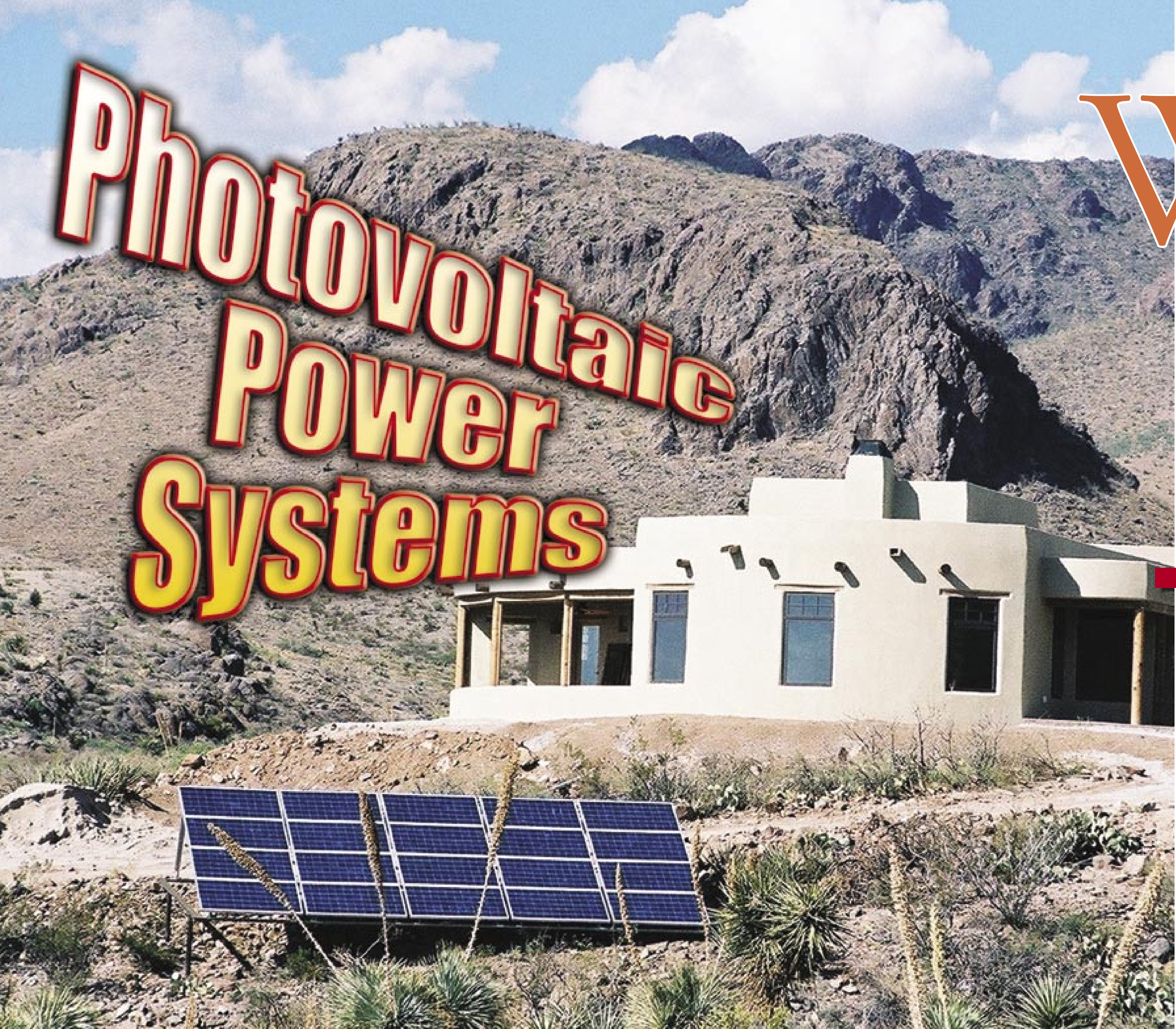
Photovoltaic Power Systems



What inspectors need to know

by John Wiles

Photovoltaic (PV) power systems are being installed by the thousands throughout the United States. In states like California, New York, New Jersey and a few others where financial incentives are available, the PV business is booming. Over 560 megawatts of PV modules were produced internationally in 2002 and annual production is increasing each year.[1] The first PV cells produced nearly fifty years ago are still producing power and modern PV modules are expected to produce energy for the next forty years or longer. The power output from PV systems ranges from a few hundred watts to several megawatts. Most of the systems are not operated or owned by any electric utility and therefore come under the requirements of the *National Electrical Code*. They must be inspected to ensure the safety of the owners, operators, service personnel, and the public.

The *Code* requirements for a typical residential PV system are at least as complex as those for residential wiring, and the direct current (dc)

Photo 1. This aerial view of two PV systems at the Salt River Project (SRP) Park and Ride in Phoenix, AZ shows a 200 kW utility-interactive system mounted on the shading roof of a parking structure in the left center and a 2 kW utility-interactive PV system mounted on the roof of a small building in the upper right. PV modules are blue in color.

Photo 2. The 200 kW inverter associated with the larger 200 kW PV array

Photo 4. A view from the ground of the smaller 2 kW PV system

Photo 3. The 2.5 kW inverter associated with the smaller 2 kW PV array

portions of the system coupled with the alternating current (ac) interconnection to the utility grid make PV installations somewhat unique. Because the PV industry is thriving and growing rapidly, individuals, companies, and organizations with varying degrees of knowledge, skill, and experience are installing these systems. Large (and some small) PV systems integrators and vendors working with experienced electrical contractors who have jointly pursued additional PV-specific training and who work closely with the local permitting and inspecting authorities usually (but not always) perform the best, most *Code*-compliant installations.

On the other hand, individuals or organizations who have little or no experience or training in installing electrical systems of any type are installing more than half

of new PV systems. These systems may be unsafe (not *Code*-compliant) at initial installation, may develop hazardous conditions over the life of the system, may be hazardous to operate or service, and may fail to deliver the full performance of a well-designed and installed PV system.[2]

The authority having jurisdiction (AHJ) is the key player in ensuring that these less-than-good PV installations do not proliferate further. Inspectors need to demand additional training in the inspection of PV systems and then inspect these systems very closely. Yes, it is a relatively unfamiliar technology, but 80 percent of the *Code* already familiar to inspectors applies and it is relatively easy to learn the inspection requirements that are unique to PV systems.

Photo 5. Off-grid home with 3.6 kW PV array

Photo 6. Off-grid PV power system

The North American Board of Certified Energy Practitioners (NABCEP at www.NABCEP.org), a voluntary certification program for PV installers, has certified the first installers. The training, experience, and skill requirements of PV designers/installers obtaining this certification will help to ensure that safer, higher quality PV systems are installed.

PV System Types

Two main types of PV systems are being installed in the U.S.: utility-interactive (grid-connected), photos 1–4, and stand-alone (off grid), photos 5–6. Both types use PV modules connected in series and parallel to form PV arrays that produce dc energy at various voltages from about 12 volts to 600 volts. Generally, energy storage batteries are found in the stand-alone systems, but few are found in the utility-interactive systems. Variations of each system are possible with some utility-interactive systems having battery banks to provide energy when the utility power is not available. The larger residential stand-alone systems will usually have a back-up generator, and these systems are known as hybrid stand-alone systems.

Utility-interactive Systems

Utility-interactive PV systems are by far the most numerous of the types of PV systems being installed. A typical residential system might have a PV array and an inverter (converts dc to ac) capable of delivering 2500 watts of ac power to either ac loads in the house or to the utility grid when the power output is in excess of those local loads. In residential PV systems, single and multiple inverter installations are common. The single inverter may have an ac output rating of 700 to 3500 watts, and systems are frequently seen with 2–4 inverters used to increase the system power output (see photo 7, on page 14). Residential PV systems have had ac outputs up to 30 kW! These residential-sized inverters interface with the grid at 120 volts or 240 volts, are listed to UL Standard 1741, and have all of the necessary safety equipment built in and verified as part of the listing process. The inverters inherently meet *NEC* 690.5 ground-fault protection equipment requirements (fire protection) for use with PV arrays mounted on the roofs of dwellings.

In commercial systems, the three-phase inverters usually start at about 10 kW and go up to 250–300 kW, and interface with the grid at 208–480 volts and higher (see photo 8, on page 14).

The utility-interactive inverters have all of the automatic ac line disconnect devices built in that protect the utility linemen who are working on a supposedly unenergized utility feeder. The utility-interactive PV inverter will not energize a dead line and in fact will disconnect from the line when the line voltage varies more than 10

Photo 7. Four 2.5 kW inverters used on a 10 kW utility-interactive residential PV system.

Photo 8. 15 kW 3-phase utility-interactive inverter

percent from nominal or when the frequency varies by more than a few hertz from the normal 60 Hz. Many PV owners in California were surprised when their utility-interactive PV systems did not work during the rolling utility blackouts and brownouts a few years ago. Utility-interactive PV systems with battery backup were popular for months following the blackouts.

Stand-alone Systems

Stand-alone systems are typically installed in remote areas where the utility grid is not available or where the connection fees to the grid are higher than the costs of an alternative energy system. While stand-alone systems sales are far smaller than the fast-growing utility-interactive PV system business, there is and has been a steady market for off-grid systems.

The stand-alone inverter converts dc energy stored in batteries from the PV array to ac energy to support the loads (see photo 9). Inverter power ratings are from about 250 watts to 5000 watts for residential systems and, as before, multiple inverters may be connected together for greater power outputs. Battery banks usually operate at a nominal 12, 24, or 48 volts so the current levels to the inverters can be hundreds of amps at full load. The stand-alone inverter may not include the Section 690.5 ground-fault equipment, so if the dwelling installation has the PV array on the roof, an external, field-installed ground-fault protective device must be used.

Larger stand-alone systems are found at national parks, telecomm sites, and federal facilities. These can be as small as the residential system with ac outputs in the 2–10 kW range, but they can also have single inverters up to 250 kW. A few of these larger systems have multiple large inverters with combined outputs approaching 500 kW or more. Battery banks for the larger systems operate in the 200–600 volt range and dc currents to the inverters can be hundreds of amps at these higher voltages.

Starting with the PV modules on the roof, here are some areas where inspectors need to examine the systems closely.

Conductor Types and Ampacity Calculations

PV modules may be connected with any of the numerous *NEC* chapter 3 wiring methods suitable for fixed installations. The conductors and wiring methods must be suitable for the outdoor (wet) environment, be suitable for exposure to sunlight, and able to operate in temperatures in the 65–80°C range. Conductors should be sized based on ampacity calculations after temperature corrections. Section 690.31 of the *NEC* also allows exposed, single-conductor cables (USE-2, SE, and UF) for interconnecting the modules, and many PV modules have the appropriate conductors permanently attached as wiring leads with connectors.

Ampacity calculations for the circuits from the PV modules are based on the rated short-circuit current marked on the back of each module. The PV module is a current-limited source, and this rated short-circuit

Photo 9. 4 kW stand-alone inverter

current must be multiplied by several factors that account for environmental factors and *Code* requirements to reach a conductor ampacity figure. Because of the unique nature of the solar resource and the way PV modules generate current, all PV source currents are considered to be continuous with no non-continuous currents. These continuous output currents under real-world outdoor conditions may exceed the rated short-circuit current, and this requires that a multiplier of 125 percent be applied to the rated value [NEC 690.8(A)]. A second 125 percent multiplier (for a combined multiplier of 156 percent) is then applied to ensure that conductors and overcurrent devices are not operated at more than 80 percent of rating [*NEC* 690.8(B)].

Also, because the rated open-circuit voltage is measured in a laboratory at room temperature (25°C/77°F) and the modules operate over a wide range of outdoor temperatures (including solar heating) from -40°C (-40°F) to 80°C (176°F), the rated open-circuit voltage is multiplied by a temperature-dependent factor that can be as large as 125 percent (*NEC* 690.7). Although the modules have a rated open-circuit voltage of 22 to 44 volts, when they are connected in series, the rated open-circuit voltage of the string can rapidly approach 600 volts under cold weather temperatures.

When batteries are used, many installers use welding cable (listed and unlisted) or automotive battery cables to avoid having to deal with stiff 4/0 AWG and larger standard cables. Neither of these cable types meet *NEC* requirements, but flexible THW and RHW cables are available that do meet *NEC* chapter 3 requirements for fixed electrical installations.

Color Codes

The color codes for dc wiring are just like those for ac wiring. Remember in the early days of the *Code*, Edison was a dc man. The grounded conductor (usually the negative conductor) is to be white or have three white stripes. There is no color code specified for the ungrounded conductor (usually the positive conductor) in dc systems and installers use red or black. A common error is to use a red conductor for the positive conductor (OK) and a black conductor for the grounded negative conductor (not to *Code*), but this doesn't meet *Code* and is a holdover from electronic wiring practices (see photo 10). Since USE-2, SE, and UF conductors are

Photo 10. Grounded conductors should be white, not black!

generally available only with black insulation, there is an allowance in Section 200.6(A)(2) to let PV module interconnection cables be marked white even when they are 6 AWG and smaller. Current outputs from typical PV modules generally result in interconnection conductors in the 14–10 AWG range. Of course, when the source circuits are paralleled, the currents increase and the conductor must be larger.

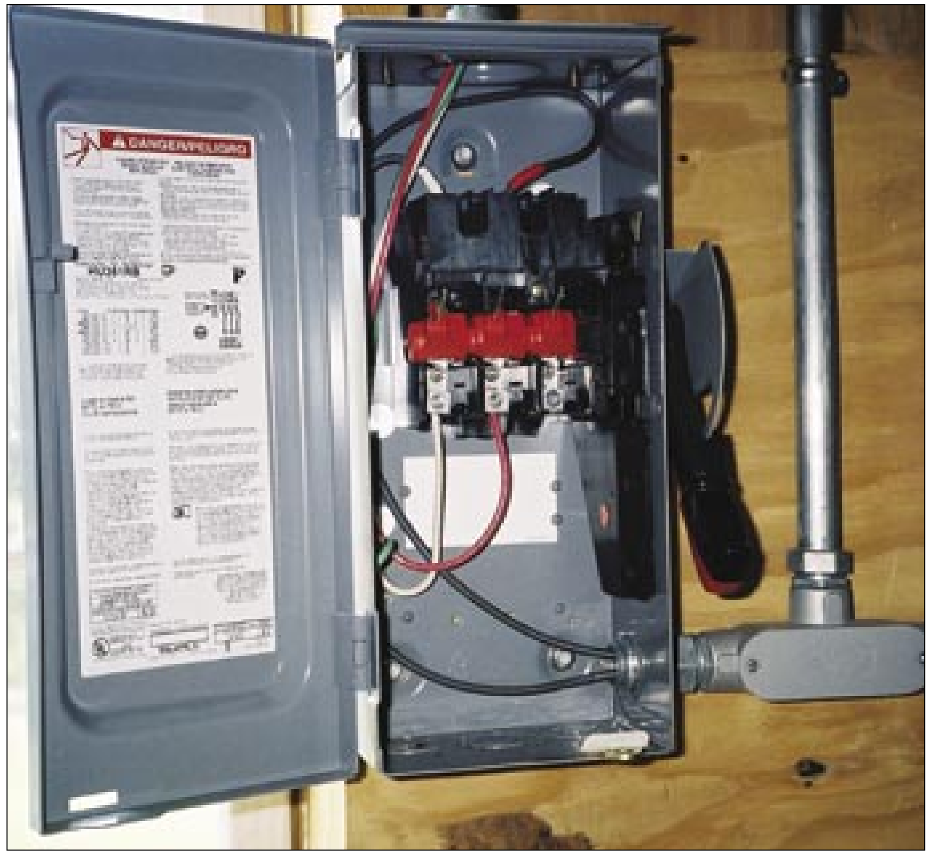


Photo 11. Don't switch that grounded conductor!

Disconnects

Since most, if not all, PV systems will have the negative dc conductor from the PV array operating as a grounded conductor, there should never be a switch, fuse, or circuit breaker in this grounded conductor. This is particularly important in PV source and output circuits where a disconnected (and energized with respect to ground) conductor that was marked white as a grounded conductor could represent a shock hazard whenever the PV array was illuminated. A common *Code* violation on PV systems operating from 100–600 volts dc is to use a fused or unfused safety switch for the PV disconnect that breaks both the ungrounded positive conductor and the grounded negative conductor (see photo 11).

Some automated ground-fault protection devices (required for roof-top dwelling unit PV systems by 690.5) may open the negative conductor during a ground-fault action, and this possibility is noted with marking requirements providing an appropriate warning (see 690.5 and 690.13).

PV DC Disconnect Location

NEC 690.14(C)(1) requires that the position of the main PV dc disconnect and the conductors routed from the PV array on the roof to that disconnect be addressed in much the same manner as ac service-entrance conductors and disconnects. The conductors from the PV array must remain outside the structure until they get to the PV dc disconnect that must be in a readily accessible location at the point where the conductors first penetrate the building. The disconnect may also be located immediately inside the structure at the point of penetration and that location is acceptable in many jurisdictions.

PV installations are frequently seen where the PV source and output circuit conductors penetrate the roof, are routed through the interior of the structure and finally reach the dc PV disconnect that may or may not be mounted in a readily accessible location. An installation such as this does not meet *Code* and the daylight-energized conductors inside the building structure pose potential hazards for emergency response personnel who are unable to turn them off.

There is no *Code* requirement for a disconnect to be located on the roof at the PV array (much like an air-conditioning service disconnect) because the PV array is always energized in the daytime, the PV array needs minimal servicing, and the disconnect would not make the PV array any safer for servicing [*NEC* 690.14(C)(5)]. Section 690.18 establishes the means to make a PV array safe for servicing including covering the modules with an opaque material.

Overcurrent Protection

PV modules are subject to reverse current flow (under line-to-line and ground faults) from external sources such as strings of other PV modules connected in parallel, backfeed from batteries in systems that have them, and backfeed from the utility grid through inverters. These reverse currents may damage the module if allowed to exceed the value marked on the back of the module as the "Maximum Series Fuse." For this reason, most series-connected strings of modules require an overcurrent device in the circuit to protect all modules in the string from the reverse overcurrents. The overcurrent device (either fuse or circuit breaker) is usually located at the source of the overcurrents (usually at a PV combiner box) and also provides the *Code*-required overcurrent protection for the conductors in that circuit.

Some recent utility-interactive inverters are certified by the manufacturers to be not capable of backfeeding currents from the grid and these inverters can be connected to one, two and possibly more strings of modules in parallel with no overcurrent devices in the dc circuits [*NEC* 690.9(A)Ex.].

Grounding

Grounding PV systems is no more or less complex than grounding any other electrical system. The intent is to keep all exposed metal surfaces that could be energized at the same zero potential with respect to earth no matter whether they are associated with the dc part of the system or the ac part. Since the inverter is the common element between the dc portion of the system and the ac portion, its enclosure is common to both equipment-grounding systems and keeps the exposed metal surfaces at the same potential. Of course, the size of the equipment-grounding conductors will vary with the various circuits and those associated with PV source circuits have unique sizing requirements (690.45).

Inverters usually have internal transformers that isolate the dc grounded conductor from the ac grounded conductor, so essentially the dc system becomes a separately derived system at least in fact, if not by *Code* definition. Internal connections in the residential-size utility-interactive inverters will usually provide the bonding connection between the grounded dc negative conductor and the equipment-grounding system. Provisions are also made for the connection of a dc grounding electrode conductor. In stand-alone systems, the inverters generally do not have the dc main bonding jumper, so this connection will have to be made by the installer.

The grounding of the ac grounded conductor is accomplished in the existing service equipment on utility-interactive systems and in the ac distribution equipment (ac load center—a.k.a. in *Code* language: panelboard in an enclosure) in stand-alone systems.

The dc and ac grounding electrode conductors are either connected to separate grounding electrodes (which are then bonded together) or are connected to a single grounding electrode or grounding system. Changes proposed for Article 690 in the 2005 *NEC* should clarify this area since Article 250 doesn't specifically address electrical systems where both ac and dc grounding are required.

The Utility Connection–Commercial

In most residential PV installations and many commercial installations, the output of the utility-interactive inverter is commonly connected to a backfed circuit breaker in the load center associated with the service entrance. *NEC* 690.64(B) establishes rather strict requirements on how these interconnections must be made, and the ratings for the load center and the language of subparagraph (2) deserves special attention. Note that in a commercial installation the *sum of the ratings* of all overcurrent devices *feeding* the panel must not exceed the rating of the panel. Circuit breakers *feeding* the panel would be the main and any PV breakers. In many commercial installations, the main breaker is sized the same as the panel rating, and this leaves NO ability to install a back-fed PV breaker. One solution is to install a larger panel with a higher rating while retaining the original size main breaker. This will allow PV breakers to be added up to the difference between the main breaker rating and the rating of the panel. Another solution is to add a second service entrance to the building if the service entrance voltage matches the inverter output voltage.

The *NEC* 690.64(B)(2) requirement applies to all load centers/distribution equipment and feeders between the point where the PV inverter is connected and the service entrance panel. As can be readily seen, if the 15-amp PV system feeds a 400-amp panel that receives power from a 1000-amp service-entrance panel, the situation gets problematic at that 1000-amp panel. If this 1000-amp panel has a 1000-amp main breaker, then there is no allowance to connect a backfed circuit at this point, which would be the 400-amp breaker feeding the remote 400-amp panel. And, yes, the backfed "PV breaker" at this point has to be counted as 400-amps even if the output of the PV inverter at that 400-amp panel only required a 15-amp breaker. A little inspector understanding and common sense in this area will go a long way, but all those involved must keep in mind that after the OK is given, the installation has been completed, and everyone has forgotten the project, the unwary occupant may add loads to the system that could overload one of the panels if *NEC* 690.64(B)(2) has not been followed.

The Utility Connection–Residential

Residential PV applications are given a 120 percent allowance on the sum of the breakers feeding a load center, because most residential panels are more lightly loaded than commercial panels based on *Code* requirements (see *NEC* 690.64(B)(2)Ex). The 120 percent allowance will allow moderate sized PV systems (up to 7680 watts on a 200-amp panel) to be installed on dwelling units without modifying the service equipment. However, larger residential PV systems can have outputs that will exceed this 120 percent allowance and the existing installation must be modified.

Summary

Excellent performing, *Code*-compliant PV systems are being installed throughout the country; however, many don't measure up. Inspectors, being familiar with most aspects of the *NEC*, can easily pick up the necessary additional knowledge required to inspect PV systems. PV systems designers and installers are gaining additional training and experience, but everyone can benefit from that final once over by the AHJ.

For Additional Information

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See the article "Photovoltaic Power Systems and the National Electrical *Code*" in the January/February 1999 issue of the *IAEI News* for additional information on PV systems.

A PV Systems Inspector/Installer Checklist will be sent via e-mail to those requesting it. A copy of the 100-page *Photovoltaic Power Systems and the National Electrical Code: Suggested Practices*, published by Sandia National Laboratories and written by the author, will be sent at no charge to those requesting a copy by e-mail. The Southwest Technology Development web site (http://www.nmsu.edu/-tdi) maintains all copies of the "Code Corner Columns" written by the author and published in *Home Power Magazine* over the last 10 years.

The author makes 6–8 hour presentations on "PV Systems and the *NEC*" to groups of 40 or more inspectors, electricians, electrical contractors, and PV professionals for a very nominal cost on an as-requested basis.

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[1] *PV News*, Vol. 22, No. 3, March 2003. Paul Maycock, Editor. 4539 Old Auburn Road, Warrentown, VA 20187

[2] Wiles, John C. Jr., William Brooks, and Bob-O Schultze. "PV Installations, A Progress Report" presentation at the 29th IEEE Photovoltaics Specialists Conference, New Orleans, LA, May 2002

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