Flex is Out and the Dodo Diode Isn't Dead

John Wiles

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The news is not good, but please don't shoot the messenger. First, an electrical inspector has pointed out that the very popular flexible non-metallic conduit should not be used with PV modules. Second, although some system designers have said that the blocking diode is as dead as the extinct Dodo bird, there may be good reasons for using diodes or fuses in all systems.

Flexible Conduit

Liquidtight flexible nonmetallic conduit as described in Section B of Article 351 of the National Electrical Code (NEC) is often used for containing the wiring from PV modules to nearby junction boxes. This flexible, light-weight, gray plastic conduit is widely available in building supply stores and electrical supply houses in both precut and bulk lengths. The conduit cuts easily with a knife and the termination fittings are easy to install.

Unfortunately, this type of conduit is listed by Underwriters Laboratories (UL) for use at 70 or 80°C when dry and only 60°C when wet. NEC Section 351-23 (b) (2) states that this conduit may not be used where any combination of ambient temperatures and conductor temperatures are in excess of that for which the conduit is approved.

Conduit attached to PV modules is in an exposed location and wet-rated conductors must be used in all conduit that is exposed-see Definitions (location) in the NEC and NEC Handbook. Most PV modules are listed for use with 90°C conductors because junction-box and back-of-module temperatures can exceed 70°C. For these reasons, the conductors used in the installation of PV modules must have a 90°C insulation rating when wet. Typical cables are THWN-2, RHW-2, and XHHW-2 all having a 90°C insulation rating.

With 90°C cables, high ambient temperatures (70°C+), and possible wet conditions, the NEC says that the liquidtight flexible nonmetallic conduit marked 70°C dry/60°C wet cannot be used. UL is considering revisions to UL Standard 1703 that might require that either the listed PV module or the instructions for the listed module state that the use of this conduit is unacceptable. The flexible nonmetallic conduit can deform at high temperatures and reduce the internal area (needed to maintain the ampacity of the conductor), or the deformation and water can cause the fitting on the end of the conduit to come loose from the conduit.

Alternatives that can be used for PV module connections include liquidtight flexible metal conduit, ridged nonmetallic conduit (PVC), and several of the metal conduits. In addition, where conduit is not needed, outdoor-rated, exposed (not in conduit) single-conductor cables may be used. While these alternatives are, in some cases, more expensive or more difficult to use, they will ensure that the cables are adequately protected and that the protection will not fail due to high temperatures or wet conditions.

The Dodo Diode and The Series Fuse

Each PV module listed to UL Standard 1703 by a recognized testing laboratory is marked with the maximum current value of a series fuse intended to protect the module from overcurrents that may be forced through the module under fault conditions. The NEC requires that all instructions and labeling provided with listed modules be followed. This fuse requirement is in addition to other NEC system requirements to provide proper overcurrent protection for all conductors.

As PV system designs have matured over the last ten years, there has been a divergence of the design and installation practices between high-voltage (over 50-volts) and low-voltage systems. High-voltage systems, usually utility-interactive, have always employed blocking diodes and overcurrent protection for each string of series-connected modules. This NEC-required overcurrent device usually has been sized to provide overcurrent protection for the conductors in the series string and has been generally near the value of the required series fuse (required by UL Standard 1703) used to protect the PV module.

In low-voltage systems, system designers have been very concerned with power losses and voltage drops in these mostly stand-alone, battery-charging systems. Blocking diodes went the way of the dodo bird as designers found that the daytime losses through the diode exceeded the very low losses associated with

night-time reverse current flow through the modules when the diode was removed. Many of these systems, but not all, have charge controllers without blocking diodes that disconnect the battery at night. There are many systems that do not employ charge controllers at all. Other charge controllers respond only to battery voltage and do not prevent reverse current flow from the batteries into the modules. Although overcurrent protection is usually provided for the conductors in the system, the rating of these overcurrent devices may be many times the value needed for the PV module protective fuse. Typical conductors used for module and array wiring have an ampacity several times that required by the individual module or module strings, and the overcurrent device is rated at these higher values to protect the conductors from backfeed currents from the batteries. Thus, in common practice, when a module fuse or blocking diode is not used, the module has insufficient overcurrent protection. On typical 12 and 24-volt systems, as much as 1000 watts of PV modules may be connected to a single source circuit without blocking diodes or module overcurrent protection.

Simulations

Simulations were run by David King at Sandia National Laboratories. The simulated 36-cell PV modules were equipped with bypass diodes around every 18 cells, but no blocking diode or series fuse. Two modules were connected in series to charge a simulated 24-volt battery. Various fault conditions were simulated.

First, a ground fault was simulated in the wiring between the PV modules. The battery voltage forced a reverse current of 7.5A through the first module, dissipating 198W in the module. The result was dynamic where the module heated up, its resistance to current flow decreased, the reverse current increased, and power dissipation increased until thermal equilibrium or an open circuit occurred. At 60°C module temperature, the simulated reverse current was 10.8A (285W). If a single string of 18 cells remained in the circuit, as might happen if a ground fault occurred at a bypass diode termination in the module junction box, over 50A of reverse current passed through the cells and 1350W were dissipated. A ground fault internal to the module (cell interconnect to frame or other grounded surface) was simulated leaving a single cell in the circuit. This case would be catastrophic with hundreds of amps of reverse current flowing through the single cell. In each of these cases, the simulated fault current from the battery would have been high enough to cause damage to the PV module. These simulated failure modes were verified with tests on PV modules and PV cells.

Test Results

A typical 40-watt, 33-cell, glass/Tedlar, 12-volt PV module was tested in a manner that might duplicate the conditions created by a ground fault in the series interconnecting cable between two such modules in a 24-volt PV system. This conceptual PV system had a number of parallel module strings and/or a battery bank capable of back feeding the array. A PV-charged battery bank at 26.5 volts was connected to the test module-positive-to-positive and negative-to-negative. Initial reverse current flow was 18.5A (490W). The module was shaded. Over the next 45 minutes, the cell temperatures went from 28°C to well over 200°C as the current increased to 39A (1034W). Bubbling of the encapsulant and some smoke were noted around the cells backed by the junction boxes (less heat radiation to the rear of the module in these areas). The Tedlar backing delaminated in a non-uniform manner from the rear of the module in areas where the cell temperatures were the highest. Forty-six minutes into the test, the PV module developed an open circuit, probably due to solder bond failures on the cells in front of the junction boxes. Although no flames were evident, the Tedlar was significantly discolored and the module was damaged beyond repair.

To evaluate a more severe situation, a similar test was conducted on a series string of nine silicon PV cells where the negative connection of the laminated string was connected to battery ground simulating a ground fault that could occur in an aluminum-backed module or a thin-film module laminated to a steel roofing panel. In this situation, the battery voltage (26.5V) was applied across the cell string. The reverse currents of more than 100 amps quickly caused the string of cells to develop an open circuit as the internal solder bonds melted. Tests on strings of 18 cells in series also resulted in open-circuited modules.

In no case was fire evident, but module temperatures in these tests were over 200°C (392°F) which could possibility start fires in dried leaves, grass, or even bird nests behind modules.

Solutions

Wiring the PV array to the requirements of the NEC with the correct size cable and the proper overcurrent protection for that cable will help to reduce the magnitude of the problem. Such wiring will limit the magnitude of potential backfeed current from parallel strings of modules or from the battery. Even with NEC-compliant wiring and overcurrent protection, the backfeed currents described above are sufficient to damage PV modules. Adherence to the markings on listed for a series fuse for each module or string of modules is necessary to provide full protection.

Fuses, while meeting all NEC and UL requirements, can present problems. Numerous fuses (one per module in 12-volt systems) installed in 12, 24, and 48-volt systems may pose significant operational and maintenance

(O&M) costs to the PV system. A few out-of-sight-out-of-mind, failed fuses installed in PV module junction boxes may never be replaced until the system fails entirely.

Although blocking diodes are not tested or listed as overcurrent devices, they do, in fact, prevent reverse currents from flowing. While diodes can fail in a short-circuited manner, they may prove to be more reliable than fuses in this application. Diodes, if considered by a modified UL Standard 1703 and the NEC as a required integral part of the PV module, could be the solution to this problem. Diode losses in low-voltage, battery-charging systems would have to be addressed. A modification to UL-1703 could require that blocking diodes be installed in each PV junction box on 12-volt systems and in one junction box per module string on higher voltage systems. Equivalent protection provided by fuses or other means could also be allowed.

It is suggested that blocking diodes or series fuses be installed on all systems. In a 12-volt system, each module needs a blocking diode or fuse. On 24 and higher voltage systems, each series string of modules needs a diode or fuse. The diode should have a current rating at least 1.56 times the short-circuit current rating of the module or string of modules. Electronic parts suppliers can supply silicon power diodes at low cost. At least a 400-volt diode should be used on a low-voltage PV system to provide some degree of surge protection. For example, Digi-Key Corporation (800-344-4539) has 6-amp, 400-volt diodes available at about $6.50 for 10 diodes (part # GI754CT-ND). The diode or fuse should be installed in series with the positive output of the module or string of modules. The band on the diode should point toward the positive battery terminal. The diode can usually be installed in the module junction box using the spare terminal (if any) provided.

DC rated, UL-listed fuses such as the Littelfuse KLK-D are available that are rated at 600 volts and various current levels. They are about $6-7 each and require a fuse holder. They are probably too large to mount in a module junction box. They do not, however, have the voltage drop and power loss associated with the blocking diode. Type ABC fuses from Bussmann may be a little cheaper and also have a DC rating. Fuses can be ordered from the larger electronic supply houses like Digi Key, Newark, and Allied. The ampere rating of the fuse should match the fuse size marked on the back of listed modules. If the modules are not listed and have no marking suggesting the proper fuse size, then the fuse size should have an ampere rating of about 1.56 times the module short-circuit current.

Your Failed Modules

It is suspected that ground faults described above may be more common than previously realized. These faults may have caused modules to fail for no apparent reason. The Southwest Technology Development Institute and Sandia National Laboratories are interested in examining failed modules that may have failed for the reasons described below. Anyone having modules that have failed for unknown reasons should contact me at the address below. Please be prepared to provide a description of the system where the modules were installed and the type of module including all information from the back of the modules and the stamped production date code. If the modules are types that are of interest, we may be able to provide a limited number of new modules at no cost in exchange for the failed modules.

Conclusions

It is evident from the simulations and actual tests that PV systems without protective module fuses or blocking diodes on each module or string of modules can be subject to extensive damage in ground-fault situations. Systems that have the capability to generate reverse currents in excess of the values indicated by the required protective fuse on a PV module can cause damage to the PV modules and may cause fires. PV systems that are ungrounded or systems that have insufficient sources of current would not be subject to this problem. The installation of fuses and/or blocking diodes in each module (12-volt system) or string of modules (24-volt and higher systems) appears to be the only solution to this serious problem.

Questions or Comments?

If you have questions about the NEC or the implementation of PV systems following the requirements of the NEC, feel free to call, fax, email, or write me at the location below. 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-AC04-94AL8500. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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Questions Questions

John Wiles

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Sandia National Laboratories

Every week, I get calls from around the country from electrical inspectors, electricians, PV dealers and installers, PV manufacturers, and PV users. These calls cover a wide range of subjects related to the installation of PV systems and how they are to comply with the requirements of the National Electrical Code® (NEC®). Here are some of the more common questions and the best answers that I have.

Where can I find large, flexible cables for inverter and battery connections?

Automobile battery cables and welding cables do not meet NEC requirements and, while readily available, are not suitable for inverter-to-power center and power center-to-battery connections. What is needed is a flexible cable that is UL-Listed and is marked as a building-type of cable such as USE, THW, RHW, XHHW, etc.

For the individual installing a single PV system, many of the PV Dealers and Distributors are stocking the appropriate cables. For the dealer who installs a lot of systems, the major cable distributors like Anixter can get the proper cable. Cobra Wire and Cable also makes an appropriate cable and will accept orders of at least $250.00 (see access).

What can I use for conduit between modules?

In the last Code Corner, I pointed out that non-metallic flexible conduit did not have the proper temperature range needed for connections to modules where a 90°C wet rating was required. The non-metallic flexible conduit is rated for only 60°C wet.

Unfortunately, the metallic flexible liquid-tight conduit that I suggested using in the last Code Corner may have this same limitation, but I have not been able to complete the research in this area. For now, it appears that we are limited to rigid electrical PVC conduit. It can be bent when heat is applied with a heat gun so it is possible to connect adjacent modules even though there is frame structure between them. Of course, metal conduit can be used if you are a professional and have that experience.

There are some types of metal covered cables that could be used.

Where conduit is not required, the single-conductor USE-2 cables are permitted by the NEC as is tray cable and other wiring methods.

Where can I get Ground-Fault Protection Equipment?

Section 690-5 of the NEC requires that PV systems installed on the roofs of dwellings have a device that detects ground faults in the PV array, interrupts the ground fault current, and disables the array. This requirement has been in the NEC since 1987 and electrical inspectors are beginning to require it.

Such devices are available as an integral part of listed, utility-interactive inverters from Trace Engineering and Omnion Power Engineering. Both Trace Engineering and Alternative Power Technologies (APT) are working on ground-fault units that will be listed and that can be used with stand-alone PV systems (see access).

Where can I get a copy of the National Electrical Code?

Most electrical supply houses and some major bookstores have the NEC for sale. It is also available directly from the National Fire Protection Association (see access).

What is a current-limiting fuse?

By definition, a current-limiting fuse limits the short-circuit current flowing in a faulted circuit to a level that is significantly below the short-circuit current that would be flowing in the same circuit without the fuse under the same fault conditions.

Don't all fuses limit current by blowing?

In a given circuit without a fault, the current is at zero or some nominal low value (e.g. 20 amps). When a fault occurs in a circuit without a current-limiting fuse, the current increases very rapidly from the initial value to a maximum determined by the system voltage, the available current from the source, and the circuit resistance. The fault current may increase to 10,000 amps or more in a battery circuit. The current-limiting fuse senses the rapidly increasing fault current and opens the circuit so rapidly that the current never reaches the maximum, but is limited at the 2,000-4,000 amp level by the opening fuse. Fuses that are not

designed as current-limiting fuses may let the current reach the maximum value before opening the circuit.

While the current-limiting fuse limits the fault current, it may also be designed so that it has a time delay that allows it to carry normal surge currents from motor starting actions without opening. These currents may be 4-10 times the rating of the fuse (e.g. 600 amps for a 100 amp fuse).

What is the relationship between the current rating and the interrupt rating of a fuse?
The current rating (e.g. 100 amps) is the current that the fuse can carry continuously. The fuse is required to open for currents above 110% of rating, but there is a time dependent function involved that is different for each fuse. The interrupt rating (e.g. 20,000 amps) is the maximum short-circuit that the fuse can interrupt under fault conditions. Both the current rating and the interrupt rating are given with an associated voltage rating (e.g. 125 volts direct current (DC)).

While the current rating of a fuse may be the same for ac and DC use, the interrupt ratings and the voltage ratings for ac and DC circuits may be considerably different. For example, a 100-amp fuse may have a 300-volt , 200,000-amp interrupt rating for use in ac circuits. The DC rating for the same fuse may be 125 volts and 20,000 amps - both of which are significantly lower than the ac ratings.

Is a current-limiting fuse necessary in all systems?
If the PV system does not have a battery or other source of high short-circuit currents, then a current-limiting fuse is not necessary. Non-current-limiting fuses or circuit breakers may be necessary, however, for proper conductor protection.

If the overcurrent device, either a fuse or a circuit breaker, has sufficient interrupt rating for the circuit, then a current-limiting fuse is not required. For example, the Heinemann circuit breakers used in Trace and APT products have an interrupt rating of 25,000 amps at 65 Volts DC and this is in excess of the available fault current in most battery systems.

However, if Square D QO breakers are used, they have an interrupt rating of only 5,000 amps at 48 volts dc and require the use of a current-limiting fuse between the circuit breaker and the battery. The current-limiting fuse limits the current under fault conditions to 3,000-4,000 amps which is within the interrupt capability of the circuit breaker.

Are there current-limiting circuit breakers?
I have not yet seen a DC-rated, UL-Listed circuit breaker that meets the definition of current limiting. Some circuit breakers are advertised as current limiting, but they are either rated only for ac or are rated by European Standards that are not the same as the US UL Standards.

Why don't you use more diagrams and pictures in Code Corner?
I am only partially computer literate and am just exploring the capabilities of Word 6, Excel 5, Mac Draft, Power Point, and the Power Mac 7300/200 64 Meg 12 x CD ROM/166 Pentium 48 Meg computer that I use for the Code Corner columns. Maybe next issue.

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Minutia

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Understanding and applying the minutia of the National Electrical Code(NEC) has been the primary reason that for the last 100 years, the United States has had one of the safest electrical power systems in the world. Since PV systems are electrical power systems and must be safe, we (the people involved in all phases of PV system manufacture, design, and installation) must strive for complete understanding of the NEC.

While the NEC is not as clearly worded as some would like, there is a wealth of information contained in the various chapters—information that applies to PV systems just as it does other electrical systems. Ignoring this information or maintaining that it does not apply to PV systems dooms us to repeat the mistakes that led to the various sections of the code being developed in the first place. The PV industry, in it's relative infancy, cannot afford to make mistakes. A fire or electrical problem that damages property or causes loss of life in a highly visible PV system will attract the attention of the insurance industry. Such attention may be more than the PV Industry can stand. We must work together to understand and apply the various codes and standards to prevent this from happening. I welcome the dialog that the Code Corner Columns generate.

In 1990, there were PV installers who were not putting fuses or disconnects between the batteries and the inverters on PV systems, even though the NEC and common sense required them. Fortunately, the word has reached most in the PV industry that the NEC represents a minimum set of safety requirements and that fuses and disconnects are good ideas that don't result in significant performance penalties.

Feedback

In response to the letters that appeared in Home Power 61 (Code Curveballs) and other letters, e-mail, and telephone calls concerning the Code Corner Column in Home Power 60, I would like to address some of the details that are involved in understanding and applying the NEC to achieve safe PV systems. The information presented below is obtained from the NEC, the NEC Handbook, and various UL and IEEE Standards. The NEC Handbook is published by the National Fire Protection Association and is written by the electrical engineers at NFPA who are responsible for editing the NEC and making formal interpretations of it. The appeal process for differences in interpretation between electrical inspectors and the PV installer ends at the NFPA if the differences cannot be resolved at a lower level. Local codes supplement the NEC and may impose different requirements.

Cable Ampacities and Temperature Deratings

The Insulated Cable Engineers Association (ICEA) in conjunction with Underwriters Laboratories (UL) and the Institute of Electrical and Electronic Engineers (IEEE) have developed detailed cable standards (e.g. ICEA T 22-294 on testing cables in wet locations). If the cables are built to the published standards, tested and listed to those standards, and installed in accordance with the appropriate codes, they are designed to last at least 20-years. An important aspect of conductor life is the insulation temperature. If the insulation temperature is allowed to increase above the design specification, then the life of that insulation will be reduced and the cable may fail unexpectedly.

PV Module Cable Sizes

Most PV modules less than 100 watts in size have terminals or lugs that can accept cables in the range of number 14–8 AWG. Some modules come with number 16–10 AWG conductors that are attached as pigtails. Contrary to the opinion that no one would use cables that are too small to meet code because they don't want to waste valuable PV power, I have worked with several large PV module manufacturers and PV systems integrators that were trying to use cables as small as number 18 AWG to save money on copper costs and connectors. In large (50–100 kW) PV arrays, there is a lot of wiring and the costs mount up rapidly if oversized cable is used.

The NEC requires that cables be sized based on the ampacity of the cable because it is amperage that causes cables to overheat and overcurrent devices to trip. Voltage drop, important in RE systems, is not directly addressed in the NEC except as a non-directive Fine Print Note. I have found that after the proper temperature deratings have been applied to the ampacity of a PV module cable, the voltage drop for the minimum size code-compliant cable is usually acceptable. Of course, voltage drop should always be checked. When dealing with the cables that can be connected to the 100 watt and smaller modules, the number 12 and 10 AWG cables are most common.

Temperature Derating Cable

Ampacities start with the conductor material, the insulation material, the number of cables in close proximity, the installation method, and the ambient temperature in the vicinity of the cable. NEC Tables 310-16 and 310-17 give the starting points for the ampacities and these values are further modified by a series of footnotes and other restrictions. An engineer

can also make detailed ampacity calculations (real arcane minutia) and not use the tables in the NEC.

For example, a number 10 AWG conductor may have insulation rated at 90°C and may be installed in a conduit. Table 310-16 of the NEC gives data that infers that if the current in the conductor is at or below 40 amps (the ampacity) and the ambient temperature around the conductor is 30°C, then the temperature of the insulation will go no higher than the 90°C rating.

If the ambient temperature around the conduit is 40°C, then the temperature derating factor of 0.91 reduces the maximum allowable current to 40 x 0.91 = 36.4 amps. Currents at this level coupled with an ambient temperature of 40°C allow the insulation temperature to remain at or below 90°C.

If the conductor is connected to a PV module (by connecting it to terminals in the PV module junction box), the conductor can be exposed to temperatures of 70°C and higher. Temperatures in PV junction boxes have been measured as high as 73–80°C when the ambient temperature has been 40°C (104°F) and the solar irradiance at 1050 watts/meter squared (W/m2). It should be noted that in many portions of the country ambient temperatures can exceed 104°F and irradiance, on clear days, is usually above 1050 W/m2 for several hours. Modules mounted close to dark roofs with little air circulation can be exposed to temperatures higher than the ambient temperature of the surrounding air.

At the 70°C temperature, the ampacity derating factor for the conductor rated at 90°C is 0.58 which limits the ampacity of the number 10 AWG cable in conduit to 23.2 amps (0.58 x 40). If the current in the cable exceeds 23.2 amps under these conditions, then the insulation may be exposed to temperatures higher than the rated 90°C which will shorten the life of the cable. Keeping the current at or below 23.2 amps allows the insulation temperature to remain at or below 90°C and the cable will meet longevity specifications.

In a similar manner, cables with insulations rated 60°C and 75°C can also have their ampacities derated for temperatures higher than 30°C.

It is generally assumed that if a cable with a 90°C insulation is operated at a current that is equal to the rated ampacity of the same size cable with a 60°C insulation, then the insulation will remain at or below 60°C. For example, the ampacity of a number 10 AWG cable with 60°C insulation is 30 amps at 30°C (compared to the 40 amps of the number 10 AWG cable with 90°C insulation). If the 90°C insulated cable is operated in conduit at 30 amps, it is assumed that its insulation temperature will be 60°C or lower. While this assumption is generally made, it has not been extensively verified through tests. The insulation materials, thickness, and thermal conductivity on 60°C cables can be quite different than the same factors in 90°C cables.

However, it should be noted that ambient temperature also affects the 90°C conductors being operated at 60°C. If we take a 90°C rated, number 10 AWG conductor and operate it at 30 amps in an ambient temperature of 40°C, the insulation temperature will probably exceed 60°C. Table 310-16 shows a temperature derating factor of 0.82 for 60°C conductors operating in 36-40°C ambient temperatures. The derated ampacity now becomes 0.82 x 30 = 24.6 amps. If operated under these conditions at 30 amps, the insulation temperature would probably exceed 60°C. Some installers have suggested that the temperature derate factor be only 0.91 (the number associated with the 90°C conductor actually used), but there is no general agreement on this from the people that wrote this section of the NEC. Some think that the non-linear nature of the heat transfer equations (See NEC Section 310-15(b) and Appendix B) suggests that the higher derate factor associated with the 60°C cables be used.

There is some question about the value of the ambient temperature that should be used to derate the ampacity of conductors that are in conduit which is exposed to sunlight. The NEC, in earlier editions, had solar-gain tables to assist in calculating this temperature. These were removed for unknown reasons several years ago. However, most people know that it is unwise to touch a steel or gray plastic pipe that has been sitting in the sunlight on a hot day. The external and internal temperatures of such conduits are considerably hotter than the ambient temperatures of the surrounding air. Solar water heaters work well because of solar gain. However, the NEC requires that only the ambient temperatures be used in the ampacity derating calculations. This might indicate that PV installers be somewhat conservative when using conduits and cables exposed to sunlight.

A Test

I ran an informal test on a new, two-foot piece of 3/4 inch flexible non-metallic conduit. This conduit had a shiny, somewhat reflective surface and had not turned brown or chalky gray as these conduits do when exposed to sunlight and the weather. I inserted two number 10 AWG THWN-2 conductors and a thermocouple probe into the conduit. I partially blocked the open ends of the conduit to simulate the restricted air flow in a longer piece of conduit. I connected the thermocouple to a digital thermometer and placed the conduit in a shady area. It was a bright, clear afternoon

and there was no wind. The solar irradiance was about 925 W/m2. The temperature of the ambient air was 30.5°C (87°F). This also was the temperature inside the conduit when the conduit was in the shade.

I then placed the conduit in the sunlight away from any other structure or body that might reflect sunlight or heat onto it. Within 30 minutes, the internal temperature of the conduit was 58.5°C (137°F). This represents a 38°C rise in conduit temperature above the surrounding ambient air temperature due to solar gain alone.

I have no doubt whatsoever that if the ambient temperature had been a few degrees higher and/or the irradiance had been nearer the peak noon-time value of 1075+ W/m2, the internal temperature of the conduit would have exceeded the 60°C wet rating. As the conduit ages, the color changes will result in even more solar energy being absorbed. Keep in mind that these temperatures were measured with no current flowing in the conductors that were inserted in the conduit. With aged conduit (non-reflective or darkened), current flowing in conductors, high ambient temperatures (40°C), and expected daily normal insolation values (>1000 W/m2), I would expect the internal temperatures of this type of conduit to exceed even the 80°C dry rating when exposed to sunlight.

Installations

Flexible conduit is exposed to sunlight in many PV installations. In some installations, there are gaps between the modules and sets of modules that allow sunlight to shine on the conduit. The conduit is also routed to junction boxes and down the poles of trackers exposing these sections to sunlight.

So What, I'm in the Shade

If the conduit is installed behind the modules, it appears that there would not be any direct solar heating. However, we must keep in mind that the back of module temperature and the j-box temperatures can be in the 60–80°C range when the ambient temperatures are at 40°C. If the conduit touches the back of the module or the conduit fitting is connected to the j-box, then the conduit and the fitting on the end may be exposed to temperatures above the rated value. The NEC does require that good mechanical connections be made when attaching the conduit fitting to the PV j-box. The code also requires that the conduit be well supported within 12 inches of the j-box and at not more than 3-feet intervals elsewhere along the maximum allowable six-foot length [NEC Section 351-27]. These mechanical constraints indicate that there is a possibility that one or more points on the conduit or fittings will be at temperatures higher than 60°C due to just thermal conductivity and convection in the shade without direct solar heating.

Wet Locations

All exposed, outdoor electrical installations are considered wet locations. Wet-rated conductors (types THWN-2, RHW-2, and XHHW-2 for 90°C wet ratings) must be used in conduits installed in outdoor locations. The conduits may not be used at the higher dry temperature ratings when used outdoors. This is fully explained in the NEC Handbook in Article 100 under the definitions of "location." Conduits attached to PV modules are in outdoor, wet locations. The NEC and the NEC Handbook are very clear on the point that outdoor exposed conduits frequently have water in them from wind-driven rain and condensation. The assumption is that they may have water in them at any time, even when the sun is and has been shining brightly. I have personally seen professionally-installed PV systems that had water in the module junction boxes and array-wiring conduits days after any rain. NEC instructions for installing conduit point to the requirement to install it in a manner that will minimize the collection of water. The NEC and the NEC Handbook mention sloping it downward at all points and making provisions for drains at low points [NEC Sections 100A., 225-22, and 230-53]. Of course, no one knows how to make it drain—do we leave the fittings loose (a definite no-no), or do we drill holes in it (another no-no)? These requirements indicate that the conduits in PV systems must be used at their wet temperature rating of 60°C.

Some flexible, non-metallic conduits have a 70°C wet rating (Kaf-Tech brand), but I believe that even this temperature may be exceeded in many installations. The Carlon brand flexible non-metallic conduit has three-piece end fittings that are rated at 107°C (but the conduit is still rated at 60°C wet, 80°C dry). The cheaper Carlon one-piece fittings are only rated at 60°C (presumably wet or dry).

Flexible Nonmetallic Conduit—Can We Use It?

Maybe. Although I have not experienced mechanical failures of the conduit connectors coming loose from the conduit, I do have one report of such a failure to the extent that the installer will not use this product . While this report may be a simple problem of mismatched components or improper installation, it may also be due to a product being operated beyond its ratings.

As Bob-O Schultze and Redwood Kardon pointed out in their letter in Home Power 61, if we use 90°C, wet-rated cables and keep the current in the cable below the ampacity of a 60°C insulated cable (derated for any elevated ambient temperature), we can operate with the flexible non-metallic conduit. As shown above, the current in a number 10 AWG cable in a 40°C ambient temperature must be kept below 24.6 amps. While we

can accomplish this, it appears that we cannot keep the temperature of the conduit due to sunlight heating from exceeding the 60°C wet rating. Conduit heated by sunlight to 60°C, plus additional conduit heating due to conductors operating at 60°C indicates to me that flexible, non-metallic electrical conduit should not be used in PV installations. To do so would violate the provisions of the National Electrical Code.

In moderate to cold climates (maximum ambient temperatures below 30°C (86°F)), with proper temperature deratings of the conductors, high-temperature fittings, careful mounting, and good ventilation to the backs of the modules, it may be possible to keep the conduit temperature below 60°C and not violate the provisions of the NEC in Section 351-23(b).

What Happens if I Do Use It?

If the flexible conduit is installed where the 60°C temperature limitation is exceeded, the effects will probably not be dramatic. The combination of moisture and temperature may result in some, none, or all of the following: conduit and conductor insulation deteriorating faster than specified, conduit separating from the fittings, or conduits deforming causing conductors to operated at even higher temperatures with possible accelerated insulation failures. The deterioration of the conduit and insulation are related to chemical changes in the compounds that make them up. Many chemical reactions are accelerated by a factor of two for every 10°C increase in temperature. The increased temperatures are the main cause for the shortened lives of cable insulation and conduits. Heat can also soften the conduit and insulation making them more subject to mechanical abuse and failure.

Other Options

Manufacturers like Heyco and T&B produce high-temperature tubing that is sunlight and moisture resistant. Unfortunately, it is only a recognized product and is not listed as a flexible non-metallic conduit. I will continue to search for a suitable product. Ideas from others are welcome and will be included in this column when appropriate.

I have heard about (from an IBEW member), but not seen, expansion joints that are used for rigid electrical PVC conduit. These gasketed, water-tight slip joints would make it easier to install rigid PVC conduit. They are available from Graybar and probably other suppliers.

Single-conductor USE-2 or Tray Cable (type TC) in the two-conductor version looks better and better all the time where conduit is not required.

Summary

We install PV systems with PV modules that will be producing energy day-in-and-day-out for 25 years or more. We install other balance of systems components that we hope will be equally long lived. I see no reason to use a product like flexible non-metallic conduit beyond its ratings. To do so only invites system failures and possibly worse.

We all would like to see PV become a real player in the energy supply of the United States and the world. The Department of Energy's Million Roofs Program (250,000 for PV, 750,000 for Solar Hot water) will be another addition to the hundreds of thousands of stand-alone residential systems already operational. As the number of PV installations approaches a million or more in all forms, we must be ready to address and deal with the failures that might happen once in 10,000 installations. Those one hundred failures may be prevented if we all carefully study and apply the minutia of the NEC.

Next issue I will address some more of the code and performance issues as they apply to the use of fuses, circuit breakers, and diodes to protect PV modules. Dave Katz made some very good points in Home Power #61 and I would like to elaborate on them.

Questions or Comments? If you have questions about the NEC or the implementation of PV systems following the requirements of the NEC, feel free to call, fax, email, or write me at the location below. 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-AC04-94AL8500. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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Code Writing Processes and Series Diodes

John Wiles

Sponsored By The Photovoltaic Systems Assistance Center Sandia National Laboratories

Some readers that have written to *Home Power Magazine* and to me have expressed concerns about the contents of the National Electrical Code® (NEC®). They have also asked for reasons for some requirements and also how proposed changes related to PV systems for the code come about. A brief review of how recent 1999 code changes were developed will answer most of these questions and will give some background on "Article 690 - Solar Photovoltaic Systems." The Code Corner articles that I have been writing have been an important effort to extend the PV industry activities related to the NEC to *Home Power* readers.

Article 690 - Solar Photovoltaic Systems

Article 690 first appeared in the 1984 issue of the NEC, several years after the first terrestrial PV systems were installed to power homes or to tie them to the utility grid. The Code Corner column actually started with issue #13 of *Home Power Magazine* (in Oct./Nov. 1989) and has appeared in nearly every issue since then. Thanks to a successful *Home Power Magazine*, and in response to years of Code Corner articles, I get more than a half dozen calls a month from *Home Power* readers with questions about the code requirements. One call recently came from the Falkland Islands while others have come from as far away as England and South Africa. No one can doubt the scope of the *Home Power Magazine* international audience.

I have discussed the manner in which the NEC is developed in a number of Code Corner Columns. Readers of issues 51, 52, 53, and 54 were given the name of a person to contact for anyone that desired to participate with a Task Group in the process of formulating proposals for the 1999 NEC. The National Fire Protection Association (NFPA) appointed this nine person Task Group named "CMP#3 Task Group, Article 690 - Photovoltaic Solar Systems" to review and propose changes to bring the Article up to the state-of-the-art for PV systems. In *HP* #55, PV industry representation for the group of volunteers that served on the Task Group was identified. That Task Group helped to formulate and approve for submittal some of the proposals for Article 690 for the 1999 NEC. Proposals were also submitted by individuals outside the Task Group.

The formation of the Task Group was at the request of the CMP#3 Chairperson. I was elected the Secretary of that Task Group, therefore my name is used as submitter of all the Task Group proposals and comments. More important than the Task Group in this process was the PV industry support provided by a team of experienced people belonging to the Solar Energy Industries Association Technical Review Committee (TRC) on Standards and Codes. They prioritized issues and then proceeded to formulate code language to address those issues. The TRC consisted of more than 60 volunteers representing the entire spectrum of the PV industry. The group included customers, dealers, installers, systems houses, electrical contractors, utilities, university researchers, and module, inverter, and charge controller manufacturers plus two from the national laboratories. This group met two to three times each year during 1995, 1996, and 1997 to work on the 1999 NEC proposals.

Each Task Group proposal submitted to the NFPA for the 1999 NEC contained the following statement: "This proposal is the result of work by NFPA Ad Hock Task Group to CMP-3; Task Group-Article 690-Solar Photovoltaic Systems and supported by the Solar Energy Industries Association (SEIA) Technical Review Committee on Standards and Codes." Each proposal was balloted within the TRC and the Task Group before submittal.

The proposals for the 1999 NEC were submitted to the NFPA in November 1996, nearly two years before the publishing date of the NEC. They have also gone through an extensive NFPA technical and public review

process. The process and suspense dates for the 1999 NEC, for those who read the NEC in detail, are printed in the back of each copy of the 1996 NEC. Everyone is invited to participate by the NFPA and the NFPA proposal form is printed in the NEC. All it takes to propose changes are some good, well substantiated requirements, needs, or solutions. Put them on the form, drop them in an envelop with a 32 cent stamp and mail them to the NFPA before the NFPA established deadline. Once in the system, code making panels must pass proposals by a 2/3 majority before they can become code.

Series Diodes — Old Technology with New Applications

Blocking diodes have been used for years to prevent batteries from feeding current back into PV arrays at night. Only in recent times have they been eliminated from low voltage PV systems. In *HP* #59 it was mentioned that diodes were one possible way to protect PV modules from reverse currents caused by module or wiring faults. Overcurrent protection is required on all modules and the requirement is marked on the back of all listed modules. Fuses are currently required, but these are seldom used to provide this required protection. There are cost and performance considerations involved in the selection of any device used to provide this protection for the PV module.

Although the use of diodes in this manner does not currently meet UL or code requirements for module protection, future consideration might be given to changing the UL Standards to allow such use. As Dave Katz pointed out, there are some performance impacts of using diodes. These impacts are nothing new and have always been associated with the use of diodes, especially in low voltage PV systems (12 to 24 volt).

In utility interconnected systems that employ peak power trackers in the inverters, power lost in the diodes is due to the PV current through the diode and the voltage drop across the diode. Since most utility interactive systems operate at 48 volts and above, the diode losses, while measurable, are not significant. For example, a 2,000 watt PV system operating at 200 volts and 10 amps might have 14 watts of loss in the diodes — only 0.7%.

Low voltage, stand alone PV systems using crystalline silicon PV modules that charge batteries may have the available battery charging current reduced when series protection diodes are used. These reductions in available charging current are primarily a function of the system voltage (12 or 24), battery charging voltages (ranging from low states of charge to equalizing voltages), the PV module characteristics, and the module operating temperature.

The use of a diode in series with each string of PV modules in 12 or 24 volt systems causes the module(s) to shift the module operating point to a higher voltage. The shift in operating point is a function of the battery (charging) voltage and the module operating temperature. The resulting shift in available PV module current is an inverse function of the battery voltage and module operating temperature. The shift (with the diode and with the operating voltage higher than the maximum power point voltage) lowers the available PV current that can flow to the battery. The table below was generated using a generic 49 watt PV module that at standard test conditions of 25° C cell temperature and 1000 watts per square meter of irradiance, has the following parameters: Isc=3.18 amps, Voc=21 volts, Vmax=16.6 volts, Imax=2.95 amps, and Pmax=49.

As an example, a PV module simulation and performance program was used to obtain the numbers shown. Battery temperatures were assumed to be constant and were not considered in this analysis. I ran the simulation at module temperatures of 45° C (113° F), 55° C (131° F), and 65° C (149° F) to represent the range of temperatures that modules operate at when ambient temperatures are 25° C (77° F) to 40° C (104° F). In windy conditions, or conditions with lower or higher ambient temperatures, the modules may operate at temperatures higher or lower than the 45 to 65° C range.

I used battery voltages of 12, 13.4, 14.8, and 15.5 volts (twice those values for 24 volt systems) to simulate a battery at various states of charge. The 15.5 volt (31 volts on 24 volt systems) operation represents an equalizing voltage of a flooded lead acid battery.

Percentage of Current Reduction when Diode is Added to Circuit

	12 Volt System		*24 Volt System*	
° Module Temp.	*Battery Voltage*	*Current Reduction*	*Battery Voltage*	*Current Reduction*
45	12.0	0.6%	24.0	0.3%
45	13.4	1.6%	26.8	0.6%
45	14.8	4.2%	29.6	1.6%
45	15.5	7.1%	31.0	3.0%
55	12.0	0.6%	24.0	0.3%
55	13.4	2.5%	26.8	1.0%
55	14.8	7.4%	29.6	3.4%
55	15.5	11.8%	31.0	5.4%
65	12.0	1.6%	24.0	0.6%
65	13.4	4.5%	26.8	2.3%
65	14.8	12.3%	29.6	5.4%
65	15.5	19.4%	31.0	8.9%

When the battery voltages are low (low states of charge) and the module temperatures are moderate (cool ambient temperatures), the reduction in the available current is very small. On the other hand, when the batteries are at a higher voltage (mid to high states of charge or being equalized) and the PV modules are at high temperatures (in hot climates) the reduction in available charging currents can approach 20% on a 12 volt system. For a 24 volt system, the reductions in current due to the use of a diode are less than half the reductions in a 12 volt system.

All voltage drops in a PV system shift the operating point of the PV module. Once the operating voltage of the PV array is higher than the maximum power point voltage, then each additional voltage drop (including the drop caused by the use of a diode) enhances the decrease in available current from the PV modules. All PV systems, especially low voltage systems, should be designed for low voltage drops, code compliant wiring, and tight connections.

Dave Katz was on the money, so to speak. If you live in the hot sunny southwest and your PV system is sized such that your batteries operate in a high state of charge (high voltages) for much of the day, measurable reductions in available charging current (if a diode is inserted in the system) are likely. On the other hand, the reduction of charging current may not be critical since the charge regulation process will also result in average current reductions as the battery becomes fully charged. When low voltage systems operate in cooler climates, the reductions are less.

Miscellaneous Material

Drake Chamberlin, in his letter in *Home Power* #62, made some interesting points about code practice. Drake is a practicing electrician who installs PV systems. I would urge caution, however, when using 90° C wiring on Square D circuit breakers and fused safety switches. All of those devices that I can find require 60° C or 75° C conductors and some require 75° C conductors without allowing 60° C conductors. The reason that 60° C conductors are not allowed on some circuit breakers is that these devices normally operate at high temperatures that would damage conductors with 60° C rated insulation. Even where the devices are rated for 60° C/75° C or 60° C conductors, 90° C conductors may be used if operated at currents that keep the conductor cooler than the 60° C or 75° C. This can be easily accomplished by using the 60° C or 75° C ampacity columns from NEC Table 310-16 and 310-17 when using 90° C conductors. Such temperature limitations may also apply to terminals used for splices and even terminals used on switches.

Drake also pointed out that he thought there wasn't much reason to use 90° C conductors on PV modules. However, with a very few exceptions, most listed PV modules are marked on the back that 90° C conductors must be used. UL and the PV industry are considering a 90° C marking for all listed modules. In some installations, the J-box temperature exceeds 65 to 70° C where conductors rated at only 75° C lose most, if not all, of their current carrying rating.

Questions or Comments?

If you have questions about the NEC or the implementation of PV systems following 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-AC04-94AL8500. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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Grounding

John Wiles

Sponsored By The Photovoltaic Systems Assistance Center Sandia National Laboratories

In my last Code Corner Article, I mistakenly stated that Drake Chamberlin, in his Code Counterpoint letter in HP 62, thought there wasn't much reason to use 90°C wiring on PV modules. I am sorry that I misunderstood what Drake was trying to say. As a practicing electrician in Colorado, he is installing PV systems and knows the requirements of the NEC® and local codes. We both know that most listed PV modules are marked with a requirement to use 90°C conductors.

Grounding

I get more calls each month on grounding PV systems than any other subject. The NEC covers this subject in Article 250, Article 690, and in several other locations including definitions in Article 100. For those who want to achieve a good understanding of the subject of grounding, I recommend the National Electrical Code Handbook and the International Association of Electrical Inspectors (IAEI) Soares Book on Grounding. See Access. The Soares book even gives some of the 100-year history on the grounding requirements in the United States.

Definitions

Electrical systems (including PV systems) are solidly grounded to limit the voltage with reference to ground during normal operation and to prevent excessive voltages due to surges from lightning or unintentional cross connections with higher voltage lines. In PV systems, the modules are usually mounted in high, exposed locations where they are prone to picking up surges from nearby lighting strikes. Utility-interactive inverters are subjected to surges on the power line. Systems using PV power to run computers with hardwired modems are subject to surges from the telephone line. Proper grounding effectively deals with these potential problems and more.

The term "grounded" indicates that one or more parts of the electrical system are connected to the earth, which is considered to have zero voltage or potential. Unfortunately, the earth isn't always at zero potential, and that complicates the grounding requirements. To better understand the grounding requirements, it is necessary to examine several terms used in conjunction with grounding.

The grounded conductor is a conductor that normally carries current and is connected to the earth. Examples are the neutral conductor in an ac wiring and the negative conductor in many DC systems. Note that some DC systems such as telephone systems connect the positive conductor to ground rather than the negative conductor.

An equipment grounding conductor is a conductor that does not normally carry current (except under fault conditions) and is also connected to earth. It is used to connect the exposed metal surfaces of electrical equipment together and then to ground. An example of an equipment grounding conductor is the bare conductor in non-metallic sheathed cable (Romex®). The green-insulated conductor in power cords for ac-operated portable equipment is another example of an equipment grounding conductor. These equipment grounding conductors help to prevent electrical shocks and allow overcurrent devices to operate properly when ground faults occur.

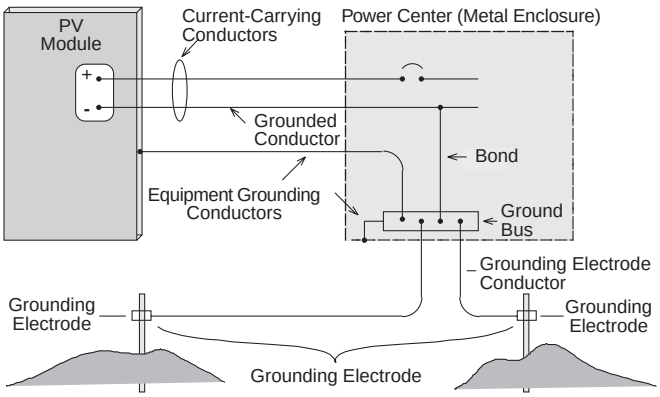
A grounding electrode conductor is a conductor between a common single grounding point in the system and the grounding electrode. Splices in this conductor must be made with special devices or welded.

A grounding electrode can refer to the common 5/8 inch diameter, 8-foot long ground rod or other metallic device that is used to make actual contact with the earth. There are "made" grounding electrodes (ground rods) and other types of grounding electrodes such as metal water pipes, metal building frames, and concrete-encased cables (known as UFERs after their inventor). Specific requirements for each of these grounding electrodes can be found in Article 250 of the NEC. Local codes and practices vary greatly and should be investigated to determine which types of electrodes are being used.

Bond is a term that, as a verb, means to connect two or more points together. In common usage as a noun, it usually refers to the connection (bond) between the grounded conductor, the equipment grounding conductors, and the grounding electrode conductor. Bonding is also used to describe connecting all of the exposed metal surfaces together to complete the equipment grounding conductors.

A grounding electrode system is a system where two or more grounding electrodes are connected together. These systems are common in PV installations where there are two grounds such as an existing one for the ac system and a new grounding electrode that has been installed for the DC system. See NEC Sections 250-81 through 250-86.

Figure 1 shows how these conductors are related in a PV system.



NEC Requirements

The NEC covers nearly all field-installed electrical systems that are not owned and operated by a utility on utility property. For example, it covers PV systems (Article 690), Cranes and Hoists (Article 610), EV charging stations (Article 625), electric welders (Article 630), computers (Article 645), communications systems (commercial and amateur) (Chapter 8) and most other electrical installations.

The NEC covers low-voltage systems (less than 50 volts in Article 720) and high-voltage systems (up to 230 kilovolts in Article 710). It covers systems with zero frequency (direct currents) through radio frequency (RF) systems.

With respect to grounding, the NEC requires that all PV systems (those that have field-installed wiring) have an equipment grounding system connected to a grounding electrode (690-43). Those systems with a rated voltage over 50 volts are required to be grounded by having one of the current-carrying conductors connected to the grounding electrode. The rated voltage is the maximum open-circuit voltage of the system after any UL requirements have been met. UL-listed PV modules come with instructions that require that the module rated open-circuit voltage (measured at 25°C and marked on the back of the module) be multiplied by 125% (UL Standard 1703) before any NEC requirements are addressed. This multiplier is used to ensure that modules used in cold temperatures (below 25°C -77°F) have connected components rated for adequate voltage. The output voltage of crystalline PV modules increases as temperature decreases.

This calculation indicates that a nominal 12-volt PV system has a rated voltage of about 27 volts (22 volts open circuit voltage at 25°C times 125%). A nominal 24-volt system has a rated voltage of about 55 volts which means that, in addition to the equipment grounding conductors, one of the current-carrying conductors must be connected to the grounding electrode.

The 1999 NEC will have a change that allows the maximum system voltage to be calculated based on the lowest temperature in the installation area. The 125% factor, presently a requirement UL Standard 1703 for listed modules, will be moved to the NEC and will apply only when low temperatures get to -40°C. In areas where low temperatures are more moderate, factors less than 125% (listed in a table) may be used when the 1999 NEC is adopted in those areas.

On 12-volt PV systems, the grounding of one of the current-carrying conductors is optional (NEC Section 690-41). However, the NEC, in Articles 240, 230, and 690, requires that each ungrounded conductor in any electrical system have overcurrent protection and disconnects. Since a 12-volt PV system must already have equipment grounding conductors, grounding electrode conductor, and a grounding electrode, there is a significant cost advantage and sometimes a performance advantage to grounding the system. With the addition of one wire (the bond shown in Figure 1), the number of disconnect poles and overcurrent devices can be cut in half since these devices are not required in the now grounded current-carrying conductor. Furthermore, low-voltage fluorescent lamps start more reliably when installed in a grounded system and inverters and other electronic devices can be installed so that they radiate less noise when one conductor is grounded.

Hows and Whys

Equipment Grounding Table 250-95 in the NEC specifies the size of the equipment grounding conductors for each circuit. The size is based on the rating of the overcurrent device protecting the circuit and ranges from number 14 AWG conductor in a 15-amp circuit to a number 3 AWG equipment grounding conductor in a 400-amp circuit.

Of particular interest to PV installers is Section 250-95 of the NEC that states that if the current-carrying conductors have been oversized to minimize voltage drop, then the equipment grounding conductors must also be oversized in the same proportion. Oversized conductors (above minimum ampacity requirements) are frequently used between the PV array and the charge controller to reduce voltage drops in these lines. Table 8 in Chapter 9 of the NEC shows the cross sectional area of different sized conductors, and the calculation is straight forward. Oversizing the equipment grounding conductors is required by the NEC to ensure that overcurrent devices function properly during ground faults.

Equipment that must be connected to the equipment grounding system includes the exterior metal surfaces of PV modules, power centers, charge controllers, inverters, and switchgear and overcurrent devices. Equipment listed to UL standards will have properly marked connections and instructions for connection of the equipment grounding conductors.

The equipment grounding requirement in renewable energy systems is usually met by using a separate conductor. If the system uses metal conduit (and many commercial systems do), then the conduit can serve as the equipment grounding conductor when used with listed fittings.

The connection of the equipment grounding conductor can run from module frame to module frame and then to switch gear and then the power center. The order of the connections is not critical and multiple connections or parallel connections do not cause problems. Each equipment grounding conductor may also be run from the metal surface being grounded to a central point like the power center. The connections and wiring for the equipment grounding conductor must be continuous to allow fault currents to properly operated overcurrent devices. Removal of a piece of equipment for service must not interrupt the equipment grounding system for other equipment.

Generally, module frames are made of aluminum which is anodized. The anodized coating or aluminum oxide that forms on aluminum surfaces is a relatively good insulator. This is why listed PV modules have a special point marked for connecting the equipment grounding conductor. A stainless steel screw is usually supplied which helps to ensure a good electrical connection. It should be noted that while the anodized surface insulation on PV modules makes it hard to get a good equipment grounding connection, the aluminum frame is still exposed metal, and if not grounded, can produce an electric shock when ground faults occur between the current-carrying parts of the module and the frames or when the frames are inadvertently energized by other power sources.

Aluminum PV module frames do not stay well grounded when they are only bolted to the metal mounting stands. If the UL listing allows and the module manufacturer provides special parts and instructions, some PV modules may be grounded through the mounting bolts to the frame. The NEC prohibits

the earth from being used as the sole equipment grounding conductor, so bolting the PV modules to a metal stand that is inserted in the ground does not meet the requirements for a safe installation unless a separate equipment grounding conductor is used from the frame to the main grounding point or electrode.

The NEC requires that all conductors for a given circuit be routed together in the same cable or conduit. An exception is the equipment grounding conductor for DC circuits.

When secondary grounding electrodes are used and they are bonded to the primary grounding electrode (as described below for surge protection) the bonding conductor may become an equipment grounding conductor and should be sized appropriately.

Grounding the Current-Carrying Conductor

The connection between one of the current-carrying conductors and the grounding electrode conductor is made only at one point in the system and is known as the system ground. This single-point connection is usually made in a power center and is shown as the bonding conductor in Figure 1. If this connection is inadvertently made in more than one place (e.g. at the PV modules and in the power center), then unwanted currents will flow in the equipment grounding conductors. These unwanted currents may cause inverters and charge controllers to be unreliable and may interfere with the operation of ground-fault detectors and overcurrent devices.

The use of RV and automotive electrical appliances and audio gear sometimes causes problems as does the use of dc-powered radio and telephone equipment. Much of this equipment operates at 12-volt dc with chassis and antenna ground connections that are common with the negative dc power conductor. It is pretty easy to get the negative dc conductor connected inadvertently to ground in two or more places when using these types of electrical devices. Since the NEC also requires that equipment grounding conductors be used with these appliances to ground the exposed metal surfaces, it becomes problematic on how to do this with a third conductor that does not result in multiple point system grounds. Solutions to minimize the problems include non-metallic enclosures to isolate the grounded chassis and ground-isolated antenna connections.

Listed power centers and disconnect switches usually have a provision for the single-point connection. In some DC power centers, ac load centers, and disconnect switches the connection is automatically made when all equipment grounding conductors, the negative conductors, and the grounding electrode are tied to a single, grounding bus bar. A central location such as the inverter disconnect, battery disconnect or main power center is where the connection to the grounding electrode conductor is made.

When using standard, fused safety switches for disconnects throughout the system (PV subarray, string, array, battery, etc.), an insulated bus bar usually must be added for making the connections for the unswitched, grounded conductor running through the switch enclosure. While there is frequently a bus bar supplied for the unswitched conductor, this bus bar is sometimes grounded to the enclosure presenting the opportunity for an inadvertent second grounding of the conductor that is intentionally grounded elsewhere in the system. Insulated, or ungrounded, bus bars should be used in these devices to prevent that second ground connection.

The Grounding Electrode Conductor

The grounding electrode conductor (a.k.a. the ground wire), is usually a single conductor bare wire (it can also be insulated-color is not specified) connected from a grounding bus bar in a power center or other disconnect to the grounding electrode (a.k.a. the ground rod).

In the 1993 and earlier editions of the NEC, this ground wire had to be the same size as the largest conductor in the DC system. In the 1996 NEC, a number of exceptions, when met, allow smaller conductors to be used. There are jurisdictions throughout the country that are still applying the 1993 and earlier versions of the NEC so some inspectors may require the larger conductors.

If there is only one conductor connected to the grounding electrode, then Section 250-93 of the 1996 NEC allows grounding electrode conductors as small as number 8 AWG copper to be used (see NEC Section 250-93 for the exact requirements). Appropriate mechanical protection is required where this conductor may be subject to physical abuse. However, if multiple conductors are connected to the grounding electrode, then the exceptions do not apply and a grounding electrode conductor as large as the largest conductor in the dc system must be used. Multiple connections to the grounding electrode conductor refer to connections from the power system and do not refer to telephone, TV, cable, or other types of communications grounds. Multiple connections to the grounding electrode occur when several ground rods are bonded together to form a grounding electrode system and when metal water pipes or well casings are bonded to the ground rod. Multiple connections are also common where DC and ac grounding electrode conductors are connected to the same ground rod. Several equipment grounding conductors tied to the ground rod also nullify the exceptions that allow a small grounding electrode conductor.

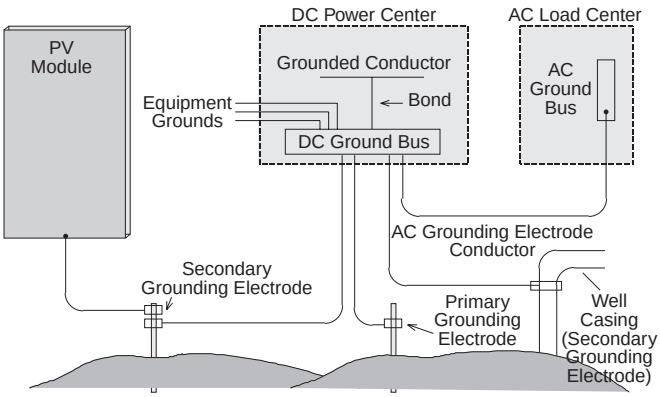
The reasoning behind the exceptions is that if more than one conductor is connected to the ground rod, some of those conductors may be required to carry high fault currents. If only one conductor is connected to the ground rod, then the other properly sized and connected conductors in the system will carry the fault currents, and the Number 8 AWG conductor to the ground rod will only be required to stabilize the system voltage with respect to earth. Only in lightning strikes and inadvertent connections to high-voltages, will the grounding electrode conductor be required to carry high currents.

There are similar requirements and exceptions for the ac grounding electrode conductor.

How then, can the system be connected so that a small equipment grounding conductor be used?

One method is to designate a single grounding bus bar in the system. This bus bar is usually found in listed DC power

centers. All equipment grounding conductors should be connected to this bus bar. If there are multiple grounding electrodes in the system, the secondary electrodes should all be connected to this bus bar to complete the grounding electrode system. If there is a requirement to provide a single-point ground for the ac portions of the system, then the grounding electrode conductor from the ac part of the system should be tied to this bus bar. Finally, the smaller (as allowed by the NEC) grounding electrode conductor can be connected from the grounding bus bar to the primary grounding electrode conductor. Figure 2 demonstrates these connections.



While this method meets the requirements of the NEC it may not provide the best protection against lightning damage. Running all grounding conductors to a common point inside the building may have the potential for increasing damage from nearby lightning strikes. In high lightning areas, it may be preferable to bite the bullet and use the larger grounding electrode conductor from the power center to the ground rod. Then secondary grounding rods and pipes and metal well casings can be connected directly to the primary grounding electrode without coming into the building. Equipment grounding conductors from the PV modules may also be run directly to secondary or primary grounding electrodes providing additional surge protection.

Each of the grounding electrodes described below, where used as a primary electrode, has a different requirement for the size of the grounding electrode conductor. See NEC Sections 250-93 and 250-94. If the requirements for the ac and DC grounding electrode conductors are different, then the larger of the two should be used for any common conductor.

Grounding Electrodes

The NEC, in Sections 250-81 and 250-83, considers that metal building frames that are in contact with the earth and metal water pipes (also connected to the earth) are the preferred grounding electrodes. Unfortunately, wood frame buildings, plastic pipes, and plastic sleeves on copper pipes make these options frequently unavailable to the renewable energy user. The NEC details the more commonly available grounding electrodes such as “made” electrodes (the common 8-foot ground rod), concrete encased cables or electrodes, and ring electrodes which consist of buried conductors encircling the building. Made grounding electrodes are listed by UL and are bonded (connected) to the grounding electrode conductors with clamps that are listed for this purpose. If the clamps are to be buried, they should be listed and marked for such use.

As a primary grounding electrode, the ground rod must be driven into the earth to a depth of at least 8 feet. Angles of no more than 45° away from the vertical are allowed where the ground is rocky. If these conditions cannot be met, then a second rod (best performance will be achieved if more than six feet away) or one of the other grounding electrodes must be used to supplement the primary electrode.

In some areas of the country where homes are built on concrete slabs, a grounding electrode is buried in the concrete slab and usually works better as a grounding electrode than an eight-foot ground rod.

Summary

System grounding is an important detail of the renewable energy power system. It reduces the potential for electrical shock and allows the system to respond safely to ground faults. The requirements for PV systems are generally the same as the requirements for other electrical power systems that have evolved over the 100-year history of electrical power systems in the United States.

In the next Code Corner, several different types of grounding systems will be shown including examples of PV systems located in power buildings separate from the main house.

Questions or Comments?

If you have questions about the NEC or the implementation of PV systems following the requirements of the NEC, feel free to call, fax, email, or write me at the location below. 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-AC04-94AL8500. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

Access

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Grounding Separate Structures

John Wiles

Sponsored By
The Photovoltaic Systems Assistance Center,
Sandia National Laboratories

In many stand-alone PV installations, the main ac loads for the system are located in a building or structure separate from the PV array, batteries, and the inverter. This poses the question: "How is the ac system grounded to meet the requirements of the National Electrical Code?"

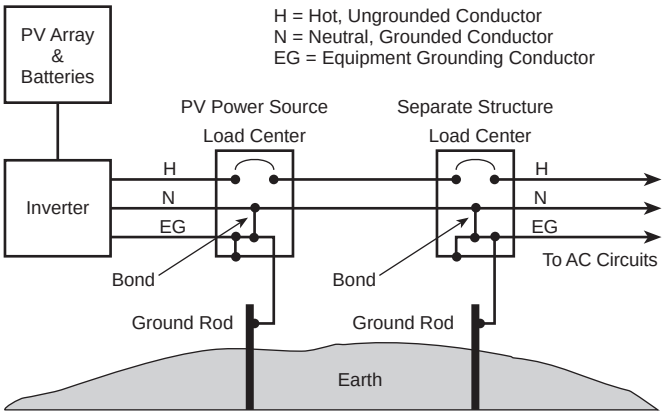
The general requirements for grounding were covered in the Code Corner column in *HP* 64 for a system where all of the sources and loads were in the same building. In this article, the requirements for grounding the ac circuits running to separate structures will be covered. In general, where the loads are some distance from the source, it is best to group the low-voltage circuits (PV, batteries, and inverter) in one location and then run the 120-volt or 120/240-volt output of the inverter to the loads at the separate structure. This configuration will minimize losses in the cables since the 120-volt ac circuits operate at lower currents than the low-voltage DC circuits. There are two accepted methods of grounding the ac circuits leading to separate structures.

Common to both methods is the requirement for a grounding electrode (e.g., a ground rod) at each structure—both the PV power source building and the structure (residence) where the distant loads are located. Grounding electrodes in both locations are required to serve as a grounding system for the equipment-grounding conductors at each location. As discussed in *HP* 64, all exposed conductive (metal) surfaces in the power system must be connected together with the appropriately sized conductors and then connected to a grounding electrode.

Method 1

The first method of grounding the separate structure is similar to the grounding used in a grid-connected home for grounding the service entrance conductors.

At the PV/inverter location, there is a bond or connection between the ac neutral conductor on the output circuit of the inverter and the grounding system leading to the grounding electrode. This bond is usually made in the load center or circuit breaker box that is used to provide overcurrent protection for the inverter output.



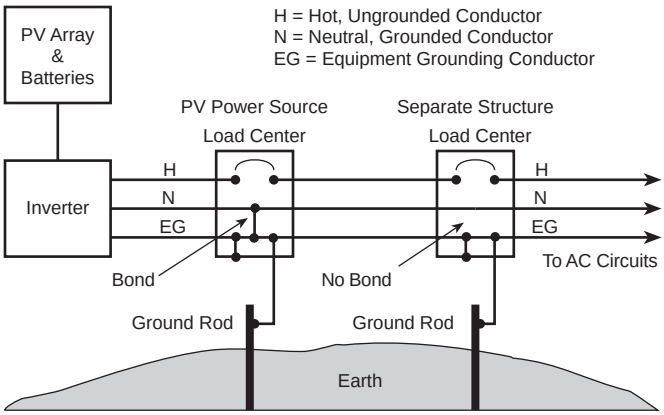
Only the ungrounded (hot) and neutral ac conductors are run to the separate structure. The equipment-grounding conductor (bare or green wire) is not connected between the two locations. In a 120-volt system, there will be only two conductors (one hot and one neutral) connected between the two locations. In a 120/240-volt system, there will be three conductors (two hot and one neutral) connected between the two systems. The two grounding electrodes must not be connected together by a separate bonding conductor.

At the separate structure, the neutral conductor is again bonded or connected to the grounding system. As mentioned above, this is identical to utility practice where the neutral service entrance conductor is bonded to ground at the utility transformer and again at the residential load center. Only ungrounded (hot) and neutral conductors are brought to the house.

Method 2

In the second method, the neutral conductor is bonded to the grounding system at the inverter location, but is not bonded to the grounding system at the separate structure. A separate, isolated (insulated) bus bar is required so the neutral conductors can be isolated from the grounding system. In this method, shown in Figure 2, an equipment-grounding conductor is connected between the two locations and run along with the hot and neutral conductors. In a 120-volt system, there will

be three conductors between the two locations (hot, neutral, and equipment-grounding). In a 120/240-volt system there will be four conductors between the two locations (two hot, one neutral, and one equipment-grounding).



Sizing the Equipment-Grounding Conductor

The equipment-grounding conductor should be sized according to the requirements of Table 250-95 in the NEC, which is based on the overcurrent device protecting the circuit. For example, if the circuit overcurrent device is 60 amps, the equipment-grounding conductor should be a number 10 AWG (American Wire Gauge) copper conductor. If the circuit is a 100-amp circuit, then the equipment-grounding conductor should be a number 8 AWG copper conductor.

Changes Required for Voltage Drop

Since the distances between the inverter location and the building with the loads may be significant, many installations use oversized hot and neutral conductors to reduce the voltage drop between the two locations. To ensure proper operation of overcurrent devices in this instance, Section 250-95 of the NEC requires that the equipment-grounding conductor be oversized proportionally.

For example: A Trace SW4024 4000-watt inverter has the 60-amp ac output connected to a circuit which is protected with an 80-amp circuit breaker. From ampacity calculations (NEC Table 310-16), a number 4 AWG conductor with 75°C insulation is selected with an ampacity of 85 amps at 30°C ambient temperature. The use of an 80-amp circuit breaker, providing overcurrent protection for this conductor, would dictate a number 8 AWG equipment-grounding conductor. A very long distance between the inverter and the house results in excessive voltage drop on even this 120-volt circuit. Voltage-drop calculations indicate that the conductors (hot and neutral) should be increased in size to number 1 AWG conductors.

Table 8 in Chapter 9 of the NEC is used to find the cross-sectional areas of each of the conductor sizes. They are: 8 AWG = 16,500 circular mils(cir mil), 4 AWG = 41,740 cir mil, 1 AWG = 83,690 cir mil.

The ratio of areas between the new number 1 AWG conductor and the original number 4 AWG conductor is 83,690/41,740=2.005. The NEC requires that the equipment-grounding conductor be increased in size by this factor of 2.0. The calculation shows that the new area is 2.005 x 16,500 = 33,083 cir mil which, from Table 8-Chapter 9, is a number 4 AWG cable.

The circuit now has two number 1 AWG conductors (hot and neutral) and a number 4 AWG equipment-grounding conductor.

Additional Requirements for the Equipment-Grounding Conductor

The equipment-grounding conductor may be bare (no insulation) or have green insulation. For sizes larger than number 6 AWG, only black-insulated conductors are generally available, so the NEC allows these conductors to have the exposed insulation marked with a green tape at each termination and at other places where the cable is accessible.

For ac circuits, the equipment-grounding conductor must be run in the same cable, conduit, or raceway as the current-carrying conductors.

An Aside for DC circuits

The same procedure for oversizing equipment-grounding conductors for voltage-drop considerations in ac circuits can be used for DC circuits.

Summary

In stand-alone PV systems, where the ac load circuits are some distance from the ac source (the inverter) in separate buildings or structures, there are two options for correctly grounding the system. Of the two grounding methods presented in this article, the first method uses one less conductor and is therefore less expensive. Other design considerations, such as using oversized conductors to reduce voltage drop and losses, require that the equipment-grounding conductor also be oversized.

Questions or Comments?

If you have questions about the NEC or the implementation of PV systems following the requirements of the NEC, feel free to call, fax, email, or write me at the location below. 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-AC04-94AL8500. Sandia is a multi-program laboratory operated by Sandia Corporation, a

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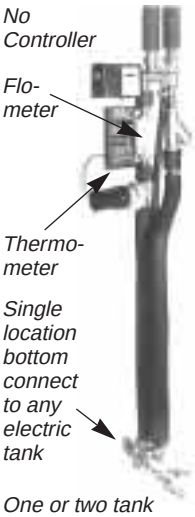

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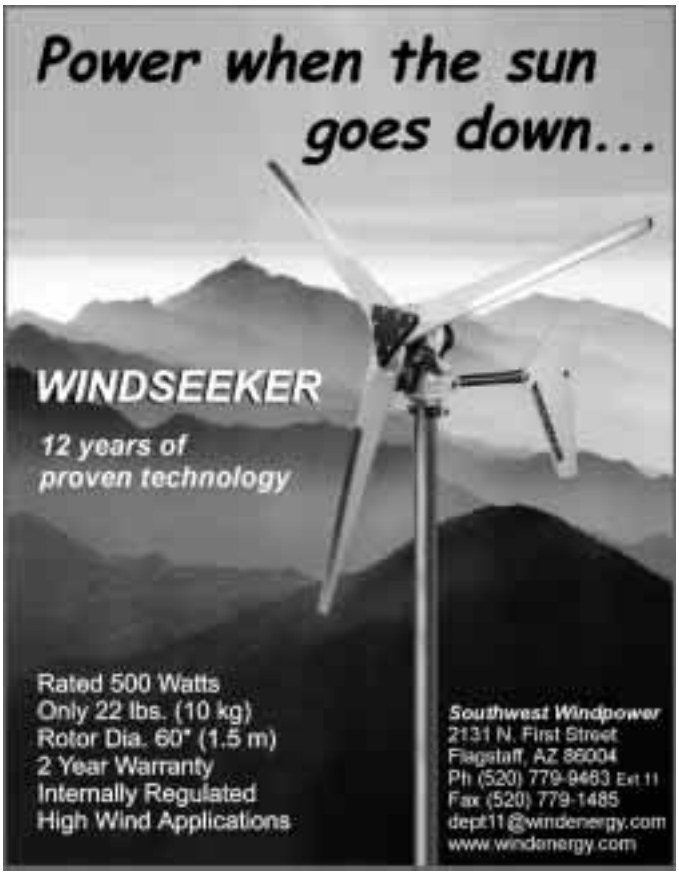

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Clarifying Confusing Cables

John Wiles

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The National Electrical Code (NEC)® contains numerous references to different cable and conductor types. Some types are intended for fixed, non-moving installations. Other types are designated for installations where various parts must move. Some cable types can be used in either fixed or moving installations. Each cable type is designated by a series of letters and numbers that refer to the size of the conductor and the type of insulation. This Code Corner will attempt to shed a little light on the murky subject of conductors and cables.

Conductors, Cables, or Wires?

A conductor is something that is meant to conduct or carry electricity. It is normally made of copper, but can also be made of other metals like aluminum. Today, however, copper is the most commonly used conductor in both PV and residential electrical systems. It can be bare, with no covering or electrical insulation, or insulated.

The size of the conductor is expressed as an American Wire Gauge (AWG) with designations from number 27 AWG, the smallest size mentioned in the NEC®, to number 4/0 AWG or 0000 AWG (called "4 aught"). Conductors larger than 4/0 AWG are specified in kcmil (thousands of circular mils), a cross-sectional area designation, and range from 250 kcmil up to 2000 kcmil (with a diameter of about 1.6 inches).

Conductors may be solid copper (usually 6 AWG and smaller) or may be stranded. Stranded conductor is composed of several strands of a smaller conductor twisted together. Typical stranded conductors from 18 AWG through number 2 AWG have seven strands. Conductors from 1 AWG through 4/0 AWG have 19 strands. Conductors 250 kcmil through 500 kcmil have 37 strands. In each of these sizes, conductors are available on special order that have considerably more strands for added flexibility. For example, a 4/0 AWG conductor may have 437 strands of very small copper conductors rather than the 19 strands in the standard conductor.

Cables are usually defined as conductors covered by insulation, although in many cases, the term conductor and cable are used interchangeably. Cables may have only a single conductor, or may have multiple, individually-insulated conductors. Some multiple conductor cables have an external insulating outer covering or sheath. Others do not, and the individual conductors are just twisted together.

The term "wires" is used in the NEC® to refer to the general use of cables or conductors. Reference may be made to a wiring system, wire size, wire sag, and similar terms.

Grouping of Cable Types

In the NEC®, there are two distinct groups of cables. One group represents the building-wiring types of cables. They are primarily used in fixed, non-moving installations such as buildings and are the principle types of cables used in wiring PV systems. These types of cables are identified in Table 310-13 of the NEC®, and the proper methods of installing these cables may be found in Chapter 3 of the NEC®.

The second grouping of cable types is the Flexible Cords and Cables found in Article 400 of the NEC® and described in Table 400-4. These cables are used where there is motion between two parts that are electrically wired together. Such cables are used on appliances, tools, elevators, cranes, and other industrial applications. PV trackers represent a moving installation where flexible cords could be used.

These types of cables are specifically prohibited in Section 400-8 of the NEC® from being used as a replacement for fixed wiring. One of the reasons for this prohibition is that flexible cords have not been tested, evaluated, or listed for fixed uses such as being placed in conduit or run through walls. Another reason is that these flexible cables are generally installed in exposed locations where damage is readily visible and the need for replacement is evident. There are numerous other prohibited uses where the code says that if a fixed,

building-wire cable can be used, the fixed cable is to be used in lieu of a flexible cable.

Insulations and Cable Markings
Cables have insulations that are made of different materials for different applications. The letters and numbers of the outer covering of the cable provide information on the cable and where it can be used. The tables in Chapter 3 and Article 300 of the NEC® generally specify under what conditions each cable type can be used. Listed below are some of the cables that can be used in PV systems starting with the building-wire types of cables.

Cables for PV module connections
Exposed, single-conductor cables are allowed for PV module connections by NEC® Section 690-31. The following are the types allowed:

USE: Underground Service Entrance • 75°C, wet insulation rating • Heat and moisture resistant • Sunlight resistant, but not marked as such.

USE-2: As above, but with a 90°C, wet insulation rating. The most commonly recommended cable for PV module wiring.

UF: Underground Feeder • 60°C, wet insulation rating • Not sunlight resistant unless marked • Hard to find and not recommended due to the low, 60°C temperature rating.

SE: Service Entrance • Temperature rating is variable and is marked on the jacket • Sunlight resistant, but not marked • Hard to find in a single conductor.

PV modules may also be connected with conductors installed in conduit (metal, plastic, flexible, rigid, etc.). Since the conduits are exposed to the elements, they are considered to be wet locations (even in the hot, dry, sunny Southwest), and wet-rated conductors with 90°C insulation should be used for PV module wiring. The following types are the cables typically used.

THWN-2: Moisture and heat-resistant thermoplastic • 90°C, wet and dry insulation rating • May also be marked THHN. A cable marked only with THHN is not suitable for use in exposed conduits.

THW-2: Moisture and heat-resistant thermoplastic • 90°C, wet and dry insulation rating • May also be marked THHW.

RHW-2: Moisture and heat-resistant thermoset (rubber) • 90°C, wet and dry insulation rating • May also be marked USE-2 and/or RHH.

XHHW-2: Moisture and heat-resistant thermoset (cross-linked synthetic polymer) • 90°C, wet and dry insulation rating.

In these and other markings on cables, the letters and numbers have meaning.

- **T:** Thermoplastic insulation
- **R:** Thermoset insulation (rubber or synthetic rubber)
- **X:** Cross-linked synthetic polymer insulation
- **H:** High temperature (usually 75°C when dry or damp)
- **HH:** Higher temperature (usually 90°C when dry or damp)
- **W:** Moisture resistant (usually 60°C when wet)
- **N:** Nylon jacket
- **-2:** High temperature and moisture resistance (90°C wet or dry)

Combinations of these letters and numbers change the definitions somewhat.

Wiring away from the PV modules must be one of the building-wire type of wiring systems. These methods are discussed in Chapter 3 of the NEC®. Single-conductor exposed cables are generally not allowed nor are unjacketed multiple-conductor cables.

If protected from mechanical damage and not exposed to high temperatures, a UF multiple-conductor jacketed cable might be used. However, since the cable is limited to 60°C by Section 339 of the NEC®, it is generally not applicable outside the structure where higher temperature ratings are required.

Inside the structure, the conductors listed above may be used inside conduit. Additionally, since the temperature requirements are less, and the conduits are no longer exposed, 75°C, damp-rated insulation versions of these conductors may also be used (THHN, THW, RHW, XHHW, or RH). Local electrical codes generally require conductors in conduit for all commercial wiring.

Non-metallic sheathed cable (Type NM) also know as Romex® is commonly used for interior residential wiring where it can be installed properly inside walls in accordance with NEC® Section 336. Note that type NM cable is specifically excluded from storage-battery room applications.

PV Trackers
Trackers contain moving parts and as such may be wired with flexible cables. However, the slow rotation rates of trackers (1300 revolutions per decade) generally allow the use of the stiffer building-wire types of cable, and are therefore recommended. Also available are building-wire types of cables with extra-fine strands for additional flexibility where required.

If flexible cables are to be used, then types identified in Article 400 of the NEC® are appropriate. The markings

shown below should always be accompanied with the letters “W-A” to indicate that the cable is suitable for outdoor use.

Flexible cords suitable for PV tracker connections on trackers are: SE, SEO, SEOO, SJ, SJE, SJEO, SJEOO, SJO, SJOO, SJT, SJTO, SJTOO, SO, and SOO. These are all hard-service or extra-hard-service flexible cords. With the “W-A” rating, they are also suitable for outdoor use. Again, each of the letters has meaning:

S: Hard Service Flexible Cord

SJ: Junior Hard Service Flexible Cord

E: Thermoplastic elastomer insulation

T: Thermoplastic insulation

O: Jacket is oil resistant

OO: Jacket and Conductors are oil resistant

Battery Cables

Battery-to-inverter cables are usually large in size. They should be installed in conduit when being used between the battery enclosure and other equipment. As mentioned above, extra-flexible building-wire cables are available that may make the installation somewhat easier. Extra-flexible types that are available include THW, RHW, and USE. Since most batteries are in sheltered areas, cables with only a damp-rated, 75°C insulation are required.

Section 690-74 of the NEC® allows the use of Article 400 flexible cables for inter-cell battery connections as well as the connections from the battery to a fixed-wiring system. Since single-conductor Article 400 cables (types SC and W-this is not welding cable) are not readily available, it is suggested that extra-flexible, building-wire types of cables be used for connections to the battery when it is deemed necessary to use flexible cables.

Welding cables and automotive battery cables are not recognized by the NEC® for use in wiring electrical power systems.

Listed Cables

All conductors (except bare) and all cables should have all size and insulation type information plus the listing mark printed on them. The listing mark will normally be the “UL”, indicating that Underwriters Laboratories, Inc. has evaluated the cable for the intended use.

Summary

The choice of the proper cables for PV installations is relatively straightforward. Most cables are available locally or are stocked by PV distributors. Using the correct cable in each application will ensure a durable, safe, long-lasting PV system.

Questions or Comments?

If you have questions about the NEC® or the implementation of PV systems following the requirements of the NEC®, feel free to call, fax, email, or write me at the location below. 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-AC04-94AL8500. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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Focusing On Fuses

John Wiles

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There are fuses and there are fuses. Using the wrong electrical fuse in the wrong circuit can produce results as explosive as those produced by the fuse in a large firecracker. In this Code Corner, information will be presented on the various types of fuses that can be safely used in a photovoltaic (PV) power system.

Why Use a Fuse?

A fuse is one type of overcurrent device that is designed to be a sacrificial element in an electrical power system. Fuses are designed to open circuits when excessive currents are present due to overloads or faults, and in this manner are designed to prevent further damage to the system that might result if the fuse were not present. Fuses are sacrificial in that they are generally good for one time use and are destroyed in the process of operating. The use of fuses in a circuit provides cheap insurance should there be an accidental or unintentional fault in the system wiring or components.

Properly used, fuses can prevent fires and other damage when accidents happen. Such accidents include: a cable coming loose in the battery-to-inverter circuit, a cable in a module junction box contacting a grounded terminal, a nail driven through unprotected wiring, a wrench dropped across the DC inverter terminals, or an animal chewing through insulation and causing a ground fault.

In general, fuses melt internally when subjected to currents above their rating, and if the fuse rating is below the rating (ampacity) of the connected cable, the fuse will melt before the cable melts or is otherwise damaged. There are resettable fuses, electronic fuses, and renewable link fuses, but these types are not generally applicable to direct-current renewable energy systems.

Fuse Ratings

Fuses are rated by current, voltage, interrupt capability, and whether they are designed to operate on ac or DC circuits. The current rating of a fuse is the current that it can carry for indefinite time periods without opening. The voltage rating relates to the ability of the fuse to function and extinguish internal arcs when it opens. The interrupt rating is how large a short-circuit or fault current the fuse can interrupt or stop safely without allowing a continuing arc and without damaging the fuse body or fuse holder.

Are ac and DC Fuses the Same?

Direct currents are very difficult to stop or interrupt when compared to alternating currents. Alternating-current sources reverse the flow of current 120 times a second (in some locations 100 times a second on 50 Hz systems). Each time the current reverses, it goes to zero in magnitude. A zero current is very easy for a melting fuse to stop or interrupt—it is already stopped, and there is no force trying to sustain an arc across the fuse element.

DC currents, as the name implies, are currents that travel in one direction only. They do not reverse. Fuses bear the entire burden (with no help from the current) of acting to stop these currents. The internal elements of a fuse must react to an overcurrent condition (usually by melting) and as they react, they must do so with enough capability to interrupt the current from flowing while extinguishing any arc that might form. DC fuses are relatively sophisticated devices that have many different internal elements that must work together. The complexity of DC fuses makes them cost more than ac fuses that may contain only a single, meltable link.

What about fuses marked for both ac and DC? Fuses that can pass the harsh Underwriters Laboratory (UL) Standards testing for direct currents are also able to pass the less rigorous ac testing standards. Some manufacturers elect to put both markings on the fuse. To illustrate the difference in the tests used to evaluate fuses, consider the type RK-5 fuse (discussed below) which, from most manufacturers, has both ac and DC ratings. For a 100-amp fuse, the ac rating would be 600 volts with an interrupt rating of 200,000 amps. The DC rating for the same 100-amp fuse would be only 300 volts with an interrupt rating of 20,000 amps—both significant reductions from the ac ratings. There are fuses with equal ac and DC voltage ratings, but the DC interrupt rating is significantly less than the ac interrupt rating. In normal operation, a properly-designed fuse must carry the rated current and not respond to short-term (2-10 seconds) current surges from motors that are 2-6 times the fuse rating. Time-delay fuses, like the RK-5 fuses, can resist even longer surges.

Which Fuses are Suitable for DC?
Fuses suitable for DC fall into several types. Any fuse used in DC renewable energy circuits should have the DC ratings printed on the fuse or be shown in the UL Listing information in the technical data for the fuse. The technical data is available in the manufacturer's catalog, data sheets, and even on the WWW. Beware that seemingly identical fuses from different manufacturers may not have the same DC rating even though they are given as exact replacements in the manufacturer's cross-reference data. The DC rating and UL Listing should always be verified.

The branch-circuit rated "class" fuse is the most robust of the DC fuses for use in renewable energy systems. While the manufacturer's exact catalog number may vary, these fuses fall into several classes, each having different performance characteristics and sizes. Some of these classes are: RK-1 and RK-5 (1/10-600 amps), T (1-1200 amps), and CC (1/10-30 amps). Many manufacturers have DC ratings for some of these fuses, but not all of them.

The RK-1 and RK-5 fuses are the types of fuses that fit in the fused, safety-switch disconnects available from all electrical supply houses and many home centers. These RK fuses are grouped in sizes by voltage with the shorter sizes having a 125-volt rating and longer sizes having a 250 or 600-volt DC rating. They are also grouped by current range (1/10-30, 35-60, 70-100, 110-200, 225-400, and 450-600 amps). The actual sizes on the commonly used fuses range from 13/32" x 1-1/2" for the Class CC fuses up to 3-11/32" x 13-3/8" for the 600-volt, 600-amp RK-5 fuses.

For each voltage rating of fuses, there are fused safety switches that are sized to accept the largest and smallest fuse in each current range.

The "midget" type of fuse (13/32" x 1-5/16") is similar in size to the class CC fuse, but is not listed for branch circuit use. They may be listed and have DC ratings for use as a supplementary fuse. Ratings are 1/10-30 amps. The NEC allows the use of supplementary fuses in the PV source circuits. The values available below 10 amps make this fuse easy to match up with the maximum series fuse requirement listed on the back of PV modules.

Bussmann Division of Cooper Industries has a DC rating (125 volts) and a UL Listing on their type ABC ceramic-bodied fuse in certain ratings up to 20 amps. The DC interrupt rating of this 1/4" x 1" fuse varies from 35 to 750 amps depending on fuse size. These inexpensive fuses can be used in the PV source circuits as supplementary overcurrent protection, but should be protected by a current-limiting fuse in systems with batteries.

What is a Current-limiting Fuse?
Many people are not familiar with the concept of a current-limiting fuse. They think that since a fuse opens a circuit, it must limit current to zero and therefore all fuses are current limiting. Current limiting actually refers to how fast a fuse can open under fault conditions. When a fault occurs in a circuit without a fuse, the current ramps up to the short-circuit value that is determined by the voltage and current characteristics of the power source and the resistance and inductance of the circuit. The time the current takes to get to the final value is very short, but not zero. A fuse that is not current limiting operates so slowly (still in fractions of a second) that it lets the current get to the final value before opening the circuit. The entire circuit, and any other components in the circuit, are exposed to the full value of the short-circuit current.

A current-limiting fuse, on the other hand, operates so fast under fault conditions, that it limits the current in the circuit before it has had time to reach the maximum. With this fast action, components in the circuit are not subjected to the full fault current, and are somewhat protected from the abuse of being subjected to fault currents in excess of their interrupt rating.

There are no listed circuit breakers that are DC-rated and tested to UL Standards that meet the definition of current limiting for DC circuits. Some distributors carry circuit breakers that are identified as current limiting, but these items have been tested to European standards that are not the same as the UL Standards for current limiting.

When should a current-limiting fuse be used? The National Electrical Code (NEC) requires that current-limiting overcurrent devices be used wherever the available fault current exceeds the interrupt rating of the other components in the system. In PV systems, this might happen when circuit breakers or fuses with limited interrupt ratings (i.e. 3,000-5,000 amps) are used with a battery having a 15,000-20,000 amp short-circuit current capability. If these circuit breakers or fuses were subjected to the full 15,000 amps of fault current, they would probably not be able to open the circuit and would more than likely be destroyed in the attempt with flames evident. A current-limiting fuse installed near the battery would limit the fault current at the second overcurrent device location to 3,000 amps that could be safely interrupted. The class RK-1, RK-5, and T fuses described above are current-limiting fuses.

Are current-limiting fuses required in all systems with batteries? There are two cases where current-limiting

fuses are not needed. If all of the overcurrent devices and switchgear used in the system have sufficiently high interrupt ratings for the fault currents in their respective circuits, then each device will have no trouble interrupting fault currents should they occur. In this case, current-limiting fuses would not be necessary. Some of the power centers and power panels on the market are designed this way.

In small PV systems, the conductors to the battery may be small gage conductors (i.e. 18-10 AWG) and these small conductors have a resistance per foot that quickly adds up in a very few feet. Since the resistance of the circuit determines the magnitude of fault current, the available fault current at the overcurrent device may be limited to a value that is less than the interrupt rating of the overcurrent device. The calculations required to make this determination are beyond the scope of this article.

What About Automobile Fuses?

Automobile electrical systems are designed to operate in a different manner from stationary PV systems. In an automobile, the electrical loads are designed to operate when the engine is running and the alternator is charging the battery and supplying the loads. The alternator output is in the 14–16-volt range and the radios and lights are designed to run at about 12.8 volts. A voltage drop is allowed in the conductors to reduce the alternator voltage to that needed by the loads. With the exception of the starting circuit, most conductors to the lights, fans, and other loads have relatively high resistance. This circuit resistance includes the resistance of the steel body parts used for the negative conductor. The system is not designed to power the loads for any length of time on the battery alone when the engine is stopped—the result would be a dead battery. This high-resistance wiring limits the available fault current from the battery and allows the use of automotive fuses with a very low interrupt rating.

A PV system, on the other hand, operates for extended periods of time on the battery without charging from the PV. Voltage drop must be minimized since the batteries start out at only 12.6 volts when fully charged. To minimize voltage drop, larger, low-resistance conductors are used in PV systems. These low-resistance conductors allow higher fault currents throughout the circuits. These higher fault currents are substantially in excess of the very limited interrupt ratings of automotive type fuses.

Another factor in the use of automotive fuses is that most PV systems (except the very smallest) have several batteries with high short-circuit current capabilities when compared to the single automobile battery found in vehicles. While there are a few UL-Listed automotive fuses, most are not listed. Even those that are listed are listed for use only in vehicles, and are tested to standards for use in vehicles. They have none of the conventional interrupt and voltage ratings. Automotive fuses do not meet NEC requirements for installation in PV systems that come under the Code. For these reasons, it is inadvisable to use automotive fuses in renewable energy systems to meet NEC requirements.

Who Makes the Proper Fuses?

UL-Listed, DC-rated fuses are available from a number of manufacturers. They include Littelfuse, Bussmann, Gould Shawmut, and Ferraz. These manufacturers will provide technical information on the correct fuse to use in renewable energy applications that require listed, DC-rated fuses.

Where Can I Get the Proper Fuses?

Many of the advertisers in *Home Power Magazine* carry the proper fuses and can advise a RE system designer on the correct fuse to use. Local electrical supply houses and home building supply centers also carry fuses. There are a few large mail-order sources, but some require minimum purchases that may run into hundreds of dollars. Digikey Corporation, Newark Electronics, and Allied Electronics are also sources. In every case, the UL-Listed, DC rating of the fuse should be verified.

Questions or Comments?

If you have questions about the NEC or the implementation of PV systems following the requirements of the NEC, feel free to call, fax, email, or write me at the location below. 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-AC04-94AL8500. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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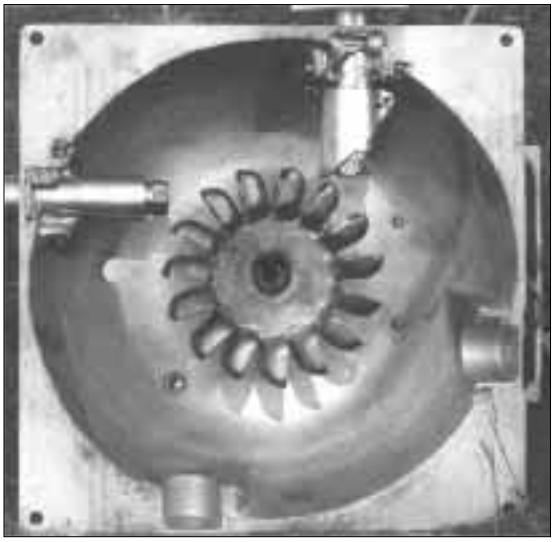

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Surfing through Breakers

John Wiles

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Breakers, the electrical kind—not those used for surfing—are used in electrical circuits as both overcurrent protective devices and as disconnect devices. This Code Corner will present some general information on circuit breakers and where they may be properly used.

Circuit breakers offer several advantages over the combination of fuses and disconnects and in many cases provide equivalent functions. They can be reset after they are tripped by overcurrents and do not have to be replaced, and they are usually more compact than fuses and switches with the same ratings.

Circuit breakers are found in nearly all modern residential load centers. While these breakers are rated for alternating current (AC) there are also circuit breakers rated for direct current (DC). The AC and DC breakers are not interchangeable (AC breakers should be used for AC circuits and DC breakers for DC circuits), although a few circuit breakers are rated for both AC and DC.

Branch Circuit vs. Supplementary

Like fuses, circuit breakers are used in branch circuit and supplementary applications. The branch circuit-rated breakers, like those found in the typical AC residential load center, are generally larger and more robust than the supplementary breakers that are used inside electronic equipment like radios, televisions, microwave ovens, and the like. It is generally required that both AC and DC supplementary circuit breakers be protected by a circuit breaker rated for branch circuit use nearer the power source.

In PV applications, the less expensive supplementary breakers may be used in PV source circuits. In these circuits they are used to provide overcurrent protection for the conductors to the modules while serving as a disconnect for these same source circuits. They can be used in source circuits because the fault currents from PV modules are limited. These breakers may also be used in these circuits because they are sufficiently far from the battery that the potential fault currents can be handled by these low-interrupt rating devices. Usually there is also a required current-limiting fuse located near the battery that may serve to further limit fault currents.

Some circuit breakers are also equipped with auxiliary switches that can be used in alarm circuits to signal when they are open. This allows breakers to be mounted in remote locations, e.g., on the roof (out of sight, out of mind), and have an alarm inside the house to indicate when they have tripped due to a fault or surge.

DC Rated Circuit Breakers

Listed, DC-rated circuit breakers installed in listed enclosures are generally not available to the individual but are manufactured by original equipment manufacturers (OEM) like Trace Engineering, Pulse Energy Systems, Heliotrope General, and others. These manufacturers are now producing assemblies of DC-rated circuit breakers in enclosures that can be used in renewable energy systems. Examples of these are the Trace Engineering “DC 250 Disconnect” which includes a 250 Amp circuit breaker to provide the disconnect and overcurrent protection for the circuit between the inverter and the battery bank. Up to four additional circuit breakers for either source or load circuits can be installed in the enclosure. Another example is the Trace ground-fault protection device which includes a dual circuit breaker and associated equipment to provide the PV array ground-fault protection required by section 690-5 of the National Electrical Code® (NEC).

When an OEM uses DC-rated circuit breakers in a piece of equipment, the ratings that apply to the individual circuit breakers may differ from the ratings that apply to the overall equipment. The equipment was fully tested for the application by an organization like Underwriters Laboratories (UL), and with laboratory testing of the entire product, ratings for the equipment may be in excess of the circuit-breaker ratings alone.

AC-Rated Circuit Breakers

Circuit breakers for AC use are usually installed in load centers made by the manufacturer that makes the breakers. These load centers hold a number of individual breakers and the necessary bus bars to connect them together. They are readily available in building supply stores and at electrical equipment supply houses. These AC circuit breakers and AC load

centers should only be used in AC circuits and never in DC circuits.

Dual-Rated Circuit Breakers

The Square D line of QO breakers and QO load centers are rated for 120/240 Volts AC, and they also have a lower voltage DC rating. When used in DC branch circuits (circuits from the battery to the load) they can be used on 12 and 24 Volt battery systems. Although rated for 48 Volts DC, the higher battery voltages (above 48 Volts) in normal charging and during equalizing pose stresses on these breakers and they should not be used in 48 Volt battery systems.

In PV source circuits there is the potential for higher than nominal voltages. A 24 Volt system with crystalline silicon modules may have an open-circuit voltage above 48 Volts. Because of this consideration, Square D QO breakers and load centers should be used only on 12 Volt PV systems. Some thin-film modules may not have open-circuit voltages this high and it may be possible to use these breakers in PV source circuits in 24 Volt systems. In both uses (source circuits and load branch circuits), the interrupt-current rating is only 5000 Amps and if they are placed in systems with large batteries and are located in the circuits near the batteries, they should have a current-limiting fuse between the battery and the circuit breaker. An analysis (beyond the scope of this column) of potential fault currents may be used to determine the need for a current-limiting fuse.

Disconnects

When circuit breakers are used as disconnects, their overcurrent rating must also be sufficient to handle the normal and expected operating currents. The OEM can obtain devices that look like circuit breakers, but have no overcurrent function, and are used only as switches or disconnects. These molded case switches, when they are used, must be accompanied by some form of overcurrent protection for the circuit.

In many cases, circuit breakers are more compact than equivalent fused safety switches. Like other devices used as disconnects, circuit breakers must be mounted so that the handles in the up position are no higher than six and one-half feet above the floor.

Current Limiting

There are no listed, DC-rated circuit breakers that are considered to be current limiting by US standards. There are some breakers on the market that are marketed as current limiting but they have been tested only to European standards and should not be used for current limiting in DC circuits that must meet NEC requirements. Wherever circuit breakers are used, the interrupt rating must be greater than the short-circuit current at that point. If the circuit breaker interrupt rating is less than the short-circuit current at the point where it is used, a current-limiting fuse should be used to limit the available short-circuit current.

1999 National Electrical Code®

The 1999 NEC® has been published and is available from most electrical equipment distributors in jurisdictions where the 1999 Code will be adopted at the first of the year. The National Fire Protection Association (see Access) also sells the NEC and will have the 1999 NEC Handbook® available by the end of the year. The next Code Corner will summarize the changes that appear in Article 690 in the 1999 NEC.

Questions or Comments?

If you have questions about the NEC or the implementation of PV systems following the requirements of the NEC, feel free to call, fax, email, or write me at the location below. 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-AC04-94AL8500. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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PV and the 1999 National Electrical Code

John Wiles

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The 1999 NEC has been published. It is available in large bookstores, local electrical supply houses, and directly from NFPA and other organizations. It will be automatically adopted by many states on January 1, 1999, but other jurisdictions may require legislative actions for adoption. The following information summarizes the most significant changes that were made in this code cycle.

Figure 690-1, long a source of confusion to many who thought it was a design diagram for a PV system, has been completely revised to show most of the components in different types of PV systems and how they typically interrelate.

In Section 690-2, many definitions were updated and five new ones were added to clarify the terms used in Article 690. For example, the term “Power Conditioner” was replaced with the more commonly used term “Inverter” and confusing references to solar hot water control systems were removed. The new AC PV module was defined (by the NFPA editors) as an Alternating Current Module, and definitions relating to stand-alone, hybrid, and utility-interactive systems were revised.

Section 690-4 was revised to clarify the interconnections of modules. Except for the Underwriters Laboratory (UL) label requirement for module-protection fuses, “daisy chaining” modules from junction box to junction box should not cause any problems.

Section 690-5, requiring ground-fault protection for the PV array on dwellings, was extensively revised for clarity and to simplify the requirement, while still maintaining system safety. Listed equipment (in utility-interactive inverters, power centers, and as separate components) is now available to meet this requirement. The hard-to-define term “disable” was removed from this section and from Section 690-18.

Section 690-6 is new, and was added to fully define the uses and connection requirements of the AC PV module. Among other things, a ground-fault protection device is required on the dedicated circuit connecting the AC PV module or modules to the load center. Since a receptacle outlet GFCI violates the dedicated circuit requirement, a panel device must be used. Some of the equipment protection ground-fault circuit breakers are not suitable for back feeding.

The UL requirements (found in the instruction manual of listed modules) for multiplying module open-circuit voltage and short-circuit current by 125% before using the NEC have now been included in the NEC. Section 690-7 includes new Table 690-7 that assigns the voltage multiplier as a function of the lowest expected ambient temperature. The factor will increase to 1.25 only when the expected temperature reaches -21° C (-5° F). The correction factor on open-circuit voltage will only be 1.06 if the modules are to be installed where the coldest expected temperature is a balmy 10-25° C (50-77° F). UL Standard 1703 will be modified to remove the requirement from the module instruction manuals. While that is being done, there may be modules in the pipeline that still have this requirement in the instruction manual. Those using the 1999 NEC are cautioned not to duplicate the requirement.

In a similar manner, Section 690-8 was revised to include the 125% multiplier on PV source circuit and PV output circuit currents, previously required in the PV module instruction manual. This section now includes both the 125% multiplying factor required to deal with daily variations in PV module output and the same 125% multiplier required to derate all conductors and overcurrent devices throughout the code. The combined factor of both 125% multipliers for PV source and output circuits is 156%. All other circuits are subject to only a single 125% multiplier (or the 80% derating factor found throughout the NEC).

Section 690-9 has exceptions that do not require overcurrent devices on limited types of circuits. These exceptions generally apply to small, single-module, direct-connected water pumping systems.

Section 690-10 is a new section that should benefit the installer and owner of stand-alone PV systems when

the overly cautious inspector has questions. The code now allows the PV system inverter AC current output to be less than the rating of the building load center or service entrance equipment. A 500 watt inverter may now be legally connected to a 120/240 volt, 200 amp load center. The conductor that is used for this connection only has to be rated to carry the 500 watt output of the inverter, not the 48,000 watts that the service entrance can carry. Also, it is now legal to connect a 120 volt inverter to a 120/240 volt load center when certain conditions are met. There must be no 240 volt circuits and no multi-wire branch circuits in the building.

Section 690-13 was revised to clearly state (at least as clearly as is possible in a code) that a switch or circuit breaker should not be placed in a grounded conductor.

AC PV modules may be grouped together on a single circuit with a single disconnect for all modules according to additions in Section 690-15.

Section 690-17 allows the use of a connector for a disconnect device as long as it is listed for the use and meets certain other code requirements. This applies primarily to AC PV modules.

The new Section 690-52 lists the markings required on AC PV modules.

Utility-interactive systems (including AC PV modules) received considerable attention in the 1999 NEC because of the expected proliferation of these systems. Marking the points of connection of these systems is required by Section 690-54. Most of Part G (Connection to Other Sources) was revised to allow easier connection of utility-interactive systems while still maintaining high levels of safety.

Section 690-72 was revised to require no charge controls for batteries on systems where the maximum charging currents are very low (less than 3% of battery capacity).

A new Part I was added to Article 690 to specifically address systems operating over 600 volts. Some of the larger utility-interactive systems may operate above 600 volts.

1999 NEC Handbook

The 1999 NEC Handbook (available from NFPA) includes significantly more detail, substantiation, and explanation of Article 690 and the changes that were made for 1999. It is also an excellent reference to have for other articles of the NEC, many of which apply to PV systems. It is now in an 8 1/2 by 11 inch format which makes for easier reading, but harder handling.

Changes to the NEC

The 1999 National Electrical Code® (NEC®) has just hit the streets, but complete and well-substantiated proposals for changes to the 2002 NEC are due to the National Fire Protection Association (NFPA) no later than 5 PM EST on Friday, November 5, 1999.

This gives those individuals wishing to change the new 1999 Code less than a year to write and submit the proposed changes and required substantiations. The correct form for submittal to the NFPA can be found in the back of the 1999 NEC. Electronic submissions may also be made. Contact NFPA for details. I can also forward substantiated proposals to the established PV Working Group regarding Article 690 for review.

Questions or Comments?

If you have questions about the NEC or the implementation of PV systems following 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 is supported by the United States Department of Energy under Contract DE-AC04-94AL8500. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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Perspectives on the National Electrical Code®

John Wiles

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The *National Electrical Code (NEC®),* updated and published every three years by the National Fire Protection Association (NFPA), is the most current and comprehensive electrical safety installation requirements document in the world. The 1999 *NEC* has just been published and work is already underway on the 2002 edition.

Hundreds of volunteers work on a three year cycle to review and update the *NEC* with the latest technology and methods of connecting electrical power systems. Representatives from the photovoltaic (PV) industry, academic institutions, the inspector community, Underwriters Laboratories, Inc. (UL), and the electrical utility industry meet regularly to modify and update Article 690 of the *NEC* which deals with PV systems. Although Article 690 covers only nine pages, most of the remaining 644 pages of the code also deal with aspects of PV installations.

The *NEC* has been made into law by over 40 states and by most major cities in the United States. It has been published for over 100 years. It represents the best ideas that have evolved in over a century of electrical power systems theory, design, and installation practice. There is always room for improvement and the document continues to evolve.

Paperback copies of the *NEC* are available for $30-45 at most electrical equipment distributors. The *NEC* and the hardbound *NEC Handbook* are available from NFPA (see Access). The *NEC Handbook* provides significant amounts of explanatory detail and numerous pictures and diagrams.

Safety Requirements

The *NEC* began as a fire safety code, but now includes personnel safety. The *NEC* requires that all equipment be examined for safety. While the local electrical inspector or authority having jurisdiction (AHJ) will inspect the field-installed wiring, the AHJ relies on the listing or labeling mark of an acceptable testing laboratory like UL or ETL to provide an indication that all equipment, conductors, and devices have been examined for safety.

The listing mark ensures that the equipment has been tested to meet a number of appropriate safety standards relating to electrical shock and fire hazards. Many inspectors will only inspect or approve systems that have been assembled with listed components. Insurance and mortgage companies may require electrical inspections, particularly on new construction or on additions to existing policies.

The inspector will be looking for the good workmanship required by the *NEC.* PV installations that resemble other electrical power installations will be more readily accepted than those installations that have unconventional installation practices or equipment that does not resemble normal electrical supply equipment.

All listed equipment comes with labels and/or instructions that define the requirements (developed in conjunction with the requirements of the *NEC*) for installation and use of that equipment. Violations of these instructions or requirements may result in unsafe systems and equipment damage. The inspector, in many cases, will verify that these instructions have been followed.

Almost all of the material that is printed on labels attached to electrical equipment has been placed there to meet a safety requirement—either established by the *NEC* or by the listing laboratory. Much of the material found in equipment instruction and installation pamphlets and manuals is also mandated by safety requirements.

Safety vs Performance

NEC requirements for PV installations and the requirements found on labels and in instructions for listed equipment, when followed, will generally result in a safe installation. While using equipment listed to UL Standards and installing that equipment to *NEC* requirements does not guarantee high levels of performance, higher performance and reliability frequently are achieved.

The required manner of sizing components, covered in past Code Corners, and the quality of listed equipment will generally result in PV systems that have higher levels of performance and reliability than systems that do not meet *NEC* requirements. Of course, it is possible to install a code compliant system using listed equipment in a poorly designed system or with misadjusted equipment, and then performance and reliability may suffer.

The 2002 Code Cycle

Although the 1999 *National Electrical Code* has just hit the streets, complete and well-substantiated proposals for changes to the 2002 *NEC* are due to the National Fire Protection Association (NFPA) no later than 5 PM EST on Friday, November 5, 1999. This gives those individuals wishing to change the new 1999 *NEC* less than a year to write and submit proposed changes with the required substantiations. The correct form for submittal to the NFPA can be found in the back of the 1999 *NEC.* Electronic submissions may also be made. Contact NFPA for details.

Ward Bower at Sandia National Laboratories and a team of people from the PV industry will be meeting several times throughout the year to write and substantiate proposals for the 2002 Code. Contact Ward directly if you wish to participate in these meetings. You can also send your ideas to me for entry into the system if you provide, or we can develop, the necessary substantiation. For now, we have the following items under consideration:

- Figure 690-1: Label the Energy Storage
- Section 690-5: Rewording for clarity
- Section 690-6: Developing ground fault equipment requirements for AC PV modules
- Section 690-7: Consider expanding for some thin film devices
- Section 690-8(b): Possible exception for current-limited devices
- Section 690-31(b): Modifying for clarity and technical correctness
- Section 690-45: Rewording or deleting
- Section 690-54: Reword for consistency
- Section H: Adding prohibition on flooded, steel cased batteries in systems operating over 50 volts

What are your ideas? Where have you had trouble with the code or with language not clear to electrical inspectors? What can be added or changed to make your job easier?

Please keep in mind that the *NEC* is a consensus document. If you participate with an input directly to NFPA, you will get a copy of all of the 2002 *NEC* proposals. You will also have a chance to comment on any of them and will get a copy of all of the comments on all of the proposals for the 2002 *NEC.* The proposal and comments documents weigh about eight pounds each and they include the deliberation, comments, and actions taken by each of the code making panels.

Also remember that the *NEC* is not a design document. To quote a senior code making official, "The *NEC* will not contain anything that will keep stupid people from making stupid mistakes."

Jump in—the code-making water is fine!

Access

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Code Summary, Checklist, & Manual

John Wiles

Sponsored by the Photovoltaic Systems Assistance Center
Sandia National Laboratories

Photovoltaic (PV) power systems should be installed in accordance with the requirements of the *National Electrical Code® (NEC®).* The local authority having jurisdiction should inspect these systems. The owner should be able to operate the system and know when maintenance is required.

This Code Corner will look at the chapters and articles in the *NEC,* and describe how they apply to PV systems. A checklist is presented that may be used by PV installers and electrical inspectors. Finally, an abbreviated Owner/User Operations and Maintenance manual is presented for use with utility interactive PV systems.

The Code

The *NEC* is divided into nine chapters with numerous articles in each chapter. The first four chapters of the *NEC* are considered general chapters and apply to nearly all systems:

Chapter 1—General

Chapter 2—Wiring and Protection

Chapter 3—Wiring Methods and Materials

Chapter 4—Equipment for General Use

Later chapters in the *NEC* cover specific installations, equipment, and conditions, and serve to modify and expand on the information in the first four chapters:

Chapter 5—Special Occupancies

Chapter 6—Special Equipment

Chapter 7—Special Conditions

Chapter 8—Communications Systems

Chapter 9—Tables

Article 90

Article 90 comes before Chapter 1 in the code. It is important because it describes what the code does and does not apply to. This article also discusses what information is mandatory, permissive, or explanatory.

Chapter 1

Article 100 covers definitions of terms used in the code. These are necessary for understanding the requirements throughout the code. Article 110 establishes general requirements for all electrical installations. Many of the good workmanship requirements are found in this section.

Chapter 2

Article 200 covers grounded conductors and the required color codes for these conductors. Articles 210, 215, 220, 225, and 240 cover circuit requirements and are applicable to both AC and DC circuits. Article 240 covers overcurrent devices and is particularly important to PV systems with multiple power sources and high available short-circuit currents from battery banks. Article 250 contains the grounding requirements and was completely revised in the 1999 *NEC.* Part H in the 1999 *NEC,* starting with Section 250-160, covers the grounding requirements for DC circuits. Article 280 covers the requirements for surge arrestors.

Chapter 3

Article 300 covers wiring methods. This is a meaty chapter of the code and contains most of the wiring methods that are used in PV systems as well as the ampacity tables for conductors (Article 310). Both multiconductor cables and individual cables in various types of raceways are covered in this chapter. The last few articles in this chapter cover the size and conductor limitation requirements associated with outlet boxes, pull boxes, and panel boards.

Chapter 4

In Chapter 4, the most commonly used articles are 400 and 402 on flexible cords and cables, which can be used for PV trackers and some other uses listed in Article 690. Article 430 on motors may have requirements that apply to well pump motors and the like. Article 445 covers the requirements for generators, and Article 450 covers transformers, both of which are used in PV systems. Article 480 establishes the requirements for storage batteries, but some of these are modified by Article 690 when batteries are used in PV systems.

Chapter 5

This chapter covers special occupancies. It generally only applies to PV systems when they are installed on one of these occupancies. Hazardous locations, such as those that might be found on oil rigs, are also covered. The recreational vehicle requirements covered by the code are addressed in this chapter.

Chapter 6

This chapter addresses special equipment, which includes PV systems (Article 690). Other articles that may involve PV power systems include Article 625 on electric vehicles, Article 640 on sound systems, Article 645 on computers, and Article 680 on pools and fountains.

Chapter 7
This chapter deals with special conditions such as emergency systems (Article 700) and standby power systems (Articles 701 and 702). Article 705 covers interconnected power systems that some inspectors look at when inspecting PV systems. The connection between PV systems and other power systems was eliminated in the 1999 code, but is still mentioned in the 1999 *NEC Handbook.* Article 720 addresses systems of less than 50 volts, which applies to many PV systems. However, Article 690 takes precedence when there is a conflict. Some inspectors will apply the requirements for power limited control circuits found in Article 725 to the low-power control circuits in PV systems.

Chapter 9
This chapter contains numerous tables that are used to provide additional information not found elsewhere in the code. For example, Table 8 gives the resistance of cables and that data can be used to calculate voltage drop in PV circuits.

PV Systems Inspector Checklist
It is advisable to get the authority having jurisdiction/electrical inspector involved at the earliest possible stage in the process. That person can provide valuable input to the design and identify potential problem areas before the system is installed. After the renewable energy system has been installed, it may be inspected by the local electrical inspector. Here is an abbreviated checklist that has been developed for use both by electrical inspectors and PV installers. The checklist may be used for early interactions, installation checks, and final inspections. It applies to both stand-alone and utility interactive systems.

The checklist is an outline of the general requirements for PV systems installations, found in the 1996 and 1999 *National Electrical Code (NEC)* Article 690. This list should be used in conjunction with Article 690 and other applicable articles of the *NEC. It* includes inspection requirements for both stand-alone PV systems (with and without batteries) and utility interactive PV systems. Where Article 690 differs from other articles of the *NEC,* Article 690 takes precedence [690-3].

References in brackets [ ] refer to sections in the 1996 NEC *and other relevant documents. Some sections have different numbers in the 1999* NEC. *The 1999* NEC *has been adopted by only a few states. The 1996* NEC *is the most commonly adopted version at this time. Some states are still using the 1990* NEC. *Legislatures and unions take time to change things.*

PV Arrays
- Listed PV modules are available from 6-7 manufacturers [110-3].

Conductors
- 90° C, wet-rated conductors are necessary. If exposed, use conductor type USE-2, UF (not a good choice due to availability and temperature limitations), or SE [690-31(b)]. Use RHW-2, THWN-2, or XHHW-2 in conduit [310-15].
- Conductor insulation must be rated at 90° C [UL-1703] to allow for operation at 70° C or greater near modules and in conduit exposed to sunlight.
- Temperature-derated ampacity calculations should be based on 156% of short-circuit current (Isc), and the derated ampacity must also be greater than the rating of the overcurrent device (156% Isc—see *Overcurrent Protection)* [690-8,9].
- Temperature derating factors of 60-65° C are suggested in cooler areas, 70° C in hotter areas, and 75° C in desert areas for ampacity calculations.
- Portable cords are allowed only on moving tracker connections [690-31(c), 400-3].
- Strain reliefs/cable clamps or conduit should be used on all cables and cords [300-4, 400-10].

Overcurrent Protection
- DC rated and listed fuses and circuit breakers are available from several sources. If the device is not marked DC, then verify the DC listing with the manufacturer.
- Overcurrent protection devices must be rated at 1.56 times short-circuit current (1.25 x 1.25 = 1.56) from modules [UL-1703, 690-8, module instructions]. Both of these 125% factors are now in the 1999 *NEC.*
- Supplementary devices are allowed, but branch-circuit rated devices are preferred [690-9(c)].
- Each module or series string of modules must have an overcurrent device protecting the module [UL-1703/NEC 110-3(b)]. This provision is frequently not used.
- Devices must be located near the charge controller or battery [690-9(a) FPN].
- Devices must protect the smallest conductor used to wire modules. Sources of overcurrent are parallel-connected modules, batteries, and AC backfeed through inverters [690-9(a)].

Charge Controllers
- Listed devices are available separately and inside listed PV power centers [110-3].
- There should be no exposed terminals unless the device is installed in a listed enclosure.

Disconnects
- Listed, DC-rated devices are available: Examples are Square D QO breakers for 12 volt DC systems, and Square D Heavy Duty Fused Safety Switches up to 600 volts DC.
- Listed PV Load Centers by Pulse Energy, Trace, and others for 12, 24, and 48 volt systems contain charge controllers, disconnects, and overcurrent protection for entire DC systems.
- Disconnects must be provided for all current-carrying conductors of PV source [690-13].
- Disconnects must be provided for equipment [690-17].
- Grounded conductors should not be fused or switched, but may have bolted disconnects.
- Connectors may be used as disconnects if they meet 690-33.

Inverters (Stand-Alone Systems)

- Listed stand-alone inverters are available from several manufacturers [110-3].
- DC input currents must be calculated for cable and fuse requirements: Input current equals rated AC output in watts divided by lowest battery voltage divided by inverter efficiency [690-8(b)(4)]. Note: The RMS value of current (particularly with reactive loads) may significantly exceed the average current calculated by this method. RMS current is what heats conductors and fuses.
- Cables to batteries must handle 125% of input currents [690-8(a)].
- Overcurrent devices should be located within 4–5 feet of batteries.
- Overcurrent/Disconnects mounted near batteries and external to PV load centers are suggested if cables are longer than 5-6 feet to batteries or inverter.
- Listed, DC-rated fuses and circuit breakers are available. AIC (amps interrupting current) should be at least 20,000 amps. Littelfuse marks DC rating; Bussmann and others sometimes do not [690-71(c), 110-9]. Verify listed DC rating with manufacturer, if unmarked.
- 120 volt inverters connected to 120/240 volt load centers with multiwire branch circuits have the potential for neutral overloading in the branch circuit [100–Branch Circuit, Multiwire].

Batteries

- None are listed.
- Cables should be building-wire type cables [Chapter 3]. Welding cables and auto battery cables don't meet *NEC* standards. Flexible USE/RHW cables are available. Article 400 cables are OK for cell connections, but not in conduit or through walls [690-74, 400-8]. See *Inverters (Stand-Alone Systems)* for ampacity calculations.
- Access should be limited [690-71(b)]. Install batteries in well-vented areas (garages, basements, outbuildings—not living areas).
- Cables to inverters, DC load centers, and/or charge controllers should be in conduit [300-4].
- Exposed battery terminals should be accessible only to qualified people.

Inverters in Utility Interactive (UI) Systems

- Listed units are available from three manufacturers and should be used for the safety of utility personnel. These units eliminate the possibility of energizing unenergized utility lines.
- UI inverters must be on dedicated branch circuits with backfed overcurrent protection [690-64].
- UI inverters must have external DC and AC disconnects and overcurrent protection [690-15,17].
- Total rating of overcurrent devices connected to an AC load center (main breaker plus PV breaker) must not exceed load center rating (120% of rating in residences) [690-64(b)(2)].

Grounding

- Only one grounding electrode conductor connection (a bonding conductor) to DC circuits (grounded conductor) and one connection to AC circuits (neutral) should be used for system grounding [250-21].
- AC and DC grounding electrode conductors may be connected to the same grounding electrode system (ground rod) [690-41,47, 250-21].
- Equipment grounds are required even on ungrounded, low voltage systems [690-43].
- On 12 volt and some 24 volt ungrounded systems [690-41], disconnects and overcurrent devices are required in both of the ungrounded conductors in each circuit [240-20(a)].
- Equipment grounding conductors for DC circuits from PV arrays may be run apart from other conductors [250-57 (b) Ex 2]. This routing is suggested to minimize damage in areas where lightning surges are common.

Conductors (General)

- Standard building-wire cables and wiring methods can be used [300-1(a)].
- Wet-rated conductors should be used in conduits in exposed locations [100 Definition of Location, Wet].
- DC color codes are the same as AC color codes—grounded conductors are white and equipment grounding conductors are green or bare [200-6(a), Ex 5]. Ungrounded terminals/conductors should be labeled to show polarity.

Owner/User Operations and Maintenance Instructions For Utility Interactive Photovoltaic Power Systems

After the system has been installed and inspected to ensure that it meets the safety requirements of the *NEC,* the installer/vendor should work with the owner/user to ascertain that the owner knows how the system is supposed to operate. While maintenance is not normally done by the owner, that person must at least know when the system is not performing properly so that service personnel can be notified. The brief manual presented below is intended for the owner of a utility interactive PV system.

Introduction

utility interactive photovoltaic (PV) electrical power systems in general require relatively little user operational involvement/control and low levels of user maintenance. These systems tend to operate well until there is some sort of component failure and then a qualified person such as an electrician or electrical contractor must usually perform maintenance actions.

In no case should the unqualified owner/user open any cabinet, enclosure, or junction box containing electrical wiring. These systems are electrical power systems, and as such may pose hazards when an untrained, unqualified person attempts to troubleshoot or repair them.

System Performance Verification

After the system has been installed and has been inspected

for safety by the authority having jurisdiction (electrical inspector), the installer/vendor should turn on the system and demonstrate the proper operation to the user/owner. The installer should test the system on a bright, clear, sunny day using a pyranometer (to measure the solar resource) and AC wattmeter (to measure the AC power out of the system) and document the system performance.

Operation

In nearly all cases, utility interactive systems will automatically start to produce power whenever the sun is shining, the utility grid is present, and all disconnects are closed. There are no controls that need to be operated or adjusted on a daily or other periodic basis. The installer/vendor should close all disconnects at the time of installation and show the owner/user where they are located. In many cases, these disconnects will also be circuit breakers that can trip open under fault conditions. If there are user serviceable fuses, the installer should also show the owner/user where they are located and how to change them. These basic instructions should be documented and presented to the owner/user at the time of installation.

Each system indicates power production in a different way. Some inverters may have numerical or meter power displays, some may have flashing lights, and others may have only a kilowatt-hour meter on the output. A few systems may have no readily discernible method of determining if the system is operating. Depending on the utility billing and the way in which the energy is measured, there may or may not be an indication in the utility bill of the amount of energy that is produced from the PV system.

The installer/vendor should show the owner how the PV output can be observed (digital readout, flashing light, KWH meter dial spinning, etc.). On subsequent sunny days, the user may make the same observation to determine qualitatively that the system is operating. If the energy production is metered (kilowatt-hour meter) or appears on the utility bill, then the customer may estimate performance from month to month based on this reading and the estimated number of sunny days.

Some newspapers report a solar index related to the amount of solar energy each day and this may be correlated with an energy meter reading for more of a quantitative evaluation of system performance. It should be noted that shading and microclimate at the site of the PV system may result in significantly different levels (usually lower) of available solar energy than the numbers from an official solar monitoring station. If the qualitative or quantitative assessment indicates that the PV system is not performing as expected, maintenance actions should be initiated.

Maintenance

When maintenance actions are indicated, the owner/user should verify that all disconnects/circuit breakers are closed, as they were at the time of the initial installation. User serviceable fuses that are thought to be open (blown) may be changed for fuses that are known to be good. Instructions provided by the system installer should show how to do this.

If circuit breakers continue to trip open, fuses continue to blow, or the qualitative/quantitative indicators of correct performance do not become normal, then the owner/user should contact the installer/vendor or other qualified person. This qualified person should troubleshoot the system, find and correct any deficiencies, and then retest the system for power output while measuring the solar resource.

Periodically (once every year or two), the owner/user should have the AC output of the system tested by a qualified person while the solar resource is measured to determine if the system meets the expected or warranted performance levels.

Summary

Happy owners and profitable PV installations are ensured by using listed equipment, installing to code, inspecting for safety, verifying performance, and ensuring that the owner understands how to operate the system and monitor the performance.

Access

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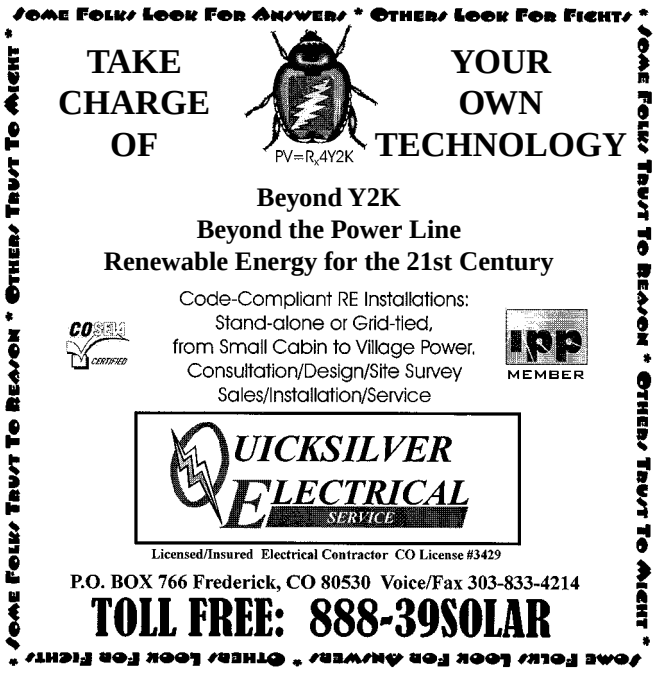


To Ground or Not to Ground: That is *Not* the Question (in the USA)

John Wiles

Sponsored by the Photovoltaic Systems Assistance Center, Sandia National Laboratories

"Even most 12 volt PV systems shall be grounded in some way," sayeth ye *National Electrical Code (NEC).* This Code Corner will begin with the code requirements for a PV system from the ground up.

Subsequent articles will discuss the code requirements for PV hardware on the roof and for the components in between. The terminology, the whys, and the hows of grounding PV systems will be addressed. Proper grounding will enhance safety (both user and equipment), improve performance, and may even reduce costs. Article 250 (Grounding) was completely revised in the 1999 edition of the *NEC* and references to Article 250 will refer to the new edition.

Why?

Research and experience have indicated that both grounded and ungrounded electrical systems can be safe. Europeans have a 100 year tradition of operating ungrounded electrical power systems, and European codes reflect this. The European Community also makes use of double-insulated components and electronic ground-fault detectors in many applications.

Reports in the U.S. have indicated that on ungrounded DC electrical systems (non-PV) used by electrical utilities, when a ground fault occurs that is undiscovered or unrepaired, a second ground fault will frequently occur for the same reason within two weeks. Double ground faults create problems because overcurrent devices may not sense them and may not offer protection. The utilities always rely on extensive electronic ground-fault detectors in their ungrounded DC electrical systems.

In the United States, the arguments for and against grounding were carried out over several decades as the *NEC* was being developed, just before the turn of the century. Unlike the Europeans, the U.S. decided to require the use of grounded systems. For those who want to achieve a good understanding of the subject of grounding, the *NEC Handbook* and the International Association of Electrical Inspectors (IAEI) *Soares Book on Grounding* are recommended (see Access). The IAEI book even gives some of the history of grounding requirements in the U.S.

Electrical systems in the U.S. (including PV systems) are generally solidly grounded to limit the voltage with reference to ground during normal operation, and to prevent excessive voltages due to surges from lightning or unintentional cross connections with higher voltage lines.

In PV systems, the modules are usually mounted in high, exposed locations where they are prone to picking up induced surges from nearby lightning strikes. Utility-interactive inverters are also subjected to surges on utility power lines. In addition, systems using PV power to run computers with hardwired modems are subject to surges from the telephone line. Proper grounding effectively reduces these potential problems and more.

Terminology

The term "grounded" indicates that one or more parts of the electrical system are connected to the earth, which is considered to have zero voltage or potential. The earth is used as a reference because there is so much of it, and many conductive surfaces are connected or in contact with it. Most metallic objects such as metal building frames, as well as other electrical/electronic systems (TV, telephones, etc.) are in contact with or connected to earth. In some areas, the term "earthing" is used instead of "grounding."

Plumbing (including bathtubs and sinks) used to be solidly grounded. But now it may be not connected to ground because of the use of plastic pipes and drains. When faults occur in electrical systems, those faults are frequently faults to earth (ground faults). To better understand the grounding requirements of the *NEC,* it is necessary to examine several terms used in conjunction with grounding.

A *grounded conductor* is a conductor that normally carries current and is connected to the earth. Examples are the neutral conductor in AC wiring and the negative conductor in many DC systems. Note that some DC systems such as telephone systems connect the positive conductor to ground rather than the negative conductor. A system is a "grounded system" when one of the current-carrying conductors is grounded.

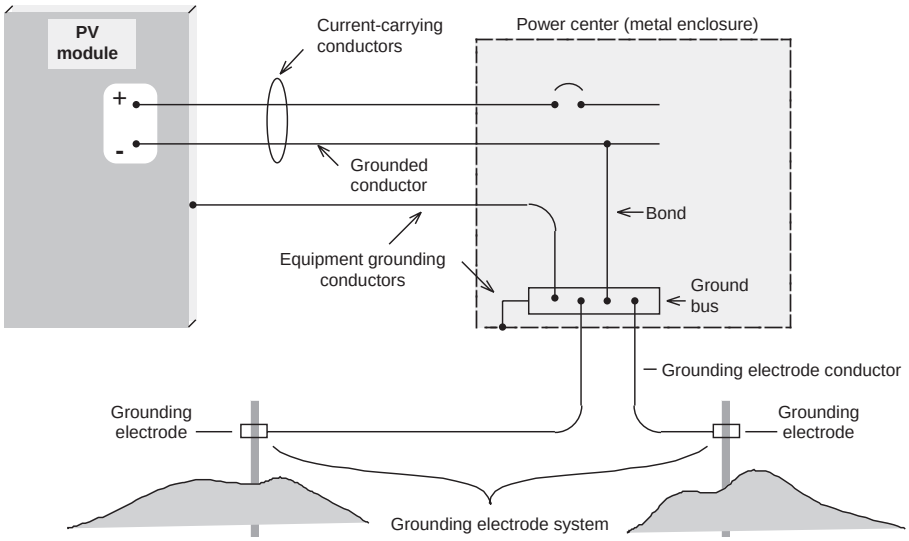
An *equipment-grounding conductor* is a conductor that does not normally carry current (except under fault conditions) and is also connected to earth. It is used to connect the exposed metal surfaces of electrical equipment together and then to ground. Examples are the bare conductor in non-metallic sheathed cable (Romex®) and the green, insulated conductor in power cords for portable equipment. These equipment-grounding conductors help to prevent electrical shocks and allow overcurrent devices to operate properly when ground faults occur.

A *grounding electrode conductor* is the conductor between a common single grounding point in the system and the grounding electrode. Splices are not normally made in this conductor. The *common single grounding point* is a point where the grounded conductor and the equipment-grounding

conductors are connected to the grounding electrode conductor.

A *grounding electrode* is the metallic device that is used to make actual contact with the earth. There are "made" grounding electrodes, such as the common 5/8 inch diameter, 8 foot long (16 mm x 2.4 m) ground rod. Other types of grounding electrodes include metal water pipes, metal building frames, and concrete-encased cables (known as Ufers, after their inventor). Specific requirements for each of these grounding electrodes can be found in Article 250 of the *NEC.* Local codes and practices vary greatly and should be investigated to determine which types of electrodes are in common use.

Figure 1: Grounding Electrodes



Bond is a term that, as a verb, means to connect two or more points together. As a noun, it usually refers to the connection between the grounded conductor, the equipment-grounding conductors, and the grounding electrode conductor. Bonding is also used to describe connecting all of the exposed metal surfaces together to complete the equipment-grounding conductors.

A *grounding electrode system* is a system where two or more grounding electrodes are connected together. These systems are common in PV installations where there are two grounds (such as an existing one for the AC system and a new grounding electrode that has been installed for the DC system). See *NEC* Sections 250-81 through 250-86.

Figure 1 shows how the grounding components are related in a PV system.

There is Grounding and There is Grounding

***NEC* Requirements**

The *NEC* establishes requirements for nearly all field-installed electrical systems that are not owned and operated by a utility on utility property. For example, it covers PV systems (Article 690), cranes and hoists (Article 610), EV charging stations (Article 625), electric welders (Article 630), computers (Article 645), communications systems (commercial and amateur, Chapter 8), and most other electrical installations.

The *NEC* covers low voltage systems (less than 50 volts) in Article 720 and high voltage systems (over 75 kilovolts) in Section 110. It covers systems with zero frequency (direct current) through radio frequency (RF) systems into the gigahertz range.

Equipment Grounding

With respect to grounding, the *NEC* requires that all PV systems have equipment-grounding conductors that connect all of the exposed metal surfaces of the system to a grounding electrode (690-43). This applies to any PV system that has field-installed wiring (items like solar wristwatches and path lights are excluded), even those operating at 12 volts. As noted above, the non-current-carrying conductors may be bare (uninsulated) or covered with green insulation. They are normally routed along with the current-carrying conductors.

System Grounding

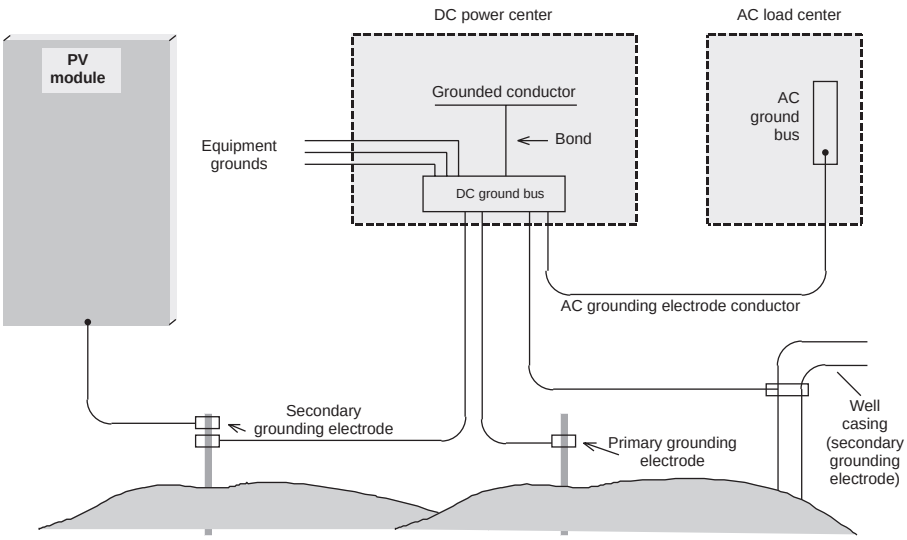
When it comes to the grounding of one of the current-carrying conductors, different rules apply. Those systems with a system voltage over 50 volts are required to be grounded by having one of the current-carrying conductors connected to the grounding electrode. The system voltage is the maximum open-circuit voltage of the system as defined in Article 690.

PV modules (crystalline silicon-based) have open-circuit voltages that increase with decreasing temperatures. At temperatures below 25°C (77°F), the open-circuit voltage will be higher than the open-circuit voltage marked on the back of the PV module. Since this system voltage is dependent on temperature, a temperature correction factor is necessary (Table 690-7). The correction factor is selected based on the lowest expected ambient temperature where the PV system is to be installed, and is used as a multiplier on the rated, open-circuit voltage of the module. At low temperatures and with high winds, or in the early morning hours, the PV module may not heat up, so the lowest ambient temperatures for the area should be used.

The calculations required by Section 690-7 and Table 690-7 of the *NEC* indicate that a nominal 12 volt PV system has a system voltage of about 27 volts in worst case, low-temperature installations. This is determined by multiplying the 22 volts open-circuit voltage at 25°C (77°F) by a correction factor of 1.25 for temperatures below -21°C (-6°F). Therefore, 12 volt systems do not have to have one of the current-carrying conductors grounded.

A nominal 24 volt system has a rated open-circuit voltage of about 44 volts at 25°C (77°F). This means that one of the current-carrying conductors must be connected to the grounding electrode when the expected lowest temperatures are below about -10°C (14°F). Temperatures below this will cause the open-circuit voltage to exceed 50 volts.

Figure 2: Multiple Grounding Electrodes



Prior to the 1999 edition, the *NEC* did not have Table 690-7, and the voltage multiplication factors were included in the instructions provided with listed PV modules. Since Underwriters Laboratories (UL) Standard 1703 for PV modules has not yet been revised, there will be PV modules in the distribution network that have the older instructions, duplicating the instructions in the 1999 *NEC.* Either the 125 percent factor in the PV module instructions or the Table 690-7 corrections should be applied, but not both.

System Grounding of 12 Volt Systems —Other Considerations

On 12 volt PV systems and some 24 volt PV systems, the grounding of one of the current-carrying conductors is optional, as noted above. However, in Articles 230, 240, and 690, the *NEC* requires that ungrounded conductors in any electrical system have overcurrent protection and disconnects. Since a 12 volt PV system must already have equipment-grounding conductors, a grounding electrode conductor, and a grounding electrode, there is a significant cost advantage and sometimes a performance advantage to grounding the system.

With the addition of one wire (the bond shown in Figure 1), the number of disconnect poles and overcurrent devices can be cut in half since these devices are not required in the now grounded, current-carrying conductor. Since each of those disconnects and overcurrent devices has some small but measurable voltage drop, eliminating as many of them as possible will improve system performance and increase reliability.

It should be noted that most PV power centers on the market have one of the conductors grounded internally and have provisions for only single-pole overcurrent devices and disconnects. They cannot be used in an ungrounded 12 volt system.

Furthermore, low-voltage fluorescent lamps start more reliably when installed in a grounded system and inverters and other electronic devices can be installed so that they radiate less noise when one conductor is grounded.

Equipment Grounding

Table 250-122 in the *NEC* specifies the size of the equipment-grounding conductors for each circuit. The size is based on the rating of the overcurrent device protecting the circuit and ranges from number 14 AWG (2 mm^2) conductor in a 15 amp circuit to a number 3 AWG (26.7 mm^2) equipment-grounding conductor in a 400 amp circuit.

Recent research has determined, however, that the equipment-grounding conductor for PV source and PV output circuits must at least be able to handle 125 percent of the PV short circuit currents. In most cases, this indicates that the equipment-grounding conductors for PV source circuits and PV output circuits must be the same size as the current-carrying conductors. These are sized at 156 percent of the module short-circuit current. Proposals for the 2002 *NEC* will be submitted to reflect this requirement.

Of particular interest to PV installers is Section 250-122(b) of the *NEC.* It states that if the current-carrying conductors have been oversized to minimize voltage drop, then the equipment-grounding conductors must also be oversized in the same proportion. But the grounding conductors never have to be larger than the current-carrying conductors. Oversized conductors (above minimum ampacity requirements) are frequently used on long circuits between the PV array and the charge controller to reduce voltage drops in these lines. Table 8 in Chapter 9 of the *NEC* shows the cross sectional area of different sized conductors, and the calculation is straightforward.

Oversizing the equipment-grounding conductors is required by the *NEC* to ensure that overcurrent devices function properly during ground faults. Section 250-122(a) says that the equipment-grounding conductors do not have to be larger than the current-carrying conductors.

In summary, the equipment-grounding conductor should be as large as the current-carrying conductors in PV source and PV output circuits. In other circuits, follow Table 250-122.

Equipment that must be connected to the equipment-grounding system includes the exterior metal surfaces of PV modules, power centers, charge controllers, inverters, switchgear, outlet boxes, and overcurrent devices. Equipment listed to UL standards will have properly marked connections and instructions for connection of the equipment-grounding conductors.

The equipment-grounding requirement in renewable energy systems is usually met by using a separate conductor run with the current-carrying conductors. If the system uses metal conduit (and many commercial systems do), then the conduit can serve as the equipment-grounding conductor when used with listed fittings.

The connection of the equipment-grounding conductor can run from module frame to module frame and then to the switchgear and power center. The order of the connections is not critical and multiple connections or parallel connections do not cause problems. Each equipment-grounding conductor may also be run from the metal surface being grounded to a central point like the power center.

The connections and wiring for the equipment-grounding conductor must be continuous to allow fault currents to properly operate overcurrent devices. Removal of a piece of equipment for servicing must not interrupt the equipment-grounding system for other equipment.

Generally, module frames are made of anodized aluminum. The anodized coating or aluminum oxide that forms on aluminum surfaces is a relatively good insulator. This is why listed PV modules have a special point marked for connecting the equipment-grounding conductor. A stainless steel screw is usually supplied which helps to ensure a good electrical connection.

It should be noted that while the anodized surface insulation on PV modules makes it hard to get a good equipment-grounding connection, the aluminum frame is still exposed metal. If it is not grounded, it can produce an electric shock when ground faults occur. These can occur between the current-carrying parts of the module and the frames, or when the frames are inadvertently energized by other power sources.

Aluminum PV module frames do not stay well grounded when they are only bolted to the metal mounting stands. If the UL listing allows, and the module manufacturer provides special parts and instructions, some PV modules may be grounded through the mounting bolts to the frame. The *NEC* prohibits the earth from being used as the sole equipment-grounding conductor, so bolting the PV modules to a metal stand that is inserted in the ground does not meet the requirements for a safe installation unless a separate equipment-grounding conductor is used from the frame to the main grounding point or electrode.

The *NEC* requires that all conductors for a given circuit be routed together in the same cable or conduit. An exception is the equipment-grounding conductor for DC circuits. When secondary grounding electrodes are used and they are bonded to the primary grounding electrode (as described below for surge protection) the bonding conductor may become an equipment-grounding conductor and should be sized appropriately. In this case, the DC equipment-grounding conductor may not be grouped with the current-carrying conductors.

Grounding the Current-Carrying Conductor

The connection between one of the current-carrying conductors and the grounding electrode conductor is made only at one point in the system. This is known as the system ground. This single-point connection is usually made in a power center and is shown as the bonding conductor in Figure 1. If this connection is inadvertently made in more than one place (for example, at the PV modules and in the power center or at the load), then unwanted currents will flow in the equipment-grounding conductors. These unwanted currents may cause inverters and charge controllers to be unreliable and may interfere with the operation of ground-fault detectors and overcurrent devices.

The use of RV and automotive electrical appliances and audio gear sometimes causes problems, as does the use of DC-powered radio and telephone equipment. Much of this equipment operates at 12 volts DC, with chassis and antenna ground connections that are common with the negative DC power conductor. It is pretty easy to get the negative DC conductor connected inadvertently to ground in two or more places when using these types of electrical devices.

The *NEC* also requires that equipment-grounding conductors be used with these appliances to ground the exposed metal surfaces. It becomes difficult to do this with a third conductor in a way that does not result in multiple point connections between the negative, current-carrying conductor and the grounding system. Solutions to minimize the problems include non-metallic enclosures to isolate the grounded chassis and ground-isolated antenna connections.

Listed power centers and disconnect switches usually have a provision for the single-point connection. In most DC power centers and AC load centers, the connection is automatically made when all equipment-grounding conductors, the negative conductors, and the grounding electrode are tied to a single, grounding bus bar which is also bolted to the metal enclosure.

When using standard, fused safety switches for disconnects throughout the system (PV array and subarray, battery, etc.), an insulated bus bar usually must be added. This is used to make the connections for the unswitched, grounded conductor running through the switch enclosure or subpanel.

There is frequently a bus bar supplied for the unswitched conductor. But this bus bar is sometimes grounded to the enclosure, presenting the opportunity for an inadvertent second grounding of the conductor that is intentionally grounded elsewhere in the system. Insulated, or ungrounded, bus bars should be used in these devices to prevent that second ground connection.

Grounding Electrode Conductor

The grounding electrode conductor (also known as the ground wire), is usually a single-conductor bare wire (it can also be insulated—color is not specified). It connects a grounding bus bar in a power center or another disconnect device to the grounding electrode (also known as the ground rod).

In the 1993 and earlier editions of the *NEC* this ground wire had to be the same size as the largest conductor in the DC system. In the 1996 *NEC* a number of exceptions, when met, allowed smaller conductors to be used. There are jurisdictions throughout the country that still are applying the 1993 and earlier versions of the *NEC* so some inspectors may require the larger conductors.

If there is only one conductor connected to the grounding electrode, then Section 250-166 of the 1999 *NEC* allows DC grounding electrode conductors as small as number 6 AWG (13 mm^2) copper to be used. Appropriate mechanical

protection is required where this conductor may be subject to physical abuse. However, if multiple conductors are connected to the grounding electrode, a grounding electrode conductor as large as the largest conductor in the DC system must be used.

Multiple connections to the grounding electrode conductor refer to connections from the power system and do not refer to telephone, TV, cable, or other types of communications grounds. Multiple connections to the grounding electrode may also occur when several ground rods are bonded together to form a grounding electrode system, and when metal water pipes or well casings are bonded to the ground rod. Multiple connections are also common where DC and AC grounding electrode conductors are connected to the same ground rod. Several equipment-grounding conductors tied to the ground rod also nullify the use of a small grounding electrode conductor.

The reasoning behind not allowing a small grounding electrode conductor is this: if more than one conductor is connected to the ground rod, some of those conductors may be required to carry high fault currents. If only one conductor is connected to the ground rod, then the other properly sized and connected conductors in the system will carry the fault currents, and the smaller conductor to the ground rod will only be required to stabilize the system voltage with respect to earth. Only in lightning strikes and inadvertent connections to high voltages will the grounding electrode conductor be required to carry high currents. There are similar requirements and allowances for the AC grounding electrode conductor.

Practical Considerations

How then, can the system be connected so that a small equipment-grounding conductor can be used? One method is to designate a single grounding bus bar in the system. This bus bar is usually found in listed DC power centers. All equipment-grounding conductors should be connected to this bus bar. If there are multiple grounding electrodes in the system, the secondary electrodes should all be connected to this bus bar to complete the grounding electrode system.

If there is a requirement to provide a single-point ground for the AC portions of the system, then the grounding electrode conductor from the AC part of the system should be tied to this bus bar. Finally, the smaller (as allowed by the *NEC*) grounding electrode conductor can be connected from the grounding bus bar to the primary grounding electrode conductor. Figure 2 demonstrates these connections where the DC grounding electrode conductor is larger than the AC grounding electrode.

While this method meets the requirements of the *NEC,* it may not provide the best protection against lightning damage. Running all grounding conductors to a common point inside the building may increase the potential for damage from nearby lightning strikes.

In high lightning areas, it may be preferable to “bite the bullet” and use the larger grounding electrode conductor from the power center to the ground rod. Then secondary grounding rods and pipes and metal well casings can be connected directly to the primary grounding electrode without coming into the building. Equipment-grounding conductors from the PV modules may also be run directly to secondary or primary grounding electrodes providing additional surge protection.

Each of the grounding electrodes described below, where used as a primary electrode, has a different requirement for the size of the grounding electrode conductor. See *NEC* Sections 250-66 (AC) and 250-166 (DC). If the requirements for the AC and DC grounding electrode conductors are different, the larger of the two should be used for any common conductor. The common grounding point should be associated with the largest required grounding electrode conductor.

Grounding Electrodes

In Section 250-50, the *NEC* considers metal building frames that are in contact with the earth and metal water pipes connected to the earth to be the preferred grounding electrodes. Unfortunately, wood frame buildings, plastic pipes, and plastic sleeves on copper pipes make these options frequently unavailable to the renewable energy user.

The *NEC* describes commonly available grounding electrodes, such as “made” electrodes (the common 8 foot (2.4 m) ground rod), concrete encased cables or electrodes, and ring electrodes which consist of buried conductors encircling the building. Made grounding electrodes are listed by UL and are connected to the grounding electrode conductors with clamps that are listed for this purpose. If the clamps are to be buried, they should be listed and marked for such use.

As a primary grounding electrode, the ground rod must be driven into the earth to a depth of at least 8 feet (2.4 m). Angles of no more than 45 degrees away from vertical are allowed where the ground is rocky. If these conditions cannot be met, then a second rod or one of the other grounding electrodes must be used to supplement the primary electrode. Best performance will be achieved if the second electrode is more than six feet (1.8 m) away.

In some areas of the country where homes are built on concrete slabs, a grounding electrode is buried in the concrete slab. This usually works better as a grounding electrode than an eight foot (2.4 m) ground rod.

Summary

Equipment and system grounding are important details in a renewable energy system. They reduce the potential for electrical shock and allow the system to respond properly to ground faults. Proper application of the *NEC* requirements for grounding will result in safer systems, higher levels of performance, and reduced costs. The requirements for PV systems are generally the same as the requirements for other electrical power systems.

Questions or Comments?

If you have questions about the *NEC* or the implementation of PV systems within the requirements of the *NEC,* feel free to call, fax, email, or write me at the location below. 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-AC04-94AL8500. Sandia is a multi-program laboratory

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Access

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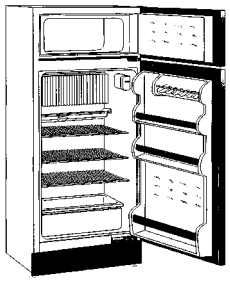

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