Conductor Sizing & Overcurrent Device Ratings

by John Wiles

Conductor sizes and overcurrent device ratings are critical to the safe, long-term operation of any electrical system, but are particularly important in PV systems where the outdoor environment can be extreme and the PV modules will be putting out energy for 40 years or more.

PV installers, plan reviewers and inspectors need to know how to do conductor sizing and overcurrent device ratings properly to get safe, reliable, and cost-effective PV systems. In general, the complete procedure we will cover can be used for any type of electrical circuit, except possibly HVAC and other motor protection circuits. A part of this procedure is in Section 690.8(B) of the 2011 *National Electrical Code*.

Historically, most residential and light-commercial electrical wiring has involved indoor wiring at room temperatures—30°C (86°F) or less. The ampacity tables in Section 310.15 and Table 310.16 of the *NEC* were developed with those conditions in mind. Additionally, the commonly used molded-case circuit breaker has a terminal temperature limit of 75°C (167°F) and is rated for use with conductors with 75°C insulation. These circuit breakers have a rated maximum operating temperature of 40°C (104°F), which is greater than typical indoor room temperatures. If the circuit breaker is connected with conductors rated at 75°C and operates in a temperature less than 30°C, then electricians typically don't perform temperature corrections for ampacity on the conductors nor do they have to consider terminal temperature limits. They just look up an ampacity value for the conductor being used out of the 75°C column in *NEC* Table 310.16 and that's it as far as temperatures are concerned.

However, direct current (DC) PV conductors normally operate in an environment that requires conductors with 90°C insulation, and appropriate temperature and conduit fill corrections must be applied, along with addressing the operating temperature limitations of overcurrent devices.

Throughout the code, circuits are sized based on 125% of the continuous load plus the noncontinuous load—see *NEC* Sections 210.19(A)(1) and 215.2(A)(1). This requirement establishes a situation where conductors and overcurrent devices are not subjected to continuous current more than 80% of rating (note: 1 ÷ 1.25 = 0.80). The term "continuous current" is used because PV modules produce current and are not loads. The PV ampacity calculations assume that all PV currents are continuous (more than three hours in duration) and are adjusted for worst-case conditions This *NEC* requirement has evolved over 60 years to prevent nuisance tripping of overcurrent devices.

Sizing Conductors

In the *Code*, there are several requirements that must be met in sizing conductors.

First is the definition of ampacity found in Article 100. Ampacity is "the current in amperes that a conductor can carry continuously under the conditions of use without exceeding its temperature rating."

Next is the 125% requirement in 210.19(A)(1) and 215.2(A)(1): "The minimum feeder-circuit conductor size, *before the application of any adjustment or correction factor*, shall have an allowable ampacity not less than the noncontinuous load plus 125 percent of the continuous load." The emphasized words indicate that there's no requirement to apply the 125% *and* the conditions of use at the same time.

Section 110.14(C) requires that the temperature of the conductor in actual operation not exceed the temperature rating of terminals on the connected equipment, primarily to prevent nuisance tripping of overcurrent devices.

An added requirement for listed equipment such as overcurrent devices is that they not be used in a manner that deviates from the listing or labeling on the product (110.3(B)). Most PV source-circuit combiners operating outdoors in the sunlight will have internal temperatures that exceed the 40°C rated operating temperatures of commonly used fuses and circuit breakers.

The following method of determining ampacity and conductor size meets three of the requirements above. (Terminal temperature limitations are not addressed in this article.) It also determines the rating of the overcurrent device where such a device is required.

Step 1

Determine the continuous current in the circuit. For code calculations, all DC and AC PV currents are considered continuous and are based on worst-case scenario output or are based on safety factors applied to rated output.

A. PV DC Circuits. In the DC PV source and DC PV output circuits, the continuous currents are defined as 1.25 times the rated short-circuit current Isc. This 125% factor accounts for normal and expected values of sunlight intensity (irradiance) that exceed the standard rating value of 1,000 W per m^2. If a module or module string had an Isc of 7.5 A, the continuous current would be 1.25 × 7.5 = 9.4 A. 690.8(A)(1).

If three strings of modules (module Isc = 8.1 A) were connected in parallel through a fused combiner, the PV output circuit of the combiner would have an Isc of 3 × 8.1 = 24.3 A. The continuous current is this circuit would be 1.25 × 24.3 = 30.4 A. 690.8(A)(2)

B. AC Inverter Output Circuits. In the AC output circuits of a grid-tied or stand-alone inverter, the continuous current is taken at the full power rated output of the inverter. It is not measured at the actual operating current of the inverter (which may be a small fraction of the rated current if a small PV array is connected to a large inverter). The rated output current is usually specified in the manual, but may be calculated by dividing the rated power by the nominal AC voltage. For stand-alone inverters, which can provide some degree of surge current, it is the rated power that can be delivered continuously for three hours or more (690.8(A)(3)). Three hours is the time period defined in Article 100 for "continuous load."

In some cases, the inverter specifications will give a rated current that is higher than the rated power divided by the nominal voltage. In that situation, the higher current should be used.

For a grid-tied inverter operating at a nominal voltage of 240 V and a rated power of 2,500 W, the continuous current would be:

2,500 W ÷ 240 V = 10.4 A

An example stand-alone inverter operates at 120 V and can surge to 3,500 W for 60 minutes. However, it can only deliver 3,000 W continuously for three hours or more. The rated AC output current would be:

3,000 W ÷ 120 V = 25 A

C. Battery Currents. The design current between a battery and an inverter in either a stand-alone system or a battery-back up grid-tied system must be based on the rated continuous output power of the inverter at the lowest input battery voltage that can provide that output power (690.8(A)(4)). Normally the output current from the battery in the inverting mode is greater than the current to the battery in the charging mode. This current in the inverting mode is usually marked on the inverter or found in the specifications.

The current in inverting mode can be calculated by taking the inverter rated AC output power, dividing it by the lowest battery voltage that can sustain that power, and also by dividing by the inverter DC-to-AC conversion efficiency at that battery voltage and power level. For example:

A 4,000 W inverter can operate at that power with a 44 V battery input and under these conditions has a DC-to-AC conversion efficiency of 85%. The DC continuous current will be:

4,000 W ÷ 44 V ÷ 0.85 = 107 A

On single-phase inverters, the DC input current is rarely smooth and may have 120 Hz ripple current with a larger RMS (root mean square) value than the calculated continuous current. The inverter technical specifications should list the greatest continuous current and that number should be used when given.

Step 2

Calculate the rating of the overcurrent device, where required. Since PV modules are current-limited, overcurrent devices are frequently not needed for one or two paralleled strings of PV modules. In systems with three or more paralleled strings of modules, overcurrent devices are usually required in each string to protect not only the conductors, but also the module internal connections.

A. Rating Determined from Continuous Currents. The overcurrent device rating is determined by taking the continuous current for any of the circuits listed in Step 1 and increasing it by 125%. This helps ensure that the overcurrent device is operating under 80% of its ampacity rating (even under the high irradiance conditions [1.25 x Isc] that we calculated in Step 1A), and thus meets *NEC* requirements. Calculated non-standard overcurrent device values should be rounded up to the next standard rating in most cases to ensure that under continuous currents, the overcurrent device will operate at no more than 80% of rating.

In a very few rare cases, an overcurrent device installed in an enclosure or an assembly may be listed as an assembly for operation at 100% of rating. In these cases, the overcurrent device rating is the same as the continuous current (listed in Step 1) and no 125% factor is used. (I know of no such PV system devices at this time.)

A circuit has a continuous current of 15 amps. The overcurrent device would have a rating of 18.75 A (1.25 × 15). However, there are no standard overcurrent devices rated at 18.75 A, so a 20 A overcurrent device needs to be used.

B. Operating Temperature Affects Rating. Overcurrent devices are listed for a maximum operating temperature of 40°C (104°F). PV combiner boxes operating in outdoor environments may experience ambient temperatures as high as 50°C. When the combiner enclosures are exposed to sunlight, the internal temperatures may reach or exceed 55 to 60°C. Any time the operating temperature of the overcurrent device exceeds 40°C, it may be subject to nuisance trips at current values lower than its rating. In this situation, the manufacturer must be consulted to determine an appropriate derating. At high operating temperatures, an overcurrent device with a higher rating will activate at the desired current. In PV source circuits, the marked rating of the revised overcurrent device (under cold-weather conditions) must not exceed the ampacity of the conductors or the maximum series fuse value marked on the back of the module.

Step 3

Select a conductor size. The conductor selected for any circuit must meet both the ampacity requirement and the 125% requirement. Size the cable for the larger of A or B below.

A. Ampacity Requirement. The conductor, after corrections for conditions of use, must have an ampacity equal to or greater than the continuous current found in Step 1. Article 100, Definition of Ampacity.

B. 125% Requirement. The cable must have an ampacity of 125% of the continuous current established in Step 1. 215.2(A)(1).

Example 1: Three current-carrying conductors are in a conduit in an outdoor location in the shade where the temperature is 40°C The continuous current in all three conductors is 50 A. A copper, 90°C insulated cable is specified.

Temperature correction factor = 0.91, and because there are only three current-carrying conductors in the conduit, the conduit fill correction factor = 1.0

A. Ampacity Rule. To handle the 40°C temperature, the required ampacity of the conductor will be higher than 50 A. The required ampacity is 50 ÷ 0.91 ÷ 1.0 = 54.9 amps and this would require an 8 AWG cable from the 90°C cables in *NEC* Table 310.16.

B. 125% Rule 1.25 × 50 = 62.5 amps and this would indicate a 6 AWG cable from the 90°C cables in *NEC* Table 310.16.

The 6 AWG cable is the larger of the two and is required.

Example 2: There are six current-carrying conductors in the conduit and the temperature has increased to 50°C. The continuous current is still 50 A. Temperature correction factor = 0.82; conduit fill factor = 0.8 (Table 310.15(B)(2)(a).

A. Ampacity Rule. 50 ÷ 0.82 ÷ 0.80 = 76.2 A and a 4 AWG cable is needed (Table 310.16).

B. 125% Rule. 1.25 × 50 = 62.5 A calling for a 6 AWG cable (Table 310.16).

The 4 AWG cable is the larger of the two and must be used.

These are just the beginning steps to conductor sizing. There are additional factors that must be considered before arriving at the final conductor size.

Access

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Southwest Technology Development Institute • www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/Codes-Stds.html • PV systems inspector/installer checklist, previous “Perspectives on PV” and *Code Corner* articles, and *Photovoltaic Power Systems & the 2005 National Electrical Code: Suggested Practices*, by John Wiles