QA Quality Assurance

Code-Compliant Conductor Sizing

Conductor sizing is a critical step in PV system design. You must be sure you satisfy the *NEC* requirements both for the conductor's ability to carry the current and the performance criteria for the power delivered. To properly size conductors for the *NEC,* you must determine the correct current to use, the conditions of use and the required overcurrent protection—and then, finally, you must select a conductor.

As a designer, you must account for all the conditions that the conductors will be exposed to. The temperature they will operate in, the number of conductors in the conduit, the length of the conduit and the terminals the conductors are attached to each play a role. Proper selection requires following a sequential and methodical process when sizing your conductors. Although this process is common for sizing all conductors, here I specifically address conductor sizing as it pertains to satisfying the *NEC* for the dc source and output circuits of PV systems. Throughout this article, the *NEC* references are from the 2011 version, unless otherwise noted. For those familiar with the *Code,* the relocation of tables in Article 310 is the most notable change from earlier versions.

Maximum Current Calculations

The first step—determining the correct current value—is probably the most unique item to PV dc conductors. For most conventional electrical calculations, this is typically simple or at least well understood. PV modules have multiple ratings, are composed of organic materials, and they operate with a fluctuating power source. These factors seem to confuse people and may make calculations for PV seem more complicated. Determining the correct current value is actually relatively simple once you break it down. Section 690.8 in the 2008 and 2011 *NEC* outlines the requirements for proper conductor sizing.

Section 690.8 defines how to calculate the maximum circuit current. In 2008, an FPN was added that states "Where 690.8(A)(1) and B(1) are both applied, the resulting multiplication factor is 156%." Historically, many PV designers have used the "1.56 rule" to size all dc conductors, in all conditions. However, you must understand what the individual components of the 1.56 rule are so you know when both 690.8(A)(1) and B(1) apply and when they do not.

Sections 690.8(A)(1) and (2) in the *NEC* define the maximum current for PV circuits. I_{MAX} is calculated as "the sum of parallel module rated short-circuit currents multiplied by 125%." The multiplier is needed because solar irradiance fluctuates throughout the day and from region to region. Modules' Isc ratings are calculated in laboratory-controlled standard test conditions (STC) of 1000W/m^2. Natural conditions are different from STC and give rise to a different current than the rated value. Multiplying Isc by 1.25 defines what current to use for PV circuits. This is the maximum current expected from the PV source and output circuits under extreme conditions of short circuit and high irradiance.

Overcurrent Protection and Terminal Ratings

Now that you have determined I_{MAX} per 690.8 (A)(1) and (2), you need to determine how to size the conductors based on the terminals used in the junction boxes and overcurrent protection devices (OCPDs) where required. Section 690.8(B) states that PV circuits shall be considered a continuous load, and this requires a second 1.25 multiplier. The *NEC* rules that apply to other continuous loads also apply to PV circuits. The language in 690.8(B) changed in 2011, clarifying the process and requirements. The changes do not affect the methodology you need to use when evaluating PV circuits.

Section 690.8(B)(1)(a) of the 2011 *NEC* states that OCPDs shall be sized to carry not less than 125% of the maximum current as calculated in 690.8(A). To determine the minimum OCPD, multiply the I_{MAX} for a given conductor run by 1.25. The resulting continuous current (I_{CONT}) is the minimum OCPD required to protect the conductor in the circuit and the minimum rating of all terminals used to make the wiring connections.

Terminal requirements. *NEC* Section 690.8(B)(1)(b) requires that you evaluate the terminal temperature limits independent of the conductor ratings. It is common to use conductors that are rated at 90°C, yet the terminals they are connected to are rated for only 75°C. This requires that you evaluate the conductor ampacity values twice: once at the terminals where the conductor is considered 75°C and again for the length of the run where the conductors' 90°C properties are valid. *NEC* Section 310.15(B)(16) has multiple columns of allowable ampacity, arranged according to the conductor's insulation temperature rating. Note the new *Code* reference for the ampacity table, previously Table 310.16. To find the minimum conductor size, look at the thermal ratings of the devices that the conductor is terminated on, regardless of the insulation of your selected conductor. The conductor should have a greater ampacity than the termination rating.

Use the column that corresponds with the thermal rating of the terminals. For terminals used in conjunction with PV circuits, the most common rating is 75°C. To satisfy 690.8(B)(1)(b), select a conductor that has an ampacity rating in the proper termination thermal rating column CONTINUED ON PAGE 16

that is greater than the calculated I_{CONT} or OCPD if required.

For example, consider a PV output circuit that has a rated Isc of 50 A and is connected to a terminal that is rated at 75°C:

$$I_{MAX} = 1.25 \times 50 \text{ A} = 62.5 \text{ A}$$
$$I_{CONT} = 1.25 \times 62.5 \text{ A} = 78.1 \text{ A}$$

According to Table 310.15(B)(16), under the 75°C column, 4 AWG is the smallest conductor that has an ampacity greater than 78.1A.

OCPD Requirements. Section 690.8(B)(1)(c) in the 2011 *NEC* requires that the OCPD ratings are corrected per the manufacturer's instructions when the system is operating at temperatures greater than 40°C. This is a site- and material-specific consideration. Given that fuses are the most typical type of OCPD used in these locations and that fuse ampacity changes along with conductor ampacities, this will generally not be an issue. As long as a fuse properly protects the conductor in normal operating temperatures, it will continue to protect the conductor in elevated temperatures. However, in extreme elevated temperatures, the fuse could nuisance trip if not corrected for temperature.

OCPD ratings are defined in Section 240.4(B), (C) and (D). Where the OCPD is rated at 800 A or less, 240.4(B) allows you to use the next-higher standard OCPD above the ampacity of the conductors being protected. Be careful about applying this allowance to size the conductor below the OCPD rating, especially when dealing with small currents and sizing conductors from modules to a string-combining device. This is because Section 690.9(C), "Photovoltaic Source Circuits," states that standard OCPD values used for source circuits "shall be in one ampere size increments, starting at one ampere up to and including 15 amperes." This ability to use the next standard size requires that you evaluate the conductors used in the source circuits and verify that they have the correct ampacity for their conditions of use. In addition, be sure not to exceed the modules' maximum series fuse rating.

Sizing the Conductors

The final step necessary to meet Section 690.8 requirements is to select a conductor that can handle the current and will be protected by the OCPD under 690.8(B)(2). The 2011 *NEC* offers two different methodologies to properly select a conductor. You need to do both calculations and then choose the larger conductor. Under 690.8(B)(2)(a), the first test is to find the conductor ampacity that is greater than 156% of Isc. There are no conditions of use applied here, only the two 125% factors. The second test under 690.8(B)(2)(b) is to apply conditions of use to the I_{MAX} found in 690.8(A). It is worth noting that the second method uses the value for I_{MAX} found after multiplying Isc by 1.25 only once.

Adding conditions of use. *Conditions of use* are defined by the temperature the conductors are exposed to at the site and the number of conductors that are run in close proximity to each other according to the correction factor subsections of Section 310.15. Table 310.15(B)(3)(a) provides adjustment factors for conductors run in conduit or bundled together in continuous lengths greater than 24 inches. Table 310.15(B)(3)(c) provides temperature adjustment values for circular raceways run along rooftops.

To determine conditions of use, first determine your ambient temperature. This sounds simple, but it has caused many a debate in many a jurisdiction. The 2008 *NEC* added an FPN at the end of Section 310.15(B)(2) that states, "One source for average ambient temperatures in various locations is the ASHRAE Handbook." This indicates that an average high should be used. The Solar ABCs website (solarabcs.org) provides a readily accessible source for ASHRAE data. You can search for a location based on zip code, and the site returns ASHRAE data from local weather stations. The data include two high temperature values—the 0.4% and 2% average values in °C. Many in the solar industry use the 2% high in the ASHRAE tables as the standard for design temperatures. You should determine if the jurisdiction you are designing for has published engineering standards that include design temperatures. The same design temperatures used for other engineering disciplines should be consistently applied to PV applications. If the jurisdiction does not have published design temperature information, ASHRAE tables are the safest and most accurate source for this information.

Once you have determined your starting design temperature, you have to determine the other conditions of use. Is your conductor in free air or in conduit? Is it exposed to sunlight? How far from the roof is it installed? How many current-carrying conductors are in the same conduit? Conductors are often exposed to many different conditions of use in a single run. Technically, you should do calculations for each unique condition; however, the most important thing is to do the calculation for the worst case. The worst case is the maximum correction factor caused by coincident conditions that result in the lowest ampacity of the conductor.

Exceptions can often come into play. Section 310.15(B)(3)(a)(2) states, "Adjustment factors shall not apply to conductors in raceways having a length not exceeding 600 mm (24 in.)." The Exception to Section 310.15(A)(2) states, "Where two (or more) different ampacities apply to adjacent portions of a circuit, the higher ampacity shall be permitted to be used beyond the point of transition, a distance equal to 3.0 m (10 ft) or 10% of the circuit length figured at the higher ampacity, whichever is less."

Worst-case conditions. The following example illustrates the method for determining the worst-case condition for the conductor. Consider the PV source-circuit conductors from a module to a string combiner. A conductor leaves a module in free air secured 3.5–12 inches off the roof. It passes through a 12-inch conductor tray located 0–0.5 inch off the roof, CONTINUED ON PAGE 20

Sample Calculations

Example calculation #1 PV source circuits from array to combiner where the worst-case scenario is 20 current-carrying conductors run in conduit supported 0.5–3.5 inches off the roof. Weather data is from the Denver International Airport as reported at solarabcs.org/permitting/map/index.html.

Isc	= 8 A
I_{MAX} = 8 A x 1.25	= 10 A
I_{CONT} = 10 A x 1.25	= 12.5 A
Ambient temperature	= 34°C
Table 310.15(B)(3)(c), 3.5–12 inches off roof	= 17°C temperature increase
Effective temperature = 34° + 17°	= 51°C
Table 310.15(B)(2)(a), 90°C temp. column at 51–55°C	= 0.76 correction factor
Table 310.15(B)(3)(a), 10–20 conductors	= 0.50 correction factor

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690.8(B)(1) calculation:

Minimum OCPD required = I_{CONT}	= 12.5 A
Next standard size OCPD	= 13 A (If <15 A, then increase in 1 A increments)
Table 310.15(B)(16), 75°C conductor ampacity	= 25 A
25 A > 12.5 A (I_{CONT})	12 AWG satisfies 690.8(B)(1)(b)
25 A > 13 A (OCPD)	12 AWG satisfies 690.8(B)(1)(d)

690.8(B)(2)(a) calculation:

Minimum conductor ampacity = I_{CONT}	= 12.5 A
Table 310.15(B)(16), 90°C conductor ampacity	= 30 A
30 A > 12.5 A (I_{CONT})	12 AWG satisfies 690.8(B)(2)(a)

690.8(B)(2)(b) calculation:

Table 310.15(B)(16), 90°C conductor ampacity	= 30 A
Conditions of use ampacity = 30 A x .076 x 0.5	= 11.4 A
11.4 A > 10 A (I_{MAX})	12 AWG satisfies 690.8(B)(2)(b)

690.8(B)(2)(c) calculation:

Next standard OCPD for conductor with conditions of use applied = 12 A

12 A < 13 A	12 AWG does not satisfy 690.8(B)(2)(c)

Look at the next size conductor to verify that it passes the final checks, since the smaller conductor passed up to that point.

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690.8(B)(2)(c) calculation:

Table 310.15(B)(16), 90°C conductor ampacity	= 40 A
Conditions of use ampacity = 40 A x .076 x 0.5	= 15.2 A
Next standard OCPD = 16 A > 13 A	10 AWG satisfies 690.8(B)(2)(c)

with four other conductors, and then is bundled with 19 other conductors in free air, supported at 0.5–3.5 inches off the roof. Finally, for physical protection, it passes through 36 inches of EMT conduit that is secured at 3.5–12 inches off the roof before entering a combiner box.

You do not need to consider each individual worst-case condition, but you should consider the coincident worst-case conditions When the conductor passes through the conductor tray at 0–0.5 inch off the roof, Section 310.15(B)(3)(a)(2) applies because the conduit was less than 24 inches. The bundled conductors are subject to Section 310.15(B)(3)(a). Because the conductors are in free air, you do not apply the 0.5–3.5 inches sunlight-exposed temperature increase to the conductor nor consider the conductor *in conduit.* The worst case in this example is a 20-conductor conduit fill and 3.5–12 inches sunlight-exposed temperature increase. Use ampacity from Table 310.15(B)(16) for conductors installed in conduit.

Final Considerations

Once you have defined the conditions of use, refer to CONTINUED ON PAGE 22

Sample Calculations (continued)

Example calculation #2 Two PV output circuits from a combiner box to inverter. All terminals have 75°C ratings. Weather data is from Colorado Springs as reported at solarabcs.org/permitting/map/index.html.

Isc	= 50 A
I_{MAX} = 50 A x 1.25	= 62.5 A
I_{CONT} = 62.5 A x 1.25	= 78.1 A
Ambient temperature	= 32°C
Table 310.15(B)(3)(c), 3.5–12 inches off roof	= 17°C temperature increase
Effective temperature = 32° + 17°	= 49°C
Table 310.15(B)(2)(a), 90°C temp. column at 46–50°C	= 0.82 correction factor
Table 310.15(B)(3)(a), 4–6 conductors	= 0.80 correction factor

690.8(B)(1) calculation:

Minimum OCPD required = I_{CONT}	= 78.1 A
Next standard size (240.6(A))	= 80 A
Table 310.15(B)(16), 4 AWG, 75°C conductor ampacity	= 85 A
85 A > 78.1 A (I_{CONT})	4 AWG satisfies 690.8(B)(1)(b)
85 A > 80 A (OCPD)	4 AWG satisfies 690.8(B)(1)(d)

690.8(B)(2)(a) calculation:

Minimum conductor ampacity = I_{CONT}	= 78.1 A
Table 310.15(B)(16), 90°C conductor ampacity	= 95 A
95 A > 78.15 (I_{CONT})	4 AWG satisfies 690.8(B)(2)(a)

690.8(B)(2)(b) calculation:

Table 310.15(B)(16), 90°C conductor ampacity	= 95 A
Conditions of use ampacity = 95 A x 0.82 x 0.8	= 62.3 A
62.3 A < 62.5 A (I_{MAX})	4 AWG does not satisfy 690.8(B)(2)(b)

Look at the next wire size, 3 AWG.

690.8(B)(2)(b) calculation:

Table 310.15(B)(16), 90°C conductor ampacity	= 115 A
Conditions of use ampacity = 115 A x 0.82 x 0.8	= 75.4 A
75.4 A > 62.5 A (I_{MAX})	3 AWG satisfies 690.8(B)(2)(b)

690.8(B)(2)(c) calculation:

Next standard OCPD for conductor with conditions of use applied = 80 A

75.4 A < 80 A	3 AWG satisfies 690.8(B)(2)(c) under 240.4(B) ●

the *NEC* tables for adjustment values. You now have to consider the conductor's insulation rating. Instead of looking at the thermal rating of the termination device, you must consider the thermal rating of the conductor in Tables 310.15(B)(16) when the conductors are in raceways and 310.15(B)(17) when they are in free air. You use both the ampacity value and the thermal correction factor from the column that corresponds with the chosen conductor type. The thermal correction factors were relocated to Section 310.15(B)(2)(a) in 2011. For most PV dc applications exposed to extreme conditions of use, it is best to select a 90°C conductor. Currently, most installers use USE-2 for free air and THWN-2 in conduit.

To choose a properly sized conductor, compare the conditions-of-use corrected conductor ampacity to the I_{MAX} current and chosen OCPD. You do not compare the corrected conductor to the continuous current (Isc x 1.56) but rather only I_{MAX} (Isc x 1.25). This is an important distinction. You also need to verify that the conductors' ampacity, without conditions-of-use adjustments, exceeds the continuous-current value to avoid conductors that are larger than necessary. The sample calculations (pp. 18 & 20) walk through this process step-by-step.

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Conductor ampacity ratings All the conditions of use need to be considered when determining the final ampacity values for the source-circuit conductors. These conductors are bundled in close proximity to the roof, so Tables 310.15(B)(2)(a) and 310.15(B)(3)(a) both apply. However, the conductors are not in circular raceways, so Table 310.15(B)(3)(c) does not apply.