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Photovoltaic Power Systems and The National Electrical Code: Suggested Practices

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The Photovoltaic Systems Assistance Center
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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico, 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-94AL85000

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SAND96-2797
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PHOTOVOLTAIC POWER SYSTEMS AND THE NATIONAL ELECTRICAL CODE: SUGGESTED PRACTICES

A publication of

**The Photovoltaic Systems Assistance Center
Sandia National Laboratories**

by

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Las Cruces, NM**

ABSTRACT

This guide provides information on how the *National Electrical Code (NEC)* applies to photovoltaic systems. The guide 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 guide 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 guide is the best available at the time of publication and is believed to be technically accurate; it will be updated frequently. Application of this information and results obtained are the responsibility of the user.

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ACKNOWLEDGMENTS

Numerous persons throughout the photovoltaic industry reviewed the drafts of this manual and provided comments which are incorporated in this version. Particular thanks go to Joel Davidson, Solec International, Inc.; Mike McGoey and Tim Ball, Applied Power Corp.; George Peroni, Hydrocap; Bob Nicholson, Glasstech Solar; Mark Ralph and Ward Bower, Sandia National Laboratories; Steve Willey, Backwoods Solar; Tom Lundtveit, Underwriters Laboratories; and all those who provided useful information at seminars on the subject. Appendix E is dedicated to John Stevens and Mike Thomas at Sandia National Laboratories. Document editing and layout by Ronald Donaghe, Southwest Technology Development Institute.

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PURPOSE

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In most locations, all electrical wiring including photovoltaic power systems must be accomplished by a licensed electrician and inspected by a designated local authority. Some municipalities have more stringent codes that supplement or replace the *NEC*. The local inspector has the final say on what is acceptable. In some areas, compliance with codes is not required.

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APPLICABLE ARTICLES FROM THE NATIONAL ELECTRICAL CODE

Although numerous portions of the *National Electrical Code* apply to photovoltaic power systems, those listed below are of particular significance.

Article	Contents
90	Introduction
100	Definitions
110	Requirements
200	Grounded Conductors
210	Branch Circuits
240	Overcurrent Protection
250	Grounding
300	Wiring Methods
310	Conductors
331	Electrical Nonmetallic Tubing
336	Nonmetallic Sheathed Cable
338	Service Entrance Cable
339	Underground Feeders
348	Electrical Metallic Tubing
374	Auxiliary Gutters
384	Switchboards and Panel Boards
445	Generators
480	Storage Batteries
690	PV Systems
705	Interconnected Electric Power Production Sources
710	Over 600 Volts, Nominal, General
720	Low-Voltage Systems

**PHOTOVOLTAIC POWER SYSTEMS
AND
THE NATIONAL ELECTRICAL CODE**

SUGGESTED PRACTICES

OBJECTIVE

- SAFE, RELIABLE, DURABLE PHOTOVOLTAIC POWER SYSTEMS
- KNOWLEDGEABLE MANUFACTURERS, DEALERS, INSTALLERS, CONSUMERS, AND INSPECTORS

METHOD

- WIDE DISSEMINATION OF THESE SUGGESTIONS
- TECHNICAL INTERCHANGE BETWEEN INTERESTED PARTIES

INTRODUCTION

The National Fire Protection Association has acted as sponsor of the *National Electrical Code (NEC)* since 1911. The original Code document was developed in 1897. With few exceptions, electrical power systems installed in the United States in this century have had to comply with the *NEC*. This includes many photovoltaic (PV) power systems. In 1984, Article 690, which addresses safety standards for installation of PV systems, was added to the Code. This article has been revised and expanded in the 1987, 1990, 1993, and 1996 editions.

Many of the PV systems in use and being installed today may not be in compliance with the *NEC* and other local codes. There are several contributing factors to this situation:

- The PV industry has a strong "grass roots," do-it-yourself faction that is not fully aware of the dangers associated with low-voltage, direct-current (dc), PV-power systems.
- Some people in the PV community may believe that PV systems below 50 volts are not covered by the *NEC* .
- Electrical inspectors have not had significant experience with direct-current portions of the Code or PV power systems.
- The electrical equipment industries do not advertise or widely distribute equipment suitable for dc use that meets *NEC* requirements.
- Popular publications are presenting information to the public that implies that PV systems are easily installed, modified, and maintained by untrained personnel.
- Photovoltaic equipment manufacturers have been generally unable to afford the costs associated with testing and listing by approved testing laboratories like Underwriters Laboratories or ETL.
- Photovoltaic installers and dealers in many cases have not had significant experience installing ac residential and/or commercial power systems.

Not all systems are unsafe. Some PV installers in the United States are licensed or use licensed electrical contractors and are familiar with all sections of the *NEC* . These installer/contractors are installing reliable PV systems that meet the *National Electrical Code* and minimize the hazards associated with electrical power systems. However, many PV installations have numerous defects and may not meet the 1996 Code. Some of the more prominent problems are listed below.

- Improper ampacity of conductors
- Improper insulation on conductors
- Unsafe wiring methods
- No overcurrent protection on many conductors
- Inadequate number and placement of disconnects
- Improper application of listed equipment
- No short-circuit current protection on battery systems
- Use of non-approved components when approved components are available
- Improper system grounding
- Lack of equipment grounding
- Use of underrated components
- Unsafe use of batteries
- Use of ac components (fuses and switches) in dc applications

The Code may apply to any PV systems regardless of size or location. A single PV module may not present a hazard, and a small system in a remote location may present few safety hazards because people are seldom in the area. On the other hand, two or three modules connected to a battery can be lethal if not installed and operated properly. A single deep-cycle storage battery (6 volts, 220 amp-hours) can discharge about 8,000 amps into a short-circuit. Systems with voltages of 50 volts or higher present shock hazards. Short circuits on lower voltage systems present fire and equipment hazards. Storage batteries can be dangerous; hydrogen gas and acid residue from lead-acid batteries must be dealt with safely.

The problems are compounded because, unlike ac systems, there are few *UL*-Listed components that can be easily "plugged" together to make a PV system. Connectors and devices do not have mating inputs or outputs, and the knowledge and understanding of "what works with what" is not second nature to the installer. The dc "cookbook" of knowledge does not yet exist.

To meet the objective of safe, reliable, durable photovoltaic power systems, the following suggestions are made:

- Dealer-installers of PV systems become familiar with the *NEC* methods of wiring residential and commercial ac power systems.
- All PV installations be inspected, where required, by the local inspection authority in the same manner as other equivalent electrical systems.
- Photovoltaic equipment manufacturers build equipment to *UL* or other recognized standards and have equipment tested and listed when practical.
- Listed or recognized subcomponents be used in assembled equipment where formal testing and listing is not possible.
- Electrical equipment manufacturers produce, distribute, and advertise, listed, reasonably priced, dc-rated components.
- Electrical inspectors become familiar with dc and PV systems.
- The PV industry educate the public, modify advertising, and encourage all installers to comply with the *NEC* .
- All persons installing PV systems obtain and study the current *National Electrical Code*.
- Existing PV installations be upgraded to comply with the *NEC* or modified to meet minimum safety standards.

RECOMMENDED PRACTICES

Scope and Purpose of the *NEC*

Some local inspection authorities use regional electrical codes, but most jurisdictions use the *National Electrical Code*—sometimes with slight modifications. The *NEC* states that adherence to the recommendations made will reduce the hazards associated with electrical installations. The *NEC* also says these recommendations may not lead to improvements in efficiency, convenience, or adequacy for good service or future expansion of electrical use [90-1]. (Numbers in brackets refer to sections in the *NEC* .)

The *National Electrical Code* addresses nearly all PV power installations, even those with voltages less than 50 volts. It covers stand-alone and grid-connected systems. It covers billboards, other remote applications, floating buildings, and recreational vehicles (RV) [90-2(a), 690, 720]. The Code deals with any PV system that produces power and has external wiring or electrical components or contacts accessible to the untrained and unqualified person.

There are some exceptions. The *National Electrical Code* does not cover installations in automobiles, railway cars, boats, or on utility company properties used for power generation [90-2(b)]. It also does not cover micropower systems used in watches, calculators, or self-contained electronic equipment that have no external electrical wiring or contacts.

Article 690 of the *NEC* specifically deals with PV systems, but many other sections of the *NEC* contain requirements for any electrical system including PV systems [90-2, 720]. When there is a conflict between Article 690 of the *NEC* and any other article, Article 690 takes precedence [690-3].

The *NEC* suggests, and most inspection officials require, that equipment identified, listed, labeled, or tested by an approved testing laboratory be used when available [90-7,100,110-3]. Three of the several national testing organizations are the *Underwriters Laboratories (UL)*, *Factory Mutual Research (FM)*, and *ETL Testing Laboratories, Inc.* *Underwriters Laboratories* and *UL* are registered trademarks of *Underwriters Laboratories Inc.*, 333 Pfingsten Road, Northbrook, IL 60062.

Most building and electrical inspectors expect to see *UL* on electrical products used in electrical systems in the United States. This presents a problem for some in the PV industry, because low production rates do not yet justify the costs of testing and listing by *UL* or other laboratory. Some manufacturers claim their product specifications exceed those required by the testing organizations, but inspectors readily admit to not having the expertise, time, or funding to validate these unlabeled items.

THIS GUIDE

The recommended installation practices contained in this guide progress from the photovoltaic modules to the electrical outlets. For each component, *NEC* requirements are addressed, and the appropriate Code sections are referenced in brackets. A sentence, phrase, or paragraph followed by a *NEC* reference refers to a requirement established by the *NEC*. The words "**will**," "**shall**," or "**must**" also refer to *NEC* requirements. Suggestions based on field experience with PV systems are worded as such and will use the word "should." The availability of approved components is noted, and alternatives are discussed.

Appendix A lists sources for dc-rated and identified, listed, or approved products, and reference to the products is made as they are discussed.

Other appendices address details and issues associated with implementing the *NEC* in PV installations. Examples are included.

PHOTOVOLTAIC MODULES

Five manufacturers, ASE Americas, Photocomm Solavolt, Siemens, Solarex, and Tideland Signal Corp., offer listed modules at the present time. Other manufacturers are considering having their PV modules listed by an approved national testing laboratory.

Methods of connecting wiring to the modules vary from manufacturer to manufacturer. The *NEC* does not require conduit, but local jurisdictions, particularly in commercial installations, may require conduit. The Code requires strain relief be provided for connecting wires. If the module has a closed weatherproof junction box, strain relief and moisture-tight clamps should be used in any knockouts provided for field wiring. Where the weather-resistant gaskets are a part of the junction box, the

manufacturer's instructions must be followed to ensure proper strain relief and weatherproofing [110-3(b), *UL Standard 1703*]. Figure 1 shows various types of strain reliefs. The one on the left is a basic cable clamp for interior use with nonmetallic sheathed cable (Romex). The clamps in the center (T&B) and on the right are watertight and can be used with either single or multiconductor cable—depending on the insert. The plastic unit on the right is made by Heyco (Appendix A).

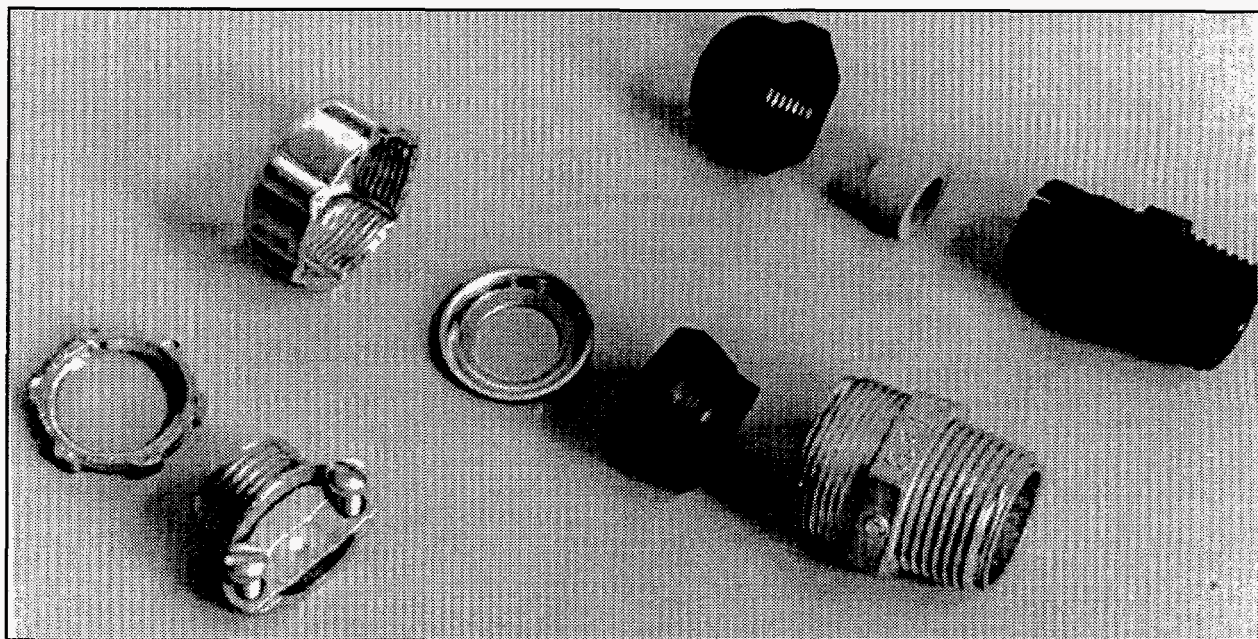


Figure 1. Strain Reliefs

Module Marking

Certain electrical information **must** appear on each module. If modules are not factory marked (required by the listing agency—*UL*), then they should be marked at the site to facilitate inspection and to allow the inspector to determine the requirements for conductor ampacity and rating of overcurrent devices. See also [690-52]. The information supplied by the manufacturer **will** include the following items:

- Polarity of output terminals or leads
- Maximum overcurrent device rating for module protection
- Rated open-circuit voltage
- Rated operating voltage
- Rated operating current
- Rated short-circuit current
- Rated maximum power
- Maximum permissible system voltage [690-51]

Although not required by the *NEC*, the temperature rating of the module terminals must be known to determine the temperature rating of the insulation of the conductors and how the ampacity of those conductors must be derated for temperature [110-14(c)]. Figure 2 shows a typical label that appears on the back of a module.

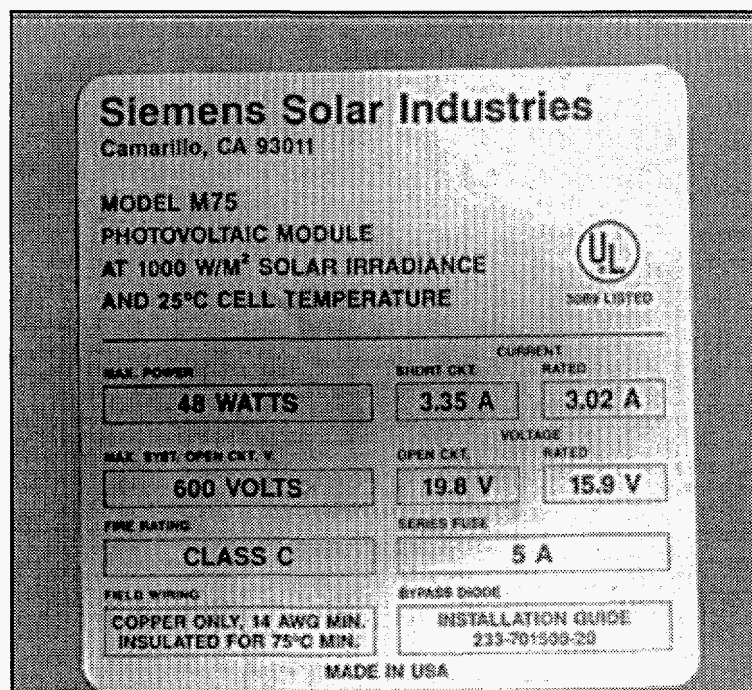


Figure 2. Label on Typical PV Module

Module Interconnections

Copper conductors are recommended for almost all photovoltaic system wiring [110-5]. Copper conductors have lower voltage drops and maximum resistance to corrosion. Aluminum or copper-clad aluminum wires can be used in certain applications, but the use of such cables is not recommended—particularly in dwellings. All wire sizes presented in this guide refer to copper conductors.

The *NEC* requires No. 12 American Wire Gage (AWG) or larger conductors to be used with systems under 50 volts [720-4]. Article 690 ampacity calculations yielding a smaller conductor size might override Article 720 considerations, but some inspectors are using the Article 720 requirement for dc circuits, and the Code has little information for conductor sizes smaller than No. 14 AWG, but Section 690-31d provides some guidance.

Single-conductor, Type UF (Underground Feeder — Identified as Sunlight Resistant), Type SE (Service Entrance), or Type USE (Underground Service Entrance) cables are permitted for module interconnect wiring [690-31(b)]. Stranded wire is suggested to ease servicing of the modules after installation and for durability [690-34]. Unfortunately, single-conductor, stranded, UF sunlight-resistant cable is not readily available, and there is some question about using the PVC insulation found on UF cables in dc circuits in the presence of moisture [310-13 FPN]. Most UF cable has insulation rated at 60°C. This insulation is not suitable for long-term exposure to direct sunlight at temperatures likely to occur on roofs near PV modules. Such wire has shown signs of deterioration after four years of exposure. Temperatures exceeding 60°C in the vicinity of the modules will preclude the use of conductors with 60°C insulation.

The widely available Underground Service Entrance Cable (USE) is suggested as the best cable to use for module interconnects. When made to the *UL* standard, it has a

90°C temperature rating and is sunlight resistant even though not commonly marked as such. Additional markings indicating XLP or XLPE (cross-linked polyethylene) and RHW-2 (90°C insulation when wet) ensure that the highest quality cable is being used [Tables 310-13, 16, and 17]. USE is acceptable to most electrical inspectors. The RHH and RHW-2 designations frequently found on USE-2 cable allow its use in conduit inside buildings. USE cable, without the other markings, does not have the fire-retardant additives that SE cable has and cannot be used inside buildings.

Where modules are connected in parallel, the ampacity of the conductors will have to be adjusted accordingly. The temperature derated ampacity of conductors at any point must be at least 125 percent of the module (or array of parallel modules) rated short-circuit current at that point [690-8(a), (b)(1)]. If flexible, two-conductor cable is needed, electrical tray cable (Type TC) is available but must be supported in a specific manner as outlined in the *NEC* [318 and 340]. TC is sunlight resistant and is generally marked as such. Although frequently used for module interconnections, SO, SOJ, and similar flexible, portable cables and cordage may not be sunlight resistant and are not approved for fixed (non-portable) installations [400-7, 8]. These cables may be used to connect tracking modules, and a "WA" marking on these or the SEO hard-service cables indicates that they have some sunlight resistance and are listed for outdoor use. The 1996 *NEC* provides data that will enable these flexible cables to be properly derated for the high temperatures found near modules [Table 690-31(c)]. Type SEO, SO, and other flexible cables have not been tested for use in conduit.

Tracking Modules

Where there are moving parts of an array, such as a flat-plate tracker or concentrating modules, the *NEC* does allow the use of Article 400, flexible cords and cables [400-7(a), 690-31(c)]. When these types of cables are used, they should be selected for extra-hard usage with full outdoor ratings [marked "WA" on the cable]. They

should not be used in conduit. Temperature derating information is provided by Table 690-31c. A derating factor in the range of 0.33 to 0.58 should be used for flexible cables used as module interconnects.

Another possibility is the use of extra flexible (475 strands) building cable type USE-RHH-RHW. This cable is available from the major wire distributors (Appendix A).

Terminals

Crimped-ring terminals are suggested in the module junction box to ensure that all strands of the conductor are connected to the screw terminal. If captive screws are used, then fork-type crimped terminals can be used, but no more than two should be used on any one screw.

Light-duty crimping tools designed for crimping smaller wires used in electronic components usually do not provide sufficient force to make long-lasting crimps on connectors for PV installations even though they may be sized for No. 12-10 AWG. Insulated terminals crimped with these light-duty crimpers frequently develop high-resistance connections in a short time and may even fail as the wire pulls out of the terminal. It is strongly suggested that only listed, heavy-duty industrial-type crimpers be used for PV system wiring. Figure 3 shows four styles of crimpers. On the far left is a stripper/crimper used for electronics work that will crimp only insulated terminals. Second from the left is a stripper/crimper that can make crimps on both insulated and uninsulated terminals. The pen points to the dies used for uninsulated terminals. With some care, this crimper can be used to crimp uninsulated terminals on PV systems if the terminals are soldered after the crimp. The two crimpers on the right are listed, heavy-duty industrial designs with ratcheting jaws and interchangeable dies that will provide the highest quality connections. They are usually available from electrical supply houses.

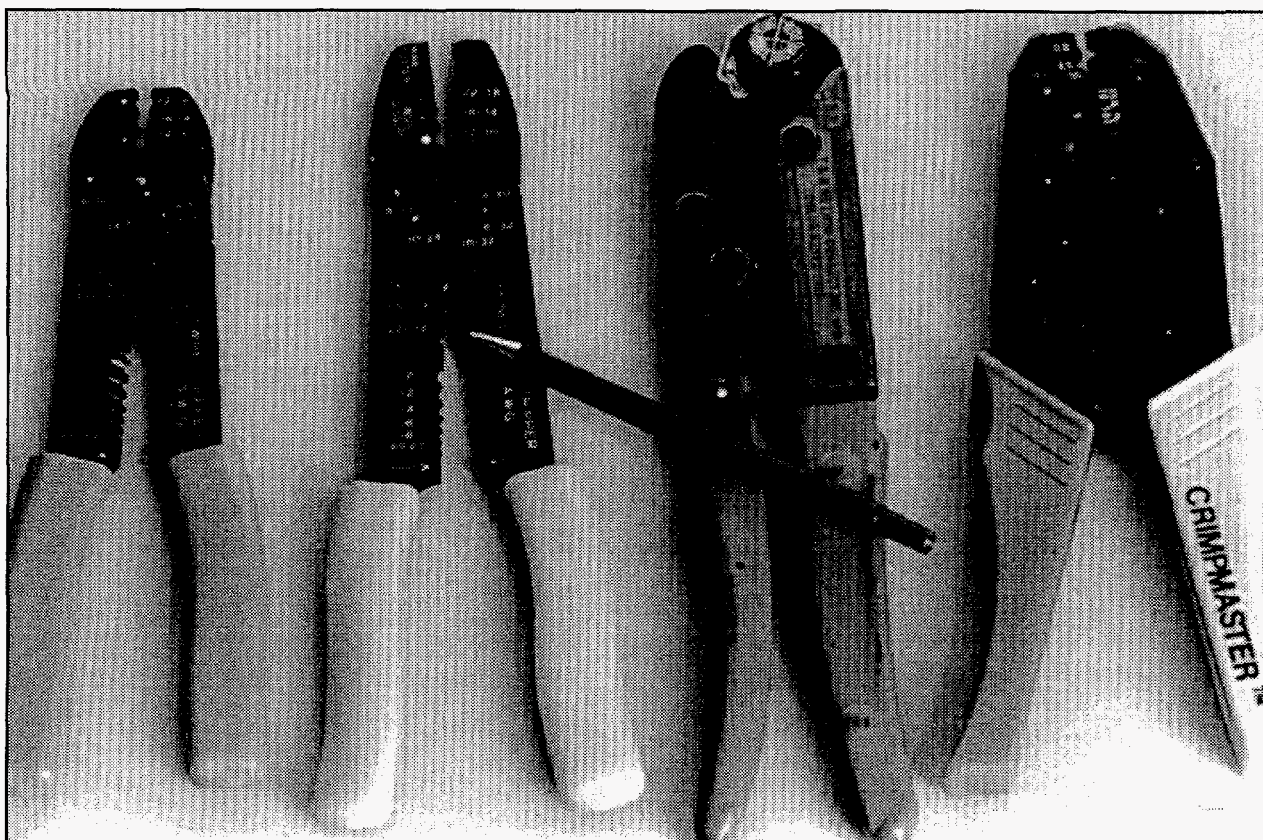


Figure 3. Terminal Crimpers

Figure 4 shows some examples of insulated and uninsulated terminals. In general, uninsulated terminals are preferred (with insulation applied later if required), but care must be exercised to obtain the heavier, more reliable *UL*-Listed terminals and not unlisted electronic or automotive grades. Again, an electrical supply house rather than an electronic or automotive parts store is the place to find the required items. Although time consuming, the crimping and soldering technique should be considered to ensure the connections last as long as the modules themselves. If the junction box provides box-style pressure terminals, it is not necessary to use the crimped and soldered terminals.

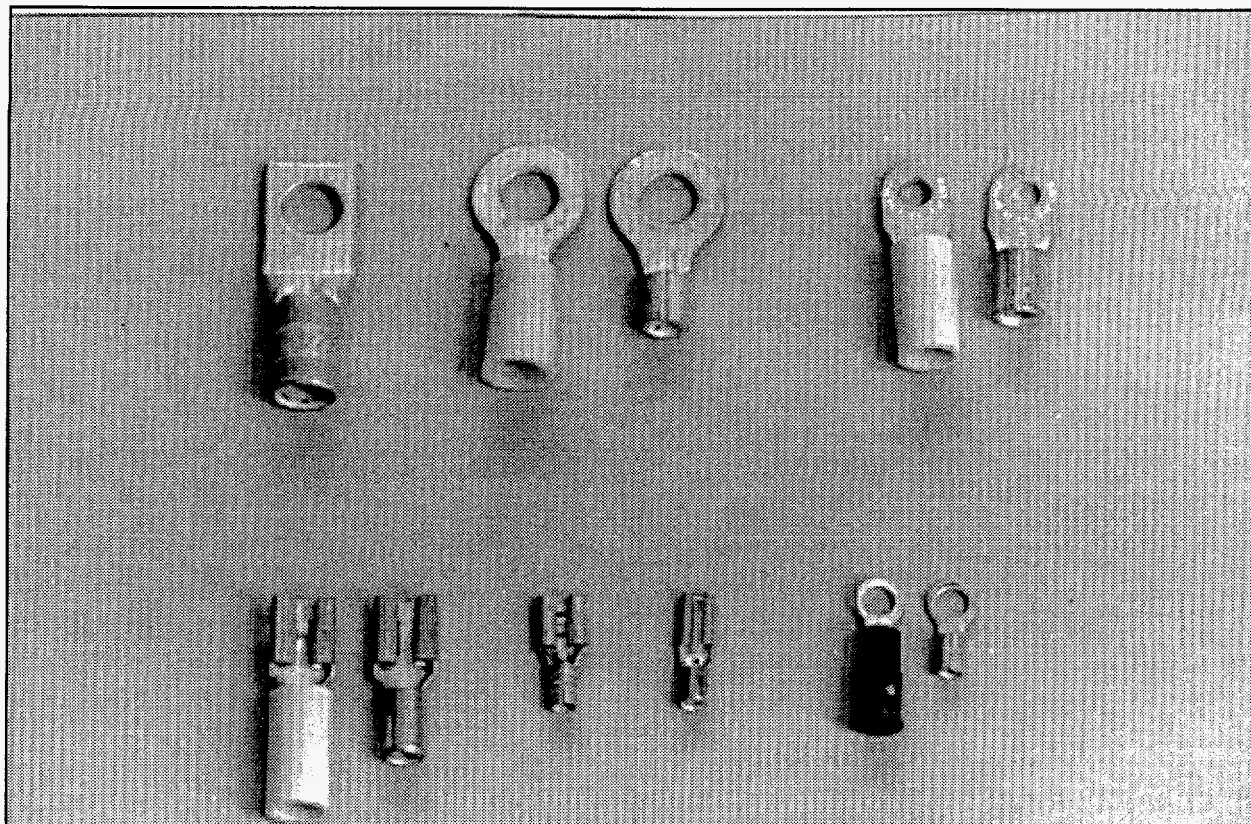


Figure 4. Insulated and Uninsulated Terminals.

Transition Wiring

Because of the relatively high cost of USE and TC cables and wire, they are usually connected to less expensive cable at the first junction box leading to an interior location. All PV system wiring must be made using one of the methods included in the *NEC* [690-31, Chapter 3]. Single-conductor, exposed wiring is not permitted except for module wiring or with special permission [Chapter 3]. The most common methods used for PV systems are individual conductors in electrical metallic tubing (EMT) and nonmetallic conduit and nonmetallic sheathed cable.

Where individual conductors are used in conduit, they should be conductors with at least 90°C insulation such as RHW-2 or XHHW-2. Conduits installed in exposed locations are considered to be installed in wet locations [100-Locations]. These conduits may have water entrapped in low spots and therefore only conductors with wet ratings

are acceptable in conduits that are in exposed or buried locations. The conduit can be either thick-wall or thin-wall electrical metallic tubing (EMT) [348], and if rigid, nonmetallic conduit is used, electrical (gray) PVC (Schedule 40 or Schedule 80) rather than plumbing (white) PVC tubing **must** be used [347].

Two-conductor (with ground) UF cable that is marked sunlight resistant is frequently used between the module interconnect wiring and the PV disconnect device. Black is the preferred color because of higher resistance to ultraviolet light, but the gray color seems durable because of the insulation associated with the jacket on the cable. Splices from the stranded wire to this wire when located outside **must** be protected in rain-proof junction boxes such as NEMA type 3R. Cable clamps must also be used. Figure 5 shows a rain-proof box with a pressure connector terminal strip installed for module wiring connections. The box penetrations (holes for screws) should be sealed with silicon rubber. Cable clamps used with this box must be listed for outdoor use.

Interior exposed cable runs can be made only with sheathed cable types such as NM, NMC, and UF. The cable should not be subjected to physical abuse. If abuse is possible, physical protection must be provided [300-4, 336 B, 339]. Exposed single-conductor cable (commonly used between batteries and inverters) **shall not** be used—except as module interconnect conductors [300-3(a)].

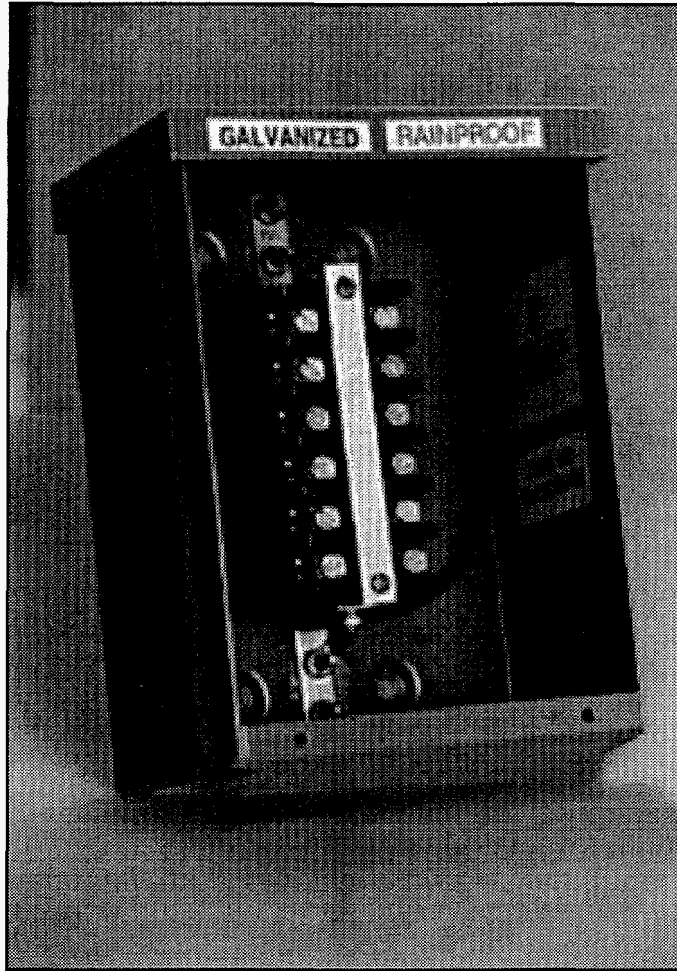


Figure 5. Listed Rain-proof Junction Box with Listed, Custom Terminal Strip

WIRING

Module Connectors

Module connectors that are concealed at the time of installation **must** be able to resist the environment, be polarized, and be able to handle the short-circuit current. They **shall** also be of a latching design with the terminals guarded. The equipment-grounding member, if used, **shall** make first and break last [690-32, 33]. The *UL* standard also requires that the connectors for positive and negative conductors **shall not** be interchangeable.

Module Connection Access

All junction boxes and other locations where module wiring connections are made shall be accessible. Removable modules and stranded wiring may allow accessibility [690-34]. The modules should not be permanently fixed (welded) to mounting frames, and solid wire that could break when modules are moved to service the junction boxes should not be used. Open spaces behind the modules would allow access to the junction boxes.

Splices

All splices (other than the connectors mentioned above) must be made in approved junction boxes with an approved splicing method. Conductors must be twisted firmly to make a good electrical and mechanical connection, then brazed, welded, or soldered, and then taped [110-14(b)]. Although solder has a higher resistivity than copper, a rosin-fluxed, soldered splice will have slightly lower electrical resistance, and potentially higher resistance to corrosion than an unsoldered splice. Mechanical splicing devices such as split-bolt connectors or terminal strips are also acceptable. Crimped splicing connectors may also be used if listed splicing devices and listed, heavy-duty crimpers are used.

If the highest reliability is needed, then exothermic welding should be used for splices. Also, properly used box-type pressure connectors (Figure 7) give high reliability. Fuse blocks, fused disconnects, and circuit breakers are available with these pressure connectors.

Twist-on wire connectors (approved for splicing wires) have not proved adequate when used on low-voltage (12-50 volts) or high-current PV systems because of thermal stress and oxidation of the contacts. These devices are not usually listed for outdoor environments or in junction boxes that may be exposed to moisture.

Where several modules are connected in series and parallel, a terminal block or bus bar arrangement **must** be used so that one source circuit can be disconnected without disconnecting the grounded (on grounded systems) conductor of other source circuits [690-4(c)]. On grounded systems, this indicates that the popular "Daisy Chain" method of connecting modules may not always be acceptable, because removing one module in the chain may disconnect the grounded conductor for all of those modules in other parallel chains or source circuits. This becomes more critical on larger systems where paralleled sets of long series strings of modules are used. Figure 6 shows unacceptable and acceptable methods. Generally, 12- and 24-volt systems can be daisy chained, but higher voltage systems should not be.

Several different types of terminal blocks and strips are shown in Figure 7. The larger blocks are made by Marathon (Appendix A).

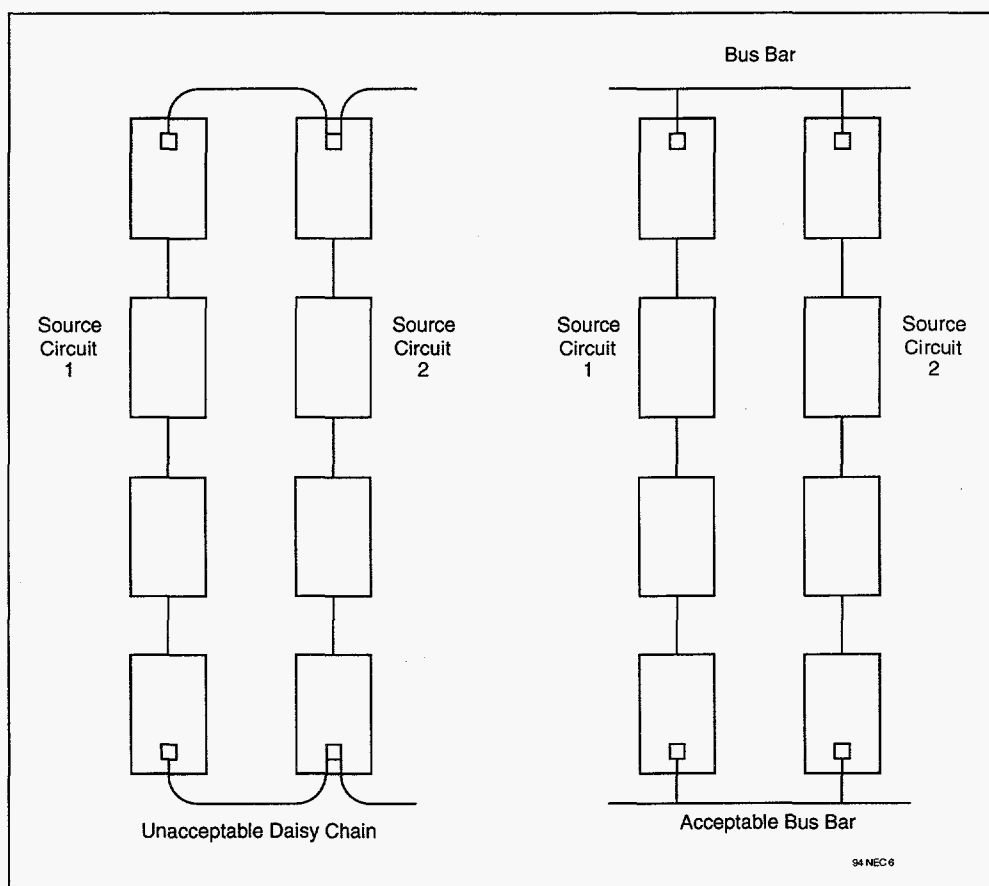


Figure 6. Module Interconnect Methods.

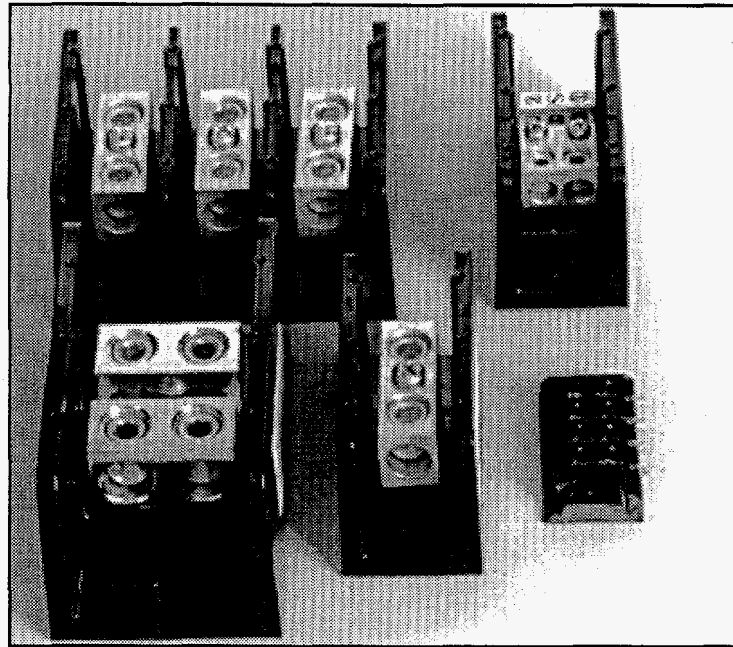


Figure 7. Power Splicing Blocks and Terminal Strips.

Conductor Color Codes

The *NEC* established color codes for electrical power systems many years before either the automobile or electronics industries had standardized color codes. PV systems are being installed in the arena covered by the *NEC* and, therefore, must comply with *NEC* standards that apply to both ac and dc power systems. In a system where one conductor is grounded, the insulation on all grounded conductors must be white or natural gray or be any color except green if marked with white plastic tape or paint at each termination (marking allowed only on conductors larger than 6 AWG). Conductors used for module frame grounding and other exposed metal equipment grounding must be bare (no insulation) or have green or green with yellow-striped insulation or identification [200-6, 7; 210-5].

The *NEC* requirements specify that the grounded conductor be white. In most PV-powered systems that are grounded, the grounded conductor is the negative conductor. Telephone systems that use positive grounds require special circuits when powered by PV systems that have negative grounds. In a PV system where the array is

center tapped, the center tap or neutral must be grounded [690-41], and this becomes the white conductor. There is no *NEC* requirement designating the color of the ungrounded conductor, but the convention in power wiring is that the first two ungrounded conductors are colored black and red. This suggests that in two-wire, negative-grounded PV systems, the positive conductor could be red or any color with a red marking except green or white, and the negative grounded conductor **must** be white. In a three-wire, center-tapped system, the positive conductor could be red, the grounded center tap conductor **must** be white and the negative conductor could be black.

The 1996 *NEC* allows grounded (non-white) array conductors, such as USE or SE that are smaller than No. 6 AWG, to be marked with a white marker [200-6].

Battery Cables

Battery cables, even though they can be No. 2/0 AWG and larger, must be of standard building-wire type conductor [Chapter 3]. Welding and automobile "battery" cables are not allowed. Flexible, highly-stranded, building-wire type cables (USE-RWH) are available for this use. Flexible cables, identified in Section 400 of the *NEC* are allowed from the battery terminals to a nearby junction box and between battery cells [690-74].

GROUND-FAULT PROTECTION AND ARRAY DISABLEMENT

Ground-Faults

Article 690-5 of the *NEC* requires a ground-fault detection, interruption, and array disablement (GFID) device for fire protection if the PV arrays are mounted on roofs of dwellings. Ground-mounted arrays are not required to have this device. Several devices to meet this requirement are under development, but none are commercially available. These particular devices may require that the system grounding conductor

be routed through the device. To keep costs to a minimum, the devices under development may replace the PV disconnect switch and may incorporate the following functions:

- Manual PV disconnect switch
- Ground-fault detection
- Ground-fault interruption
- Array disablement
- Array wiring overcurrent protection

Ground-fault detection, interruption, and array disablement devices might, depending on the particular design, accomplish the following actions automatically:

- Sense ground-fault currents exceeding a specified value
- Interrupt or significantly reduce the fault currents
- Open the circuit between the array and the load
- Short the array or subarray

These actions would reduce the array voltages to nearly zero (minimizing human shock hazards and equipment damage) and would serve to direct the fault currents away from the fault path and back into the normal conductors. For fault location and repair, the array shorting device would have to be opened.

Ground-fault devices have been developed for some grid-tied inverters and stand-alone systems, and others are under development. If a version of the *NEC* specifies equipment that is not commercially available, the authority having jurisdiction may issue a waiver on the requirement [90-4].

Array Disablement

Article 690-18 requires that a mechanism be provided to disable portions of the array or the entire array. The term "disable" has several meanings, and the *NEC* is not clear on what is intended. The *NEC Handbook* does elaborate. Disable can be defined several ways:

- Prevent the PV system from producing any output
- Reduce the output voltage to zero
- Reduce the output current to zero
- Divide the array into non-hazardous segments

The output could be measured at either the PV source terminals or at the load terminals.

Fire fighters are reluctant to fight a fire in a high-voltage battery room because there is no way to turn off a battery bank unless you can somehow remove the electrolyte. In a similar manner, the only way a PV system can have zero output at the array terminals is by preventing light from illuminating the modules. The output voltage may be reduced to zero by shorting the PV module or array terminals. When this is done, short-circuit current will flow through the shorting conductor, which in a properly wired system with bypass diodes, does no harm. The output current may be reduced to zero by disconnecting the PV system from any load. The PV disconnect switch would accomplish this action, but open-circuit voltages would still be present on the array wiring and in the disconnect box. On a large system, 100 amps of short-circuit current (with a shorted array) can be as difficult to handle as an open-circuit voltage of 600 volts.

During PV module installations, the individual PV modules can be covered to disable them. For a system in use, the PV disconnect switch is opened during maintenance, and the array is either short circuited or left open circuited depending on the circumstances. In practical terms, for a large array, some provision (switch or bolted connection) should be made to disconnect portions of the array from other sections for servicing. As individual modules or sets of modules are serviced, they may be covered and/or isolated and shorted to reduce the potential for electrical shock. Aside from measuring short-circuit current, there is little that can be serviced on a module or array when it is shorted. The circuit is usually open circuited for repairs.

GROUNDING

The subject of grounding is one of the most confusing issues in electrical installations. Definitions from Article 100 of the *NEC* will clarify the situation.

Grounded:	Connected to the earth or to a conductor that serves as earth.
Grounded Conductor:	A system conductor that normally carries current and is intentionally grounded. In PV systems, one conductor (normally the negative) of a two-conductor system or the center-tapped wire of a bipolar system is grounded.
Grounding Conductor (1 and 2):	A conductor not normally carrying current used to: (1) connect the exposed metal portions of equipment to the grounding electrode system or the grounded conductor, or (2) connect the grounded conductor to the grounding electrode or grounding electrode system.
Equipment Grounding Conductor:	See Grounding Conductor (1), above.
Grounding Electrode Conductor:	See Grounding Conductor (2), above.

Grounding—System

For a two-wire PV system over 50 volts (open-circuit PV-output voltage), one dc conductor **shall** be grounded. In a three-wire system, the neutral or center tap of the dc system **shall** be grounded [690-7, 41]. These requirements apply to both stand-alone and grid-tied systems. Such system grounding will enhance personnel safety and minimize the effects of lightning and other induced surges on equipment. Also, grounding of all PV systems will reduce radio frequency noise from dc-operated fluorescent lights and inverters.

Size of Grounding Electrode Conductor

The direct-current system-grounding electrode conductor **shall** not be smaller than No. 8 AWG or the largest conductor supplied by the system [250-93]. If the conductors

between the battery and inverter are 4/0 AWG (for example) then the conductor from the negative conductor (assuming that this is the grounded conductor) to the grounding electrode **must** be 4/0 AWG. The 1996 *NEC* allows exceptions to this large grounding conductor requirement. Many PV systems can use a No. 6 AWG grounding electrode conductor if that is the only connection to the grounding electrode [250-93].

Point of Connection

The system grounding electrode conductor for the direct-current portion of a PV system **shall** be connected to the PV-output circuits toward the module-end of the circuit [690-42, 250-22]. When this connection is made close to the modules, added protection from surges is afforded. Disconnect switches **must not** open grounded conductors [690-13]. In stand-alone PV systems, the charge controller may be considered a part of the PV-output circuit, and the point of connecting the grounding electrode conductor could be before or after the charge controller. But this grounding conductor may be a very large conductor (e.g., 4/0 AWG) while the conductors to and from the charge controller may be No. 10 AWG or smaller. Connecting the 4/0 AWG grounding conductor on the array side of the charge controller, while providing some degree of enhanced surge suppression from lightning induced surges, may not meet the full intent of the grounding requirements. Connecting the grounding conductor to the system on the battery side of the charge controller at a point where the system conductors are the largest size will provide better system grounding at the expense of less lightning protection. Since the 1996 *NEC* allows smaller grounding electrode conductors in certain circumstances, either grounding conductor point of connection may be acceptable [250-93]. Figure 8 shows two possible locations for the grounding conductor.

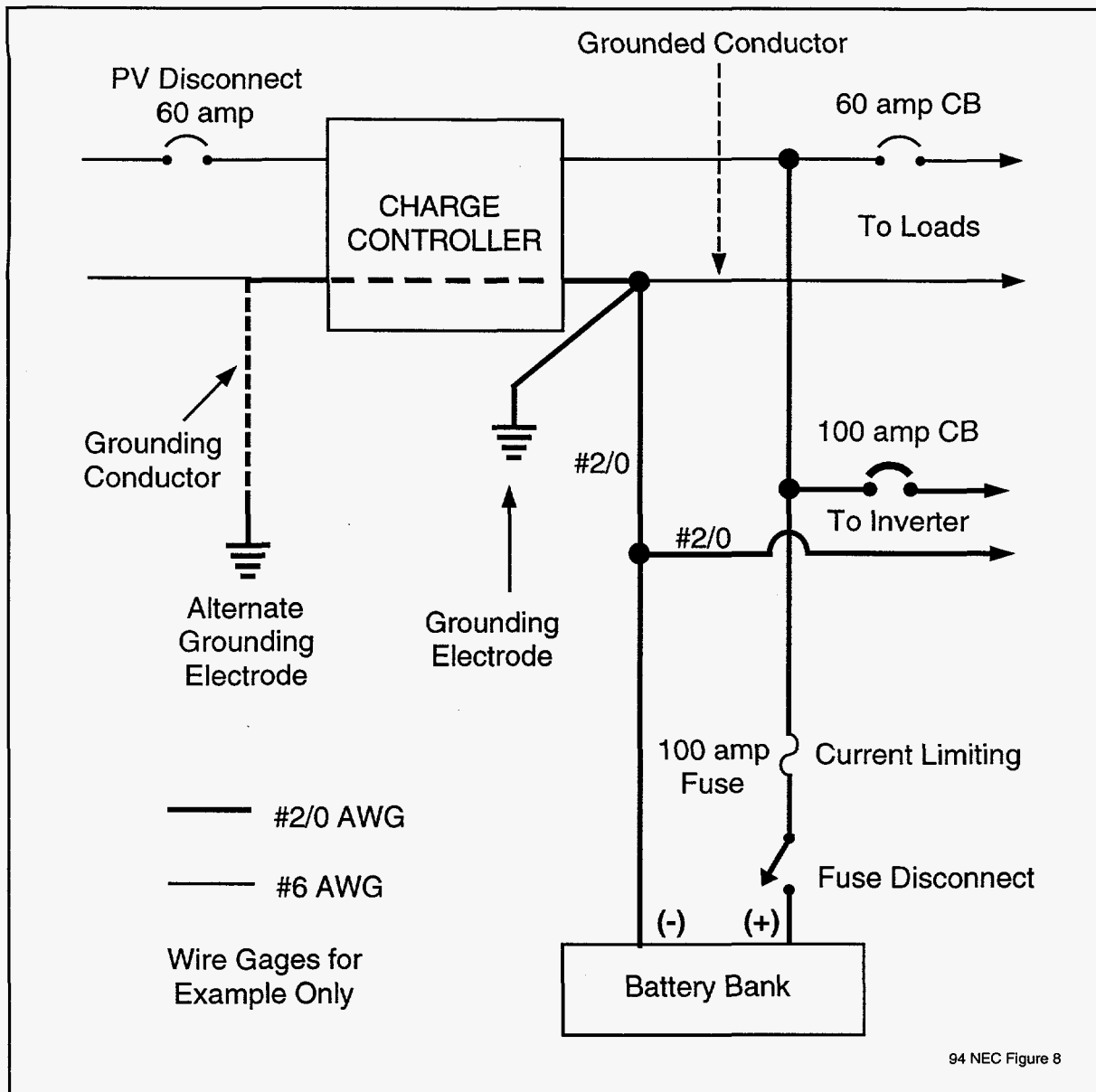


Figure 8. Typical System: Possible Grounding Conductor Locations.

The *NEC* does not specifically define where the PV-output circuits end. Circuits from the battery toward the load are definitely load circuits. Since the heaviest conductors are from the battery to the inverter, and either end of these conductors is at the same potential, then either end could be considered a point for connecting the grounding conductor. The negative dc input to the inverter is connected to the metal case in some stand-alone inverter designs, but this is not an appropriate place to

connect the grounding electrode conductor and other equipment-grounding conductors, since this circuit is a dc-branch circuit and not a PV-output circuit. Connection of the grounding electrode conductor to the negative battery terminal would avoid the "large-wire/small-wire" problem outlined above.

It is imperative that there be no more than one grounding connection to the negative conductor of a PV system. Failure to limit the connections to one (1) will allow currents to flow in uninsulated conductors and will create unintentional ground faults in the grounded conductor [250-21]. Future ground-fault interrupter systems may require that this single grounding connection be made at a specific location.

Unusual Grounding Situations

Some inverter designs use the entire chassis as part of the negative circuit. Also, the same situation exists in certain radios—automobile and shortwave. These designs will not pass the current *UL* standards for consumer electrical equipment and will probably require modification in the future since they do not provide electrical isolation between the exterior metal surfaces and the current-carrying conductors. They also create the very real potential for multiple grounding-conductor connections to earth ground.

Since the case of these non-listed inverters is connected to the negative conductor and that case must be grounded as part of the equipment ground described below, the user has no choice whether or not the system is to be grounded. The system will be grounded even if the voltage is less than 50 volts and the point of system ground is the negative input terminal on the inverter.

Some telephone systems ground the positive conductor, and this may cause problems for PV-powered telephone systems with negative grounds. An isolated-ground, dc-to-dc converter may be used to power subsystems that have different

grounding polarities from the main system. In the ac realm, an isolation transformer will serve the same purpose.

In larger utility-tied systems and some stand-alone systems, high impedance grounding systems might be used in lieu of, or in addition to, the required hard ground. The discussion and design of these systems are beyond the scope of this guide. Grounding of grid-tied systems will be discussed in Appendix C.

Charge Controllers—System Grounding

In a grounded system, it is important that the charge controller have no signal processing in the grounded conductor. Relays or transistors in the grounded conductor create a situation where the grounded conductor is not at ground potential at times when the charge controller is operating. This condition violates provisions of the *NEC* that require all conductors identified as grounded conductors always be at the same potential (i.e. grounded). A shunt in the grounded conductor is equivalent to a wire if properly sized, but the user of such a charge controller runs the risk of having the shunt bypassed when inadvertent grounds occur in the system. The best charge controller design has only a straight-through conductor between the input and output terminals for the grounded current-carrying conductor (usually the negative conductor).

Grounding—Equipment

All noncurrent-carrying exposed metal parts of junction boxes, equipment, and appliances in the entire PV and dc load system **shall** be grounded [690-43, 250 E, 720-1 & 10]. All PV systems, regardless of voltage, **must** have an equipment-grounding system for exposed metal surfaces (e.g., module frames and inverter cases) [690-43]. The grounding conductor **shall** be sized as required by Article 690-45 or 250-95. Generally, this will mean an equipment-grounding conductor size based on the size of the overcurrent device protecting each conductor. Table 250-95 in the *NEC* gives the

sizes. For example, if the inverter to battery conductors are protected by a 400-amp fuse or circuit breaker, then at least No. 3 AWG conductor **must** be used for the equipment ground for that circuit [Table 250-95]. If the current-carrying conductors have been oversized to lower voltage drop, then the size of the equipment-grounding conductor **must** also be proportionately adjusted [250-95]. In the PV source circuits, if the array can provide short-circuit currents that are less than twice the rating of a particular overcurrent device for the array circuits, then equipment-grounding conductors **must** be used that are sized the same as the array current-carrying conductors [690-45]. In other situations, Table 250-95 of the *NEC* applies.

Equipment Grounds for Non-Listed Inverters

Many non-listed inverters do not have provisions for the equipment ground connection required by the *NEC*. It is suggested that one of the holes used to mount the inverter have the paint scraped off and the mounting bolt with internal toothed lock washers be used to connect the equipment-grounding conductor. If the inverter has the case connected to the negative terminal, then the negative input terminal can be used for the equipment ground and the system ground. An appropriately sized conductor **must** be used [250-95].

Some listed inverters have provisions for only a small-gage ac output-side equipment-grounding conductor. This equipment-grounding conductor would probably be vaporized if the ground fault were to occur on the dc side of the wiring. It is suggested that the inverter equipment-grounding conductor be sized for the dc input.

Inverter AC Outputs

The inverter output (120 or 240 volts) must be connected to the ac distribution system in a manner that does not create parallel grounding paths. The *NEC* requires that both the green equipment-grounding conductor and the white neutral conductor

be grounded. The Code also requires that current not normally flow in the green wires. If the inverter has ac grounding receptacles as outputs, the grounding and neutral conductors are most likely connected to the chassis and, hence, to ground inside the inverter. This configuration allows plug-in devices to be used safely. However, if the outlets on the inverter are plug and cord connected to an ac load center used (not recommended) as a distribution device, then problems can occur.

The ac load center usually has the neutral and equipment-grounding conductors connected to the same bus bar which is connected to the case where they are grounded. Parallel current paths are created with neutral currents flowing in the equipment-grounding conductors. This problem can be avoided by using a load center with an isolated/insulated neutral bus bar which is separated from the equipment-grounding bus bar.

Inverters with hard-wired outputs may or may not have internal connections. Some inverters with ground-fault circuit interrupters (GFCIs) for outputs must be connected in a manner that allows proper functioning of the GFCI. A case-by-case analysis will be required.

Backup Generators

Backup generators used for battery charging pose problems similar to using inverters and load centers. These small generators usually have ac outlets which may have the neutral and grounding conductors bonded to the generator frame. When the generator is connected to the system through a load center, to a standby inverter with battery charger, or to an external battery charger, parallel ground paths are likely. These problems must be addressed on a case-by-case basis. A PV system, in any operating mode, **must not** have currents in the equipment-grounding conductors [250-21].

Suggested AC Grounding

Auxiliary ac generators and inverters should be hard-wired to the ac-load center. Neither should have an internal bond between the neutral and grounding conductors. Neither should have any receptacle outlets that can be used when the generator or inverter is operated when disconnected from the load center. The single bond between the neutral and ground will be made in the load center. If receptacle outlets are desired on the generator or the inverter, they should be ground-fault-circuit-interrupting devices (GFCI).

Grounding Electrode

The dc system grounding electrode **shall** be common with, or bonded to, the ac-grounding electrode (if any) [690-47, 250-H]. The system-grounding conductor and the equipment-grounding conductor **shall** be tied to the same grounding electrode or grounding electrode system. Even if the PV system is ungrounded (optional at less than 50 volts), the equipment-grounding conductor must be connected to a grounding electrode [250-50]. Metal water pipes and other metallic structures as well as concrete encased electrodes are to be used in some circumstances [250-81, 250-83]. When a grounding electrode is used, it **shall** be a corrosion resistant rod, a minimum of 5/8 inch in diameter with at least 8 feet driven into the soil at an angle no greater than 45 degrees from the vertical [250-83]. Listed connectors must be used to connect the grounding conductor to the ground rod.

A bare-metal well casing makes a good grounding electrode. It should be part of a grounding electrode system. The central pipe to the well should not be used for grounding, because it is sometimes removed for servicing.

For maximum protection against lightning-induced surges, it is suggested that a grounding electrode **system** be used with at least two grounding electrodes bonded together. One electrode would be the main system grounding electrode as described

above. The other would be a supplemental grounding electrode located as close to the PV array as practical. The module frames and array frames would be connected directly to this grounding electrode to provide as short a path as possible for lightning-induced surges to reach the earth. This electrode **must** be bonded with a conductor to the main system grounding electrode [250-81]. The size of the bonding or jumper cable must be related to the ampacity of the overcurrent device protecting the PV source circuits. This bonding jumper is an auxiliary to the module frame grounding that is required to be grounded with an equipment-grounding conductor. *NEC* Table 250-95 gives the requirements. Equipment-grounding conductors are allowed to be smaller than circuit conductors when the circuit conductors become very large. Article 250 of the *NEC* elaborates on these requirements.

Do not connect the negative current-carrying conductor to the grounding electrode, to the equipment-grounding conductor, or to the frame at the modules. There should be one and only one point in the system where the grounding electrode conductor is attached to the system-grounded conductor. See Figure 9 for clarification. The wire sizes shown are for illustration only and will vary depending on system size. Chapter 3 of the *NEC* specifies the ampacity of various types and sizes of conductors.

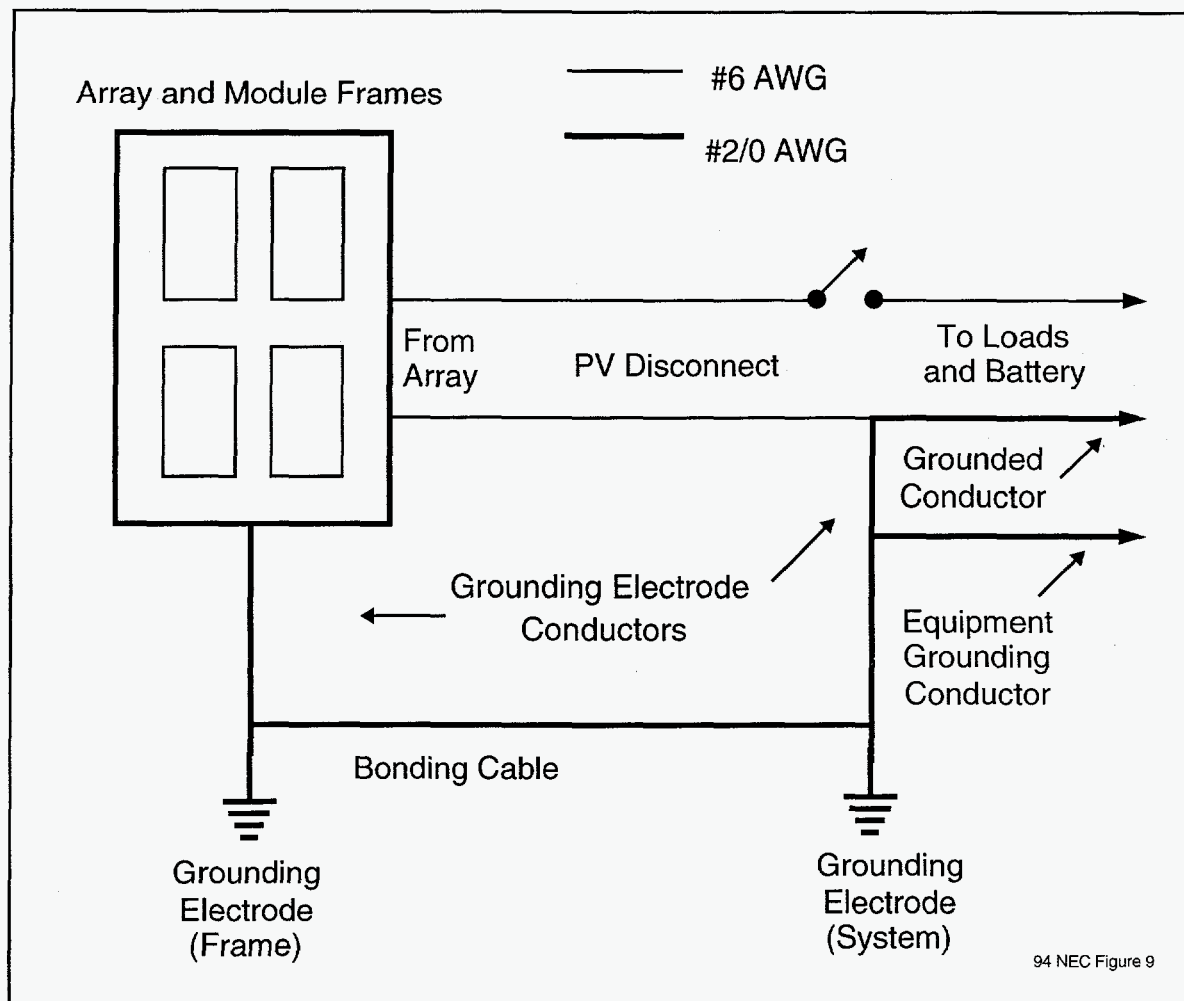


Figure 9. Example Grounding Electrode System.

CONDUCTOR AMPACITY

Photovoltaic modules are limited in their ability to deliver current. The short-circuit current capability of a module is nominally 10 to 15 percent higher than the operating current. Normal, daily values of solar irradiance may exceed the standard test condition of $1000\text{W}/\text{m}^2$. These increased currents must be considered in the ampacity calculations. Another problem for PV systems is that the conductors may operate at temperatures as high as $65\text{--}75^\circ\text{C}$ when the modules are mounted close to a structure, there are no winds, and the ambient temperatures are high. Temperatures in module junction boxes frequently occur within this range. This will require that the

ampacity of the conductors be derated or corrected with factors given in *NEC* Table 310-16 or 310-17. For example, a No. 10 AWG USE/RHW-2 single-conductor cable used for module interconnections in conduit has a 90°C insulation and an ampacity of 40 amps in an ambient temperature of 26-30°C. When it is used in ambient temperatures of 61-70°C, the ampacity of this cable is reduced to 23.2 amps.

It should be noted that the ampacity values associated with conductors having 90°C insulation can only be used if the module terminals are rated at 90°C [110-14(c)]. If the terminals are rated at only 75°C, then the ampacity values associated with 75°C insulation **must** be used, even when conductors with 90°C insulation are being used.

The ampacity of conductors in PV source circuits **shall** be at least 125 percent of the rated module or parallel-connected modules short-circuit current [690-8]. The ampacity of the PV-output circuit conductors **shall** be at least 125 percent of the short-circuit output current [690-8]. The ampacity of conductors to and from an inverter or power conditioning system **shall** be 125 percent of the rated operating current for that device [690-8]. In a similar manner, other conductors in the system should have an ampacity of 125 percent of the rated operating current to allow for long duration operation at full power [220-3(a)]. These *NEC* requirements are to ensure that the connected overcurrent devices or panel boards operate at no more than 80 percent of their ampacity. Operation when snow or cloud enhancement increases the PV output above normal may require additional ampacity. Daily expected values of solar irradiance will exceed the standard test condition of 1000W/m² at many locations.

A 1989 revision to the *UL* Standard 1703 for PV modules requires that module installation instructions include an additional 25 percent of the 25°C ratings for short-circuit current and open-circuit voltage to allow for expected daily peak irradiance and colder temperatures. Correct design practices require correctly determining wire size and the rating of overcurrent devices on PV source and output circuits. However, the

rating of the overcurrent device should always be less than, or equal to, the ampacity of the cable. The *NEC* makes only infrequent exceptions to this rule [240-3].

The ampacity of conductors and the sizing of overcurrent devices is an area that demands careful attention by the PV system designer/installer. Temperatures and wiring methods must be addressed for each site. Start with the 125 percent of I_{sc} value to comply with the *UL* requirements. Then use an additional 125 percent for code compliance. Finally, derate the cable ampacity for temperature. See Appendix E for additional examples.

Overcurrent devices may have terminals rated for connection to 60°C conductors necessitating a reduction in the cable ampacity when using 75°C or 90°C conductors.

Stand-Alone Systems—Inverters

In stand-alone systems, inverters are frequently used to change the direct current (dc) from a battery bank to 120-volt or 240-volt, 60-Hertz (Hz) alternating current (ac). The conductors between the inverter and the battery **must** have properly rated overcurrent protection and disconnect mechanisms [240, 690-8b(3), -8(b)(4), -15]. These inverters frequently have short duration (tens of seconds) surge capabilities that are four to six times the rated output. For example, a 2,500-watt inverter might be required to surge to 10,000 volt-amps for 5 seconds when a motor load must be started. The *NEC* requires the ampacity of the conductors between the battery and the inverter to be sized by the rated 2,500-watt output of the inverter. For example, in a 24-volt system, a 2,500-watt inverter would draw 105 amps at full load (100% efficiency at 24 volts) and 420 amps for motor-starting surges. The ampacity of the conductors between the battery **must** be 125 percent of the 105 amps or 131 amps.

To minimize steady-state voltage drops, account for surge-induced voltage drops, and to increase system efficiency, most well-designed systems have conductors several sizes larger than required by the *NEC*. When the current-carrying conductors are

oversized, the equipment-grounding conductor **must** also be oversized proportionately [250-95].

When the battery bank is tapped to provide multiple voltages (i.e., 12 and 24 volts from a 24-volt battery bank), the common negative conductor will carry the **sum** of all of the simultaneous load currents. The negative conductor **must** have an **ampacity at least equal to the sum** of all the amp ratings of the overcurrent devices protecting the positive conductors or have an ampacity equal to the sum of the ampacities of the positive conductors [690-8(c)].

The *NEC* does not allow paralleling conductors for added ampacity, except that cables 1/0 AWG or larger may be paralleled under certain conditions [310-4]. DC-rated switchgear, overcurrent devices, and conductors cost significantly more when rated to carry more than 100 amps. It is suggested that large PV arrays be broken down into subarrays, each having a short-circuit output of less than 64 amps. This will allow use of 100-amp-rated equipment (156 percent of 64 amps) on each source circuit.

OVERCURRENT PROTECTION

The *NEC* requires that every ungrounded conductor be protected by an overcurrent device [240-20]. In a PV system with multiple sources of power (PV modules, batteries, battery chargers, generators, power conditioning systems, etc.), the overcurrent device must protect the conductor from overcurrent from any source connected to that conductor [690-9]. Blocking diodes, charge controllers, and inverters are not considered as overcurrent devices and must be considered as zero-resistance wires when assessing overcurrent sources (690-9 FPN). If the PV system is directly connected to the load without battery storage or other source of power, then no overcurrent protection is required if the conductors are sized at 156 percent of the short-circuit current [690-8b-Ex].

When circuits are opened in dc systems, arcs are sustained much longer than they are in ac systems. This presents additional burdens on overcurrent-protection devices rated for dc operation. Such devices must carry the rated load current and sense overcurrent situations as well as be able to safely interrupt dc currents. AC overcurrent devices have the same requirements, but the interrupt function is considerably easier.

Ampere Rating

The PV source circuits **shall** have overcurrent devices rated at least 125 percent of the parallel module short-circuit current. The PV-output circuit overcurrent devices **shall** be rated at least 125 percent of the short-circuit PV currents [690-8]. Some installations have experienced the blowing of fuses and loosening of terminals for unknown reasons. Good engineering practice calls for increasing the rating of these overcurrent devices and the ampacity of the conductors they protect to 156 percent of the short-circuit current. This practice agrees with the *UL* requirements mentioned above ($1.25 \times 1.25 = 1.56$). Time-delay fuses or circuit breakers would minimize nuisance tripping or blowing. In all cases, dc-rated devices having the appropriate dc-voltage rating must be used and adequate ventilation must be provided.

All ungrounded conductors from the PV array **shall** be protected with overcurrent devices [Article 240, Diagram 690-1]. Grounded conductors (not shown in Diagram 690-1) should not have overcurrent devices since the independent opening of such a device would unground the system. Since PV module outputs are current limited, these overcurrent devices are actually protecting the array wiring from battery or power conditioning system short circuits.

Because the conductors and overcurrent devices are sized to deal with 125 percent of the short-circuit current for that particular PV circuit, overcurrents from those modules or PV sources, which are limited to the short-circuit current, cannot trip the overcurrent device in this circuit. The overcurrent devices in these circuits protect the

conductors from overcurrents from parallel connected sets of modules (diode failure) or overcurrents from the battery bank (diode or charge controller failure). In standby systems or grid-connected systems, these array overcurrent devices protect the array wiring from overcurrents from parallel strings of modules, the battery, or from the generator or ac utility power when the battery charger or inverter fails.

Often, PV modules or series strings of modules are connected in parallel. As the conductor size used in the array wiring increases to accommodate the higher short-circuit currents of paralleled modules, each conductor size must be protected by an appropriately sized overcurrent device. These devices must be placed nearest all sources of potential overcurrent for that conductor [240-21]. Figure 10 shows an example of array conductor overcurrent protection for a medium-size array broken into subarrays. The cable sizes and types shown are examples only. The actual sizes will depend on the ampacity needed.

Either fuses or circuit breakers are acceptable for overcurrent devices provided they are rated for their intended uses—i.e., they have dc ratings when used in dc circuits, the ampacity is correct, and they can interrupt the necessary currents when short circuits occur [240 E, F, G]. Figure 11 shows dc-rated, *UL*-Listed circuit breakers being used in a PV power center for overcurrent protection and disconnects. The circuit breakers in this system are manufactured by Heinemann (Appendix A). The *NEC* allows the use of listed (recognized) supplemental overcurrent devices only for PV source circuit protection.

Some overcurrent devices rated at less than 100 amps may have terminals that are rated for use with 60°C conductors. The ampacity calculations of the connected cables may have to be adjusted.

Testing and Approval

The *NEC* requires that listed devices be used for overcurrent protection. A listed device by *UL* or other approved testing laboratory is tested against an appropriate *UL* standard. A recognized device is tested by *UL* or other approved testing laboratory to standards established by the device manufacturer. In most cases, the standards established by the manufacturer are less rigorous than those established by *UL*. Many inspectors will not accept recognized devices, particularly where they are required for overcurrent protection.

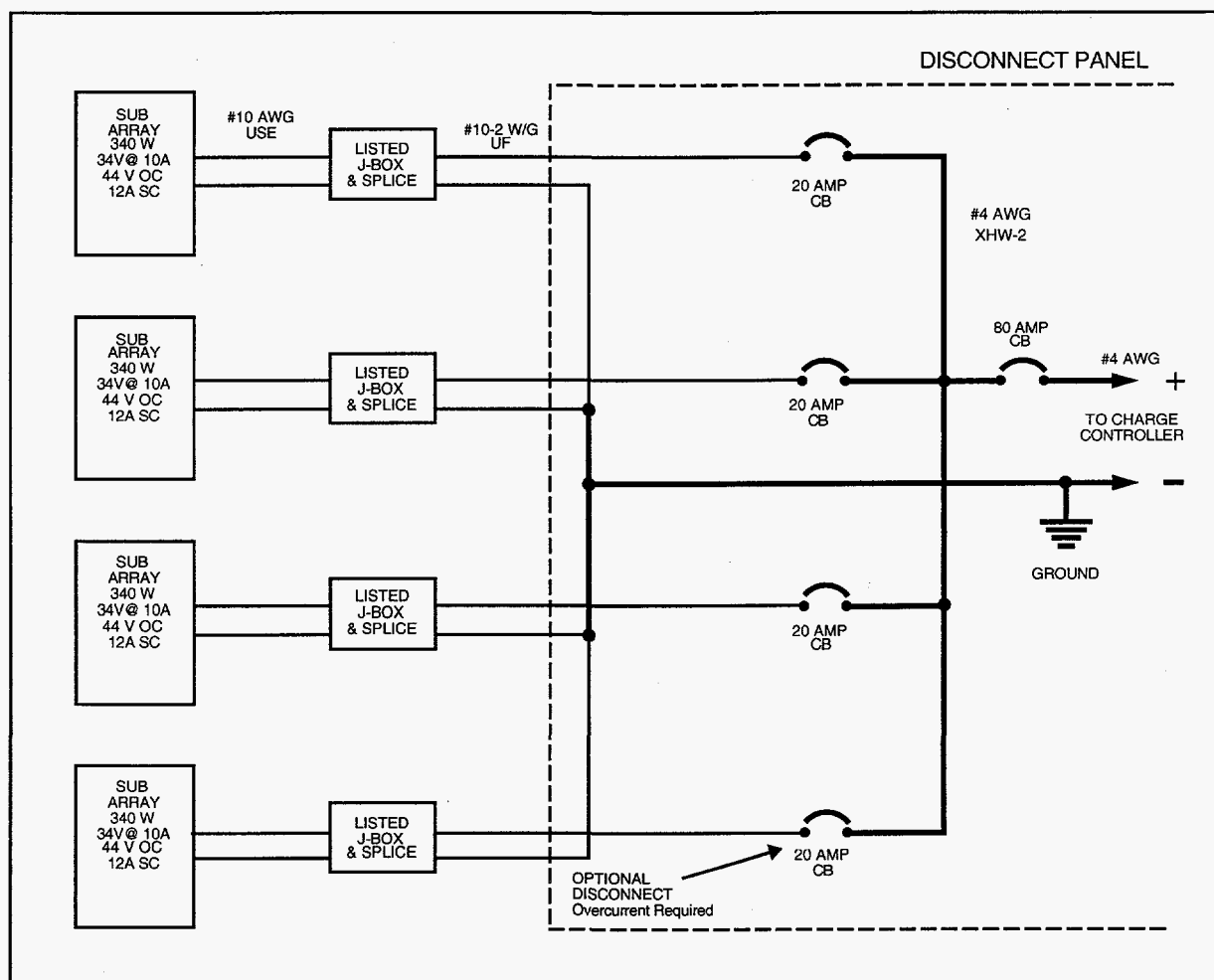


Figure 10. Typical Array Conductor Overcurrent Protection (with Optional Subarray Disconnects).

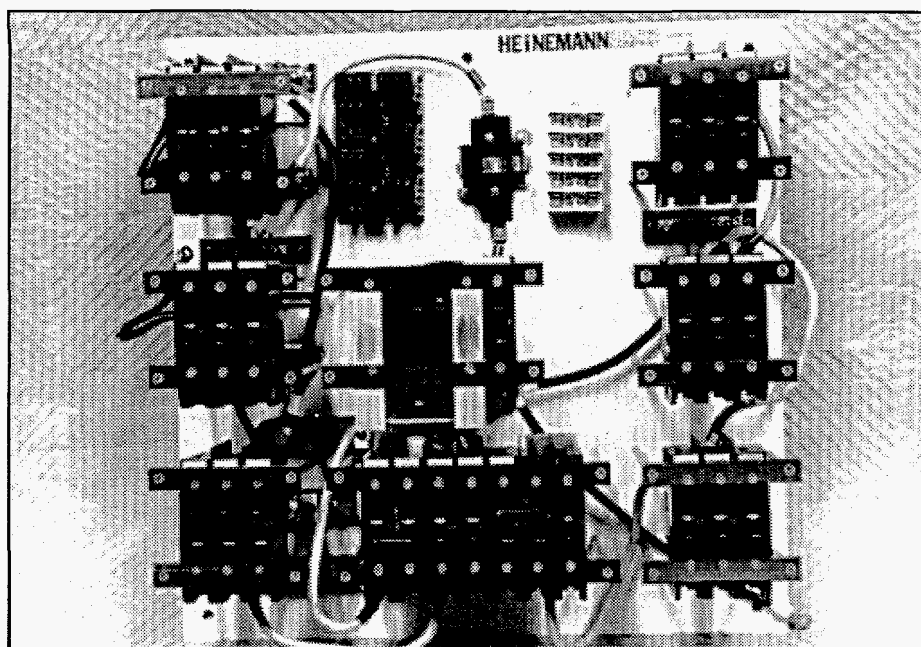


Figure 11. Listed Branch-Circuit Rated Breakers

Since PV systems may have transients—lightning and motor starting as well as others—inverse-time circuit breakers (the standard type) or time-delay fuses should be used in most cases. In circuits where no transients are anticipated, fast-acting fuses can be used. They should be used if relays and other switchgear in dc systems are to be protected. Time-delay fuses that can also respond very quickly to short-circuit currents may also be used for system protection.

Branch Circuits

DC branch circuits in stand-alone systems start at the battery and go to the receptacles supplying the dc loads or to the dc loads that are hard wired. In direct-connected systems, the PV output circuits go to the power controller or master power switch and a branch circuit goes from these to the load. In utility-intertie systems, the circuit between the inverter and the ac-load center may be considered a feeder circuit.

Fuses used to protect dc or ac branch (load) and feeder circuits must be tested and rated for that use. They must also be of different sizes and markings for each amperage and voltage group to prevent unintentional interchange [240F]. DC-rated fuses that meet the requirements of the *NEC* are becoming more prevalent. Figure 12 shows UL-Listed, dc-rated, time-delay fuses on the left that are acceptable for branch circuit use, which would include the battery fuse. Acceptable dc-rated, UL-Listed fast-acting supplementary fuses are shown on the right and can be used in the PV source circuits. The fuses shown are made by Littelfuse (Appendix A), and the fuse holders are made by Marathon (Appendix A). Other manufacturers, such as Bussman and Gould, are obtaining *UL-Listed* dc ratings on the types of fuses that are needed in PV systems. These particular requirements eliminate the use of glass, ceramic, and plastic automotive fuses as branch-circuit overcurrent devices because they are neither tested nor rated for this application.

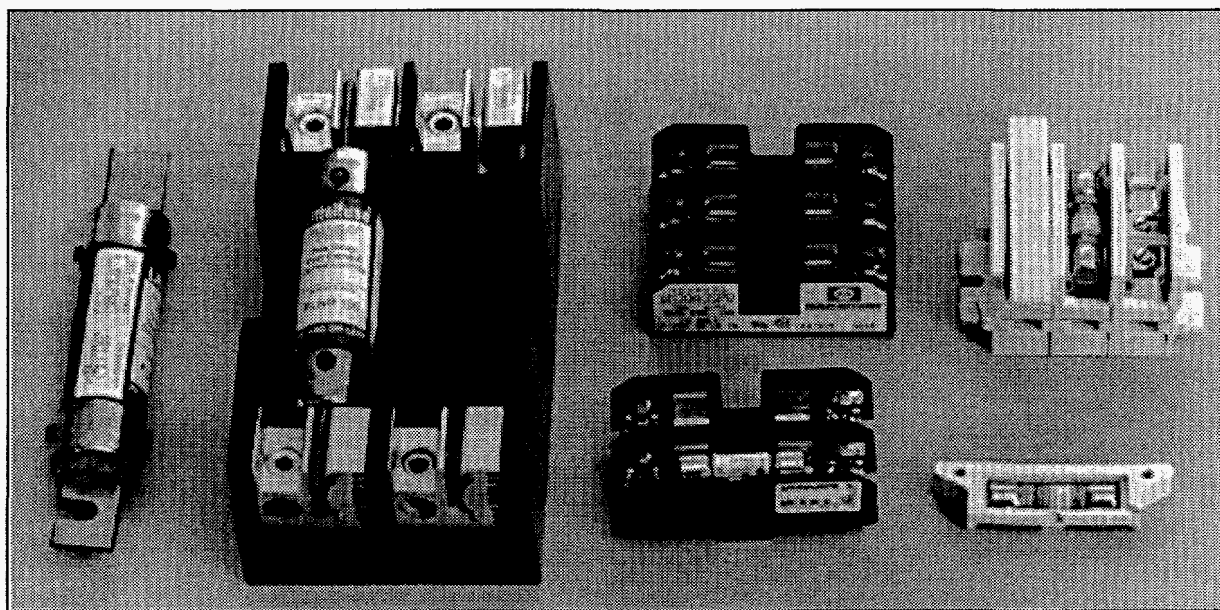


Figure 12. Listed Branch Circuit and Supplemental Fuses.

Automotive fuses have no dc rating by the fuse industry or the testing laboratories and **should not be used in PV systems**. When rated by the manufacturer, they have

only a 32-volt maximum rating, which is less than the open-circuit voltage from a 24-volt PV array. Furthermore, these fuses have no rating for interrupt current, nor are they generally marked with all of the information required for branch-circuit fuses. They are not considered supplemental fuses under the *UL* listing or component recognition programs. Figure 13 shows unacceptable automotive fuses on the left and listed supplemental fuses on the right. Unfortunately, even the supplemental fuses are intended for ac use and frequently have no dc ratings.

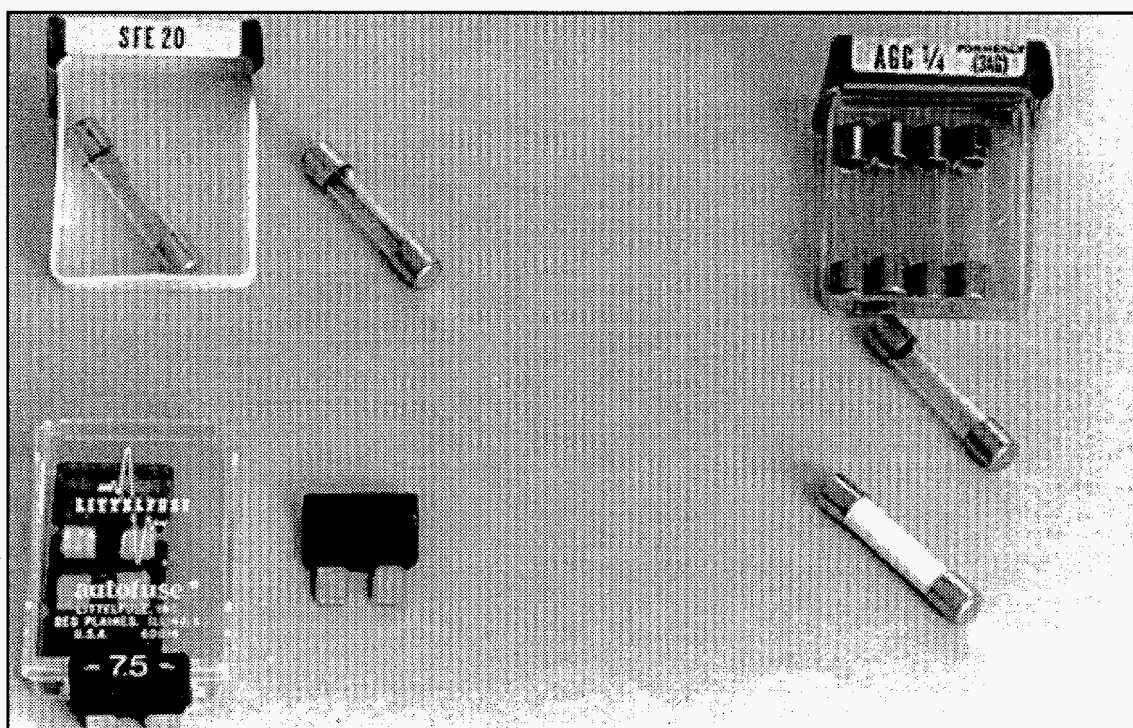


Figure 13. Non-acceptable (left) and Acceptable (when DC-rated) (right) Fuses.

Circuit breakers also have specific requirements when used in branch circuits, but they are generally available with the needed dc ratings [240 G]. Figure 14 shows examples of dc-rated, *UL-Recognized* circuit breakers (supplemental) on the left. They may be used in the PV source circuits for disconnects and overcurrent protection, but they are not listed devices and may not be allowed by the inspector. The larger units are dc-rated, *UL-Listed* branch-circuit rated circuit breakers that can be used in dc-load

centers for branch-circuit protection. The breakers shown are produced by Square D and Heinemann. Airpax also produces dc *UL*-Listed circuit breakers, and Potter Brumfield and others produce dc-rated, *UL*-Recognized, supplemental breakers.

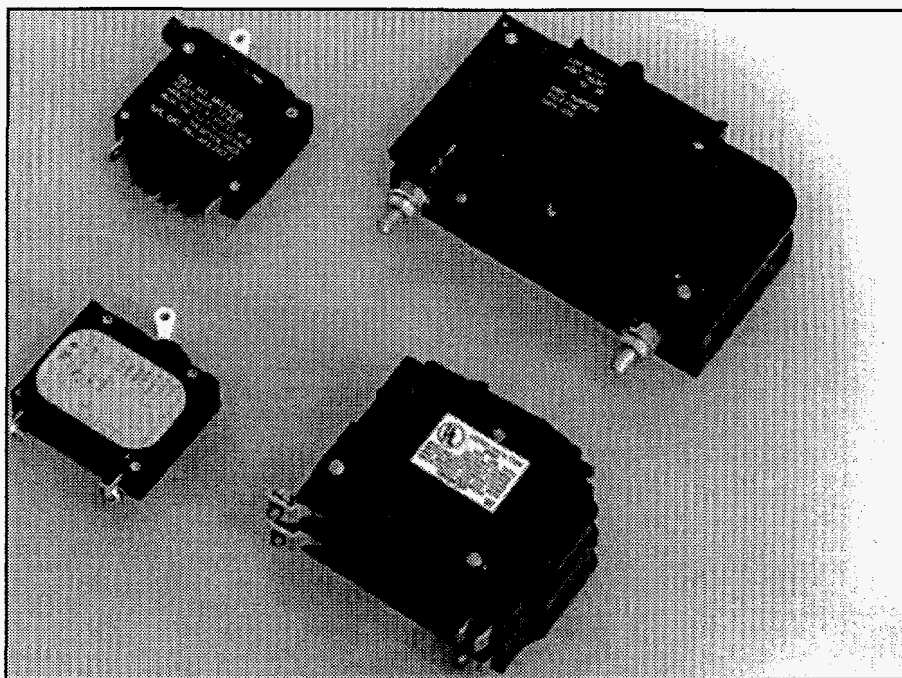


Figure 14. *UL*-Recognized and Listed Circuit Breakers.

To provide maximum protection and performance (lowest voltage drop) on branch circuits (particularly on 12 and 24-volt systems), the ampacity of the conductors might be increased, but the rating of the overcurrent devices protecting that cable should be as low as possible consistent with load currents. A general formula for cable ampacity and overcurrent device rating is 100 percent of the noncontinuous loads and 125 percent of the continuous loads anticipated [220].

Amperes Interrupting Rating (AIR)—Short-Circuit Conditions

Overcurrent devices—both fuses and circuit breakers—must be able to safely open circuits with short-circuit currents flowing in them. Since PV arrays are inherently current limited, high short-circuit currents from the PV array are not a problem when

the conductors are sized as outlined above. In stand-alone systems with storage batteries, however, the short-circuit problem is very severe. A single 220 amp-hour, 6-volt, deep-discharge, lead-acid battery may produce short-circuit currents as high as 8,000 amps for a fraction of a second and as much as 6,000 amps for a few seconds in a direct terminal-to-terminal short circuit. Such high currents can generate excessive thermal and magnetic forces that can cause an underrated device to burn or blow apart. Two paralleled batteries would generate twice as much current, and larger capacity batteries would be able to deliver proportionately more current under a short-circuit condition. In dc systems, particularly stand-alone systems with batteries, the interrupt capability of every overcurrent device is important. This interrupt capability is specified as Amperes Interrupting Rating (AIR) and sometimes AIC.

Most dc-rated, *UL*-Listed, branch circuit breakers that can be used in PV systems have an AIR of 5,000 amps. However, Heinemann Electric makes several with AIRs of 25,000 amps (Appendix A). Some dc-rated, *UL*-Recognized supplemental circuit breakers have an AIR of only 3,000 amps. Listed, dc-rated fuses normally have an AIR of up to 20,000 amps if they are of the current-limiting variety.

Fuses or circuit breakers **shall never be** paralleled or ganged to increase current-carrying capability unless done so by the factory and listed for such use [240-8].

Fusing of PV Source Circuits

The *NEC* allows supplementary fuses to be used in PV source circuits [690-9(c)]. A supplementary fuse is one that is designed for use inside a piece of listed equipment. These fuses supplement the main branch-circuit fuse and do not have to comply with all of the requirements of branch fuses. They shall, however, be dc rated and able to handle the short-circuit currents they may be subjected to [690-9d]. Unfortunately, many supplemental fuses are not dc rated, and if they are, the AIR (when available) is

usually less than 5,000 amps. The use of ac-rated supplementary fuses is **not** recommended for the dc circuits of PV systems.

Current-Limiting Fuses—Stand-Alone Systems

A current-limiting fuse **must** be used in each ungrounded conductor from the battery to limit the current that a battery bank can supply to a short-circuit and to reduce the short-circuit currents to levels that are within the capabilities of downstream equipment [690-71(c)]. These fuses are available with *UIL* ratings of 125, 300, and 600 volts dc, currents of 0.1 to 600 amps, and a dc AIR of 20,000 amps. They are classified as RK5 or RK1 current-limiting fuses and should be mounted in Class-R rejecting fuse holders or dc-rated, fused disconnects. Class J or T fuses with dc ratings might also be used. For reasons mentioned previously, time-delay fuses should be specified, although some designers are getting good results with Class T fast-acting fuses. One of these fuses and the associated disconnect switch should be used in **each** bank of batteries with a paralleled amp-hour capacity up to 1,000 amp-hours. Batteries with single cell amp-hour capacities higher than 1,000 amp-hours will require special design considerations, because these batteries may be able to generate short-circuit currents in excess of the 20,000 AIR rating of the current-limiting fuses. When calculating short-circuit currents, the resistances of all connections, terminals, wire, fuse holders, circuit breakers, and switches must be considered. These resistances serve to reduce the magnitude of the available short-circuit currents at any particular point. The suggestion of one fuse per 1,000 amp-hours of battery size is only a general estimate, and the calculations are site specific. The fuses shown in Figure 12 are current limiting.

For systems less than 65 volts (open circuit), Heinemann Electric 25,000 AIR circuit breakers may be used (Appendix A). These circuit breakers are not current limiting, even with the high interrupt rating, so they cannot be used to protect other fuses or circuit breakers. An appropriate use would be in the conductor between the battery

bank and the inverter. This single device would minimize voltage drop and provide the necessary disconnect and overcurrent features.

Current-Limiting Fuses—Grid-Connected Systems

Normal electrical installation practice requires that service entrance equipment have fault-current protection devices that can interrupt the available short-circuit currents [230-65, 208]. This requirement applies to the utility side of any power conditioning system in a PV installation. If the service is capable of delivering fault currents in excess of the AIR rating of the overcurrent devices used to connect the inverter to the system, then current-limiting overcurrent devices **must** be used [110-9].

Fuse Servicing

Whenever a fuse is used for an overcurrent device and is accessible to unqualified persons, it **must** be in a circuit where all power can be removed from both ends of the fuse for servicing. It is not sufficient to reduce the current to zero before changing the fuse. There must be no voltage present on either end of the fuse prior to service. This may require the addition of switches on both sides of the fuse location—a complication that increases the voltage drop and reduces the reliability of the system [690-16, Diagram 690-1]. Because of this requirement, the use of a fusible pullout-style disconnect or circuit breaker is recommended. For the charging and dc-load circuits, it is recommended that a current-limiting fuse be used at the battery with a switch located between the battery and the current-limiting fuse. Circuit breakers can then be used for all other overcurrent devices in down-stream circuits where the available fault currents do not exceed their AIR or where they are protected by a current-limiting fuse.

DISCONNECTING MEANS

There are many considerations in configuring the disconnect switches for a PV system. The *National Electrical Code* deals with safety first and other requirements last—if at all. The PV designer must also consider equipment damage from over voltage, performance options, equipment limitations, and cost.

A photovoltaic system is a power generation system, and a specific minimum number of disconnects are necessary to deal with that power. Untrained personnel will be operating the systems; therefore, the disconnect system must be designed to provide safe, reliable, and understandable operation.

Disconnects may range from nonexistent in a self-contained PV-powered light for a sidewalk to those found in the space-shuttle-like control room in a large, multi-megawatt, utility-tied PV power station. Generally, local inspectors will not require disconnects on totally enclosed, self-contained PV systems like the sidewalk illumination system or a pre-wired attic ventilation fan. This would be particularly true if the entire assembly were *UL*-Listed as a unit and there were no external contacts or user serviceable parts. However, the situation changes as the complexity of the device increases and separate modules, batteries, and charge controllers having external contacts must be wired together and possibly operated and serviced by unqualified personnel.

Photovoltaic Array Disconnects

Article 690 requires all current-carrying conductors from the PV power source to have a disconnect provision. This includes the grounded conductor, if any [690-13, 14; 230 F]. Ungrounded conductors **must** have a switch or circuit breaker disconnect. Grounded conductors which normally remain connected at all times **must** have a bolted disconnect that can be used for service operations and meet the *NEC* requirements.

In an ungrounded 12- or 24-volt PV system, both positive and negative conductors **must** be switched, since both are ungrounded. Since all systems **must** have an equipment-grounding system, costs may be reduced by grounding 12- or 24-volt systems and using one-pole disconnects on the remaining ungrounded conductor.

Equipment Disconnects

Each piece of equipment in the PV system **shall** have disconnect switches to disconnect it from all sources of power. The disconnects **shall** be circuit breakers or switches and **shall** comply with all of the provisions of Article 690-17. DC-rated switches are expensive; therefore, the ready availability of moderately priced dc-rated circuit breakers with ratings up to 48 volts and 70 amps would seem to encourage their use in all 12- and 24-volt systems. When properly located and used within their approved ratings, circuit breakers can serve as both the disconnect and overcurrent device. In simple systems, one switch or circuit breaker disconnecting the PV array and another disconnecting the battery may be all that is required.

A 2,000-watt inverter on a 12-volt system can draw nearly 200 amps at full load. Disconnect switches must be rated to carry this load and have appropriate interrupt ratings. Again, a dc-rated, *UL*-Listed circuit breaker may prove less costly and more compact than a switch and fuse with the same ratings.

Battery Disconnect

When the battery is disconnected from the stand-alone system, either manually or through the action of a fuse or circuit breaker, care must be taken that the PV system not be allowed to remain connected to the load. Small loads will allow the PV array voltage to increase from the normal battery charging levels to the open-circuit voltage, which will shorten lamp life and possibly damage electronic components.

This potential problem can be avoided by using ganged multipole circuit breakers or ganged fused disconnects as shown in Figure 15. This figure shows two ways of making the connection. Separate circuits, including disconnects and fuses between the charge controller and the battery and the battery and the load, as shown in Figure 16, may be used if it is desired to operate the loads without the PV array being connected. If the design requires that the entire system be shut down with a minimum number of switch actions, the switches and circuit breakers could be ganged multipole units.

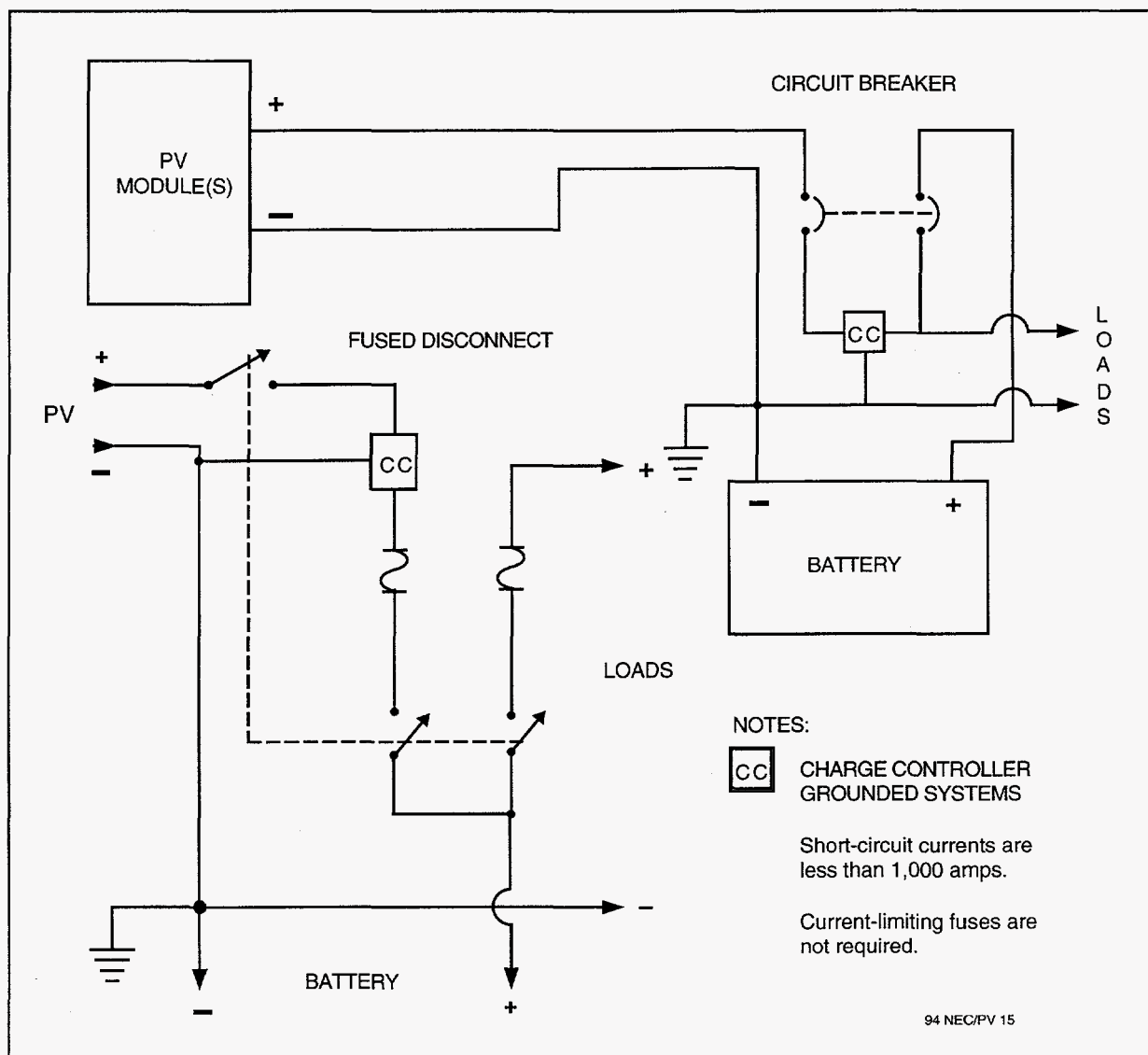


Figure 15. Small System Disconnects.

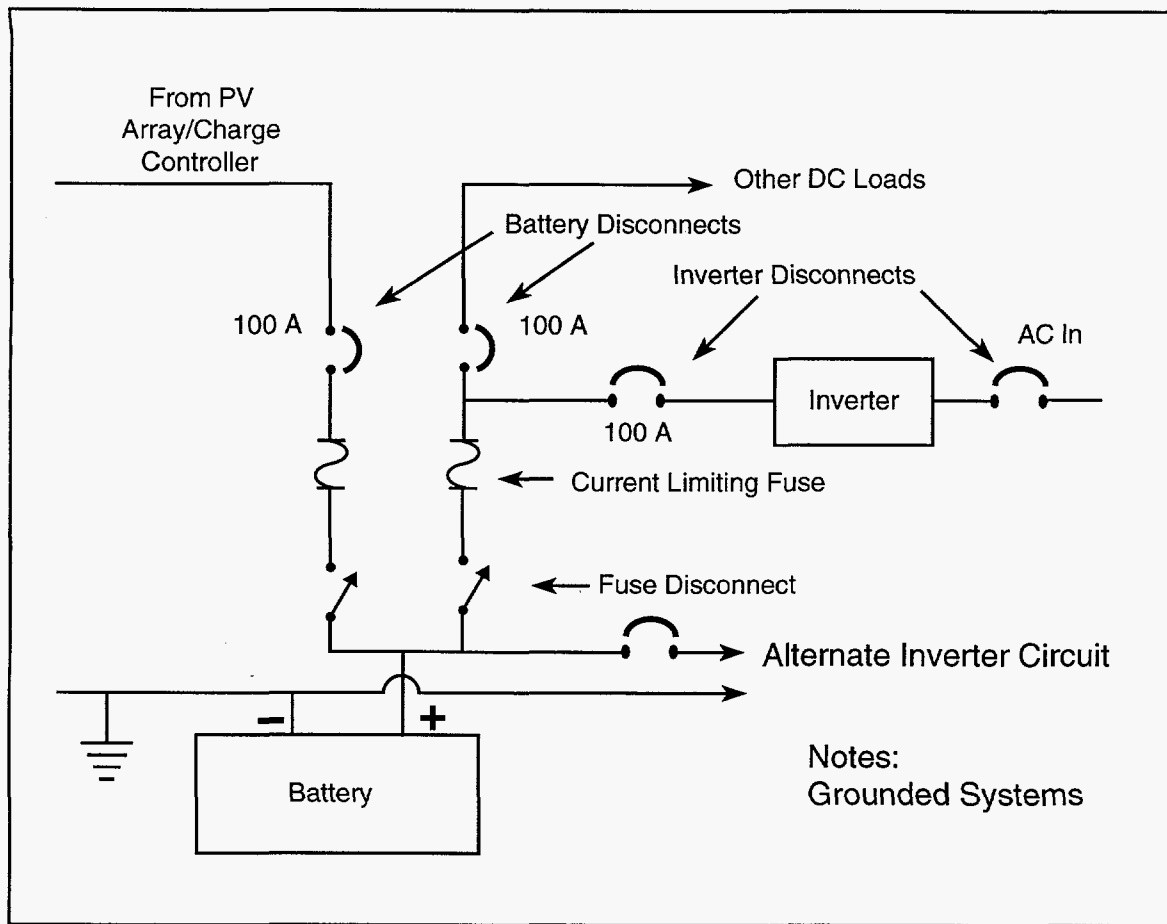


Figure 16. Separate Battery Disconnects.

Charge Controller Disconnects

Some charge controllers are fussy about the sequence in which they are connected and disconnected from the system. Most charge controllers do not respond well to being connected to the PV array and not being connected to the battery. The sensed battery voltage (or lack thereof) would tend to rapidly cycle between the array open-circuit voltage and zero as the controller tried to regulate the nonexistent charge process. This problem will be particularly acute in self-contained charge controllers with no external battery sensing.

Again, the multipole switch or circuit breaker can be used to disconnect not only the battery from the charge controller, but the charge controller from the array. Probably the safest method for self-contained charge controllers is to have the PV disconnect switch disconnect both the input and the output of the charge controller from the system. Larger systems with separate charge control electronics and switching elements will require a case-by-case analysis—at least until the controller manufacturers standardize their products. Figure 17 shows two methods of disconnecting the charge controller.

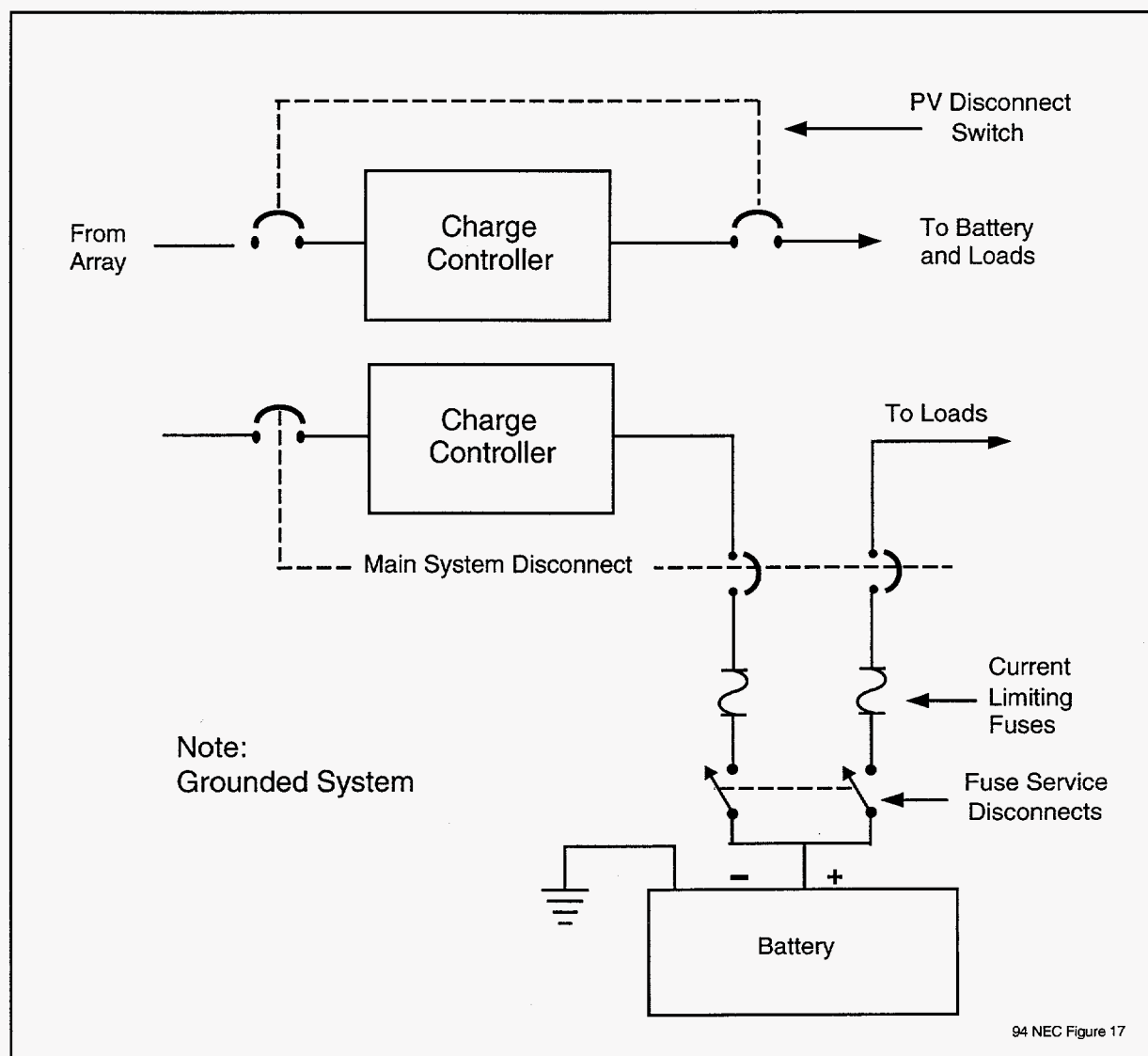


Figure 17. Charge Controller Disconnects.

Non-Grounded Systems

Systems that do not have one of the current-carrying conductors grounded **must** have disconnects and overcurrent devices in all of the ungrounded conductors. This means two-pole devices for the PV, battery, and inverter disconnects and overcurrent devices. The additional cost is considerable.

Multiple Power Sources

When multiple sources of power are involved, the disconnect switches **shall** be grouped and identified [230-72, 690-15]. No more than six motions of the hand will be required to operate all of the disconnect switches required to remove all power from the system [230-71]. These power sources include PV output, the battery system, any generator, and any other source of power. Multipole disconnects or handle ties should be used to keep the number of motions of the hand to six or fewer.

PANEL BOARDS, ENCLOSURES, AND BOXES

Disconnect and overcurrent devices **shall** be mounted in approved enclosures, panel boards, or boxes [240-30]. Wiring between these enclosures must use a *NEC* - approved method [110-8]. Appropriate cable clamps, strain-relief methods, or conduit **shall** be used. All openings not used **shall** be closed with the same or similar material to that of the enclosure [370-18]. Metal enclosures **must** be bonded to the grounding conductor [370-4]. The use of wood or other combustible materials is discouraged. Conductors from different systems such as utility power, gas generator, hydro, or wind **shall not** be placed in the same enclosure, box, conduit, etc., as PV source conductors unless the enclosure is partitioned [690-4b]. This requirement stems from the need to keep "always live" PV source conductors separate from those that can be turned off.

When designing a PV distribution system or panel board, an approved NEMA type box and approved disconnect devices and overcurrent devices should be used.

The requirements for the internal configuration of these devices are established by *NEC* Articles 370, 373, and 384 and **must** be followed. Dead front-panel boards with no exposed current-carrying conductors, terminals, or contacts are generally required. Underwriters Laboratories also establishes the standards for the internal construction of panel boards and enclosures.

BATTERIES

In general, *NEC* Articles 480 and 690-71, 72, 73 should be followed for installations having storage batteries. Battery storage in PV systems poses several safety hazards:

- Hydrogen gas generation from charging batteries
- High short-circuit currents
- Acid or caustic electrolyte
- Electric shock potential

Hydrogen Gas

When flooded, non-sealed, lead-acid batteries are charged at high rates, or when the terminal voltage reaches 2.3 - 2.4 volts per cell, the batteries produce hydrogen gas. Even sealed batteries may vent hydrogen gas under certain conditions. This gas, if confined and not properly vented, poses an explosive hazard. The amount of gas generated is a function of the battery temperature, the voltage, the charging current, and the battery-bank size. Hydrogen is a light, small-molecule gas that is easily dissipated. Small battery banks (i.e., up to 20, 220-amp-hour, 6-volt batteries) placed in a large room or a well-ventilated (drafty) area may not pose a significant hazard. Larger numbers of batteries in smaller or tightly enclosed areas require venting. Venting manifolds may be attached to each cell and routed to an exterior location, but these manifolds are not recommended because flames in one section of the manifold may be easily transmitted to other areas in the system. The instructions provided by the battery manufacturer should be followed.

A catalytic recombiner cap (Hydrocap® Appendix A) may be attached to each cell to recombine some of the evolved hydrogen and oxygen to produce water. If these combiner caps are used, they will require occasional maintenance. It is rarely necessary to use power venting [NEC Handbook 480-8]. Flame arrestors are required by NEC Section 440-9.

Certain charge controllers are designed to minimize the generation of hydrogen gas, but lead-acid batteries need some overcharging to fully charge the cells. This produces gassing that should be dissipated.

In **no case** should charge controllers, switches, relays, or other devices capable of producing an electric spark be mounted in a battery enclosure or directly over a battery bank. Care must be exercised when routing conduit from a sealed battery box to a disconnect. Hydrogen gas may travel in the conduit to the arcing contacts of the switch.

Battery Rooms and Containers

Battery systems are capable of generating tens of thousands of amps of current when shorted. A short circuit in a conductor not protected by overcurrent devices can melt wrenches or other tools, battery terminals and cables, and spray molten metal around the room. Exposed battery terminals and cable connections must be protected. Live parts of batteries must be guarded. This generally means that the batteries should be accessible only to a qualified person. A locked room, battery box, or other container and some method to prevent access by the untrained person should reduce the hazards from short circuits and electric shock. The danger may be reduced if insulated caps or tape are placed on each terminal and an insulated wrench is used for servicing, but in these circumstances, corrosion may go unnoticed on the terminals. The NEC requires certain spacings around battery enclosures and boxes to allow for unrestricted servicing—generally about three feet [110-16]. Batteries should not be installed in living

areas, nor should they be installed below any enclosures, panel boards, or load centers [110-16].

Acid or Caustic Electrolyte

A thin film of electrolyte can accumulate on the tops of the battery and on nearby surfaces. This material can cause flesh burns. It is also a conductor and, in high-voltage battery banks, poses a shock hazard. The film of electrolyte should be removed periodically with an appropriate neutralizing solution. For lead-acid batteries, a dilute solution of baking soda and water works well. Commercial neutralizers are available at auto-supply stores.

Charge controllers are available that minimize the dispersion of the electrolyte and water usage at the same time they minimize battery gassing. They do this by keeping the battery voltage from climbing into the vigorous gassing region where the high volume of gas causes electrolyte to mist out of the cells. A moderate amount of gassing is necessary for proper battery charging.

Battery servicing hazards can be minimized by using protective clothing including face masks, gloves, and rubber aprons. Self-contained eyewash stations and neutralizing solution would be beneficial additions to any battery room. Water should be used to wash acid or alkaline electrolyte from the skin and eyes.

Anti-corrosion sprays and greases are available from automotive and battery supply stores which reduce the need to service the battery bank. Hydrocap® Vents also reduce the need for servicing by reducing the need for watering.

Electric Shock Potential

Storage batteries in dwellings must operate at less than 50 volts unless live parts are protected during routine servicing [690-71]. It is recommended that live parts of any battery bank should be guarded [690-71b(2)].

GENERATORS

Other electrical power generators such as wind, hydro, and gasoline/propane/diesel must comply with the requirements of the *NEC* . These requirements are specified in the following *NEC* articles:

Article 230	Services
Article 250	Grounding
Article 445	Generators
Article 700	Emergency Systems
Article 701	Legally Required Standby Systems
Article 702	Optional Standby Systems
Article 705	Interconnected Power Production Sources

When multiple sources of ac power are to be connected to the PV system, they must be connected with an appropriately rated and approved transfer switch. AC generators frequently are rated to supply larger amounts of power than that supplied by the PV/battery/inverter. The transfer switches (external or as relays built into listed inverters) must be able to safely accommodate either power source.

Grounding, both equipment and system, must be carefully considered when a generator is connected to an existing system. There must be no currents flowing in the equipment-grounding conductor under any operating mode of the system.

The circuit breakers or fuses that are built into the generator are not sufficient to provide *NEC* required protection for the conductors from the generator to the PV system. An external (branch circuit rated) overcurrent device (and possibly a disconnect) **must** be mounted close to the generator. The conductors from the generator to this overcurrent device must have an ampacity of 115 percent of the name plate current rating of the generator [445-5]. Figure 18 show a typical one-line diagram for a system with a backup generator.

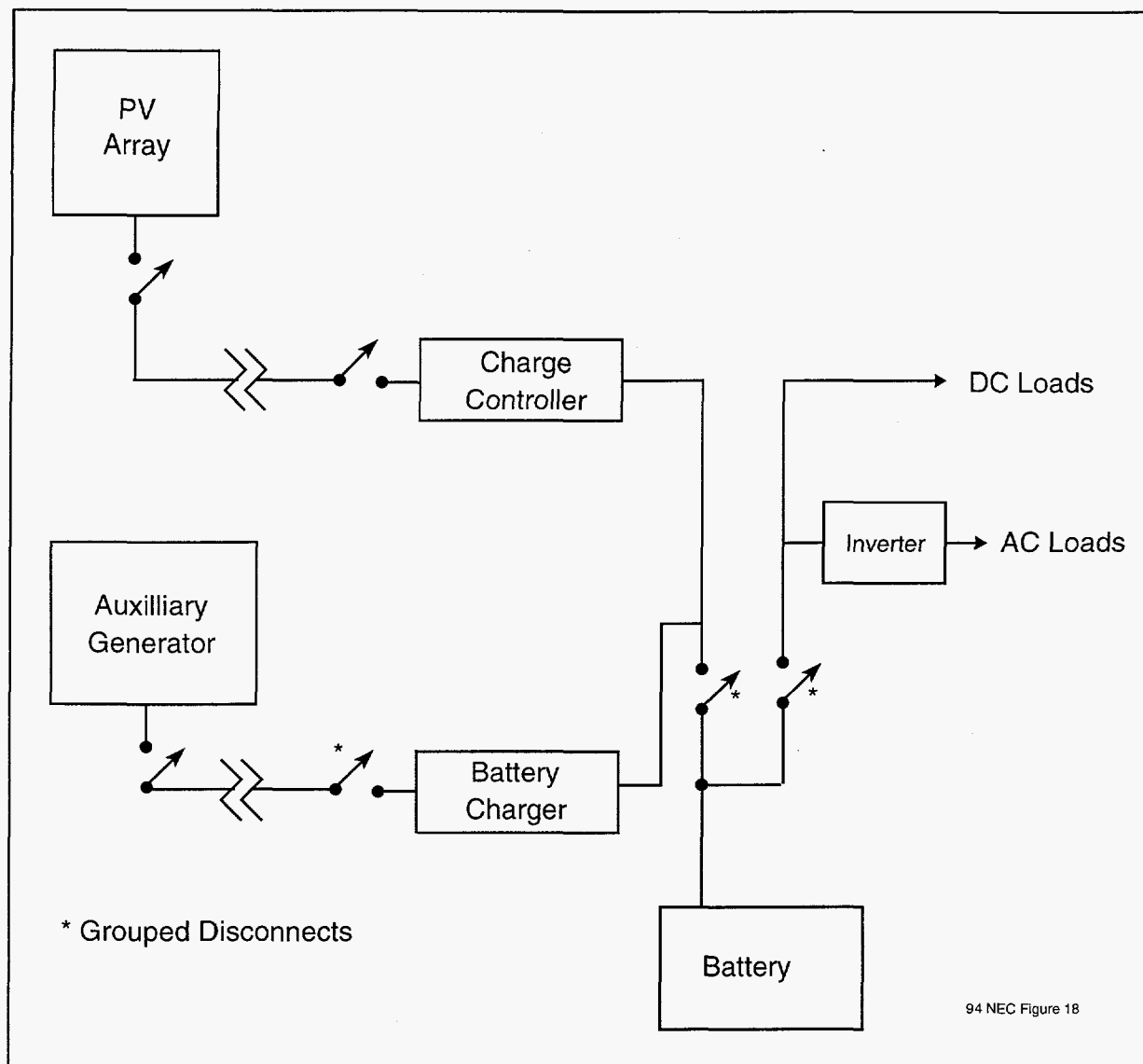


Figure 18. Disconnects for Remotely Located Power Sources

CHARGE CONTROLLERS

A charge controller or self-regulating system **shall** be used in a stand-alone system with battery storage. The mechanism for adjusting state of charge **shall** be accessible only to qualified persons [690-72].

There is only one charge controller on the market that has been tested by *UL* or other recognized testing organizations.

Surface mounting of devices with external terminals readily accessible to the unqualified person will not be accepted by the inspection authority. These charge controllers should be mounted in a listed enclosure with provisions for ventilation. Dead-front panels with no exposed contacts are generally required for safety. A typical charge controller such as shown in Figure 19 should be mounted in a *UL*-Listed enclosure so that none of the terminals are exposed. Enclosures containing charge controllers should have knockouts for cable entry and some method of attaching conduit where required. Internal space must be allocated to provide room for wire bending.

Electrically, charge controllers should be designed with a conductor between the negative input and output terminals. No shunts or other signal processing should be placed in that conductor. This design will allow the controller to be used in a grounded system with the grounded conductor running through the controller. The design of the charge controller must be reviewed to ensure proper system grounding.



Figure 19. Typical Charge Controller.

DISTRIBUTION SYSTEMS

The *National Electrical Code* was formulated when there were abundant supplies of relatively cheap energy. As the Code was expanded to include other power systems such as PV, many sections were not modified to reflect the recent push toward efficient use of electricity in the home. Stand-alone PV systems **may** be required to have dc services with 60- to 100-amp capacities to meet the Code [230-79]. DC receptacles and lighting circuits **may** have to be as numerous as their ac counterparts [220, 422]. In a small one- to four-module system on a remote cabin or small home, these requirements may be excessive, since the power source may be able to supply only a few hundred watts of power.

The local inspection authority has the final say on what is, or is not, required and what is, or is not, safe. Reasoned conversations may result in a liberal interpretation of the Code. For a new dwelling, it seems appropriate to install a complete ac electrical system as required by the *NEC*. This will meet the requirements of the inspection authority, the mortgage company, and the insurance industry. Then the PV system and its dc distribution system can be added. If an inverter is used, it can be connected to the ac service entrance. DC branch circuits and outlets can be added where needed, and everyone will be happy. If or when grid power becomes available, it can be integrated into the system with minimum difficulty. If the building is sold at a later date, it will comply with the *NEC* if it has to be inspected. The use of a *UL*-Listed power center, such as the APT Power Center will facilitate the installation and the inspection (Appendix A).

Square D has received a direct current (dc), *UL* listing for its standard QO residential **branch** circuit breakers. They can be used up to 48 volts (125% PV open-circuit voltage) and 70 amps dc. The AIR is 5,000 amps, so a current-limiting fuse (RK5 or RK1 type) must be used when they are connected on a battery system. The Square D

QOM **main** breakers (used at the top of the load center) **do not** have this listing, so the load center must be obtained with main lugs and no main breakers (Appendix A).

In a small PV system (less than 5000 amps of available short-circuit current), a two-pole Square D QO breaker could be used as the PV disconnect (one pole) and the battery disconnect (one pole). Also, a fused disconnect or fusible pullout could be used in this configuration. This would give a little more flexibility since the fuses can have different current ratings. Figure 15 on page 47 shows both systems with only a single branch circuit.

In a system with several branch circuits, the Square D load center can be used. A standard, off-the-shelf Square D residential load center without a main breaker can be used for a dc distribution panel in 12-volt dc systems. The main disconnect would have to be a "back fed" QO breaker, and it would have to be connected in one of the normal branch circuit locations. Back-fed circuit breakers **must** be identified for such use and **must** be clamped in place [690-64b(5), 384-16(f)]. Since the load center has two separate circuits (one for each phase), the bus bars will have to be tied together to use the entire load center. Figure 20 illustrates this use of the Square D load center.

Square D has listed one of their load centers that uses the QO breakers for DC operation. This load center is available with a *UL*-Listed, dc-rated, current-limiting fuse from a number of sources. The manufacturer is listed in Appendix A.

Another possibility is to use one of the phase circuits to combine separate PV source circuits, then go out of the load center through a breaker for the PV disconnect switch to the charge controller. Finally, the conductors would have to be routed back to the other phase circuit in the load center for branch circuit distribution. Several options exist in using one and two-pole breakers for disconnects. Figure 21 presents an example.

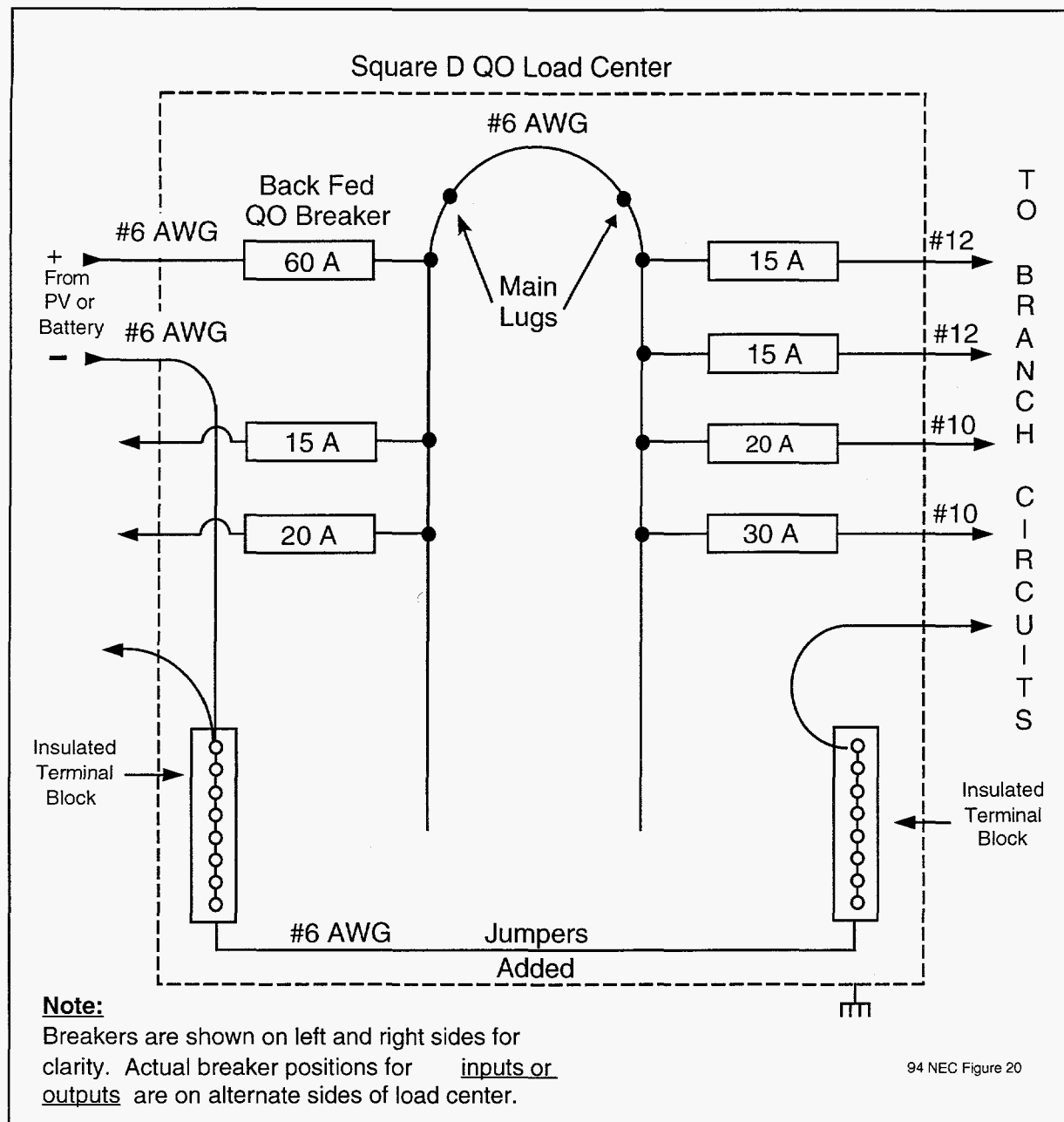


Figure 20. 12-Volt DC Load Center.

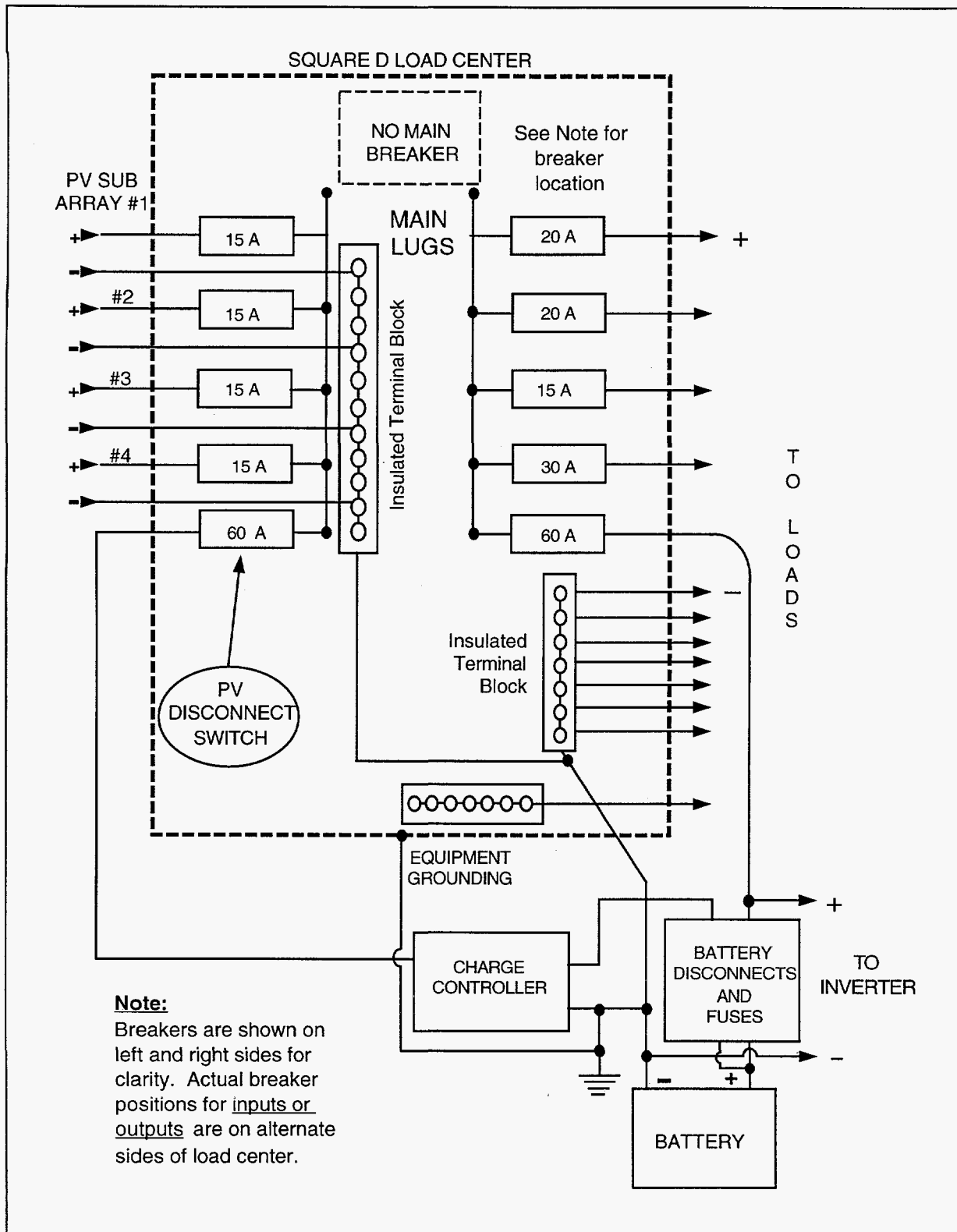


Figure 21. 12-Volt DC Combining Box and Load Center.

Interior Wiring and Receptacles

The interior wiring used in a PV system **must** comply with the *NEC*. Nonmetallic sheathed cable (type NM - "Romex") may be used, and it **must** be installed in the same manner as cable for ac branch circuits [300, 690-31a]. The bare grounding conductor in such a cable **must not** be used to carry current and cannot be used as a common negative conductor for combination 12/24-volt systems [336-30(b)]. Exposed, single-conductor cables are not permitted—they **must** be installed in conduit [300-3(a)]. Wires carrying the same current (i.e., positive and negative battery currents) must be installed in the same conduit or cable to prevent increased circuit inductances that would pose additional electrical stresses on disconnect and overcurrent devices [300-3(b)]. Equipment-grounding conductors for dc circuits only may be run apart from the current-carrying conductors [250-57(b) Ex2].

The receptacles used for dc must be different than those used for any other service in the system [210-7f, 551-20f]. The receptacles should have a rating of not less than 15 amps and must be of the three-prong grounding type [210-7a, 720-6]. Numerous different styles of approved receptacles are available that meet this requirement. These requirements can be met in most locations by using the three-conductor 15-, 20-, or 30-amp 240-volt NEMA style 6-15, 6-20, 6-30 receptacles for the 12-volt dc outlets. If 24-volt dc is also used, the NEMA 125-volt locking connectors, style L5-15 or L5-20, are commonly available. The NEMA FSL-1 is a locking 30-amp 28-volt dc connector, but its availability is limited. Figure 22 shows some of the available configurations. Cigarette lighter sockets and plugs frequently found on "PV" and "RV" appliances **do not** meet the requirements of the *National Electrical Code* and should not be used.

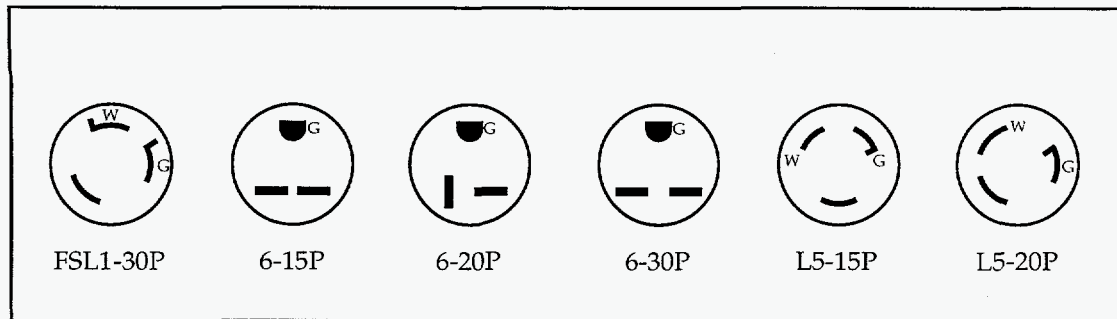


Figure 22. Plug Configurations

It is not permissible to use the third or grounding conductor of a three-conductor plug or receptacle to carry common negative return currents on a combined 12/24-volt system. This terminal must be used for equipment grounding and may not carry current except in fault conditions [210-7].

A 30-amp fuse or circuit breaker protecting a branch circuit (with No. 10 AWG conductors) **must** use receptacles rated at 30 amps. Receptacles rated at 15 and 20 amps **must not** be used on this 30-amp circuit [Table 210-21(b)(3)].

Smoke Detectors

Many building codes require that smoke and fire detectors be wired directly into the ac power wiring of the dwelling. With a system that has no inverter, two solutions might be offered to the inspector. The first is to use the 9-volt or other primary-cell, battery-powered detector. The second is to use a voltage regulator to drop the PV system voltage to the 9-volt or other level required by the detector.

The regulator must be able to withstand the PV open-circuit voltage and supply the current required by the detector alarm.

On inverter systems, the detector on some units may trigger the inverter into an "on" state, unnecessarily wasting power. In other units, the alarm may not draw enough current to turn the inverter on and thereby produce a reduced volume alarm or, in some cases, no alarm at all. Small, dedicated inverters might be used, but this would waste power and decrease reliability when dc detectors are available.

Several states now require detectors that are connected to the power line and have a battery backup. Units satisfying this requirement might also be powered by dc from the battery and by a primary cell.

Ground-Fault Circuit Interrupters

Some ac ground-fault circuit interrupters (GFCI) do not operate reliably on the output of some non-sine-wave inverters. If the GFCI does not function when tested, it should be verified that the neutral (white-grounded) conductor of the inverter output is solidly grounded and bonded to the grounding (green or bare) conductor of the inverter in the required manner. If this bond is present and does not result in the GFCI testing properly, other options are possible. Changing the brand of GFCI may rectify the solution. A direct measurement of an intentional ground fault may indicate that slightly more than the 5 milliamp internal test current is required to trip the GFCI. The inspector may accept this. Some inverters will work with a ferro-resonant transformer to produce a wave form more satisfactory for use with GFCIs, but the no-load power consumption may be high enough to warrant a manual demand switch. A sine-wave inverter could be used to power those circuits requiring GFCI protection.

Interior Switches

Switches rated for ac only **shall not** be used in dc circuits [380-14]. AC-DC general-use snap switches are available on special order from most electrical supply houses, and they are similar in appearance to normal "quiet switches." *UL*-Listed electronic switches with the proper dc ratings might also be used, but the nonstandard appearance may require that the *UL*-Listing specifications be provided to the inspector.

There have been some failures of dc-rated snap switches when used as PV array and battery disconnect switches. If these switches are used on 12- and 24-volt systems and are not activated frequently, they may build up internal oxidation or corrosion and

not function properly. Periodically activating the switches under load will keep them clean.

Multiwire Branch Circuits

Stand-alone PV and PV/Hybrid systems are frequently connected to a building/structure/house that has been previously completely wired for 120/240-volts ac and has a standard service entrance and load center.

These structures may employ one or more circuits that the National Electrical Code (NEC) calls a multiwire branch circuit. See Section 100 in the NEC, "Branch Circuit, Multiwire." These circuits take a three-conductor plus ground feeder from the 120/240-volt load center and run it to the loads in the structure where two separate 120-volt branch circuits are split out. Each branch circuit uses one of the 120-volt hot, ungrounded conductors from the 120/240-volt feeder and the common neutral conductor.

In a utility connected system or with a 120/240-volt stacked pair of inverters, where the 120/240-volt power consists of two 120-volt lines that are 180 degrees out of phase, the currents in the common neutral in the multiwire branch circuit are limited to the difference currents from any unbalanced load. If the loads on each of the separate branch circuits were equal, then the currents in the common neutral would be zero.

A neutral conductor overload may arise when a single 120-volt inverter is tied to both of the hot input conductors on the 120/240-volt load center. This is a common practice for stand-alone PV homes. At this point the two hot 120-volt conductors are being delivered voltage from the single 120-volt inverter and that voltage is in phase on both conductors. In multiwire branch circuits, the return currents from each of the separate branch circuits in the common neutral add together. A sketch of the multiwire branch circuit is presented below. Additional information is found in the NEC in sections 100, 210-4, 240-20(b), and 300-13(b), and in the NEC Handbook.

Each branch circuit is protected by a circuit breaker in the ungrounded conductor in the load center. The neutral conductor is usually the same size as the ungrounded conductors and can be overloaded with the in-phase return currents. The circuit breakers will pass current up to the ampacity of the protected conductors, but when both branch circuits are loaded at more than 50%, the unprotected, common neutral conductor is overloaded and may be carrying up to twice the currents that it was rated for.

A definite fire and safety hazard exists. All existing stand-alone PV installations using single inverters tied to both ungrounded conductors at the service entrance should be examined for multiwire branch circuits.

The NEC requires that multiwire branch circuits in some, but not all, cases use a two-pole circuit breaker so that both circuits are dead at the same time under fault conditions and for servicing. This two-pole, side-by-side circuit breaker rated at 15 or 20 amps may be one indication that multiwire branch circuits have been used. Common handle circuit breakers rated at 30 amps and higher are usually dedicated to 240-volt circuits for ranges, hot water heaters, dryers, and the like.

Examination of the wiring in the load center may show a three-wire cable (14 or 12 AWG conductors) with bare ground leaving the load center. This may be connected to a multiwire branch circuit. The circuit breakers connected to this cable and the outputs of this cable should be traced to determine the presence or absence of a multiwire branch circuit.

The following options are suggested for dealing with this problem:

- Disconnect or rewire the multiwire circuits as separate circuits ("home runs") from the load center.
- Connect both "hot" (ungrounded) conductors of the multiwire branch circuit to a single circuit breaker rated for the ampacity of the neutral conductor.

- Limit the output of the inverter with a circuit breaker rated at the ampacity of the neutral conductor (usually 15 amps). Place a warning near this circuit breaker stating that the rating must not be increased.

In systems where multiwire branch circuits are used with stacked (120/240-volt) inverters, a sign should be placed near the inverters warning that single inverter use (one inverter removed for repair) may cause overloaded circuits. The maximum current from the single inverter should be limited to the ampacity of the common neutral conductor.

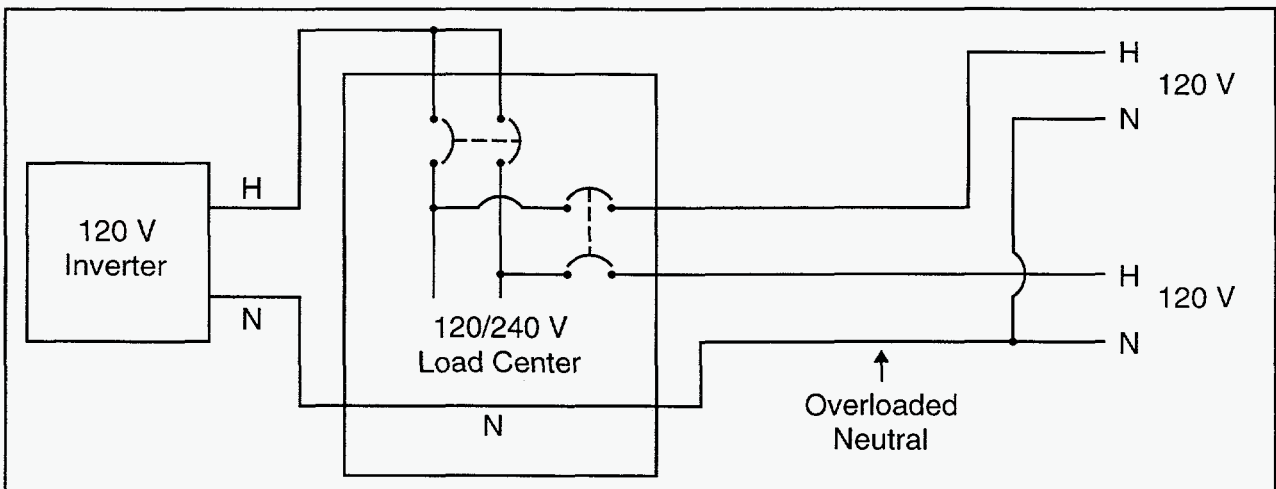


Figure 23. Diagram of a Multiwire Branch Circuit

In all systems (multiwire or not), the neutral busbar of the load center must be rated at a higher current than the output of the inverter. In other words, do not connect an inverter with a 33-amp output to a load center rated at 20 or 30 amps.

SYSTEM LABELS AND WARNINGS

Photovoltaic Power Source

A permanent label **shall** be applied near the PV disconnect switch that contains the following information: [690-52]

- Operating Current (System maximum-power current)
- Operating Voltage (System maximum-power voltage)
- Open-Circuit Voltage
- Short-Circuit Current

This data will allow the inspector to verify proper conductor ampacity and overcurrent device rating. It will also allow the user to compare system performance with the specifications.

Multiple Power Systems

Systems with multiple sources of power such as PV, gas generator, wind, hydro, etc., **shall** have a permanent plaque or directory showing the interconnections [705-10]. Diagrams are not required, but may be useful and should be placed near the system disconnects.

Switch or Circuit Breaker

If a switch or circuit breaker has all of the terminals energized when in the open position, a label should be placed near it indicating: [690-17]

- WARNING - ELECTRIC SHOCK HAZARD - DO NOT TOUCH - TERMINALS ENERGIZED IN OPEN POSITION

General

Each piece of equipment that might be opened by unqualified persons should be marked with warning signs:

- WARNING - ELECTRIC SHOCK HAZARD - DANGEROUS VOLTAGES AND CURRENTS - NO USER SERVICEABLE PARTS INSIDE - CONTACT QUALIFIED SERVICE PERSONNEL FOR ASSISTANCE

Each battery container, box, or room should also have warning signs:

- WARNING - ELECTRIC SHOCK HAZARD - DANGEROUS VOLTAGES AND CURRENTS - EXPLOSIVE GAS - NO SPARKS OR FLAMES - NO SMOKING - ACID BURNS - WEAR PROTECTIVE CLOTHING WHEN SERVICING

INSPECTIONS

Involving the inspector as early as possible in the planning stages of the system will begin a process that should provide the best chance of obtaining a safe, durable system. The following steps are suggested.

- Establish a working relationship with a local electrical contractor or electrician to determine the requirements for permits and inspections.
- Contact the inspector and review the system plans. Solicit advice and suggestions from the inspector.
- Obtain the necessary permits.
- Involve the inspector in the design and installation process. Provide information as needed. Have one-line diagrams and complete descriptions of any non-listed, non-standard equipment available.

INSURANCE

Most insurance companies are not familiar with photovoltaic power systems. They are, however, willing to add the cost of the system to the homeowner's policy if they understand that it represents no additional liability risk. A system description

may be required. Evidence that the array is firmly attached to the roof or ground is usually necessary. The system must be permitted and inspected if those requirements exist for other electrical power systems in the vicinity.

Some companies will not insure homes that are not grid connected because there is no source of power for a high-volume water pump for fighting fires. In these instances, it may be necessary to install a fire-fighting system and water supply that meets their requirements. A high-volume dc pump and a pond might suffice.

As with the electrical inspector, education and a full system description emphasizing the safety features and code compliance will go a long way toward obtaining appropriate insurance.

APPENDIX A
Sources of Equipment Meeting the Requirements of
The National Electrical Code®

A number of PV distributors and dealers are stocking the equipment needed to meet the *NEC* requirements. These additional sources are presented as sources of specialized equipment.

CONDUCTORS

Standard multiconductor cable such as 10-2 with ground Nonmetallic Sheathed Cable (NM and NMC), Underground Feeder (UF), Service Entrance (SE), Underground Service Entrance (USE), larger sizes (8 AWG) single-conductor cable, uninsulated grounding conductors, and numerous styles of building wire such as THHN can be obtained from electrical supply distributors and building supply stores.

The highest quality USE-2 cable will be listed by *UL* and will also have XLP (or XLPE), RHW-2, and 600V markings. Flexible USE and RHW cables in large sizes (1/0 - 250 kcmil) and stranded 8-, 10-, and 12-gage USE single conductor cable can be obtained from some electrical supply houses and wire distributors, including:

Anixter Bros.
2201 Main Street
Evanston, Illinois 60202
800-323-8166 for the nearest distributor

For grid-connected systems requiring cables with voltage rating higher than 600V, cable must be special-ordered. Rubber-insulated cables are available with up to 2,000-volt insulation. They should be marked RHW-2, XLP and be sunlight resistant when used for exposed module interconnects. The following manufacturers can supply such cable.

American Insulated Wire
36 Freeman Street
P.O. Box 880
Pawtucket, RI 02862
401-726-0700

The Okonite Company
PO Box 340
Romsey, NJ 07446
201-825-9026

MISCELLANEOUS HARDWARE

Stainless steel nuts, bolts and screws, and other hardware, insulated and uninsulated crimp-on terminals, battery terminals, copper lugs for heavy cable, battery cable, weather-resistant cable ties, heat shrink tubing and more may be obtained from the following source:

Chesapeake Marine Fasteners
10 Willow Street
P.O. Box 6521
Annapolis, Maryland 21401
800-526-0658

Dealer's price sheet is available

The company listed below makes plastic strain reliefs that fit the standard 1/2" electrical knockout (7/8" diameter). These watertight strain reliefs are needed for older ARCO modules and the current production Solarex modules as well as others. The single-conductor versions are hard to find, and the metal types are very expensive. A catalog and information on product 3224 (for AWG 10) or 3231 (for larger wire) can be requested. The company also makes UV-resistant black cable ties and copper, heavy-duty lugs, as well as other products that might be useful.

Heyco Molded Products, Inc.
Box 160
Kenilworth, New Jersey 07033
800-526-4182 or 908-245-0033
Quantity purchases only

DC-RATED FUSES

15, 20, 30 amps and higher rated fuses can be used for branch-circuit overcurrent protection depending on conductor ampacity and load. Larger sizes (100 amp and up) are used for current-limiting and overcurrent protection on battery outputs. DC rated, *UL*-Listed fuses are manufactured by the following companies, among others:

Bussmann
P.O. Box 14460
St. Louis, MO 63178-4460
314-527-3877
314-527-1270 (Technical Questions)

Gould Inc.
374 Merrimac Street
Newburyport, MA 01950
508-462-6662

Littelfuse
Power Fuse Division
800 E. Northwest Highway
Des Plaines, Illinois 60016
(708) 824-1188
800-TEC FUSE (Technical Questions)
800-227-0029 (Customer Service)

The following fuses may be used for battery circuit and branch circuit overcurrent protection and current limiting. If transients are anticipated in PV circuits, these fuses can also be used in those locations.

Fuse Description	Size	Manufacturer	Mfg #
125-volt dc, RK5 Time delay, current-limiting	.1-600 amp	Bussmann	FRN-R
"	"	Littelfuse	FLNR
300-volt dc, RK5 Time delay, current-limiting fuse	.1-600-amp	Bussmann	FRS-R
"	"	Gould	TRS-R
"	"	Littelfuse	FLSR
600-volt dc, RK5 Time delay, current-limiting fuse	.1-600 amp,	Littelfuse	IDS R
"	70-600 amp	Gould	TRS70R-600R

The following fuses should be used for PV source-circuit protection if problems are not anticipated with transients. They may also be used inside control panels to protect relays and other equipment.

Fuse Description	Size	Manufacturer	Mfg #
Fast-acting, current-limiting midget fuse	.1-30 amp	Bussmann	KLM*
"	"	Gould	ATM**
"	"	Littelfuse	KLK-D**

* UL-Recognized

** UL-Listed

Fuse Holders (Also See Fused Disconnects)

Each fuse manufacturer makes fuse blocks matching the voltage rating and current rating of the selected fuse.

Marathon Special Projects also makes suitable fuse holders. Information and the names of distributors of Class R and Class M (midget fuse holders) should be requested. The company also makes power-distribution blocks for control panels.

Marathon Special Products
P.O. Box 468
Bowling Green, Ohio 43402
419-352-8441

Fused Disconnects (Also See Circuit Breakers)

Since fuses must not have power applied to either end when servicing, a combination switch and fuse can be mounted in a single enclosure to meet some, if not all, of the requirements.

Indoor fused switches, 250-volt dc—JN and JF series
Outdoor fused switches, 250-volt dc—JR and FR series

Siemens I-T-E
Siemens Energy & Automation, Inc.
3333 State Bridge Rd.
Alpharetta, Georgia 30202
404-751-2000

Call for nearest regional sales office that can direct you to a stocking distributor

Indoor fused switches
250-volt-dc—H22x, H32x, and H42x series
600-volt-dc—H26xx and H36xx series

Outdoor fused switches
250-volt-dc—H22xR, H32xR, and H42xR series
600-volt-dc—H26xR and H36xR series

Square D Company
800-634-2003 for the nearest
Square D electrical supply distributor

Rainshadow Solar installs a current-limiting fuse in a *UL*-Listed, dc-rated Square D load center.

Rainshadow Solar
P.O. Box 242
Guthrie Cove Road
Orcas, WA 98280
206-376-5336

Ananda Power Technologies manufactures a line of *UL*-Listed power centers (dc source circuits, charge controller, and load circuits) with numerous options.

Ananda Power Technologies, Inc.
14618 Tyler Foote RD #143
Nevada City, CA 95959
916-292-3834

Boltswitch, Inc., makes pull-out fused disconnects that are dc rated for higher current applications. Contact factory for applications.

boltswitch®, inc.
6107 West Lou Avenue
Crystal Lake, IL 60014
815-459-6900

CIRCUIT BREAKERS

Square D QO circuit breakers (common ac residential breakers).

UL-Listed at 5000 AIC at 48 volts dc; 1 and 2 pole, 10-70 amps; 3 pole, 10-60 amps

Square D FA circuit breakers; 125- and 250-volt dc ratings, multiple currents

Enclosures for QO breakers

2 and 3 pole units

Indoor QO21xxBN, QO3100BN

Rainproof QO21xxBNRB, QO3100BNRB

Any of the load centers for Square D QO breakers without main breakers may be used—main lugs should be requested instead.

Square D Company
800-634-2003 for the nearest
Square D electrical distributor

Heinemann makes a full line of dc-rated, *UL*-Listed and recognized supplemental circuit breakers, but they must be mounted in custom-built enclosures. (The metal is punched by the installer).

CD-CE-CF 5000 AIC at 125-volt dc, 15-110 amp

25,000 AIC available on special order. Polyester case, spun rivets, and *UL*-Listed units should be requested.

GH 10,000 AIC at 250-volts dc, 15-100 amp

GJ 10,000 AIC at 125-volts dc, 100-250 amps

GJ 25,000 AIC at 65-volts dc, 100-250 amps

GJ1P 10,000 AIC at 160-volts, 25,000 AIC at 65-volts dc, 100-700 amps

Eaton Corporation
Heinemann Products
2300 Northwood Drive
Salisbury, Maryland 21801
410-546-9778

Call for nearest source and catalog
Applications engineering available

Philips Technology (formerly AIRPAX) also makes a full line of dc-rated, UL-Listed and recognized supplemental circuit breakers, but they must be mounted in custom-built enclosures.

Philips Technology
P.O. Box 520
Cambridge, Maryland
301-228-4600

Call for nearest source and catalog.
Applications engineering available.

Rainshadow Solar markets a Heinemann 250 amp circuit breaker in an enclosure that is suitable of use with 4,000-watt, 24-volt inverters.

Rainshadow Solar
P.O. Box 242
Guthrie Cove Road
Orcas, WA 98280
360-376-5336

ENCLOSURES AND JUNCTION BOXES

Indoor and outdoor (rainproof) general-purpose enclosures and junction boxes are available at most electrical supply houses. These devices usually have knockouts for cable entrances, and the distributor will stock the necessary bushings and/or cable clamps. Interior component mounting panels are available for some enclosures, as are enclosures with hinged doors. If used outdoors, all enclosures, clamps, and accessories must be listed for outdoor use. For visual access to the interior, NEMA 4x enclosures are available that are made of clear, transparent plastic.

HYDROCAPS

Hydrocap® Vents are available from Hydrocap Corp. and some PV distributors on a custom-manufactured basis. Flame arrestors are an option.

Hydrocap
975 NW 95 St.
Miami, FL 33150
305-696-2504

SURGE ARRESTORS

Delta makes a full line of large, silicon-oxide surge arrestors starting at 300 volts and up that are usable on low-voltage systems to clip the tops of large surges.

Ananda Power Technologies sells a Delta unit for low-voltage systems.

Delta Lightning Arrestors Inc.
P.O. Box 1084
Big Spring, TX 79721
915-267-1000

APPENDIX B

NEC and UL Requirements

Too Conservative?

Introduction

As the photovoltaic (PV) power industry moves into a mainstream position in the generation of electrical power, some people question the seemingly conservative and redundant requirements established by Underwriters Laboratories (*UL*) and the *National Electrical Code* (*NEC*) for system and installation safety. This short discourse will attempt to address those concerns and highlight the unique aspects of PV systems that dictate the requirements.

The *National Electrical Code* (*NEC*) is written with the requirement that all equipment and installations are approved for safety by the authority having jurisdiction (*AHJ*) to enforce the *NEC* requirements in a particular location. The *AHJ* readily admits to not having the resources to verify the safety of the required equipment and relies exclusively on the testing and listing of the equipment by independent testing laboratories such as Underwriters Laboratories (*UL*). The *AHJ* also relies on the requirements for field wiring specified in the *NEC* to ensure safe installations and use of the listed equipment.

The standards published by *UL* and the material in the *NEC* are closely harmonized by engineers and technicians throughout the electrical equipment industry, the electrical construction trades, the national laboratories, the scientific community, and the electrical inspector associations. The *UL* Standards are technical in nature with very specific requirements on the construction and testing of equipment for safety. They in turn are coordinated with the construction standards published by the National Electrical Manufacturers Association (*NEMA*). The *NEC* is deliberately written in a

non-technical manner for easy understanding and application by electricians, electrical contractors, and electrical inspectors in the field.

The use of listed (by *UL* or other laboratory) equipment ensures that the equipment meets well-established safety standards. The application of the requirements in the *NEC* ensures that the listed equipment is connected with field wiring and is used in a manner that will result in an essentially hazard-free system. Use of listed equipment and installing that equipment according to the requirements in the *NEC* will contribute greatly to not only safety, but also the durability, performance, and longevity of the system.

Sometimes Controversial Areas

The *NEC* does not present many highly detailed technical specifications. For example, the term "rated output" is used in several cases with respect to PV equipment. The conditions under which the rating is determined are not specified. The definitions of the rating conditions (such as Standard Test Conditions (STC) for PV modules) are made in the *UL* Standards that establish the rated output. This procedure is appropriate because of the *NEC* level of writing and the lack of appropriate test equipment available to the *NEC* user.

***UL* Standards**

UL Standard 1703 requires that the instructions for listed PV modules contain specific requirements for the installation of such modules. The rated (at Standard Test Conditions) open-circuit voltage and the rated short-circuit current of crystalline PV modules are to be multiplied by factors of 125 percent before further calculations are made for conductor and overcurrent devices.

The 125 percent factor on the open-circuit voltage (*Voc*) is needed because, as the operating temperature of the module decreases, *Voc* increases. The rated *Voc* is measured at a temperature of 25°C and while the normal operating temperature is 40-

50°C when ambient temperatures are around 20°C, there is nothing to prevent sub-zero ambient temperatures from yielding operating temperatures significantly below the 25°C standard test condition.

A typical crystalline silicon module will have a voltage coefficient of $-0.38 \text{ \%}/^{\circ}\text{C}$. A system with a rated open-circuit voltage of 595 volts at 25°C might be exposed to ambient temperatures of -30°C . This voltage (595) could be handled by the common 600-volt rated conductors and switchgear. At dawn and dusk conditions, the module will be at the ambient temperature of -30°C , will not experience any heating, but can generate open-circuit voltages of 719 volts ($595 \times (1 + (25 + 30) \times 0.0038)$). This voltage substantially exceeds the capability of 600-volt rated conductors, fuses, switchgear, and other equipment. The very real possibility of this type of condition substantiates the *UL* requirement for the 125 percent factor on the rated open-circuit voltage.

The *UL* Standard 1703 also requires that the rated (at STC) short-circuit current of the PV module be multiplied by 125 percent before any other factors are applied such as those in the *NEC*. This *UL* factor is to provide a safe margin for wire sizes and overcurrent devices when the irradiance exceeds the standard $1000 \text{ W}/\text{m}^2$. Depending on season, local weather conditions, and atmospheric dust and humidity, irradiance exceeds $1000 \text{ W}/\text{m}^2$ every day around solar noon. The time period can be as long as four hours with irradiance values approaching $1200 \text{ W}/\text{m}^2$, again depending on the aforementioned conditions and the type of tracking being used. These daily irradiance values can increase short-circuit currents 20 percent over the $1000 \text{ W}/\text{m}^2$ value.

Enhanced irradiance due to reflective surfaces such as sand, snow, or white roofs, and even nearby bodies of water can increase short-circuit currents by substantial amounts and for significant periods of time. Cumulus clouds also can increase irradiance by as much as 50 percent.

Another factor that must be addressed is that PV modules typically operate at 30-40°C above the ambient temperatures. In crystalline silicon PV modules, the short-

circuit current increases as the temperature increases. A typical factor might be 0.1 percent/°C. If the module operating temperature were 60°C (35°C over the STC of 25°C), the short-circuit current would be 3.5 percent greater than the rated value. PV modules have been measured operating as high as 72°C. The combination of increased operating temperatures, irradiances over 1000 W/m² around solar noon, and the possibility of enhanced irradiance certainly justify the *UL* requirement of 125 percent on the rated short-circuit current.

NEC Requirements

The *NEC* requires that the short-circuit current of the module, source circuit, or array be multiplied by 125 percent before calculating the ampacity of any cable or the rating of any overcurrent device used in these circuits. This factor is in addition to the *UL* required 125 percent and is needed to ensure that overcurrent devices are not connected to conductors that may not provide for proper operation of the overcurrent device.

Since short-circuit currents in excess of the rated value are possible from the discussion of the *UL* requirements above, and these currents are independent of the *NEC* requirements, good engineering practice dictates that both factors should be used at the same time. This yields a multiplier on short-circuit current of 1.56 (125 percent x 125 percent).

The *NEC* also requires that the ampacity of conductors be derated for the operating temperature of the conductor. This is a requirement because the ampacity of cables is given for cables operating in an ambient temperature of 30°C. In PV systems, cables are operated in an outdoor environment and should be subjected at least to a temperature derating due to an ambient temperature of 40°C. PV modules operate at high temperatures and in some installations as high as 73°C (concentrating modules operate at even higher temperatures). The temperatures in module junction boxes approach

these temperatures and conductors in free air that lie against the back of these modules are also exposed to these temperatures. Temperatures this high require that the ampacity of cables be derated by factors of 0.33 to 0.58 depending on cable type, installation method (free air or conduit), and the temperature rating of the insulation.

Cables in conduit where the conduit is exposed to the direct rays of the sun are also exposed to elevated operating temperatures.

Cables with insulation rated at 60°C have no ampacity at all when operated in environments with ambient temperatures over 55°C. This precludes their use in most PV systems.

These derating factors are applied to determine cable ampacity and are not directly related to the 125 percent factor required elsewhere in the NEC.

Redundancy and Conservatism or Not?

There appears to be little question that the 125 percent *UL* factor on voltage is necessary in any location where the ambient temperatures drop below 25°C. Even though the PV system can provide little current under open-circuit voltage conditions, these high voltages can damage electronic equipment and stress conductors and other equipment by exceeding their voltage breakdown ratings.

In ambient temperatures from 25 to 40°C and above, module short-circuit currents are increased at the same time conductors are being subjected to higher operating temperatures. Enhanced irradiance can occur at any time. Therefore the *UL* and *NEC* factors for short-circuit current output and *NEC* conductor temperature deratings are not redundant.

Good engineering practice suggests that the *UL* Standard 1703 requirements and the *NEC* requirements are neither conservative nor redundant and that they should be applied to all systems.

APPENDIX C

Grid-Connected Systems

Grid-connected systems present some unique problems for the PV designer and installer in meeting the *NEC*. Although these installations sometimes do not have batteries or charge controllers, the availability of *UL*-Listed inverters and other equipment is limited due to the low production volume.

Inverters

Some of the grid-tied inverters that are available do not currently meet the draft standard established for inverters by *UL*. Some of the inverters cannot have both the dc PV circuits and the ac output circuits grounded without causing parallel ground current paths. Newer versions of these inverters may have solutions for this problem.

Other inverters have the internal circuitry tied to the case and force the central grounding point to be at the inverter input terminals. In some installations, this design is not compatible with ground-fault equipment and does not provide the flexibility needed for maximum surge suppression.

PV Source-Circuit Conductors

Some grid-tied inverters operate with PV arrays that are center tapped and have open-circuit voltages of ± 325 volts and above. The system voltage of 650 volts or greater exceeds the insulation rating of the commonly available 600-volt insulated conductors. Each disconnect and overcurrent device and the insulation of the wiring **must** have a voltage rating exceeding the system voltage rating. Type G and W cables are available with the higher voltage ratings, but are flexible cords and do not meet *NEC* requirements for fixed installations. Cables suitable for *NEC* installations requiring insulation greater than 600 volts are available (Appendix A).

Other inverters operate on systems with open-circuit voltages exceeding ± 540 volts requiring conductors with 2000-volt or higher insulation. See Appendix D for a full discussion of this area.

Overcurrent Devices

When *UL* tests and lists fuses for dc operation, the voltage rating is frequently one-half the ac voltage rating. This makes a 600-volt ac fuse into a 300-volt dc fuse. Finding fuses with high enough dc ratings for grid systems operating at ± 300 volts (600-volt system voltage) and above will pose problems. There are a limited number of 600-volt fuses available. See Appendix A.

Although not *UL*-Listed, Heinemann Electric Company (Appendix A) can series connect poles of dc-rated circuit breakers to obtain 750-volt ratings. Square D and others have similar products.

Circuit breakers that are "back fed" for any application (but particularly for utility interactive inverter connection to the grid) **must** be identified (in the listing) for such use and **must** be fastened in place with a screw or other additional clamp [690-64b(5), 384-16(f)].

Disconnects

In addition to the Heinemann circuit breaker mentioned above, manufacturers such as GE, Siemens, and Square D may certify their switches for higher voltage when the poles are connected in series.

Blocking Diodes

Although blocking diodes are not overcurrent devices, they do block currents in direct-current circuits, in some cases, and help to control circulating ground-fault currents if used in both ends of high-voltage strings. Lightning induced surges are

tough on diodes. If isolated case diodes are used, at least 3500 volts of insulation is provided between the active elements and the normally grounded heat sink. Choosing a peak reverse voltage as high as is available but at least twice the PV open-circuit voltage, will result in longer diode life. Substantial amounts of surge suppression will also improve diode longevity.

Surge Suppression

Surge suppression is covered only lightly in the *NEC* because it affects performance more than safety and is mainly a utility problem at the transmission line level in ac systems [280]. PV arrays mounted in the open, on the tops of buildings, act like lightning rods. The PV designer and installer must provide appropriate means to deal with lightning-induced surges coming into the system.

Array frame grounding conductors should be routed directly to ground rods located as near as possible to the arrays. Grounding conductors for array frames should not be routed parallel or adjacent to current-carrying conductors to minimize the coupling of surges into the system. The *NEC* allows this separation on dc systems in Section 250-57(b) Ex 2.

Metal conduit will add inductance to the array-to-building conductors and slow down any induced surges as well as provide some electromagnetic shielding.

Metal oxide varistors (MOV) commonly used as surge suppression devices on PV systems have several deficiencies. They draw a small amount of current continually. The clamping voltage lowers as they age and may reach the open-circuit voltage of the system. When they fail, they fail in the shorted mode, heat up, and frequently catch fire. In many installations, the MOVs are protected with fast acting fuses to prevent further damage when they fail, but this may limit their effectiveness as surge suppression devices. Other devices are available that do not have these problems.

Silicon Oxide surge arrestors do not draw current when they are off. They fail open circuited when overloaded and, while they may split open on overloads, they rarely catch fire. They are not normally protected by fuses and are rated for surge currents up to 100,000 amps. They are rated at voltages of 300 volts and higher and are available from electrical supply houses or Delta Lightning Arrestors, Inc. (Appendix A).

Several companies specialize in lightning protection equipment, but much of it is for ac systems. Electronic product directories, such as the *Electronic Engineers Master Catalog* should be consulted.

APPENDIX D

Cable and Device Ratings at High Voltages

There is a concern in designing PV systems that have system open-circuit voltages above 600 volts. The concern has two main issues—device ratings and *NEC* limitations.

Equipment Ratings

Some utility-intertie inverters operate with a grounded, bipolar (three-wire) PV array. In a bipolar PV system, where each of the monopoles is operated in the 220-235-volt peak-power range, the open-circuit voltage can be anywhere from 290 to 380 volts, and above, depending on the module characteristics such as fill factor. Such a bipolar system can be described as a 350/700-volt system (for example) in the same manner that a 120/240-volt ac system is described. This method of describing the system voltage is consistent throughout the electrical codes used not only in residential and commercial power systems, but also in utility practice.

In all systems, the voltage ratings of the cable, switchgear, and overcurrent devices are based on the higher number of the pair (i.e., 700 volts in a 350/700-volt system). That is why 250-volt switchgear and overcurrent devices are used in 120/240-volt ac systems and 600-volt switchgear is used in systems such as the 277/480-volt ac system. Note that it is not the voltage to ground, but the higher line-to-line voltage that defines the equipment voltage requirements.

The *National Electrical Code (NEC)* defines a nominal voltage for ac systems (120, 240, etc.) and acknowledges that some variation can be expected around that nominal voltage. Such a variation around a nominal voltage is not considered in dc PV systems, and the *NEC* requires that the open-circuit array voltage must be used. The open-circuit voltage is defined at STC because of the relationship between the *UL* Standards and the way the *NEC* is written. The *NEC Handbook* elaborates on the definition of “circuit

voltage," but this definition may not apply to current-limited dc systems. Section 690-7(a) of the *NEC* requires that the voltage used for establishing dc circuit requirements in PV systems be the open-circuit voltage.

The 1996 *NEC* specifically defines the system voltage as the sum of the absolute value of the open-circuit bipolar voltages [690-7(a)].

The comparison to ac systems cannot be carried too far; there are differences. For example, the typical wall switch in a 120/240-volt ac residential or commercial system is rated at only 120 volts, but such a switch in a 120/240-volt dc PV system would have to be rated at 240 volts. The inherent differences between a dc current source (PV modules) and a voltage source (ac grid) bear on this issue. Even the definitions of circuit voltage in the *NEC* and *NEC Handbook* refer to ac and dc systems, but do not take into account the design of the balance of systems required in current-limited PV systems. In a PV system, all wiring, disconnects, and overcurrent devices have current ratings that exceed the short-circuit currents by at least 25 percent. In the case of bolted or ground faults involving currents from the PV array, the overcurrent devices do not trip because they are rated to withstand continuous operation at levels above the fault levels. In an ac system, bolted faults and ground faults generally cause the overcurrent devices to trip or blow removing the source of voltage from the fault. Therefore, the faults that pose high-voltage problems in PV, dc systems cause the voltage to be removed in ac, grid-supply systems. For these reasons, a switch rated at 120 volts can be used in an ac system with voltages up to 240 volts, but in a dc, PV system, the switch would have to be rated at 240 volts.

Underwriters Laboratories (*UL*) Standard 1703 requires that manufacturers of modules listed to the standard include, in the installation instructions, a statement that the open-circuit voltage should be multiplied by 125 percent (crystalline cells), further increasing the voltage requirement of the Balance of Systems (BOS) equipment.

Current PV modules that are listed to the *UL* Standard 1703 are listed with a maximum system voltage of 600 volts. Engineers caution all installers, factory and otherwise, to not exceed this voltage. This restriction is not modified by the fact that the modules undergo high-pot tests at higher voltages. *UL* Standard 1703 allows modules to be listed up to 1000 volts.

Although not explicitly stated by the *NEC*, it is evident that the intent of the Code and the *UL* Standards is that all cable, switches, fuses, circuit breakers, and modules in a PV system be rated for the maximum system voltage. This is clarified in the 1996 *NEC* [690-7(a)].

While reducing the potential for line-to-line faults, the practice of wiring each monopole (one of two electrical source circuits) in a separate conduit to the inverter does not eliminate the problem. Consider the bipolar system presented in Figure D-1 with a bolted fault (or deliberate short) from the negative to the positive array conductor at the input of the inverter. With the switches closed, array short-circuit current flows, and neither fuse opens.

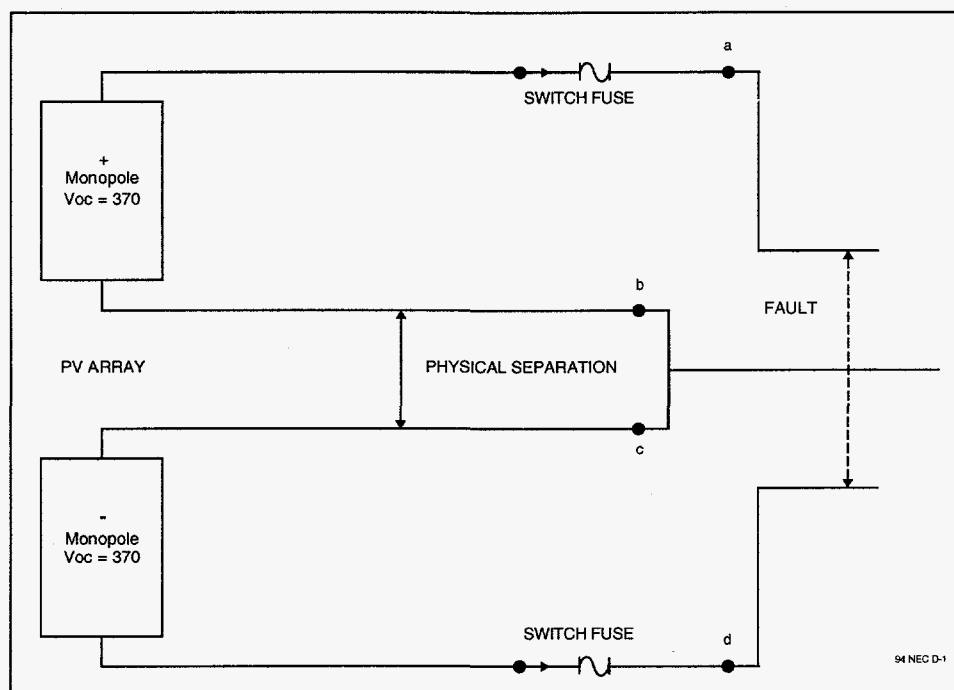


Figure D-1. Typical Bipolar System with Fault

Now consider what happens in any of the following cases.

1. A switch is opened
2. A fuse opens
3. A wire comes loose in a module junction box
4. An intercell connection opens or develops high resistance
5. A conductor fails at any point

In any of these cases, the entire array voltage (740 volts) stresses the device where the circuit opens. This voltage (somewhere between zero at short-circuit and the array open-circuit voltage) will appear at the device or cable. As the device starts to fail, the current through it goes from I_{sc} to zero as the voltage across the device goes from zero to V_{oc} . This process is very conducive to sustained arcs and heating damage.

Separating the monopoles does not avoid the high-voltage stress on any component, but it does help to minimize the potential for some faults. There are other possibilities for faults that will also place the same total voltage on various components in the system. An improperly installed grounding conductor coupled with a module ground fault could result in similar problems.

Section 690-5 of the *NEC* requires a ground-fault device on PV systems that are installed on the roofs of dwellings. This device, used for fire protection, must detect the fault, interrupt the fault current, and "disable" the array. "Disable" is not clearly defined in the *NEC*, but the *NEC Handbook* (containing supplementary guidance) says one means of disabling an array is to crowbar or short-circuit the array terminals. This crowbar creates, as a designed-in function, the fault described above. Several ground-fault devices that have been prototyped and produced have this crowbar feature.

Some large (100 kW) grid-connected PV systems like the one at Juana Diaz, Puerto Rico have inverters that, when shut down, crowbar the array. The array remains crowbarred until the ac power is shut off.

NEC Limitation

The second issue associated with this concern is that the 1996 *NEC* in Section 690-7(c) only allows PV installations up to 600 volts in one and two-family dwellings. Inverter and system design issues may favor higher system voltage levels.

SOLUTIONS

Near Term

System designers can select inverters with lower operating and open-circuit voltages. Utility-intertie inverters are available with voltages as low as 24 volts. They also can work with the manufacturers of higher voltage inverters to reduce the number of modules in each series string to the point where the open-circuit voltage is less than 600 volts. The peak-power voltage would also be lowered. Transformers may be needed to raise the ac voltage to the required level. At least one inverter manufacturer has pursued this option and is offering inverters which can operate with arrays that have open-circuit voltages of less than 600 volts.

Cable manufacturers can produce a *UL*-Listed, cross-linked polyethylene, single-conductor cable marked USE-2, RHW-2, and Sunlight Resistant. The cable is rated at 2000 volts. This cable could be used for exposed module interconnections and in conduit after all of the other *NEC* requirements are met for installations above 600 volts.

Several manufacturers issue factory certified rating on their three-pole disconnects to allow higher voltage, non-load break operation with series-connected poles. The *NEC* will require an acceptable method of obtaining non-load break operation.

Some OEM circuit breaker manufacturers will factory certify series-connected poles on their circuit breakers. Units have been used at 750 volts and 100 amps with 10,000 amps of interrupt rating. Higher voltages may be available.

High-voltage industrial fuses are available, but dc ratings are unknown at this time.

Individual 600-volt terminal blocks can be used with the proper spacing for higher voltages.

Module manufacturers can have their modules listed for higher system voltages.

Power diodes may be connected across each monopole. When a bolted line-to-line fault occurs, one of the diodes will be forward biased when a switch or fuse opens, thereby preventing the voltage from one monopole from adding to that of the other monopole. The diodes are mounted across points a-b and c-d in Figure D-1. Each diode should be rated for at least the system open-circuit voltage and the full short-circuit current from one monopole. Since diodes are not listed as over-voltage protection devices, this solution is not recognized in the *NEC*.

The 1996 *NEC* allows PV installations over 600 volts in non-residential applications, which will cover the voltage range being used in most current designs. Article 710 should be consulted for all of the numerous requirements dealing with the installation of electrical systems with voltages over 600 volts.

APPENDIX E

Example Systems

The systems described in this appendix and the calculations shown are presented as examples only. The calculations for conductor sizes and the ratings of overcurrent devices are based on the requirements of the 1996 *National Electrical Code (NEC)* and on *UL Standard 1703* which provides instructions for the installation of *UL-Listed PV* modules. Local codes and site-specific variations in irradiance, temperature, and module mounting, as well as other installation particularities, dictate that these examples should not be used without further refinement. Tables 310-16 and 310-17 from the *NEC* provide the ampacity data and temperature derating factors.

CABLE SIZING AND OVERCURRENT PROTECTION

The procedure presented below for cable sizing and overcurrent protection of that cable is based on *NEC* requirements in Sections 690-9, 690-8, 210-22(c), 220-3(a), 220-10(b), 215-3, and 240-3(b).

1. **Circuit Current.** For circuits carrying currents from PV modules, multiply the short-circuit current by 125% and use this value for all further calculations. For dc and ac inverter circuits in PV systems, use the rated continuous currents. AC and dc load circuits should follow the requirements of Sections 210, 220, and 215.
2. **Overcurrent Device Rating.** The overcurrent device must be rated at 125% of the current determined in Step No. 1. This is to prevent overcurrent devices from being operated at more than 80% of rating.
3. **Cable Sizing.** Cables shall have a 30°C ampacity of 125% of the current determined in Step No. 1 to ensure proper operation of connected overcurrent devices. There are no additional deratings applied with this calculation.

4. **Cable Derating.** Based on the determination of Step No. 3 and the location of the cable (raceway or free-air), a cable size and insulation temperature rating (60, 75, or 90°C) are selected from the NEC Ampacity Tables 310-16 or 310-17. Use the 75°C cable ampacities to get the size, then use the ampacity from the 90°C column—if needed—for the deratings. This cable is then derated for temperature, conduit fill, and other requirements. The resulting derated ampacity must be greater than the value found in Step No. 1. If not greater, then a larger cable size or higher insulation temperature must be selected.
5. **Ampacity vs. Overcurrent Device.** The derated ampacity of the cable selected in Step No. 4, must be equal to or greater than the overcurrent device rating determined in Step No. 2. If the derated ampacity of the cable is less than the rating of the overcurrent device, then a larger cable must be selected. The next larger standard size overcurrent device may be used if the derated cable ampacity falls between the standard overcurrent device sizes found in NEC Section 240-6.
6. **Device Terminal Compatibility.** Since most overcurrent devices have terminals rated for use with 75°C (or 60°C) cables, compatibility must be verified. If a 90°C-insulated cable was selected in the above process, the 30°C ampacity of the same size cable with a 75°C (or 60°C) insulation must be less than or equal to the current found in Step No. 1. This ensures that the cable will operate at temperatures below the temperature rating of the terminals of the overcurrent device.

Here is an example of how the procedure is used:

The task is to size and protect two PV source circuits in conduit, each with an $I_{sc} = 40$ amps. Four current-carrying conductors are in the conduit and are operating in a 45°C ambient temperature.

Step 1: $1.25 \times 40 = 50$ amps.

Step 2: The required fuse (with 75°C terminals) is $1.25 \times 50 = 62.5$ amps. The next standard fuse size is 70 amps.

Step 3: Same calculation as Step 2. Cable ampacity without deratings must be 62.5 amps.

- Step 4: From Table 310-16, cables with 75°C insulation: A No. 6 AWG conductor at 65 amps is needed. This meets Step 3 requirements. Plan on installing a No. 6 AWG XHHW-2 cable with 90°C insulation and a 30°C ampacity of 75 amps. Conduit fill derate is 0.8 and temperature derate is 0.87. Derated ampacity is 52.2 amps ($75 \times 0.8 \times 0.87$). This is greater than the required 50 amps in Step 1 and meets the requirement.
- Step 5: It is acceptable to protect a cable with a derated ampacity of 52.2 amps with a 60-amp overcurrent device since this is the next larger standard size. However, this circuit requires at least a 62.5 amp device (Step 2). Therefore, the conductor must be increased to a No. 4 AWG conductor with a derated ampacity of 66 amps ($95 \times 0.87 \times 0.8$). A 70-amp fuse is acceptable to protect this cable since it is the next larger standard size.
- Step 6: The ampacity of a No. 4 AWG cable with 75°C insulation (because the fuse has 75°C terminals) is 85 amps, and is higher than the calculated circuit current of 50 amps found in Step 1. Using the 75°C column in Table 310-16 or 310-17 for starting Step 4 usually ensures that this check will be passed.

EXAMPLE 1 Direct-Connected Water Pumping System

Array Size: 4, 12-volt, 60-watt modules $I_{sc} = 3.8$ amps, $V_{oc} = 21.1$ volts

Load: 12-volt, 10-amp motor

Description

The modules are mounted on a tracker and connected in parallel. The modules are wired as shown in Figure E-1 with number 10 AWG USE-2 single-conductor cable. A large loop is placed in the cable to allow for tracker motion without straining the rather stiff building cable. The USE-2 cable is run to a disconnect switch in an enclosure mounted on the pole. From this disconnect enclosure, number 8 AWG XHHW-2 cable in electrical non-metallic conduit is routed to the well head. The conduit is buried 18 inches deep. The number 8 AWG cable is used to minimize voltage drop.

The NEC requires the disconnect switch. Because the PV modules are current limited and all conductors have an ampacity greater than the maximum output of the PV modules, no overcurrent device is required, although some inspectors might require it and it might serve to provide some degree of lightning protection. A dc-rated disconnect switch or a dc-rated fused disconnect must be used. Since the system is ungrounded, a two-pole switch must be used. All module frames, the disconnect enclosure, and the pump housing must be grounded, whether the system is grounded or not.

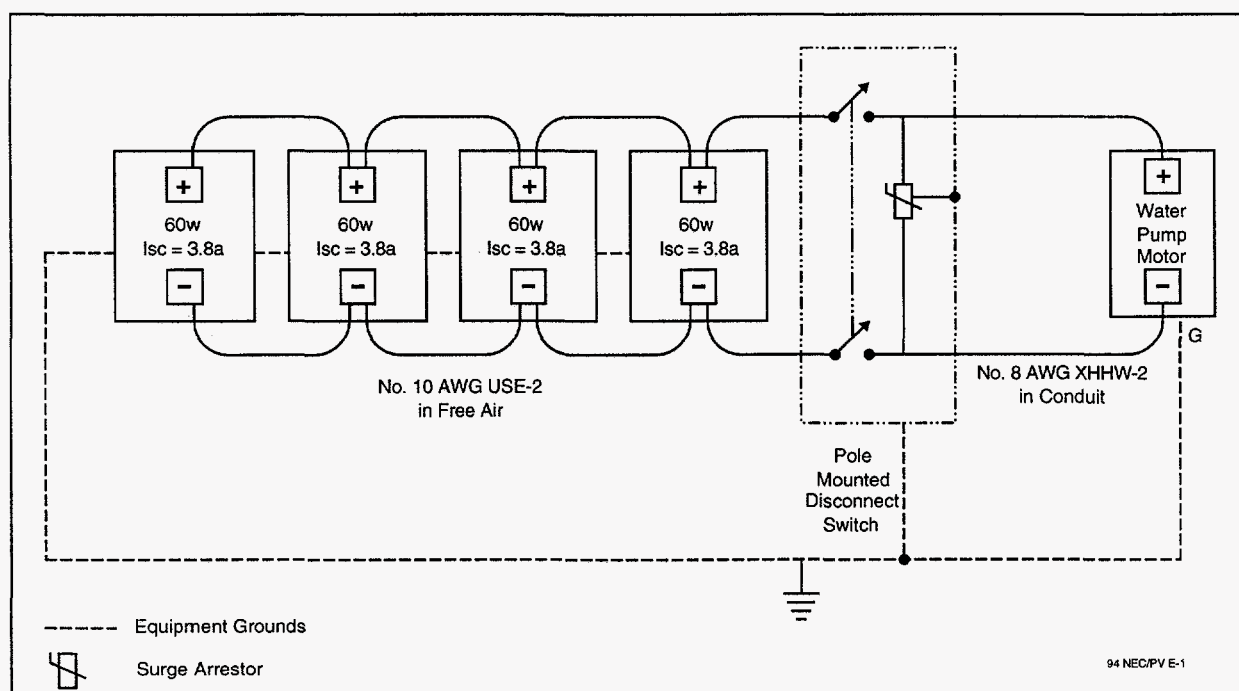


Figure E-1. Direct Connected System

Calculations

The array short-circuit current is 15.2 amps (4×3.8).

UL 125 percent: $1.25 \times 15.2 = 19$ amps

NEC 125 percent: $1.25 \times 19 = 23.75$ amps

The ampacity of 10 AWG USE-2 at 30°C is 55 amps.

The ampacity at 61-70°C is 31.9 amps (0.58×55) which is more than the 19 amp requirement.

The equipment grounding conductors should be number 10 AWG.

The minimum voltage rating of all components is 26 volts (1.25×21.1).

EXAMPLE 2 Water Pumping System with Current Booster

Array Size: 10, 12-volt, 53-watt modules $I_{sc} = 3.4$ amps, $V_{oc} = 21.7$ volts

Current Booster Output: 90 amps

Load: 12-volt, 40-amp motor

Description

This system has a current booster before the water pump and has more modules than in Example 1. Initially, number 8 AWG USE-2 cable was chosen for the array connections, but this cable has inadequate ampacity. As the calculations below show, the array was split into two subarrays. There is potential for malfunction in the current booster, but it does not seem possible that excess current can be fed back into the array wiring, since there is no other source of energy in the system. Therefore, these conductors do not need overcurrent devices if they are sized for the entire array current. If smaller conductors are used, then overcurrent devices will be needed.

Since the array is broken into two subarrays, the maximum short-circuit current available in either subarray wiring is equal to the total array short-circuit current under fault conditions. Overcurrent devices are needed to protect the subarray conductors under these conditions.

A grounded system is selected, and only one-pole disconnects are required. Equipment grounding and system grounding conductors are shown in Figure E-2

If the current booster output conductors are sized to carry the maximum current (3-hour) of the booster, then overcurrent devices are not necessary, but again, some inspectors may require them.

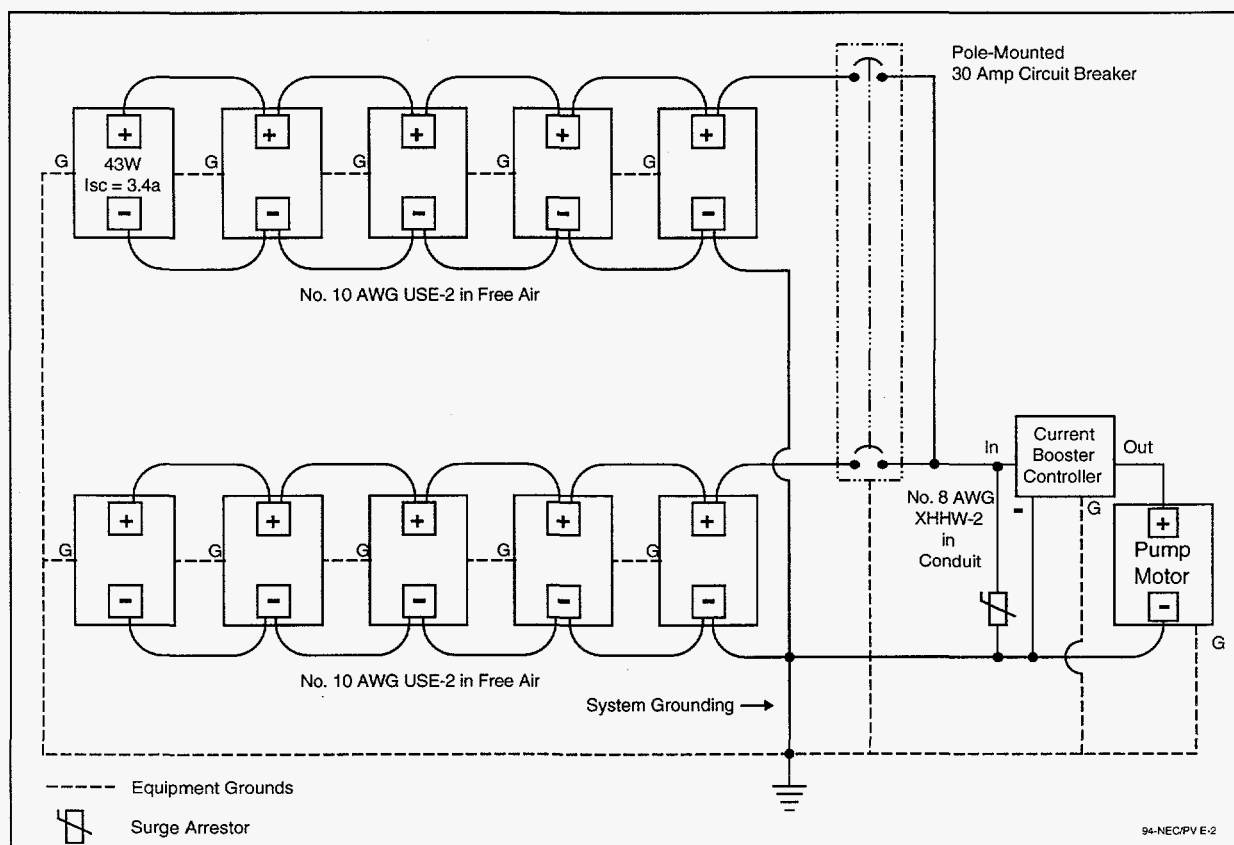


Figure E-2. Direct-Connected PV System with Current Booster

Calculations

The array short-circuit current is 34 amps (10×3.4).

UL 125 percent: $1.25 \times 34 = 42.5$ amps

NEC 125 percent: $1.25 \times 42.5 = 53.1$ amps

The ampacity of 8 AWG USE-2 cable at 30°C in free air is 80 amps.

The ampacity at 61-70°C is 46.4 amps (0.58×80), which is more than the 42.5 amp requirement, and a single array could be used. However, the array is split into two subarrays for serviceability. Each is wired with number 10 AWG USE-2 conductors.

The subarray short-circuit current is 17 amps (5×3.4).

UL 125 percent: $1.25 \times 17 = 21.3$ amps

NEC 125 percent: $1.25 \times 21.25 = 26.6$ amps

The ampacity of number 10 AWG USE-2 at 30°C in free air is 55 amps.

The ampacity at 61-70°C is 31.9 amps (0.58×55), which is more than the 21.3 amp requirement. Since this cable is to be connected to an overcurrent device with terminals rated at 60°C or 75°C, the ampacity of the cable must be evaluated with 60°C or 75°C insulation. Overcurrent devices rated at 100 amps or less may have terminals rated at only 60°C. Number 10 AWG 75°C cable operating at 30°C has an ampacity of 35 amps, which is more than the 21.3 amps requirement. Therefore, there are no problems with the terminals on a 75°C overcurrent device.

Thirty-amp circuit breakers are used to protect the number 10 AWG subarray conductors. The required rating is $1.25 \times 21.25 = 26.6$ amps, and the next largest size is 30 amps.

The current booster maximum current is 90 amps.

The current booster average long-term (3-hours or longer) current is 40 amps.

NEC 125 percent: $1.25 \times 40 = 50$ amps

The ampacity of number 8 AWG XHHW-2 at 30°C in conduit is 55 amps.

The ampacity at 36-40°C is 50 amps (0.91×55), which meets the requirements but may not meet the overcurrent device connection requirements.

The number 8 AWG conductors are connected to the output of the fuse holders, and there is a possibility that heating of the fuse may occur depending on how the holder is connected. It is therefore good practice to make the calculation for terminal overheating. The ampacity of a number 8 AWG conductor evaluated with 75°C insulation (the maximum temperature of the terminals on the overcurrent device) is 50 amps, which is greater than the 40-amp requirement. This means that the overcurrent device will not be subjected to overheating when the number 8 AWG conductor carries 40 amps.

All equipment grounding conductors should be number 10 AWG. The grounding electrode conductor should be number 8 AWG or larger.

Minimum voltage rating of all components: $1.25 \times 21.1 = 26$ volts

EXAMPLE 3 Stand-Alone Lighting System

Array Size: 4, 12-volt, 64-watt modules $I_{sc} = 4.0$ amps, $V_{oc} = 21.3$ volts

Batteries: 200-amp-hours at 24 volts

Load: 60 watts at 24 volts

Description

The modules are mounted at the top of a 20-foot pole with the metal-halide lamp. The modules are connected in series and parallel to achieve the 24-volt system rating. The lamp, with an electronic ballast and timer/controller, draws 60 watts at 24 volts. The batteries, disconnect switches, charge controller, and overcurrent devices are mounted in a box at the bottom of the pole. The system is grounded as shown in Figure E-3.

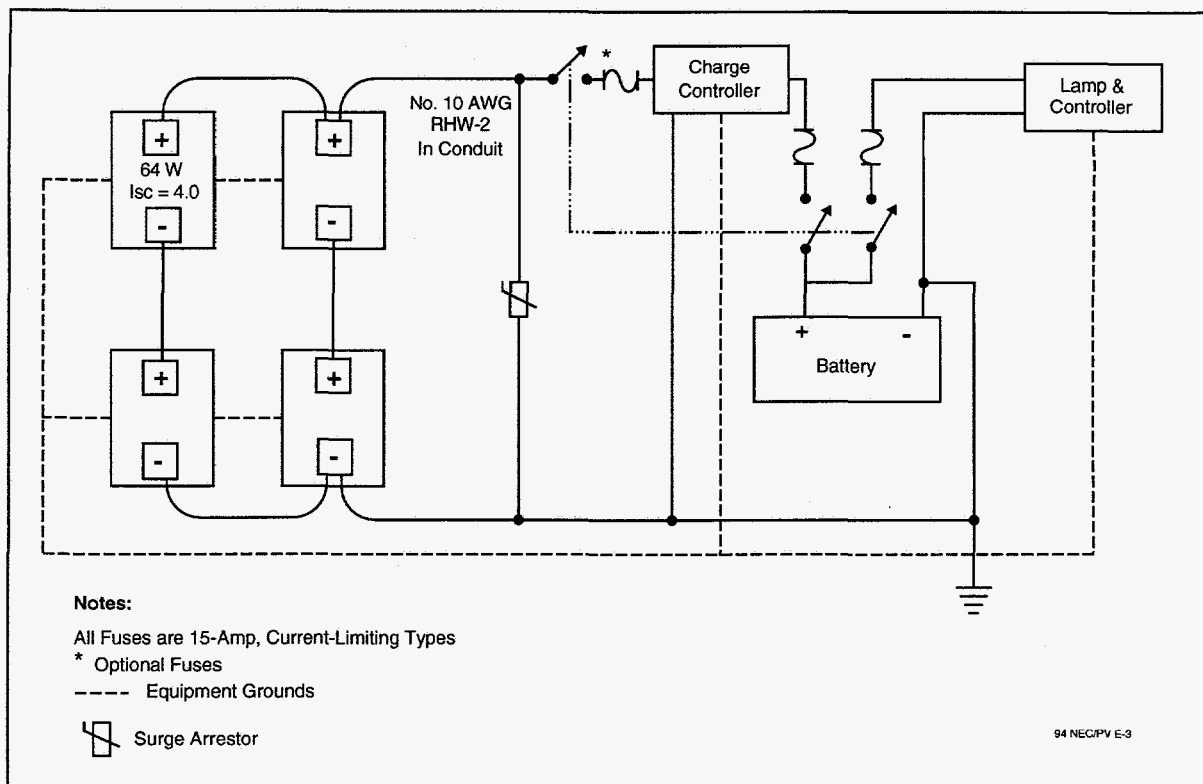


Figure E-3. Stand-Alone Lighting System

Calculations:

The array short-circuit current is 8 amps (2×4).

UL 125 percent: $1.25 \times 8 = 10$ amps

NEC 125 percent: $1.25 \times 10 = 12.5$ amps

Load Current: $60/24 = 2.5$ amps

NEC 125 percent: $1.25 \times 2.5 = 3.1$ amps

Number 10 AWG USE-2 is selected for module interconnections and is placed in conduit at the modules and then run down the inside of the pole.

The modules operate at 61-70°C, which requires that the module cables be temperature derated. Number 10 AWG USE-2 cable has an ampacity of 40 amps at 30°C in conduit. The derating factor is 0.58. The temperature derated ampacity is 23.2

amps (40×0.58), which exceeds the 10-amp requirement. Checking the cable with a 75°C insulation, the ampacity at the fuse end is 35 amps, which exceeds the 10-amp requirement. This cable can be protected by a 15-amp fuse or circuit breaker (125% of 10 is 12.5). An overcurrent device rated at 100 amps or less may only have terminals rated for 60°C, not the 75°C used in this example. Lower temperature calculations may be necessary.

The same USE-2, number 10 AWG cable is selected for all other system wiring, because it has the necessary ampacity for each circuit.

A three-pole fused disconnect is selected to provide the PV and load disconnect functions and the necessary overcurrent protection. The fuse selected is a RK-5 type, providing current-limiting in the battery circuits. A pull-out fuse holder with either Class RK-5 or Class T fuses could also be used for a more compact installation. Fifteen amp fuses are selected to provide overcurrent protection for the number 10 AWG cables. They are used in the load circuit and will not blow on any starting surges drawn by the lamp or controller. The 15-amp fuse before the charge controller could be eliminated since that circuit is protected by the fuse on the battery side of the charge controller. The disconnect switch at this location is required.

The equipment grounding conductors and the system grounding conductor to the ground rod should be number 10 AWG conductors.

The dc voltage ratings for all components used in this system should be at least 53 volts ($2 \times 21.3 \times 1.25$).

EXAMPLE 4 Remote Cabin DC-Only System

Array Size: 6, 12-volt, 75-watt modules $I_{sc} = 4.8$ amps, $V_{oc} = 22$ volts

Batteries: 700 amp hours at 12 volts

Load: 75 watts peak at 12-volts dc

Description

The modules are mounted on a rack on a hill behind the house. Non-metallic conduit is used to run the cables from the module rack to the control panel. A disconnect and control panel are mounted on the back porch, and the batteries are in an insulated box under the porch. All the loads are dc with a peak combined power of 75 watts at 12 volts due, primarily, to a pressure pump on the gravity-fed water supply. The battery bank consists of four 350-amp-hour, 6-volt, deep-cycle batteries wired in series and parallel. Figure E-4 shows the system schematic.

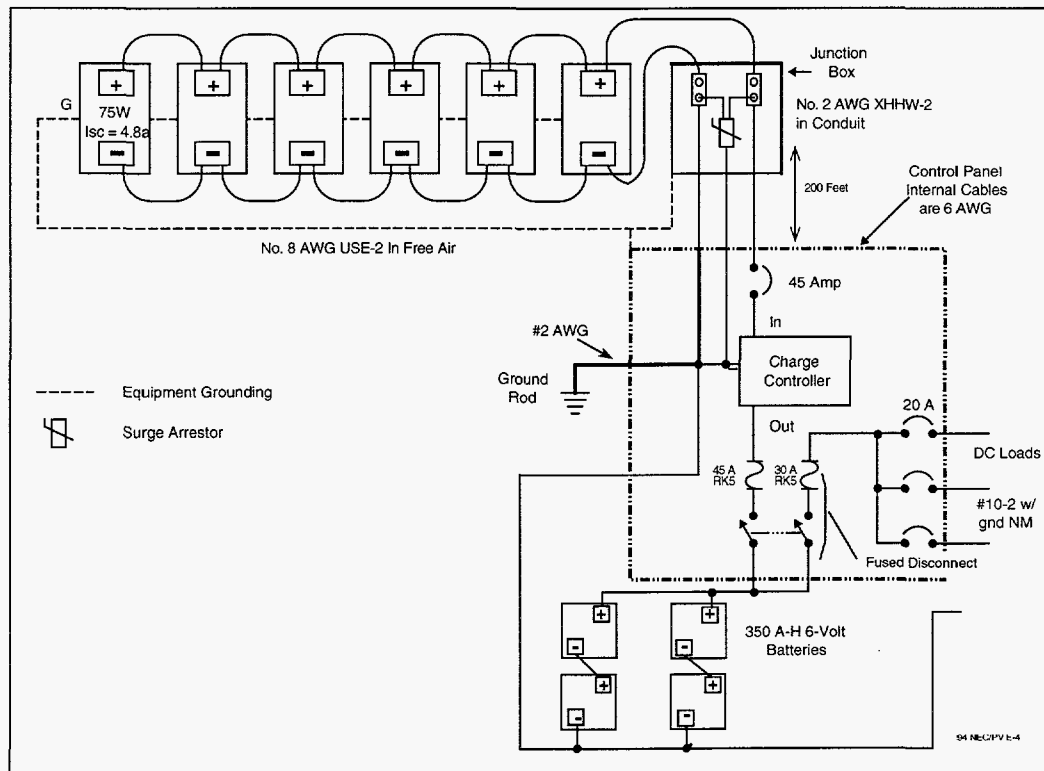


Figure E-4. Remote Cabin DC-Only System

Calculations

The array short-circuit current is 28.8 amps (6×4.8).

UL 125 percent: $1.25 \times 28.8 = 36$ amps

NEC 125 percent: $1.25 \times 36.0 = 45$ amps

The module interconnect wiring and the wiring to a rack-mounted junction box will operate at 65°C. If USE-2 cable with 90°C insulation is chosen, then the temperature derating factor will be 0.58. The required ampacity of the cable at 30°C is 62 amps ($36/0.58$), which can be handled by number 8 AWG cable with an ampacity of 80 amps in free air at 30°C. Conversely, the ampacity of the number 8 AWG cable is 46.4 amps (80×0.58) at 65°C which exceeds the 36 amp requirement.

From the rack-mounted junction box to the control panel, the conductors will be in conduit and exposed to 40°C temperatures. If XHHW-2 cable with a 90°C insulation is selected, the temperature derating factor is 0.91. The required ampacity of the cable at 30°C would be $36/0.91 = 39.6$ amps in conduit. Number 8 AWG cable has an ampacity of 55 amps at 30°C in conduit. Conversely, the number 8 AWG conductor has an ampacity of 50 amps (55×0.91) at 40°C in conduit which exceeds the 39.6 amp requirement at this temperature.

The number 8 AWG cable, evaluated with a 75°C insulation, has an ampacity at 30°C of 50 amps, which is greater than the 36 amps that might flow through it on a daily basis.

The array is mounted 200 feet from the house, and the round trip cable length is 400 feet. A calculation of the voltage drop in 400 feet of Number 8 AWG cable operating at 36 amps (125 percent I_{sc}) is $0.778 \text{ ohms per } 1000 \text{ feet} \times 400 / 1000 \times 36 = 11.2$ volts. This represents an excessive voltage drop on a 12-volt system, and the batteries cannot be effectively charged. Number 2 AWG cable (with a voltage drop of 2.8 volts) was substituted; this substitution is acceptable for this installation.

The PV conductors are protected with a 45-amp (1.25 x 36) single-pole circuit breaker on this grounded system. The circuit breaker should be rated to accept Number 2 AWG conductors rated at 75°C.

Number 6 AWG THHN cable is used in the control center and has an ampacity of 95 amps at 30°C when evaluated with 75°C insulation. Number 2 AWG cable from the negative dc input is used to the point where the grounding electrode conductor is attached instead of the number 6 AWG conductor used elsewhere to comply with grounding requirements.

The 75-watt peak load draws about 6.25 amps and number 10-2 with ground (w/gnd) nonmetallic sheathed cable was used to wire the cabin for the pump and a few lights. DC-rated circuit breakers rated at 20 amps were used to protect the load wiring, which is in excess of the peak load current of 7.8 amps (1.25 x 6.25) and less than the cable ampacity of 30 amps.

Current-limiting fuses in a fused disconnect are used to protect the dc-rated circuit breakers, which do not have an interrupt rating sufficient to withstand the short-circuit currents from the battery under fault conditions. RK-5 fuses were chosen with a 45-amp rating in the charge circuit and a 30-amp rating in the load circuit. The fused disconnect also provides a disconnect for the battery from the charge controller and the dc load center.

The equipment grounding conductors should be number 10 AWG and the grounding electrode conductor should be number 2 AWG.

All components should have a voltage rating of at least $1.25 \times 22 = 27.5$ volts.

EXAMPLE 5 Small Residential Stand-Alone System

Array Size: 10, 12-volt, 51-watt modules $I_{sc} = 3.25$ amps, $V_{oc} = 20.7$ volts

Batteries: 800 amp-hours at 12 volts

Loads: 5 amps dc and 500-watt inverter with 90 percent efficiency

Description

The PV modules are mounted on the roof. Single conductor cables are used to connect the modules to a roof-mounted junction box. UF two-conductor sheathed cable is used from the roof to the control center. Physical protection (wood barriers or conduit) for the UF cable is used where required. The control center, diagrammed in Figure E-5, contains disconnect and overcurrent devices for the PV array, the batteries, the inverter, and the charge-controller.

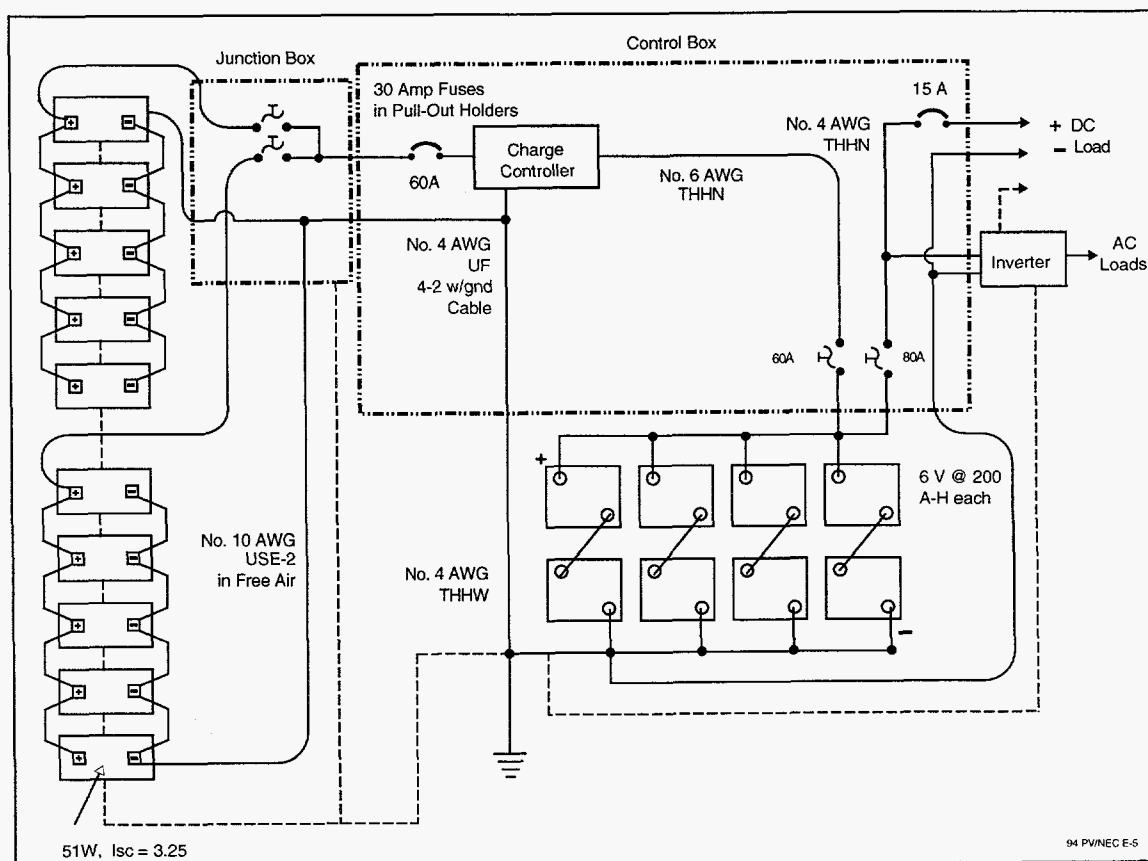


Figure E-5. Small Residential Stand-Alone System

Calculations

The module short-circuit current is 3.25 amps.

UL 125 percent: $1.25 \times 3.25 = 4.06$ amps

NEC 125 percent: $1.25 \times 4.06 = 5.08$ amps per module

The module operating temperature is 68°C.

The derating factor for USE-2 cable is 0.58 at 61-70°C.

Number 14 cable has an ampacity at 68°C of 20.3 amps (0.58×35) (max fuse is 15 amps—see notes at bottom of Tables 310-16 & 17).

Number 12 cable has an ampacity at 68°C of 23.2 amps (0.58×40) (max fuse is 20 amps).

Number 10 cable has an ampacity at 68°C of 31.9 amps (0.58×55) (max fuse is 30 amps).

Number 8 cable has an ampacity at 68°C of 46.4 amps (0.58×80).

The array is divided into two five-module subarrays. The modules in each subarray are wired from module junction box to module junction box and then to the array junction box. Number 10 AWG USE-2 is selected for this wiring, because it has an ampacity of 31.9 amps under these conditions, and the requirement for each subarray is $5 \times 4.06 = 20.3$ amps. Evaluated with 75°C insulation, a number 10 AWG cable has an ampacity of 35 amps, which is greater than the actual requirement of 20.3 amps (5×4.06). In the array junction box on the roof, two 30-amp fuses in pull-out holders are used to provide overcurrent protection for the number 10 AWG conductors. These fuses meet the requirement of 25.4 amps (125% of 20.3).

In this junction box, the two subarrays are combined into an array output. The ampacity requirement is 40.6 amps (10×4.06). A number 4 AWG UF cable (4-2 w/gnd) is selected for the run to the control box. It operates in an ambient temperature of 40°C and has an ampacity of 57.4 amps (70×0.82). This is a 60°C cable with 90°C conductors.

Care must be used when connecting to fuses that are rated for use only with 75°C conductors.

A 60-amp circuit breaker in the control box serves as the PV disconnect switch and overcurrent protection for the UF cable. The *NEC* allows the next larger size; in this case, 60 amps, which is over the 57 amps ampacity of the cable. Two single-pole, pull-out fuse holders are used for the battery disconnect. The charge circuit fuse is a 60-amp RK-5 type.

The inverter has a continuous rating of 500 watts at 10.75 volts and an efficiency of 90 percent at this power level. The ampacity requirement of the input circuit is 64.6 amps $((500 / 10.75 / 0.90) \times 1.25)$.

The cables from the battery to the control center must meet the inverter requirements of 64.6 amps plus the dc load requirements of 6.25 amps (1.25×5) . A number 4 AWG THHN has an ampacity of 85 amps when placed in conduit and evaluated with 75°C insulation. This exceeds the requirements of 71 amps $(64.6 + 6.25)$. This cable can be used in the custom power center and be run from the batteries to the inverter.

The discharge-circuit fuse must be rated at least 71 amps. An 80-amp fuse should be used, which is less than the cable ampacity.

The dc-load circuit is wired with number 10 AWG NM cable (ampacity of 30 amps) and protected with a 15-amp circuit breaker.

The grounding electrode conductor is number 4 AWG and is sized to match the largest conductor in the system, which is the array-to-control center wiring.

Equipment grounding conductors for the array and the charge circuit can be number 10 AWG based on the 60-amp overcurrent devices [Table 250-95]. The equipment ground for the inverter must be a number 8 AWG conductor.

All components should have at least a dc voltage rating of $1.25 \times 20.7 = 26$ volts.

EXAMPLE 6 Medium Sized Residential Hybrid System

Array Size: 40, 12-volt, 53-watt modules $I_{sc} = 3.4$ amps, $V_{oc} = 21.7$ volts

Batteries: 1000 amp-hours at 24 volts

Generator: 6 kW, 240-volt ac

Loads: 15 amps dc and 4000-watt inverter, efficiency = .85

Description

The 40 modules (2120 watts) are mounted on the roof in subarrays consisting of eight modules mounted on a single-axis tracker. The eight modules are wired in series and parallel for this 24-volt system. Five source circuits are routed to a custom power center. Single-conductor cables are used from the modules to roof-mounted junction boxes for each source circuit. From the junction boxes, UF sheathed cable is run to the main power center.

Blocking diodes are not used to minimize voltage drops in the system.

A prototype array ground-fault detector provides experimental compliance with the requirements of *NEC* Section 690-5.

The charge controller is a relay type.

DC loads consist of a refrigerator, a freezer, several telephone devices, and two fluorescent lamps. Peak current is 15 amps.

The 4000-watt sine-wave inverter supplies the rest of the house.

The 6-kW natural gas fueled, engine-driven generator provides back-up power and battery charging through the inverter. The 240-volt output of the generator is fed through a 5 kVA transformer to step it down to 120 volts for use in the inverter and the house. The transformer is protected on the primary winding by a 30-amp circuit breaker [450-3(b)(1) Ex-1]. Figure E-6 presents the details.

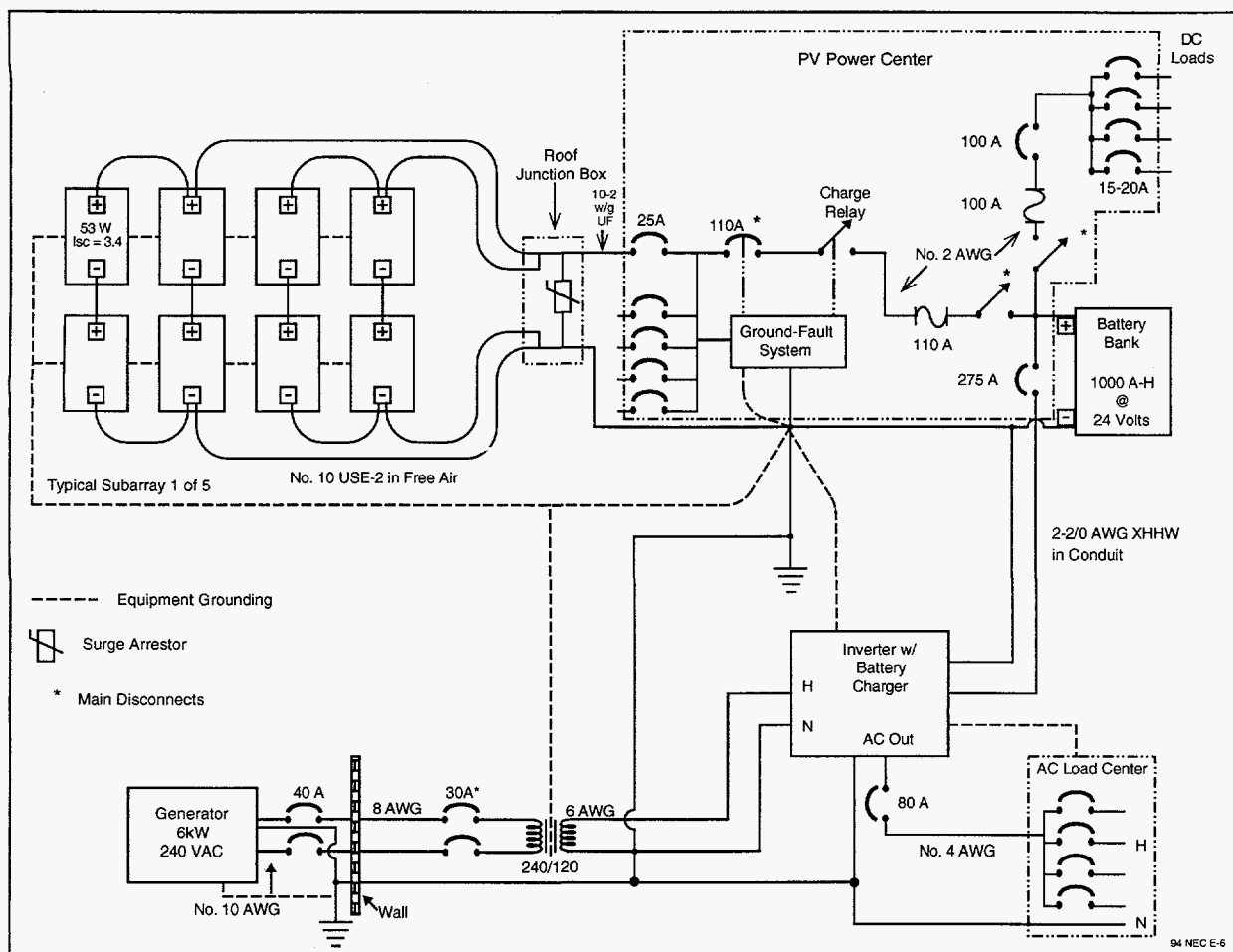


Figure E-6. Medium Sized Residential Hybrid System

Calculations

The subarray short-circuit current is 13.6 amps (4×3.4).

UL 125 percent: $1.25 \times 13.6 = 17$ amps

NEC 125 percent: $1.25 \times 17 = 21.25$ amps

The temperature derating factor for USE-2 cable at 61-70°C is 0.58.

The ampacity of number 10 AWG USE-2 cable at 70°C is 31.9 amps (55×0.58).

The temperature derating factor for UF cable at 36-40°C is 0.82.

The ampacity of number 10-2 w/gnd UF cable at 40°C is 24.6 amps (30×0.82). Since the UF cable insulation is rated at 60°C, no further temperature calculations are required when this cable is connected to circuit breakers rated for use with 75°C conductors.

The source-circuit circuit breakers are rated at 25 amps (requirement is 125% of 17 amps = 21.25).

The PV array short-circuit current is 68 amps (5×13.6).

UL 125 percent: $1.25 \times 68 = 85$ amps

NEC 125 percent: $1.25 \times 85 = 106$ amps

A 110-amp circuit breaker is used for the main PV disconnect after the five source circuits are combined.

A 110-amp RK5 current-limiting fuse is used in the charge circuit of the power center, which is wired with number 2 AWG THHN conductors (170 amps with 75°C insulation).

The dc-load circuits are wired with number 10-2 w/gnd NM cable (30 amps) and are protected with 20- or 30-amp circuit breakers. A 100-amp RK-5 fuse protects these discharge circuits from excess current from the batteries.

Inverter

The inverter can produce 4000 watts ac at 22 volts with an efficiency of 85 percent.

The inverter input current ampacity requirements are 267 amps ($(4000 / 22 / 0.85) \times 1.25$).

Two 2/0 AWG USE-2 cables are paralleled in conduit between the inverter and the batteries. The ampacity of this cable (rated with 75°C insulation) at 30°C is 280 amps ($175 \times 2 \times 0.80$). The 0.80 derating factor is required because there are four current-carrying cables in the conduit.

A 275-amp circuit breaker with a 25,000-amp interrupt rating is used between the battery and the inverter. Current-limiting fusing is not required in this circuit.

The output of the inverter can deliver 4000 watts ac (33 amps) in the inverting mode. It can also pass up to 60 amps through the inverter from the generator while in the battery charging mode.

Ampacity requirements, ac output: $60 \times 1.25 = 75$ amps. This reflects the *NEC* requirement that circuits are not to be operated continuously at more than 80% of rating.

The inverter is connected to the ac load center with number 4 AWG THHN conductors in conduit, which have an ampacity of 85 amps when used at 30°C with 75°C overcurrent devices. An 80-amp circuit breaker is used near the inverter to provide a disconnect function and the overcurrent protection for this cable.

Generator

The 6-kW, 120/240-volt generator has internal circuit breakers rated at 27 amps (6500-watt peak rating). The *NEC* requires that the output conductors between the generator and the first field-installed overcurrent device be rated at least 115 percent of the nameplate rating ($(6000 / 240) \times 1.15 = 28.75$ amps). Since the generator is connected through a receptacle outlet, a number 10-4 AWG SOW-A portable cord (30 amps) is run to a NEMA 3R exterior circuit breaker housing. This circuit breaker is rated at 40 amps and provides overcurrent protection for the number 8 AWG THHN conductors to the transformer. These conductors have an ampacity of 44 amps (50×0.88) at 40°C (75°C insulation rating). The circuit breaker also provides an exterior disconnect for the generator. Since the transformer isolates the generator conductors from the system electrical ground, the neutral of the generator is grounded at the exterior disconnect.

A 30-amp circuit breaker is mounted near the PV Power Center in the ac line between the generator and the transformer. This circuit breaker serves as the ac disconnect for the generator and is grouped with the other disconnects in the system.

The output of the transformer is 120 volts. Using the rating of the generator, the ampacity of this cable must be 62.5 amps $((6000 / 120) \times 1.25)$. A number 6 AWG THHN conductor was used, which has an ampacity of 65 amps at 30°C (75°C insulation rating).

Grounding

The module and dc-load equipment grounds must be number 10 AWG conductors. Additional lightning protection will be afforded if a number 6 AWG or larger conductor is run from the array frames to ground. The inverter equipment ground must be a number 4 AWG conductor based on the size of the overcurrent device for this circuit. The grounding electrode conductor must be 2-2/0 AWG or a 500 kcmil conductor, unless there are no other conductors connected to the grounding electrode; then this conductor may be reduced to number 6 AWG [250-93 exceptions].

DC Voltage Rating

All dc circuits should have a voltage rating of at least 55 volts $(1.25 \times 2 \times 22)$.

EXAMPLE 7 Roof-Top Grid-Connected System

Array Size: 24, 50-volt, 240-watt modules $I_{sc} = 5.6$, $V_{oc} = 62$

Inverter: 200-volt dc input, 240-volt ac output at 5000 watts with an efficiency of 0.95.

Description

The roof-top array consists of six parallel-connected strings of four modules each. A junction box is mounted at the end of each string which contains a surge arrester, a blocking diode, and a fuse. All wiring is THHN in conduit. The inverter is located adjacent to the service entrance load center where PV power is fed to the grid through a back-fed circuit breaker. Figure E-7 shows the system diagram.

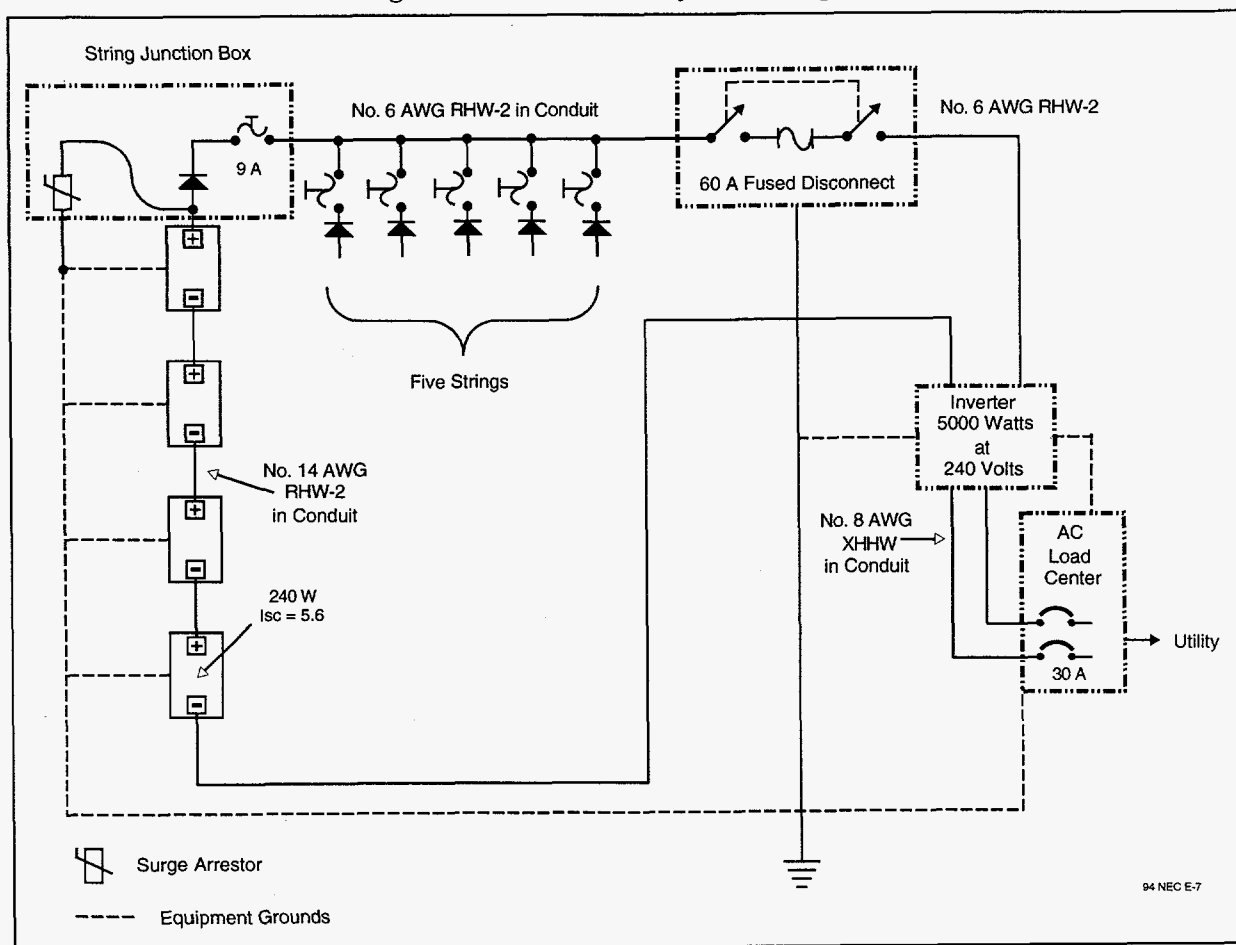


Figure E-7. Roof-Top Grid-Connected System

Calculations

The string short-circuit current is 5.6 amps.

UL 125 percent: $1.25 \times 5.6 = 7$ amps

NEC 125 percent: $1.25 \times 7 = 8.75$ amps

The array short-circuit current is 33.6 amps (6×5.6).

UL 125 percent: $1.25 \times 33.6 = 42$ amps

NEC 125 percent: $1.25 \times 42 = 52.5$ amps

The modules in each string are connected in series. The conductors operate at 63°C. The temperature derating factor for RHW-2 at this temperature is 0.58. The required 30°C ampacity for this cable is 12.1 amps ($7.0 / 0.58$). Number 14 AWG cable has an ampacity of 25 amps with 90°C insulation and 20 amps with 75°C insulation so there is no problem with the end of the cable connected to the fuse since the 7 amps is below either ampacity.

This cable is protected with a 9-amp fuse.

The cable from the string J-Boxes to the main PV disconnect operates at 40°C. The temperature derating factor for RHW-2 with 90°C insulation is 0.91. This yields a 30°C ampacity requirement of 58 amps ($52.5 / 0.91$). Number 6 AWG meets this requirement with an ampacity of 75 amps (90°C insulation), and a number 6 AWG cable with 75°C insulation has an ampacity of 65 amps, which also exceeds the 42 amp requirement.

Overcurrent protection is provided with a 60-amp fused disconnect. Since the negative dc conductor of the array is grounded, only a single-pole disconnect is needed.

The inverter output current is 21 amps ($5000 / 240$).

NEC 125 percent: $1.25 \times 21 = 26$ amps.

The cable from the inverter to the load center operates at 30°C. Number 8 AWG XHHW (evaluated with 75°C insulation) has an ampacity of 50 amps.

A back-fed 30-amp, two-pole circuit breaker provides an ac disconnect and overcurrent protection in the load center.

The equipment grounding conductors for this system should be at least number 10 AWG conductors. The system grounding electrode conductor should be a number 6 AWG conductor.

All dc circuits should have a voltage rating of at least 310 volts ($1.25 \times 4 \times 62$).

EXAMPLE 8 Integrated Roof Module System, Grid Connected

Array Size: 192, 12-volt, 22-watt thin-film modules $I_{sc} = 1.8$ amps, $V_{mp} = 15.6$
volts, $V_{oc} = 22$ volts

Inverter: ± 180 -volt dc input, 120-volt ac output, 4000 watts, .95 efficiency

Description

The array is integrated into the roof as the roofing membrane. The modules are connected in center-tapped strings of 24 modules each. Eight strings are connected in parallel to form the array. A blocking diode is placed in series with each string. Strings are grouped in two sets of four and a series fuse protects the module and string wiring as shown in Figure E-8. The bipolar inverter has the center tap dc input and the ac neutral output grounded. The 120-volt ac output is fed to the service entrance load center (fifty feet away) through a back-fed circuit breaker.

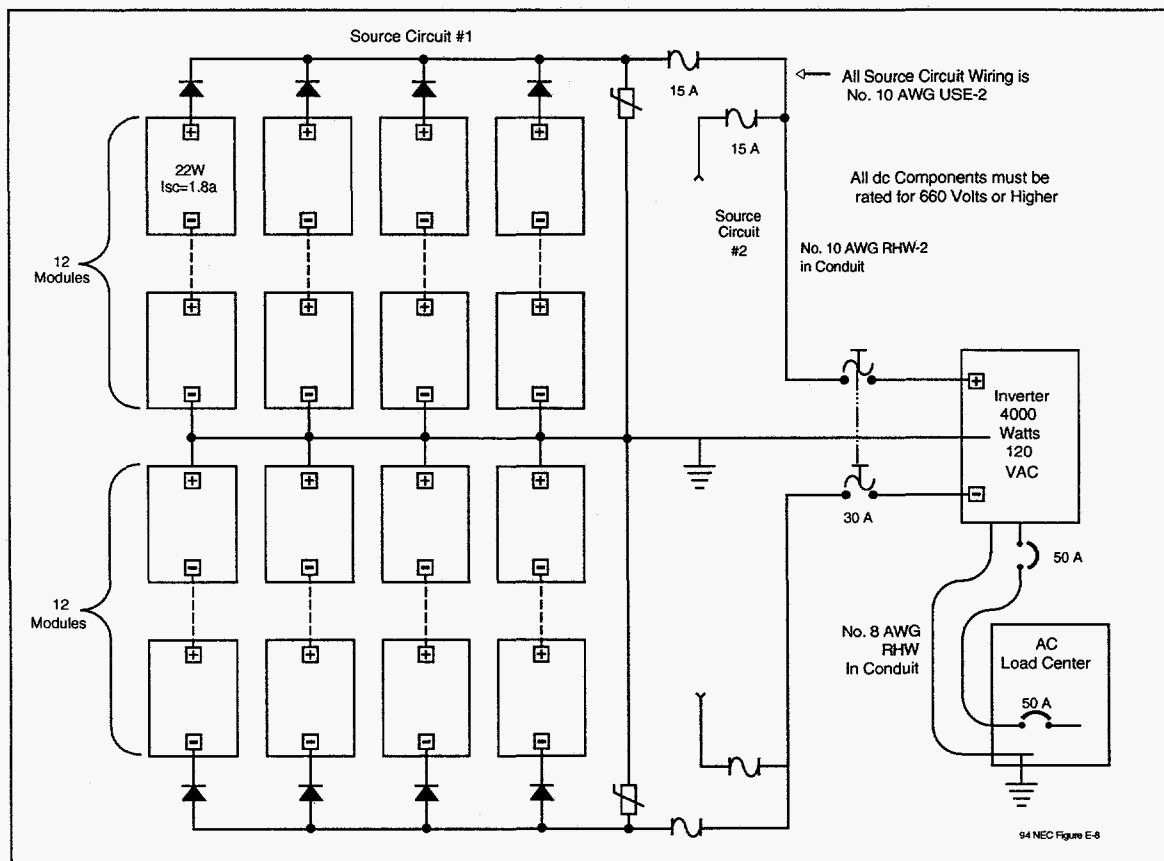


Figure E-8. Integrated Roof Module PV System

Calculations

Each string short-circuit current is 1.8 amps.

UL 125 percent (estimated for thin-film modules): $1.25 \times 1.8 = 2.25$ amps

NEC 125 percent: $1.25 \times 2.25 = 2.8$ amps

Each source circuit (4 strings) short-circuit current is 7.2 amps (4×1.8).

UL 125 percent: $1.25 \times 7.2 = 9$ amps

NEC 125 percent: $1.25 \times 9 = 11.25$ amps

The array (two source circuits) short-circuit current is 14.4 amps (2×7.2).

UL 125 percent: $1.25 \times 14.4 = 18$ amps

NEC 125 percent: $1.25 \times 18 = 22.5$ amps

USE-2 cable is used for the module cables and operates at 75°C when connected to the roof-integrated modules. The temperature derating factor in the wiring raceway is 0.41. For the strings, the 30°C ampacity requirement is 5.5 amps ($2.25 / 0.41$).

Each source circuit conductor is also exposed to temperatures of 75°C. The required ampacity for this cable (at 30°C) is 22.0 amps ($9 / 0.41$).

Number 10 AWG USE-2 cable is selected for moisture and heat resistance. It has an ampacity of 40 amps at 30°C (90°C insulation) and can carry 35 amps when limited to a 75°C insulation rating. This cable is used for both string and source-circuit wiring. Fifteen-amp fuses are used to protect the string and source-circuit conductors.

The array wiring is inside the building and XHHW-2 is used in conduit. It is operated at 50°C when passing through the attic. The temperature derating factor is 0.82, which yields a 30°C ampacity requirement of 22 amps ($18 / 0.82$). Number 10 AWG cable has an ampacity of 40 amps (90°C insulation) or 35 amps (evaluated with 75°C insulation). Both of these ampacities exceed the 22-amp requirement. Twenty-five amp fuses are required to protect these cables, but 30-amp fuses are selected for better

resistance to surges. Since the inverter has high voltages on the dc-input terminals (charged from the ac utility connection), a pull-out fuse holder is used.

The inverter is rated at 4000 watts at 120 volts and has a 33-amp output current. The ampacity requirement for the cable between the inverter and the load center is 42 amps $((4000 / 120) \times 1.25)$ at 30°C. Number 8 AWG RHW cable in conduit connects the inverter to the ac-load center, which is fifty feet away and, when evaluated at with 75°C insulation, has an ampacity of 50 amps at 30°C. A 50-amp circuit breaker in a small circuit-breaker enclosure is mounted next to the inverter to provide an ac disconnect for the inverter that can be grouped with the dc disconnect. Another 50-amp circuit breaker is back-fed in the service entrance load center to provide the connection to the utility.

The modules have no frames and, therefore, no equipment grounding requirements. The inverter and switchgear should have number 10 AWG equipment grounding conductors. The system grounding electrode conductor should be a number 8 AWG conductor.

All dc components in the system should have a minimum voltage rating of 660 volts $(24 \times 22 \times 1.25)$. This voltage exceeds the commonly available 600-volt rated equipment. Conductors should have a 1000 or 2000-volt insulation rating, and all fuses, fuse-holders, and switches should be rated for a voltage over 660 volts. As a design alternative, the input voltage requirements of the inverter might be lowered so that only 20 series-connected modules would be required in each string. This would lower the voltage requirement to 550 volts $(22 \times 20 \times 1.25)$.

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