Code Calculations

for PV Modules

by John Wiles

A PV module's or string's rated open-circuit voltage (Voc) is measured at a defined temperature, namely 25°C (77°F). But what happens as temperatures fluctuate? As temperature rises, voltage decreases. Conversely, as the temperature drops, voltage increases.

What does this have to do with system design? To avoid damaging equipment, design voltage needs to stay below an inverter's maximum input voltage, as well as the voltage rating of wiring, switch-gear, and overcurrent devices. The expected lowest temperature at the installation needs to be included in the open-circuit voltage calculation, as required by the *National Electrical Code* (*NEC)* Section 690.7. (Since parallel connections of strings do not affect the open-circuit voltage, the number of strings connected in parallel is not involved in this calculation.)

In previous editions of the *NEC,* Table 690.7 could be used to determine a multiplier, which was applied to either the rated Voc of the module or a series string. The *NEC 2008* also allows the table to be used when module temperature coefficient data is not available.

Using the table is easy: All you need to know is the lowest expected temperature at the site. Then, you can look up the corresponding factor from the table (between 1.02 at 24°C and 1.25 at -40°C), and multiply the factor by the rated Voc.

Here's an example: A module has a Voc of 35 V and is going to be installed where the temperature dips to -15°C. The factor from Table 690.7 in the *NEC 2008* is 1.16. So the "cold" temperature Voc for this module is 40.6 V (35 V x 1.16). If 12 modules were going to be connected in series, the string Voc in cold weather would be 487.2 V (12 x 40.6 V). Alternatively, you could also first calculate the string open-circuit voltage and then apply the temperature factor.

NEC 2008 *Requirements Differ*

Table 690.7 is based on an "average" type of crystalline PV module that has been the most widely used over the last 30 years. However, more accurate values can be determined by using the temperature coefficient data specific to each module. Section 690.7 in the *NEC 2008* requires that when the module manufacturer's temperature coefficient data are available they should be used instead of the table. Temperature coefficients can be obtained from the manufacturer or found in the technical literature of nearly all modules. Unfortunately, different manufacturers present the temperature coefficients in a few different forms. The two most common forms are discussed below.

Percentage Coefficients. One way of presenting this data is to specify them as a percentage change. Note that the temperature used in the calculation is a *change* in temperature from the rated 25°C.

For example: The Voc temperature coefficient is given as -0.36% per degree Celsius. If that module has a Voc of 45 V at 25°C (77°F) and is going to be installed where the expected lowest temperature is -10°C (14°F). The change in temperature is 35°C (from 25°C to -10°C). The minus sign in the coefficient can be ignored as long as we remember that the voltage *increases* as the temperature goes *down* and vice versa.

Applying the coefficient, the percentage change in Voc resulting from this temperature change is 12.6% (0.36% / °C x 35°C). This percentage change can now be applied to the rated Voc of 45 V. At -10°C, the Voc will be 50.67 V (1.126 x 45 V).

Eleven of these modules could be connected in series and the cold-weather voltage would be 557.37 V (11 x 50.67 V), less than a 600 V equipment limitation.

Millivolt Coefficients. Other PV module manufacturers express the Voc temperature coefficient as a millivolt (0.001 V) coefficient.

A typical module with an open-circuit voltage (at 25°C) of 65 V might have a temperature coefficient expressed as -240 mV per degree Celsius.

If installed where the expected low temperature is -30°C (-22°F), then there is a 55°C degree change in the temperature (from 25°C to -30°C).

Millivolts are converted to volts by dividing the millivolt number by 1,000: 240 mV / 1,000 mV/V = 0.24 V, and the module Voc will increase 13.2 V (0.24 V / °C x 55°C) as the temperature changes from 25°C to -30°C. The module Voc will increase from 65 V at 25°C to 78.2 V (65 V + 13.2 V) at the -30°C temperature.

Let's suppose that the inverter maximum input voltage was listed as 550 V. How many modules could be connected in series and not exceed this voltage? To find out, take the maximum inverter voltage of 550 V and divide it by the module's cold-weather open-circuit voltage of 78.2 V: 550 V ÷ 78.2 V = 7.03 modules. Eight modules could not be used because the open-circuit, cold-weather voltage would exceed 550 V (8 x 78.2 V = 625.6 V).

PV Math—Module Short-Circuit Current

In most silicon PV modules, the module short-circuit current does increase very slightly as temperature increases, but the increase is negligible at normal module operating temperatures and can normally be ignored.

Expected Lowest Temperature?

Normally, the lowest temperatures occur in the very early morning hours, just before sunrise on cold winter mornings. At this time, the PV modules are sometimes a few degrees colder than the air temperature due to night-sky radiation effects. The illumination at dawn and dusk are sufficient to produce high Voc, even when the sun is not shining directly on the PV array and has not produced any solar heating of the modules.

So how can you find the expected lowest temperature? A conservative approach would be to use weather data that show the record low temperatures and use this. The National Renewable Energy Laboratory maintains data that show the record lows for many locations in the United States (see Access). Local airports and weather stations may have historical data on low temperatures. Weather.com has some of this data available that can be accessed by zip codes (see Access).

Access

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Photovoltaic Power Systems and the 2005 National Electrical Code: Suggested Practices by John Wiles • www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/PVnecSugPract.html

PV Systems Inspector/Installer Checklist and previous *Code Corner* articles •www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/Codes-Stds.html

NREL Insolation Data • http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/sum2/

Weather Data • www.weather.com/weather/climatology/monthly/ Append zip code to the end of the URL.