pole fused for batteries		
Max. number of DC cables per DC input (for each polarity)	2 x 800 kcmil, 2 x 400 mm²		
Integrated zone monitoring	○		
Available DC fuse sizes (per input)	200 A, 250 A, 315 A, 350 A, 400 A, 450 A, 500 A		
Output (AC)			
Nominal AC power at cos φ =1 (at 35 °C / at 50 °C)	2500 kVA / 2250 kVA	2750 kVA / 2500 kVA	3000 kVA / 2700 kVA
Nominal AC power at cos φ =0.8 (at 35 °C / at 50 °C)	2000 kW / 1800 kW	2200 kW / 2000 kW	2400 kW / 2160 kW
Nominal AC current $I_{AC, nom}$ = Max. output current $I_{AC, max}$	2624 A	2646 A	2646 A
Max. total harmonic distortion	< 3% at nominal power	< 3% at nominal power	< 3% at nominal power
Nominal AC voltage / nominal AC voltage range[1] [8]	550 V / 440 V to 660 V	600 V / 480 V to 690 V	655 V / 524 V to 721 V[9]
AC power frequency	50 Hz / 47 Hz to 53 Hz 60 Hz / 57 Hz to 63 Hz		
Min. short-circuit ratio at the AC terminals[10]	> 2		
Power factor at rated power / displacement power factor adjustable[8] [11]	● 1 / 0.8 overexcited to 0.8 underexcited ○ 1 / 0.0 overexcited to 0.0 underexcited		
Efficiency			
Max. efficiency[2] / European efficiency[2] / CEC efficiency[3]	98.6% / 98.3% / 98.0%	98.7% / 98.5% / 98.5%	98.8% / 98.6% / 98.5%

Example ABB (single phase)

ABB string inverter design and grid connection



Example ABB (three phase)



Ground fault detection/interrupt not shown.

Summary

- Solar PV inverters employ voltage source converters to interconnect the DC output to the AC network.
- PV inverters can control the AC voltage and exchanged the referenced amount of active and reactive power.
- They perform the maximum power point tracking and ensure anti-islanding protection in the AC system.
- Different converter solutions are possible depending on the number of stages and the galvanic isolation.

Thanks for your attention!

INTERNATIONAL SOLAR ALLIANCE

CARBON TRUST

CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY

CITCEA UPC

tta Trama TecnoAmbiental