PV Modules, Conductors, & the Code

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Sponsored by the Photovoltaic Systems Assistance Center
Sandia National Laboratories

Photovoltaic (PV) modules produce electrical energy when exposed to light and connected to a load. Determining the necessary conductors to move this energy from the module to the load is frequently a confusing task.

I'll start by discussing the rating information listed on the back of the module, and how those ratings are determined. Next I'll cover the varying environmental conditions, and the requirements of the National Electrical Code *(NEC).* All of these factors will be used to establish the ampacity requirements of PV conductors.

Laboratory Ratings

PV modules are rated by the manufacturers in laboratories or on the assembly line under a set of test conditions called "standard test conditions" (STC). These conditions are: an irradiance of 1,000 watts per square meter (W/m^2), a PV cell temperature of 25°C (77°F), and some other less important (for our purposes) factors.

The actual measurements are made using a solar simulator that can produce a light of the correct intensity and spectrum. The room or test chamber is maintained at 25°C (77°F) to keep the module cells at this temperature. The duration of the light exposure is so short that there is no appreciable heating of the cells in the module. While the light is on, a specialized tester called an IV curve tester measures the open-circuit voltage, the short-circuit current, and the peak-power-point operating voltage and current. The tester can also record data for the complete current vs. voltage curve (IV curve) for the module.

Some manufacturers label each module with the test results of that particular module, while others print the average values for that model. Each manufacturer guarantees the power output of the modules in slightly different ways. In addition to the numbers mentioned above, the module label will also contain the maximum power output rating (at STC), the maximum open-circuit voltage (usually 600 volts or less), the maximum series fuse (to protect the module), and the National Fire Protection Association (NFPA) fire rating. The fire rating is used with local building codes when the PV module is to be mounted on a roof.

Field Operating Conditions

When PV modules are installed, they are no longer in benign, indoor laboratory conditions. They are exposed to long-duration sunlight, ambient air temperatures, winds, and other environmental conditions.

Ambient air temperatures in the United States may reach 50°C (122°F) in some locations, and can be lower than -40°C (-40°F) in other locations. The modules may be mounted where they are not exposed to cooling breezes, causing them to operate at higher temperatures. In other situations, the modules may be on open racks exposed to high steady winds, which can keep their operating temperatures at or very near ambient temperatures.

When sunlight falls on a module, the module is heated. The temperature rise of the module cells and the module junction box depends on the intensity of the sunlight and the amount of cooling the module experiences, either through natural convection and radiation or from cooling breezes. Modules may be exposed to sunlight that can range in intensity from 0 W/m^2 (night) to values as high as 1,500 W/m^2 under cloud-enhancement conditions. A sunlight intensity of 1,000 W/m^2 (the average over the surface of the earth at sea level) just happens to be the value used for rating modules. In many locations throughout the USA, the sunlight peaks at 1,100–1,200 W/m^2 for several hours each day.

With high winds, modules may operate in bright sunlight at the local ambient air temperature, which can be very cold in some locations. In other installations, high ambient air temperatures and no cooling winds can lead to very high operating temperatures for the modules.

Module manufacturers sometimes publish a "normal operating cell temperature" (NOCT) for their modules, which is measured with an irradiance of 850 or 1,000 W/m^2, an ambient temperature of 20°C (68°F), and a windspeed of 1 m/s (2.24 mph). The NOCT for crystalline silicon modules is in the 44–48°C (111–118°F) range. In the Southwest, with light or no wind, we typically see modules operating 25–35°C (77–95°F) above ambient air temperatures with module cell and junction box temperatures as high as 75°C (167°F)—considerably higher than the NOCT.

Crystalline PV modules lose power at about 0.5 percent per degree Celsius as their temperatures increase above the STC rating temperature of 25°C (77°F). With an NOCT of 47°C (117°F), the module is operating 22°C (72°F) above 25°C, and has lost 11 percent of its rated power. On hot summer days in many parts of the country, PV modules are frequently operating at 65°C (149°F), and have lost 20 percent of their rated power due to heating. The lost power is largely due to reductions in the peak-power operating voltage point of the module as temperatures increase. Further power losses may be experienced if the battery operating voltage pulls the module operating point off the already lowered peak-power point.

Module Operating Voltages

When a PV module operates at temperatures below 25°C (77°F) in low ambient air temperatures and/or high winds, the open-circuit voltage increases above the rated open-circuit voltage measured at 25°C. This varies slightly from manufacturer to manufacturer, and from crystalline silicon modules to thin-film technologies. The actual open-circuit voltage is the voltage that stresses the insulation on conductors and the insulation in circuit breakers, fuses, and switchgear. It also determines whether fuses and circuit breakers will function near the limits of their voltage ratings.

Since the module manufacturer and many installers do not know how low the temperatures may go in a particular installation, the instructions supplied with the module (as required by UL Standard 1703) currently state that the rated open-circuit voltage (Voc) of the module must be multiplied by 125 percent prior to determining the system operating voltage.

The *NEC* then requires that the system voltage be determined by multiplying the number of modules connected in series by this new open-circuit voltage (I call it the “design” voltage). This system voltage is then used to determine the voltage rating of conductors, switchgear, circuit breakers, and fuses. This ensures that under the worst case, cold temperature conditions, the PV array will not generate voltages that are in excess of the ratings of the components in the system.

A table was added to the 1999 *NEC* to acknowledge the fact that historical weather data may be used to determine the lowest temperature at many locations. A Web source for this data is referenced below. Instead of a straight multiplier of 125 percent, *NEC* Table 690-7 allows a variable, temperature-dependent multiplication factor to be used when the lowest temperature is above -40°C (-40°F).

These voltage correction factors are important in both high-voltage and low-voltage PV systems. In high-voltage systems, the older 125 percent (1.25) multiplication factor limited the rated open-circuit voltage to 480 volts DC. When multiplied by the 1.25 factor, this gave a system voltage of 600 volts—a significant limiting voltage in the code and on most modules. This represents about 22 PV modules (Voc of 21.8 volts) in series. Some high-voltage inverters really need 24 modules in series to function properly in high-temperature environments without added equipment. With a multiplication factor of say 1.10, 24 modules with a Voc of 22 volts could be connected in series and not exceed the 600 volt limit.

Voc Correction Factors for Temperature*

Lowest Ambient Temperature		
Centigrade	*Fahrenheit*	*Multiply Voc by:*
25 to 10°	77 to 50°	1.06
9 to 0°	49 to 32°	1.10
-1 to -10°	31 to 14°	1.13
-11 to -20°	13 to -4°	1.17
-21 to -40°	-5 to -40°	1.25

* From NEC Table 690-7

In low-voltage systems, many installers want to use the inexpensive Square D QO circuit breakers and load centers that are rated at 48 volts DC. In a nominal 24 volt system, using the 1.25 multiplier, the system voltage is about 55 volts (2 x 22 x 1.25 = 55), which exceeds the 48 volt rating of the circuit breaker. However, if it can be determined that ambient temperatures do not go below 0°C (32°F), Square D QO circuit breakers may be appropriate, since the system voltage would be 48 volts (2 x 22 x 1.10 = 48.4).

As the code mentions in Section 690-7, if you are using other than silicon-type PV modules (such as some of the newest thin-film modules), the manufacturer should be consulted for information on the maximum expected open-circuit voltages at the lowest temperatures in your location.

Eventually, the Underwriters Laboratories (UL) Standard 1703 will be revised to clarify the calculation of maximum voltage, and Section 690-7 of the *NEC* will establish and articulate the requirement. In the meantime, a good rule would to be ignore the 125 percent requirement in the instructions supplied with modules (based on UL 1703), and just apply Section 690 and Table 690 in the 1999 *NEC.* If the minimum temperature is unknown, a 125 percent multiplying factor should be used as shown in Table 690-7 for temperatures below -40°F (-40°C).

Module Operating Currents

Module currents are nearly a linear function of the intensity of the sunlight. The current does increase very slightly as temperature increases. But the voltage drop as temperature increases is much greater, and hence the module power decreases as temperature increases. The module is rated at STC with a short-circuit current and a peak-power current.

Since we want the PV modules to deliver power under all sunlight conditions, the current the wiring must handle must be carefully considered. In normal daily operation, the sunlight may be as high as 1,100–1,200 W/m^2 for several hours around solar noon. This is up to 120 percent of the 1,000 W/m^2 used to rate the modules at STC.

In some instances, clouds may gather so that reflections from the vertical cloud surfaces concentrate the sunlight on the module with irradiance values up to 1,500 W/m^2. This results in correspondingly high values of power and output. These cloud-enhancement conditions are not static, and rarely last more than a few minutes. So we need not worry about steady-state currents at these levels.

Another factor to consider is that some shunt-type PV charge controllers short circuit the PV module to control the battery charging process. That means that we want the module conductors and overcurrent devices to be able to handle the rated short-circuit current, and any normal currents that are above that value on a regular basis. Based on 30+ years of experience with terrestrial PV systems, the PV industry selected a factor of 125 percent for increasing the rated (at STC) module short-circuit current to determine a “design” current that would account for the higher current conditions. This design current is used to size the conductors and to determine the rating of overcurrent devices.

With a conductor ampacity of 125 percent of the STC-rated short-circuit current, the conductors are assured of being able to handle the normal and expected daily currents without overheating. Fuses and circuit breakers sized at this 125 percent value will not trip in normal operation. These overcurrent devices will, however, protect the module and array conductors from high fault currents originating from the batteries, parallel connected PV modules, or grid backfeed through utility-interactive inverters.

Of course, there may be some very unusual conditions where the ambient temperatures are very cold, the winds are high, there is reflective snow or water at just the right angle, or the clouds form a lens. In these very rare conditions, the overcurrent devices may trip. But the *NEC* and UL do not require us to overdesign for these conditions, just for those conditions that can be expected periodically in most systems.

We have now determined the normal, expected daily current output of a PV module. This multiplication of 125 percent will be found in both the UL-required instructions for the modules and in the 1999 *NEC* in Section 690-8,9. Again, UL Standard 1703 will be modified to clarify the current multiplier in the module instructions, and the 125 percent requirement for current correction will appear only in the code. Installers should not use both of these particular 125 percent factors, only one.

Note that the *NEC* has requirements established not only in Article 690, but in Article 240 and elsewhere throughout the code that prohibit overcurrent devices and conductors from being operated at more than 80 percent of rating. For example, a 15 amp AC branch circuit protected by a 15 amp circuit breaker may be loaded to no more than 12 amps (80 percent of 15) on a continuous basis. If we had a vacuum cleaner drawing 12 amps, it would have to be connected to a circuit rated for at least 15 amps (125% of 12 is 15). This 80 percent safety factor requirement is related to the long-term durability of components in tight, hot environments like load centers.

Conductor Ampacity Requirements

A second 125 percent multiplier (the reciprocal of the *NEC* 80 percent safety factor of 1/1.25 = 0.80) is used to determine the design current for the module. In the module and array wiring for PV systems, we must use both of the 125 percent factors (increased sunlight and 80 percent limit) to determine the ampacity of the conductors and the rating of the overcurrent devices. The combination of the two factors of 125 percent yields an overall multiplier of 156 percent (1.25 x 1.25 = 1.56).

The array wiring and overcurrent device calculations are based on the number of modules or strings of modules that are connected in parallel. A few circuit breakers are listed for operation at 100 percent of rating (consequently, one of the 125 percent factors is not required for these breakers). But these devices are usually only found in factory-assembled and listed components.

Summary

We now have a starting point for determining the ratings for PV array conductors and overcurrent devices. The voltage rating for conductors and overcurrent devices is based on a temperature-dependent factor from Table 690-7 of the *NEC.* This is used to multiply the STC-rated open-circuit voltage marked on the back of the crystalline silicon module. Thin-film module manufacturers provide this information in the module instructions. This module design voltage is then multiplied by the number of modules that are connected in series to determine the system voltage. All conductors and overcurrent devices should have a voltage rating at least this high.

The module rated short-circuit current (at STC) gives us a starting point for determining the required ampacity for conductors and overcurrent device ratings. First, we multiply the rated short-circuit current by 125 percent to allow for the normal expected daily variations in the current produced by the modules. Then, to meet the *NEC* requirements for not operating conductors or overcurrent devices at more than 80 percent of rating, the first product of 125 percent times the short-circuit current is again multiplied by a second 125 percent. The product of the two (125% x 125%) is 156 percent. This design current is the number used for overcurrent device ratings and the ampacity of conductors.

In the next *Code Corner,* I will present some examples of module and array wiring and overcurrent protection.

Questions or Comments?

If you have questions about the *NEC* or the implementation of PV systems following the requirements of the *NEC*, feel free to call, fax, email, or write me. Sandia National Laboratories sponsors my activities in this area as a support function to the PV industry. This work was supported by the United States Department of Energy under Contract DE-FC04-00AL66794. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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