MORNINGSTAR
World's Leading Solar Controllers & Inverters

Traditional PWM vs Morningstar's TrakStar™ MPPT Technology

Morningstar's MPPT charge controllers use the TrakStar advanced control MPPT algorithm to harvest maximum power from a Solar Array's peak power point. It is generally accepted that even the most basic MPPT controller will provide an additional 10-15% of charging capability, when compared to a standard PWM regulator. Besides this extra charge capability, there are several other important differences and advantages between PWM & MPPT technologies—these basic differences & advantages are outlined in this whitepaper.

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Traditional PWM vs Morningstar's TrakStar™ MPPT Technology

Introduction:

Morningstar MPPT (Maximum Power Point Tracking) charge controllers' utilize Morningstar's advanced TrakStar MPPT technology to harvest the maximum amount of power from the solar array. It is generally accepted that even the most basic MPPT controllers will provide an additional 10-15% of charging capability compared to a standard PWM regulator. In addition this efficiency, there are several other important differences and advantages between PWM & MPPT technologies—these basic differences & advantages are outlined in this whitepaper. This whitepaper will also provide an explanation on how to properly size solar arrays for each type of controller.

PWM Charging:

Traditional solar regulators featuring PWM (Pulse Width Modulation) charging operate by making a connection directly from the solar array to the battery bank. During bulk charging when there is a continuous connection from the array to the battery bank, the array output voltage is 'pulled down' to the battery voltage. The battery voltage adjusts slightly up depending on the amount of current provided by the array and the size and characteristics of the battery.

TrakStar MPPT

Morningstar's Advanced Control Algorithm to Harvest Maximum Power from a Solar Array's Peak Power Point

Even the largest and most efficient controller can give up crucial power if it is not tracking the power point of the module correctly.

Speed and logic in the tracking algorithm will yield gains that pure size and efficiency cannot make on their own.

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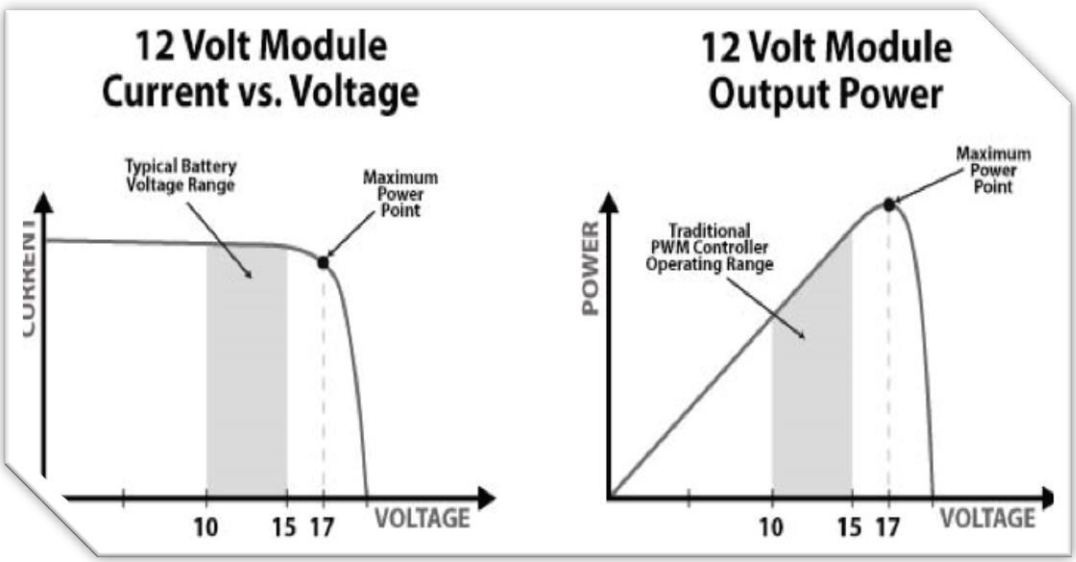
The Vmp (maximum power voltage) is the voltage where the product of the output current and output voltage (amps * volts) is greatest and output power (watts = amps * volts) is maximized. Module wattage ratings (e.g. 100W, 205W) are based on Pmp (maximum power) at Vmp under standard test conditions (STC).

Using a nominal 12V system as an example, the battery voltage will normally be somewhere between 10 – 15 VDC. However, 12V nominal solar modules commonly have a Vmp(STC) of about 17V. When the array (having Vmp of 17V) is connected to the batteries for charging, the batteries pull down the output voltage of the array. Thus, the array is not operating at its most efficient voltage of 17V, but rather at somewhere between 10 and 15V. The following graphs illustrate this phenomenon:

The greater the difference between battery voltage and the Vmp of the array, the more energy is wasted by a PWM controller during bulk charging.



Because these traditional controllers rarely operate at the Vmp of the solar array, potential energy is being wasted that could otherwise be used to better charge the battery bank and maintain power for system loads. The greater the difference between battery voltage and the Vmp of the array, the more energy is wasted by a PWM controller during bulk charging.

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TrakStar™ Maximum Power Point Tracking:

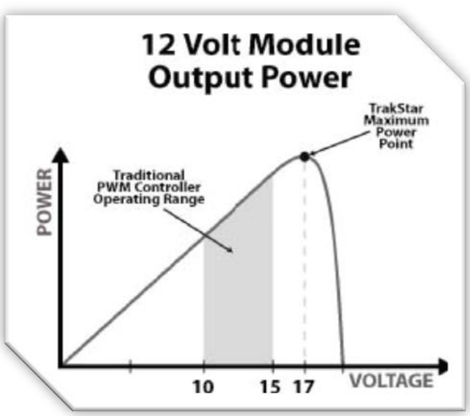
Morningstar MPPT controllers feature TrakStar technology, designed to quickly and accurately determine the Vmp (maximum power voltage) of the solar array. TrakStar MPPT controllers 'sweep' the solar input to determine the voltage at which the array is producing the maximum amount of power. The controller harvests power from the array at this Vmp voltage and converts it down to battery voltage, boosting charging current in the process.

Because power in is equal to the power out of the controller (assuming 100% efficiency, neglecting wiring and conversion losses), it follows that a down-conversion of voltage corresponds to a proportional increase in current. Power (watts) is equal to the product of voltage and current, therefore, if voltage is reduced current must be increased to keep the input/output power equal.

Assuming 100% efficiency:

Input Power = Output Power

Volts In * Amps In = Lower Volts Out * Higher Amps Out For example: a 100W panel (Vmp of 17V) is used to charge a battery at 12V with a TrakStar MPPT controller. In ideal conditions, 5.88A of solar current flow into the MPPT (100W / 17V = 5.88A). But the output voltage (battery voltage) is 12V, meaning current flow to the battery is 8.33A (100W / 12V = 8.33A). You can see that the greater the voltage difference between the Vmp and the battery, the more "boost" current the battery will receive. The graph on the left illustrates the advantage of operating at the TrakStar MPPT.



A consequence of getting more "boost" when the voltage difference is greater: the less charged the batteries are (lower battery voltage), the more "boost" current they will receive. This

Staying on Track

» Sweeps full array from 0-150V in one tenth of a second!

» Some controllers can take up to 30 seconds, during which power levels could change.

» Other controllers use dynamic tracking, adjusting locally, which can result in missing the true Vmp.

Flexible Sweep Intervals

» Morningstar's MPPT charge controllers sweep the array more often when array voltages change.

» Enabling it to spend more time on the maximum power point.

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is precisely the time when batteries will benefit from an increased amount of charging current.

Environmental Considerations:

Environmental conditions will cause the Vmp of a solar array to fluctuate with partial array shading and module temperature having the most impact. MPPT technology allows the system to track the changing Vmp and maximize energy harvest in any environmental conditions.

Another noticeable increase in charging efficiency, or taking advantage of the voltage differential "boost" will be seen in colder temperatures. As solar modules drop in temperature, their Vmp increases (see Appendix). Using a standard PWM regulator, a decrease in temperature would correspond in almost no change in power. Since the array current stays the same the charging current picks nothing up from the increased voltage. However, an MPPT controller tracks the increasing Vmp and converts the excess voltage being produced into additional charging current. In general, any rise in Vmp will increase an MPPT controller's harvest relative to a PWM controller. (Conversely, any drop in Vmp will decrease an MPPT controller's harvest relative to a PWM controller).

As seasons change, the angle of the sun striking a solar module will change as well (assuming stationary modules). The greater the angle of incidence, the less power a module will ultimately produce. During times of the year where the angle of incidence is greatest (and relative power output is decreased), MPPT technology is very useful for harvesting the maximum amount of energy.

MPPT controllers can play a big role in helping improve system performance, especially autonomy considerations, for keeping the batteries charged during the winter months with less daylight hours and sometimes poor incident angle. Again, the additional "boost" is the greatest when it may be needed the most.

Array Sizing for PWM Regulators:

The first consideration in sizing the array for a PWM controller is open circuit voltage (Voc). Every controller has a maximum input voltage rating. The array must have a temperature compensated (see Appendix) Voc less than the controller's maximum input voltage rating. During PWM switching cycles, the controller input is exposed to the array open circuit voltage. Using an array with a temperature compensated Voc greater than the controller input rating will damage the controller. Next, consider the maximum power voltage (Vmp). The Vmp of the array needs to be higher than the battery's maximum charging voltage.

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Recommended values for Vmp are listed below:

12V systems: Vmp > 15V
24V systems: Vmp > 30V
36V systems: Vmp > 45V
48V systems: Vmp > 60V

A PV module's output current will decrease significantly at voltages higher than Vmp and will be 0 Amps at Voc. Therefore, the temperature compensated Vmp of the array should be higher than full battery voltage to ensure effective charging over the entire battery voltage range.

NOTE: The Vmp of the array should be higher than, but as close to, the maximum battery voltage as possible. Vmp significantly higher than max battery voltage reduces efficiency and puts more stress on the switching components of the regulator. Typically, for proper performance, 36 Cell or 72 Cell off-grid modules (Vmp ≈ 17 to 18 V for every 12V nominal battery voltage) should be used with PWM controllers.

Finally, the current output of the array is considered. Unlike MPPT controllers, standard PWM controllers are not able to "boost" the amount of charging current by converting excess input voltage into amperage. This means that the input current from the solar array will be equal to the output current delivered to the battery. The solar array must be sized so that the short circuit current (Isc) does not exceed the nameplate current rating of the controller being used. An array with Isc greater than the current rating of the regulator may consistently trip overcurrent protections or damage the unit.

<u>IMPORTANT</u>: Local code may require additional reductions in maximum input Isc levels.

NOTE: Morningstar offers a String Sizer tool to assist in the proper sizing/configuration of your solar array with Morningstar controllers. Users may choose between a selection of pre-populated module data or input their own module specifications. This tool also allows adjustment of design parameters such as range of expected battery voltages and min/max temperatures at the site. A link to the String Calculator can be found on the Morningstar homepage: www.morningstarcorp.com.

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Array Sizing for MPPT Regulators:

As with PWM regulators, the most basic concern when sizing an MPPT solar array is open circuit voltage (Voc). The temperature compensated (see Appendix) Voc of the array must be less than the maximum input voltage rating of the MPPT controller. Higher Voc has the potential to damage the unit.

For a given MPPT current rating and nominal system voltage, there is an effective maximum solar array wattage that can be used. Morningstar MPPT controllers have current ratings which specify the maximum battery charge current the unit can support. NOTE: The battery charge current will be lower than the solar input current due to the MPPT's ability to "boost" charging amperage. The MPPT output current rating multiplied by the battery voltage is the maximum amount of power which can be used for charging the batteries. Any amount of power in excess of this could be lost when the controller limits the charging current to the maximum output current level:

Example #1:

- A 15A MPPT controller is being used in a 12V nominal system (actual battery voltage between 10V and 15V).
- Multiplying current rating and battery voltage gives about 200W (15A * 13.3V = 200W).
- The recommended maximum array wattage for this system is therefore 200W.

Example #2:

- A 15A MPPT controller is now being used in a 24V nominal system (actual battery voltage between 20V and 30V).
- The recommended maximum array wattage will therefore be 400W (15A * 26.6V = 400W).

It is important to note that exceeding the maximum array wattage for a given controller/nominal voltage combination will not damage the controller.

It is important to note that exceeding the maximum array wattage for a given controller/nominal voltage combination will not damage the controller. Any wattage in excess of the max array wattage will simply be lost. (i.e. Using a 300W array in a system where the max array W is only 200W will not damage the controller, but the 300W array will have an operating power of approximately 200W maximum).

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IMPORTANT: MPPT controllers can be used with off-grid or grid-tied modules. PWM controllers should only be used with off-grid modules.

Maximizing Efficiency:

Morningstar TrakStar™ MPPT controllers will operate at slightly different efficiencies depending upon the nominal battery voltage being used, the Vmp of the array, and the total wattage of the array. These efficiency curves are printed in the appropriate manual for every Morningstar MPPT controller. This data can be used to optimally size your solar array for best performance and maximum energy harvest.

NOTE: Morningstar offers a String Sizer tool to assist in the proper sizing/configuration of your solar array with Morningstar controllers. Users may choose between a selection of pre-populated module data or input their own module specifications. This tool also allows for the adjustment of design parameters such as range of expected battery voltages and min/max temperatures expected at the installation site. A link to the String Calculator can be found on the Morningstar homepage: www.morningstarcorp.com.

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Maximizing MPPT Boost with a Morningstar MPPT Controller:

Morningstar's *TrakStar MPPT technology* sets itself apart from other less effective MPPT solar controllers on the market. Because of the following advantages Morningstar maintains consistently better output power which translates into more MPPT Boost:

- Consistently higher efficiencies under all operating conditions
- Lower self-consumption power losses
- No fans (lower efficiency power losses get turned into heat so fans are needed to use up additional charging power)
- Staying on Track. (Operates at MPPT levels more of the time)

This additional energy translates into a more consistently larger MPPT Boost. Given an MPPT boost of 10%, just 1% higher efficiency would mean 10% more MPPT boost.

PWM Over MPPT:

The preceding discussion of PWM vs. MPPT may cause some to wonder why a PWM controller would ever be chosen in favor of an MPPT controller. There are indeed instances where a PWM controller can be a better choice than MPPT and there are factors which will reduce or negate the advantages the MPPT may provide. The most obvious consideration is cost. MPPT controllers tend to cost more than their PWM counterparts. When deciding on a controller, the extra cost of MPPT should be analyzed with respect to the following factors:

1. Low power (specifically low current) charging applications may have equal or better energy harvest with a PWM controller. PWM controllers will operate at a relatively constant harvesting efficiency regardless of the size of the system (all things being equal, efficiency will be the same whether using a 30W array or a 300W array). MPPT regulators commonly have noticeably reduced harvesting efficiencies (relative to their peak efficiency) when used in low power applications. Efficiency curves for every Morningstar MPPT controller are printed in their corresponding manuals and should be reviewed when making a regulator decision. (Manuals are available for download on the Morningstar website).
2. As explained in the Environmental Considerations section, the greatest benefit of an MPPT regulator will be observed in colder climates (Vmp is higher). Conversely, in hotter climates Vmp is reduced. A decrease in Vmp will reduce MPPT harvest relative to PWM. Average ambient temperature at the installation site may be high enough to negate any charging advantages the MPPT has over the

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PWM. It would not be economical to use MPPT in such a situation. Average temperature at the site should be a factor considered when making a regulator choice (See Appendix).

3. Systems in which array power output is significantly larger than the power draw of the system loads would indicate that the batteries will spend most of their time at full or near full charge. Such a system may not benefit from the increased harvesting capability of an MPPT regulator. When the system batteries are full, excess solar energy goes unused. The harvesting advantage of MPPT may be unnecessary in this situation especially if autonomy is not a factor.

Technology Comparison	
PWM Charge Control	**MPPT Charge Control**
PV array & battery voltages must match	PV array voltage can be much higher than battery voltage
Operates at battery voltage so it performs well in warm temperatures and when the battery is almost full	Operates above battery voltage so it is can provide "boost" in cold temperatures and when the battery is low.
Typically recommended for use in smaller systems where "boost" benefits are minimal.	170W or higher to take advantage of "boost" benefits more
Must use off-grid PV modules typically with Vmp ≈ 17 to 18 Volts for every 12V nominal battery voltage	Enables the use of lower cost/grid-tie PV Modules helping bring down the overall PV system cost
PV array sized in Amps (based on current produced when PV array is operating at battery voltage)	PV array sized in Watts (based on the Controller Max. Charging Current x Battery Voltage)
Simpler series switching charge control circuit	Additional Energy Harvest by operating at PV peak power point rather than battery voltage

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Morningstar's MPPT Controllers:

Morningstar presently offers five MPPT controllers: SunSaver MPPT™ for small PV systems and four TriStar MPPT™ controllers for larger PV systems, as summarized below:

Morningstar MPPT Controllers Specifications Summary					
Morningstar Controller	 **SunSaver MPPT**	 **TriStar MPPT (30 Amp, 45 Amp, 60 Amp versions)**			 **TriStar MPPT-600V (with & without DB)**
Maximum Battery Current	15 Amps	30 Amps	45 Amps	60 Amps	60 Amps
Nominal Maximum Operating Power for 12 Vdc batteries	200 Watts	400 Watts	600 Watts	800 Watts	NA
Nominal Maximum Operating Power for 24 Vdc batteries	400 Watts	800 Watts	1200 Watts	1600 Watts	1600 Watts
Nominal Maximum Operating Power for 48 Vdc batteries	NA	1600 Watts	2400 Watts	3200 Watts	3200 Watts
Maximum PV Open Circuit Voltage	75 Volts	150 Volts	150 Volts	150 Volts	600 Volts
Communication Ports for MeterBus	Yes	Yes	Yes	Yes	Yes
Communication Ports for RS-232	No	Yes	Yes	Yes	Yes
Communication Ports for EIA-485	No	No	No	Yes	Yes
Communication Ports for Ethernet	No	No	No	Yes	Yes

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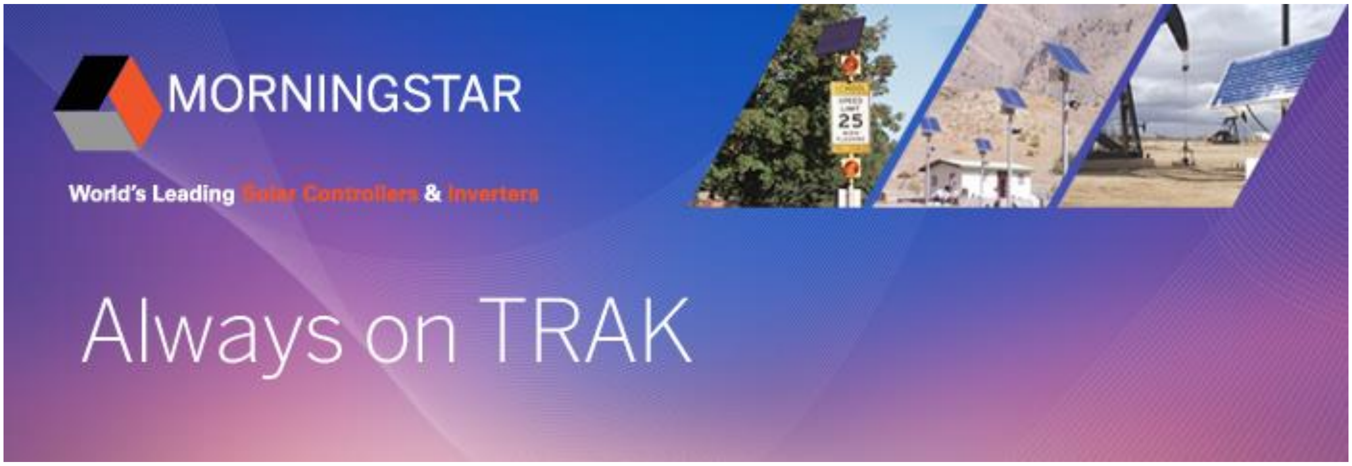

Wrap-Up:

The Solar Charge Controller is the Heart of a Stand-alone PV System. So what should you consider to choose the right solar charge controller? Here is a ***Charge Controller Checklist*** that may help:

- ✓ *PWM or MPPT*
- ✓ *Environmental Conditions*
- ✓ *Accurate Fixed or Adjustable Regulation Set Points*
- ✓ *Protections:*
  - ✓ *Lightning & Voltage Transient*
  - ✓ *Environmental (Tropicalization)*
  - ✓ *Electronic*
  - ✓ *Electrical Isolation*
- ✓ *Communication Protocols & Interfaces:*
  - ✓ *Open (or Proprietary)*
    - ✓ *Modbus TCP/IP, SNMP & SMTP*
    - ✓ *Ethernet, EIA-485 & EIA-232*

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- ✓ *Self-Diagnostic Capabilities*
- ✓ *Information – LEDs, Meters, Alarms, Data Acquisition & Communication Ports*

✓ *Temperature Compensation*

✓ *Low Voltage Disconnect (LVD)*

✓ *Battery, PV & Load Status*

✓ *Low Self Consumption*

✓ *Overall Quality (Automated or Hand Production):*

- ✓ *Operating Life (MTBF & FIT Rates)*
- ✓ *ISO 900x*
- ✓ *Certifications: CE, UL, Class 1 Division 2, FCC Class B Part 15, etc…*
- ✓ *5 Year Warranty*
- ✓ *Proven Track Record*

✓ *Ease of Use:*

- ✓ *Large Wire Terminals*
- ✓ *Clear Product Labels*
- ✓ *User Friendly Documentation*

✓ *Commercial:*

- ✓ *Delivery Time*
- ✓ *Inventory Levels*
- ✓ *Variety*
- ✓ *Post-Sales Support*
- ✓ *Technical Support*

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Appendix - Temperature Compensation:

It is important to take into account temperature compensation and understand how it relates to both the output voltage and output current of a solar module.

Solar modules have performance ratings under standard test conditions (STC); normally a cell temperature of 25°C and 1000W/m2 irradiance. Actual operating conditions will, of course, vary from STC. Manufacturers publish temperature coefficients which can be used to determine module output current/voltage under expected conditions. The two most important are the Voc and Isc Temperature Coefficients.

The Voc temp coefficient, specified in volts per °C (or °F), is a negative value. This indicates that the open circuit voltage of the module has an inverse relationship with temperature (Voc decreases with increasing temperature and increases with decreasing temperature). When determining if the Voc of an array is appropriate for the controller's maximum input voltage, it is essential to take into account temperature effects. In warm weather, the Voc of a module may be low enough to use with a certain controller. However, as seasons change and temperature drops, the Voc may rise past a voltage safe to use with that controller.

Worst case temperature effects should always be used when sizing an array. For example: the Voc of a module under STC (25°C) is 21V. The Voc temp coefficient is -0.05V/°C. If the record low temperature for the area in which the module will be placed is -10°C, the worst case (highest) Voc will be 22.75Voc:

> -10°C - 25°C = -35°C
> -35°C * -0.05V/°C = 1.75V
> 21V(@STC) + 1.75V = 22.75V(@-10°C)

The Isc temp coefficient, specified in amps per °C (or °F), is a positive value. This indicates that the short circuit current will rise with increasing temperature and fall with decreasing temperature. Normally, the Isc coefficient is small enough to be neglected.

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