Code Calculations

for an Off-Grid PV System

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Sponsored by the Photovoltaic Systems Assistance Center, Sandia National Laboratories

Judy LaPointe's home is on its way to becoming a finished, off-grid home.

The walls are up and the PV system is being assembled for the off-grid home described in *Code Corner* in *HP94.* This article presents most of the calculations required to design the photovoltaic (PV) system within the requirements of the *National Electrical Code (NEC).*

These calculations may not be all that are needed in the total design of every PV system. Local electrical codes may impose other requirements, and building codes may require calculations involving the mechanical installation. The calculations shown here are typical for a stand-alone PV system. But PV design is very system specific, and the calculations will be different for other PV systems.

The PV system detailed in this article will provide electricity for a residence located about 0.5 miles (0.8 km) from the utility grid in rural New Mexico. The PV array consists of twenty, 165 watt PV modules—3,300 watts DC at standard test conditions (STC) of 1,000 watts per square meter of irradiance and a module temperature of 25°C (77°F). See *Code Corner* in *HP94* for a description of the loads and system. References to the *NEC* are presented in brackets.

PV Source Circuit Calculations

The PV source circuits consist of the wiring from the modules to the combiner box.

Overcurrent Protection—Step 1. Overcurrent protection is required for each ungrounded conductor. The first overcurrent device is a fuse installed in series with each string of two modules. The fuse size for each of the ten PV source circuits was determined by meeting several requirements. The first requirement is to allow PV output to flow unimpeded to the charge controller. By multiplying the module short circuit current (Isc) of 5.46 amps by two adjustment factors of 1.25, we get a design current of 8.52 amps (5.46 x 1.25 x 1.25 = 8.52).

One of the 1.25 adjustment factors is due to expected and normal module current outputs above the rated value around solar noon. The other 1.25 factor is related to the *NEC* requirement to keep overcurrent devices and conductors from operating above 80 percent of rating (1 ÷ 1.25 = 0.80).

Although a 9 amp fuse is the next highest standard value above the design current of 8.52 amps and is available by special order, a 10 amp fuse is more commonly available and will meet all requirements for conductor ampacity and overcurrent protection discussed below. The above calculation determines the basic minimum fuse rating and conductor ampacity required by the *NEC* [690.8-9].

Module Conductors. The Sharp 165 modules we chose have #14 (2 mm^2) pigtail leads and no junction box. The ampacity of a #14 USE-2 conductor in free air is 35 amps at 30°C (86°F) [310.17]. The ampacity temperature correction factor for an estimated maximum 75°C (167°F) module operating temperature is 0.41 [310.17]. See the table on page 97.

The ampacity of conductors and temperature correction factors can be found in the *NEC* [310.15 and Tables 310.16 (conduit installations), 310.17 (free air installations)]. The correction factor is multiplied by the conductor ampacity at 30°C (86°F) to determine the corrected ampacity at the elevated operating temperature. The temperature-corrected ampacity of the #14 conductor at 75°C is 14.35 amps. (0.41 x 35 = 14.35).

We will splice #10 (5 mm^2) USE-2 conductors to the #14 pigtails. Their ampacity in free air is 55 amps at 30°C [310.17]. Some of these conductors will touch the backs of the PV modules and are therefore exposed to 75°C module operating temperatures. The temperature correction factor for an estimated maximum 75°C module operating temperature is 0.41. The temperature-corrected ampacity of the #10 conductor at 75°C is 22.55 amps (0.41 x 55 = 22.55).

Overcurrent Protection—Step 2. Ten, 10 amp fuses protect the module conductors from excess currents from the battery or from parallel strings of modules. The fuse rating is equal to the maximum module series fuse of 10 amps (marked on the back of the module), which protects the internal connections of the module. It cannot be more than this marked value. It is less than the cable ampacity of 14 amps (#14) or 23 amps (#10), and protects both conductor sizes used in the module wiring in this system.

The fuse rating is above the required rating of 8.52 amps needed to carry the current from each module. These fuses are installed in the DC combiner boxes that combine the outputs of the ten modules in each subarray to the two circuits running to the charge controllers. RV Power Products MPPT PV charge controllers are being used with a 48 volt input and a 24 volt output.

Voltage Drop Calculations. Although voltage drop calculations are not an *NEC* requirement, the length of your wire runs should be a factor that you consider in system design. In our design, each PV module has a 50 inch (127 cm) length of #14 (2 mm^2) conductor connected to a length of #10 (5 mm^2) conductor to reach the combiner box. The maximum length (for both the positive and negative conductors) in any of the source circuits totals about 20 feet (6 m).

Just meeting code ampacity requirements may not always yield an efficient system.

Wire resistance is specified in ohms per 1,000 feet (305 m) of conductor length. [Ch. 9, Table 8]. To determine the total resistance for a wire run, the wire resistance in ohms per 1,000 feet is multiplied by the number of feet and then divided by 1,000. If we considered (for simplicity) that the entire run of cable is #14 (with a resistance of 3.14 ohms per 1,000 ft.), the resistance would be 0.0628 ohms (20 x 3.14 ÷ 1,000 = 0.0628).

Using the formula, voltage = amperage x resistance (V = I x R), we can determine the voltage drop. At a peak power current of 4.77 amps (Imp), the conductors attached to each set of two modules have a voltage drop of 0.3 volts (4.77 x 0.0628 = 0.299). To figure out the percentage of voltage drop as a result of resistance, you divide the voltage drop by the nominal system voltage and multiply by 100 percent. On a 48 volt system, this is a 0.625 percent loss on the longest circuit (0.3 ÷ 48 x 100 = 0.625).

With a portion of the circuit consisting of a #10 (5 mm^2) conductor, and on circuits where the circuit length is less than 20 feet (6 m), the voltage drop and power loss (which is expressed as the same percentage because P = V x I) are even less. It is not practical to use a larger size cable at this point because the combiner box accepts no conductors larger than a #10 conductor.

PV Output Circuit Calculations

The PV output circuits include all the wiring from the combiner box to the charge controller.

Conductor Sizing. The next step in the system design is to calculate the size of the conductors between the PV combiner boxes and the DC power center. Pairs of modules are series-connected in sets of two for a 48 volt nominal output. Five strings (sets of two) of modules are paralleled in each combiner box.

The continuous output current from each of the combiner boxes (for conductor ampacity calculations) is determined by multiplying the number of paralleled strings of modules (five) by the short-circuit current (5.46 amps) of each string, and then by a current adjustment factor of 1.25 to yield an expected current of 34.125 amps (5 x 5.46 x 1.25 = 34.125) [UL Standard 1703, 690.9]. An additional 1.25 factor is then applied to get a current of 42.65 amps, and this is the current on which the conductor size and the overcurrent device must be based (34.125 x 1.25 = 42.65) [690.9].

Ambient temperatures for this system are 45°C (113°F) around the exposed portions of the metal conduits running from the combiner box to the DC power center. But the conductor ampacity tables [310.16] are based on 30°C (86°F) ambient temperatures, so we must use temperature correction factors to select a properly sized conductor.

For 90°C (194°F) insulated conductors (RHW-2 or THWN-2) in conduit, the temperature correction factor is 0.87 at an ambient temperature of 45°C (113°F) [310.16]. To determine the required ampacity for the conductor at 30°C (86°F), divide the 42.65 amps by the temperature correction factor to get 49 amps (42.65 ÷ 0.87 = 49). Use this number to find the proper wire size on the 30°C ampacity tables in the *NEC* [310.16].

This ampacity value of 49 amps dictates that a #8 (8 mm^2) conductor be used. We can verify our selection by working the calculation backward. A #8 conductor in conduit has a 30°C ampacity of 55 amps [310.16]. At 45°C, the ampacity is corrected to 47.9 amps (55 x 0.87 = 47.9), which exceeds the requirement of 42.65 amps.

Voltage Drop Calculations. (Not an *NEC* requirement) From the combiner boxes located across the driveway from the house to the DC power center, the total conductor distance (positive and negative conductors) is 300 feet (90 m). The resistance of a #8 (8 mm^2) conductor is 0.778 ohms per 1,000 feet and for the 300 foot length, the resistance is 0.233 ohms (300 x 0.778 ÷ 1,000 = 0.233) [Ch. 9, Table 8].

At the maximum power point for the PV array, the five strings of modules with a current of 4.77 amps each generate 23.85 amps when connected in parallel in the combiner box (5 x 4.77 = 23.85). The voltage drop in each of the PV output circuits is calculated by multiplying the current by the resistance, and is 5.56 volts (23.85 x 0.233 = 5.56). In a 48 volt system, this represents an 11.6 percent voltage drop, which also represents an 11.6 percent power loss (5.56 ÷ 48 x 100 = 11.58).

Just meeting code ampacity requirements may not always yield an efficient system. A design goal (not a code requirement) was to keep the voltage drop and power loss below 2 percent. This required increasing the size of the PV output circuit conductors.

A 2 percent voltage drop can be translated into a drop of 0.96 volts on a 48 volt system (48 x 0.02 = 0.96). The allowable maximum conductor resistance can be calculated by dividing the maximum voltage drop (0.96 volts) by the current (23.85 amps). This yields 0.04 ohms for the entire 300 feet of conductor (0.96 ÷ 23.85 = 0.04). The resistance per 1,000 feet would need to be 0.133 ohms (0.04 ÷ 300 x 1,000 = 0.133) or less. This indicates that a #1/0 (5 mm^2) conductor should be used, which has a resistance of 0.122 ohms per 1,000 feet [Ch. 9, Table 8].

Using this #1/0 (53 mm^2) conductor with a resistance of 0.122 ohms per 1,000 feet yields a voltage drop of 1.82 percent when carrying 23.85 amps (0.122 x 300 ÷ 1,000 x 23.85 ÷ 48 x 100 = 1.82). A larger conductor could be used to reduce the voltage drop and power loss even further. Using a #2/0 (67 mm^2) conductor, for example, would reduce the voltage drop to 1.44 percent (0.0967 x 300 ÷ 1,000 x 23.85 ÷ 48 x 100 = 1.44). This is not a very significant decrease in the voltage drop or power loss. Also, #2/0 is larger than the terminals on some of the equipment will accept.

The one-time expense of the larger wire should be weighed against the loss in energy over the life of the system. It usually pays to install the largest conductor that can be easily connected to the devices at each end. Stand-alone PV energy has been estimated to cost as much as US$2 per kilowatt-hour over the 20 to 30 year life of a system! Why go to the trouble of eliminating hidden loads and increasing the efficiency of all other loads, or choosing a more efficient inverter and charge controller when you don't address a constant (forever) loss of PV energy (and power) due to smaller than maximum (although code compliant) conductor sizes.

Overcurrent Protection. The DC circuit breakers used in the power center for PV output circuit overcurrent protection are rated at 100 percent duty in their listed enclosures and do not require an *NEC* 80 percent derating [690.8(B)(1)EX]. These circuit breakers are mounted in the power center and protect the PV output conductors from overcurrent from possible backfed current from the batteries or the inverter. These circuit breakers must be rated to carry the continuous short-circuit current of 34 amps, determined previously when making calculations for conductor sizing (5 x 5.46 x 1.25 = 34.125). The second 1.25 factor is not used in this calculation because the circuit breakers do not have to be derated to 80 percent of rating.

Circuit breakers rated as low as 35 amps could have been used. We are using circuit breakers rated at 75 amps. They were ordered when the PV modules were going to be connected

Laying out the energy conversion equipment.

Copper Conductor Temperature Correction Factors

Conductor		Ambient Temperature; °C & (°F)									
Temp. Rating	Types	21–25 (70–77)	26–30 (78–86)	31–35 (87–95)	36–40 (96–104)	41–45 (105–113)	46–50 (114–122)	51–55 (123–131)	56–60 (132–140)	61–70 (141–158)	71–80 (159–176)
75°C (167°F)	RHW THHW THW THWN XHHW	1.05	1.00	0.94	0.88	0.82	0.75	0.67	0.58	0.33	None
90°C (194°F)	RHH RHW-2 THHN THHW THW-2 THWN-2 USE-2 XHH XHHW XHHW-2	1.04	1.00	0.96	0.91	0.87	0.82	0.76	0.71	0.58	0.41

For ambient temperatures other than 30°C (86°F), multiply the 30°C ampacities [310.16, 310.17] by the appropriate factor.
Source: *NEC* 2002

for 24 volts rather than the present 48 volts. These breakers protect the #1/0 (53 mm^2) conductors, which have a temperature-corrected ampacity of 148 amps—170 amps at 30°C times 0.87 correction factor for 45°C operating temperature (170 x 0.87 = 148).

The two, 75 amp circuit breakers are connected to a single, 175 amp circuit breaker mounted in the same enclosure as the battery disconnect. This 175 amp circuit breaker serves as the main PV disconnect, and is connected to the conductors going to the battery. Conductors sized at #1/0 are used to connect this breaker to the main battery circuits and to the 75 amp breakers.

Equipment-Grounding Conductor Size. For this ground-mounted PV system, *NEC* 690.45 requires that the PV array equipment-grounding conductor be able to carry a current equal to the continuous current from the modules (each set of ten), which is calculated by multiplying the short circuit current (Isc) of 27.3 amps (5 x 5.46 = 27.3) by an *NEC* factor of 1.25, which in this case yields 34.1 amps (27.3 x 1.25 = 34.1). This requires a #10 (5 mm^2) equipment-grounding conductor.

NEC 250.122(B) requires that this conductor be increased in size if the circuit conductors are increased in size for voltage drop. Circuit conductors were increased from #8 (8.4 mm^2) to #1/0 (53.5 mm^2), a ratio of 6.4 to 1. Applying this ratio to the #10 (5 mm^2) conductor indicates that the equipment-grounding conductor should be increased to about a #2 (33 mm^2) conductor. A #2 black, insulated conductor is marked on both ends with green tape and routed in each conduit containing the #1/0 circuit conductors.

Conduit Fill. "Conduit fill" refers to the number of wires of a particular size and type allowed in a particular size of conduit. There are no short-cuts or easy explanations about conduit fill. The code and all electricians handle it with numerous tables (more than 50) that are a function of the exact conductor type, exact conductor size, and the conduit material, type, and size. The *NEC* tables must be used.

We chose a 2.5 inch (64 mm) conduit to use from the PV array location to the DC power center, and it carries the four, #1/0 (53 mm^2) circuit conductors and the #2 (33 mm^2) equipment-grounding conductor. There is additional room in this conduit for using larger conductors if additional modules are ever added to the array. The conduits are run underground and beneath the concrete slab of the house from the array to the DC disconnect. The house is built on a pad made of sand so the trenching was easy.

A T will be installed near the combiner boxes at the PV array. The single, #2 (33 mm^2) equipment-grounding conductor will be spliced into two (one to each combiner box). Separate 1.5 inch (38 mm) conduits will run from the T to each combiner box.

Battery to Inverter Circuit

Conductors. The inverter has a 24 VDC nominal input and a rated AC output of 4,000 watts at 120 VAC. At the lowest battery voltage of 22 volts, the inverter efficiency is 85 percent. A maximum continuous DC input current for the inverter is calculated using the AC power output divided by the inverter DC-to-AC efficiency to get a DC power input. This DC power input is then divided by the lowest input battery voltage to get a continuous DC input current of 214 amps (4,000 ÷ 0.85 ÷ 22 = 214). An additional factor of 1.25 is used to allow for the 80 percent conductor derating required by the *NEC*. The resulting ampacity requirement is 267 amps (1.25 x 214 = 267) for the conductors between the inverter and the batteries [690.8(A)(4)].

A 90°C (194°F), 300 kcmil (152 mm^2) conductor has an ampacity of 291 amps when used in conduit and corrected for an operating temperature of 40°C (104°F) (320 x 0.91 = 291). We chose to use two, #2/0 (67 mm^2) conductors connected in parallel (four in conduit). Each of these #2/0 conductors has an ampacity of 195 amps when used in conduit at 30°C. Using these two conductors instead of the one above required that a conduit fill correction factor of 0.8 and a temperature correction factor of 0.91 be used to calculate their combined ampacity of 284 amps (2 x 195 x 0.8 x 0.91 = 284).

Conductors #1/0 (53 mm^2) and larger may be connected in parallel to increase the ampacity if they are exactly the same length and connected at each end in exactly the same manner to the same point. When large conductors are required, paralleling smaller conductors to achieve the required ampacity is common practice. Besides, the Heinemann GJ 250 circuit breaker that we used will accept no conductor larger than 250 kcmil (127 mm^2). Nearly all electricians start paralleling conductors above #4/0 (107 mm^2) because the ampacity does not go up as fast as the conductor size increases.

Terminal Temperature. Most overcurrent devices have upper limits on the temperature at which their terminals are allowed to operate. If these temperatures are exceeded, the device may be subject to nuisance trips and premature failures.

We must estimate the actual temperature of the 90°C insulated conductor when carrying actual currents to ensure that the conductor temperature is not higher than the terminal to which it is connected. This estimation is made by taking the same size conductor (2 x #2/0 in this case) and finding the temperature derated ampacity when these conductors are insulated with an insulation having the same temperature rating as the terminal (in this case 75°C).

We can look up the 30°C ampacity of the paralleled #2/0 conductors in the 75°C insulation column in Table 310-16, apply the new (75°C insulation/45°C ambient) temperature correction factor and the conduit fill factor (0.8) to get the ampacity of the cable. If the actual currents in the cable are lower than this ampacity, then we can be assured that the cable will operate below 75°C.

The actual maximum continuous current of 214 amps is less than the conduit fill and temperature-corrected ampacity of a pair of 75°C (167°F) insulated #2/0 (67 mm^2) conductors (2 x 175 x 0.8 x 0.88 = 246), so the terminals on the batteries and circuit breakers always operate below their temperature rating of 75°C.

Battery Disconnect. The battery disconnect is a 250 amp circuit breaker rated for 100 percent duty in its listed enclosure. This breaker serves as overcurrent protection for the battery cables and as a disconnect for the batteries. This circuit breaker can carry the continuous current of 214 amps and also protects the paralleled #2/0 (67 mm^2) conductors between the disconnect and the inverter. A 2 inch (51 mm) conduit is used between the inverter and the battery disconnect and between the disconnect and the first battery enclosure.

Battery String Circuits. The four, 6 volt batteries in each string are connected in series using 1/8 by 1 inch (3 x 25 mm) copper bus bars in free air that have an equivalent area of #2/0 conductors (ampacity is greater than 300 amps). The four strings of batteries (four batteries per string) are connected in parallel using high current terminal blocks with #2/0 conductors running from the common terminal block (one positive, one negative) to the ends of each battery string. The ampacity of each of these conductors at 30°C (86°F) is 265 amps in free air, which is significantly more than the 54 amps (one-fourth of the 214 amps continuous current) that they may be expected to carry.

This oversizing allows for battery aging, where one of the four battery strings may have to carry higher current than the other three strings. In fact, with an ampacity of 265 amps, the conductors in a single string of batteries could carry the entire 214 amps maximum expected continuous current.

DC Circuit Equipment-Grounding Conductors. The battery enclosures are nonconductive, so no equipment-grounding conductors are required between the battery enclosures and the battery disconnect. The battery disconnect is in a metal enclosure and is connected to the inverter with metal conduit, providing the equipment-grounding conductor. A #6 (13 mm^2) bare equipment-grounding conductor is also used between the inverter and the disconnect to provide additional insurance of good bonding.

A #6 bare conductor is used as an equipment-grounding conductor between the generator and the enclosure containing the 175 amp battery starting circuit breaker. This enclosure is also bonded to the main battery/inverter disconnect with a #6 bare copper conductor [Table 250.122].

The pump circuit uses a #8 (8 mm^2) equipment-grounding conductor—oversized from the #14 (2 mm^2) minimum requirement by *NEC* 250.122. The DC lighting circuit uses a #14 equipment-grounding conductor.

AC Circuits

Generator to Inverter. The rated continuous AC output current of the generator is 54.2 amps at 120 volts (6,500 watts) up to an elevation of 3,000 feet (915 m). At an estimated elevation of 4,500 feet (1,370 m), the output current is reduced to about 51 amps because of lower air pressure. The generator manual gives the correction factor of 0.9475 (54.2 x 0.9475 = 51).

Increasing the output current of 51 amps by a factor of 1.25 to meet code requirements yields a required cable ampacity of 64 amps (1.25 x 51 = 63.75). A #4 (21 mm^2), 90°C (194°F) conductor in conduit at 40°C (104°F) has a temperature-corrected ampacity of 86 amps (95 x 0.9 = 85.5).

Checking Terminal Temperatures. The actual generator current of 51 amps is less than the temperature-corrected ampacity of a #4, 75°C insulated conductor, which is calculated, using the *NEC* tables, to be 75 amps (85 x 0.88 = 75). So the circuit breakers protecting these conductors operate with terminal temperatures of less than their rating of 75°C.

A 70 amp circuit breaker is used at the generator to serve both as overcurrent protection for this circuit and as a disconnect located outside at the generator. The 70 amp overcurrent protection dictates a #8 (8 mm^2) equipment-grounding conductor for this circuit [250.122].

A 1 inch conduit is used between the generator and the inverter bypass switch to carry the two, #4 (21 mm^2) conductors and the #8 equipment-grounding conductor [Ch. 9, Table C-10].

Inverter Output. The continuous output of the inverter in the inverting mode is about 33 amps. That is calculated by dividing the rated inverter power of 4,000 watts by the AC output voltage of 120 volts (4,000 ÷ 120 = 33.3). In the battery charging mode, the inverter may draw up to 51 amps from the generator and send it to the house AC load center. The *NEC* 1.25 factor increases the needed conductor ampacity to 64 amps (51 x 1.25 = 63.75). A #4 (21 mm^2) conductor in conduit at 40°C (104°F) has a temperature-corrected ampacity of 86 amps (95 x 0.91 = 86).

A second 70 amp circuit breaker (part of the inverter bypass switch) is mounted near the inverter in the AC output circuit of the inverter and provides overcurrent protection and a disconnect for the AC circuit to the house AC load center. Once again, the 70 amp overcurrent protection requires the use of a #8 (8 mm^2) equipment-grounding conductor [250.122].

Calculation Process

This calculation process is lengthy, but it is necessary to achieve a safe, code-compliant, reliable, and durable system. 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, e-mail, or write. See the SWTDI Web site for technical notes and articles on installing code-compliant PV systems and frequently asked questions (and answers—of course).

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