More Module Wiring

John Wiles

Sponsored by the Photovoltaic Systems Assistance Center,
Sandia National Laboratories

In *HP81,* I presented an example of module wiring as a sizing exercise. Here is a second example of the calculations required to select and size the proper array conductors for a PV system.

This 2,000 watt, 48 volt PV array will be mounted on the roof of a residence. This system will be one of the utility-interactive designs that are so popular in California and elsewhere these days. But the PV array wiring would be similar in a stand-alone system.

Specifications

The system will have twenty 12 volt, 100 watt modules that will be connected in series strings of four modules each. There will be five strings of modules. The modules have ratings marked on the back as follows: open-circuit voltage (Voc) is 20 volts; short-circuit current (Isc) is 6.4 amps; the peak-power current is 5.8 amps; maximum system voltage is 1,000 volts; and the maximum series fuse is 15 amps.

The lowest temperature measured over the last thirty years at this location is -15°C (5°F). So from Table 690-7 in the *National Electrical Code (NEC),* we must use a multiplier of 1.17 on the open-circuit voltage to determine our DC system voltage. The DC system voltage is 93.6 volts (4 x 20 x 1.17 = 93.6). All wiring disconnects and overcurrent devices in the DC PV circuits must be rated for at least this voltage.

The inverter for this system has eight fused inputs. The short-circuit current will be 6.4 amps in each string of four modules. Using the factors required by *NEC* section 690-8, we must multiply this current by 1.56. The result is a design current of about 10 amps. This value must be applied to the ampacity of the module and source-circuit wiring, and to any overcurrent devices in the PV source circuits.

Overcurrent Protection

The module protective fuse can be as high as 15 amps. So we can use the inverter input fuses (sized at 10 amps) to protect not only the conductors in the system (when properly sized), but also to provide the necessary module reverse-current protection. This technique will require that we run five separate source circuits from the PV array to the inverter (one for each of the five strings of modules).

As an option, the five source circuits might be combined on the roof with a fused PV source circuit combiner box like the Trace Engineering (Xantrex) TCB-10. Then a single circuit can be run to the inverter. While this may be possible, depending on the inverter input circuits (or an input to a stand-alone charge controller), it would require additional calculations.

The highest measured temperature in this location over the last thirty years is 45°C (113°F). The PV array is mounted close to the roof. So we will assume that the module junction boxes and the back of the modules may operate at as high as 75°C (167°F) on hot summer days when there is little wind.

PV modules generally operate at temperatures from 30 to 45°C (86–113°F) above the ambient temperature. For temperature derating purposes, it is suggested that an operating temperature of 75°C (167°F) be used if the modules are mounted less than 6 inches (15 cm) from any structure that prevents cooling air from reaching the back of the modules. If the modules are mounted on open racks or at least 6 inches (15 cm) from a surface, an operating temperature of at least 65°C (149°F) is suggested.

Conductor Routing & Selection

We will use exposed single-conductor cables for the module interconnections. We want to continue with the same conductors in conduit through a roof penetration and the attic and inner walls of the house to the inverter.

With 75°C (167°F) module operating temperatures, we need a type USE-2/RHW-2 cable. This cable is sunlight resistant for use as the exposed module interconnections, and has a wet-rated, 90°C (186°F) insulation. The additional designation of RHW-2 indicates that it has a flame-retardant insulation, can be used in conduit, and is also wet-rated at 90°C.

Short lengths of this cable are connected between each of the four modules in a series string to make each of the five source circuits. Continuous lengths of conductors (five pairs) are run from each set of four modules into a weatherhead on the end of the conduit. They then go through the conduit to the inverter—about 100 feet (30 m) away.

The 30°C (86°F) ampacities for USE-2 conductors are presented in *NEC* Tables 310-16 (conduit runs) and 310-17 (free air). The basic ampacity requirement for each circuit is 10 amps. This number must be increased for both the exposed sections of the conductors (75°C module operation) and the conduit sections (45°C ambient temperature). For this type of conductor, the derating factors are 0.87 in conduit at 45°C, and 0.41 in free air at 75°C.

Since there will be ten current-carrying conductors in the conduit, an additional derating factor of 0.5 must be applied to the conductors in the conduit run. *NEC* Table 310-15(b)(2)(a) provides conduit fill derating factors for situations with more than three conductors in conduit. If we apply these numbers to the basic 10 amp requirement, we get 23 amps (10 ÷ 0.87 ÷ 0.5 = 23) for the conductors in conduit, and 24 amps (10 ÷ 0.41 = 24) for the conductors attached to the module and then in free air.

Since we are using only one size and type of conductor throughout, we must use the highest ampacity requirement, which is 24 amps. However, we must also check the ampacity in both areas. For this example, a #16 (1.3 mm^2) conductor seems to meet our ampacity requirements. *NEC* Table 310-17 indicates that it has a 30°C (86°F) ampacity of 24 amps. However, Table 310-16 indicates that a #16 conductor has an ampacity of 18 amps in conduit, which does not meet the 23 amp requirement. A #14 (2 mm^2) conductor has ampacities of 25 amps in conduit and 35 amps in free air, meeting our requirements.

Since USE-2 conductors are hard to get in sizes #18 to #12 (0.8–3 mm^2), let's see what a #10 (5 mm^2) conductor gives us. The ampacity in free air (Table 310-17) is 55 amps, but is limited to the use of a 30 amp fuse. The conduit ampacity (Table 310-16) is 40 amps, also limited by the requirement to use a 30 amp fuse. Calculations show that #14, #12, and #10 (2, 3, & 5 mm^2) conductors all meet our ampacity requirements. When using these ten #10 conductors, a 1-1/4 inch (trade size) rigid PVC schedule 40 conduit will be required. Other types of conduit might also be used.

Voltage Drop

Our conductor length totals 200 feet (61 m). Stranded #14 (2 mm^2) conductors have a resistance of 3.14 ohms per thousand feet (305 m). For a 200 foot length, the resistance will be 0.628 ohms (200 ÷ 1,000 x 3.14 = 0.628).

Using the peak-power current of 5.8 amps, the voltage drop is 3.64 volts. This represents a 7.6 percent voltage drop on a 48 volt system (3.64 ÷ 48 x 100 = 7.6), which is too high. The *NEC* suggestion is 3 to 5 percent voltage drop, but it is generally referring to 120/240 volt AC circuits.

#12 (3 mm^2) conductors, with a resistance of 1.98 ohms per 100 feet, have a voltage drop of 4.8 percent (200 ÷ 1,000 x 1.98 x 5.8 ÷ 48 x 100 = 4.8). With stranded #10 (5 mm^2) conductors (resistance of 1.24 ohms per 1,000 feet), the resistance for the 200 foot run is 0.248 ohms (1.24 x 200 ÷ 1,000 = 0.248). At 5.8 amps, the voltage drop is 1.44 volts (5.8 x 0.248 = 1.44), which is 3 percent of the nominal system voltage of 48 volts—an acceptable number.

Terminal Temperature Limitations

The fuse holders and most other overcurrent devices are limited to connections to wires with 75°C (167° F) maximum temperatures. We establish this condition by ensuring that the actual expected maximum circuit current of 8 amps (1.25 x 6.4 = 8) is less than the ampacity of a 75°C cable of the same size.

We assume that the inverter is operating at a temperature of 30°C (86°F), and that the ampacity of a #10 (5 mm^2), 75°C conductor is 55 amps (based on Table 310-17; the inside of enclosures are considered to be free air). This is much higher than our expected circuit current of 8 amps, so the cables and the terminals will be below 75°C where connected to the fuses.

If you think that this is a very conservative design when looking at that 8 amp to 75 amp ratio, consider the following. The bundle of ten conductors operating at full current of 8 amps each in the conduit at 45°C ambient temperatures will be pretty hot. And then remember that some of the conduit may also be heated by the sun to even higher temperatures.

Grounding

Based on the 10 amp fuse that we will be using, the modules can be grounded by using #14 (2 mm^2) bare or insulated conductors. These should be connected from each of the marked module grounding points on the module frames to the nearest module in the array in a daisy-chain fashion. Then, a single equipment-grounding conductor is routed in the conduit to the inverter. However, since we oversized the circuit conductors for voltage drop from a #14 to #10 (2 to 5 mm^2) conductors, this equipment-grounding conductor should also be increased to a #10 (5 mm^2) conductor.

Color Codes

This system will have the negative conductor grounded. It is difficult to get USE-2 conductors with the required white insulation. *NEC* section 200-6(a)(2) allows us to mark each end of the negative conductors from the modules to the inverters with white tape or other permanent white marking.

The equipment-grounding conductor, if insulated, should have green or green with yellow striped marking. No code provisions have been made for marking these smaller conductors with tape, so bare conductors would be the standard practice.

Metric Equivalents
The metric equivalent wire sizes that the editors have added to the standard American (AWG) wire sizes above should be used with caution. They are based on geometric calculations and may not represent actual, available metric wire sizes. The quality and type of insulation has an influence on the ampacity of any cable. So the locally available ampacity guides for each country should be used for selecting wire sizes, both AWG and metric. Some countries have more stringent standards for insulation quality than the U.S., but many countries have lower or no standards.

Summary
This 2 KW, 48 volt PV array can be connected with five source circuits, each using #10 (5 mm^2) USE-2/RHW conductors. The conductors are in free air at the modules, and are routed in 1-1/4 inch conduit to the inverter location. The negative conductor of each source circuit is marked white at each end. A bare #10 conductor is used for the equipment-grounding conductor. A 10 amp fuse is installed in the inverter input circuit for each source circuit. This provides overcurrent protection for the conductors, and reverse current protection for the modules.

Sandia National Laboratories PV Systems Symposium And PV/*NEC* Workshop
Sandia National Labs will be hosting a PV Systems Symposium July 18–20, 2001 in Albuquerque, New Mexico. System people from all over the country will be making presentations on what does and does not work with PV systems. All types of systems will be covered, including utility-interactive, stand-alone, and hybrid systems. Cost, performance, infrastructure, and other issues will be addressed. Advance registration is required.

In conjunction with this symposium, I will be making an eight-hour presentation on PV and the *NEC* on Tuesday, July 17, 2001 at the workshop location—the Sheraton Uptown Hotel. The cost will be US$35 for this eight-hour workshop. Advance registration for the workshop is required.

Registration information for both the symposium and the PV/*NEC* workshop may be obtained from Connie Brooks at Sandia Labs (see Access).

Revised Manual
Photovoltaic Power Systems and the National Electrical Code is a 117 page manual, written by the *Code Corner* column author. It is published by Sandia National Laboratories, and has been revised to the 1999 *NEC.* It is available in PDF form on our Web site: www.NMSU.Edu/~tdi/pvandnec.htm

Questions or Comments?
If you have questions about the *NEC* or the implementation of PV systems that follow 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.

Access
John C. Wiles, Southwest Technology Development Institute, New Mexico State University, Box 30,001/ MSC 3 SOLAR, Las Cruces, NM 88003 • 505-646-6105
Fax: 505-646-3841 • jwiles@nmsu.edu
www.nmsu.edu/~tdi

Sponsor: Sandia National Laboratories, Ward Bower, Department 6218, MS 0753, Albuquerque, NM 87185
505-844-5206 • Fax: 505-844-6541
wibower@sandia.gov • www.sandia.gov/pv

Connie Brooks, Sandia National Laboratories, PV Program, PO Box 5800, Albuquerque, NM 87185-0753
505-844-4383 • Fax: 505-844-6541
cjbrook@sandia.gov • www.sandia.gov/pv

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