Solar Panels

- They consists of arrays of solar cells connected in series or parallel together.
- Solar panel and solar module terms are interchangeable.
- For stand-alone PV system, the output voltage is 12 V or 24 V.
- A PV panel with a nominal voltage of 12 V operates between **14 V to 18 V** when exposed to full sunlight and the system is under load.
- Under standard test conditions, a solar panel with nominal voltage of 12 V may generate 21.5 V when tested at the back of the panel (Voc = 21.5 V).
- When the load is connected, the same panel's voltage will fall to 16.9 V which is the maximum voltage the panel can produce under load.
- This maximum voltage is sometimes called, the **rated voltage**.

Solar Panels

- The highest current a panel can generate under standard test conditions is called the short circuit current (Isc).
- Panel can generate higher currents as the temperature falls.
- Under load, the panel current will drop.
- The maximum current under load is called the maximum power current or rated current (under standard test conditions).

Solar Panel Specifications

Electrical Properties under STC

Module Type	**325 W**	**330 W**
Maximum Power Pmax(W)	325	330
MPP Voltage Vmp (V)	33.3	33.7
MPP Current Imp (A)	9.77	9.80
Open Circuit Voltage Voc(V)	40.8	40.9
Short Circuit Current Isc (A)	10.41	10.45
Module Efficiency (%)	19.0	19.3
Operating Temperature (℃)	-40 → +90	
Maximum System Voltage (V)	1000	
Maximum Series Fuse Rating (A)	20	
Power Tolerance (%)	0 → +3	

Solar Panel Specifications

Mechanical Specifications

Format	**66.3in×39.4in×1.26in (including frame) (1685mm×1000mm×32mm)**
Weight	41.2 lbs (18.7 kg)
Front Cover	0.13in (3.2mm) thermally pre-stressed glass with anti-reflection technology
Back Cover	Composite Film
Frame	Black anodized aluminum
Cell	6×20 monocrystalline Q.ANTUM solar half cells
Junction Box	2.09-3.98×1.26-2.36×0.59-0.7in (53-101×32-60×15-18mm), Protection class IP67, with bypass diodes
Cable	$4mm^2$ Solar cable; (+)≥43.3in (1100mm), (-) ≥43.3in (1100mm)
Connector	Staubli MC4, Amphenol UTX, Renhe 05-6, Tonglin TL-Cable01S, JMTHY JM601; IP68 or Friends PV2e; IP67

Solar Panel Specifications

Temperature Specifications

Temperature Coefficients			
Temperature Coefficient of Isc	α	[%/K]	+0.04
Temperature Coefficient of Pmpp	γ	[%/K]	-0.36
Temperature Coefficient of Voc	β	[%/K]	-0.27
Normal Module Operating Temperature	NMOT	[°F]	$109 \pm 5.4 (43 \pm 3℃)$

Panel Junction Boxes

- Located on the back of the PV panel.
- Ease the connection and disconnection of the wiring system.
- Contain blocking diodes to prevent reverse current.

Solar Panel Connectors

- MC4 connectors are used in solar panel connections.
- MC stands for the manufacturer Multi-Contact.
- 4 stands for 4mm diameter contact pin.
- They provide waterproof connection.
- They are double-insulated and UV resistant.

Combiner Boxes

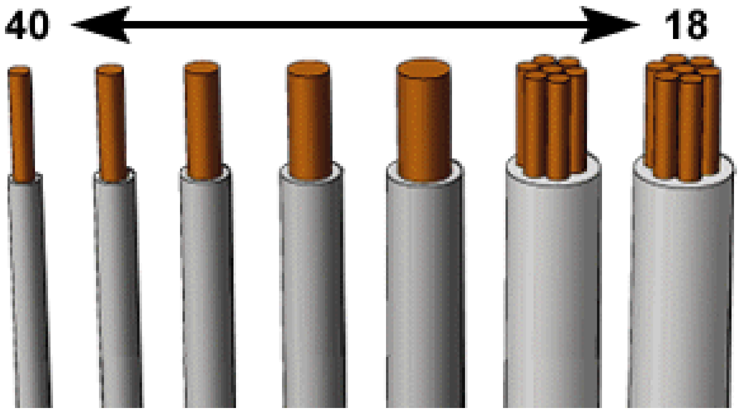
- <u>Strings</u> refer to the panels connected in series.
- Combiner boxes combine <u>string</u> wires to one circuit that is going away from the array.
- Also provide overcurrent protection for each <u>string</u>.
- Data monitoring can also be incorporated into the combiner box.

Lightning and Surge Protection

- Designed to clamp down on extreme surges (as high as 115,000 A) to the level that does not harm the system.
- Usually installed in:
  - Combiner boxes to protect from lightnings that occurs in the array.
  - Main AC load panel to protect from surges that may happen in the utility grid

Wiring the System

- **American Wire Gauge (AWG):** The system of measuring wire in the US.
- Common wire sizes for PV systems in the US: AWG 0000 (largest) to AWG 40 (smallest).
- The thicker the wire, the more current it can carry.
- NEC Table 310-15 (B) 16 shows the maximum allowable current that a wire can carry without being damaged.



Wiring the System

NEC Table 310-15 (B) 16. Ambient temperature is 30℃

Table 310.15(B)(16) (formerly Table 310.16) Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60°C Through 90°C, Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)*			
Temperature Rating of Conductor [See Table 310.104(A).]			
Size AWG or kcmil	Temperature Rating of Conductor		
	60°C Types TW, UF	75°C Types RHW, THHW, THW, THWN, XHHW, USE, ZW	90°C Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2
	COPPER CONDUCTORS ONLY. ALUMINUM PORTION OF TABLE NOT SHOWN		
18**	—	—	14
16**	—	—	18
14**	15	20	25
12**	20	25	30
10**	30	35	40
8	40	50	55
6	55	65	75
4	70	85	95
3	85	100	115
2	95	115	130
1	110	130	145

Effect of Temperature on Wire

- The more the temperature, the more the resistance.
- Temperature correction factors are used to adjust for the increase in the temperature (NEC Table 310.15 (B) (2)(a)).
- The high temperature of a rooftop installation site is measured to be **46**°C.
- Assume the installer is using USE-2 cable (high heat rated at **90**°C).
- The correction factor for the ampacity is **0.82** (46°C and 90°C axes in Table next page)
- Assume a circuit was supposed to be designed for a maximum current of 38 A.
- The planned wire to be used was #10 AWG whose maximum current is 40 A.
- Based on correction factor, #10 AWG has the maximum current of $40 \times 0.82 = 32.8$A
- Therefore, based on the table on previous page, #8 AWG should be selected.

Effect of Temperature on Wire

NEC Table 310.15 (B) (2)(a)

Temp (°C)	Temperature Correction Factors		
	60°C (140°F)	75°C (167°F)	90°C (194°F)
21-25	1.08	1.05	1.04
26-30	1	1	1
31-35	0.91	0.94	0.96
36-40	0.82	0.88	0.91
41-45	0.71	0.82	0.87
46-50	0.58	0.75	0.82
51-55	0.41	0.67	0.76
56-60	--	0.58	0.71
61-65	--	0.47	0.65
66-70	--	0.33	0.58
71-75	--	--	0.5
76-80	--	--	0.41
81-85	--	--	0.29

Wires in Conduit

- Based on the NEC suggestion, wires in conduits in exposed sunlight should be placed with the bottom of the conduit or raceway no closer than 23 mm to the deck of the roof to be protected against excess heat.
- If it is placed closer than this, then 33°C correction should be added to the highest ambient temperature.
- Following the previous example, if the wire #10 AWG is placed in the conduit that is placed directly on the roof, then the new temperature will be 46+33 = 79 °C which is corresponding to the temperature correction factor of 0.41.
- Based on this correction factor, #10 AWG has the maximum current of $40\times0.41=16.4$ A.
- Therefore, #4 AWG should be selected ($95\times0.41=38.95$ A).

Wires in Conduit

- To avoid ampacity problems:
  - Using shaded places such as the solar panels to avoid the ampacity problems.
  - Offsetting the conduits from the roof using mounting brackets.
- The wires in a conduit can generate heat which increases the conduit temperature.
- So, adjustments must be considered to the ampacity of the wires.

Number of wires in a single conduit	Percent of ampacity values
4-6 Wires	80%
7-9 Wires	70%
10-20 Wires	50%
21-30 Wires	45%
31-40 Wires	40%
41 or more Wires	35%

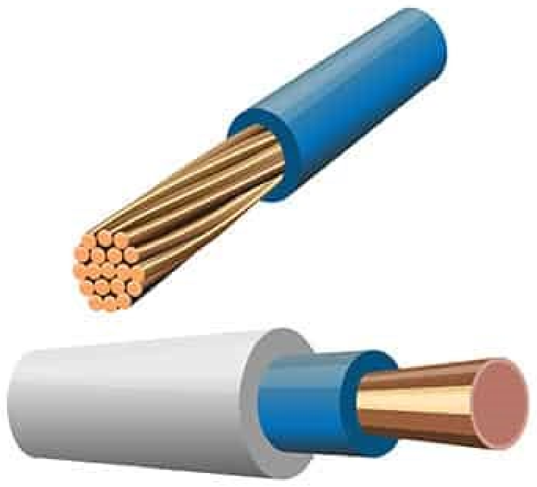
Types of Wire

Aluminum or Copper

- Copper has better conductivity.
- Aluminum is usually cheaper than copper, but it is weaker than copper.

Solid or Stranded

- Solid wires are more rigid compared to stranded ones.
- At 60Hz, there is no skin effect (tendency for AC current to flow mostly near the outer surface of a wire. The effect becomes more and more apparent as the frequency increases).
- DC currents use the whole conductor.
- Therefore, in PV systems, both wire types are suitable.



Insulation

- Protects the conductor from the heat, moisture, UV light, or chemicals.
- A wire with the designation “-2” means that it is allowed to used in environments having continuous 90°C operating temperatures.
- Wires that are inside the building should be rated for indoor uses.
- Wires inside a conduit should be assumed to be placed in a wet environment.

Common Types of Conductors in PV Systems

Type	Name	Max. Temp.	Environment	Insulation
THHN	Heat Resistant Thermoplastic	90°C (194°F)	Indoor Dry or Damp Location	Flame Retardant, Heat Resistant Thermoplastic
THW	Moisture and Heat Resistant Thermoplastic	75-90°C (167-194°F)	Indoor Dry or Wet Location	Flame Retardant, Moisture and Heat Resistant Thermoplastic
THWN	Moisture and Heat Resistant Thermoplastic	75°C (167°F)	Indoor Dry or Wet Location	Flame retardant, moisture and heat resistant Thermoplastic
TW	Moisture Resistant Thermoplastic	60°C (140°F)	Indoor Dry or Wet Location	Flame Retardant, Moisture Resistant Thermoplastic
UF and USE	Underground Feeder and Underground Service Entrance	60-75°C (140-167°F)	Outdoor Service Entrance	Moisture and Heat Resistant
USE-2 and RHW-2*	Underground Service Entrance	90°C (194°F)	Outdoor Dry or Wet and Service Entrance	Moisture and Heat Resistant
PV Wire	Photovoltaic cable	90°C (194°F) wet 150°C (302°F)	Dry or Wet and Service Entrance	Moisture and Heat Resistant

Color Coding of Wires

- Color of a conductor insulation shows its function.
- In practice, red is selected for the positive leg of the DC circuit and black for the negative.
- According to NEC, grounded conductors in today's PV systems are functionally grounded (not solidly).
- For wires with the size of #4 AWG or larger, the NEC permits using colored tape to be used around the wire near to termination points.
- But for smaller wires, the appropriate colored insulation must be utilized.

Insulation Color Coding of Wires

AC		DC	
Color	Application	Color	Application
Black, Red, or Other	Ungrounded Hot	Black, Red, or Other	Positive
White or Gray	Grounded Conductor (Neutral)	White or Gray	Solidly Grounded Conductor (Negative)
		Black, Red, or Other	Functionally Grounded Conductor (Negative)
Green, Green with Yellow Stripes, or Bare	Equipment Grounding Conductor	Green, Green with Yellow Stripes, or Bare	Equipment Grounding Conductor

Color Coding Conventions of Wires

Typical Color Coding (US)	
Application	Color
DC Wiring	Positive: Red Negative: Black
120V AC Wiring (single phase)	Hot: Black Neural: White
240V AC Wiring (single phase)	Line 1: Black, Line 2: Red, Neutral: White
120V, 208V, 240V Three Phase AC Wiring	Line 1: Black, Line 2: Red, Line 3: Blue, Neutral: White
277V, 480V Three Phase AC Wiring	Line 1: Brown, Line 2: Orange, Line 3: Yellow, Neutral: Gray

DC Disconnects

- DC system power should be easily disconnected from the rest of the system.
- In a solidly grounded system, only the ungrounded conductor should be switched (usually the positive)

Six Handle Rule

- There are several power sources such as generators, PV systems, and the utility that operate independently or together. Each of them is considered to be a separate service.
- During emergency, it is vital that we can disconnect all power sources in a timely manner.
- The NEC allows a maximum of six disconnects for any electrical service which is called the **six-handle rule** and is found in NEC Article 230.71.
- The disconnects from all services should operate together.

Overcurrent Protection

- The wiring and equipment in a PV system are designed for certain current values.
- If the current flowing through the system is more than the maximum value, various components of the system could be damaged significantly.
- So, fuses and circuit breakers are introduced to the system.
- These protection devices are generally referred to as **overcurrent protection devices (OCPD).**
- We can find such OCPDs in combiner boxes, disconnects, charge controllers and/or inverters.

Overcurrent Protection

- Short-circuit current in the output of the PV array is unlikely to be more than the rated operating output current.
- But, if short circuit happens in the battery system, thousands of amperes can flow through the system.
- **AIR: Ampere Interrupt Rating** → The rating on fuses and circuit breakers.
- The OCPD opens the circuit in case the current passing through it exceeds the rated value.
- Available OCPD sizes based on 2014 NEC: 1,3,6, 10, 15,20,25,30,35,40,45,50,60, 70,80,90, 100,110,125,150, 175, 200, 225, 250, 300, 350, 400, 450, 500, and 600 A ratings.

Overcurrent Protection

- Specific certifications are provided by Underwriter Labs (UL) for fuses (UL 2579) and circuit breakers (UL 489B) which are only used for DC PV systems.
- Circuit breakers can be found as single-pole, two-pole, and three-pole.

Overcurrent Protection

- **Back-fed Breaker:** Any breaker that is not specifically stated to be fed from the line or the load side. In other words, this breaker opens when its current exceeds its rating, regardless of the power flow direction.
- **Ground-Fault Protection of Equipment (GFPE) breakers:** Only designed to protect their circuit against ground fault currents.

Charge Controller

- By modifying the voltage and current, it determines how much power should be delivered to various locations of the system (in this case of PV, to the batteries).
- Early **series charge controllers** acted like a thermostat to charge the battery bank in such a way that they charged the batteries when their voltage fell below a certain point and stopped charging when the battery voltages exceeded a preset level.
- Recent charge controllers use **Pulse Width Modulation (PWM)**.

Charge Controller Charging Stages

- **Bulk Charging:** When the battery voltage is low, the charge controller tries to use all the energy coming from the PV arrays to charge the battery. If a load is consuming energy at the same time, this energy comes from the battery. This phase is called **bulk charging** (constant charging).
- **Absorption Charge:** When the battery charge level reaches 80-90%, the charge controller goes into the **absorption (tapering)** charging mode. The voltage remains the same (constant), but the current is slowly reduced until the battery is fully charged.
- **Floating Charge (Trickle or Maintenance Charge):** Once the battery is fully charged, the voltage is decreased, and the system is in maintenance mode.
- Float voltage ranges from 13.2 Vdc to 13.8 Vdc at 25℃.

Benefits of PWM Charge Controllers

- Recovering a lost battery capacity and disulfate it.
- Increasing the charge acceptance of the battery.
- Maintaining high average battery capacities (90%-95%).
- Decreasing battery heating and gassing.
- Adjusting for battery aging.
- Compensating for the battery temperature changes to avoid over/under charging (when too hot/too cold).
- Self-control for voltage drops and temperature effects in PV systems.
- The voltage of a PV system which has PWM controller is determined by the amount of voltage required by the battery bank.

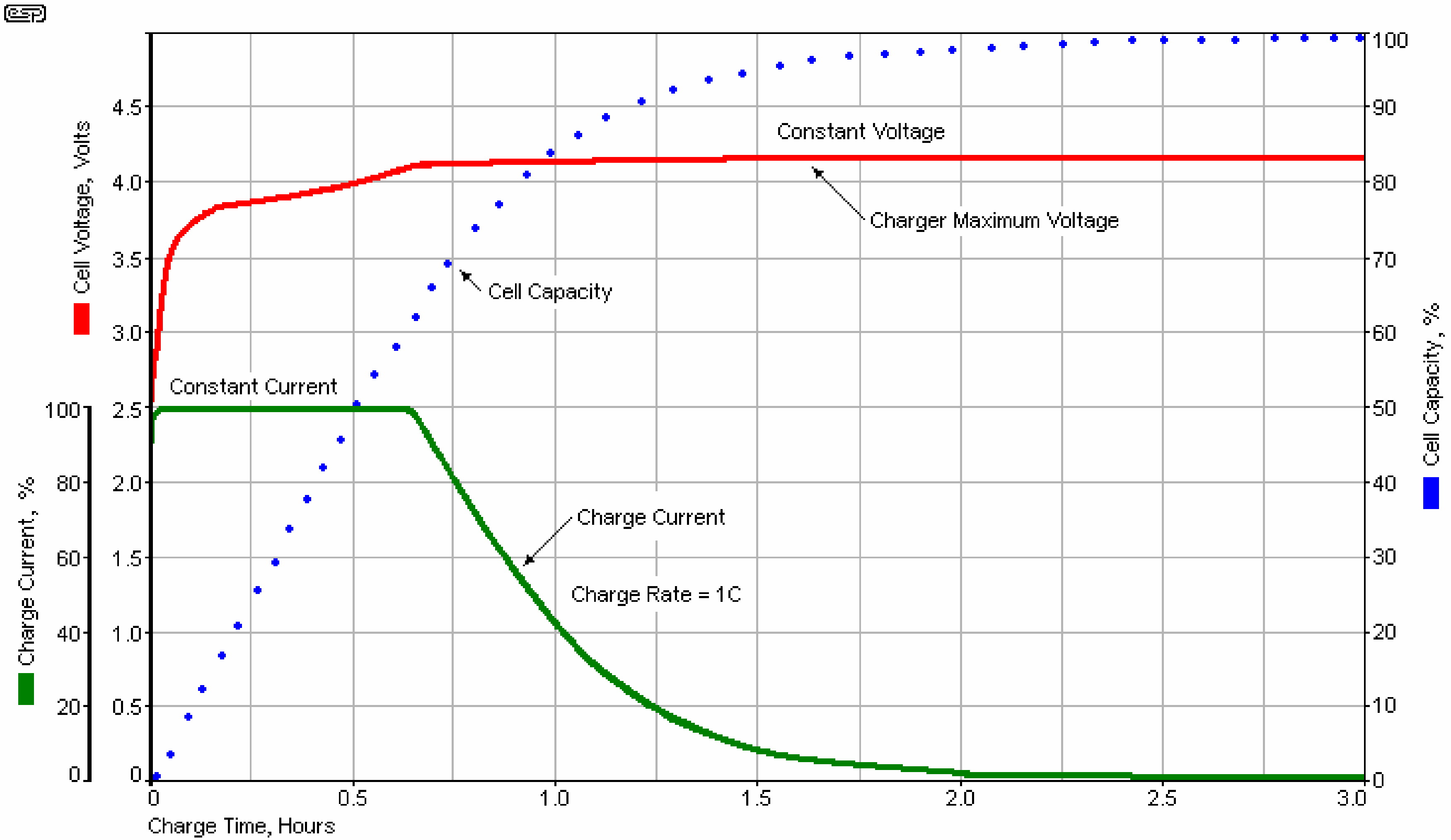
MPPT Charge Controllers

- Maximum power point tracking (MPPT) system monitors the output from the PV array and the battery bank state-of-charge and adjusts the voltage from the PV panels so that it matches the demand of battery bank.
- Let's say an array generates 800 watts. The battery bank is being charged with the current 28.57 A at 28 V (800 watts = 28×28.57). Now if the MPPT reduces the voltage to 19 V, the battery bank will be charged with 42.1 A. So, we can see that MPPT can decide how much current should be delivered to the batteries by adjusting the voltage coming from the PV arrays.
- MPPT systems usually increase the effective useable power coming from the PV arrays by 20-45% during winter, and 10-15% during summer.
- Charge controllers are basically DC-DC inverters. They have a maximum DC input voltage and maximum DC output current rating.

MPPT Charge Controllers

- In traditional charge controllers, the nominal voltage of the PV array should match the nominal voltage of the charge controller and also voltage of the battery bank.
- But using MPPT charge controllers, we can increase the input voltage from the PV array to 600 Vdc which is the maximum allowable voltage determined by the NEC for the residential systems.
- The MPPT charge controller steps down the voltage using a DC to DC voltage converter so that the voltage matches the nominal voltage of the battery bank.
- Such charge controllers are referred to as a buck (lowering the voltage)/boost (increasing the voltage) charge controller.

Charging Lithium-Ion Batteries



Inverters

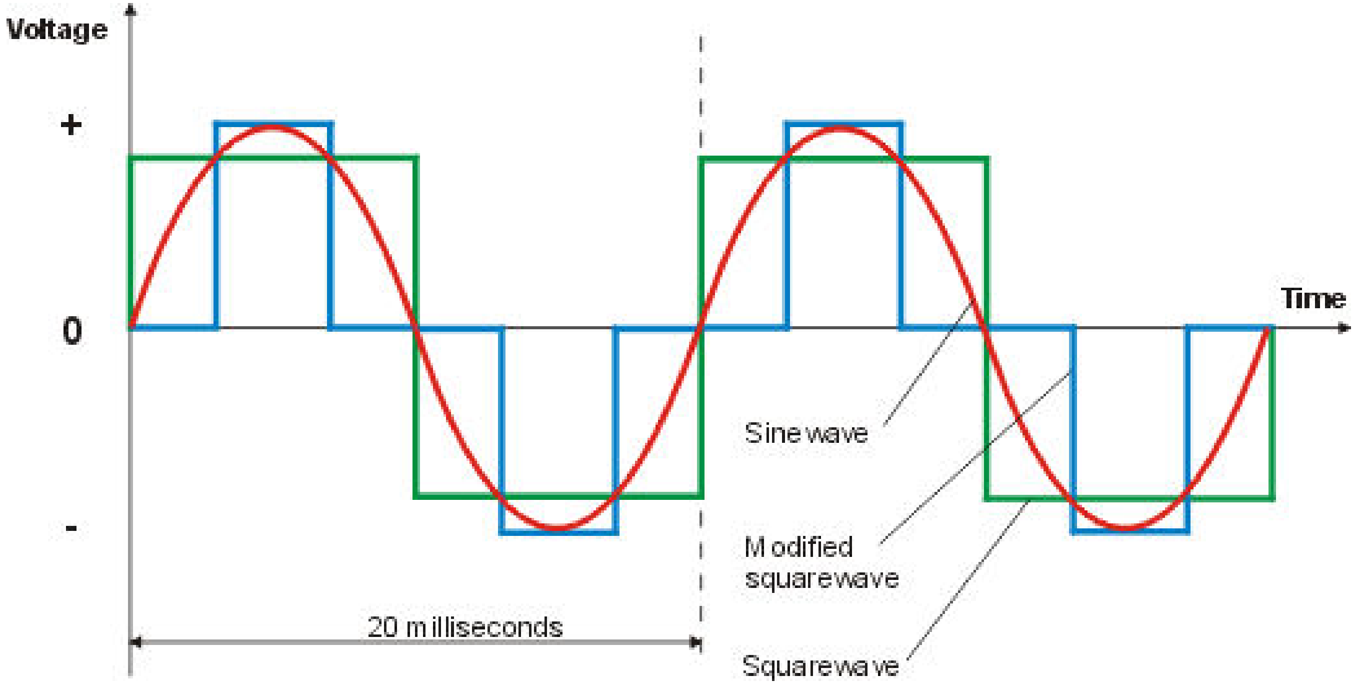
- **DC to AC conversion**
- They are divided into two main categories:
  - Stand-alone inverters (battery-based)
  - Grid-connected inverters (Microinverters and power optimizers)

Stand-alone Inverters

- They convert the DC voltage of the batteries into AC voltage.
- In case the batteries have low voltage, the inverter shuts off and no power can be sent to the loads.
- The solar panel should be used to recharge and/or keep the batteries charged.
- Specifications to be considered when selecting stand-alone inverters:
  - The battery bank voltage should be compatible with the inverter rated voltage.
  - The power rating or surge rating of the system. The amount of power that a stand-alone inverter can produce depends on the load. If the load consumes more power than the surge rating of the inverter, the system will shut down and may be damaged.
  - The output frequency (60 Hz).
  - The system waveform.
  - The unit efficiency (80-98%).

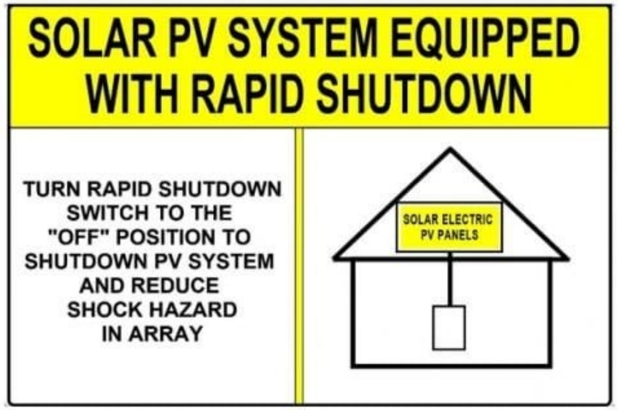
Inverter Waveforms

- Pure Sine Wave (Compatible with all electronic equipment)
- Modified Sine Wave
- Square Wave (Rarely used these days)



Grid-connected Inverters

- Used in systems connected to the utility grid.
- They have anti-islanding features which means that they automatically shut down the PV system whenever they detect that no power comes from the grid. The reason is that although there is no active power from the grid, the PV system can still generate deadly electricity on the inverter side.
- Rapid shutdown of PV systems on buildings: 2014 NEC, Section 690.12 states that all rooftop arrays must have a method to shut down at the source.



Grid-connected Inverters

- 2014 NEC requires the following when the PV system disconnect is turned off:
  - Conductors more than 5 ft (1.5 m) inside the building and less than 10 ft (3 m) from the array should be limited to have the maximum voltage of 30 V (touch safe in the wet environment) and 240 Watts within 10 seconds of the system shutdown.
  - Systems with **rapid shutdown** should be labeled
  - Equipment that perform the **rapid shutdown** should meet the rapid shutdown requirements.
- System designers should consider the followings:
  - Using microinverters that disconnects at the panel when there is grid power.
  - Using power optimizers that disconnects at the panel when there is grid power.
  - Using disconnecting combiner box (located within 10 ft of the array) wired to an emergency shutoff switch.
  - Locate the string inverter within 10 ft of the array.

Grid-connected Inverters

- 2017 NEC requires that when the PV system disconnect is turned off, the voltages of the conductors that are placed within 1 foot of the array boundary (rather than 10 ft) must not be more than 30 V within 30 seconds (rather than 10 seconds).
- Additional requirements of 2017 NEC:
  - Specific component parts used should be listed that they comply with rapid shutdown provisions (rapid shutdown equipment, or PVRSE).
  - Array should not have any exposed metal and be more than 8 feet away from any grounded metal.
  - There should be no conductor with a voltage more than 80 VDC within the array boundaries when rapid shutdown happens.
- After 2018, all arrays must have module-level power electronics (MLPE), such as power optimizers or microinverters, with new rapid shutdown provisions.

Inverter Standards

- IEEE standard 1547 was originally designed for generators producing less than 10 MVA.
- Germany and other European countries: Power Generating Plants Connected to the Low-voltage Grid Application Rule (VDE-AR-N 4105).
- Australia and New Zealand: AS4777.2
- UL1741: Standard for Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources (in conjunction with IEEE 1547).
- Anti-islanding, ground fault protection, and arc fault protection
- European equivalent of UL1741: IEC 62109: Safety of Static Inverters standard.

Selecting a Grid-Tied Inverter

- The maximum DC voltage received from the solar array is limited to 600 VDC in US.
- The minimum DC voltage the unit receives from the PV array and still produce power.
- AC output voltage. Output voltages of grid-tied inverters in the US are 240 VAC for residential units.
- The power rating of the inverter. This power rating for grid-tied inverters are not based on the house load (as opposed to stand-alone case).
- The output frequency: 60 Hz in US.
- Compatible with the local utility provider.
- The conversion efficiency of the unit.

Bimodal Inverters

- Works like a grid-connected inverter until the grid shuts down.
- This inverter detects the grid shutdown and disconnects physically from the grid.
- Then, it changes the flow of power from the battery bank to critical loads.
- When the grid power is restored, it switches back to grid-connected mode.
- There is special inverter named SMA Sunny Boy 5000TL-US-22.
- This inverter does not incorporate batteries.
- Instead, it redirects the available power coming from solar arrays to a single outlet at the base of the inverter.
- Critical loads are connected to this outlet.

Micro-Inverters Advantages

- High system efficiency because of reduced voltage drop.
- Scalability. New panels can be easily added as needed.
- Use of mismatched panels of different types.
- Individualized panel efficiency, meaning that each inverter is matched to each panel via MPPT. If a panel malfunctions, the performance of that panel will not affect any other portion of the array.
- Reduce the effect of aging panel mismatch.
- The entire system will shut down at the panel when the AC disconnect is open.

Power Optimizers (DC-DC Converters)

- They are attached to each solar panel.
- They incorporate MPPT and anti-islanding functions.
- It converts each solar panel DC voltage to another DC voltage.
- Then the array is connected to a string inverter, which operates at a set voltage (instead of a range) and does not have the MPPT and anti-islanding systems.
- They allow the use of mismatched panels.
- Increase individualized panel efficiency.
- Reduce the effect of panel aging.
- Shut down at the panel when the grid is down.

Additional Advantages of Power Optimizers

- No temperature adjustments are needed for string computations because MPPT adjusts for temperature so that the panel generates fixed voltage all the time.
- Longer strings can be used.
- Increased safety because unless the entire system is connected to the grid, the DC voltage is not present.

Solar Power Generation Meter

- To measure how much AC electricity the PV system has generated.
- Can be digital readout connected to the internet, or can be analog meter.

AC Disconnect

- Allows the whole PV system to be isolated from the household electrical wiring system.
- Should be placed in an accessible location and compatible with the voltage and amps of the inverters.
- The following should be considered in choosing AC disconnects:
  - Ampacity rating of the AC output from the inverter(s).
  - Voltage rating of the AC output from the inverter
  - Power phase: single phase or three phase.
  - Poles: single phase 120 V (1 pole), two phase 240 V (2 poles), and three phase (3 poles)
  - If they are placed outdoors, make sure they are rated for outdoor use
  - Fused or unfused
  - AC/DC disconnects should be located at the inverter.
  - AC disconnect should also be located within 10 ft of the service connection point.

Electrical Panel

- AC disconnect separates the PV system from the rest of the electrical system.
- After the AC disconnect, the system is wired to the electrical service panel.
- This panel is usually referred to as the circuit breaker box.
- In most residential solar systems, the last connection to the grid happens within the service panel.

Bi-Directional Meter

- When a PV system is connected to the grid, the grid acts as a virtual battery bank.
- If the energy produced by the solar panels is more than the required amount, the extra energy is sold back to the grid.
- Most states in the US have laws that requite investor-owned utilities to **<u>net meter</u>** PV systems.
- They allow bi-directional flow of power and charge only for the net amount of electricity consumed by the customers.
- The utility will periodically calculate how much electricity has been used from the grid, and how much the system has produced over that same time period. The customer only need to pay the difference.