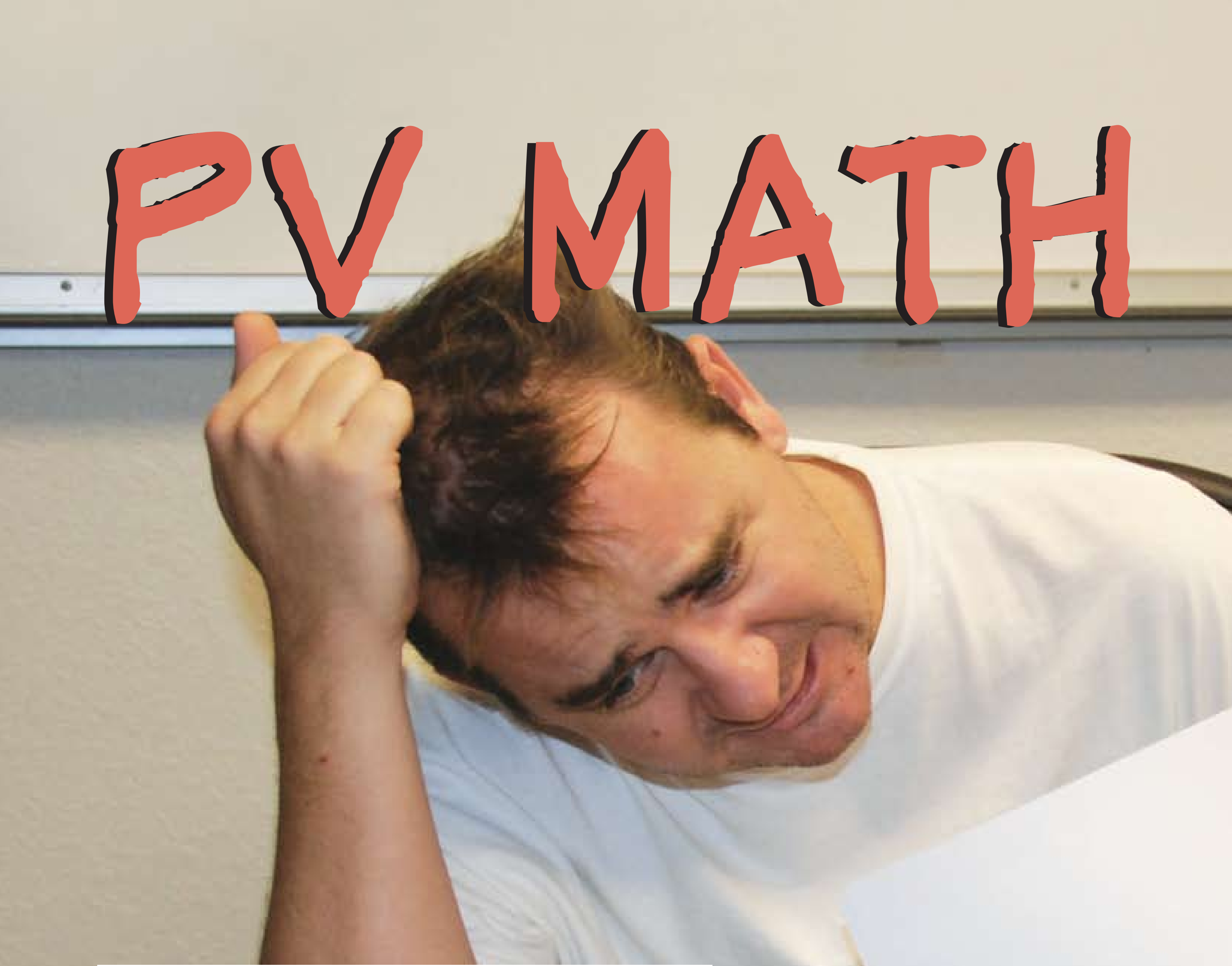
PV MATH

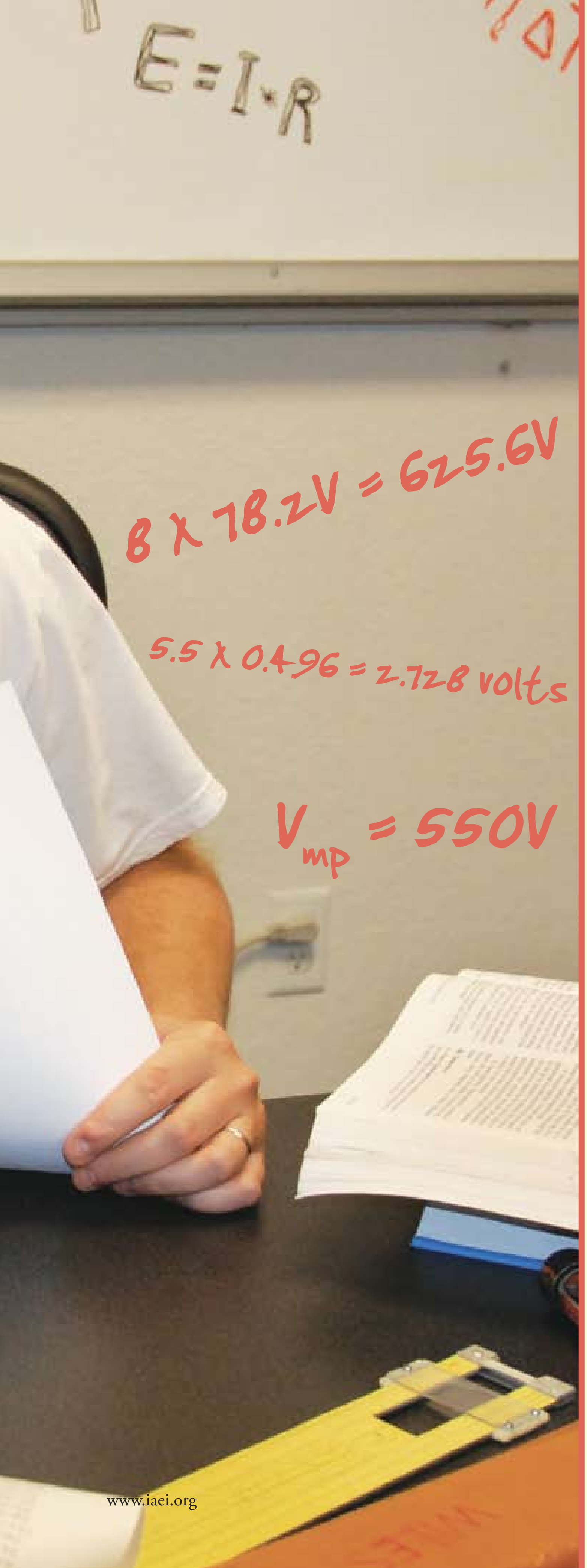


by John Wiles

As we look at the PV array in a PV system, we find that many installers and inspectors are confused by the new system voltage calculations that may be required by the *Code* specific to PV systems. *Code* fine print notes (FPN) also address voltage drop that may be applied to the dc wiring from the array to the inverter. This article will cover both of those subjects.

PV Math—Module Open-Circuit Voltage

A PV module or a string of series-connected modules has a rated open-circuit voltage (V_{oc}) that is measured (and labeled) at 25 degrees Celsius (C) [77 degrees Fahrenheit (F)]. This voltage increases from the rated voltage as the temperature drops below 25°C. It is necessary to calculate this voltage at the expected lowest temperature at the installation location to ensure that it is less than the maximum input voltage of the inverter *and* less than the voltage rating of any connected cables, switchgear, and overcurrent devices (usually 600 volts). Since parallel connections of strings do not affect the open-circuit voltage, the number of



strings connected in parallel is not involved with this calculation.

Section 690.7 in the *2008 NEC* requires that the open-circuit voltage (V_{oc}) of a PV array be determined at the lowest expected temperature at the installation location where module temperature coefficients are available. In previous editions of the *NEC*, Table 690.7 could be used to determine a multiplier that was applied to either the module or string (series connection of PV modules) rated V_{oc}. The table can also be used under the *2008 NEC* where module temperature coefficient data are not available.

The rated V_{oc} is measured at 25°C (77°F) and is printed on the back of the module and in the technical literature of the module. To use the table, all one has to do is to determine the lowest expected temperature, look up the factor from the table for that temperature (which ranges between 1.02 at 24°C to 1.25 at -40°C), and multiply the factor by the rated V_{oc}.

For example, a module has a V_{oc} of 35 volts and is going to be installed where the temperature dips to -17°C. The factor from Table 690.7 in the *2008 NEC* is 1.16 and the cold temperature V_{oc} for this module is 35 x 1.16 = 40.6 volts.

If 12 modules were going to be connected in series, the string V_{oc} in cold weather would be 12 x 40.6 = 487.2 volts.

We could also calculate the string voltage at rated conditions first and then apply the temperature factor. In this case, the 12 modules in series would have a string open-circuit voltage of 12 x 35 = 420 volts at 25 degrees C. Then we apply the 1.16 factor and get 1.16 x 420 = 487.2 volts; the same answer as before.

While the table is still valid and has been refined with 5°C increments, new modules may have different technologies than the silicon module technology used to develop the table.

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 thirty years. However, we now have modules with different internal types of PV cells, and the table may not apply very well to these newer modules. Section 690.7 in the *2008 NEC* requires that where the module manufacturer's temperature coefficients data are available they will be used. These temperature coefficients are found in the technical literature of nearly all modules and can also be obtained directly from the manufacturer. Unfortunately, different manufacturers present the temperature coefficients in two different forms.

Photo 1. Cold weather increases module open-circuit voltage.

Percentage Coefficients

One way of presenting these data is to specify them as a percentage change, and they are expressed as a percentage change in V_{oc} for a *change* in temperature measured in degrees C. Note that the temperature used is a *change* in temperature from the rated 25°C.

For example: The V_{oc} temperature coefficient is given as

-0.36% per degree C or -0.36% / °C.

The module has a V_{oc} of 45 volts at 25°C (77°F) and is going to be installed where the expected lowest temperature is -10°C (14°F). Because the temperature coefficient is given in degrees C, we must work in degrees C. The change in temperature is from 25°C to -10°C. This represents a change in temperature of 35 degrees. The minus sign in the coefficient can be ignored as long as we remember that the voltage *increases* as the temperature goes *down* and visa versa.

If we apply the coefficient, we can see that the percentage change in V_{oc} resulting from this temperature change is

0.36% / °C x 35°C = 12.6%.

This percentage change can now be applied to the rated V_{oc} of 45 volts. And, at -10°C, the V_{oc} will be 1.126 x 45 = 50.67 V.

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

Millivolt Coefficients

Other PV module manufacturers express the V_{oc} temperature coefficient as a millivolt coefficient. A millivolt is one, one-thousandth of a volt or 0.001V.

A typical module with an open-circuit voltage (at 25°C) of 65 volts might have a temperature coefficient expressed as

-240 mV per degree C or -240 mV/°C.

If we install it where the expected low temperature is -30°C (-22°F), then we have a 55°C degree change in the temperature from 25°C to -30°C. Again, we must work in degrees Celsius since that is the way the coefficient is presented.

Millivolts are converted to volts by dividing the millivolt number by 1000.

240 mV / 1000 mV/V = 0.24 volts

The module V_{oc} will increase 0.24 V/°C x 55 °C = 13.2 volts as the temperature changes from 25°C to -30°C.

The module V_{oc} will increase from 65 volts at 25°C to 65 + 13.2 = 78.2 volts at the -30°C temperature.

Let us suppose that the inverter maximum input voltage was listed as 550 volts. How many modules could be connected in series and not exceed this voltage? We take that maximum inverter voltage of 550 volts and divide it by the cold-weather open-circuit voltage for the module of 78.2 volts.

550 / 78.2 = 7.03 modules and the correct answer would be seven (7) modules.

7 x 78.2V = 547.4V

Eight modules could not be used because the open-circuit, cold-weather voltage would exceed 550 volts.

8 x 78.2V = 625.6V

Expected Lowest Temperature?

Where do we get the expected lowest temperature? Normally, this temperature occurs in the very early morning hours just before sunrise on cold winter mornings. The PV modules are, in many cases, 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 V_{oc}, even when the sun is not shining directly on the PV array and has not produced any solar heating of the modules. A conservative approach would get weather data that show the record low temperatures and use this as the expected low temperature. Other data show more moderate low temperatures associated with the data used to size heating systems. However, these data are not widely available. The National Renewable Energy Laboratory (NREL) maintains data on a web site that shows the record lows for many locations in the US.

http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/sum2/state.html

Local airports and weather stations may have historical data on low temperatures

Also, weather.com has some of these data on file accessed by zip codes

http://www.weather.com/weather/climatology/monthly/zip code

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 so small as to be negligible at normal module operating temperatures. It is normally ignored.

Fine Print Notes—Voltage Drop

Fine print notes are not part of the *Code*—at least until the AHJ reads them, and then they become part of his or her personal code.

In the common, utility-interactive PV system, the PV array may operate at a nominal 48 volts to voltages near 600 volts. With nominal, peak-power, and open-circuit voltages to deal with, the installer and inspector are sometimes in a quandary as to how to calculate the voltage drop from the PV array to the inverter.

The utility-interactive inverter will normally operate in a manner that keeps the array voltage near the peak-power voltage (also called the maximum power point). While this voltage can vary with temperature, and temperatures vary considerably, using the rated maximum power point voltage and current of the modules results the easiest method of calculating voltage drop.

A typical PV array may have a single string of ten modules in series connected through 200 feet of 10 AWG USE-2/RHW-2 conductors to the inverter. The maximum power point numbers for the module are:

V_{mp} = 55V I_{mp} = 5.5 amps, where the subscript mp means at maximum power.

For a single string of 10 modules, the string maximum power point numbers are:

V_{mp} = 550V I_{mp} = 5.5 amps.

Table 8 in Chapter 9 of the *NEC* gives conductor resistance per 1000 feet at 75°C.

For an uncoated, stranded 10 AWG conductor, the resistance is 1.24 ohms per 1000 feet.

The total conductor length (both ways) must be used in the calculation and this is 400 feet.

The resistance for 400 feet of a 10 AWG conductor is 400/1000 x 1.24 = 0.496 ohms.

The current at the maximum power point is 5.5 amps. Voltage drop is found by multiplying this current by the conductor resistance:

5.5 x 0.496 = 2.728 volts.

Expressed as a percentage, 2.278/550 x 100 = .496% or about 0.5% and that is much less than the FPN recommendation of three percent for most circuits. Of course, the losses in the PV dc disconnect were not counted, but they are typically less than one percent on these circuits.

For Additional Information

If this article has raised questions, do not hesitate to contact the author by phone or e-mail. E-mail: jwiles@nmsu.edu Phone: 575-646-6105

A color copy of the latest version (1.8) of the 150-page, *Photovoltaic Power Systems and the 2005 National Electrical Code: Suggested Practices*, published by Sandia National Laboratories and written by the author, may be downloaded from this web site: http://www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/Codes-Stds.html

The Southwest Technology Development Institute web site maintains a PV Systems Inspector/Installer Checklist and all copies of the previous "Perspectives on PV" articles for easy downloading. Copies of "Code Corner" written by the author and published in *Home Power Magazine* over the last 10 years are also available on this web site: http://www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/Codes-Stds.html

The author makes 6–8 hour presentations on "PV Systems and the *NEC*" to groups of 40 or more inspectors, electricians, electrical contractors, and PV professionals for a very nominal cost on an as-requested basis. A schedule of future presentations can be found on the IEE/SWTDI web site.

John Wiles works at the Institute for Energy and the Environment (IEE) (formerly the Southwest Technology Development Institute) at New Mexico State University. IEE has a contract with the US Department of Energy to provide engineering support to the PV industry and to provide that industry, electrical contractors, electricians, and electrical inspectors with a focal point for Code issues related to PV systems. He serves as the secretary of the PV Industry Forum that is formulating proposals for the 2011 NEC. He provides draft comments to NFPA for Article 690 in the NEC Handbook. As an old solar pioneer, he lived for 16 years in a stand-alone PV-power home in suburbia with his wife, two dogs, and a cat—permitted and inspected, of course. The PV system on his home is a 5 kW (dc) utility-interactive with a full-house battery back up.

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