PV Basics Affect the Code

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Photovoltaic modules have some very important characteristics that affect the electrical safety of PV installations. These characteristics drive the installation requirements found in the *National Electrical Code*. Let's review some of these characteristics and see how they should be dealt with.

Sunlight

The intensity of sunlight is called irradiance, and for PV systems the units are watts per square meter (W/m^2). A square meter is about 11 square feet. A typical, clear sky, solar-noon value of irradiance falling on the surface of the earth at sea level is 1,000 W/m^2. This value of irradiance is one of the standard test conditions (STC) factors used to rate PV module and PV array output.

On clear, cloudless days, irradiance will peak at solar noon. A plot of irradiance vs. time of day is presented in the peak sun hour diagram, and makes an arc-like curve. PV system designers need to know the amount of solar energy available each day (known as irradiation or insolation). Working with irradiance vs. time curves is difficult, since it requires mathematical integration of the data.

To simplify the calculations used in PV system design, tables are provided that do the math and present the total available solar energy as the equivalent number of hours of solar irradiance at the 1,000 W/m^2 level. This is seen in the diagram as the rectangular area with the top at 1,000 W/m^2. The rectangle covers the same area as the area under the curve. The width of the rectangle in hours is known as the peak sun hours. These numbers are published by the National Renewable Energy Laboratory (NREL), and can be found on the NREL Web site (see Access) for numerous latitudes, various array tilts, and for each month of the year. Data is provided for fixed and one and two-axis tracking arrays.

Although PV modules are rated at 1,000 W/m^2, it should be noted, as shown in the diagram, that the irradiance frequently exceeds this value when clouds, dust, or high humidity levels are not present. This peak level of irradiance will vary depending on a number of factors including orientation of the surface, altitude, and the local microclimate. Solar irradiance greater that 1,000 W/m^2 may be expected in many locations where PV systems are installed. At higher elevations, less air is between the surface and the sun (atmospheric density is lower), and the range of irradiance values is higher than at sea level.

In many areas, the time period that the irradiance exceeds 1,000 W/m^2 can be three hours or more. This has an impact on the electrical design of the system and will, as we delve into the code requirements in subsequent columns, drive some PV system design considerations. The peak may be well above 1,000 W/m^2, and values in the range of 1,100 to 1,200 W/m^2 are common. Short-term (10-15 minutes) peaks of more than1,400 W/m^2 have been measured when cumulus clouds have formed a reflective lens around the sun and concentrated the sunlight on the surface.

Temperature

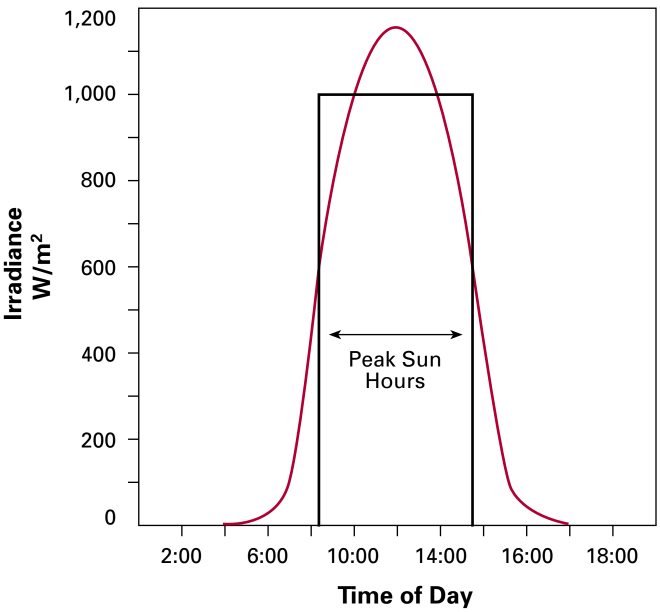
PV modules are rated (power, voltage, current) at a standard test condition (STC) temperature of 25°C (77°F). Surfaces (including PV modules) mounted in exposed outdoor locations are subject to widely varying temperatures that are a result of the ambient temperatures, solar exposure, and cooling by radiation and convection.

A typical PV module mounted outdoors in a well-ventilated area and exposed to 1,000 W/m^2 of solar irradiance with no wind blowing can be expected to operate at 30 to 35°C (54-63°F) above the ambient temperature. If the ambient temperature is 40°C (104°F), the typical PV module will operate in the 70 to 75°C (158-167°F) range on hot sunny days during the solar peak period.

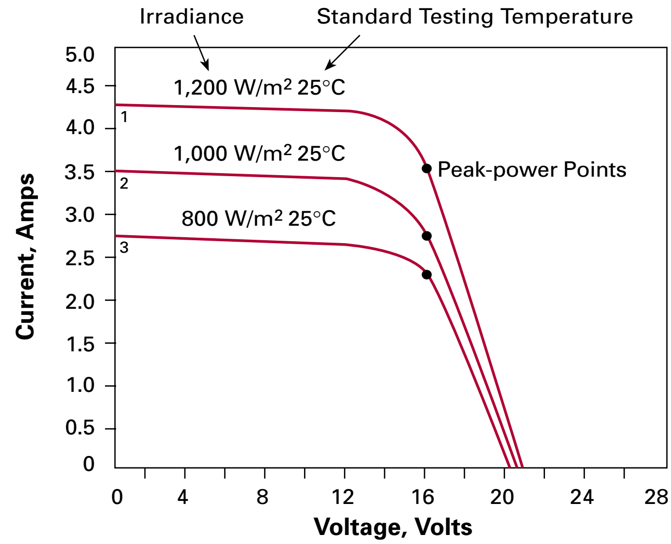
On the other hand, a PV module operating in cold, windy weather may have the heat removed from the module so rapidly that the sun never increases the module temperature more than a few degrees above ambient temperatures. With winter ambient temperatures in some locations in the U.S. as low as -40°C (-40°F), modules can operate at these temperatures. The NREL Web site also shows the record and average high and low temperatures for hundreds of locations around the U.S. This information is also used in designing a code-compliant, high performance PV system.

Furthermore, surfaces facing the clear, nighttime and early-morning sky may be subject to radiation cooling, and the surface may be a few degrees cooler than the ambient

Peak Sun Hours



I-V Curve



1. Increased Isc by approximately 20%
2. Rated Isc.
3. Decreased Isc by approximately 20%

temperature. At dawn, when no sun is shining directly on the modules, the available indirect light and the low temperature can create the highest open circuit voltages the system will ever see.

PV Module Characteristics

Crystalline silicon PV modules respond to the widely varying environmental conditions addressed above. From a performance perspective (needed to calculate the output of the PV system), the electrical output is directly proportional to the irradiance and has an inverse relationship with the module operating temperature.

If irradiance increases by 10 percent, the power available from the module will also increase by 10 percent. As the module temperature increases above the 25°C (77°F) level, the module power output will drop about 0.5 percent per degree C increase in temperature. Conversely, if the module temperature decreases, the power output will increase about 0.5 percent per degree C. When a PV module operates at 75°C (167°F; experienced on hot sunny days with no wind), the output may be only 75 percent of the STC rated output, due to the increased operating temperature.

Module power output is the product of the output current and the output voltage. Typically at the peak-power point on the module operating curve (IV curve; see diagram), the peak-power voltage will change about -0.5 percent per degree C, and the module peak-power current will change very little with respect to temperature. Voltage is the primary temperature-dependent factor in the power equation.

For safety purposes and to meet code requirements, we need to determine how the open-circuit voltage and the short-circuit current vary. For silicon PV modules, the open-circuit voltage is an inverse function of temperature. As temperature decreases, open-circuit voltage increases at about 0.38 to 0.4 percent per degree C. At a module operating temperature of -40°C (-40°F), the open-circuit voltage may be 25 percent higher than the STC value.

Open-circuit voltage is only slightly influenced by irradiance. Obviously, in total darkness, the voltage output is zero. However, even in dim light (dusk, dawn, heavy clouds) the open-circuit voltage is very nearly the STC rated value. Direct sunlight does not have to be shining on the module for voltage to be on the output terminals. Current may be extremely low, but nearly full voltage can be expected in dim light. Thin film modules may have different characteristics, and the module manufacturer should be contacted for details.

The short-circuit current is a direct function of irradiance. Increase or decrease the irradiance by 20 percent and the short-circuit current changes by the same percentage and in the same direction. Short-circuit current also increases a slight amount as module temperature increases, but this effect is generally ignored in PV design.

With the irradiance and temperature variations addressed above, PV modules may be expected to have open-circuit voltages from about 15 percent below the STC value in hot, still weather to about 25 percent above the STC value in cold, windy weather. The short-circuit current may be 120 percent or more of the STC value on sunny, hot days, and that output may exist for three hours or more.

Addressing the Problem

Early PV module manufacturers, inverter manufacturers, Underwriters Laboratories (UL), and individuals involved with codes and standards recognized that these variations in temperature and irradiance from standard test conditions affect module output and must be addressed.

Excessive, unexpected voltages can cause arcing in switchgear and overcurrent devices, deterioration and breakdown of the insulation on conductors, and damage to electronic devices such as inverters, charge controllers, and the PV modules themselves. Higher than rated current can cause nuisance tripping of overcurrent devices, overheating of conductors, and the subsequent deterioration of the wiring as well as failed switchgear, electronic devices, and power relay contacts.

AC Is Easy; DC Is Tough

At this point, it should be noted that direct current (DC) is a very different beast than alternating current (AC). Alternating current, as the name implies, alternates its polarity or direction of electron flow 120 times per second in a 60 Hertz electrical system. To alternate the flow, the current becomes zero 120 times a second. When the current is zero, any arcs in switch contacts, circuit breaker contacts, or in melting fuse links are extinguished.

If an arc is visible in an AC current path, the eye-to-brain filter makes it look continuous. In reality, it is extinguishing itself 120 times per second when the current is zero, and reigniting 120 times per second as the voltage across the gap increases away from zero. This self-extinguishing feature of the AC arc makes it relatively easy for an AC-rated device to fully extinguish the arc and open the circuit. Typically AC-rated devices are simpler and cheaper than equivalent DC-rated devices.

DC electricity flows only in one direction in the conductor or in the arc that forms when a contact opens or a fuse link melts. The arc has no self-extinguishing capability, and the device must be capable of extinguishing the arc and opening the circuit without help from the arc. This imposes significant design complexities and costs on the DC-rated device. Since opening an AC circuit is easier than opening a DC circuit, many DC-rated devices also have AC ratings, but the opposite is not true.

Unlike AC-rated devices that have a nominal rated voltage, fuses, circuit breakers, and switches that are rated for DC have a voltage rating that is the absolute maximum value that can be applied to the device. Applying DC voltages higher than the rated value may cause the device to fail or to catch fire.

PV Fudge Factors

For the reasons stated above, the early PV pioneers developed mathematical tools to deal with the uncertain nature of the DC voltage and current. The following instructions are found in the documentation supplied with every listed PV module-everyone reads the manuals, don't they?

The rated short-circuit current (at STC, as marked on the back of the module) is to be multiplied by 125 percent to account for those bright, sunny days where the irradiance is above 1,000 W/m^2. This is done before any instructions or requirements in the *NEC* are implemented.

The rated open-circuit voltage (at STC, as marked on the back of the module) is to be multiplied by 125 percent to account for those bright, sunny and cold, windy days. This is also done before any instructions or requirements in the *NEC* are addressed.

Hazards Await the Uninformed

Now let's see what this means in just one aspect of a typical utility-interactive PV system. This example system uses six, 24 volt (nominal) modules connected through a DC disconnect to an 1,800 watt inverter. The peak-power voltage and the open-circuit voltage for each of the six modules at STC are 34 volts and 43 volts respectively. The PV array peak-power voltage is 6 x 34 = 204 volts, and the PV array open-circuit voltage is 6 x 43 = 258 volts.

Can a DC-rated disconnect with a voltage rating of 250 volts be used? The answer is *no* because the STC (25°C; 77°F) open-circuit voltage is 258 volts, and when the temperature drops below this mild value, the voltage will increase as noted above. It is quite possible that depending on the temperature and irradiance, a disconnect rated at 250 volts may be damaged when opened under these conditions. It most certainly would not pass the rigorous (multiple operations) testing required by Underwriters Laboratories at this higher-than-rated voltage, and could pose problems even in a less rigorous PV environment.

In my next column, I'll talk about how the PV industry influenced the *NEC* in a positive manner, and how UL has been lagging behind in modifying the PV module standards that affect what is written in the module instruction manuals.

Access

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National Renewable Energy Laboratories (NREL) solar data • http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/sum2/state.html

The 2002 *NEC* and the *NEC Handbook* are available from the National Fire Protection Association (NFPA), 11 Tracy Dr., Avon, MA 02322 • 800-344-3555 or 508-895-8300 • Fax: 800-593-6372 or 508-895-8301 • custserv@nfpa.org • www.nfpa.org