nominal volts. The lower voltage of the array will result in high current, and the need for larger wire.

MPPT Charge Controllers

To avoid this potential system inefficiency, most high-quality charge controllers now employ **maximum power point tracking (MPPT)**, which electronically monitors both the output from the array,and the state-of-charge of the battery bank, and automatically adjusts the charging voltage coming from the panels to best match what is needed by the battery bank.

MAXIMUM POWER POINT TRACKING (MPPT)

If an array is generating 800 watts, for example. At 28 volts the battery bank is being charged with 28.57 amps (800 W = 28 V x 28.57 A). If the MPPT reduced the voltage from the array to 19 volts, then the battery bank would receive a charge of 42.1 amps from the same energy output of 800 watts (800 W = 19 V x 42.1 A). By increasing or decreasing the voltage of the system, an MPPT can dramatically affect how much current is received by the battery bank.

MPPT systems will typically increase the effective useable power from the array by 20-45% during winter months, and 10-15% during summer months. They are, however, usually more expensive than the less sophisticated PWM controllers.

Remember that charge controllers are **DC-to-DC voltage converters**. They specify a maximum DC input voltage rating, as well as a maximum DC output current rating. In a MPPT charge controller, the DC voltage is subtly altered (from input to output) to more efficiently charge the battery bank

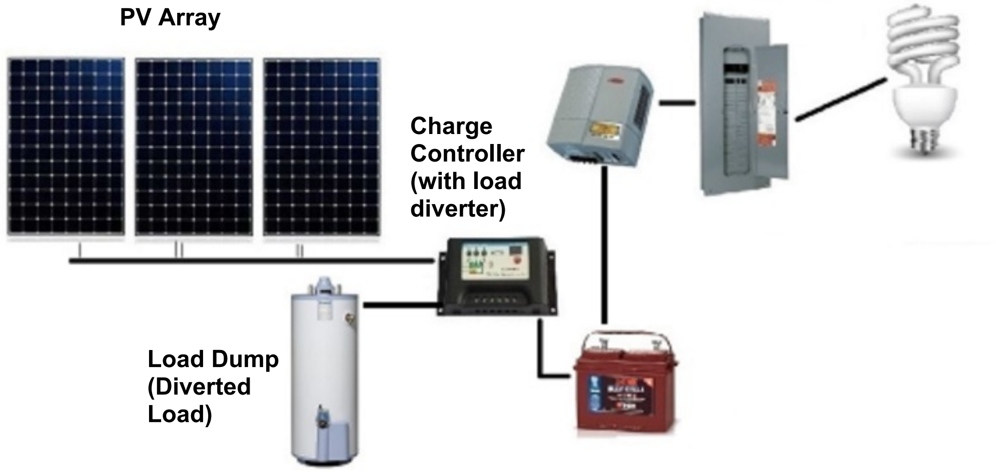
DC TO DC VOLTAGE CONVERTER

Traditional charge controllers require that the nominal voltage of the array matches the nominal voltage of the charge controller which then matches the nominal voltage of the battery bank. In other words, if the battery bank was rated at 48 nominal volts, then the charge controller must be rated for 48 volts, and the array must be configured to generate 48 nominal volts.

FIGURE 5-19: MORNINGSTAR TRISTAR MPPT 60-AMP CHARGE CONTROLLER, WITH 600-VOLT INPUT AND 48-VOLT OUTPUT

But with the advent of MPPT charge controllers (Figure 5-19), manufacturers have recently begun to extend the input voltage range of the charge controllers to accept array output as high as 600 volts DC, the maximum allowed by the NEC for residential systems. Through a DC to DC voltage converter, the charge controller then "steps down" to voltage to match the battery bank's nominal voltage. This allows for maximum flexibility in the design of the

FIGURE 5-20: STAND-ALONE PV SYSTEM WITH LOAD DIVERTER AND LOAD DUMP INCORPORATED



BUCK/BOOST CHARGE CONTROLLER

array and can result in substantial cost savings. This type of charge controller is often referred to as a **buck/boost charge controller**, as they can boost (raise) and buck (lower) voltage levels.

LOAD DIVERTER

LOAD DUMP

Many charge controllers can also serve as a **load diverter**. This prevents energy produced by the solar array from being wasted when the batteries are fully charged and all load demands are being met - yet additional power is still being produced by the array. In such an instance, the charge controller can direct the excess power to a **load dump**, such as a hot water heater or perhaps even a heated swimming pool. The excess energy from the array is then captured and stored in the form of hot water as depicted in Figure 5-20.

Charging Lithium Ion Batteries

Lithium Ion batteries charge differently than do lead acid batteries. For this reason, make sure the charge controller is rated for lithium ion batteries if they are to be incorporated into the PV system. Many charge controllers that work with lead acid batteries are also designed to properly charge lithium ion batteries as well.

SET POINT VOLTAGE

Lithium Ion batteries charge at a constant voltage (usually referred to as the **set point voltage**). Since solar power varies with the intensity of the sun, the charge controller must adjust the amps coming from the array while holding the voltage constant. Once the battery is fully charged, the controller then draws only as many amps as required to hold the voltage of the battery steady.

The set point voltage is critical and must match the requirements of the battery bank. If it is set too high, the number of charge cycles the battery can complete is reduced (shortening the battery life). Lithium ion batteries do not have to function at their maximum voltage, and doing so actually adds stress to the unit and will limit its life, as indicated in Table 5-7. If the voltage is too low, the battery will not be fully charged.

Charge V/cell	Capacity at cut-off voltage	Charge time	Capacity with full saturation
3.8	60 %	120 min	~65%
3.9	70 %	135 min	~75%
4	75 %	150 min	~80%
4.1	80 %	165 min	~90%
4.2	85 %	180 min	100%

TABLE 5-7: TYPICAL CHARGE CHARACTERISTICS OF LITHIUM-ION BATTERY CELL

CURRENT LIMIT

The lithium ion battery charging cycle is divided into two separate segments. The first is the **current limit** (sometimes called constant current) phase of charging. During this phase the maximum charging current is flowing into the battery, because the battery voltage is below its set point.

However, the charger controller must limit the current coming from the solar array to the maximum allowed by the manufacturer to prevent damaging the batteries.

CONSTANT VOLTAGE

When the battery reaches its set point voltage (usually at about 65% of its full charge), the charging process enters its second phase. This phase is referred to as the **constant voltage** phase.

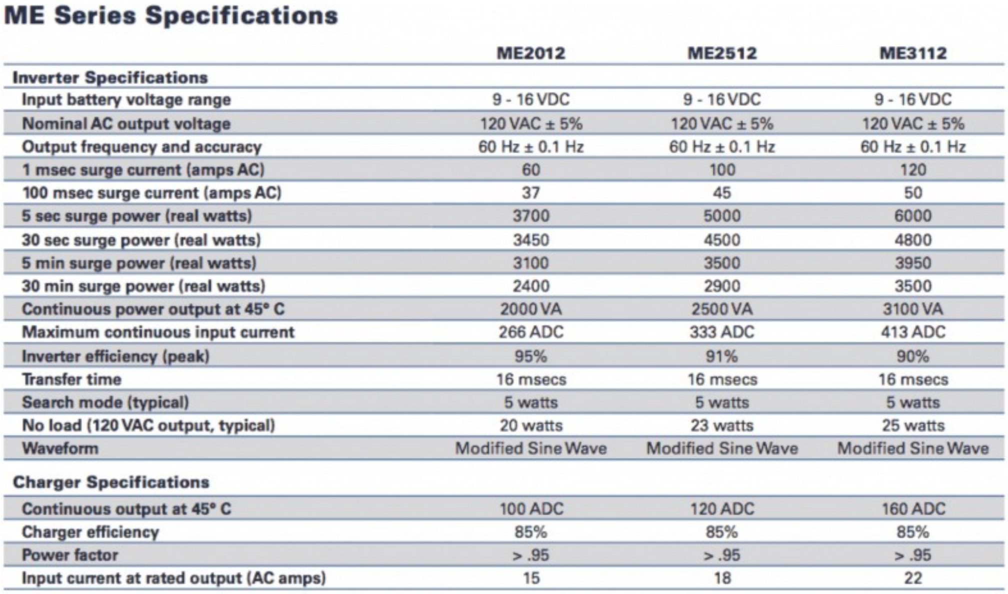
Even though the battery has reached the desired voltage, the charge has not fully saturated the battery. The charge controller holds the voltage constant while reducing the current over time as the battery charge reaches full saturation.

Inverters

INVERTER

The role of an **inverter** is to convert the DC current from a solar array or battery bank into AC current (that can then be used by conventional AC appliances and fixtures). In the early days of solar electricity, inverters were often not incorporated into the system. Without the inverter's power conversion, the entire system needed to be wired to handle the DC current, and DC fixtures and appliances had to be purchased and installed. This added greatly to the cost of a PV system, and often made the installation in an existing structure (already wired for AC) impractical.

Today, nearly all home and commercial PV systems incorporate an inverter, so that conventional AC wiring and loads (appliances, lighting, etc) can be serviced by the system. This makes converting an existing home to run off a



ME Series Specifications

	ME2012	ME2512	ME3112
Inverter Specifications			
Input battery voltage range	9 - 16 VDC	9 - 16 VDC	9 - 16 VDC
Nominal AC output voltage	120 VAC ± 5%	120 VAC ± 5%	120 VAC ± 5%
Output frequency and accuracy	60 Hz ± 0.1 Hz	60 Hz ± 0.1 Hz	60 Hz ± 0.1 Hz
1 msec surge current (amps AC)	60	100	120
100 msec surge current (amps AC)	37	45	50
5 sec surge power (real watts)	3700	5000	6000
30 sec surge power (real watts)	3450	4500	4800
5 min surge power (real watts)	3100	3500	3950
30 min surge power (real watts)	2400	2900	3500
Continuous power output at 45° C	2000 VA	2500 VA	3100 VA
Maximum continuous input current	266 ADC	333 ADC	413 ADC
Inverter efficiency (peak)	95%	91%	90%
Transfer time	16 msecs	16 msecs	16 msecs
Search mode (typical)	5 watts	5 watts	5 watts
No load (120 VAC output, typical)	20 watts	23 watts	25 watts
Waveform	Modified Sine Wave	Modified Sine Wave	Modified Sine Wave
Charger Specifications			
Continuous output at 45° C	100 ADC	120 ADC	160 ADC
Charger efficiency	85%	85%	85%
Power factor	> .95	> .95	> .95
Input current at rated output (AC amps)	15	18	22

FIGURE 5-21: STAND-ALONE INVERTER SPECIFICATIONS SHEET

(PHOTO FROM THEINVERTERSTORE.COM)

PV system much easier, since the existing wiring and appliances do not need to be replaced. It also provides a maximum degree in flexibility, allowing the homeowner to use either grid-supplied power (AC power), or power from the solar array (DC converted to AC).

Inverters are available in many sizes and with many features. However, they can be divided into two broad categories: those that service systems that are not attached to the electrical grid, and those that must be able to communicate with the existing electric utility provider.

Stand-Alone Inverters

Stand-alone PV systems are typically independent of the electrical grid. Often they are installed in remote locations where power from utilities is not available.

STAND-ALONE INVERTER

These systems rely on battery banks to store power for use when the sun is not shining. **Stand-alone inverters** connect to the battery bank, converting the DC power of the batteries into AC power to use within the home. When the batteries run low on power, the inverter shuts off – and no power is available to service loads within the building. The solar array is required to recharge and/or keep the battery bank adequately charged.

BATTERY-BASED INVERTER

When selecting a stand-alone inverter (sometimes referred to as off-grid or **battery-based inverter)**, specifications to be considered (Figure 5-21) include:

- the battery bank voltage (the inverter should be compatible with the system voltage). The input voltage tolerance should be able to accept the maximum voltage generated by your battery bank or solar array.

Inverters of this type will be rated at either 12 V, 24 V, 36 V, or 48 V. Output voltages in the U.S. should be 120 Vac or 240 Vac– for typical household systems.

POWER RATING

CONTINUOUS RATING

SURGE RATING

- the **power rating**, or the watts the system is designed to handle. Power ratings will often be listed as **continuous** power (the amount of power the unit can safely produce on an ongoing or indefinite period of time), or a **surge rating** (the maximum amount of power the unit can handle for a very brief period of time). The amount of power produced by a stand-alone inverter is determined by the load. Turn on more appliances, and the inverter will produce more power. If the load exceeds the surge rating of the inverter, the system will shut down (and perhaps be damaged). The inverter should have enough capacity to be able to handle the anticipated load of the system (as determined by a load analysis) on a continuous basis.
- the output frequency, measured in hertz. In most of the western hemisphere (including the U.S) and a few other nations, it is around 60 Hz. Much of the rest of the world operates at 50 Hz.
- the **waveform** of the system.
- the efficiency of the unit. Some power is lost as the signal is converted from DC to AC. The efficiency of various inverters can range from 80 - 98% percent. The more efficient the unit, the more power from the battery bank will be available for use to service the loads.

WAVEFORM

Inverter Waveforms

Inverters are available that produce the AC output in three waveforms (illustrated in Figure 5-22). These include **pure sine wave**, **modified sine wave**, and **square wave.**

PURE SINE WAVE

MODIFIED SINE WAVE

SQUARE WAVE

Square wave inverters are rarely used today except in the most inexpensive systems. But some legacy PV installations may still have them incorporated as part of the system. This type of inverter is not compatible with modern electronics or complex motors. These inverters can run simple tools with universal motors or lights, but little else.

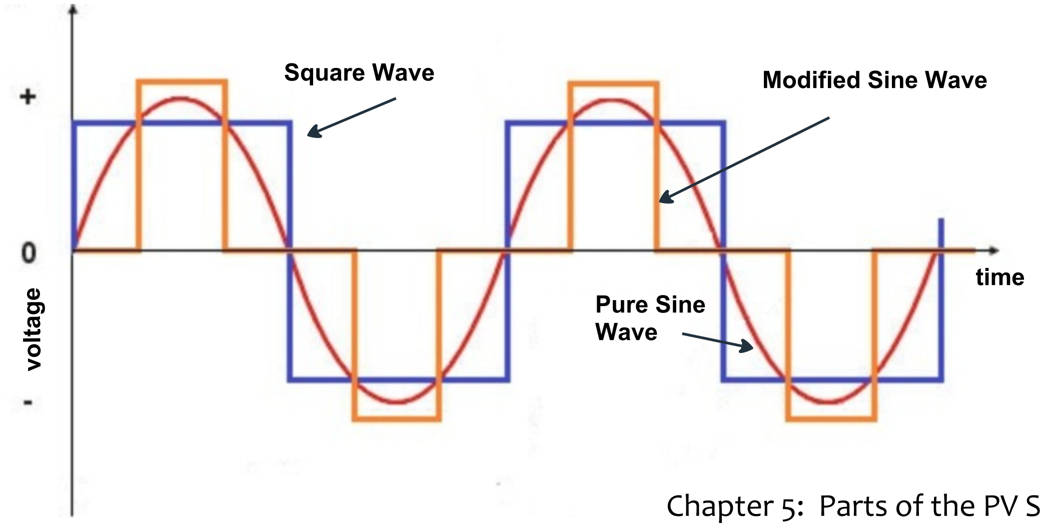
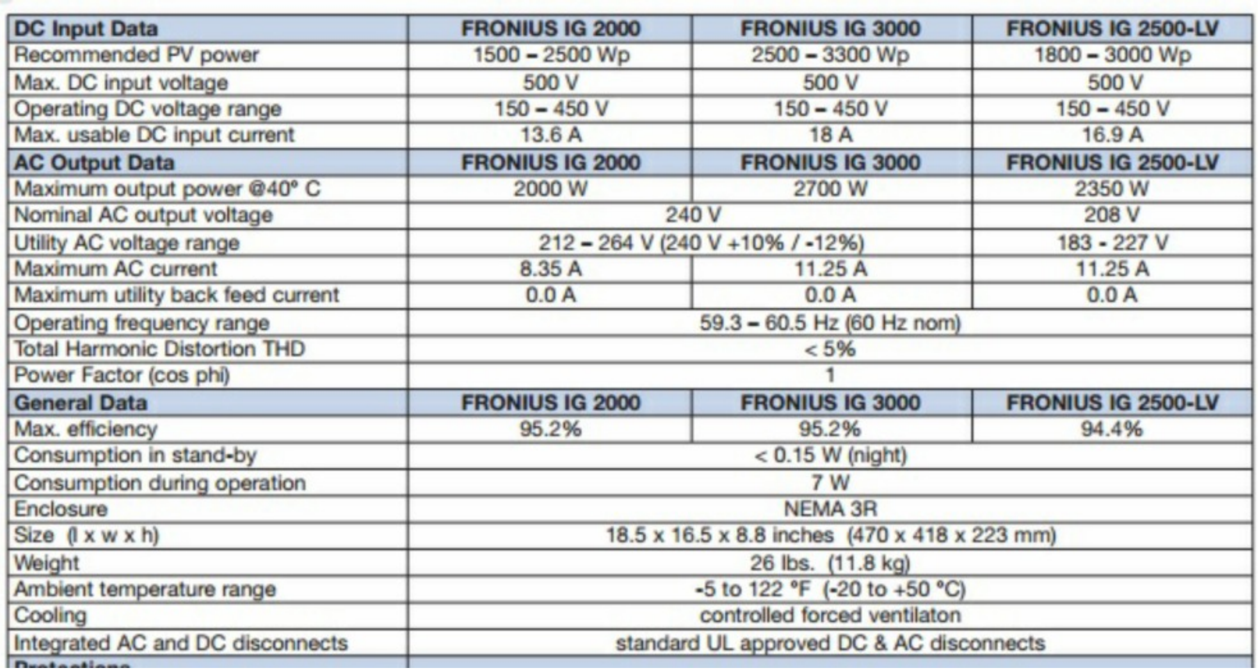


FIGURE 5-22: WAVEFORMS UTILIZED WITHIN VARIOUS INVERTERS



DC Input Data	FRONIUS IG 2000	FRONIUS IG 3000	FRONIUS IG 2500-LV
Recommended 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	18 A	16.9 A
AC Output Data	**FRONIUS IG 2000**	**FRONIUS IG 3000**	**FRONIUS IG 2500-LV**
Maximum output power @40° C	2000 W	2700 W	2350 W
Nominal AC output voltage	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
Maximum 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		
General Data	**FRONIUS IG 2000**	**FRONIUS IG 3000**	**FRONIUS IG 2500-LV**
Max. efficiency	95.2%	95.2%	94.4%
Consumption in stand-by	< 0.15 W (night)		
Consumption during operation	7 W		
Enclosure	NEMA 3R		
Size (l x w x h)	18.5 x 16.5 x 8.8 inches (470 x 418 x 223 mm)		
Weight	26 lbs. (11.8 kg)		
Ambient temperature range	-5 to 122 °F (-20 to +50 °C)		
Cooling	controlled forced ventilaton		
Integrated AC and DC disconnects	standard UL approved DC & AC disconnects		

FIGURE 5-23: EXAMPLE OF GRID-TIED INVERTER SPECIFICATIONS

(FROM FRONIUS)

Modified sine wave inverters adjust the AC electrical signal to more closely reflect a sine wave, but not quite. Converting the signal from digital to analog takes energy. Most motors running off a modified sine wave inverter will use about 20% more power than it would use if being powered by a sine wave inverter. Other equipment such as photocopiers, battery chargers, digital clocks, and some fluorescent lights will not work at all in a system that uses a modified sine wave inverter. These units are, however, less expensive than a pure sine wave inverter.

Sine wave inverters cost two to three times as much as a similarly sized modified sine wave inverter, however they have a major advantage in that all electronic equipment on the market are designed to function with the power output from these units. This matches the wave form of AC electricity produced by utility company generators.

Grid-Tied Inverters

GRID-TIED INVERTER

ANTI-ISLANDING

Grid-tied inverters are used in systems that are connected to the utility grid. These units are designed to match the energy form coming from the utility company. They also include **anti-islanding** features, which automatically shut down the PV system whenever they detect that there is no power on the grid. This is a safety issue – protecting utility workers who may be repairing the grid. The utility worker may assume there is no electricity flowing (as the power grid is down), however the system could still be pumping electricity onto supposedly “dead” lines... and the result could be fatal. An example of a grid-tied inverter specification sheet can be seen in Figure 5-23.

Rapid Shutdown of PV Systems on Buildings

Perhaps the most dramatic change in the 2014 NEC, from the perspective of PV design, was the incorporation of a provision (in Section 690.12) that all rooftop arrays must incorporate a method where they can be effectively shut down at the source.

The reason for this provision comes from the increasing risk faced by first responders when responding to a fire at a structure where a PV system is installed.

Historically, when a first responder disconnects power from the grid (by pulling the meter, for example), they can safely assume that they will not come into contact with any live electrical wires within the building.

However, if a PV system is present and the sun is shining, wires within the structure may still be energized, even when the main AC disconnect has been opened and the system is no longer operating (power can still be present from the panels to the string inverter where the anti-islanding feature has shut down the system).

To prevent this situation, the 2014 NEC required that when the PV system disconnect is turned off:

- conductors more than 5 ft (1.5 m) inside the building structure and no more than 10 feet (3 m) from the array be limited to a maximum of 30 volts and 240 watts within 10 seconds of system shutdown. 30 volts is considered "touch safe" in a wet environment,
- systems with rapid shutdown should be labeled as such,
- equipment that performs the rapid shutdown should be listed and identified as meeting the rapid shutdown requirements.

System designers could comply with this 2014 provision in a number of ways. These include:

- use of micro inverters, which disconnect at the panel when the grid is not present,
- use of power optimizers, which also disconnect at the panel when the grid is down,
- use of a **disconnecting combiner box** (must be located within 10 feet (3 m) of the array) that is wired to an emergency shutoff switch located near the utility service entrance, an example is shown in Figure 5-24,
- or locate the string inverter within 10 ft (3 m) of the array.

Disconnecting Combiner Box

Figure 5-24: Emergency Disconnect switch connected to combiner box

(From Bentek Solar)