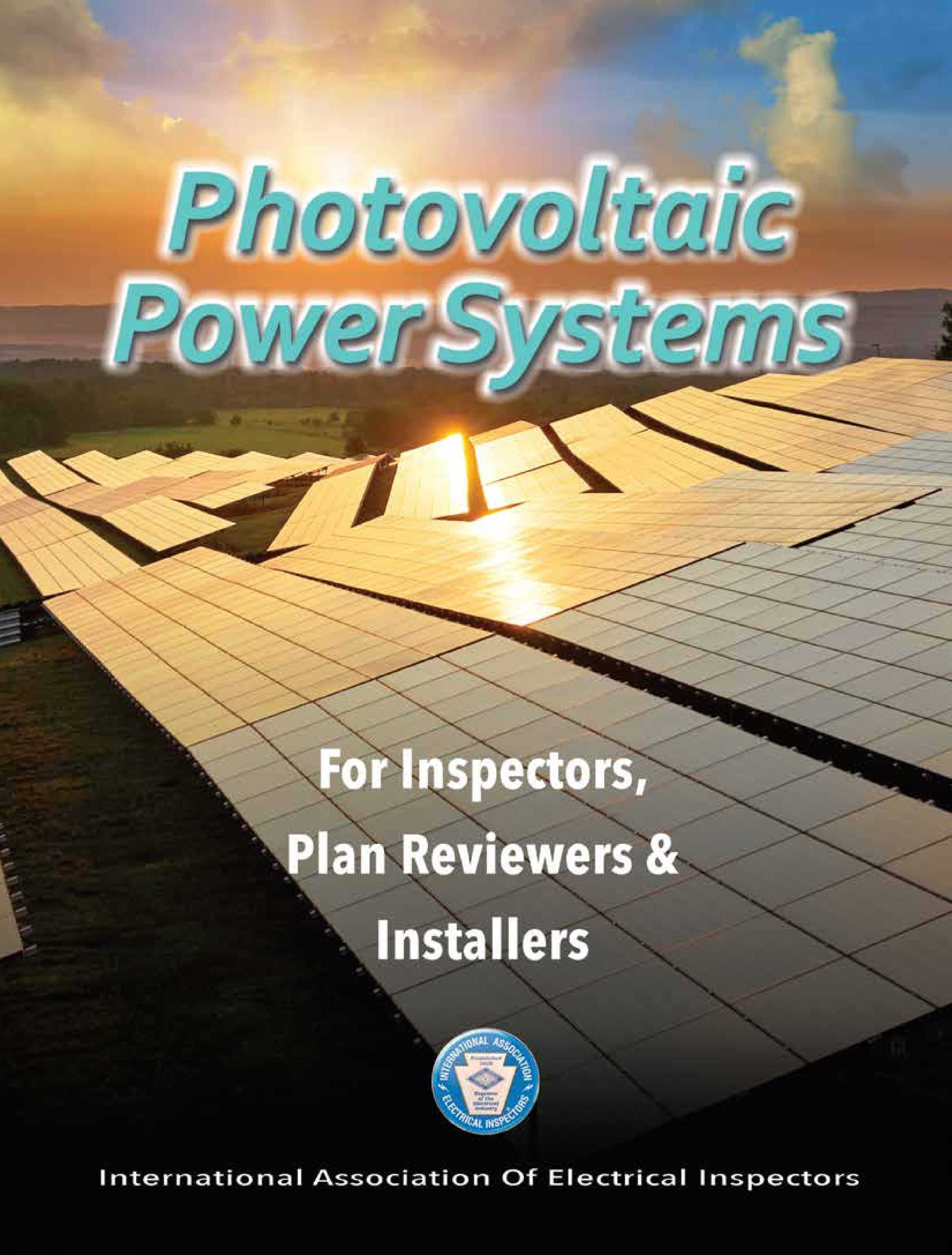


Photovoltaic Power Systems

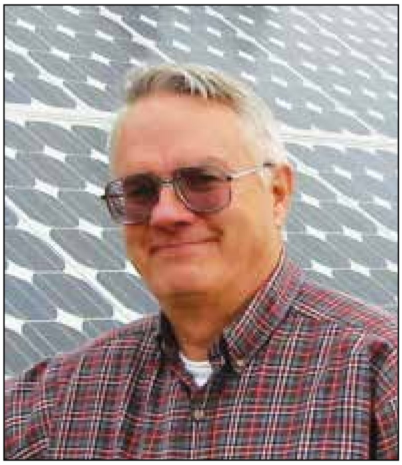
For Inspectors, Plan Reviewers & Installers

International Association Of Electrical Inspectors

Photovoltaic Power Systems

For Inspectors, Plan Reviewers & PV Professionals

BASED ON THE 2017 *NATIONAL ELECTRICAL CODE*



About the author

John Wiles is perhaps the most recognized name in the solar industry for his numerous contributions to the development of codes and *National Electrical Code* compliance for photovoltaic systems. He has written hundreds of articles on *Code*-related photovoltaic system topics and is a regular contributor to *IAEI News*.

Wiles retired from his full-time position as a research engineer at the Southwest Technology Development Institute at New Mexico State University in 2013 after 24 years in the position. He continues to volunteer his time to keep active in the codes- and standards-development processes; to assist inspectors and plan reviewers with *Code* questions; to make "PV and the *National Electrical Code*" presentations throughout the country; and to consult with the PV industry on code-related issues.

Wiles is a member of several Standards Technical Panels for Underwriters Laboratories and is active in formulating standards for PV equipment, such as modules, inverters, charge controllers, combiners, cables, racks, and connectors. He continues to write the "Perspectives on PV" articles in the *IAEI News* and is active in the development of proposals for the 2020 *NEC*.

As an old solar pioneer, he lived for 16 years in a stand-alone, off-grid, PV-powered home in suburbia. His new owner-designed and -built retirement home has a 7.5 kW utility-interactive PV system with whole-house battery backup, where he lives with his wife Patti, three dogs, and two cats.

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For Inspectors, Plan Reviewers
& PV Professionals

BASED ON THE 2017 *NATIONAL ELECTRICAL CODE*

THIRD EDITION

JOHN WILES

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the manufacturers or the products.

The material in this book has been extracted from and expanded upon the series of articles "Perspectives on PV" found in *IAEI News* published by the International Association of Electrical Inspectors. The articles are based on the author's understanding of the 2005, 2008, 2011, 2014, and 2017 NFPA 70 *National Electrical Code (NEC)* [1]; his activities in developing that *Code*; his design reviews, inspections and testing of photovoltaic (PV) systems for more than twenty years; and his interaction with electrical inspectors, PV systems designers, and PV installers throughout the country. In all cases, the *NEC* is the requirement and local authorities having jurisdiction provide the interpretations of the *Code*.

DISCLAIMER

This book provides information on how the 2005, 2008, 2011, 2014, and 2017 *National Electrical Codes* apply to photovoltaic systems. The book is not intended to supplant or replace the *NEC*; it paraphrases the *NEC* where it pertains to photovoltaic systems and should be used with the full text of the *NEC*. Users of this book should be thoroughly familiar with the *NEC* and know the engineering principles and hazards associated with electrical and photovoltaic power systems. The information in this book is the best available at the time of publication and is believed to be technically accurate. Application of this information and results obtained are the responsibility of the user.

In most locations, all electrical wiring (including photovoltaic power systems) must be accomplished by, or under the supervision of a licensed electrician and then inspected by a designated local authority. Some municipalities have additional codes that supplement or replace the *NEC*. The local inspector has the final say on what is acceptable.

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Table of Contents

1 An Overview of PV Systems and the 2017 *National Electrical Code* 8

2 PV Fundamentals and Calculations 42

3 PV Modules — Installation Considerations 65

4 The Inverter — Operation and Connections 81

5 Energy Storage Systems (ESS), Batteries in PV Systems 97

6 Grounding, Disconnects, and Overcurrent Protection 113

7 Utility Interconnections 133

8 Plan Checking and Inspecting 156

9 The Process of Inspecting PV Systems 168

10 The 15-Minute PV Inspection – Can You? Should You? 178

Appendix A 2014 and 2017 *NEC* Photovoltaic Electrical Power Systems Inspector/Installer Checklist 184

Appendix B Bibliography 191

Preface

In a time where photovoltaic plan reviewers and inspectors are getting pressured to expedite the inspection and review process, this book could not have come at a better time. If we are expected to accomplish faster turnaround times with fewer inspections, we must be informed to ensure safe, *Code*-compliant installations. Rubber-stamping plans and drive-by inspections may be what the industry is pushing for, but are those actions what the customer deserves? The customer is relying on a qualified inspector to verify that their PV system is safe and that it will continue to be safe for years of operation.

What makes this book stand out is how it correlates to the *National Electrical Code* (*NEC*). When citing corrections or comments, we need to be able to reference the *Code* to justify our calls. The last thing that we should be doing is trying to enforce our opinion.

Stamping a set of PV drawings for approval or signing a permit card for an inspection does not require skill or knowledge of the *NEC* requirements we need. The knowledge and skill before we sign or stamp documents is where most of us need some help and guidance. Having a document such as *Photovoltaic Power Systems* provides inspectors with a great tool for gathering information on what to look for in plan review and during inspections.

Article 690 is a small section when compared to the entire *NEC*. The size of Article 690 does not make it any less important than other articles found in the *NEC*. Due to its size, it is often not a focus of the combination inspector. It is no wonder it gets overlooked when you stack up all the codes the combination inspector must enforce.

When the *NEC* book and handbook are not enough to help you understand what or how you should be enforcing the regulations, this document can provide clarity. The information provided in *Photovoltaic Power Systems* has been compiled by someone who is known throughout the industry as a PV expert. John Wiles has been a resource and has been providing training for more than 20 years to inspectors and plan reviewers.

Not only is this book originally based on the 2011 *Code* and earlier editions, but also the 2014 and 2017 *NEC*. With knowledge comes credibility. This document will help plan reviewers and inspectors know and understand what they are looking at and what to look for. If you want to understand what is on the plans, this book will help. Even for those who have a solid understanding of PV systems, it is helpful to have a book to refer to when questions arise. Whether questions come from us or from PV designers or installers, this book can help answer these PV-related questions. You will find this book to be an excellent resource.

Having ready access to this book can help us all be more informed about PV systems, where expertise is often limited. John Wiles is known for having such expertise.

— Rhonda Parkhurst, Electrical Specialist
City of Palo Alto, California

01

*An Overview of PV Systems and the 2017 **National Electrical Code***

Photovoltaic (PV) power systems are being installed by the tens of thousands throughout the United States. In states where financial incentives are available (like in California, New York, and New Jersey), the PV business is booming. The first PV cells produced more than 50 years ago are still producing power, and modern PV modules are expected to produce energy for the next 40 years or longer. The power output from PV systems ranges from a few hundred watts to many megawatts. Most of the systems are *not* operated or owned by any electric utility and therefore come under the requirements of NFPA 70 *National Electrical Code* (*NEC*). Unless otherwise noted, all references to the *NEC* will be to the 2017 *NEC*.

Systems as large as 700 megawatts have been installed by third parties on private land in the United States, and are not under utility control or ownership. Larger systems of up to 1500 megawatts have been installed in other countries and will more than likely be installed in the United States in coming years. These systems operate at 1000 volts to 1500 volts and, in the larger commercial systems, direct current (dc) and alternating current (ac) can range up to 2000 amps or more. These levels of voltage and current, if not properly managed, pose shock, life safety, and fire hazards. These systems must be inspected to ensure the safety of 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 dc portions of the system coupled with the ac interconnection to the utility grid make PV installations unique. Because the PV industry is growing rapidly, individuals, companies, and organizations (with varying degrees of knowledge, skill, and experience) are installing these systems. Large, and some small, PV-system 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 with little or no experience or training installing electrical systems of any type are installing many new PV systems. These systems may be unsafe (not *Code*-compliant) at initial installation;

develop hazardous conditions over the life of the system; be hazardous to operate or service; and fail to deliver the full performance of a well-designed and -installed PV system.

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

Several organizations in the PV industry provide training and certification for individuals. The training, experience, and skill requirements of PV designers and installers obtaining this certification will help ensure that safer, higher quality installations of PV systems take place.

PV System Types

Two main types of PV systems are being installed in the United States: utility-interactive (grid-connected) (see photo 1.1) and stand-alone (off grid) (photo 1.2). Both types use PV modules connected in series and in parallel to form PV arrays that produce direct current energy at voltages ranging from approximately 12 volts to 1500 volts (photos 1.1, 1.2, 1.3 and 1.4). Refer to Article 100 and Section 690.2 of the *NEC* for definitions of the terms used to describe PV equipment and systems. These systems will be

Photo 1.1 • Carport PV systems generate energy and keep cars cool.

Photo 1.2 • 3.3 kW stand-alone, off-grid PV system.

Photo 1.3 • Commercial PV array mounted horizontally with some shading.

Photo 1.4 • Five mW utility-scale PV system with PV subarrays mounted on two-axis trackers.

defined and further described in the following chapters

Generally, energy storage batteries are found in stand-alone systems but are not normally found in 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. These multimode PV systems are becoming more common as energy storage system prices decline, the utility power grid becomes less reliable, and natural disasters like hurricanes result in significant periods of utility power loss. Larger residential stand-alone systems will usually have a back-up generator, and these systems are known as hybrid stand-alone systems (photo 1.5).

Photo 1.5 • 10 kW backup generator, powered by natural gas, used when utility is out during extended periods of cloudy weather.

Photo 1.6 • Utility-interactive inverter. External ac and dc disconnects not shown.

Utility-Interactive Systems

Utility-interactive (U-I) PV systems are by far the most numerous type of PV system currently being installed. A typical residential system might have a PV array and an inverter (which converts dc to ac) capable of delivering 3000 watts to 10,000 watts of ac power to either ac loads in the house or to the utility grid when the PV 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 2000 watts to 7000 watts or more, and systems are frequently seen with two to four inverters used to increase the system power output (photo 1.6). A few residential PV systems have had ac outputs up to 90 kW!

These residential-sized inverters interface with the grid at 120 volts or 240 volts; are certified or listed to Underwriters Laboratories Standard for Safety 1741 (UL 1741 — *Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources)*; and have all the necessary safety equipment built-in and verified as part of the listing process.

In commercial systems, the three-phase inverters commonly used usually start at approximately 10 kW and go up to 250 kW and to 2.5 MW (yes, 2.5 megawatt in a single inverter). They interface with the grid at 208 to 480 volts and higher (photo 1.7).

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 lower than sales in 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

Photo 1.7 • 2.2-MW Sunny Central Inverter. *Courtesy of SMA Solar Technology AG.*

Photo 1.8 • Four 6-kW stand-alone inverters in an ac-coupled, battery-backed-up PV system

Photo 1.9 • Inverters and charge controllers for 10-kW off-grid, stand-alone PV system.

stored in batteries by the PV array to ac energy to support the loads (photos 1.8 and 1.9). Inverter power ratings are from about 250 watts to 6500 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.

Larger stand-alone systems can be found in national parks, at telecom sites, and at federal facilities. These can be as small as residential systems with ac outputs in the 2 kW to 10 kW range, but they can also have single inverters of 250 kW or more. 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-volt to 600-volt range and dc currents to the inverters can be hundreds of amps at these higher voltages.

PV System Component Descriptions

PV Modules

The first thing inspectors see are PV modules. While most have glass fronts, aluminum frames (colored mill-finish aluminum or anodized brown or black), and plastic backs, some will be made with plastic frames or with no frames (photo 1.10). Others will be used as roofing materials (photo 1.11) or laminated directly to standing seam metal roofs (photo 1.12). PV modules come in many sizes and shapes.

Inspectors need to determine the listing of the modules and the electrical ratings. These are printed on the back of the module and may be available

Photo 1.10 • (*left*) Framed PV modules (anodized and clear-coated aluminum in natural aluminum color or brown/black).

Photo 1.11 • (*top right*) Building-integrated photovoltaics (BIPV) PV modules as roofing material.

Photo 1.12 • (*bottom right*) Thin-film PV modules laminated to a metal standing seam roof.

in the instruction manual or module specification sheet. Some unlisted, custom modules are being installed in architect-designed projects. Unlisted modules are being sold through various channels (including the internet), but unlisted modules no longer meet *Code* requirements and should not be installed [690.4(D)]. Although appearances may differ, these PV modules all produce electricity when illuminated and the normal cautions associated with any electrical power system should be followed.

PV modules come in differing power and voltage ratings and the sizes and ratings are continually changing. The modules must be connected in a manner that produces the needed voltage, current, and power because the output of a single module is usually not sufficient to operate the connected equipment or provide the needed amount of energy.

PV Combiners

PV combiners (PV j-boxes or PV combining enclosures) are common in PV systems operating at dc nominal voltages of 12, 24, and 48 volts and are also used in higher voltage systems (up to 1500 volts). They must be certified/listed by a nationally recognized testing laboratory (NRTL) to UL Standard 1741 [690.4(D)]. In these systems, it is a normal practice to connect modules in series (called a PV source circuit [690.2]) to get the proper voltage and then to connect each series source circuits of modules in parallel with other source circuits through a PV combiner to increase the current to get the desired power level.

These combiners will usually contain the overcurrent devices (fuses in the high voltage systems or circuit breakers in the 12-, 24-, or 48-volt systems) that are required to protect the module interconnecting conductors from fault currents

Photo 1.13 • PV combiner with fuses in the positive conductor only. Manual and contactor disconnects in positive conductor only. Not 2017 *NEC* compliant [690.15(C)].

Photo 1.14 • PV combiner in white enclosure with manual switch opening both positive and negative conductors. Plastic shield covers energized, exposed conductors.

and the individual modules from reverse currents. Reverse currents may originate from parallel-connected strings of modules; reverse currents from the batteries in a system that has them; or from backfeed currents from a utility-interactive inverter (unlikely in listed inverters). See chapter 2 for additional details on the requirements for combiners.

Inverters

Inverters are found in both stand-alone systems and utility-interactive systems. They essentially convert dc)energy from the PV system (or the dc energy stored in batteries) to ac energy for use by local loads or for feeding into the utility system (photos 1.15 and 1.16). Some utility-interactive inverters, known as multimode inverters, have the capability to power selected load circuits from batteries or the PV system when the utility is not present.

Many PV owners in California were surprised when their utility-interactive PV systems did not work during the rolling utility blackouts created by the energy shortage and brownouts a few years ago. Utility-interactive PV systems with multi-mode inverters (photo 1.17) and battery backup were popular for months following the blackouts.

Unfortunately, installation manuals for these complex inverters (particularly the stand-alone types) can be several hundred pages long. The inspector should verify the proper dc and ac conductor sizes and overcurrent protection. Both are based on the rated ac power output of the inverter. (See Sections 690.8 and 690.9 and Articles 705 and 706 in the *NEC*.)

Utility-interactive inverters have all the automatic ac utility disconnect devices built-in, which protects utility linemen who are working on supposedly de-energized utility feeders. 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 -12% to +10% from nominal (typically 120, 208, 240, 277, or 480 volts) or when the frequency varies by more than -0.7 to +0.5 Hz from the normal 60 Hz.

The inverter monitors the utility line voltage and frequency, and that voltage and frequency must remain stable and within tolerance for five

Photo 1.15 • Dual 4 kW utility-interactive inverters.

Photo 1.16 • Transformerless (non-isolated) inverters, typically used on most recent residential and small commercial PV systems. *Courtesy of SMA Technologies AG.*

minutes before the inverter can resume power transfer from the dc output of the PV system to the ac loads or to the utility.

All PV systems, with a few exceptions, must have a device known as a ground-fault detection/interruption device (GFID). *See* 690.41. These GFIDs are normally built into all utility-interactive inverters and some charge controllers. Early utility-interactive inverters used a fuse that blew on ground faults, but this method proved inadequate in detecting all ground fault, particularly those in grounded circuit conductors. The stand-alone inverter will usually not include the Section 690.41 ground-fault device, so if it is not built into the charge controller, an external, field-installed ground-fault protective device must be used. The author developed a system of circuit breakers in 1990 to meet the existing *NEC* requirement, but like the use of a fuse GFDI, it was not adequate to detect all low-level faults in grounded conductors.

Photovoltaic systems mounted on buildings will require a PV rapid shutdown system (PVRSS) which is system manually activated by first responders to reduce electric shock hazards due to energized PV conductors on or in a building (690.12). Many of these systems will be built into the U-I inverter, but separate versions are also available.

Photovoltaic systems with dc circuit voltages over 80 volts will require a device known as a dc PV arc-fault circuit interrupter (DCPVAFCI) and, in most cases, these devices will be built into the string inverter (690.11).

PV and the 2017 *National Electrical Code*

The 2017 *NEC* incorporated sweeping changes in the way it addresses requirements for PV and related systems and that will resonate into the future.

Changes Are Here

Two main areas stand out among the numerous changes that have been accomplished by Code-Making Panel 4 and the NFPA Technical Correlating Committee and its task groups. The first major change is a redefinition of what a PV system is and the exclusion or removal of most non-PV system information and requirements from Article 690. The second major change is a redefinition of what is meant by "grounding" and "grounding requirements" as they pertain to PV systems.

Photo 1.17 • Multimode Inverters. These inverters provide whole-house battery-backed-up energy and are ac coupled to utility-interactive inverters.

PV Systems Redefined

The first major change to Article 690 was to more narrowly define exactly what a PV system is. As we know them today, PV systems may include several interconnected sources of energy, including battery storage systems, multimode inverters, generators, and similar devices. Photovoltasic system disconnects are located in various locations throughout the “so-called” PV system in a manner that is sometimes confusing.

In the 2017 *NEC*, the PV system is primarily concerned with and defined by the PV modules and any device connected directly to them that does not involve energy storage or another source of energy. Changes to Diagram 690.1 will highlight these differences in the definition of a PV system. Primarily, we are looking at the PV system ending where the PV system disconnect occurs. In the 2017 *Code*, the PV system disconnect may be either an ac or dc disconnect depending on the configuration of the system. For example, as shown in Figure 1.1 (part of Figure 690.1 from the 2017 *NEC*) the PV system disconnect on a pure utility-interactive PV system occurs at the ac output of the utility-interactive inverter. If there are ac PV modules involved, the PV system disconnect will be at the output of the combined outputs of all the ac PV modules in the system. These PV disconnects separate the PV system from another energy source: the utility.

Even though it is acknowledged that the diagrams are not complete, the multimode dc-coupled system diagram (Figure 1.2) and the stand-alone system shown (Figure 1.3) are possibly confusing in one aspect. Typically, the output of a PV array cannot be connected directly to a stand-alone or multimode inverter, to dc loads, or to an energy storage system as shown in these diagrams. If done as shown, the PV output voltages to these circuits would be unregulated (changing throughout the day and as clouds appear) and

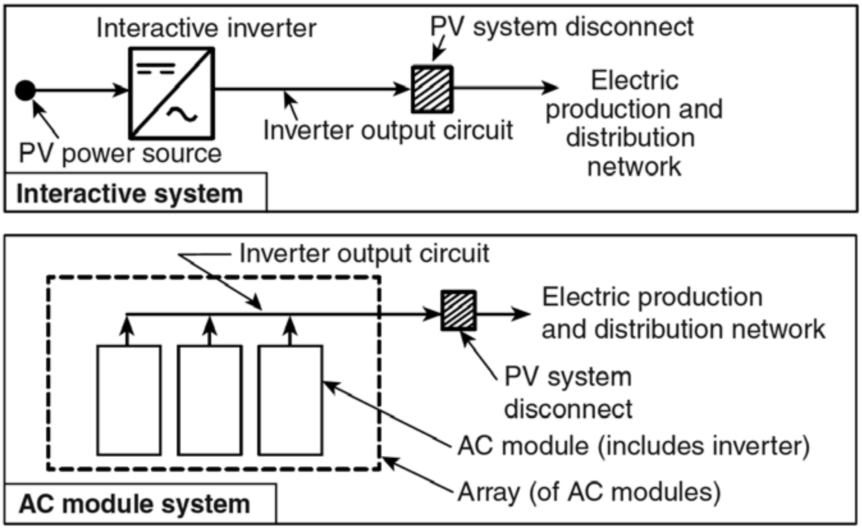

Figure 1.1 • Disconnects for simple PV systems. From Figure 690.1 in the 2017 *NEC*.

Photovoltaic Power Systems

For Inspectors, Plan Reviewers & PV Professionals

In a time of rapid advancement in photovoltaic power systems, this third edition of John Wiles' acclaimed book serves as a comprehensive manual for inspectors, plan reviewers, and installers to ensure *National Electrical Code*-compliant PV system installations. Updated for the *2017 NEC*, this extensive guide covers everything plan reviewers, installers, and inspectors need to know about these systems.

John Wiles is perhaps the most recognized and influential name in the solar industry. He's worked extensively in the development of the *NEC* and UL Standards and is an active trainer on *Code*-compliant PV systems. Wiles has written hundreds of articles on *Code*-related photovoltaic system topics and continues to write *Perspectives on PV articles* for *IAEI News*.

Chapters include:

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- PV module installation considerations
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