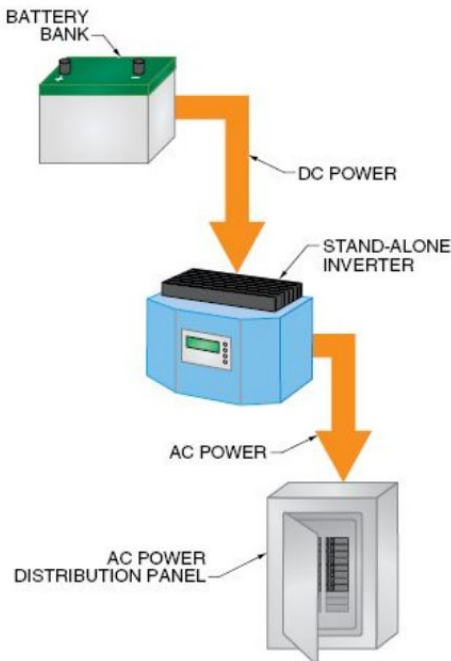


Overview of inverter

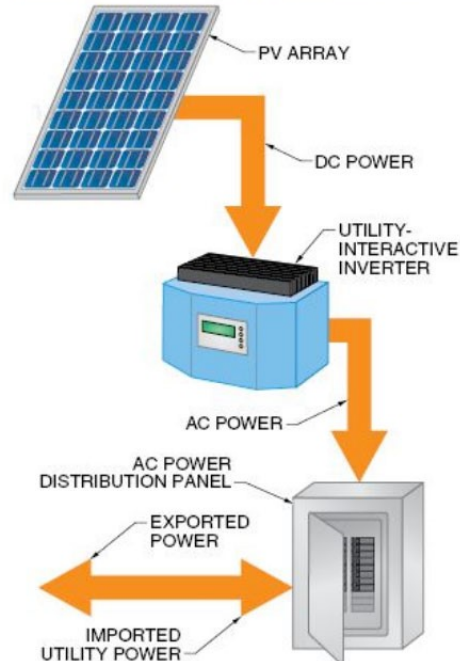
PV systems produce variable DC power. Therefore, inverters are used to convert DC power to AC devices use.

Types of inverters:

Stand-Alone Inverters



Utility-Interactive Inverters



- **Stand-alone:** These inverters invert DC power of batteries to AC and **operate independently** of the PV array and the utility grid.
- **Utility interactive:** These inverters interface between the PV array and the utility grid and convert the PV DC output to **AC power that is synchronous** with the utility grid.

Types of inverter (1)

Utility- interactive inverters can be classified as **string inverters**, **central inverters**, **utility-scale inverters**, **multimode inverters**, or **module-level inverters**.



String inverters are commonly used in residential and small commercial PV systems.
AC power rating: **1 kW - 12 kW.**



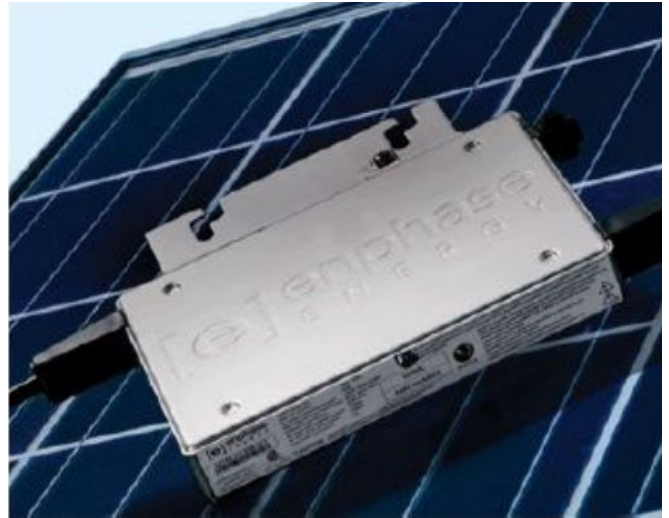
Central inverters have higher power ratings and are suited for arrays with identical modules that are aligned alike.
AC power ratings: ~ **30 kW - 500 kW.**

Types of inverter (2)



Utility-scale inverters are very large systems that output about **500 kW to 1 MW and higher** to the grid at voltages up to 35 kV.

These inverters are used in PV power plant installations.



Module-level or **Micro-inverters** are small utility-interactive inverters that are supplied by a single PV module.

AC power rating: 200 W to 300 W, which is consistent with standard individual PV module sizes.

Inverter features (1)

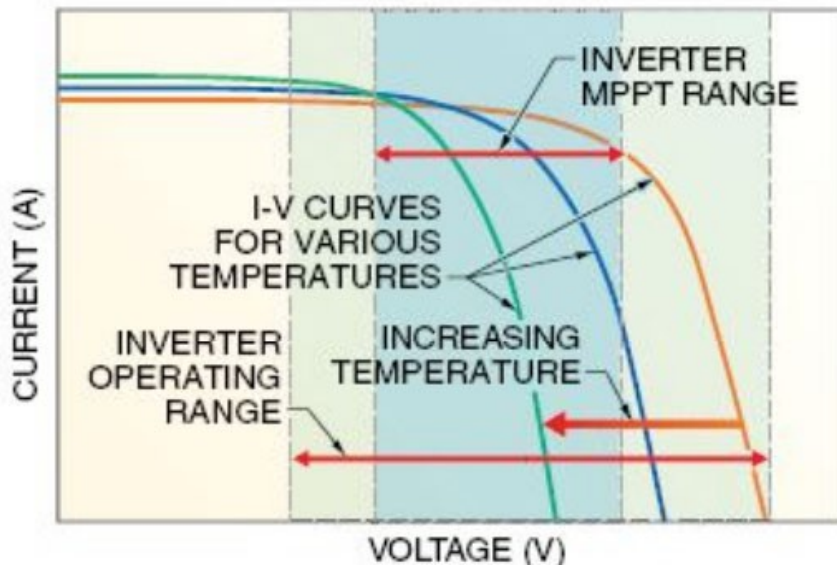
Multimode inverters can operate in either interactive or stand-alone mode.

PV system inverters specifications: Power rating, voltage rating, temperature limitations, operating limits, installation requirements, safety, and maintenance, and other performance data.

Maximum Power Point Trackers (MPPT): A MPPT device continuously adjusts the load on a PV device under changing temperature and irradiance conditions to keep it operating at its maximum power point.

Since they are connected directly to the array, **all interactive inverters include MPPT circuits**. Stand-alone inverters usually do not have MPPT.

Inverter features (2)



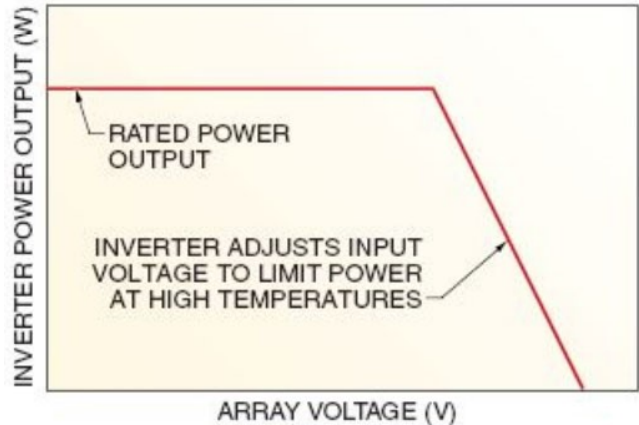
DC input voltage ranges

- Most inverters operate from a relatively **wide range of input voltages**, but the range for **MPPT operation is usually smaller**.
- The **DC voltage from an array** is affected by **ambient temperature**, which complicates sizing.

Inverter features (3)

Power output limiting

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



Efficiency:

- Inverter efficiency is the **ratio of its AC power output to DC power input**. Losses include heat in the switching processes and stand-by losses.
- Most **interactive PV inverters** are rated **90% to 95%** efficient. Quality **stand-alone inverters** have peak efficiencies of **~ 90%**. Lesser-quality inverters may have efficiencies of **75% to 85%**.
- **High-frequency and high-voltage inverters** are generally **more efficient** than lower-voltage inverters operating at low frequency.

Inverter features (4)

Example of inverter nameplate data

Fronius IG	IG 2000	IG 3000	IG 2500-LV
DC Input Data			
Recommend PV power	1500 - 2500 Wp	2500 - 3300 Wp	1800 - 3000 Wp
Max. DC input voltage	500 V	500 V	500 V
Operating DC voltage range	150 - 450 V	150 - 450 V	150 - 450 V
Max. usable DC input current	13.6 A	13.6 A	13.6 A
AC Output Data			
Max. Output power @ 40°C	2000 W	2700 W	2350 W
Nominal AC output voltage	240 V	240 V	208 V
Utility AC voltage range	212 - 264 V (240 V + 10% / -12%)		183 - 227 V
Maximum AC current	8.35 A	11.25 A	11.25 A
Max. utility back feed current	0.0 A	0.0 A	0.0 A
Operating frequency range	59.3 - 60.5 Hz (60 Hz nom)		
Total Harmonic Distortion THD	<5%		
Power Factor (cos phi)	1		

Sizing of PV system & inverter

Sizing problem: An optimization problem where an optimal capacity of PV system is selected to **maximize certain benefits** (typically profit).

PV array sizing:

- NREL provides tools for residential PV system sizing (e.g. **PVWatts Calculator**). For utility PV systems, sizing is specific to the utility grid features and requirements.

Inverter sizing:

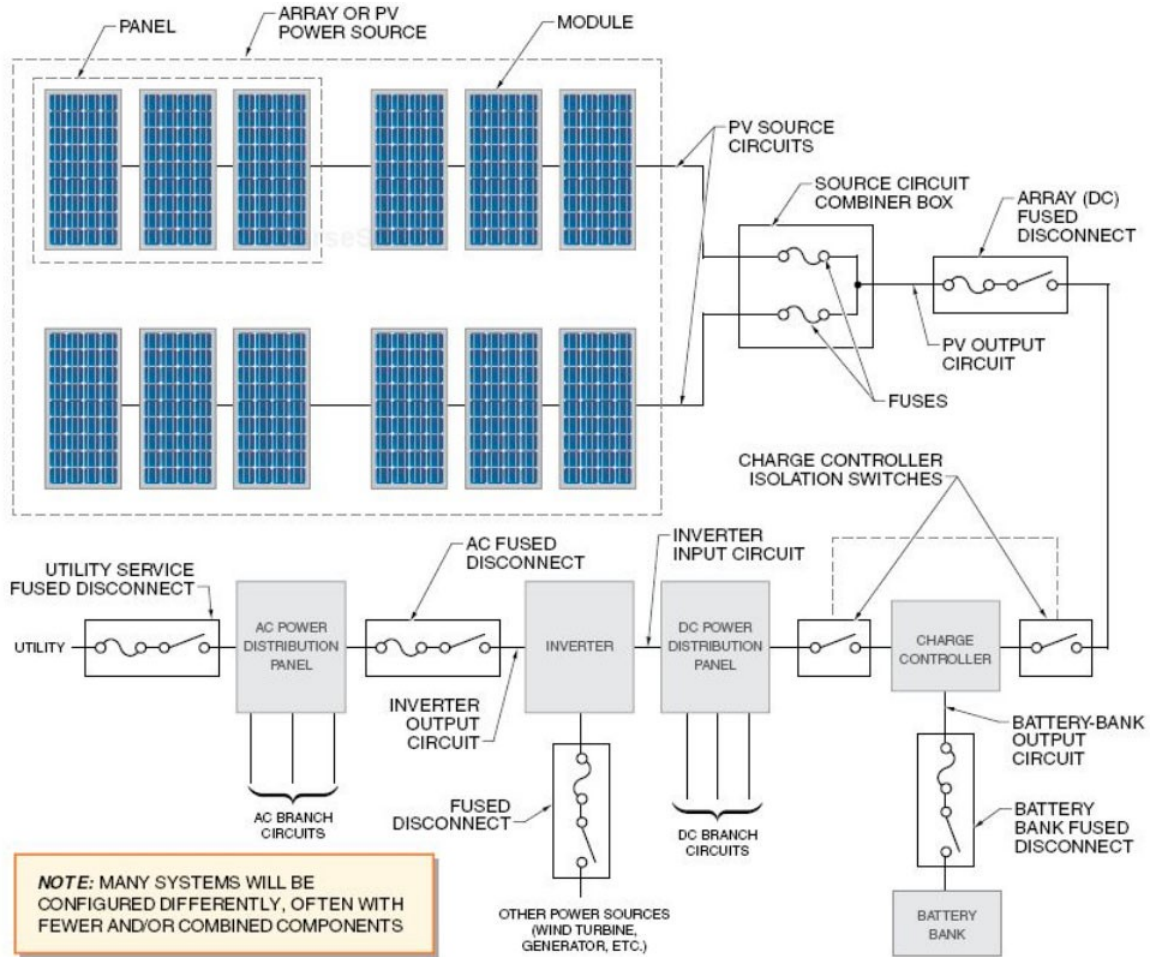
- May be the **same as the PV array capacity**, or equal to the biggest load size.
 - Many inverter manufacturers offer **string sizing software** to determine the **minimum and maximum number of series-connected PV modules** for proper inverter operation.
- ➔ **Sizing is a complex problem** which requires detailed analysis and optimization methods for solving.

PV system circuit design (1)

Regulation:

- Majority of the regulations governing electrical installations, including PV systems, are found in **National Electrical Code (NEC)** .
- NEC is a nationally recognized standard on safe electrical installation practice and is used as the **governing electrical code in most jurisdictions in the U.S.**
- Many articles in the NEC are applicable to the electrical integration of a PV system, particularly **Article 690**.

PV system circuit design (2)



Maximum PV circuit voltage (1)

- The **maximum DC voltage of a PV source circuit** or output circuit is determined by the **sum of the rated V_{oc} of the series-connected modules corrected** for the lowest expected ambient temperature.
- This voltage dictates the **minimum voltage ratings**, which **must be less than the maximum voltage limits** of all components on the DC side of the system (PV modules, inverter, charge controller, disconnects, and conductors).
- For **one- and two- family dwellings**, the maximum voltage for PV source and output circuits **cannot be greater than 600V**.
- Systems over 600 V are allowed for commercial or utility-scale PV systems, which must follow different requirements, particularly those in NEC Article 490.

Maximum PV circuit voltage (2)

The **maximum PV source-circuit** or output-circuit voltage is calculated as:

$$V_{\max} = V_{\text{oc}} * n_m * C_T$$

V_{\max} = maximum PV system voltage

V_{oc} = module rated open-circuit voltage at 25°C

n_m = number of series-connected modules

C_T = low-temperature voltage correction factor from NEC Table 690.7

Voltage Correction Factors for Crystalline and Multicrystalline Silicon Modules
NEC® Table 690.7.

AMBIENT TEMPERATURE* in °C	VOLTAGE CORRECTION FACTOR
24 to 20	1.02
19 to 15	1.04
14 to 10	1.06
9 to 5	1.08
4 to 0	1.10
-1 to -5	1.12
-6 to -10	1.14
-11 to -15	1.16
-16 to -20	1.18
-21 to -25	1.20
-26 to -30	1.21
-31 to -35	1.23
-36 to -40	1.25

Example 1: Maximum PV circuit voltage

An PV array of **22** series-connected modules, each with an open-circuit voltage of **21.7 V**. The lowest expected temperature of the array is **-25° C**, which corresponds to a low-temperature correction factor of **1.2**.

- 1) What is the maximum PV source circuit voltage?
- 2) Is this voltage acceptable for a single-family home?

Solution:

$$V_{\max} = V_{\text{oc}} * n_m * C_T$$
$$V_{\max} = 21.7 \times 22 \times 1.20 = \mathbf{573 \text{ V}}$$

From NEC, for one-family home, $V_{\max} \leq 600\text{V}$

→ Source circuit voltage is **OK**, provided that it **does not exceed** the rating of any connected component.

Example 2: Maximum PV circuit voltage

Bipolar PV systems: Systems with positive and negative voltages must use the **sum of the absolute values of the open-circuit voltages of each monopole array** to determine the rated open-circuit system voltage.

Example: Consider a bipolar PV system with open-circuit voltages of **+/- 550 V** with respect to ground at lowest expected temperature of **- 25° C**.

What is the maximum source circuit voltage?

Solution:

$$\begin{aligned}V_{\max} &= (|- 550| + |550|) * C_T \\ &= 1100 * 1.2 = \mathbf{1320 \text{ V}}\end{aligned}$$

Maximum PV circuit current

PV source circuits:

- The maximum current is **125% of the sum** of the short-circuit current ratings of parallel-connected modules.
- For a **single series string** of modules, the maximum current is simply **125% of the module short-circuit current**.

PV output circuits: The maximum current is the **sum of the maximum currents** of the parallel-connected source circuits.

Example:

A PV output circuit combining **3 parallel strings of modules**, each with a maximum source circuit current of 6 A has the **maximum PV output circuit current of $3 \times 6 = 18 \text{ A}$** .

Maximum inverter input current

Maximum inverter input current:

For an interactive inverter with the PV output circuit connected directly to the inverter input, the inverter input circuit is the same as the PV output circuit and, therefore, has the **same maximum current**.

For stand-alone systems with batteries, the inverter input current depends on battery voltage. The maximum current is calculated as

$$I_{\max} = \frac{P_{AC}}{V_{\min} \times \eta_{\text{inv}}}$$

I_{\max} = maximum inverter input current, A

P_{AC} = rated inverter maximum continuous AC power output, W

V_{\min} = minimum inverter operating voltage, V

η_{inv} = inverter efficiency

Example: Max. inverter input current

Consider a nominal **48 VDC 5500 W stand-alone inverter** that is **85% efficient** and can operate at input voltages down to **44 V**.

What is the maximum inverter input current?

Solution:

$$I_{\max} = \frac{P_{AC}}{V_{\min} \times \eta_{\text{inv}}}$$

$$I_{\max} = \frac{5500}{44 \times 0.85} = 147 \text{ A}$$

Note: If the input current were calculated at **48 V**, the resulting **current would be 135 A**, and the conductors and overcurrent devices may be **undersized**.

Maximum inverter output current

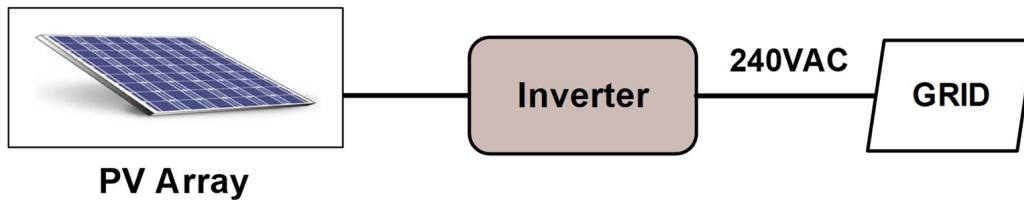
Maximum inverter output current:

- Since inverters are limited-power devices, **their AC output circuits are sized based on the maximum inverter output** rather than load calculations.
- The maximum current for the inverter output circuit is **equal to the inverter maximum continuous output current rating**.
- This information is provided on inverter labeling and specifications.

Example: 2500-W inverter outputting 240 VAC at PF of 1.0 will have a listed continuous output rating around

$$2500 / 240 = \mathbf{10.4\ A}$$

Practice: Array design with inverter



The above PV array design has a single PV array with 15 series-connected modules, each module has an open-circuit voltage of 18V and short-circuit current of 6A. The array is connected to grid via an inverter. The lowest expected operating temperature of the array is -25°C . Calculate:

- 1) PV source circuit voltage & maximum PV output circuit voltage
- 2) PV source circuit current & maximum PV output circuit current
- 3) Maximum inverter input current
- 4) Inverter power rating
- 5) Maximum inverter output current.

Protection of PV circuits (1)

Overcurrent protection: Using fuse or circuit breaker

- **Each PV source circuit** usually requires overcurrent protection.
- **All ungrounded array conductors** must include overcurrent protection. The **conductors in each branch circuit** (AC or DC) must be protected from overcurrent.
- Other protection (e.g. against ground fault) is also required.

Disconnect:

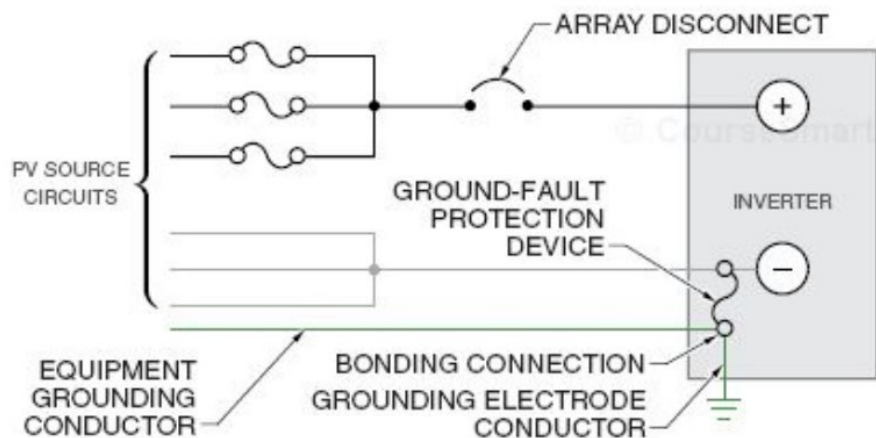
- **A disconnect** must be installed **on the AC side of a PV system** to isolate the system if required.
- **A disconnect must be used for each power source** when a system includes multiple power sources, such as a PV array, battery bank, engine generator, wind turbine, or utility power.

Protection of PV circuits (2)

- A **ground fault** is the condition where **current flowing through the grounding conductor**.
- Ground faults are typically **caused by damage to the protective insulation of normally current-carrying conductors**, which may energize metallic equipment such as enclosures, conduit, structures, and bare grounding conductors.

Array ground-fault protection with inverter fuse:

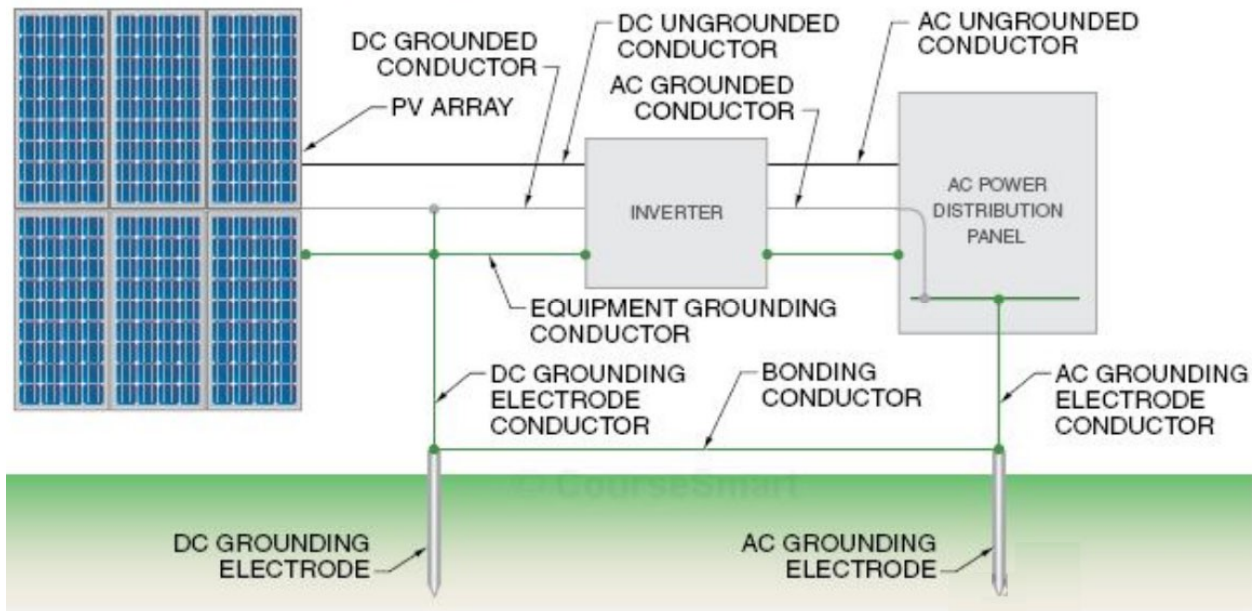
Some inverters include fuses as array ground-fault protection in their DC input circuits.



Grounding of PV circuits

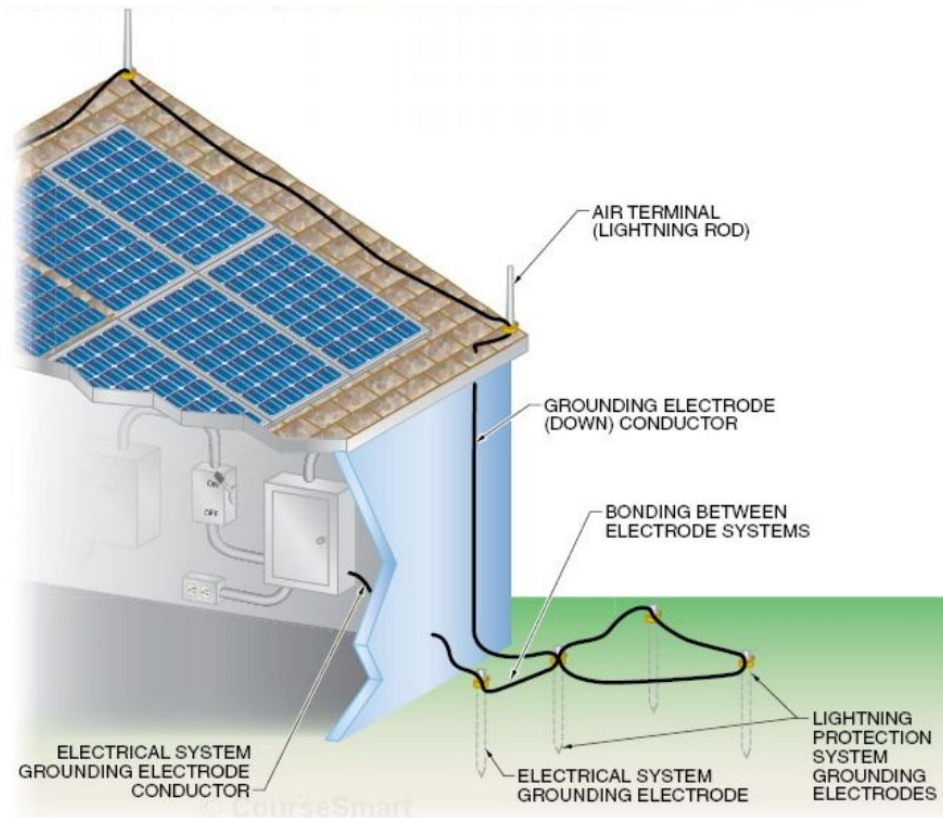
Grounding provides a **path for fault currents and lightning-induced surges to dissipate** safely, protecting people and equipment from hazards or damage.

The **DC and AC grounding systems must be connected** together with a bonding conductor. The **array may also require a separate grounding electrode system**.



Lightning protection

Lightning protection system includes a **network of air terminals, a grounding conductor, and a set of grounding electrodes.**



Grid integration issues (1)

Regulation:

- Technical requirements for **PV systems as distributed generators** are established through national codes and standards published by the IEEE, Underwriters Laboratories (UL), and the National Fire Protection Association (NFPA i.e. NEC).

Net metering scheme:

- Offered in 42 states and Washington D.C. where the PV owners can **inject any generated surplus power to the grid anytime**.
- They obtain a **full retail value at the time of power injection**.
- Power is measured using **a single smart meter to two meters**, one for inflow power from grid and the other for outflow from customer.

Grid integration issues (2)

Major issues related to grid-connected PV systems are:

- 1) **Islanding:** Islanding is the undesirable condition where a PV system continues to supply power to the utility grid during a utility outage.
- 2) **Power quality:** PV systems use inverters, which can **inject harmonics** into the host power system.
- 3) **PV power fluctuation:** Intermittent flow, causing **power deficit or power surplus many times per day** in distribution networks, leading to many problems (increased losses, overload, instability etc.)
- 4) **Reverse power flow:** The power flow from PV systems can take up feeder power-carrying capacity, which **lowers the networks ability to bring power to other consumers**. Many utility substations **cannot handle reverse power flow**.