ENEE 5307

L14 - 26/4/2021

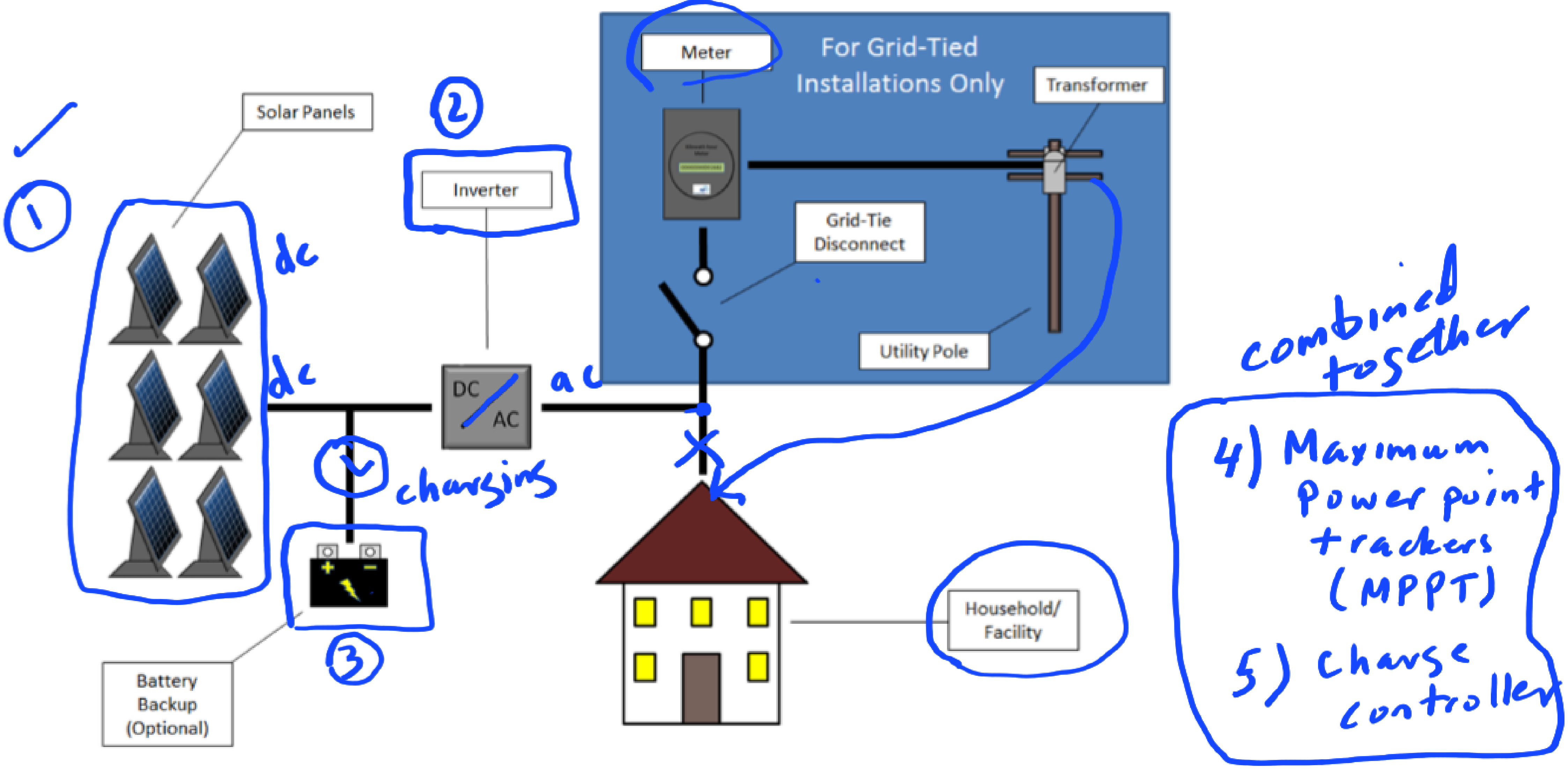
PV Inverters

S2021

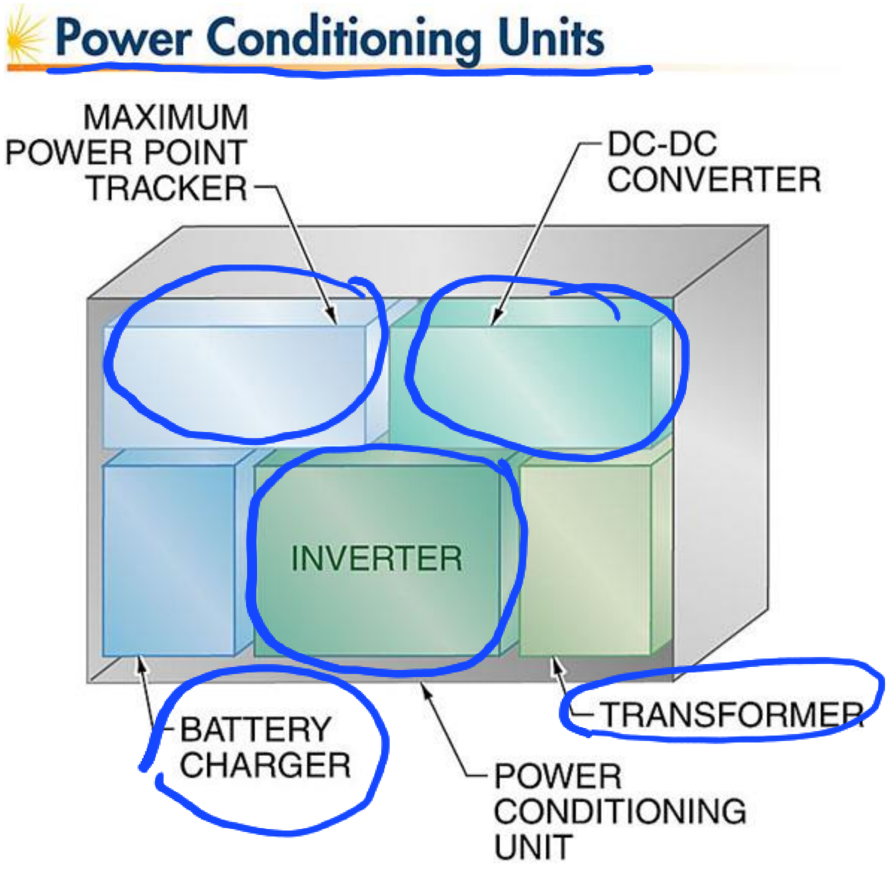
Start @ 12 $\underline{50}$

The Photovoltaic System

On - Grid (Batteries are optional)
off - Grid (Batteries are a must)



- **Power conditioning units (PCU)** are inverters that also perform other power control and conversion functions.

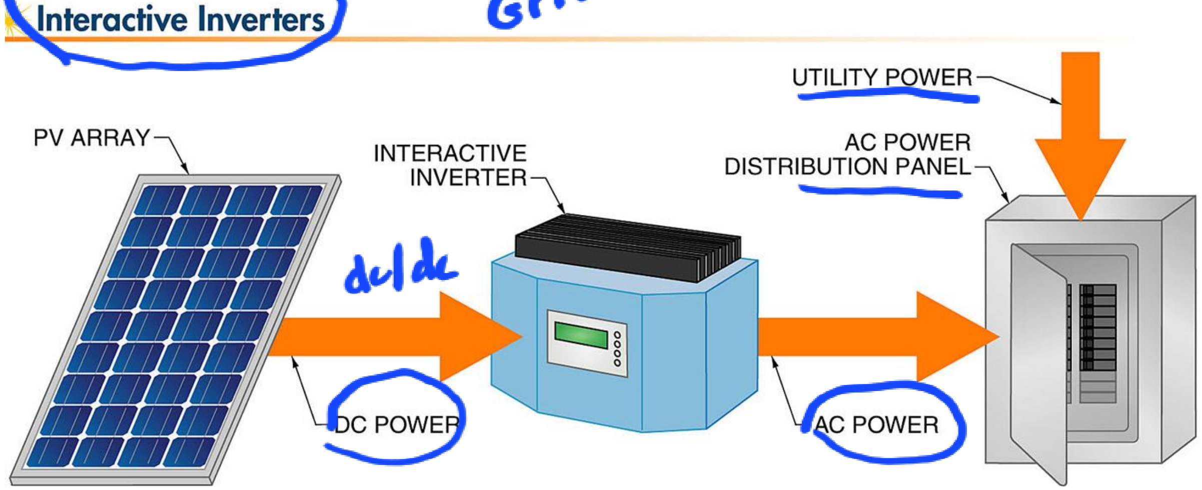


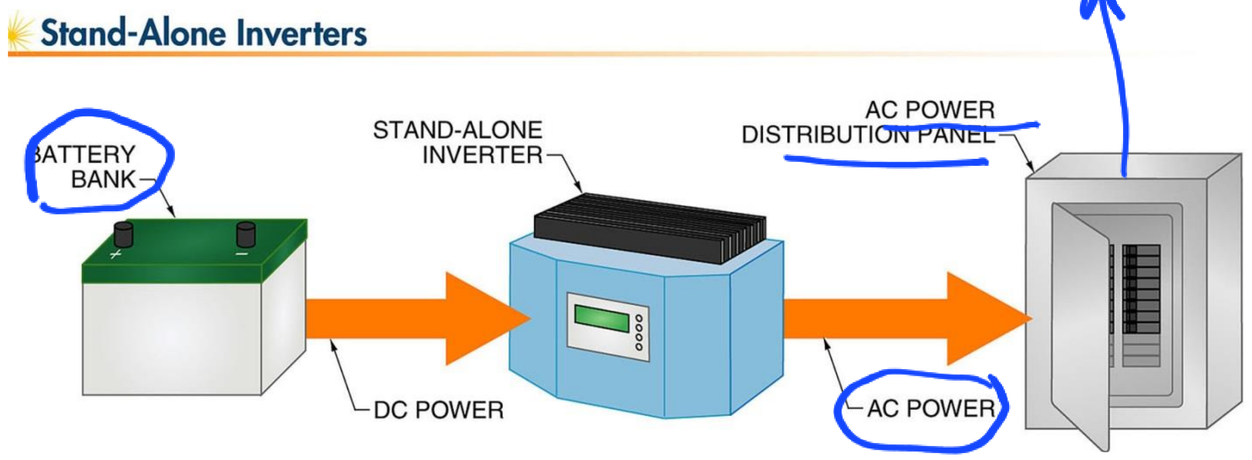
- An *inverter* is a device that converts DC power to AC power.
- Inverters are available in many different configurations and ratings.

- **Interactive inverters** are connected to the PV array and supply AC power that is synchronized with the utility grid.
- Sometimes called grid-connected or grid-tie inverters, these inverters interface between the PV array and the utility grid

Stand-alone inverters are connected to the battery bank and supply AC power to a distribution panel that is independent of the utility grid.

- PV arrays charge the batteries but do not directly influence the operation of the inverter.
- For stand-alone inverters, it is the electrical load connected to the AC output, rather than the DC power source, that affects the performance of the inverter.





- **AC module inverters** are small interactive inverters that are supplied by a single PV module.
- However, while the DC portion of the system is minimized, it is still accessible and may be subject to some requirements.

Enphase Energy

PV Inverters - Basic Facts for Planning PV Systems

- The inverter is the heart of every PV plant
- It converts direct current of the PV modules into grid-compliant alternating current and feeds this into the public grid.
- At the same time, it controls and monitors the entire plant.
- This way, it ensures on the one hand that the PV modules always operate at their radiation- and temperature-dependent maximum power.
- On the other, it continually monitors the power grid and is responsible for the adherence to various safety criteria.

The Right Inverter for Every Plant

- A large number of PV inverters is available on the market – but the devices are classified on the basis of **three important characteristics: 1.Power, 2. DC-related design, 3. and circuit topology**.
- **1.Power**
  The available power output starts at two kilowatts and extends into the megawatt range. Typical outputs are
- 5 kW for private home rooftop plants,
- 10 – 20 kW for commercial plants (e.g., factory or barn roofs)
- 500 – 800 kW for use in PV power stations.

The Right Inverter for Every Plant: Module wiring.

- **2. The DC-related design concerns the wiring of the PV modules to the inverter.**
- In this connection, distinctions are made between string, multistring and central inverters,
- whereby the term "string" refers to a string of modules connected in series.
- Multistring inverters have two or more string inputs, each with its own MPP tracker (Maximum Power Point, see below). These make a particularly sensible choice when the PV array consists of differently oriented subareas or is partially shaded.
- Central inverters only have one MPP tracker despite a relatively higher power output. They are especially well-suited for large-scale plants with a homogeneous generator.

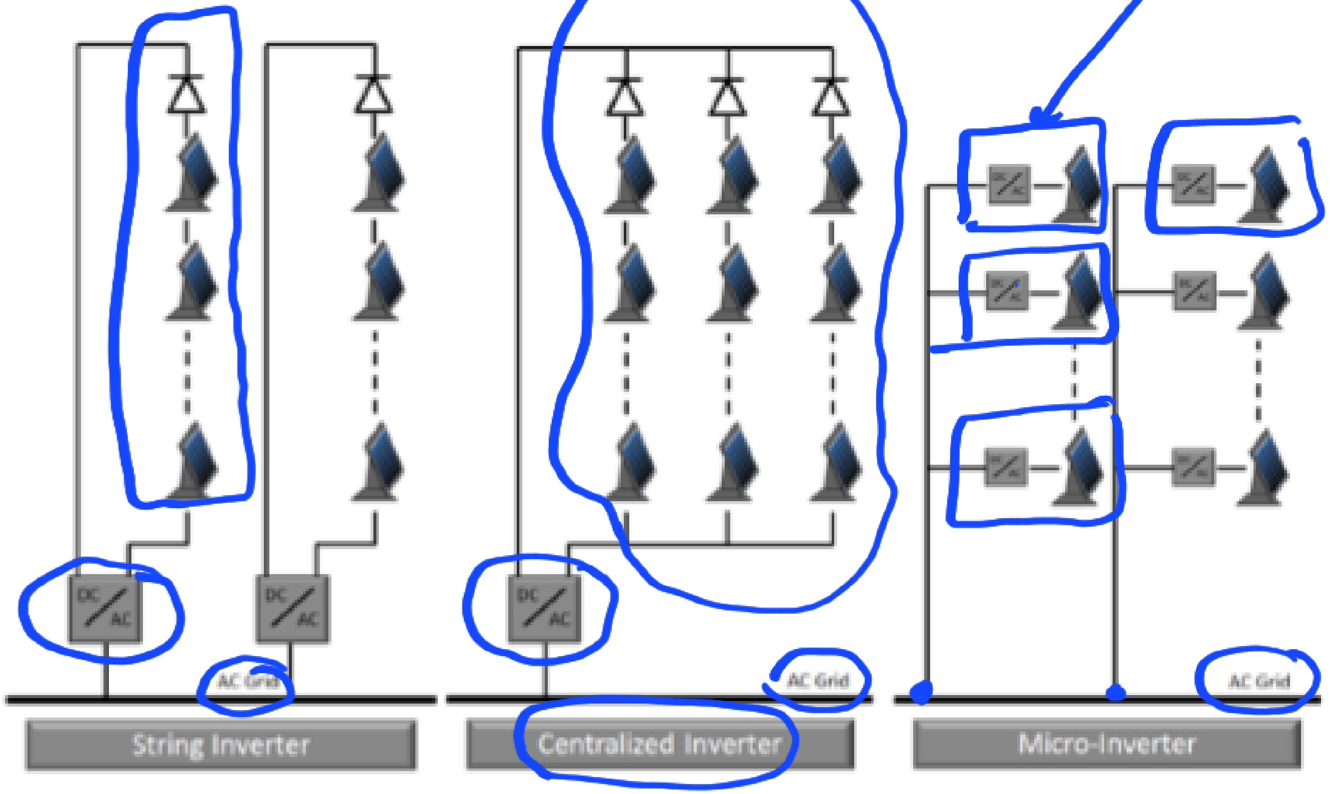
↓ PV modules

The Right Inverter for Every Plant: Module wiring.

- String Inverter
- Multistring inverters
- Central inverters
- Micro-Inverter

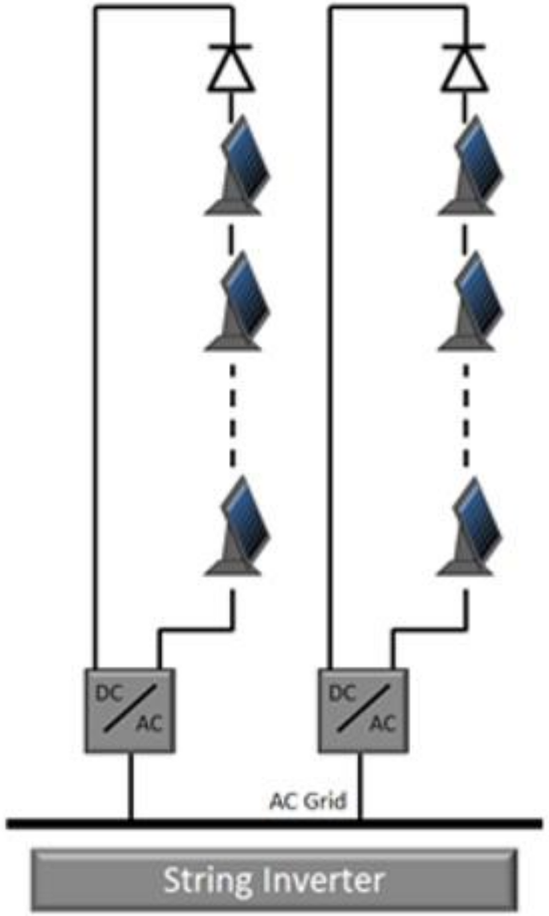
same as ac module inverter

two strings inverters



String Inverters

- As their name suggests, string inverters are designed to manage a single string of PV panels; therefore, each string of panels requires its own inverter.
- This is by far the most popular configuration for PV installations, due in part to the long lifetimes of the string inverters as well as the increased efficiency compared to centralized configurations.
- In a string configuration, each inverter is responsible for maximum power point tracking (MPPT) on a single string rather than the whole installation, allowing each string to operate at maximum efficiency

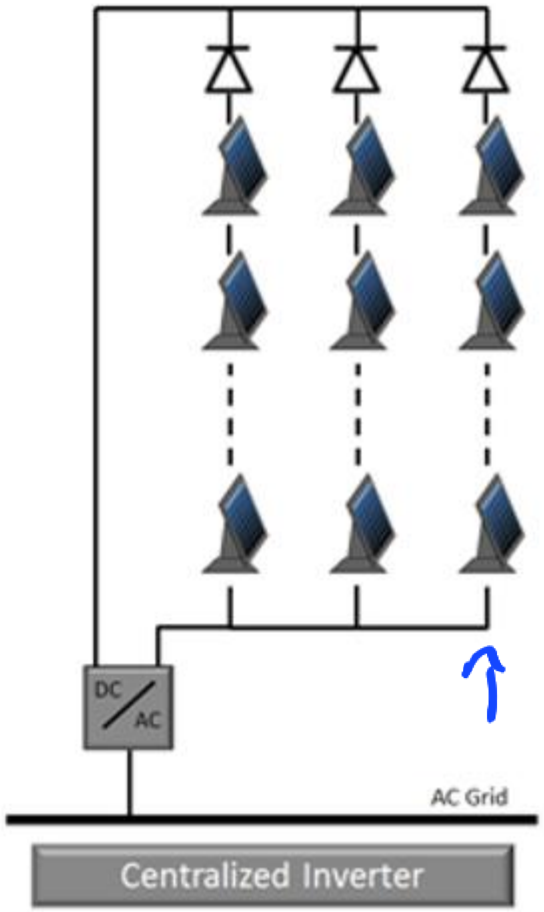


String Inverters

- This configuration does not have parallel connections of strings; instead smaller inverters for each string are used.
- Each string has its own MPPT, which means that all strings are completely independent from each other.
- So it is easy to build PV-systems even under constraints like different orientation of parts of the roof, different shading conditions or even various types or number of PV-modules.
- Of course, the modules of each string should be matched and operated under the same conditions because of the series connection within the string.
- A disadvantage of string-inverters in comparison to central inverters is the higher price per kW because of the rather low power level (1..5 kW) per unit.
- String inverters are build as single-phase inverters due to the low power level.

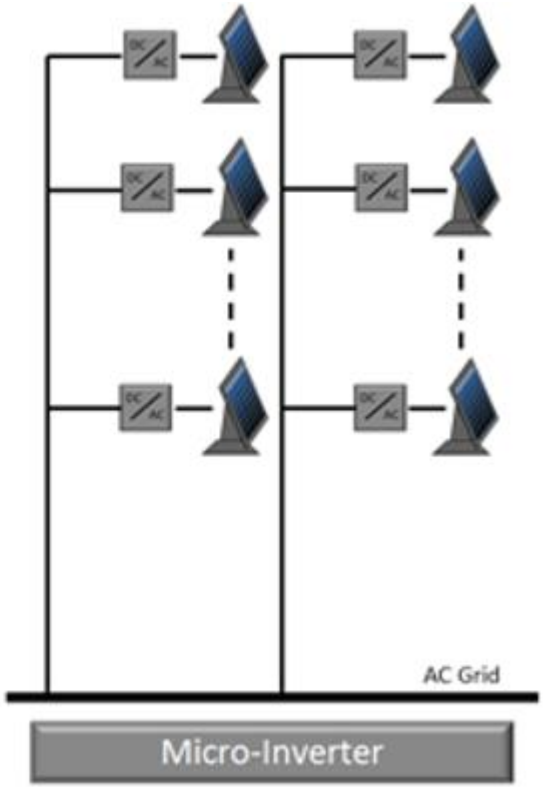
Centralized Inverters

- **They are intended to manage multiple strings in an installation.**
- **This means that an entire distributed energy resource (DER) will require only one inverter.**
- **Centralized inverters are very popular for larger installations due to their increased lifetimes as well as the simplicity arising from having only one inverter.**



Micro-Inverters

- Micro-inverters are intended to manage a single solar panel.
- Thus, each panel in the installation will require its own inverter.
- Many claim that with an inverter managing the MPPT of each panel individually, the installation as a whole will see a drastic increase in efficiency.
- For reasons of complexity, inconclusive data, and lack of smart capabilities, PPL generally recommends against the use of micro-inverters.



3. The Right Inverter for Every Plant: Circuit topology

- With regard to circuit topology, distinctions are made between one- and three-phase inverters,
- and between devices with and without transformers.
- One-phase inverters are usually used in small plants,
- in large PV plants either a network consisting of several one-phase inverters or three-phase inverters have to be used on account of the unbalanced load of 4.6 kVA.
- However, transformers serve the purpose of galvanic isolation (required in some countries) and make it possible to ground the PV module (necessary for some types of modules).
- Whenever possible, however, inverters without transformers are used.
- They are a little smaller and lighter than transformer devices and operate with a higher efficiency.

Tasks of the PV inverter

- The tasks of a PV inverter are as varied as they are demanding:

➢ **1. Low-loss conversion**
One of the most important characteristics of an inverter is its conversion efficiency.

➢ This value indicates what proportion of the energy “inserted” as direct current comes back out in the form of alternating current.

➢ Modern devices can operated with an efficiency of around 98 percent.

➢ 2. **Power optimization**
The inverter must find and continually observe the optimal operating point on the power characteristics curve, in order to “bring out” maximum power from the PV modules in every situation.

➢ The optimal operating point is called the "maximum power point" (MPP), and MPP tracking is extremely important for the energy output of a PV plant.

Tasks of the PV inverter:
3.Monitoring and securing

- On the one hand, the inverter monitors the energy yield of the PV plant and signals any problems.
- On the other, it also monitors the power grid that it is connected to. Thus, in the event of a problem in the power grid, it must immediately disconnect the plant from the grid for reasons of safety or to help support the grid – depending on the requirements of the local grid operator.
- In addition, in most cases the inverter has a device that can safely interrupt the current from the PV modules.
- If the cutout device is integrated directly in the inverter, installation and wiring efforts are reduced considerably.

Tasks of the PV inverter: 4. Communication

- Communication interfaces on the inverter allow control and monitoring of all parameters, operational data, and yields.
- Data can be retrieved and parameters can be set for the inverter via a network connection, industrial fieldbus such as RS485, or wireless via Bluetooth®.
- In most cases, data is retrieved through a data logger, which collects and prepares the data from several inverters and, if desired, transmits them to a free online data portal (e.g. Sunny Portal from SMA).

- Inverter interfaces include on-board screens, remote data monitors, and computerized data acquisition and processing software.

Tasks of the PV inverter:
5.Temperature management

- The temperature in the inverter housing also influences conversion efficiency. If it rises too much, the inverter has to reduce its power.
- Under some circumstances the available module power cannot be fully used.
- On the one hand, the installation location affects the temperature – a constantly cool environment is ideal. On the other hand, it directly depends on the inverter operation: even an efficiency of 98 percent means a power loss of two percent –in form of heat. If the plant power is 10 kW, the maximum thermal capacity is still 200 W. Therefore, an efficient and reliable cooling system for the enclosure is very important –.
- The optimum thermal layout of the components allows them to dissipate their heat directly to the environment, while the whole encasing acts as a heat sink at the same time.
- This allows the inverters to work at maximum rated capacity even at ambient temperatures of up to 50° C.

Tasks of the PV inverter:
6.Protection

- A weather-proof enclosure, ideally built in line with protective rating IP65, allows the inverter to be installed in any desired place outdoors.
- The advantage: the nearer to the modules the inverter can be installed, the lower the expenditure for the comparatively expensive DC wiring.

- Inverter enclosures may include protective devices such as circuit breakers.

Planning PV plants

- Professional planning and plant design takes the conditions at the set-up location into account in terms of module selection and wiring: roof pitch, any shade and, of course, alignment. In Palestine, maximum yield is achieved when the modules are aligned to the south at an angle of around 32 deg.
- Next, the selection of a suitable inverter in terms of performance and technology is absolutely essential.
- The rated capacity of the PV array may be up to ten percent above the rated of the inverter.
- If an inverter is greatly undersized, this can have a negative effect on plant yield, since the inverter can no longer process part of the module power supplied during periods of high radiation.
- It is also important that the maximum DC voltage never exceeds the permissible inverter input voltage – otherwise damage to the inverter may be the result.

Planning PV plants

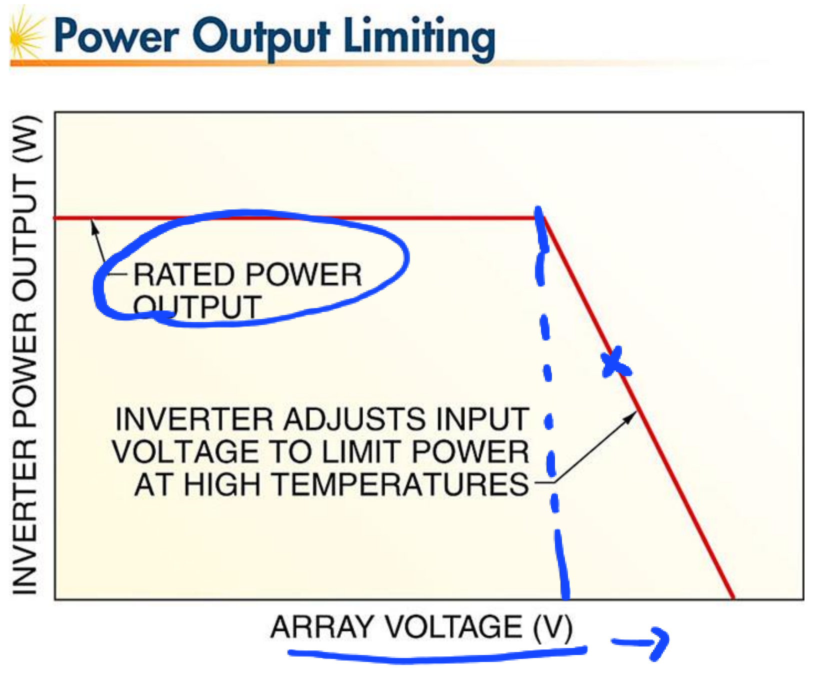
- Basically, almost every PV plant is unique and has to be designed customized for the specific location and requirements involved.
- For installers to make planning a plant easier, manufacturers, like SMA, provide professional planning tools.
- The free software **Sunny Design** allows solar specialists to design a tailor-made grid-tied PV plant for their customers.
- The program accesses a database containing all the current PV plants and high-resolution weather data, verifies the technical components, works out cable lengths and cross-sections and delivers data for an economic evaluation of the plant.

PVSYST ← for design

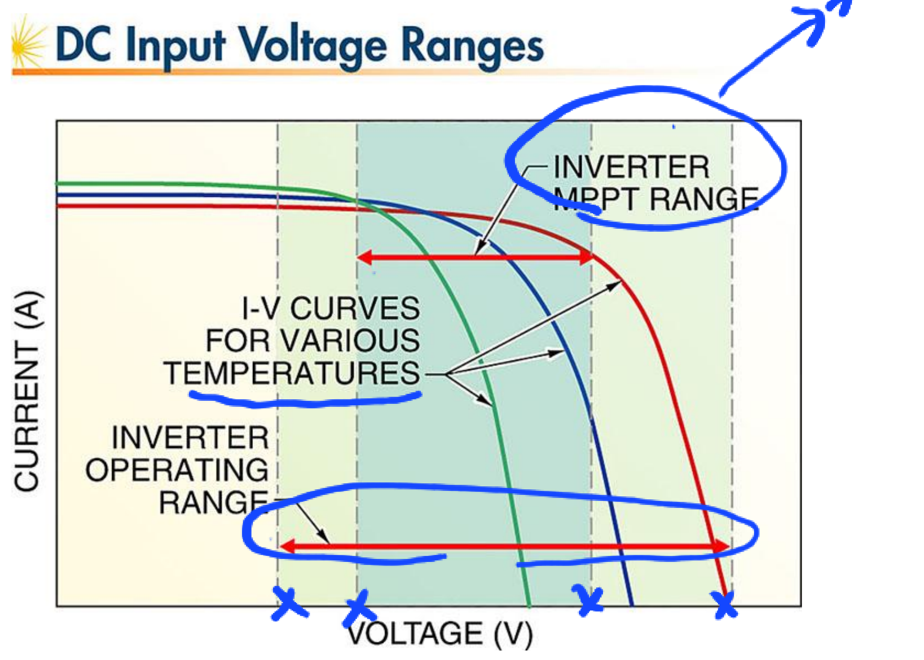
Inverter Nameplates

- Inverter nameplates include much of the needed information for sizing and operating the inverter.

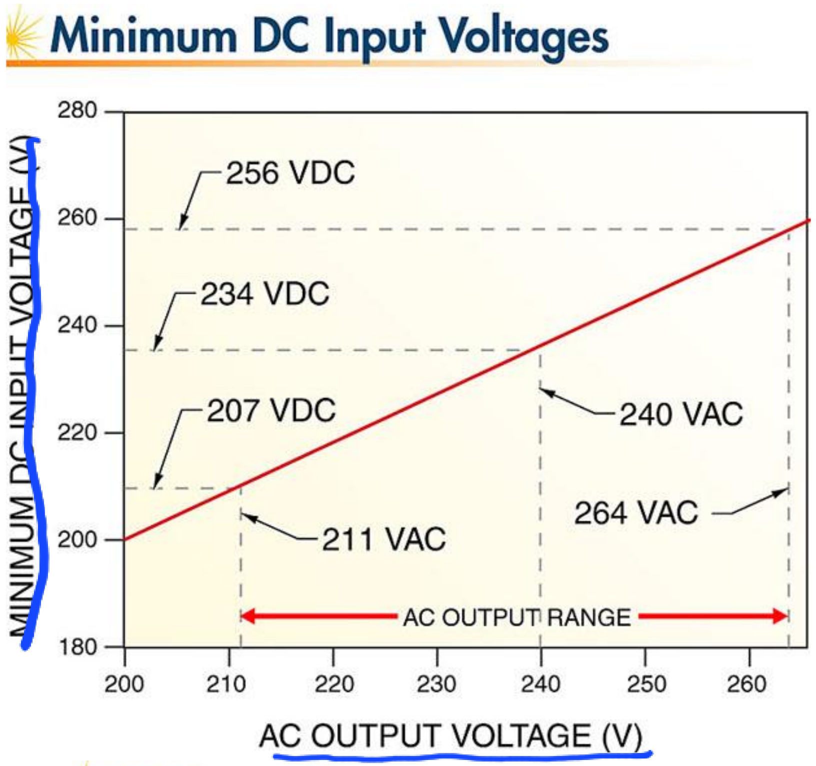
- At high temperatures, an interactive inverter may limit current input by raising the input voltage, which also lowers power input and output.



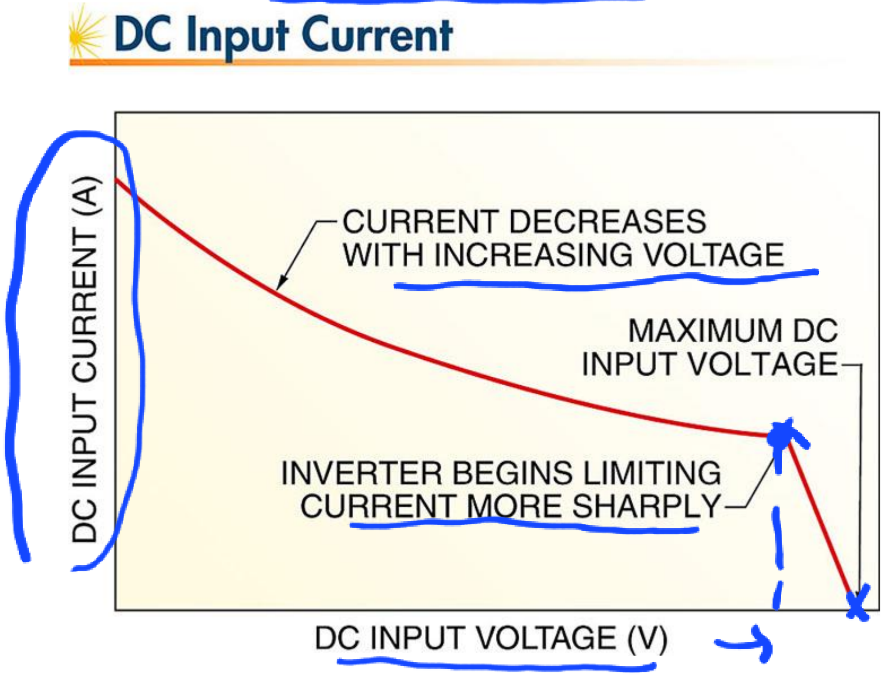
- Most inverters operate from a relatively wide range of input voltages, but the range for MPPT operation is smaller.



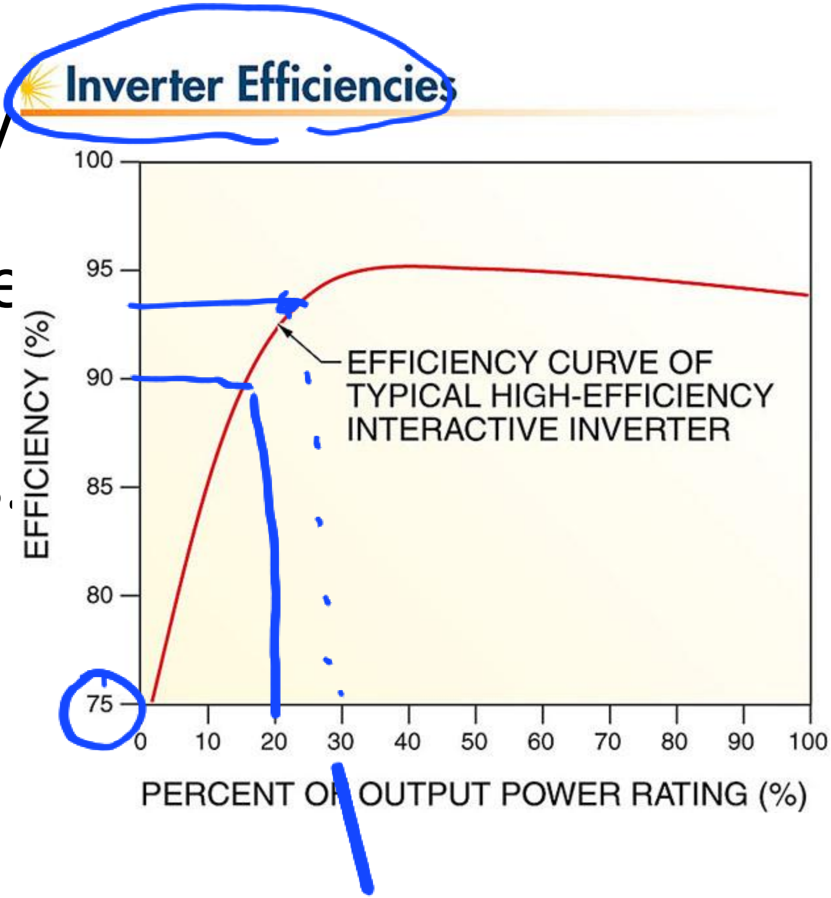
- In order to output AC voltage within the specified range, the DC input voltage must meet certain minimum values.



- Inverters may limit maximum DC input current with increasing DC input voltage.



- Most sine wave inverters maintain high efficiency over a wide operating-power range.
- Another important design issue that is driving the development of new topologies is the ability to exhibit a high efficiency also at partial loads, i.e. during the periods with reduced irradiation levels.
- Actually a weighted efficiency called 'European efficiency' has been defined that takes into consideration the periods for different irradiation levels across Europe.
- Today there are many PV inverter manufacturers in the market, such as SMA, Sunways, Conergy, Ingeteam, Danfoss Solar, Refu, etc., offering a wide range of transformerless PV inverters with very high European efficiency (>97 %) and maximum efficiency of up to 98 %.

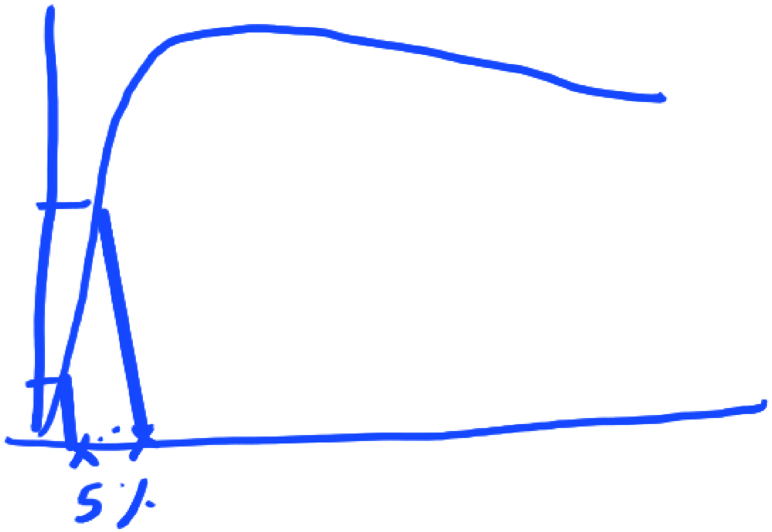


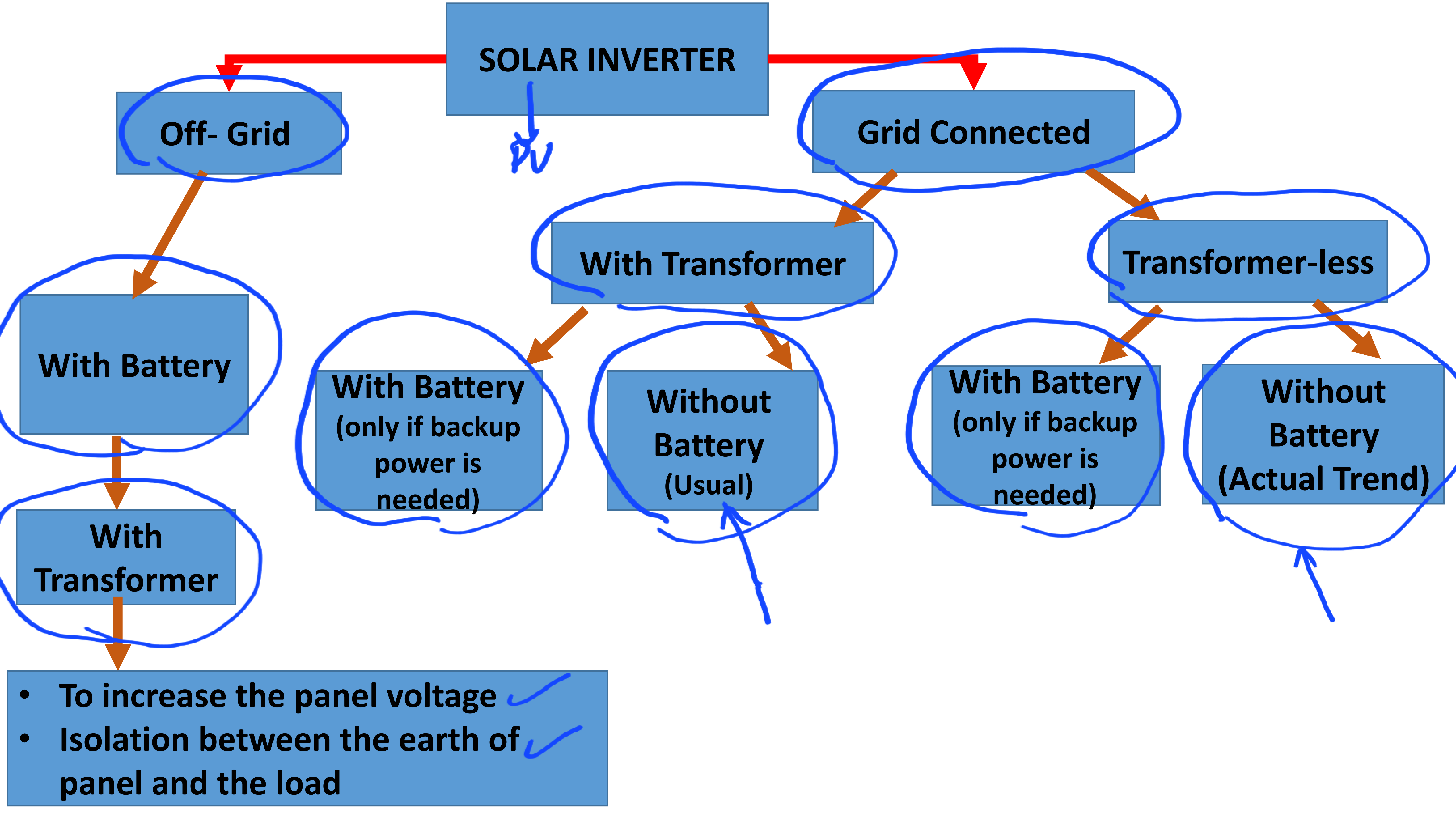
Efficiency of Grid Inverters

- **Euro Efficiency** = 0.03 x Eff5% + 0.06 x Eff10% + 0.13 x Eff20% + 0.1 x Eff30% + 0.48 x Eff50% + 0.2 x Eff100%.
- Now for climates of higher insolations like US south-west regions, the California Energy Commission (CEC) has proposed another weighting, which is now specified for some inverters used in the US.

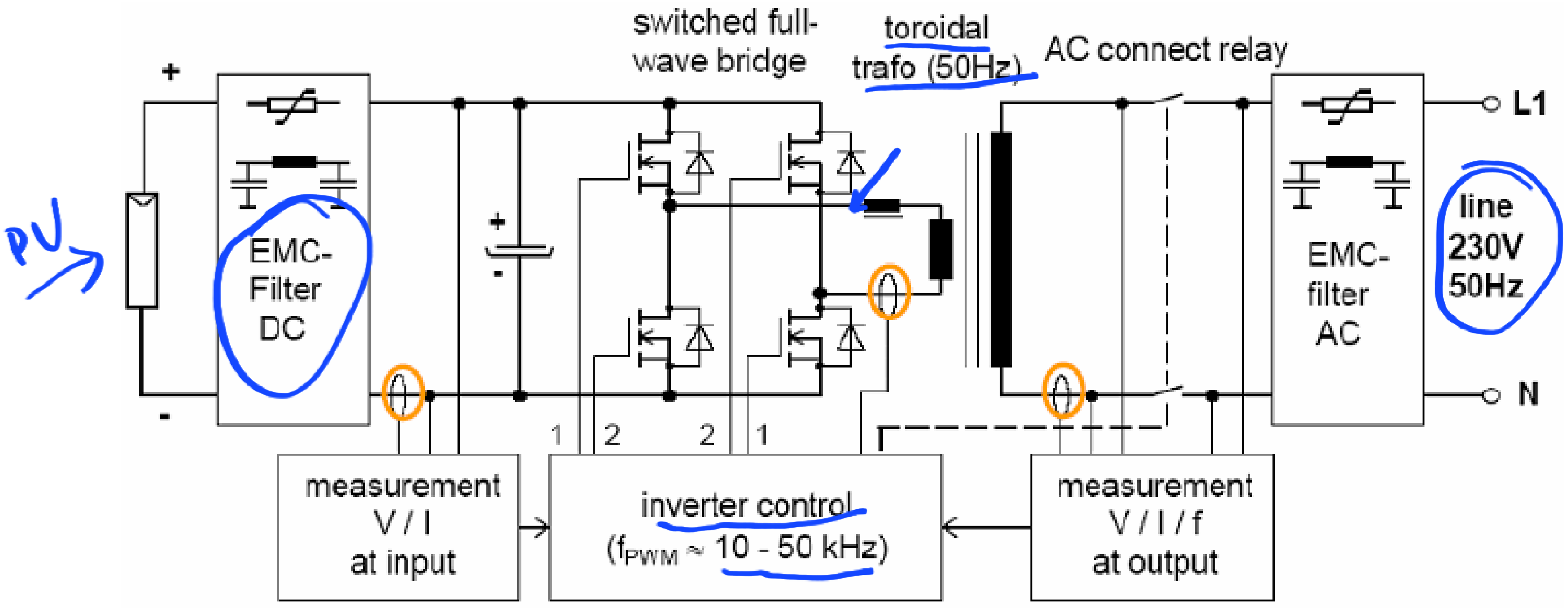
CEC Efficiency = 0.04 x Eff10% + 0.05 x Eff20% + 0.12 x Eff30% + 0.21 x Eff50% + 0.53 x Eff75%. + 0.05 x Eff100%

- **90 % of the market is grid-connected**
- **10 % of the market is off-grid**




SOLAR INVERTER
PV
Off- Grid
Grid Connected
With Battery
With Transformer
With Transformer
Transformer-less
With Battery (only if backup power is needed)
Without Battery (Usual)
With Battery (only if backup power is needed)
Without Battery (Actual Trend)
• To increase the panel voltage
• Isolation between the earth of panel and the load

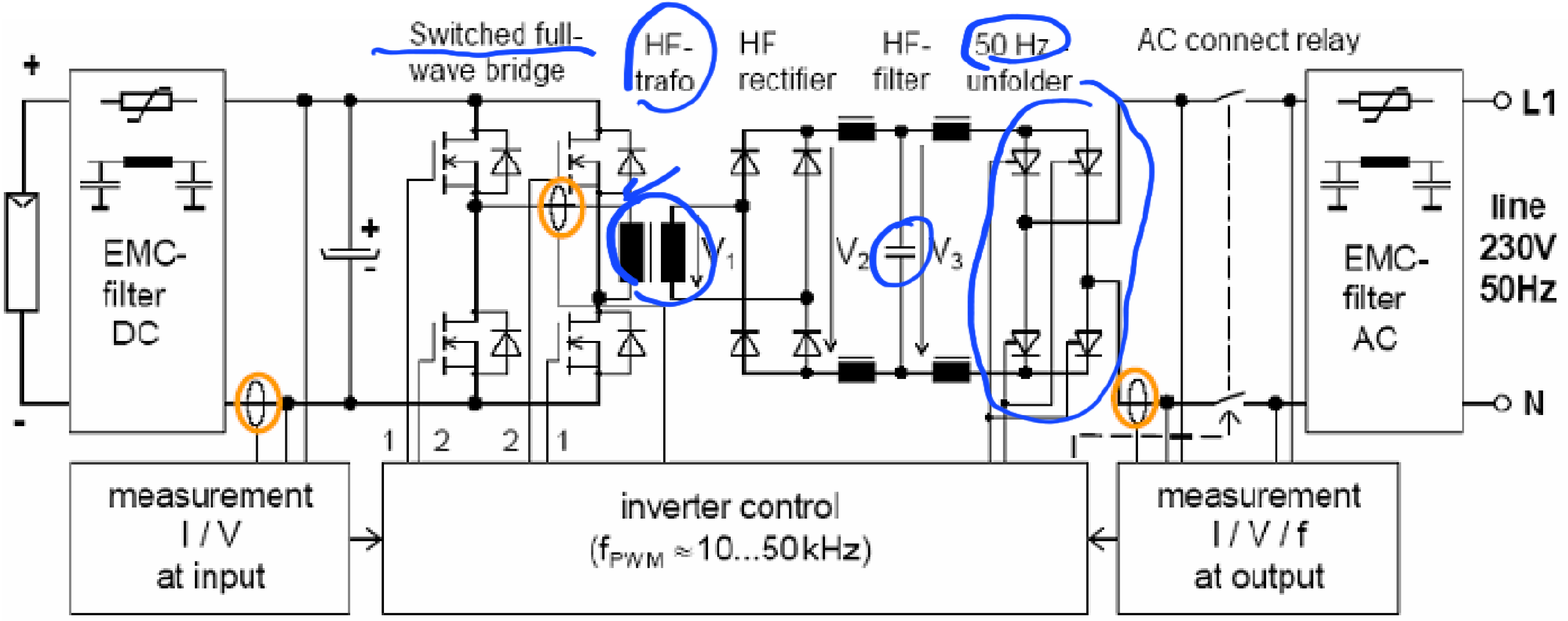
Grid Connected with LF transformer



Source : Evolution of Inverters for Grid Connected PV-Systems from 1989 to2000, H. Haeberlin

- **Advantages: very reliable, cost effective, No DC current injection, efficiency up to 96 %**
- **Disadvantages: weight, size** → 50 Hz transfo

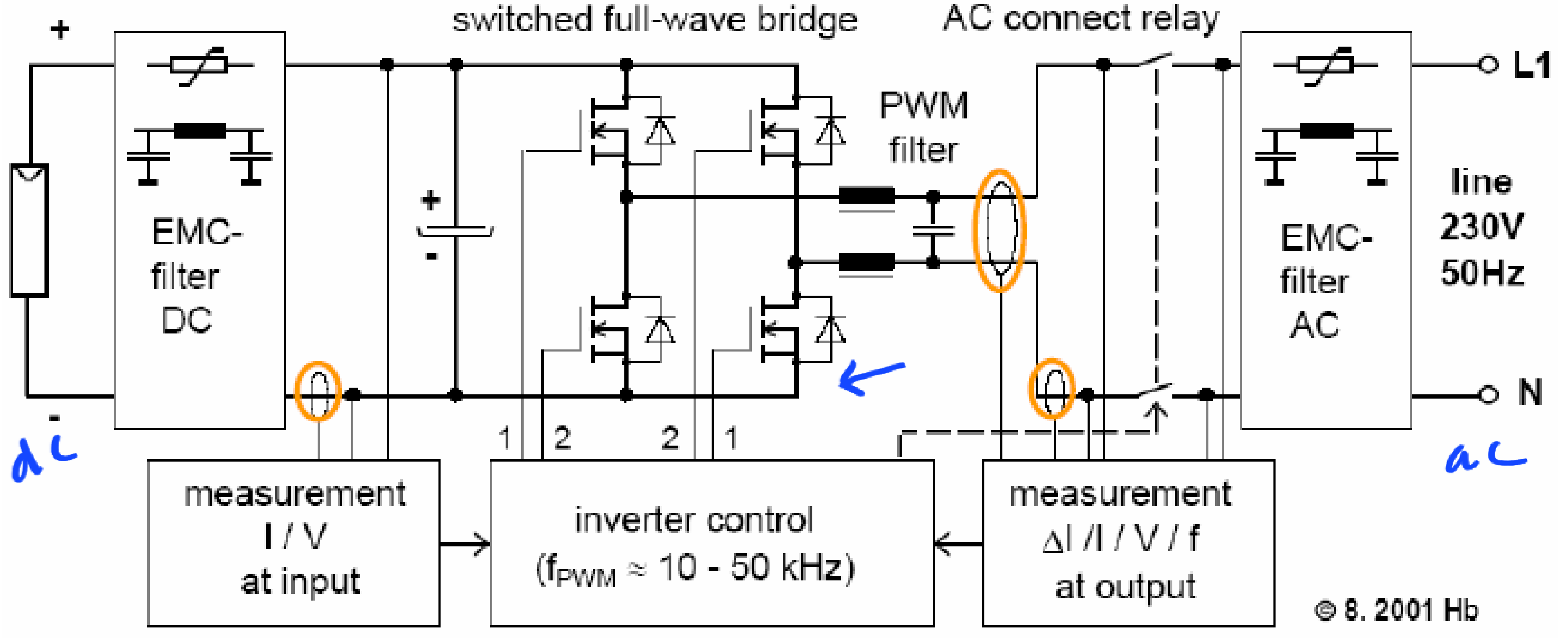
Grid Connected: Inverter with HF transformer (16…100 kHz)



Source : Evolution of Inverters for Grid Connected PV-Systems from 1989 to2000, H. Haeberlin

- Advantages: low weight, small size → HF transformer
- Disadvantages: high number of components (reliability), DC current injection is possible, efficiency over 95 % difficult to achieve

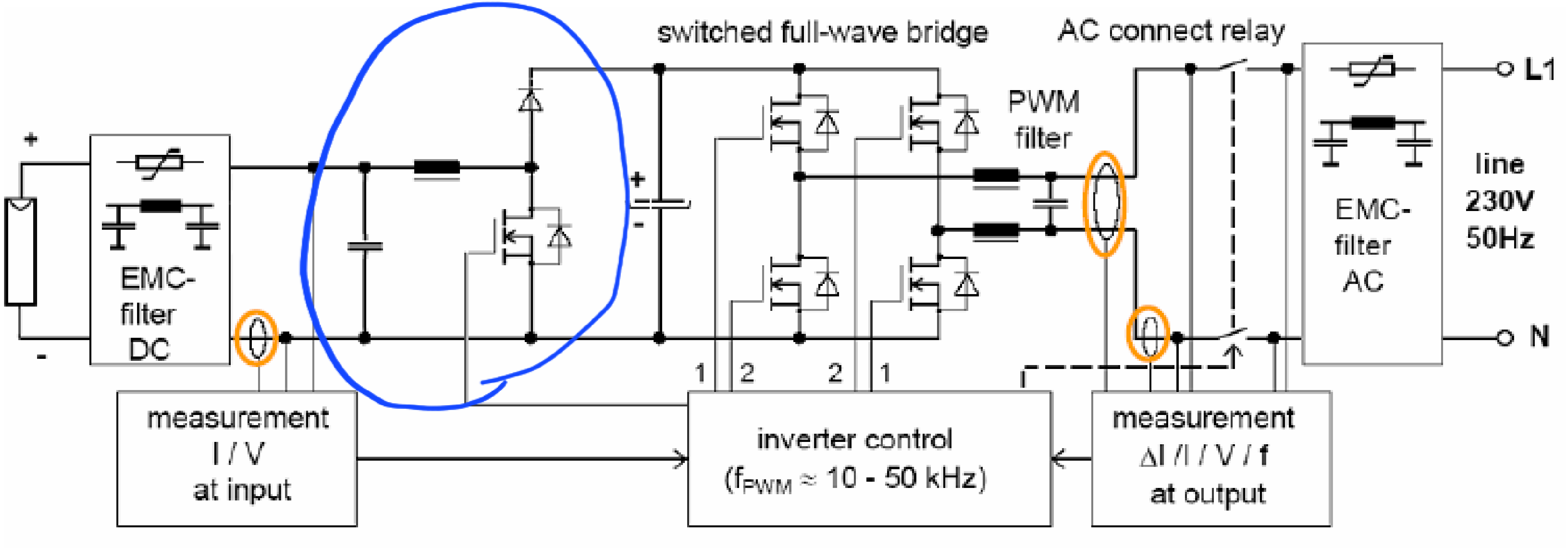
Grid Connected: Transformerless Inverter without DC Chopper



Source : Evolution of Inverters for Grid Connected PV-Systems from 1989 to2000, H. Haeberlin

- **Advantages: very high efficiency, low weight, small size**
- **Disadvantages: small input voltage range, no galvanic isolation, DC injection < 5 mA difficult to achieve, leakage current due to the AC component in PV module to earth**

Grid Connected: Transformerless Inverter with DC Chopper

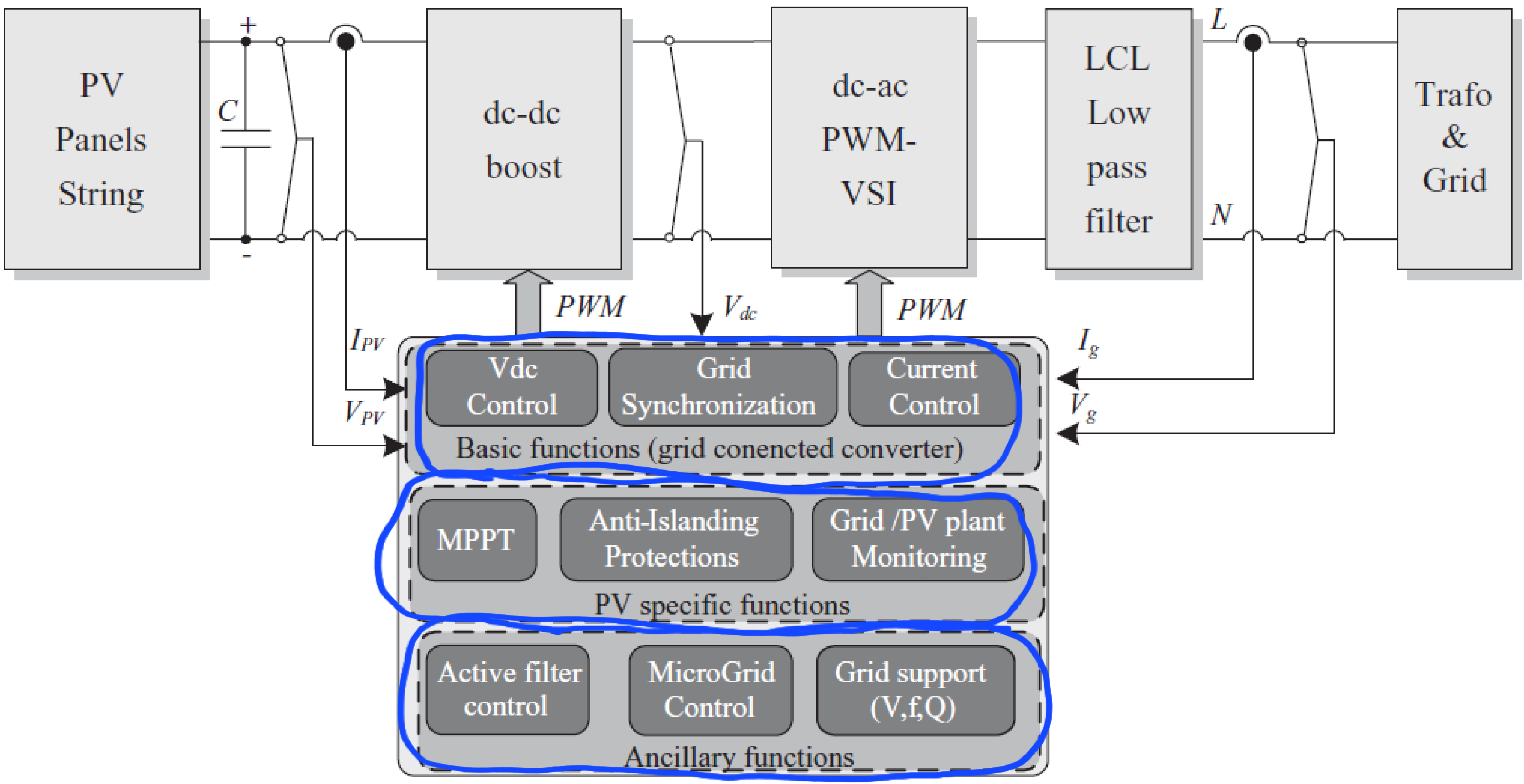


- **Advantages: very high efficiency, low weight, small size, wide input voltage range**
- **Disadvantages: no galvanic isolation, DC injection < 5 mA difficult, leakage current due to the AC-component in PV module to earth**

Control Structures

- Due to the very large variety of **transformer-less PV inverter topologies**, the control structures are also very different.
- In the following a generic, topology invariant control structure will be presented for a typical transformer-less topology with boost stage
- As can be seen, three different classes of control functions can be defined:

1) **Basic functions – common for all grid-connected inverters**
2) **PV specific functions – common for all PV inverters**
3) **Ancillary functions**


PV Panels String
C
+
-
dc-dc boost
dc-ac PWM-VSI
LCL Low pass filter
L
N
Trafo & Grid
PWM
V_{dc}
PWM
I_{PV}
V_{PV}
I_g
V_g
Vdc Control
Grid Synchronization
Current Control
Basic functions (grid conencted converter)
MPPT
Anti-Islanding Protections
Grid /PV plant Monitoring
PV specific functions
Active filter control
MicroGrid Control
Grid support (V,f,Q)
Ancillary functions

Basic functions – common for all grid-connected inverters

- **Grid current control**

==> ◦ THD limits imposed by standards

==> ◦ Stability in the case of large grid impedance variations

==> ◦ Ride-through grid voltage disturbances

- **DC voltage control**

==> ◦ Adaptation to grid voltage variations

==> ◦ Ride-through grid voltage disturbances

- **Grid synchronization**

==> ◦ Operation at the unity power factor as required by standards

==> ◦ Ride-through grid voltage disturbances

PV specific functions – common for all PV inverters

- Maximum power point tracking (MPPT)

==> ◦ Very high MPPT efficiency during steady state (typically >99 %)

==> ◦ Fast tracking during rapid irradiation changes (dynamical MPPT efficiency)

==> ◦ Stable operation at very low irradiation levels

- Anti-islanding (AI), as required by standards (VDE 0126, IEEE 1574, etc.)
- Grid monitoring

==> ◦ Synchronization

==> ◦ Fast voltage/frequency detection for passive AI

- Plant monitoring

==> ◦ Diagnostic of PV panel array

==> ◦ Partial shading detection

Ancillary functions

- **Grid support**

==> ◦ Local voltage control

==> ◦ Q compensation

==> ◦ Harmonic compensation

==> ◦ Fault ride-through

Future Trends

- PV inverter structures are evolving at a high pace. A high number of new patented transformer-less topologies based on either H-bridge or NPC appeared on the market with very high efficiency, up to 98 %.
- The obvious trend is more silicon for lower losses, as the number of switches has increased.
- The PV inverter market is driven by efficiency rather than cost, mainly due to the still very high price for PV energy.
- To increase even more the efficiency could be quite difficult using the current technology, but new research shows a real good potential in replacing the silicon switches by silicon-carbide ones.
- an efficiency increase of roughly 1 % was demonstrated on an HERIC topology by simply replacing the IGBT with a SiC MosFet.
- It is thus expected that in a few years the SiC MosFets will become commercially available, along with the SiC diodes, which are currently used today in very high efficiency boost converters.

→ new topologies
→ new device technologies

Future Trends

- Another trend in the design of PV inverters will be influenced by the grid requirements.
- At the moment, in many countries it is required that eventual islanding should be quickly detected and the inverter should be disconnected from the grid immediately in order to avoid any personal safety issues, especially for residential PV systems.
- However, as the PV weight in the grid integration is expected to grow very fast, it is possible that grid requirements will change and will require fault ride-through capability in order to stabilize the power system.
- Just like the case for wind power systems, this requirement has been introduced after a long period when its share in the power generation became important.
- This will most probably apply for large PV plants connected to distribution systems.

Future Trends

- Finally, integration of power components is an important factor as it is known from the electric drives sector that this will reduce the costs in the long term.
- The problem with PV inverters is that there are so many topologies and it is actually very difficult to find standard modules for implementation.
- A good example is SMA, which managed to produce customized power modules for the H5 topology.
- Semikron and Vincotech (previously a Tyco division) are now offering power modules for NPC topologies,
- Mitsubishi is offering intelligent power modules (IPM) with one or two boost converters plus an H-bridge inverter specially designed for PV applications,
- and this trend is expected to continue also with other major device manufacturers as the PV inverter market is growing very fast.

Disconnection Time for Voltage & Frequency Variation

Table 3.2 Disconnection time for voltage variations

IEEE 1547		IEC 61727		VDE 0126-1-1	
Voltage range (%)	Disconnection time (sec.)	Voltage range (%)	Disconnection time (sec.)	Voltage range (%)	Disconnection time (sec.)
$V < 50$	0.16	$V < 50$	0.10	$110 \le V < 85$	0.2
$50 \le V < 88$	2.00	$50 \le V < 85$	2.00		
$110 < V < 120$	1.00	$110 < V < 135$	2.00		
$V > 120$	0.16	$V > 135$	0.05		

Table 3.3 Disconnection time for frequency variations

IEEE 1547		IEC 61727		VDE 0126-1-1	
Frequency range (Hz)	Disconnection time (sec.)	Frequency range (Hz)	Disconnection time (sec.)	Frequency range (Hz)	Disconnection time (sec.)
$59.3 < f < 60.5^a$	0.16	$f_n - 1 < f < f_n + 1$	0.2	$47.5 < f < 50.2$	0.2

Reconnection after Trip and DC current Injection

Table 3.4 Conditions for reconnection after trip

IEEE 1547	IEC 61727	VDE 0126-1-1
$88 < V < 110$ (%) AND $59.3 < f < 60.5$ (Hz)	$85 < V < 110$ (%) AND $f_n - 1 < f < f_n + 1$ (Hz) AND Minimum delay of 3 min.	

Table 3.5 DC current injection limitation

IEEE 1574	IEC 61727	VDE 0126-1-1
$I_{DC} < 0.5$ (%) of the rated RMS current	$I_{DC} < 1$ (%) of the rated RMS current	$I_{DC} < 1$ A Maximum trip time 0.2 sec.

THD and harmonics levels

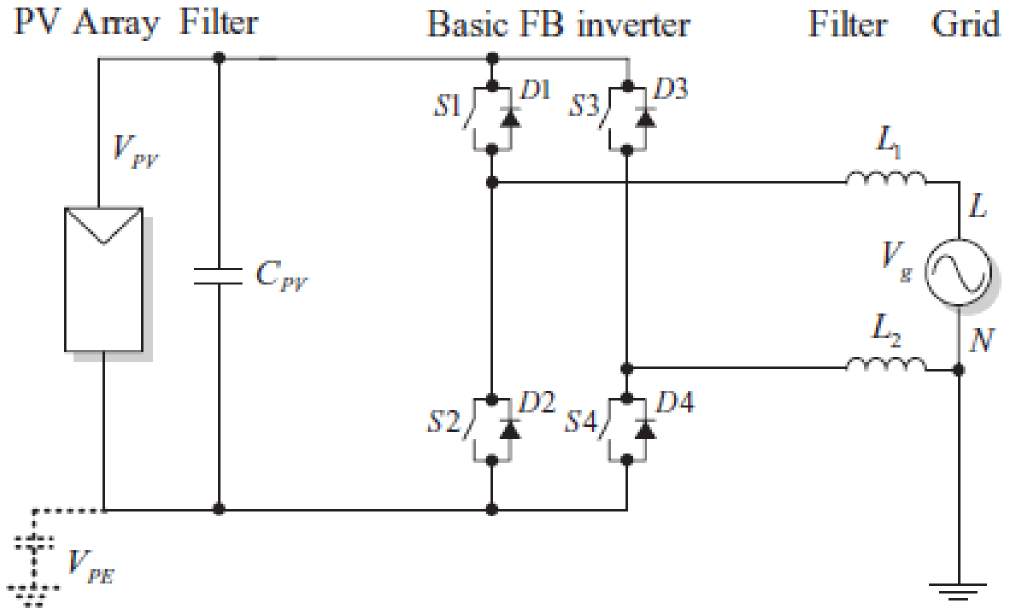
Table 3.6 Maximum current harmonics

IEEE 1547 and IEC 61727						
Individual harmonic order (odd)[a]	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	Total harmonic distortion THD (%)
(%)	4.0	2.0	1.5	0.6	0.3	5.0

[a]Even harmonics are limited to 25 % of the odd harmonic limits above.

Table 3.7 Current harmonic limits set by IEC 61000-3-2 (class A)

Odd harmonics		Even harmonics	
Order h	Current (A)	Order h	Current (A)
3	2.30	2	1.08
5	1.14	4	0.43
7	0.77	6	0.30
9	0.40	$8 \le h \le 40$	$0.23 \times 8/h$
11	0.33		
13	0.21		
$13 \le h \le 39$	$0.15 \times 15/h$		

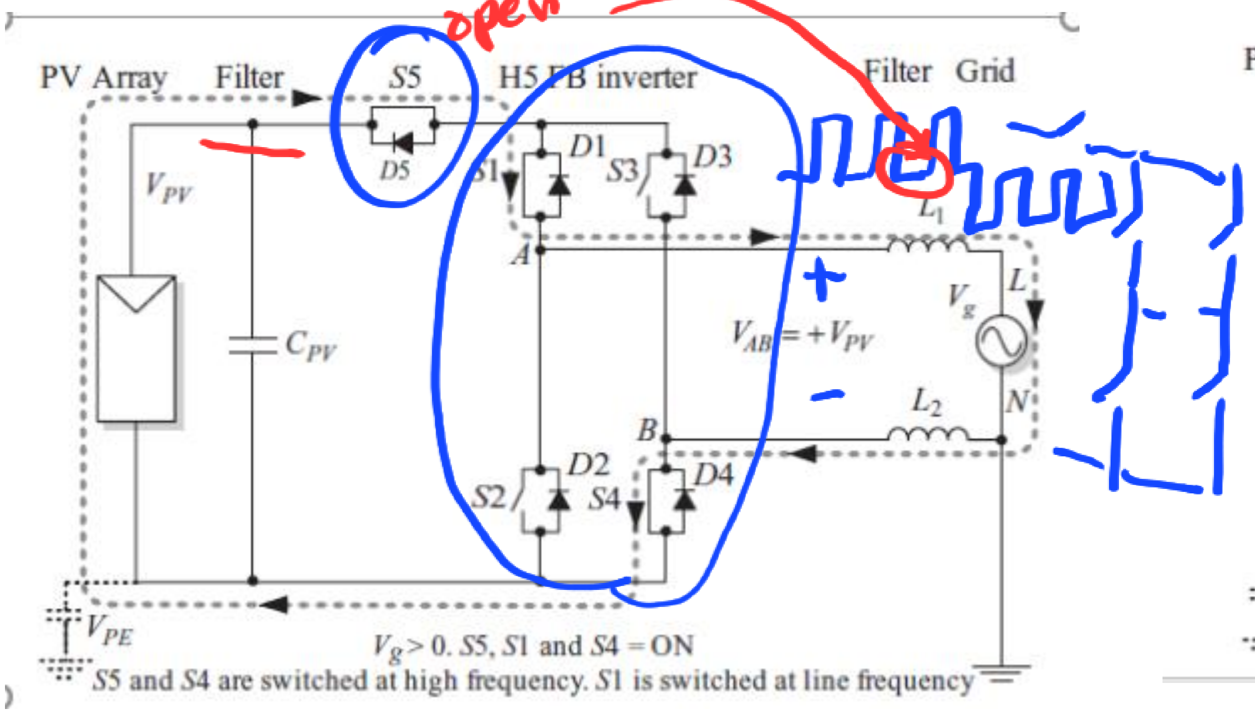

PV Array
Filter
Basic FB inverter
Filter
Grid
V_{PV}
C_{PV}
S1
D1
S3
D3
S2
D2
S4
D4
L_1
L_2
L
N
V_g
V_{PE}

H5 Inverter (SMA)

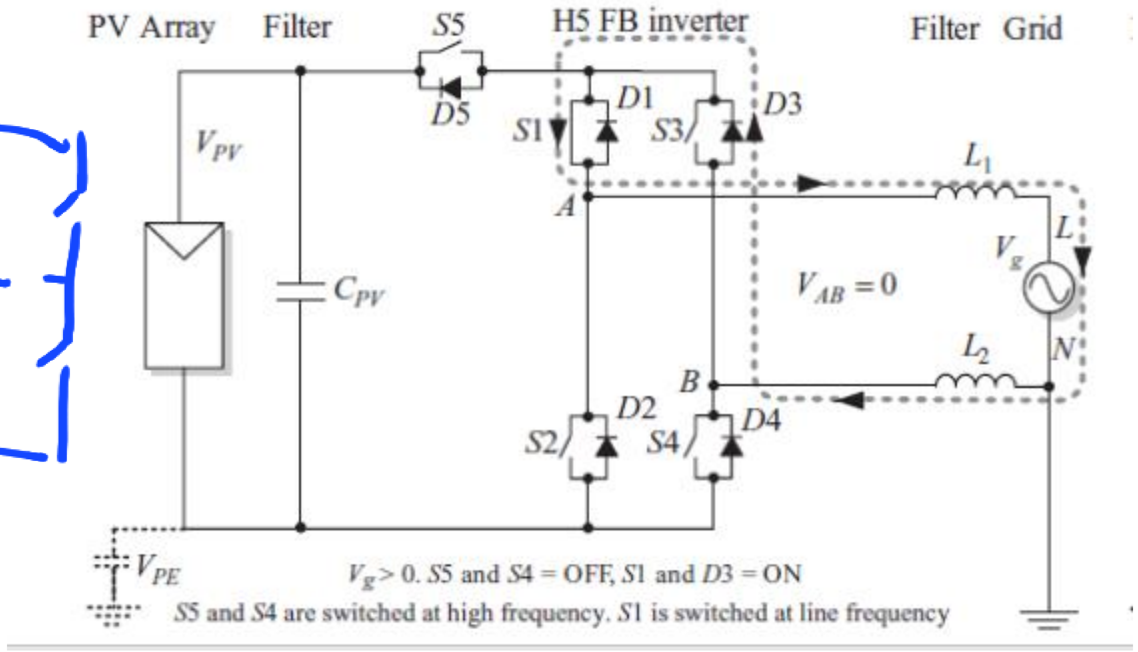
- In 2005 SMA patented a new inverter topology called H5 .
- it is a classical H-bridge with an extra fifth switch in the positive bus of the DC link which provides two vital functions:

1) Prevents the reactive power exchange between *L*1(2) and *CPV* during the zero voltage state, thus increasing efficiency to about 98%

2) Isolates the PV module from the grid during the zero voltage state, thus eliminating the high-frequency content of *VPE*, and yielding a very low leakage current and EMI.



$V_g > 0$. S5, S1 and S4 = ON
S5 and S4 are switched at high frequency. S1 is switched at line frequency



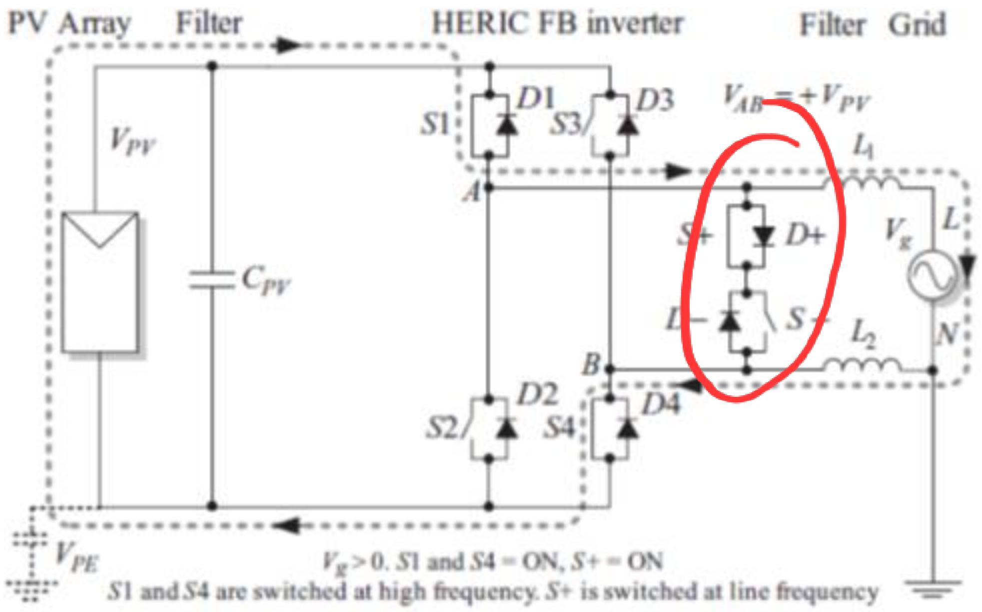
$V_g > 0$. S5 and S4 = OFF, S1 and D3 = ON
S5 and S4 are switched at high frequency. S1 is switched at line frequency

HERIC Inverter (Sunways)

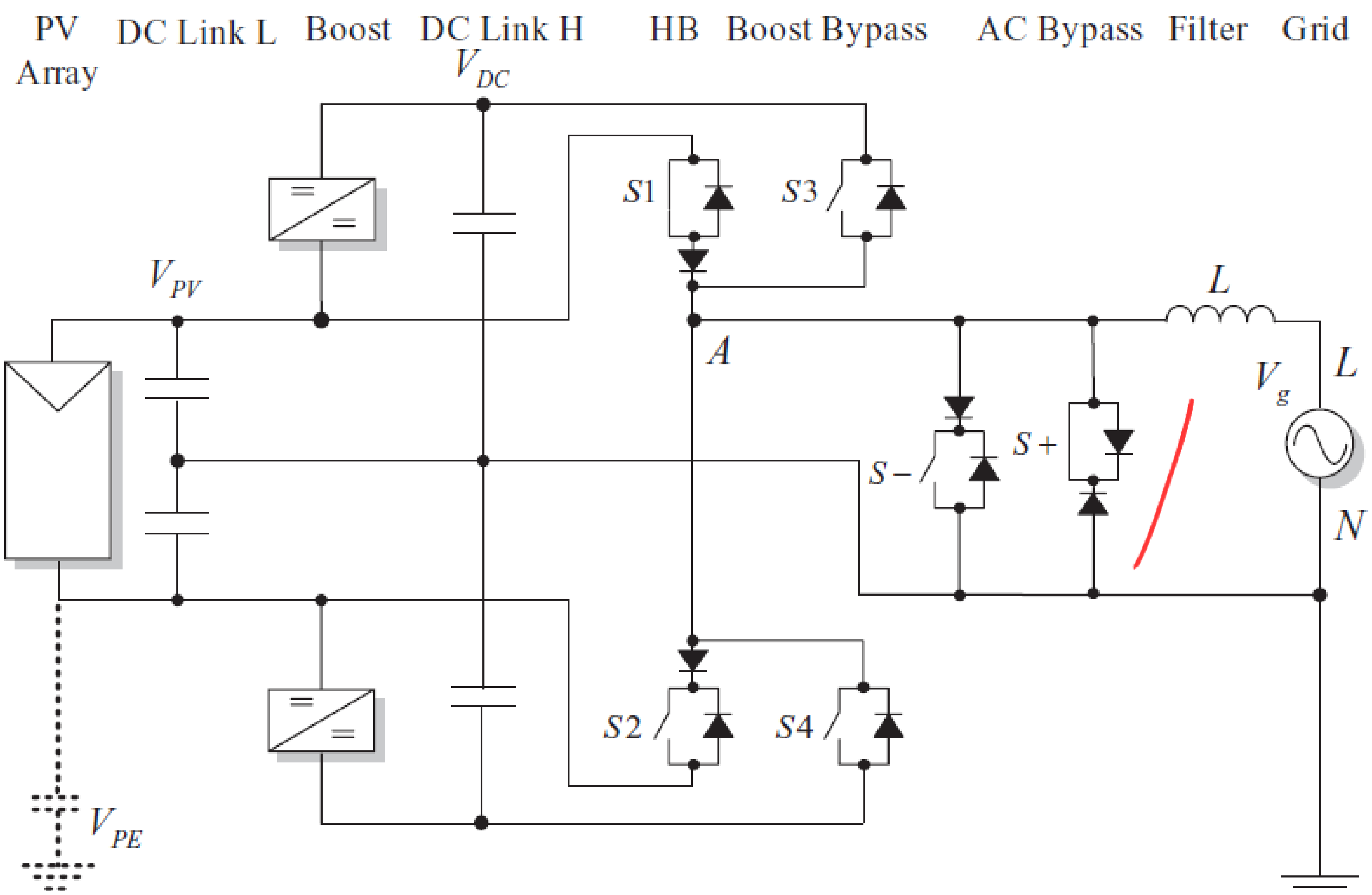
- In 2006, Sunways patented a new topology also derived from the classical H-bridge called HERIC (highly efficient and reliable inverter concept) by adding a bypass leg in the AC side using two back-to-back IGBTs
- The AC bypass provides the same two vital functions as the fifth switch in case of the H5 topology:

1) Prevents the reactive power exchange between *L*1(2) and *CPV* during the zero voltage state, thus increasing efficiency to ~97%

2) Isolates the PV module from the grid during the zero voltage state, thus eliminating the high-frequency content of *VPE*, yielding very low leakage current and EMI.

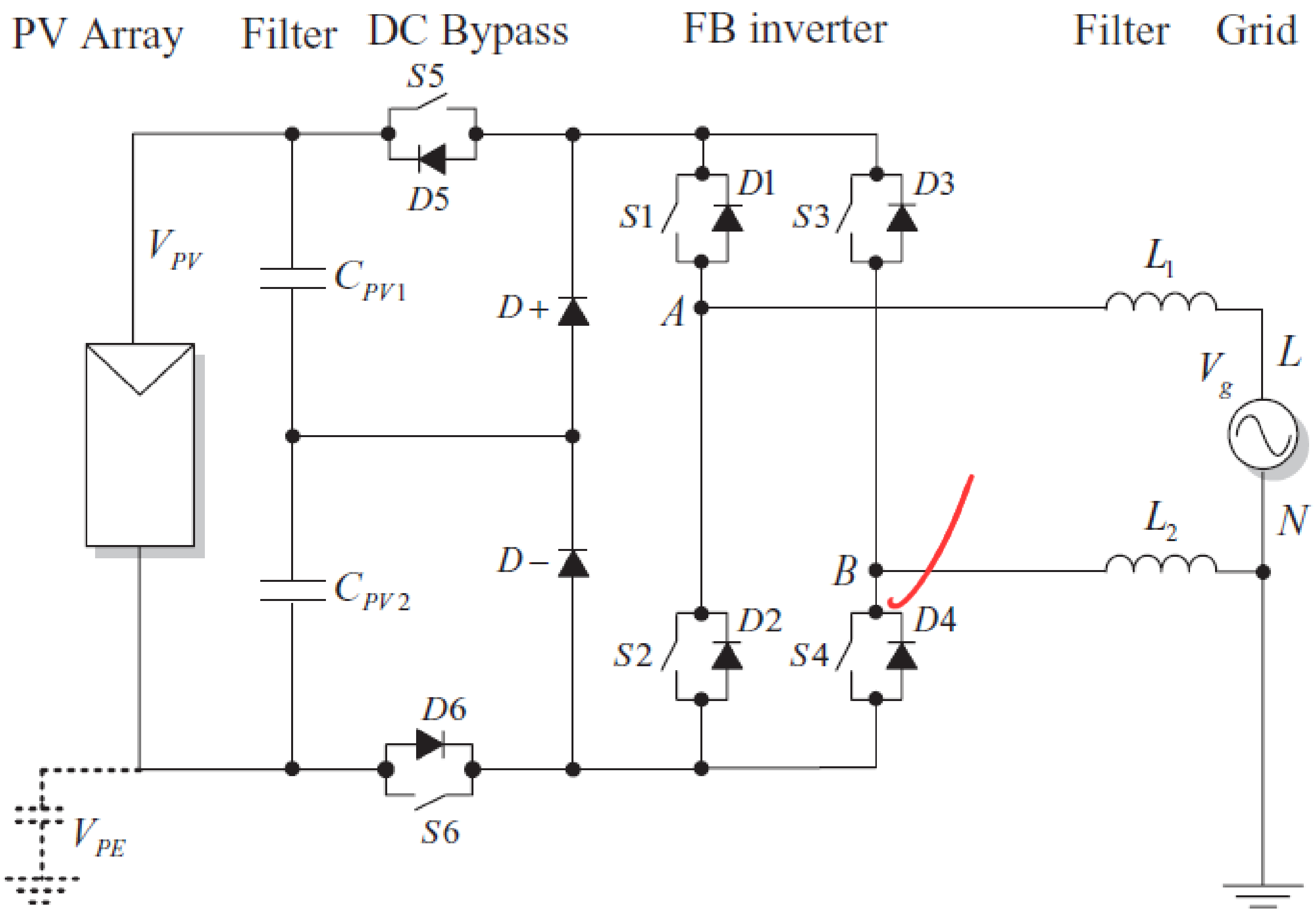


REFU Inverter



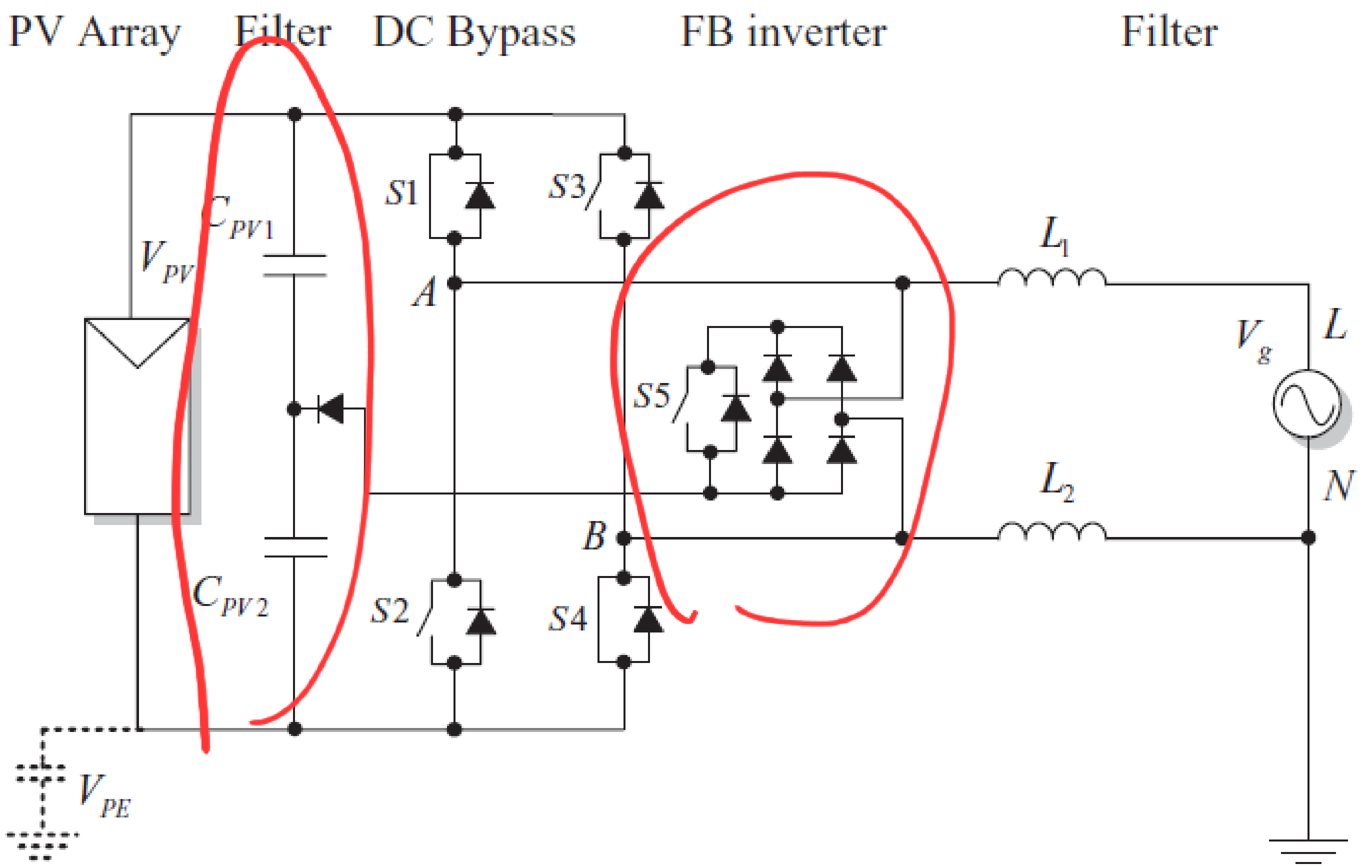
Full-Bridge Inverter with DC Bypass – FB-DCBP (Ingeteam)

- *The FB-DCBP topology is very suitable for use in transformer-less PV applications due to high efficiency and low leakage current and EMI.*
- *This topology is currently commercialized by Ingeteam in the Ingecon Sun TL series (2.5/3.3/6 kW) with reported European efficiency of 95.1%and maximum efficiency of 96.5%(Photon International, August 2007).*



Full-Bridge Zero Voltage Rectifier – FB-ZVR

- *The FB-ZVR inherits the advantages of the HERIC in terms of high efficiency and low leakage.*
- *Due to the high switching frequency of S5, the efficiency is lower than at HERIC, but it provides the advantage that can work at any power factor*

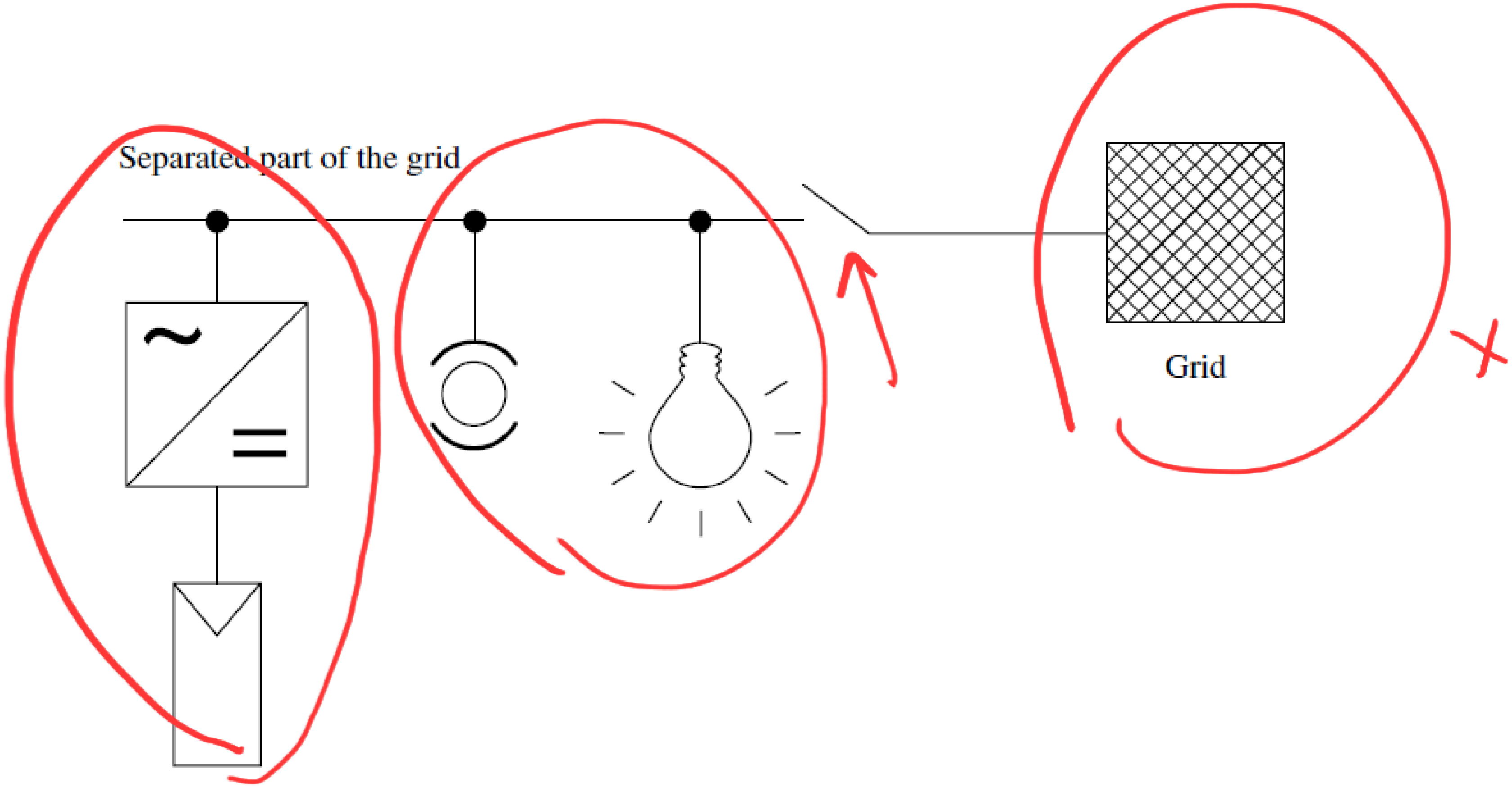


Safety Aspects with Grid-connected Inverters

- An important issue for grid-connected systems is associated with islanding protection.
- Islanding may occur, if a part of the local grid is switched off, for example, for maintenance reasons and if the injected power is equal to the actual load in the separated part of the grid. This situation is shown in the following figure (next slide)
- The situation described above becomes very unlikely since not only the effective power but the reactive power as well must be equal between production and consumption.

Safety Aspects with Grid-connected Inverters

- After switch-off, the separated part of the grid may continue operation, if the injected power by the PV system equals the actual load



Safety Aspects with Grid-connected Inverters

- As a first measure, frequency and voltage monitoring will identify by far most situations in grids turned off since the smallest deviations in production or in consumption will lead to changes in frequency or voltage or in both of them.
- The experience with big wind farms has shown that limitation of voltage or frequency may lead to undesired results, however.
- In case of heavy loads on the grid, both the voltage and the frequency may fall below the set point. In this situation, cut-off of power sources takes place when they would be needed urgently to support the grid.
- As a further method to identify islanding conditions, monitoring of the grid's impedance is being performed by injecting power peaks, which do not correspond with the fundamental frequency (50 or 60 Hz), by the inverter into the grid and by monitoring this influence on the grids voltage shape. This method is currently accepted by German safety code.

→ End of Inverter Topic

→ We will do inverter choice and calculation in the design