Power Electronic Inverters

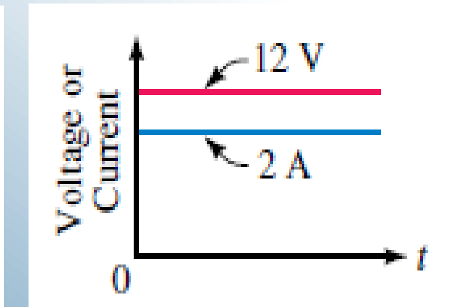
- Basics of converters
- Electric circuits fundamentals
- Solar inverters functionalities
- I-V and P-V characteristics
- Maximum power point tracking
- Control principles
- Single / two stage inverters
- Inverter Data sheet examples (ABB)

DC/AC Power Converters

- Power electronics converters are used to exchange power in a controllable way between two non-compatible electrical systems
  - DC to AC Conversion
    - Used to transform DC from Solar farm to three phase AC for connection to the National Grid.
    - Used to transform DC from Wind turbine farm to three phase AC for connection to the National Grid.
  - AC to DC to AC: This type of conversion is called a DC Interconnect. Such an interconnect exists between the Texas Grid and the Eastern Grid.
- Power electronics converters are used to exchange power in a controllable way between two electrical systems (electrical power source and sink).

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 (50 or 60 Hz)
    - Single phase / three phase



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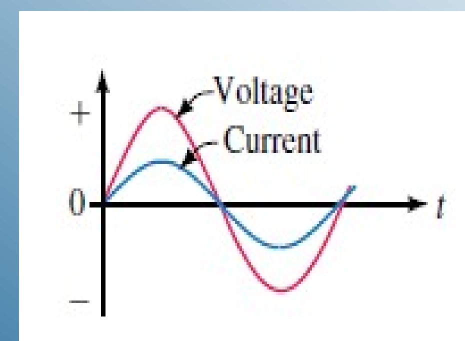
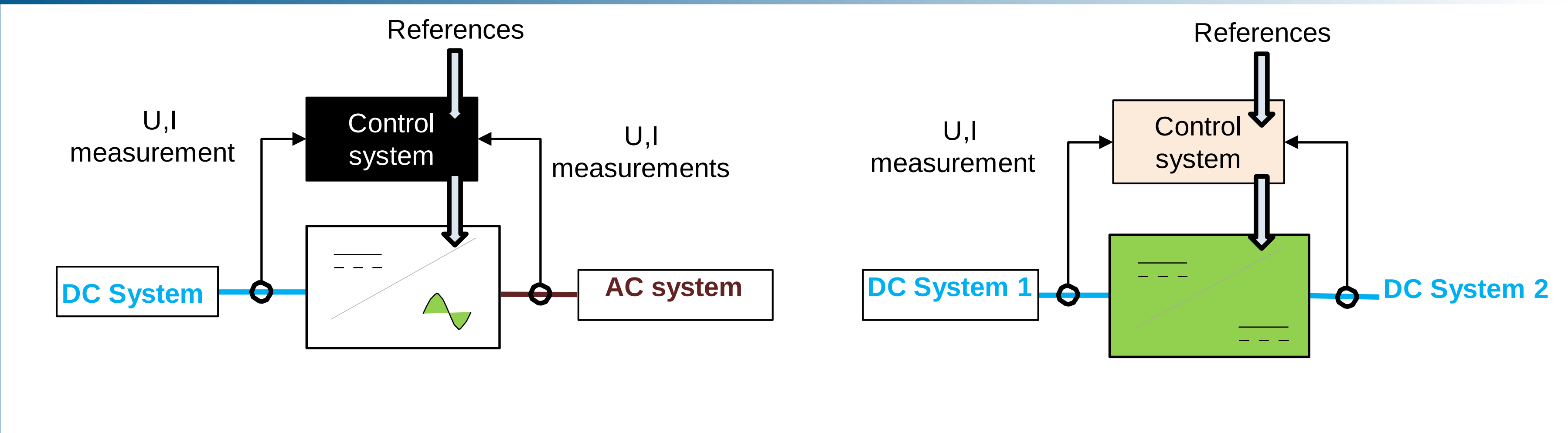


Solar Edge

POWER ELECTRONICS CONVERTERS

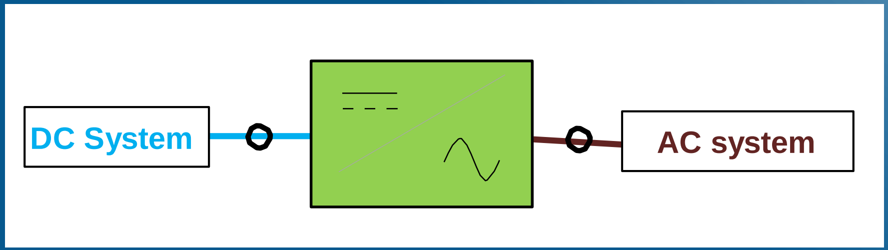
- Power converters can be AC-DC (or DC-AC), DC-DC or AC-AC

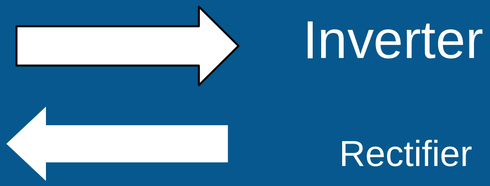


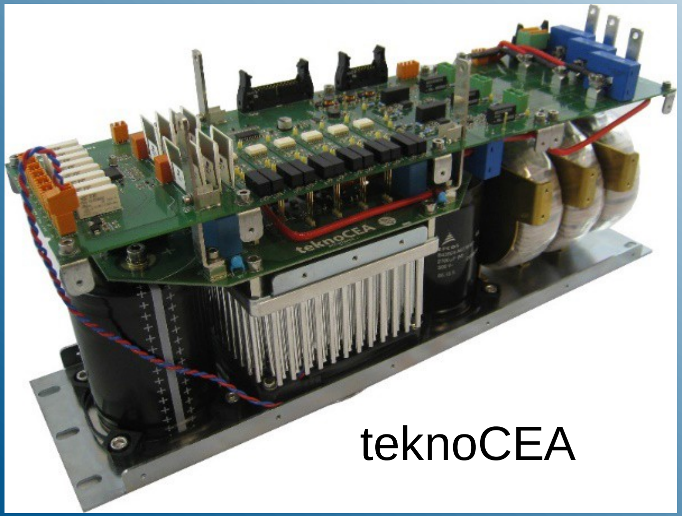
- The converter controls
  - measures the relevant voltages and currents
  - implements the control algorithms to track references
  - applies the appropriate modulation in the converter

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

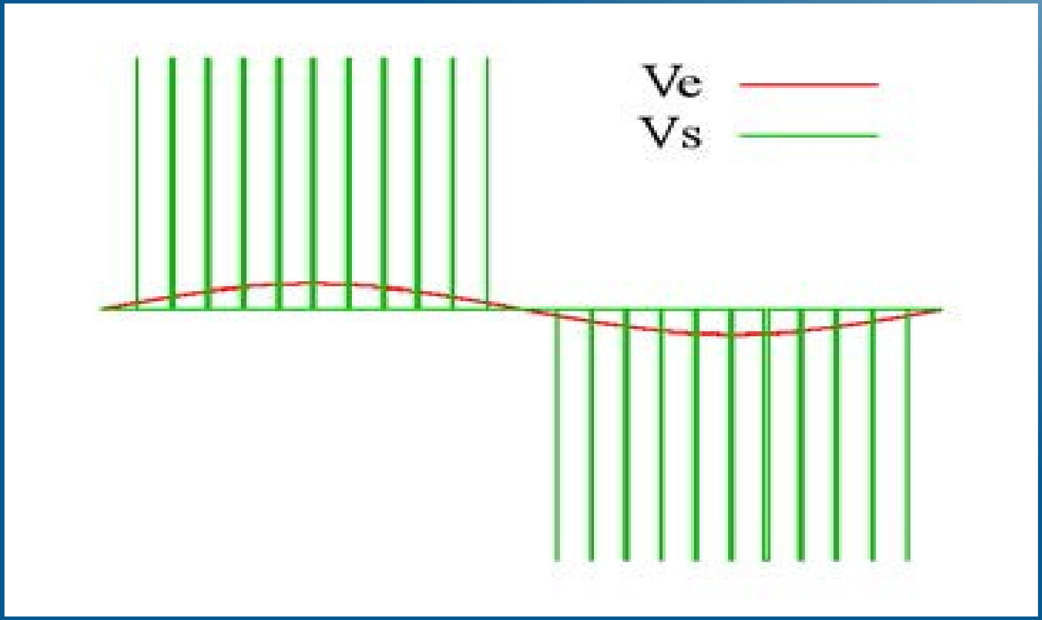






VOLTAGE SOURCE CONVERTERS (VSC)

- 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

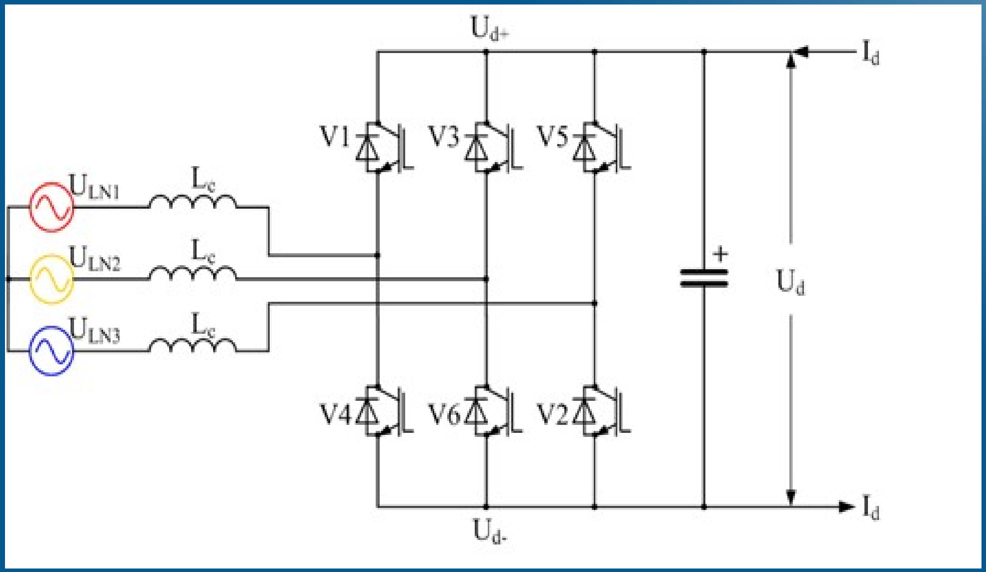


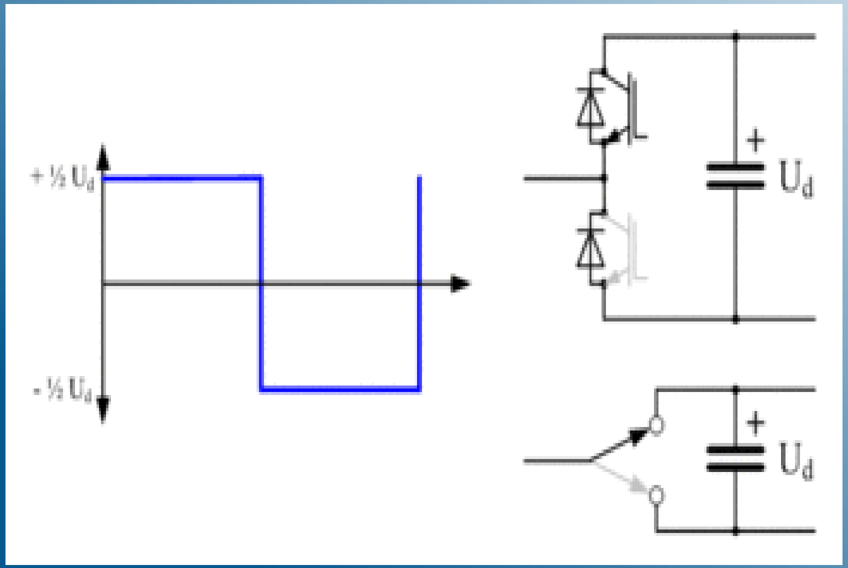
TWO LEVEL CONVERTERS

Two level converters can modulate the voltage with two possible levels (positive and negative voltages)

They are used for low power applications.

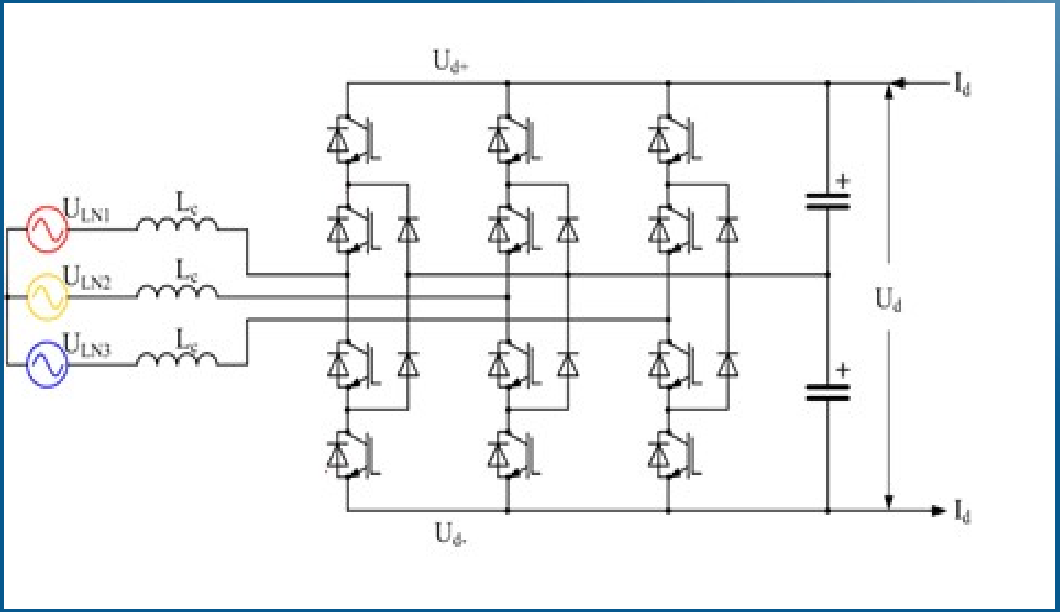
To have good quality on the waveforms, high switching frequency is needed. Losses increase with switching frequency → Trade-off between power quality and losses.

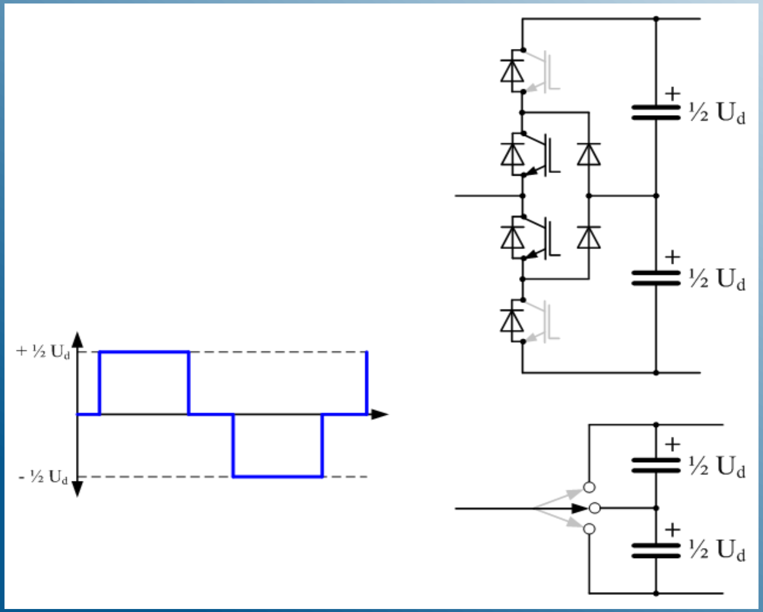




THREE LEVEL CONVERTERS

- 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



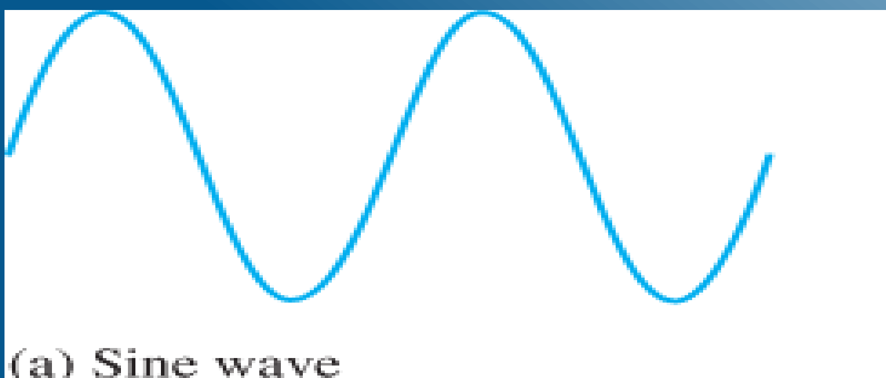


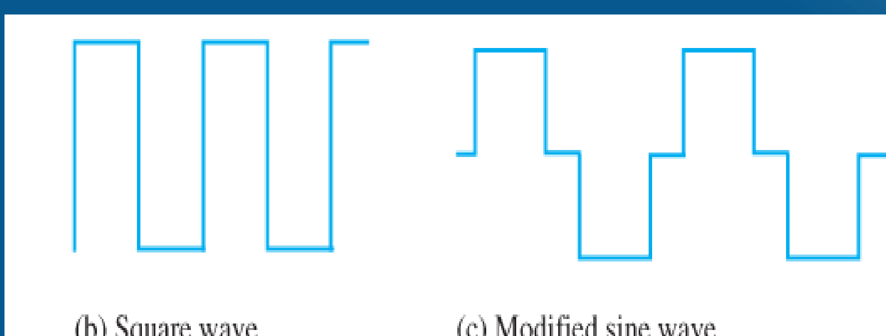
COMPARING TWO-THREE LEVEL

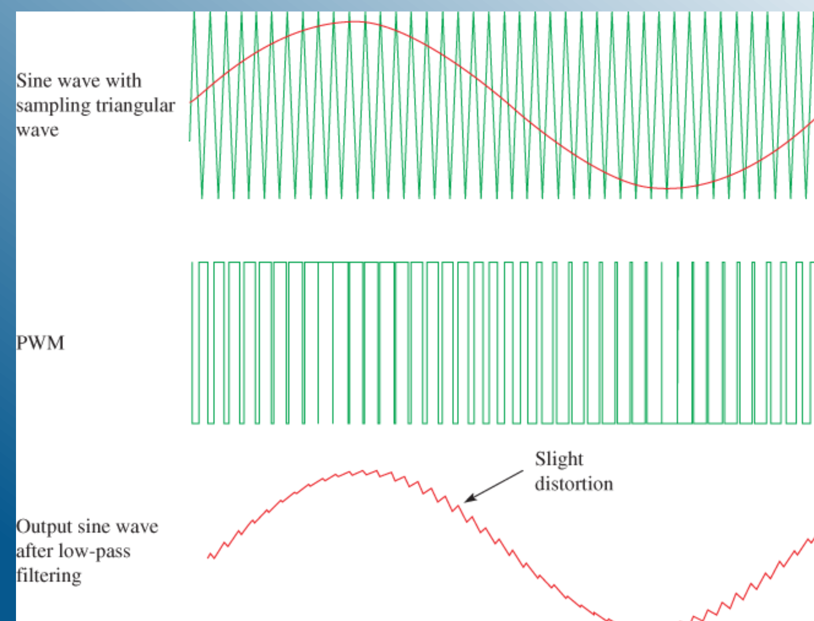
The square waveform has a THD (Total Harmonic Distortion) of about 45 %.

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.


(a) Sine wave


(b) Square wave (c) Modified sine wave

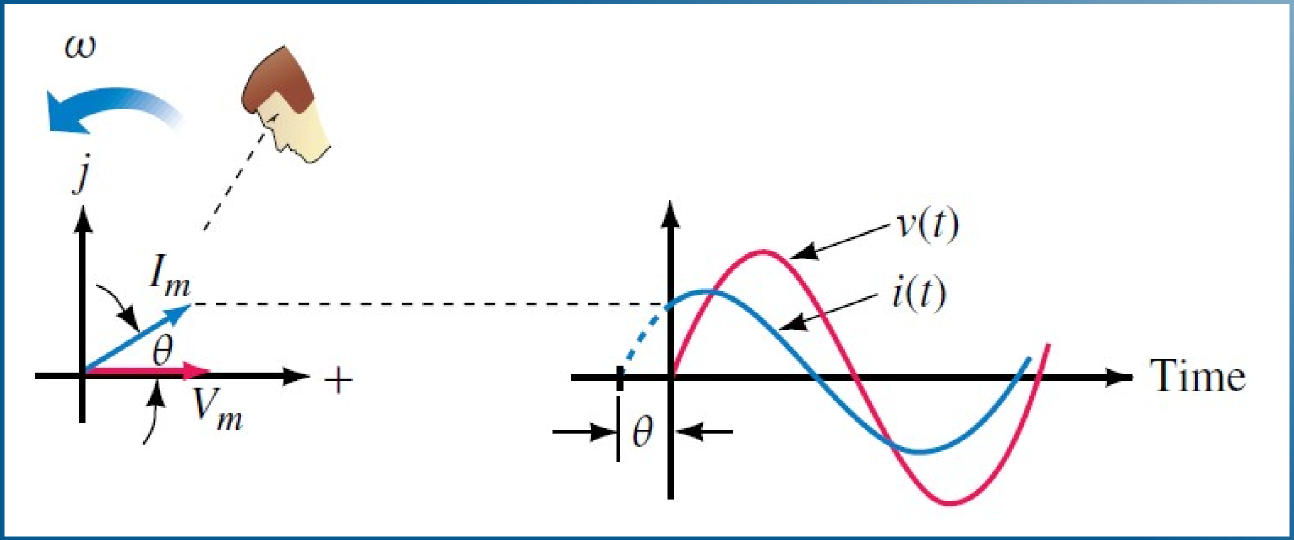


AC systems basics

Voltages and currents can be defined by phasors

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

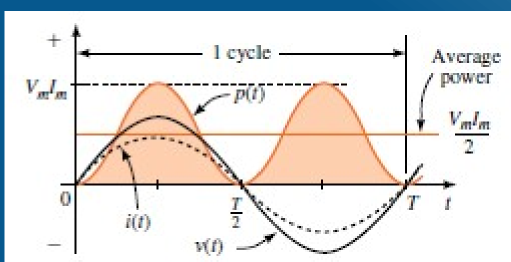
$$\underline{X} = X \angle \alpha = X e^{j\alpha} = a + jb = \underbrace{X \cos \alpha}_{a} + j \underbrace{X \sin \alpha}_{b}$$

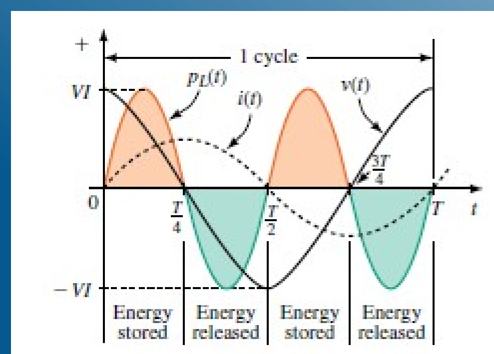


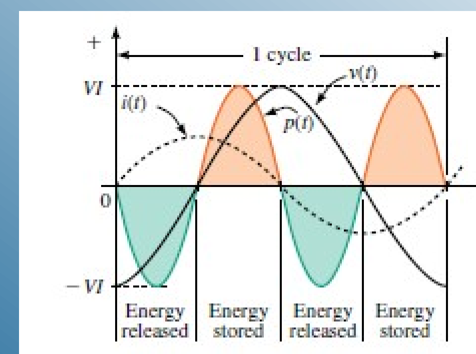
POWER IN AC SYSTEMS

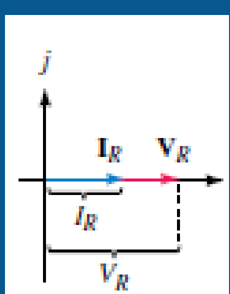
Real power is oscillating for single phase AC systems but constant for three phase balanced systems.

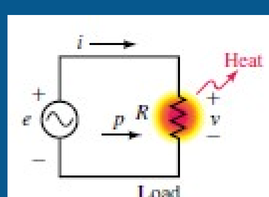
- ❖ Apparent complex power $\underline{S} = P + jQ = \underline{U}\,\underline{I}^*$
- ❖ Apparent power $S = VI$
- ❖ Active (real) power $P = S\cos\varphi$
- ❖ Reactive power $Q = S\sin\varphi$

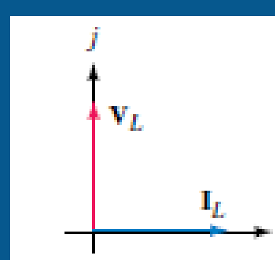


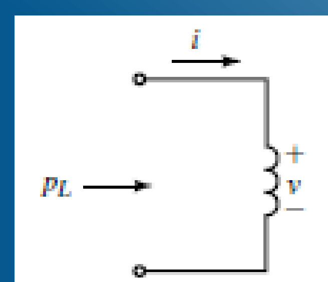


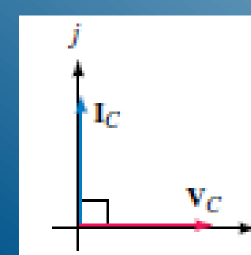


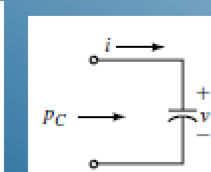






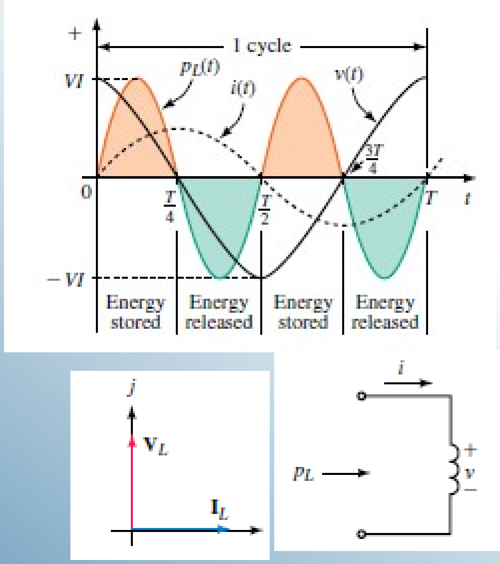


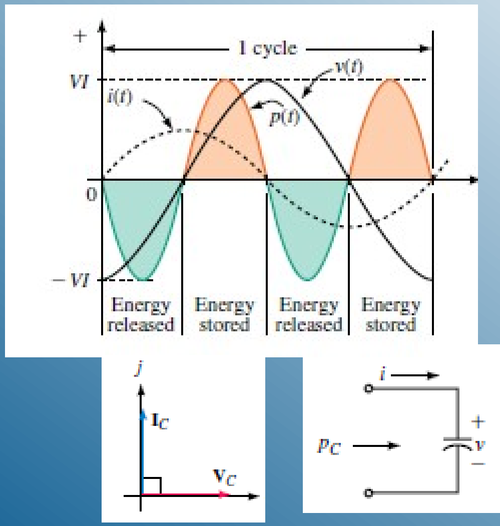




WHAT IS REACTIVE POWER?

- 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.





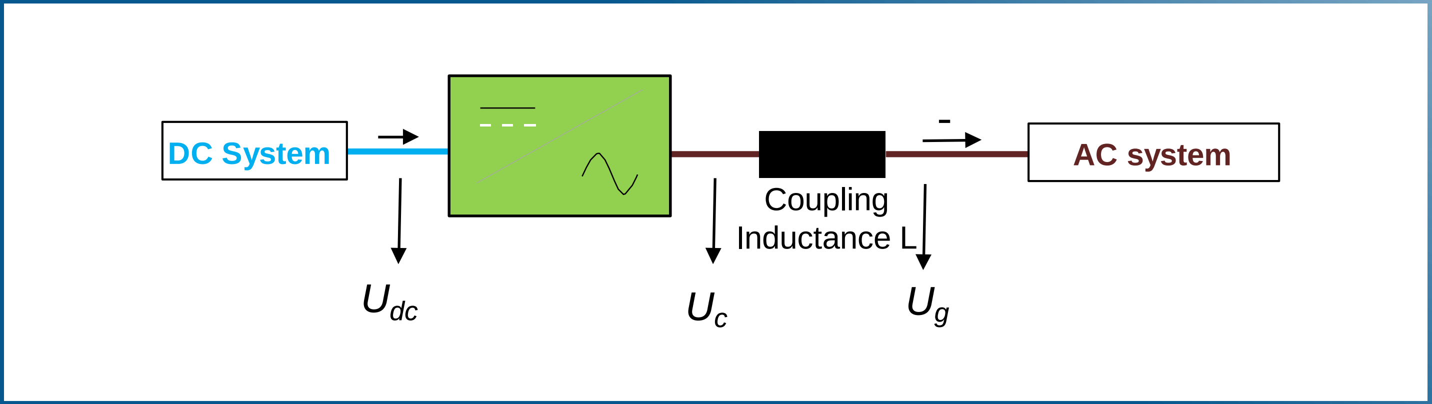
VOLTAGE SOURCE CONTROLER OPERATION PRINCIPLE

- 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

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

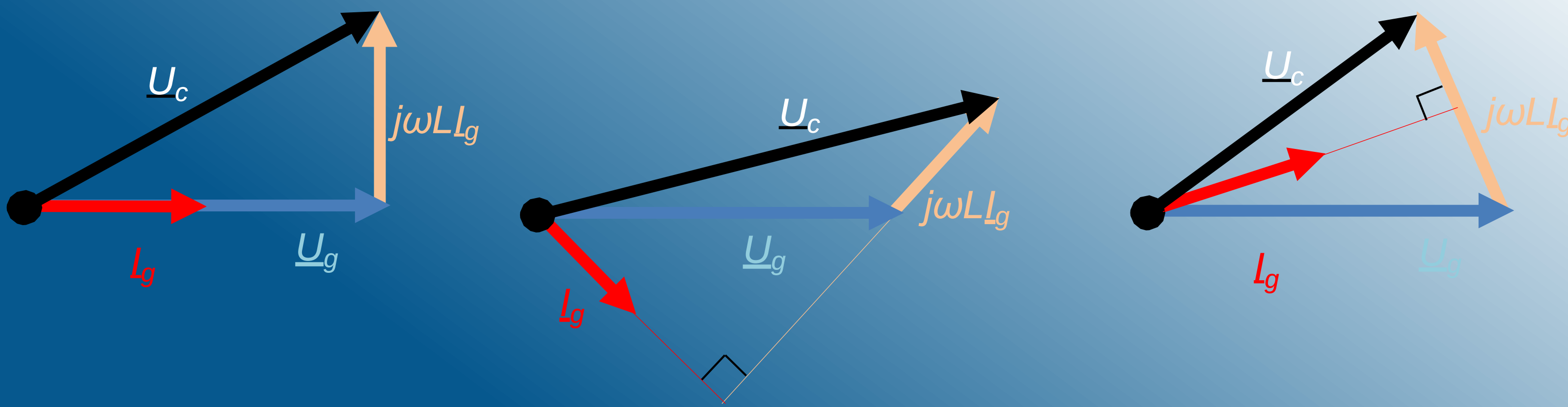
- This current can be obtained adjusting the converter voltage as (which can be modulated by the VSC)

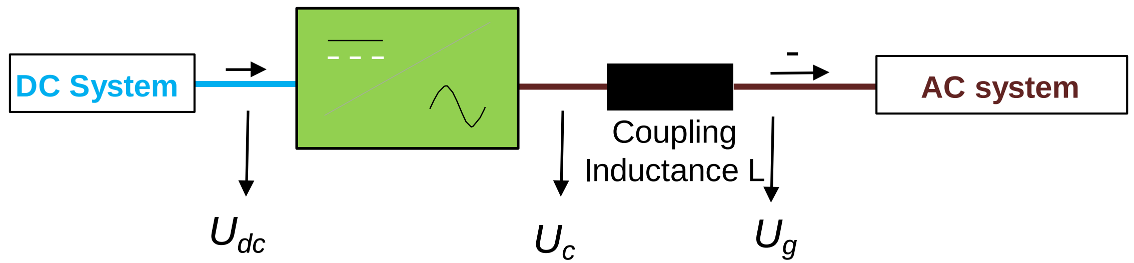
$$\underline{U}_c = \underline{U}_g + j\omega L \underline{I}_g$$



VOLTAGE SOURCE CONTROLER OPERATION PRINCIPLE

$$\underline{S} = P + jQ = \underline{U}_g \underline{I}_g^* \rightarrow \underline{I}_g = \frac{\qquad}{\underline{U}_g^*} = \frac{P - jQ}{U_g} \qquad \underline{U}_c = \underline{U}_g + j\omega L \underline{I}_g$$





SOLAR PV INVERTERS

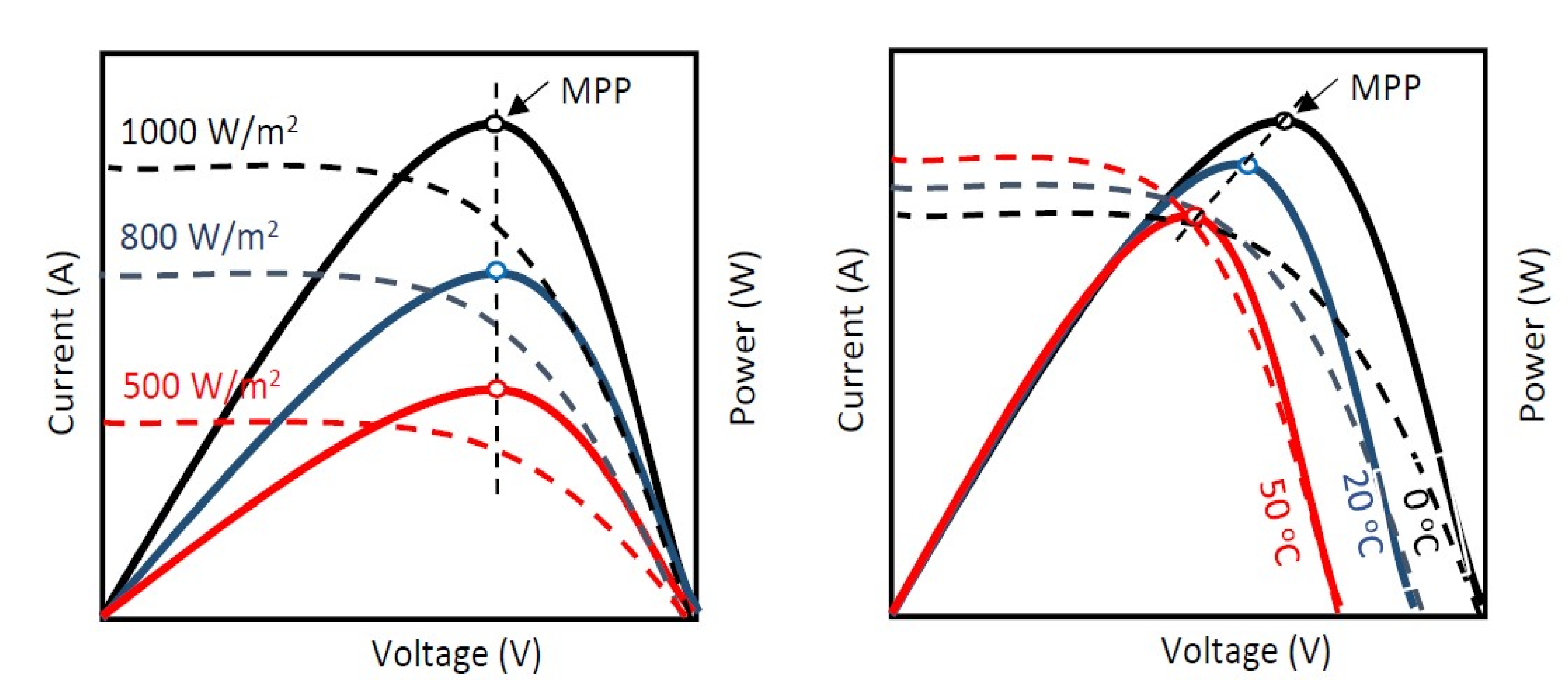
convert the DC output

solar panels or strings of

- **Solar PV Inverters** convert the DC output of photovoltaic (PV) 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

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.



MAXIMUM POWER POINT TRACKING (MPPT)

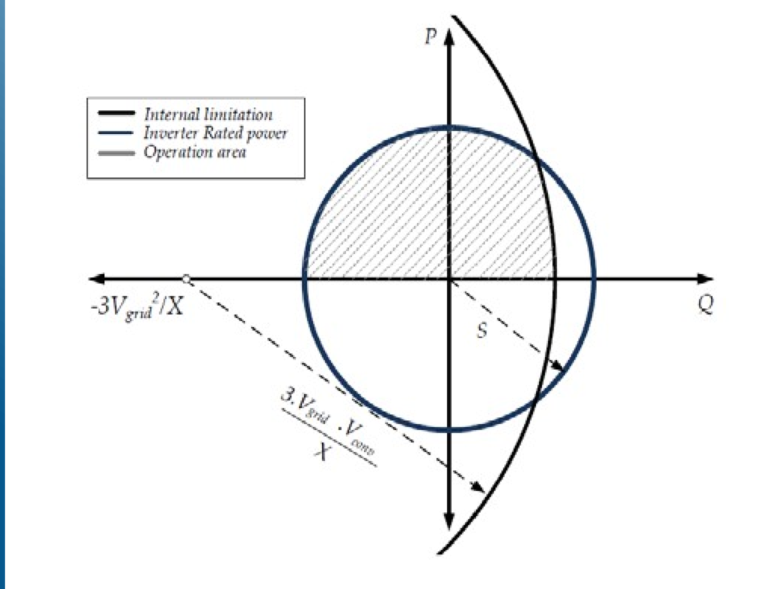
The converter can modify the DC voltage to track the maximum power.

Different methods can be used:

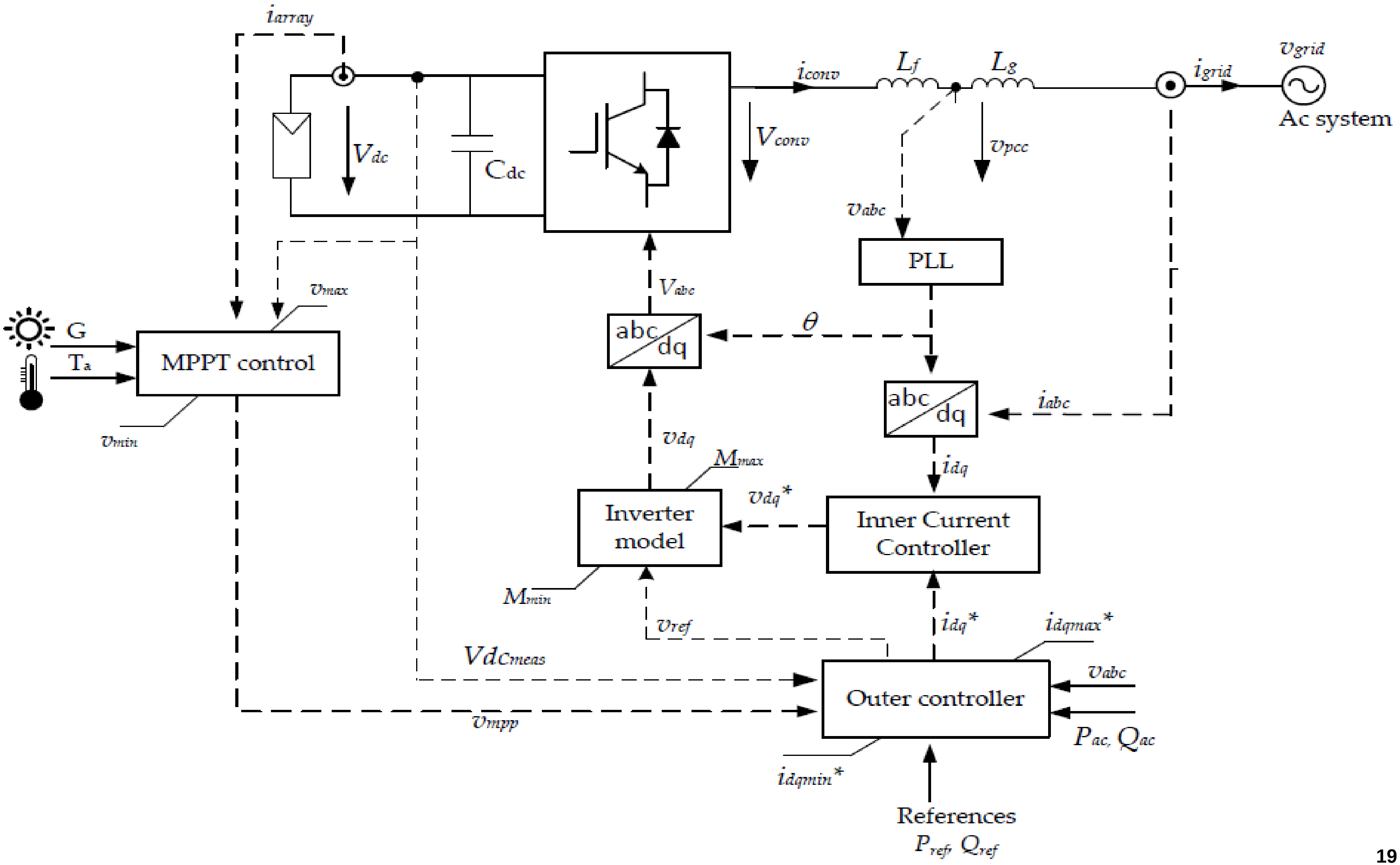
- ❖ Constant voltage method
- ❖ Short-Current Pulse Method
- ❖ Open Voltage Method
- ❖ Perturb and Observe Methods
- ❖ Incremental Conductance Methods
- ❖ Temperature Methods

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)



SOLAR INVERTER CONTROL



PV POWER ELECTRONICS

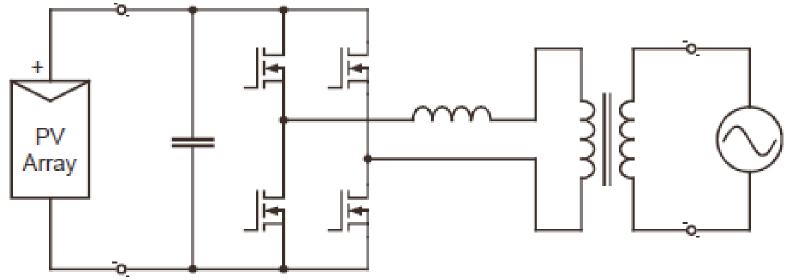


Figure 4.38 Basic grid-connected PV inverter

1 stage
(isolation low frequency)

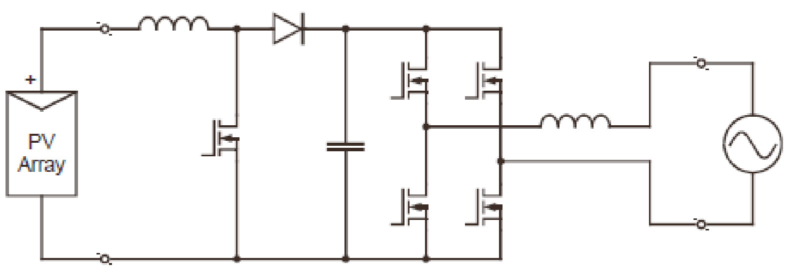
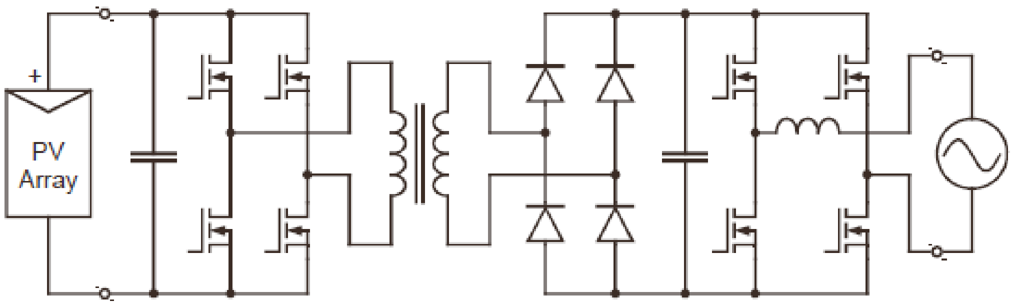


Figure 4.39 Transformerless grid-connected PV inverter



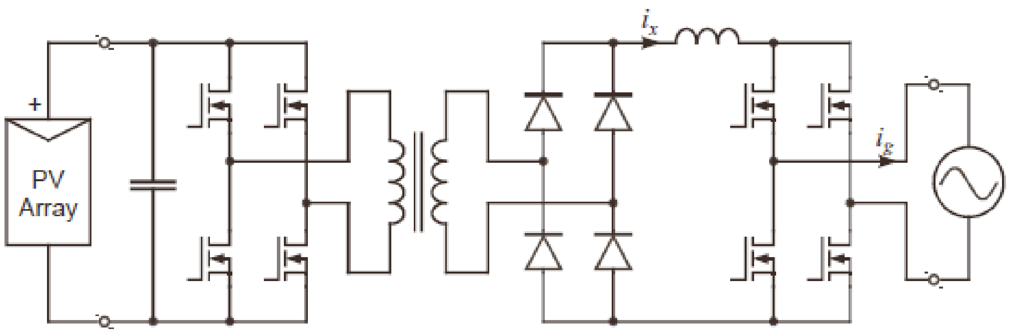


Figure 4.41 PV Inverter using a steering bridge

2 stage without isolation

2 stage with isolation (high frequency)

PV INVERTERS EFFICIENCY

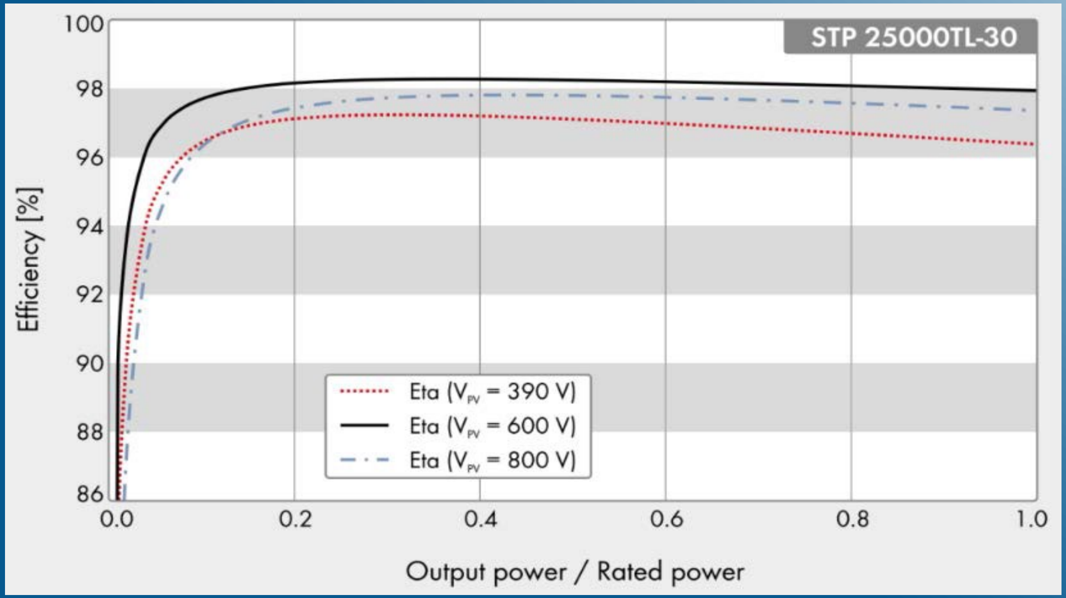
The efficiency of the converter is not constant for different operating points.

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



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_{PVmax})	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				

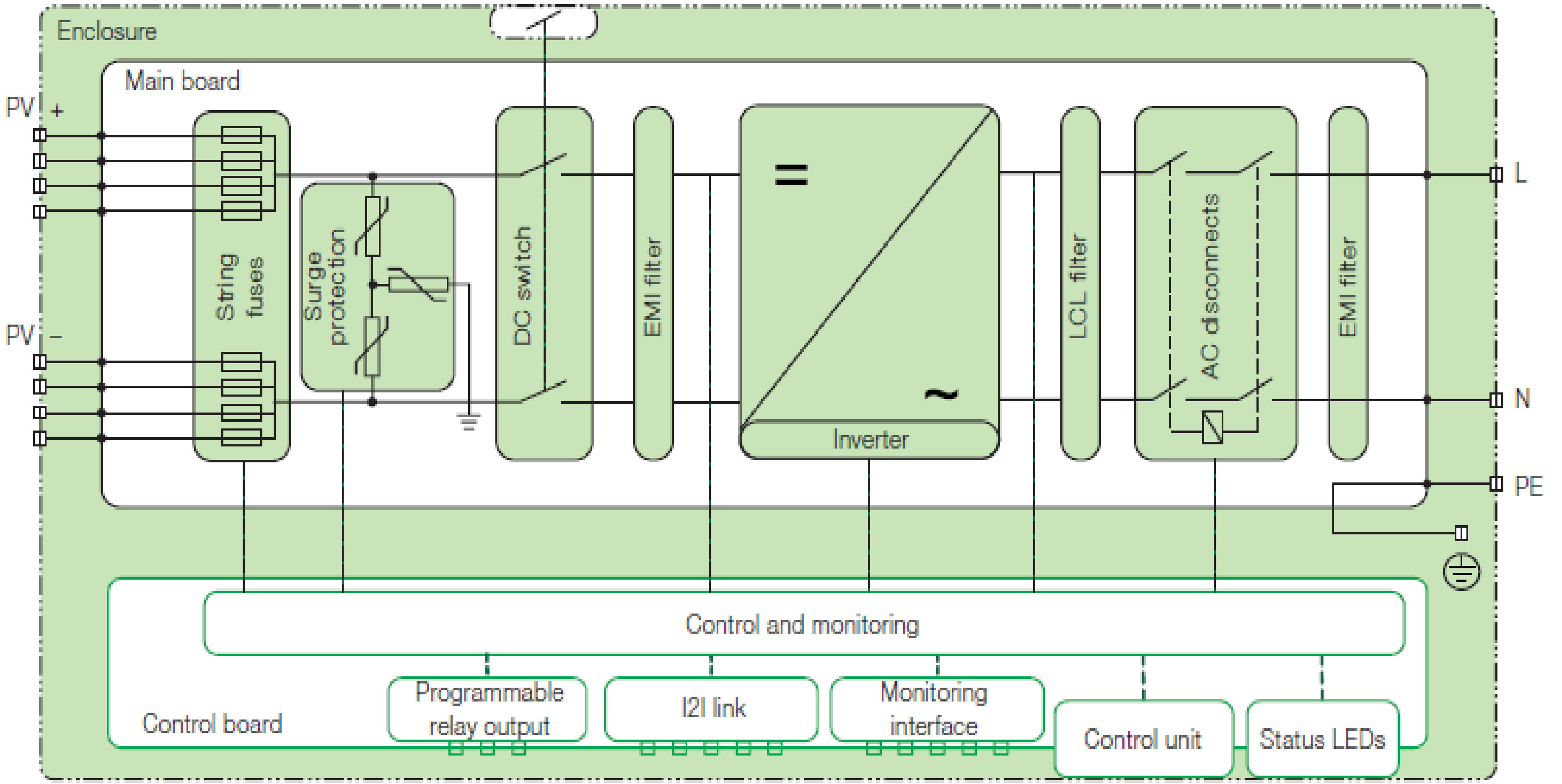
EXAMPLE DATASHEET (LARGE INVERTER)

SUNNY CENTRAL 1500 V

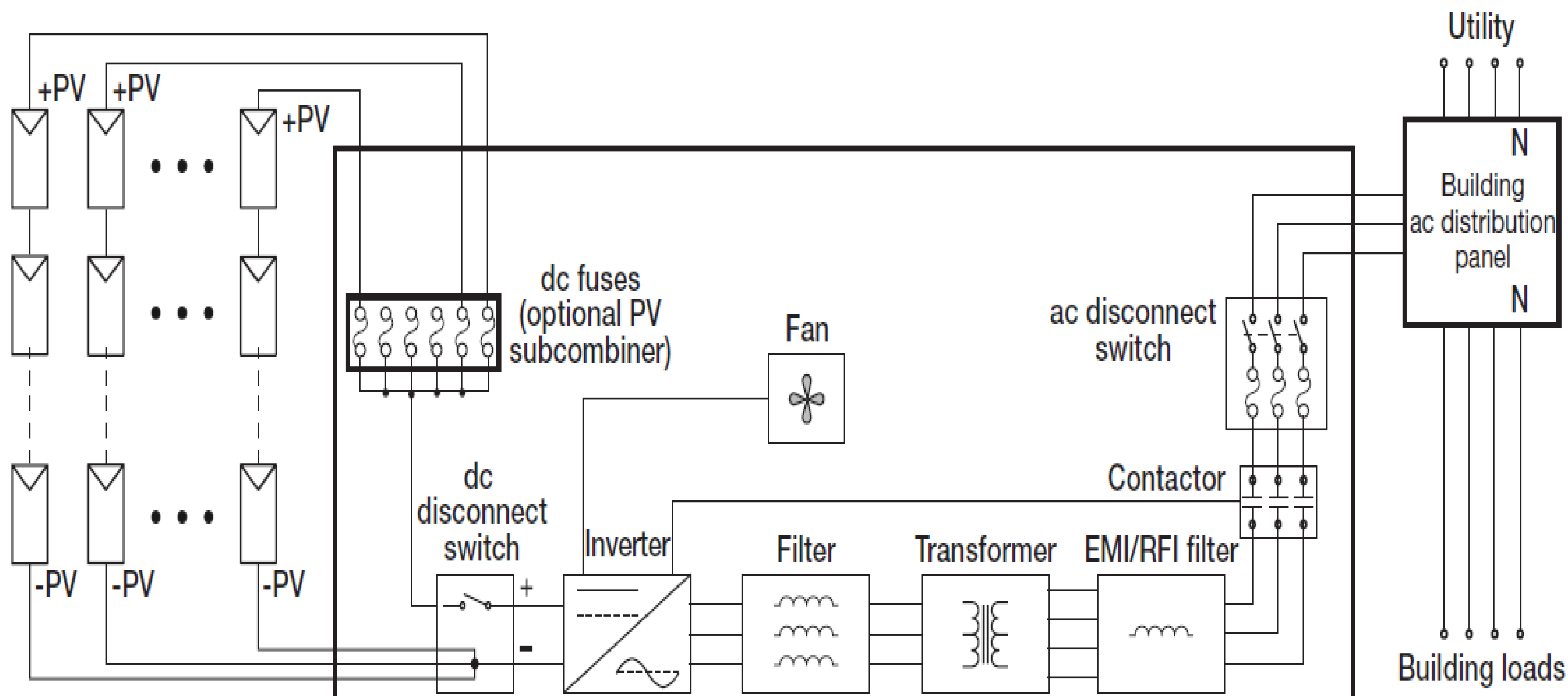
Technical Data	Sunny Central 2500-EV	Sunny Central 2750-EV	Sunny Central 3000-EV
Input (DC)			
MPP voltage range V_{DC} (at 25 °C / at 35 °C / at 50 °C)	850 V to 1425 V / 1200 V / 1200 V	875 V to 1425 V / 1200 V / 1200 V	956 V to 1425 V / 1200 V / 1200 V
Min. input voltage $V_{DC, min}$ / Start voltage $V_{DC, Start}$	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.