

IEEE Guide for Terrestrial Photovoltaic Power System Safety

Sponsor

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on Photovoltaics**

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Abstract: The design, equipment applicability, and hardware installation of electrically safe, stand-alone, and grid-connected PV power systems operating at less than 50 kW output are addressed. Storage batteries and other generating equipment are discussed briefly.

Keywords: ampacity, cable types, PV system

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Introduction

(This introduction is not part of IEEE Std 1374-1998, IEEE Guide for Terrestrial Photovoltaic Power System Safety.)

This guide applies to all terrestrial photovoltaic power systems regardless of application up to about 50 kW that are not owned by an electrical utility and operated by an electrical utility on utility property. The governing safety standard is the National Electrical Code® (NEC®) (NFPA-70-1996).

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IEEE Guide for Terrestrial Photovoltaic Power System Safety

1. Overview

Photovoltaic (PV) power systems are being installed in ever increasing numbers in areas that are accessible to the general public. This is in contrast to earlier PV systems, which were installed as demonstration systems in limited access areas. Safety is an issue that is coming to the forefront as PV systems proliferate into nearly every area of the U.S. More than 100 000 residential PV systems have been installed as have countless thousands of other stand-alone PV systems in both remote and urban locations. PV electrical power systems, like all other electrical power systems, should be designed, specified, and installed in a manner that ensures the safety of the user, the equipment, the facility, and anyone who may come in contact with the system.

PV systems as dc power sources have unique electrical characteristics that are not common in other electrical power systems and are, therefore, unfamiliar to the average contractor (including electricians and installers). These systems have current-limited PV generating sources that are energized when exposed to light. They may employ large banks of batteries, and they may have more than one source of energy.

The requirements for installing conventional (non-PV) electrical power systems are detailed and complex. Codes and common practices in the U.S., as well as standardized equipment, have evolved over the last 100 years. Safety-related problems that have occurred have been solved and integrated into the industry practices that are familiar to electricians, contractors, and electrical inspectors. Most, if not all, of these practices and requirements are applicable to PV installations.

Electrical power systems are generally installed by electrical contractors. Contractors employ electricians who are familiar with common ac electrical installation practices required by national and local electrical codes. PV system engineers who are not contractors frequently do not have detailed knowledge of these codes or the required practices for the proper installation of safe electrical systems. A team consisting of individuals from both disciplines has proven effective in achieving safety in PV systems.

PV power system engineers have a wide range of utility-grade, industrial, commercial, and special-purpose cables, overcurrent devices, disconnects, power conditioners, modules, and other optional equipment to choose from in the design and installation of electrically safe systems. The details of selection and application of the available equipment covered in this guide are generally not covered in other existing standards.

1.1 Scope

This guide addresses the design, equipment applicability, and hardware installation of electrically safe, stand-alone, and grid-connected PV power systems operating at less than 50 kW output. It discusses storage batteries and other generating equipment only in brief. This guide is PV-specific and is based on good engineering practices specific to the U.S.

1.2 Purpose

The purpose of this guide is to describe PV-specific topics or components relating to the design and installation of PV power systems that affect safety and to suggest good engineering safety practices for PV electrical balance of system design, equipment selection, and hardware installation. The areas to be emphasized are those PV-unique electrical power areas that would be of value to a team consisting of a PV engineer working with an electrical contractor, or a person with significant experience in both areas.

1.3 Limitations

This guide is PV specific and is not intended to be all inclusive of the entire spectrum of safety requirements. Some of the recommended safe practices given in this guide may not fully comply with the requirements of local jurisdictions. In those cases, the local requirements take precedence over any national codes or the material found in this guide.

2. References

This guide shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

Accredited Standards Committee C2-1997, National Electrical Safety Code® (NESC®).¹

IEEE Std 928-1986 (Reaff 1991), IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems.²

IEEE Std 929-1988 (Reaff 1991), IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic (PV) Systems.

IEEE Std 937-1987 (Reaff 1993), IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic (PV) Systems.

NFPA 70-1996, National Electrical Code® (NEC®).³

UL 1703-1993, Flat-Plate Photovoltaic Modules and Panels.⁴

¹This publication is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (www.standards.ieee.org/).

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (www.standards.ieee.org/).

³The NEC is available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269, USA (www.nfpa.org/). It is also available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (www.standards.ieee.org/).

⁴UL standards are available from Global Engineering, 15 Inverness Way East, Englewood, Colorado 80112, USA (global.ihs.com/).

3. Definitions

For the purposes of this guide, the following definition applies:

3.1 hybrid PV system: A PV system connected to one or more sources of nonrenewable energy such as an engine-driven generator, or connected to another source of renewable energy such as a wind turbine.

Additional definitions of terms used in this guide may be found in the following documents:

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.

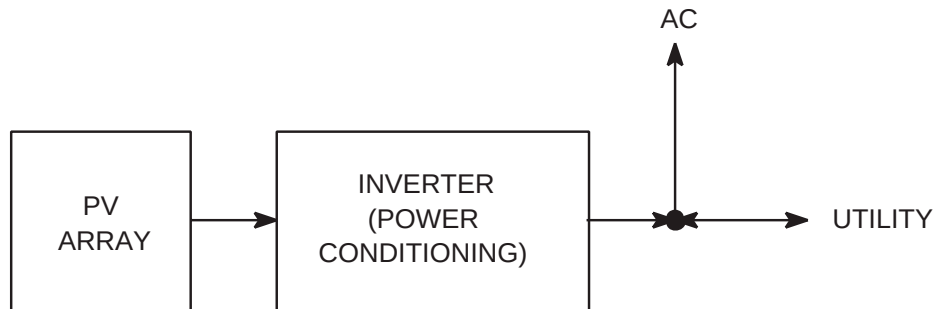
IEEE Std 928-1986 (Reaff 1991), IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems.

NFPA 70-1996, National Electrical Code® (NEC®).

4. System types

There are two basic categories of PV systems. They are generally recognized as the following:

- Grid- or utility-interconnected (utility-intertie) (Figure 1); and
- Stand-alone.



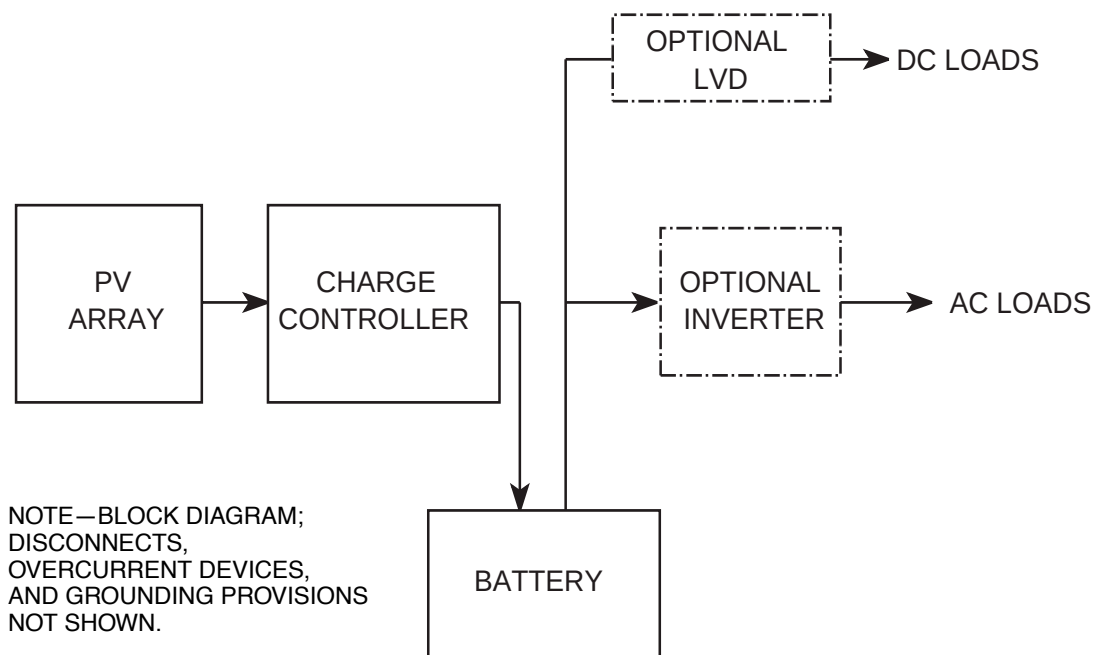
NOTE—BLOCK DIAGRAM;
DISCONNECTS, OVERCURRENT
DEVICES, AND GROUNDING
PROVISIONS NOT SHOWN.

Figure 1—Example of utility-intertie system

The stand-alone systems further break down into several other categories. These are

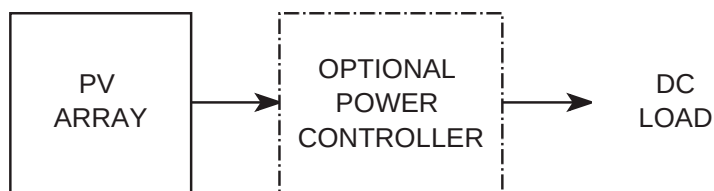
- Stand-alone (PV plus storage) (Figure 2);
- Direct-connected (PV-to-load with no storage) (Figure 3);
- Hybrid (PV and other optional renewable energy source plus non-renewable backup generator) (Figure 4).

These systems are not always clearly distinguishable. Some essentially stand-alone systems utilize inverters that not only change dc to ac for on-site loads, but also contain battery chargers to accept ac power from a generator or a utility grid, and have the ability to feed excess power into the grid like a utility-intertie inverter. Annex A presents more detailed diagrams of typical systems.



LVD = LOW VOLTAGE DISCONNECT

Figure 2—Example of stand-alone PV system



NOTE—BLOCK DIAGRAM;
DISCONNECT,
OVERCURRENT DEVICES,
AND GROUNDING PROVISIONS
NOT SHOWN.

Figure 3—Example of stand-alone direct-connected PV system

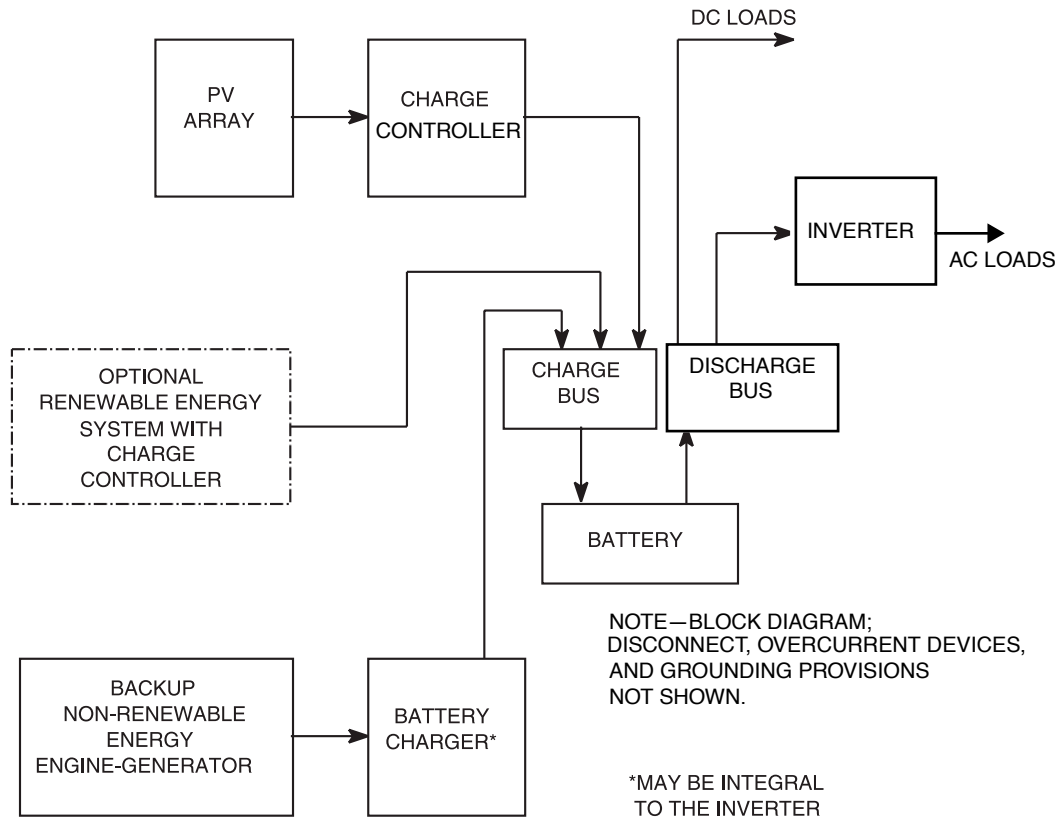


Figure 4—Example of one type of hybrid PV system

5. Wiring

Wiring methods and cables used for PV systems should meet certain minimum standard requirements for safety. While there may be some provisions for certain PV-unique wiring methods (intermodule connections), the wiring methods for PV systems do not differ significantly from the wiring methods used for other electrical power systems. In conventional wiring methods, the individual insulated conductors are afforded physical protection by installing them in a rigid or flexible conduit or making them part of a multiconductor cable with an overall outer sheath—either metallic or nonmetallic. The PV-specific exceptions to conventional wiring methods are presented in the following subclauses.

The wiring used for PV systems should *not* be installed using the wiring techniques or materials associated with the wiring or interconnections used in electronic equipment or automobiles. Some equipment and methods used in these applications have not been tested or approved for use in residential and commercial power applications.

Specifically, examples where the applications differ include the following:

- Color codes in automobile and electronic wiring do not meet power wiring color code requirements.
- Automotive and electronic fuses have not been tested or listed for electrical power systems in dwellings or commercial applications.
- Conductors for automotive and electronic wiring have not been tested for use outdoors or in residential and commercial power systems.

Annexes B, C, and D provide examples of the calculations in the following subclauses.

5.1 PV module

PV modules operate in an environment that is more severe than the operating environment of other types of wiring found in residential, commercial, or industrial areas. The wiring in and around PV modules can be exposed to temperatures 75 °C or higher, moisture (rain and atmospheric humidity), and ultraviolet and infrared energy from sunlight. Some PV modules are also manufactured with the individual output terminals at opposite ends of the module. Because of these environmental conditions, either the sheathed or in-conduit methods described above or single-conductor, sunlight-resistant, outdoor-rated cables in free air (that are not part of a larger cable or installed in conduit) may be used.

Exposed single-conductor cables should only be used in the area near the PV module. This exposed wiring should be connected (in a conjunction box) to wiring using one of the other standard cabling methods for further routing to the rest of the system. In this way, physical and fire reduction protection is afforded to all wiring in the building.

Junction boxes or covered terminal blocks on PV modules are typically designed to receive a single-conductor cable, a multiconductor cable, a conduit, or all three. Some local jurisdictions require the use of conduit for all installations, and modules with junction boxes designed for conduit should be used. In some cases, modules meeting this requirement are special-order items or are not at all available from some manufacturers. Because the module junction boxes are usually plastic, grounding of the metal conduit is required, and all modules should include provisions for grounding the module frame when it is conductive.

5.1.1 Cable types

Cables (single and multiconductor) are designated by types that correspond to the conditions under which they have been tested and listed. To deal with the environmental exposure, the exposed, single-conductor cables should be identified as one of the following types: underground service entrance (USE), service entrance (SE), or underground feeder (UF). These cables are generally identified as sunlight resistant—either on the cable or through testing and listing to the appropriate standard. While “identified” as sunlight resistant by the listing process, they may not be so marked.

Type USE-2 or SE cable that has cross-linked polyethylene insulation (marked XLPE or XLP) and is further marked RHW-2 or RHW and RHH is one of the more durable, readily available cables for module wiring. Table 1 shows some of the frequently used cables for module wiring.

Welding cables, battery cables, and diesel locomotive cables, while flexible and available, should not be used for PV installations because they have not been fully tested in the environment and may not be allowed for residential and commercial use in electrical power systems. Flexible, multistranded, USE/RHH/RHW single-conductor cables that satisfy national and local requirements are available and may be used when flexible, building-wire types of cable are needed.

Tray cable (TC) comes in two or more conductor cables and is generally marked sunlight resistant, but some jurisdictions may object to its use if not mechanically supported by a cable tray or other means. Tray cable should not be used as open cable on brackets or cleats because it is not afforded physical protection in these installations. Tray cable requires special calculations for current-carrying capacity (ampacity); appropriate tables should be consulted when using this cable and when temperature derating data are not available for this cable.

Table 1—Cables commonly used for module wiring

Type	Temperature rating	Features
USE-2	90 °C (194 °F) wet/dry	Most suitable; not for indoor use without conduit
USE	75 °C (167 °F) wet	Not for indoor use without conduit
RHW	75 °C (167 °F) wet	Suitable in conduit
RHH	90 °C (194 °F) dry	Suitable in conduit in dry locations
SE	90 °C (194 °F)	Flame retardant, acceptable for indoor use in multiconductor sheathed cables
RHW-2	90 °C (194 °F) wet	Suitable in conduit in exposed locations
XHHW-2	90 °C (194 °F) wet	Suitable in conduit in exposed locations

5.1.2 Ampacity requirements

PV modules are rated for short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) at standard test conditions (STC) of 1000 W/m² irradiance and 25 °C (77 °F) cell temperature. For several hours around solar noon, the irradiance in many locations exceeds 1000 W/m².

Single and polycrystalline PV modules have a short-circuit current that increases with irradiance and temperatures. On hot, sunny days around solar noon, the module short-circuit current can be well above the rated STC value. Also, many locations experience temperatures that are significantly below 25 °C (77 °F). The open-circuit voltage increases as temperatures decrease, and on clear, cold days, the open-circuit voltage can significantly exceed the rated STC value. Both of these conditions—high irradiance coupled with either high temperatures or low temperatures—are normal and expected conditions.

A multiplicative factor of 125% N (N for normal operation) is used to account for these effects. Both rated I_{sc} and V_{oc} should be multiplied by this 125% N factor. If actual temperature and irradiance array coefficients are available for a given system and historical data on temperature are available, then calculated maximum values of open-circuit voltage and short-circuit current could be used instead of the fixed 125% N factor. Figures 5 and 6 show the effects of temperature and irradiance on PV module characteristics.

Most overcurrent devices are tested and rated for continuous operation (greater than 3 h) at only 80% of their nameplate rating. Some industrial devices are listed for 100% operation, but they are not generally used in PV systems. PV modules and arrays provide power for periods that exceed 3 h. The devices may overheat, and the terminals used on devices connected with field-installed wiring may loosen when operated repeatedly at 100% of the device ratings. Therefore, all cables used in the PV source circuits should have the given ampacity values derated by 20% to protect connected overcurrent devices. The rated short-circuit current of the PV module or modules is multiplied by 125% to determine the ampacity requirements of the cable. Annex B discusses the selection of cable types and presents ampacity calculations. National codes contain tables that provide the most widely available and used ampacity tables for commonly available conductors. To avoid confusion with the 125% N factor, this derating factor shall be annotated as 125% E (E for equipment limitations). This 125% E factor is applied to I_{sc} after any 125% N factor is applied. In most cases, the I_{sc} rated at STC shall be multiplied by 156% (125% N × 125% E), and the STC V_{oc} shall be multiplied by 125% N.

In summary, the cable should be sized so that 80% of the rated 30 °C (86 °F) ampacity (125% E factor) is greater than or equal to 125% of the short-circuit current (125% N factor). Operating temperatures may require further adjustments to the ampacities.

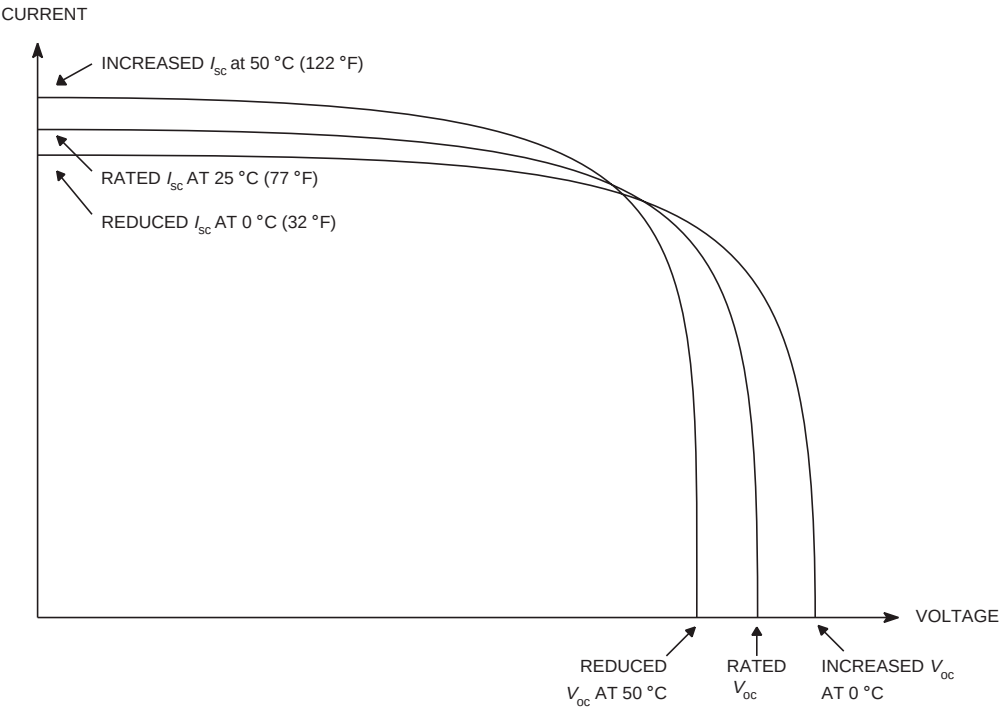


Figure 5—Effect of temperature on PV module parameters

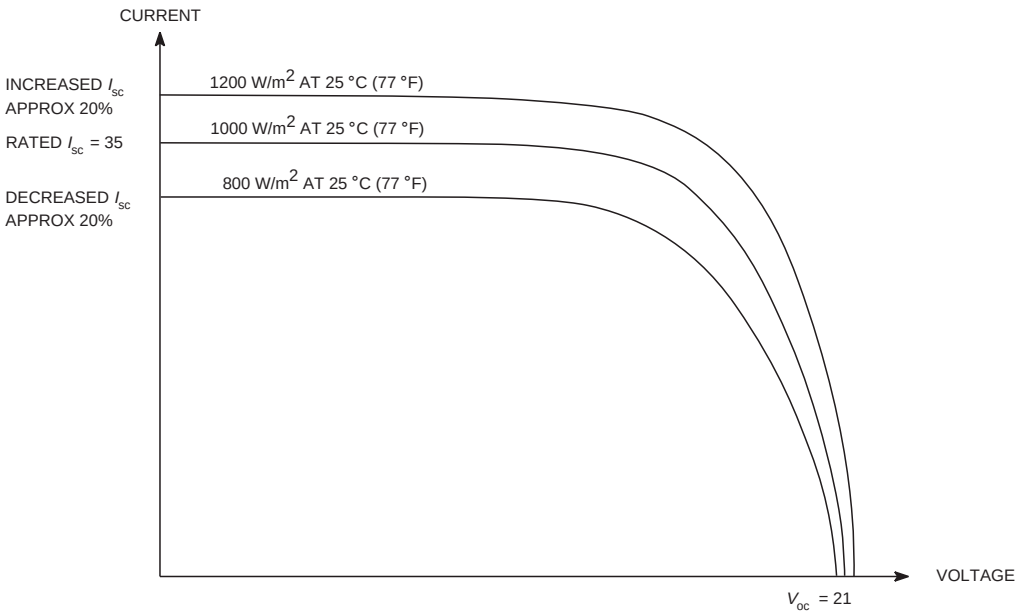


Figure 6—Effect of irradiance on PV module parameters

5.1.3 Temperature considerations

Because PV modules can typically operate at temperatures of 75 °C (167 °F) or higher, and these temperatures are found in the module junction boxes and on the back surface of the modules, good engineering practice dictates that the ampacity of the cables used for module wiring should be derated. Cables with a 60 °C (140 °F) insulation (multiconductor UF cables) have no rated ampacity at temperatures over 55 °C (131 °F) and should not be used. A cable with a minimum insulation rating of 75 °C (167 °F) could be used if the module temperature is below 70 °C (158 °F). Cables with insulation rated at 90 °C (194 °F) or higher may allow reduced size wire to be used. In either case, the module terminals should have a temperature rating that will allow use of the higher-temperature-rated conductors.

Commonly available load centers, fuses, circuit breakers, and disconnect switches have terminals rated at 60 °C (140 °F) or 75 °C (167 °F). The use of cables with a 90 °C (194 °F) insulation at full ampacity (after temperature derating) can result in overheating and damage to these devices. The same situation applies to conductors with 75 °C (167 °F) rated insulation when used with overcurrent devices rated at 60 °C (140 °F). Annex B discusses examples of wiring temperature adjustments.

In some installations, cables may be sized above the basic derated ampacity requirements to achieve lower voltage drops and I^2R losses. As the operating temperature of the cable increases, so does its resistance. However, voltage drop may not be a significant problem after the cable sizes are increased because of temperature deratings.

The temperature derated ampacity of the conductor should be equal to or greater than 125% (N) of I_{sc} for circuits carrying currents from the PV array. Furthermore, this temperature derated ampacity should be equal to or greater than the rating of the overcurrent device protecting the circuit. This overcurrent device shall be rated at 156% of I_{sc} (see 6.1 and Annex E). Effectively, the temperature derated ampacity of the conductor should be equal to or greater than 156% of I_{sc} .

5.1.4 Voltage ratings

Many utility-intertie systems operate with PV arrays that have open-circuit, monopole voltages that exceed ± 300 V above ground (system voltage, measured pole to pole, over 600 V). Under certain normal operating conditions (some inverters short the array when off or when the grid is down) and fault conditions, the voltage across an open circuit in the modules, array wiring, or any disconnect or overcurrent device shall be equal to the sum of the absolute monopole voltages. If this voltage exceeds 600 V, the standard 600 V rated equipment may be unsafe, and higher voltage conductors and equipment are required.

Listed crystalline or poly-crystalline silicon PV modules have the requirement that the open-circuit voltage [at 25 °C (77 °F)] be multiplied by 125% N to allow for operation in cold temperatures.

Cable insulation is rated without regard to the frequency. A 600 V cable is rated for 600 V ac and 600 V dc. There is no allowance for the peak ac voltage to dc voltage difference. Refer to Annex C for a detailed discussion of this issue.

5.2 Balance of systems wiring

With the exception of the module wiring discussed in 5.1 and the battery-to-inverter wiring discussed in 5.3, all other balance of system wiring is accomplished using normal electrical power wiring techniques for residential and commercial buildings and is generally well understood by PV engineers and contractors. Only a few areas need special attention.

The ampacity of conductors installed in hot attics or in under-roof areas should be derated for high ambient temperatures.

The following color codes have been established for certain power system conductors by national codes:

- a) Grounded current-carrying conductors (neutrals in ac systems) should be white or a natural light gray color.
- b) Equipment-grounding conductors should have no insulation (bare) or have a green insulation or a green insulation with a yellow stripe.
- c) DC systems have no specific color codes, and there is no color code for ungrounded conductors.
- d) AC systems usually have the first ungrounded conductor black and the second ungrounded conductor red.
- e) Three-phase systems sometimes use the color orange to designate the conductor with the highest potential above ground.

Conductor and cable splices, other than those made with listed connectors, should be made only in listed junction boxes to minimize the possibility of fire resulting from the failure of the splice.

5.3 Battery-to-inverter wiring

In stand-alone PV systems, the conductors between the battery bank and the inverter can carry currents of hundreds of amperes. Selection of an appropriate cable type, ampacity of that cable, and proper installation of that cable are critical to achieving desired levels of safety, performance, and durability.

5.3.1 Cable types

Battery-to-inverter conductors often may be large in terms of ampacity and physical size. Building-wire type cables (e.g., USE, RHW, and XHHW) should be used in these fixed (no moving parts) installations. These cables normally have very few strands. In sizes 2/0 AWG and larger, these cables are very stiff and difficult to install without the use of specialized wire-handling tools to pull the cables through conduits and to install the proper terminations.

UF cable should not be used in the battery enclosures because it lacks the necessary acid and moisture resistance. Aluminum conductors should not be used in these environments due to corrosion problems.

The difficulty in using this stiff cable has led many PV dealers and installers to use highly flexible welding cables or battery cables, neither of which should be considered suitable for electrical power systems. In most cases, welding, automotive, and battery cable have not been tested or listed by an independent testing laboratory; and even welding cable, when it is listed, is only allowed when connected to welding machines.

Cable manufacturers do produce a highly flexible building-wire type cable that is marked USE/RHH/RHW and is listed. It is the preferred cable for wiring batteries to inverters. Cables 1/0 AWG and larger may be safely paralleled. This provides for additional ease in the installation, but more than three conductors in a conduit should receive additional ampacity derating due to the added self heating.

5.3.2 Installations

If single-conductor cables are installed between the battery bank and the inverter, they should be installed in conduit to afford physical protection for the cables and to constrain the cables from motion under fault conditions. The conduit also serves to provide some degree of flame suppression if the cables should ignite. Single-conductor cables such as these are not allowed in exposed locations or in walls without additional protection provided by conduit. Sheathed, multiconductor cables (except UF and aluminum) may be allowed from the battery to the inverter without conduit if they have proper physical protection. Both conductors for a given circuit should be run in the same conduit or cable to avoid inductance effects, which may prevent proper overcurrent device functioning. In larger installations, cable trays are sometimes used.

Inside the battery enclosure or room, short runs of exposed cable may be used to interconnect the individual batteries or cells, but such exposed cable should be terminated in a junction box near the batteries. Single-conductor cables without a protective conduit should not penetrate walls or partitions.

To avoid installation and maintenance difficulties and to avoid conductor overheating, conduits should not be filled over 40% of the cross-sectional area with cables. Multiple conductors in a conduit should have derated ampacities. National codes provide extensive tables and restrictions on conduit fill.

5.3.3 Ampacity

Listed inverters have an established continuous power output rating. The ac output voltage is regulated and maintained over a wide range of dc input voltages from the battery. As the dc input voltage varies, the dc input current varies inversely, because the inverter maintains a constant ac voltage output. Input cables should have sufficient ampacity to carry the highest input current that occurs at the lowest battery voltage. The cables should also be derated for continuous current flow at these higher currents.

Ampacity calculations of the input cables are based on the rated output of the inverter, the range of dc operating voltages, and the efficiency of the inverter at full power. Annex D provides details on these calculations.

6. Overcurrent protection

PV power systems, like other electrical power systems, should have the wiring protected from overcurrents. The PV module is a current-limited power source, which makes some of the overcurrent protection somewhat unique. But, in general, every conductor should be protected from overcurrents from all sources. If conductors are not properly protected, the possibility exists that they may be damaged under fault conditions or they may overheat and start a fire. The overcurrent protection in most cases protects only the conductors and not the connected devices, such as inverters, charge controllers, and loads. Supplemental, internally-mounted overcurrent devices are used to provide additional protection for the connected devices.

Annexes E and I provide examples of the calculations in the following subclauses.

6.1 Overloads and short circuits

There are two different types of overcurrent conditions that occur in electrical power systems.

The first overcurrent condition is an overload that represents a sustained condition of current flowing in an electrical circuit at about 1.5 to 3 times the rated ampacity of the circuit. This overload may be caused by inadvertent application of excessive loads, a stalled motor, or a resistive line-to-line fault. The sustained nature of the currents (usually lasting 1 min or more) differentiates them from transient surge currents in the same range due to motor starting or other momentary loads.

The second overcurrent condition is a short circuit that causes current to flow at many times the rated circuit ampacity. These currents are caused by low resistance (bolted) line-to-line and line-to-ground faults. The currents may be as high as the short-circuit current capabilities of the source, but are usually limited by the circuit impedance between the source and the fault. In PV systems, the battery banks on stand-alone systems and the utility on utility-intertie systems represent the sources of the greatest short-circuit currents.

6.2 Device types

Overcurrent devices may be either fuses or circuit breakers. These devices come in numerous styles and configurations. Any device used in the dc circuits of a PV system should have listed dc ratings for voltage, cur-

rent, and interrupt ratings (required to handle short-circuit currents) that meet or exceed the parameters of the system. Accepted laboratory testing procedures establish the ratings for devices listed to the appropriate standard. The devices may be listed as branch-circuit-rated devices, or as lighter-duty supplementary-rated overcurrent devices. Supplementary rated devices are similar to those found inside electrical and electronic equipment. Each has a particular application in the PV system. Annex E presents more details on the device types and their application.

6.3 Module conductors

Because the available short-circuit current from PV modules is limited, there is a tendency to disregard short-circuit protection for the conductors used for interconnecting the PV modules. The source of short circuit and overcurrents that may cause problems on the conductors connected to a given module are not derived from that module or that string. The problematic currents come from parallel connected modules, batteries, and/or the utility grid. All of these current sources should be considered, since equipment such as blocking diodes, charge controllers, and inverters may fail in a shorted condition, thus allowing currents to flow into faulted module conductors. Although these devices normally block reversed current flow, they are not tested or listed as overcurrent devices and should not be considered as overcurrent devices. Figure 7 shows an example of PV array overcurrent protection and a possible fault location.

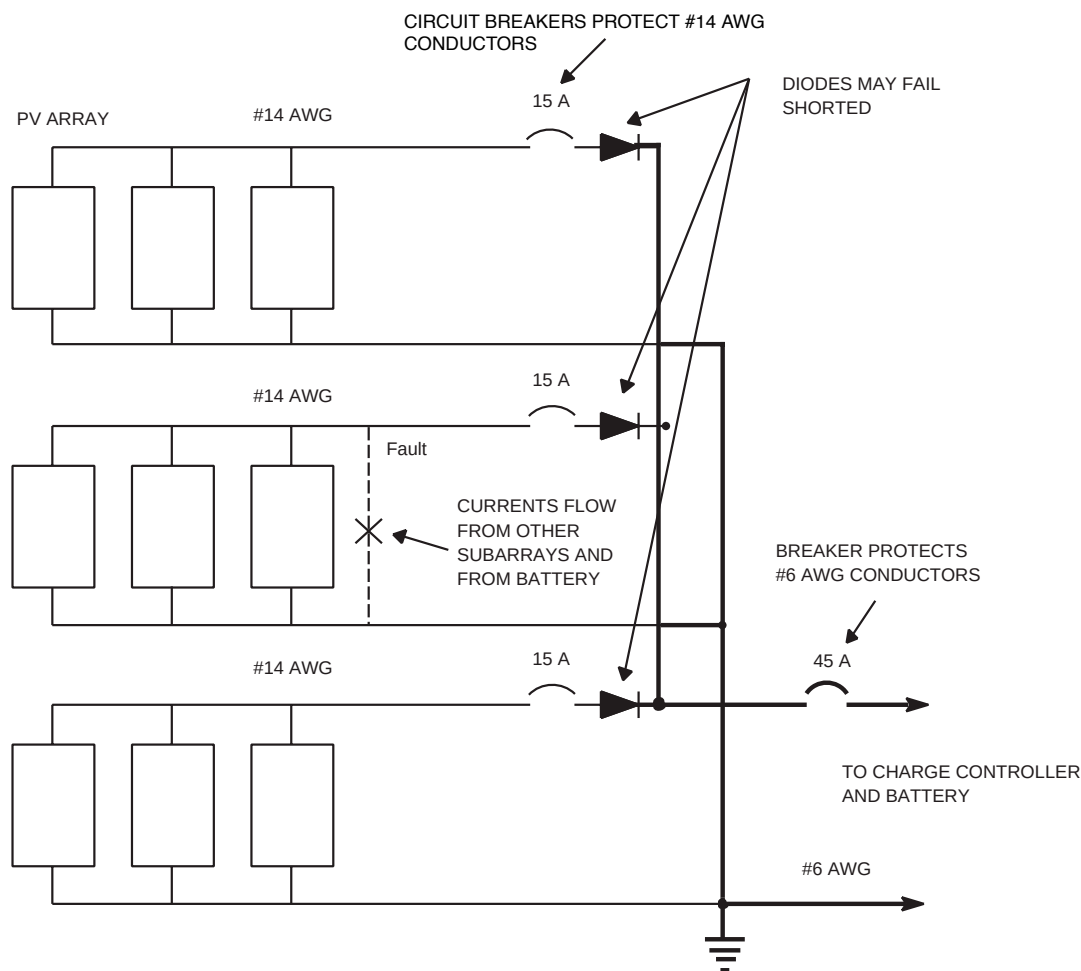


Figure 7—Overcurrent protection and fault in module wiring

The calculations for the current ratings of overcurrent devices used to protect module conductors are similar to those used to determine the ampacity of the conductors used for module wiring. Annex E provides full details.

PV systems operating at voltages approaching and exceeding 600 V are discussed in Annex C.

6.4 Battery conductors

Overcurrent protection for battery conductors is as critical as the ampacity of battery conductors and can be subjected to a number of stresses. Batteries represent a significant electrical hazard in PV systems. Most renewable energy sources (PV, wind, hydro) are limited in their ability to generate high short-circuit currents. Batteries, on the other hand, are not limited. A *single* 6 V, 220 Ah golf-cart battery can deliver 6000–8000 A of current into a direct short across the terminals. While this current can be maintained for only a fraction of a second, the battery can deliver 4000–5000 A for a number of seconds until the terminals melt. Larger banks of batteries connected in series and parallel can deliver far larger amounts of short-circuit current. The resistance of battery connectors and wiring will reduce the magnitude of the short-circuit currents, but these resistances are very low and the available short-circuit currents from the battery banks in most stand-alone PV systems can exceed 10 000 A.

These high short-circuit currents present a battery/PV-unique hazard. If PV-module bypass diodes are installed with reverse polarity in a system without proper overcurrent and short-circuit protection, they can explode when the battery is connected.

Fuses and circuit breakers that open or trip when these high short-circuit currents flow should be rated to withstand the stresses involved. The interrupting rating [amperes interrupting rating (AIR)] is very important. While some low-voltage (65 V dc or lower) circuit breakers have AIRs of 25 000 A, many standard de-rated circuit breakers and fuses have an AIR of only 5000 A. When circuit breakers and fuses are required to open for short-circuit currents that exceed their rating, they may be destroyed, catch fire, or not open at all. These devices with low interrupting ratings should be protected with other devices that have current-limiting capabilities or be replaced with devices that have the necessary high interrupting rating.

Fuses are designed to handle normal overloads in either a fast-acting mode (for protection of electronic and other sensitive devices) or in a time-delay mode (for motor-starting surges). Either fast-acting or time-delay fuses may be designed to respond to short-circuit currents in a current-limiting fashion. Current-limiting fuses open so fast under short-circuit conditions that the let-through current is substantially reduced. *Current-limiting fuses should be used on each circuit connected to the battery when the available short-circuit current exceeds the interrupting rating of other devices on that circuit.*

The current-limiting fuse from the battery to any dc load should be a branch-circuit listed device with appropriate dc ratings for voltage, current, and interrupt ratings. Branch-circuit fuses are those designated as having a rating class such as K, RK, T, H, L, J, and CC. Not all “class” fuses have dc ratings. If available, a listed, *supplemental*, current-limiting fuse could be used on the circuit from the battery to the PV source circuits. Supplemental fuses do not fall into the classes listed above. It is general practice, however, to use the more robust branch-circuit device in both positions.

In any system operating at high currents, the resistance of each connection should be held to an absolute minimum. Fuses, fuse holders, and fuse disconnects may present an excessive amount of voltage drop. To maximize the performance (minimize voltage drops) in low-voltage stand-alone systems, a single, magnetic/hydraulic (nonthermal) circuit breaker is often used between the batteries and the inverter. Such a circuit breaker should be selected with voltage, current, and AIR ratings consistent with the ratings of the inverter. Circuit breakers with an AIR of 25 000 A at 65 V dc may be obtained with dc ratings up to 700 A.

Cable-limiters or fusible links, where appropriately rated, may be used to protect battery cables within the bank of batteries.

Calculation of the ampacity ratings of the overcurrent devices protecting these heavy conductors is addressed in Annex D.

6.5 Branch circuits

In systems with dc load circuits, the circuits from the battery to the dc loads are considered branch circuits and should have overcurrent devices listed as branch-circuit rated. In addition, the branch-circuit devices should have the appropriate dc ratings.

6.6 Direct-connected systems

Some PV systems have loads connected directly to the PV modules with no battery storage systems or other source of power. These systems, such as water pumps, operate only during the times of sunlight. The modules are the only source of energy in the system. If the module interconnecting cables and the conductors between the PV array and the load are all sized so that 80% of their temperature-rated ampacity is greater than 125% of the short-circuit current produced by the PV array, overcurrent devices may not be required. The 80% factor accounts for the 125% E requirement of the codes and the 125% factor is the 125% N dictated by the module characteristics. However, it should be noted that unusual environmental conditions may result in PV modules delivering significantly more than the rated short-circuit current.

The use of electronic devices that boost the current from a PV array in a direct-connected system may dictate that overcurrent devices be used to protect the output conductors of the device. If the conductors are sized for the maximum short-circuit currents, then overcurrent devices would not normally be required.

7. Disconnects

7.1 Location

Disconnects should be installed in an easily accessible location, and they should be grouped, plainly marked, and operable with no more than six motions of the hand. All sources of power, which may include one or more renewable energy sources, a battery bank, the utility grid, and a backup engine-driven generator, should have disconnects. The main power disconnecting devices may also serve as the equipment disconnecting devices.

Good engineering practices dictate that all equipment such as inverters, filters, charge controllers, batteries, and the like, have means for disconnecting that equipment from all sources of power. These disconnects allow power to be removed from individual pieces of equipment for servicing. Such servicing may be done by people unfamiliar with the overall power system, hence the need for the external disconnects. These disconnects should not be built into the equipment. Disconnects mounted on, or external to, the equipment (such as a connector on a module) are acceptable if the equipment can be serviced or replaced without the service person coming into contact with live conductors. Annex F provides additional details about the location of disconnects.

Because PV modules become energized when exposed to light, some means should be provided to break PV arrays into segments for safety during installation and servicing. This can be accomplished with connectors. Cost and durability may, however, dictate that no connectors be used and that the entire array be hardwired at the initial installation. In this case, appropriate personnel protective equipment should be used during installation.

Disconnects for battery systems should not be installed in the battery enclosures or in locations where explosive hydrogen gas may be present.

7.2 Ratings

In all cases, devices used for disconnects should have dc ratings that exceed the voltage and current ratings of the circuit in which they are used. These may consist of various types of switches and circuit breakers. On grid-connected systems with bipolar PV arrays, the voltage of the system has exceeded 600 V (the most common rating for available switchgear—see Annex C) in some installations. This may exceed the system voltage rating allowed by codes for one- and two-family residential PV systems.

Disconnecting devices should be load-break rated except for PV array switches, which are permitted to be non-load-break rated if means (hardware or procedure/markings) are provided to prevent them from operating under load. Such a device may be used on a utility-intertie system where a non-load-break switch is mounted inside an enclosure. The door of the enclosure would be electromechanically linked to an inverter shutdown switch in such a manner that the disconnect could not be operated until the inverter and, hence, the load, was off.

7.3 Switches

Switches with appropriate listed, dc ratings are available with voltage ratings of 125–600 V and current ratings of 10–2000 A. Some of these switches are original equipment manufacturer (OEM) designs that should be mounted in custom enclosures. Pull-out switches are acceptable if they present a dead-front panel when pulled.

Some manufacturers will provide factory certification of a dc continuous current and voltage rating on an ac switch if it is not used for load-break operation.

7.4 Circuit breakers

Circuit breakers are frequently used as disconnects because they provide both the disconnect function and the overcurrent function in one device. When the added contacts (and contact resistance) associated with the combination fuse, fuse holder, and disconnect switch are considered, the performance benefits of circuit breakers in low-voltage systems are more apparent. They include low-voltage drops and increased reliability due to the low number of contacts.

Circuit breakers are available with listed dc current ratings up to 700 A at 125 V dc and voltage ratings up to 250 V dc at 100 A. Factory-certified ratings (non-listed devices) are available up to 100 A at 500 V dc and 750 V dc from some manufacturers.

When circuit breakers are used in a back-fed mode to route power from an inverter to the grid, they should be listed for such use and secured with an additional mechanical device (supplied by the breaker manufacturer) such as a clamp or screw. Circuit breakers that only plug into a bus in a load center do not meet this requirement. Circuit breakers marked with “load” and “line” terminals are generally not listed for back feeding. Ground-fault circuit interrupter (GFCI) breakers or circuits may not be backfed.

8. Grounding

Grounding is critical to the safety of people, equipment, and the durability of operation of electrical power systems. The history of electrical power systems in the U.S. has relied on a grounded electrical power grid. The National Electrical Safety Code® (NESC®) (Accredited Standards Committee C2-1997)⁵ and the National Electrical Code® (NEC®) (NFPA 70-1996) require grounded systems. European and Japanese PV systems, on the other hand, are generally not grounded. There are a few exceptions to the U.S. requirements (such as systems operating at less than 50 V and systems using impedance grounding) where hard, solid grounding is not always required.

8.1 Equipment grounding

Equipment grounding is required to keep all exposed metal surfaces (containing energized conductors) that may be unintentionally energized, at or near ground potential. This grounding also provides some shielding from electromagnetic interference (EMI) from switching power supplies used in charge controllers and inverters. Annex G presents added details.

If there is potential between the ungrounded cases and/or frames and ground, then further investigation is needed to isolate the faults. Terminal potential to ground should also be checked. Conductive acid films in battery enclosures usually coat all surfaces and make normally-insulating surfaces conductive. These conductive surfaces become potential shock hazards and fault-current paths.

8.2 System grounding

System grounding (grounding a current-carrying conductor) for all bipolar systems and two-conductor systems operating over 50 V is required by national codes.

System grounding is used to stabilize the voltage on the system conductors with respect to ground (maximum voltage with a grounded system is the open-circuit PV voltage). System grounding also provides a path to ground for excessive voltages and a means to trip overcurrent devices on higher voltage services if they become accidentally connected to the grounded system. The grounding of one of the current-carrying conductors also provides a means to trip overcurrent devices in the event of a ground fault. Annex G presents additional details.

The lightning protection benefits of grounding are discussed in Clause 10.

8.3 Auxiliary equipment

Some engine-driven generators have internal bonding between the neutral and equipment-grounding conductors. When these generators are connected to PV systems where an ac load center is used, the bonding connection is duplicated. This double connection allows unwanted currents to flow in the equipment-grounding conductors, which may create safety and operational problems and is not allowed by some codes. Removing the extra neutral-to-equipment bonding conductors is a solution and is discussed in Annex H.

In a similar manner, some stand-alone inverters have the same connection and present the same problem. Annex H discusses these issues and presents solutions.

⁵Information on references can be found in Clause 2.

8.4 Ground-fault equipment

8.4.1 PV arrays

PV arrays mounted on the roofs of dwellings (residences) should have a device that detects ground faults in the array, interrupts the fault current, and disables the array. This is a fire-prevention device and should not be confused with the common GFCI used on ac circuits for shock protection. It is suggested that the ground-fault protection equipment detect the fault, interrupt the fault current, and provide some indication that a ground fault has occurred.

There is no specific level of fault current that constitutes a ground fault. Normal and unavoidable array leakage to ground may vary depending on array size and construction, irradiance, temperature, moisture, age, and soiling. To account for these unknown and uncontrollable variables, ground-fault detectors have typically used 0.5–1.5 A as a detection value to avoid tripping on normal leakage currents. The only way that the ground-fault current (from a single fault) can be interrupted is to unground the array when a fault is detected.

Ground-fault protection for PV systems is available for both grid-connected and stand-alone systems.

8.4.2 Batteries

The batteries used in a PV system become grounded when connected to the grounded PV system.

When being serviced, grounded batteries pose higher risks for maintenance personnel. Where operational constraints allow, batteries may be disconnected from grounded PV systems for servicing by qualified persons. Disconnecting the battery system from the PV system will allow the battery to be serviced in an ungrounded state.

When grounded, batteries may be more susceptible to ground faults than the ungrounded battery systems used in non-PV applications. Ground-fault detection equipment on these grounded batteries can provide early detection of leakage currents that can pose shock hazards and lead to ground faults.

Annex J provides additional information on battery safety.

9. Surge and transient suppression

PV arrays, due to the requirement to be mounted in the open in unobstructed areas, are frequently the highest metallic structure in the vicinity. This condition makes them susceptible to lightning strikes and to the possibility of induced transients and surges from nearby strikes.

There are a number of companies that design and install transient and surge protection systems; however, protection systems are far more common for ac systems and wiring than for the dc wiring found in PV systems.

Proper equipment grounding and a grounding system are necessary first steps if lightning surges are to be successfully bled to ground. Minimizing the pickup of any induced electromagnetic transients from nearby disturbances through the use of metallic conduit and underground cabling is the next consideration. As a final step, suppression devices are installed on the various conductors throughout the system.

The main purpose of surge suppression is to minimize transients to the extent required by end-use loads. Inverters and charge controllers in PV systems may also be considered candidates for protection from surges. Annex K presents some additional details on surge suppression.

10. Diodes

The use of bypass and blocking diodes depends on the system operating voltage and the PV module wiring configuration as well as the specific module used. PV modules are manufactured with and without internal bypass and/or blocking diodes. Bypass and blocking diodes should be used in accordance with the PV module manufacturer's instructions.

The use of parallel sets of connected PV modules with an external bypass diode has resulted in diode failures (possibly due to underrating), hot spots, and circulating ground-fault currents. The series connection of strings of modules, with each series string isolated by a blocking diode before paralleling with other strings may yield a more trouble-free installation. Individual modules in the series strings are protected by internal bypass diodes.

Although diodes pass current in only one direction, they do not provide overcurrent protection for conductors.

11. Instrumentation

Although not all PV systems have instrumentation, and instrumentation is not a part of the power wiring, data instrumentation, when installed, can have a safety impact on the PV system. Failures in the data instrumentation wiring may cause failures in the power wiring, failure of the system controls, or personnel safety hazards.

All instrumentation conductors that are attached to an electrical power system should have the appropriate ampacity and voltage ratings. Every instrumentation conductor connected to an ungrounded conductor should be protected with an appropriately rated overcurrent device or have an ampacity equal to the available short-circuit currents under fault conditions.

The output conductors of current shunts carrying 50–100 mV signals can operate at the system voltage aboveground when the shunt is connected in an ungrounded conductor. Both of the shunt output conductors should be protected by overcurrent devices.

Voltage dividers may have outputs below 10 V, but need to be protected with overcurrent devices if the current supply from the voltage source exceeds the ampacity of the data conductors.

Annex A

(informative)

System types

A.1 System diagrams—PV circuit configurations

The systems shown in the following diagrams (Figures A.1 through A.4) are representative of photovoltaic (PV) circuit configurations. These block diagrams show the equipment-grounding path and typical locations of overcurrent devices and disconnects.

Figure A.5 shows a complex PV system that uses a bidirectional inverter. This inverter includes a battery charging circuit and can operate in either a stand-alone mode or in a utility-interactive mode. It has fast internal transfer switches and processes all ac power for the site. It can support the load by operating in parallel with the generator, should generator output be insufficient, and it can feed excess power to the utility grid from the generator, the PV array, or the batteries. Power delivered to the utility may be time-shifted away from the peak output of the PV array to coincide with peak demand times using either the batteries or the generator. Uncommitted control-port switching, within the inverter and based on battery voltage, may be used to control battery charging and low-voltage disconnects for dc loads. The system supplies uninterruptible power using transfer switches that operate within milliseconds.

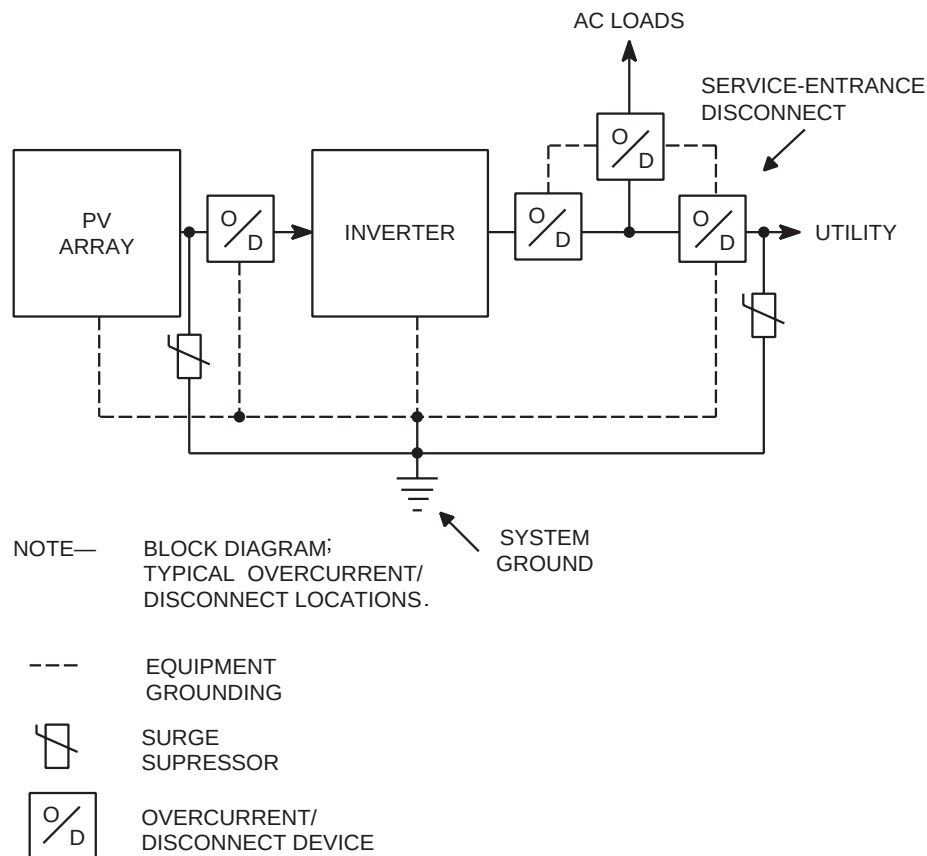


Figure A.1—Example of utility-intertie system

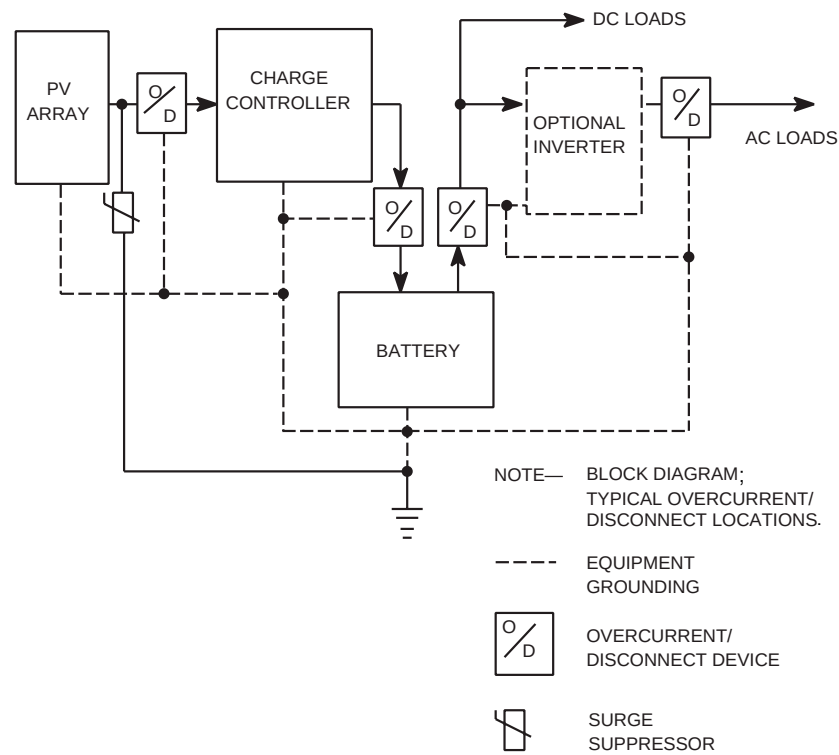


Figure A.2—Example of stand-alone PV system

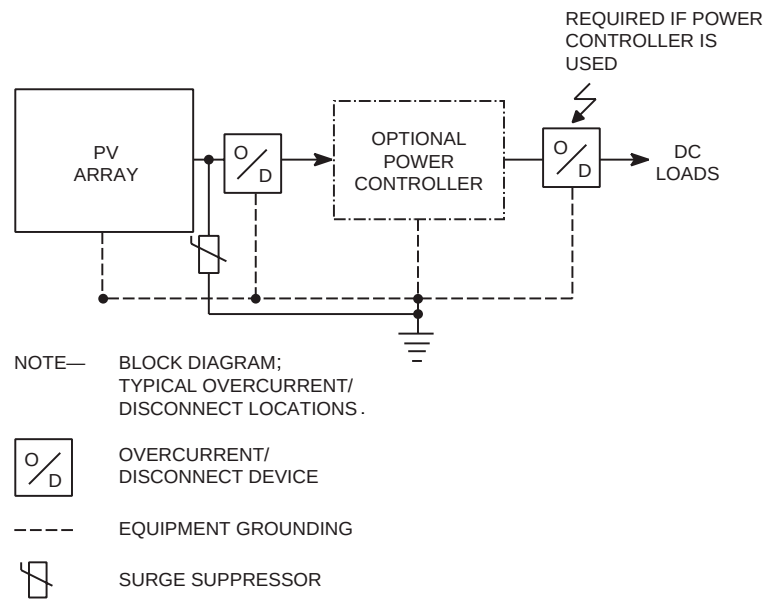


Figure A.3—Example of stand-alone direct-connected system

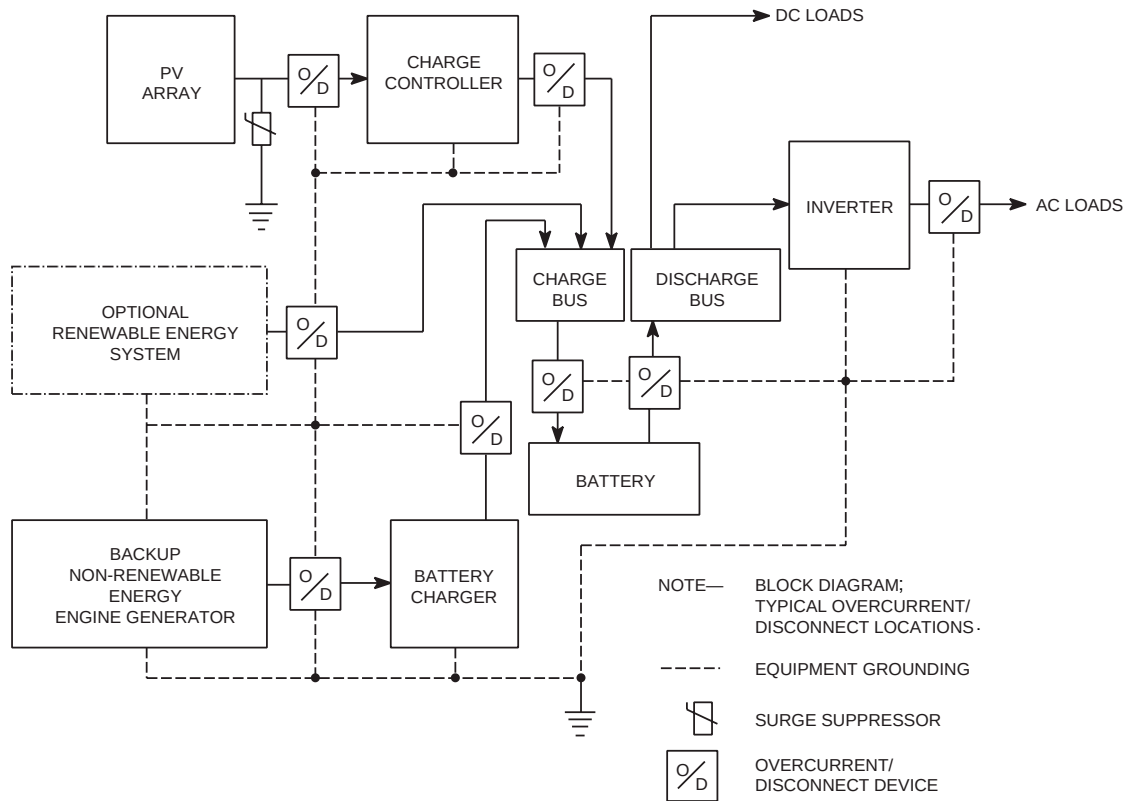


Figure A.4—Example of hybrid PV system

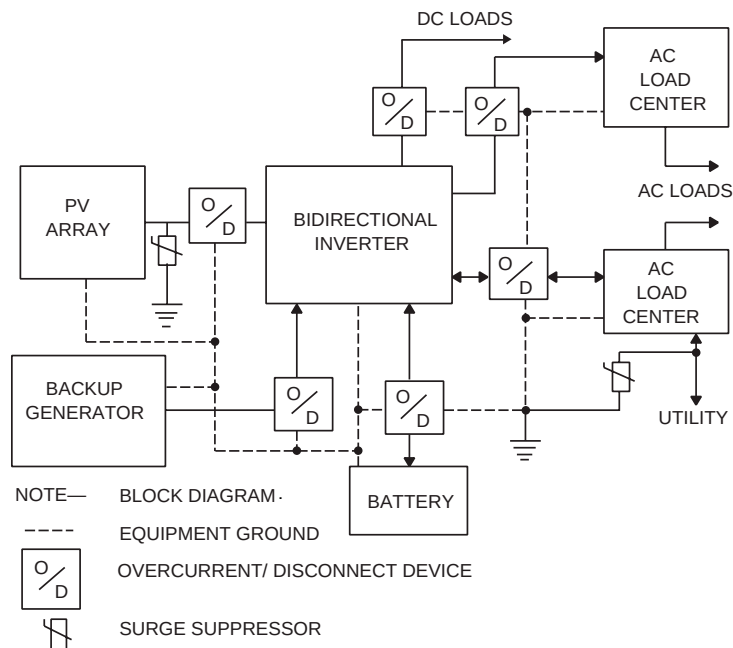


Figure A.5—Example of stand-alone, hybrid/utility-interactive system

Annex B

(informative)

Module wiring—ampacity and temperature considerations

B.1 Temperature derating

Because the PV modules operate in the sunlight, they get significantly hotter than the surrounding air temperatures. Ambient air temperatures in some parts of the country may be as high as 50 °C (122 °F). The backs of the PV modules, the module junction boxes, and other nearby areas where the conductors are located can be exposed to temperatures of 75 °C (167 °F) or higher. The ampacity of the cables used to connect the modules should be derated for these higher temperatures.

In most installations, an ambient temperature of at least 65 °C (149 °F) to derate the conductors should be used. In hot locations, with no ventilation provided for the back of the PV modules (e.g., mounted directly on a roof), a 75 °C (167 °F) or higher temperature should be used in the temperature derating calculations. In less-sunny, cooler sections of the country, maximum PV module temperatures are typically lower.

B.2 No module cooling

Number 10 AWG conductors have been selected because that is the largest size accepted by the module terminals. Single conductor #10 AWG USE-2 cable has been ordered with XLPE, RHW-2, and listing markings that indicate a 90 °C (194 °F) temperature rating. The modules are mounted on a rack on a dark colored, shingled roof, but for esthetic reasons, the spacing between the modules and the roof is only 2.5 cm (1 in). The wiring is to be in free air (not in conduit) so Table 310-17 in the NEC may be used. Since the 90 °C (194 °F) module terminal rating matches the USE-2/RHH wire temperature rating of 90 °C (194 °F), the cable may be operated at the maximum temperature for which it was rated. In Table 310-17, #10 AWG cable with 90 °C (194 °F) insulation has an ampacity (current-carrying capacity) of 55 A at ambient temperatures of 30 °C (86 °F). A footnote to the table notes that #10 AWG conductors may not have an overcurrent device rated at more than 30 A.

Because the modules have little ventilation space and the roof is dark colored, the space between the modules and the roof and in the module junction boxes can be expected to be as high as 75 °C (167 °F) on hot, sunny days. The ampacity of the conductor should be derated for this temperature because it is the ambient temperature in which the conductors operate. Ampacity correction factors are presented in the lower section of Table 310-17 in the NEC. For conductors rated at 90 °C (194 °F), the derating factor is 0.41, yielding a #10 AWG cable with a derated ampacity of 22.6 A (55×0.41).

Furthermore, NEC Section 690-8 requires that the conductors and overcurrent devices be sized so that overcurrent devices shall not be operated continuously at more than 80% [125% E (E for equipment limitations)] of their rated current. Exceptions are made for some industrial overcurrent devices that are listed for continuous operation at 100% of rating. This calculation indicates that the maximum short-circuit current that this conductor can handle is 18.1 A (22.6×0.80). UL requires another 125% N factor (N for normal operation) (or 0.8 multiplier) to allow for normal and expected operating conditions. The sum of short-circuit currents for all of the modules connected in parallel on this #10 AWG USE-2 cable should not exceed 14.5 A (18.1×0.80). Figure B.1 shows the details.

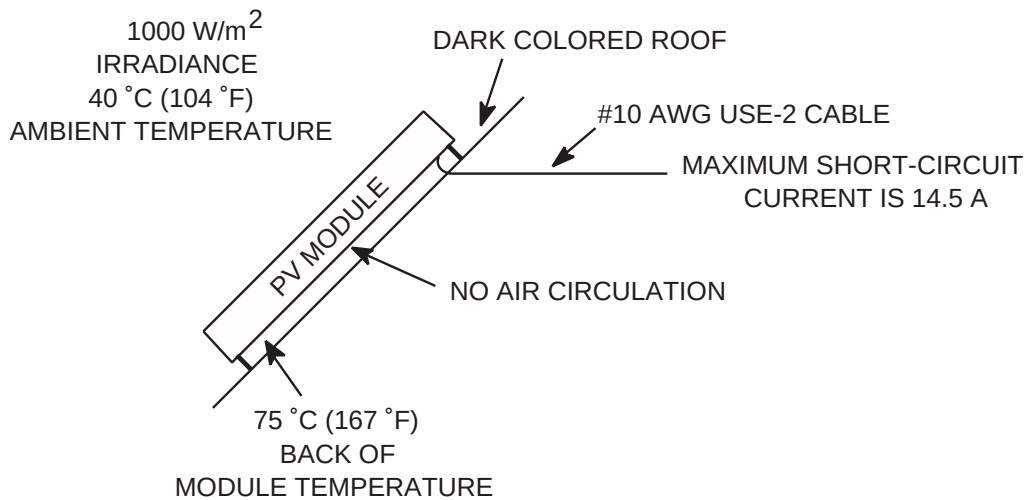


Figure B.1—Temperature derating effects—no module cooling

B.3 Partial module cooling

If the modules were spaced 15 cm (6 in) or more from the roof and ventilation was not blocked, the maximum operating temperature would drop to about 65 °C (149 °F) on hot, sunny days. In this case, a derating factor of 0.58 is given which, when multiplied by the 55 A rating of the cable at 30 °C (86 °F), gives a derated ampacity of 31.9 A (55×0.58). After the 125% E and 125% N factors are applied, the maximum short-circuit current that can be carried by this cable is 20.4 A ($31.9 \times 0.8 \times 0.8$). Figure B.2 shows the changed parameters.

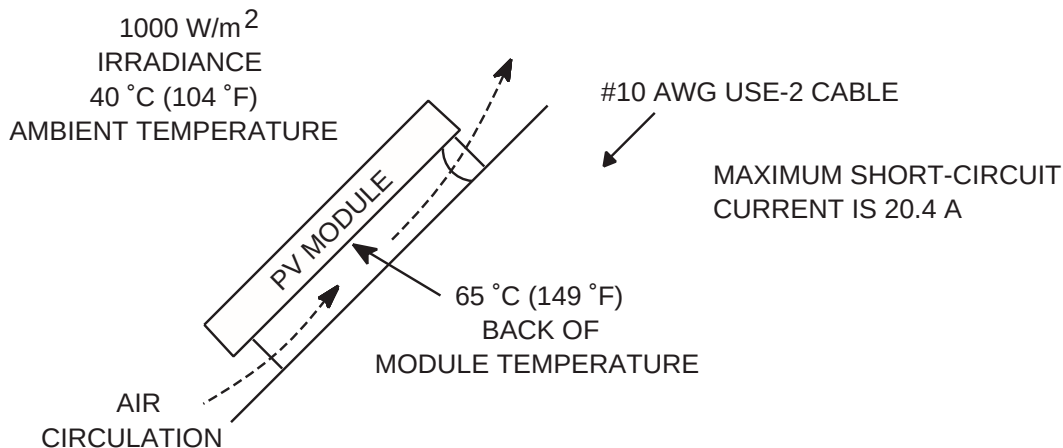


Figure B.2—Temperature derating effects—partial module cooling

Note that in these two examples, the UL 1703-1993 requirement for an additional 125% N (in addition to the NEC required 125% E) safety factor on modules listed to this standard has been applied. The application of this factor reduces the short-circuit current capability for a given size cable or requires the use of a larger size cable. This 125% N factor should be applied to the module short-circuit current, and the result should be less than the derated cable ampacity calculated in these examples.

Many circuit breakers and fuses are rated for only 75 °C (167 °F) conductors. In fact, many of the circuit breakers and fuses used in residential electrical systems are rated for only 60 °C (140 °F), which matches the temperature rating of nonmetallic sheathed cables like NM and UF. These temperature ratings are specified on cables, fuses, circuit breakers, and the like to provide information that can be used in the proper installation of these components.

Although there are no temperature-derating factors for overcurrent devices, they should be operated in ambient temperatures below their rated temperature. The current flowing through connected conductors should be compared with the current rating of the overcurrent device and adjustments made when ratings of either the conductor or the overcurrent device are exceeded.

Conductors, fuses, and circuit breakers generate heat when current is flowing through them. If a circuit breaker rated for use with 75 °C (167 °F) conductors was connected to conductors rated at 60 °C (140 °F), then the circuit breaker (when carrying full current) might overheat the 60 °C (140 °F) conductors and cause the insulation to fail. In the same manner, if 90 °C (194 °F) conductors were operated at full current (temperature derated, if required) when connected to a 75 °C (167 °F) rated fuse, the hot, 90 °C (194 °F) conductors might cause the fuse to overheat and blow prematurely. When calculating the cable sizes to use for module wiring, this situation creates an additional complexity that should be examined, as noted in B.4.

Voltage drop (performance) due to wiring losses, connections, and components is not accounted for in these examples. Optimum PV system performance may dictate larger conductors be used than is required by ampacity calculations.

B.4 High temperature considerations

In this example, four 64 W PV modules are to be connected in parallel on a 12 V system. Conduit is to be run between the modules and from the last module junction box down to a commonly available residential load center with dc-rated circuit breakers. This load center is to be used as a dc combining box. These circuit breakers are listed for 75 °C (167 °F) conductors. XHHW-2 cable with a 90 °C (194 °F) wet and dry temperature rating is to be used for all of the wiring, and it shall be temperature derated because the modules operate at 65–70 °C (149–158 °F).

The short-circuit current of the 64 W PV module is 4.0 A. Four modules in parallel shall have a combined ampacity of 16 A, which is multiplied by 125% N for normal operating conditions and by 125% E to allow the terminals of connected overcurrent devices to operate at no more than 80% of full rating. This calculation yields a requirement for a cable ampacity of 25 A. Number 10 AWG XHHW-2 has an ampacity of 40 A at 30 °C (86 °F), but should be derated by a factor of 0.58 at the module junction box because of the high temperature (NEC Table 310-16). This configuration gives a derated ampacity of 23.2 A, which does not meet the requirement of at least 25 A. Number 8 XHHW-2 has a 30 °C (86 °F) ampacity of 55 A in conduit. After derating for 65–70 °C (149–158 °F) operation, the ampacity is 31.9 A (55×0.58). Next, the temperature rating of the device connected to the other end of the XHHW-2 conductors should be considered.

The circuit breaker used has terminals rated for use with 75 °C (167 °F) conductors in an ambient temperature of 40 °C (104 °F). Therefore, the maximum current for #8 AWG XHHW-2 cable should be based on 75 °C (167 °F) insulation [rather than 90 °C (194 °F) insulation], which is 44 A in a 40 °C (104 °F) ambient temperature environment. Accordingly, the #8 AWG conductor can carry up to 44 A in an ambient temperature of 40 °C (104 °F) and not cause problems with the circuit breaker. The actual expected current is only 20 A ($16 \times 125\% N$), which indicates proper wire sizes. Figure B.3 presents the circuit and wiring details.

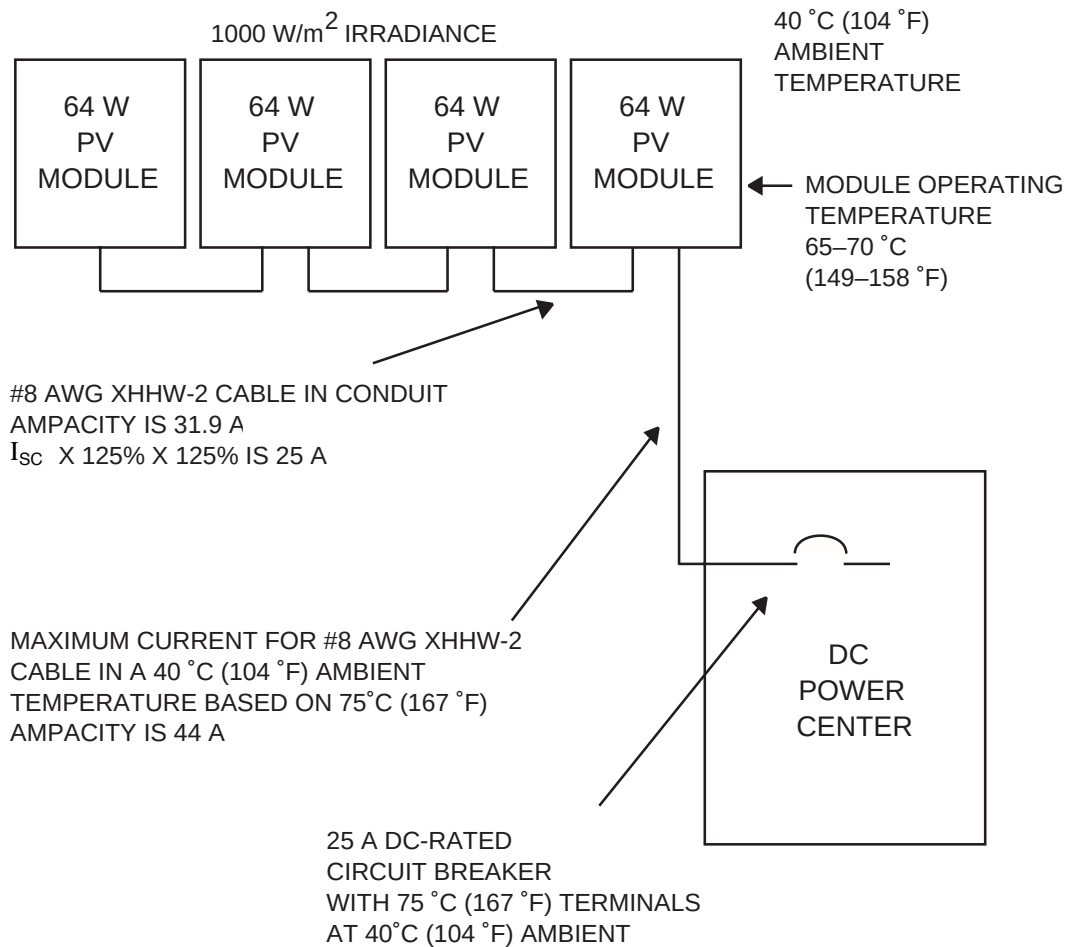
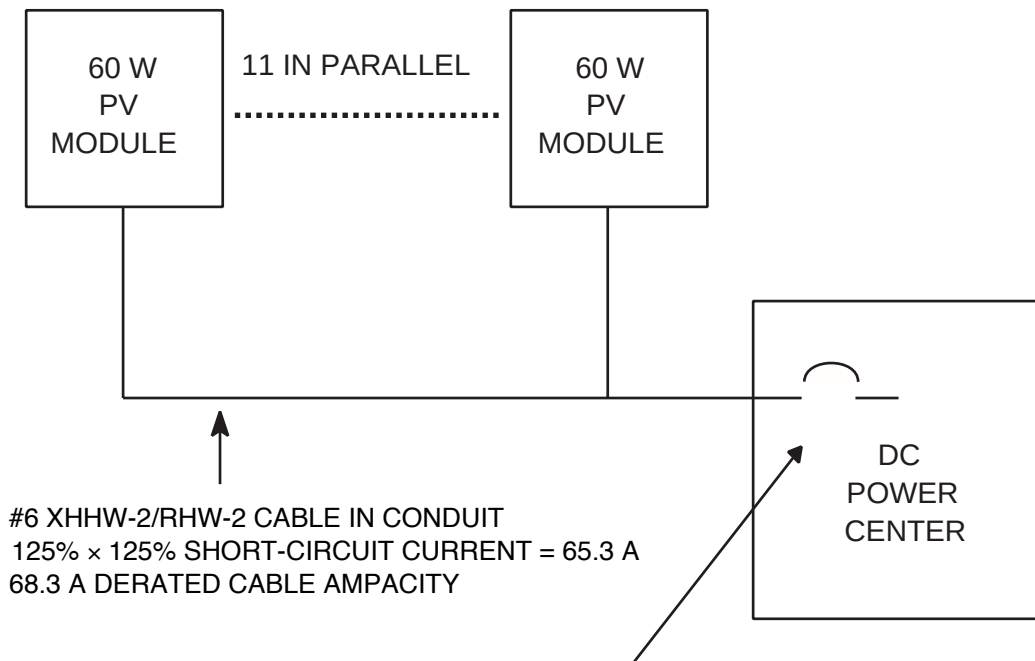


Figure B.3—High temperature considerations

B.5 Low temperature considerations

In this example, an installation is to be made in a very cold climate where the module temperatures never rise above 40 °C (104 °F). Eleven 60 W modules are to be wired in parallel. The short-circuit current calculation is 41.8 A (11×3.8) and the 125% N and 125% E calculations yield 65.3 A. With 90 °C (194 °F) XHHW-2/RHW-2 cable, the temperature derating factor is 0.91 (NEC Table 310-16), which would indicate that #6 AWG cable in conduit would be suitable ($75 \times 0.91 = 68.3$ A). At the other end of the cable is the circuit breaker with 75 °C (167 °F) terminals operating in a 46 °C (115 °F) environment (boiler room). The maximum current for the #6 AWG cable, based on 75 °C (167 °F) insulation, is 65 A in a 30 °C (86 °F) ambient environment. The ambient temperature of 46 °C (115 °F) derates the cable to 48.8 A (65×0.75). Accordingly, the rated ampacity #6 AWG conductors operating in an ambient temperature environment of 46 °C (115 °F) connected to 75 °C (167 °F) terminals is *less* than the actual required ampacity of 52.3 A (41.8×1.25); therefore, the circuit breaker may be subjected to overheating. The next larger cable size is required to keep from exceeding component ratings. Connecting large conductors to modules and circuit breakers may require special fittings. Figure B.4 presents this diagram.

AMBIENT TEMPERATURE 10 °C (50 °F)



DC-RATED CIRCUIT BREAKER WITH 75 °C (167 °F) TERMINALS.
THE MAXIMUM CURRENT FOR #6 AWG, XHHW-2/RHW-2 CABLE
IN 46 °C (115 °F) AMBIENT TEMPERATURE, BASED ON 75 °C (167 °F)
AMPACITY IS 48.8 A. THEREFORE, #6 AWG CABLE AT 52.3 A CANNOT
BE USED.

Figure B.4—Low temperature considerations

In summary, the short-circuit current requirement times 125% N and 125% E at the high-temperature end (module junction box) of the cable should be less than the temperature derated ampacity of the cable using the ampacity ratings for the insulation temperature rating of the conductor. If module terminals are rated at 75 °C (167 °F), then 75 °C (167 °F) insulation tables should be used. The 125% N short-circuit current requirement at the low-temperature end (circuit breaker) of the cable should also be less than the temperature derated (if any) ampacity of the cable using the same size cable, but rated at an insulation temperature equal to the temperature rating of the terminals of the connected device.

Another important temperature consideration should be made for nonmetallic flexible conduit. It is rated at 80 °C (176 °F) when dry and only 60 °C (140 °F) when wet. In the outdoor, exposed locations for PV modules, this 80 °C/60 °C (176 °F/140 °F) temperature rating might have some impact on the size of the cables used.

Conductors installed in conduit exposed to the weather are considered to be in a wet environment. These conductors should have insulation rated for wet locations identified by the letter W in the type designation, such as RHW, RHW-2, or XHHW.

Annex C

(informative)

Cable and device ratings at high voltages

In designing PV systems that have system open-circuit voltages above 600 V, two issues should be addressed—device ratings and NEC requirements.

C.1 Equipment ratings

Some utility-intertie inverters operate with a grounded, bipolar PV array. In a bipolar (three-wire) PV system, where each of the monopoles is operated in the 220–235 V peak-power range, the open-circuit voltage can be greater than or equal to 290 V, depending on the module characteristics such as fill factor. Such a bipolar system can be described as a 350/700 V system (for example) in the same manner that a 120/240 V ac system is described. This method of describing the system voltage is consistent throughout the electrical codes in residential and commercial power systems, as well as 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 V in a 350/700 V system). That is why 250 V switchgear and overcurrent devices are used in 120/240 V ac systems and 600 V switchgear is used in systems such as the 277/480 V 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 NEC defines a nominal voltage for ac systems (120 V, 240 V, etc.) and acknowledges that some variation can be expected around that nominal voltage. Such variation around a nominal voltage is not considered in dc PV systems, and the NEC requires that the open-circuit array voltage be used. The open-circuit voltage is defined at standard test conditions (STC) (see 5.1.2) 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 PV 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 system voltage as the sum of the absolute value of the open-circuit bipolar voltages. The open-circuit voltages shall be 125% of the nameplate STC voltages for each circuit. This is due to the UL requirement to multiply rated open-circuit module voltages by 125% before applying code requirements. This factor is known in this guide as the 125% N (N for normal operation) factor to distinguish it from the NEC required 125% E (E for equipment limitation) factor.

The comparison to ac systems can be carried too far; there are differences. For example, the typical wall switch in a 120/240 V ac residential or commercial system is rated at only 120 V, but such a switch in a 120/240 V dc PV system would have to be rated at 240 V. The inherent differences between a dc current source (PV modules) and a voltage source (ac grid) impact 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 should have current ratings that exceed the short-circuit currents (rated at standard test conditions) by at least 25% to account for expected normal operating conditions, temperature, and irradiance. 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, thus 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. Without the source voltage driving the circuit on ac systems, the fault currents are zero and cause no problems. For these reasons, a switch rated at 120 V can be used in a three-wire ac system with voltages up to 240 V, but in a dc, PV system, the switch would have to be rated at 240 V.

UL 1703-1993 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% (crystalline and polycrystalline silicon cells), further increasing the voltage requirement of the balance of systems (BOS) equipment.

Many PV modules are listed to the UL 1703-1993 with a maximum system voltage of 600 V. This restriction is not modified by the fact that the modules undergo high-pot tests at higher voltages. UL 1703-1993 allows modules to be listed up to 1000 V.

Although not explicitly stated by the NEC, it is evident that the intent of the NEC and the UL standards is that all cables, switches, fuses, circuit breakers, and modules in a PV system be rated for the maximum system voltage. This requirement was clarified in the 1996 NEC.

While reducing the potential for line-to-line faults, the practice of wiring each monopole in a separate conduit to the inverter does not eliminate the problem. Consider the bipolar system presented in Figure C.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.

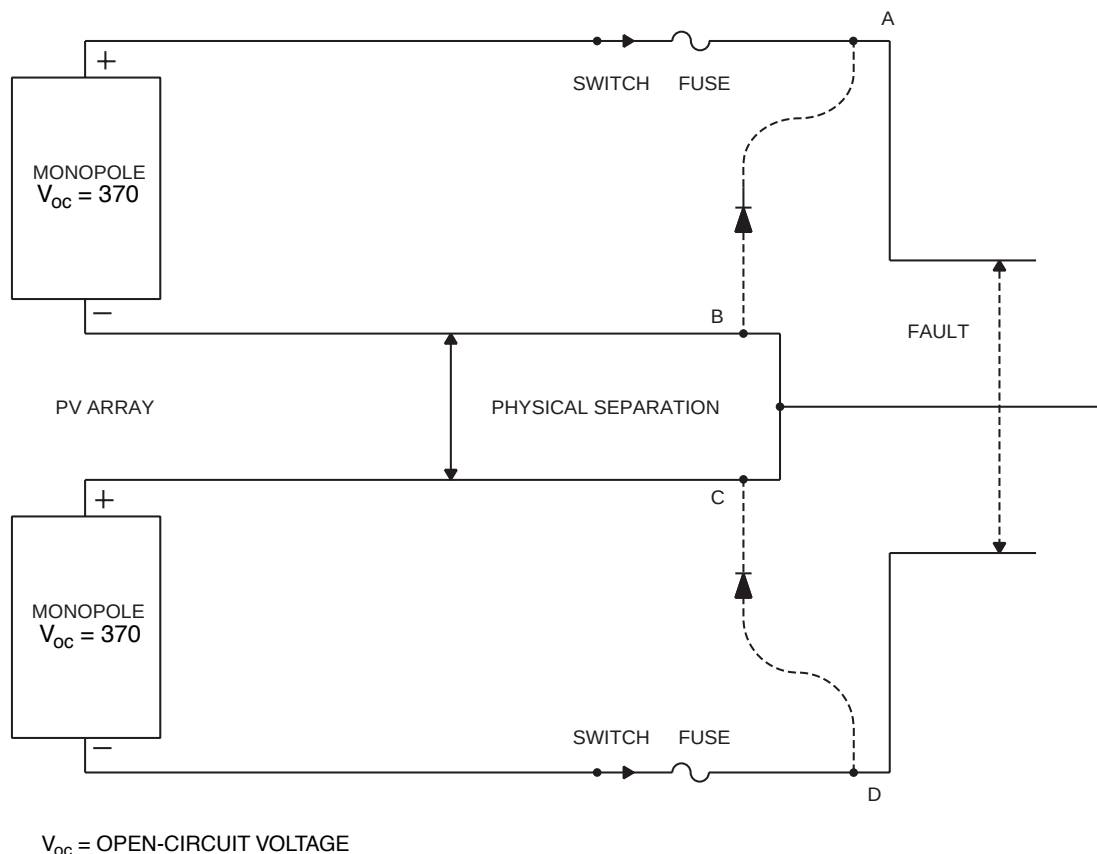


Figure C.1 — Typical bipolar system with fault

Now consider what happens in any of the following cases:

- a. A switch is opened;
- b. A fuse opens;
- c. A wire comes loose in a module junction box;
- d. An intercell connection opens or develops high resistance;
- e. A conductor fails at any point.

In any of these cases, the entire array voltage (740 V) 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 open circuit. As the device starts to fail, the current through it goes from the short-circuit current (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.

There are other possibilities for faults that may 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, should detect the fault, interrupt the ground-fault current, and “disable” the array. The term “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 have inverters that, when shut down, crowbar the array. The array remains crowbarred until the ac power is shut off.

C.2 NEC requirements

The second issue associated with PV systems that have system open-circuit voltages above 600 V is that the 1996 NEC in Section 690-7(c) only allows PV installations up to 600 V in one- and two-family dwellings. Other PV installations may have voltages higher than 600 V, but the NEC poses numerous additional safety requirements on these systems.

The NEC requirements become more restrictive as the system voltage goes over 600 V. The requirements, in general, make the live wiring accessible to only qualified persons. This restricted access is accomplished through the use of locked or special-tool-access junction boxes or locked and fenced areas. Appropriate additional clearances and working spaces are required around equipment operating over 600 V, even when accessed by qualified persons. The following sections of the NEC contain requirements for systems operating over 600 V: 110-B, 240-H, 250-M, 280, 300-B, 305-7, 370-D, 400-C, 470-B, and 710.

C.3 Near-term solutions

The system dc bus voltage level is a primary design parameter that involves tradeoffs between inverter topology (affecting efficiency and cost), module type (affecting fill factor and thereby the system V_{oc} for a given operating voltage), wiring design, and cost. In general, the efficiency rises and the unit cost drops as the voltage level is raised. The system designer determines whether the advantages of using a dc bus voltage over 600 V offsets the cost of compliance with requirements for systems over 600 V. Utility-intertie inverters are available with dc input voltages as low as 24 V and as high as just under 600 V, as well as higher than 600 V. Modules can be wired in series to obtain various dc bus voltages. Modules now listed by UL are tested and listed for use only up to 600 V. Module manufacturers can be encouraged to design,

test, and list their modules for use at higher voltages. Transformers are used to raise the inverter output ac voltage to the utility-grid voltage.

Cable manufacturers produce a UL-listed, cross-linked polyethylene, single-conductor cable marked USE-2, RHW-2, and sunlight resistant cable that is rated at 2000 V. This cable may be used for exposed module interconnections and in conduit after all of the other NEC requirements are met for installations above 600 V.

Several manufacturers issue factory certified rating on their three-pole disconnects to allow higher voltage, non-load break operation with series-connected poles. Good engineering practice requires that a safe, acceptable method be used to ensure non-load-break operation with such switches.

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

High-voltage industrial fuses are available. The manufacturer should be consulted for the dc ratings. Fuse holders with higher voltage ratings are usually the bolt-in types.

Individual 600 V terminal blocks may be used in higher voltage applications with the proper spacing for higher voltages and, when mounted on insulated surfaces, 2000 V terminal blocks are also available.

As shown in Figure C.1, power diodes have been connected across each monopole. When a bolted line-to-line fault occurs, one of the diodes may 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 and B, and across points C and D in Figure C.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 or tested as over-voltage protection devices, this solution is not specified by the NEC and may be only as safe as the durability of the diodes that are subject to failure.

Annex D

(informative)

Battery-to-inverter cables—ampacity and deratings

Calculating the ampacity of the stand-alone inverter dc input cable is complex. The following example is presented to clarify the procedure.

D.1 Ampacity of stand-alone inverter dc input cable

To determine the dc input current of a stand-alone inverter, the following items are used:

- a) The rated (by accepted testing laboratory, e.g., UL or ETL) continuous power output (e.g., 4000 W) of the inverter;
- b) The lowest battery voltage that allows the inverter to produce the rated power (e.g., 22 V);
- c) The inverter efficiency at full power (e.g., 85%).

The dc input cable ampacity and the overcurrent device rating should be equal to:

$$1.25 \times 4000 \div 22 \div 0.85 = 267 \text{ A} \quad \text{D.1}$$

The 125% E factor (E for equipment limitations) is to ensure that the overcurrent device is not operated continuously (more than three hours) at over 80% of its rating.

A 300 kcmil (mcm) (three hundred thousand circular mils), 75 °C (167 °F) cable has an ampacity of 285 A and can safely carry the 267 A in the circuit between the inverter and the battery. Two #2/0 AWG, 75 °C (167 °F) cables may be paralleled (allowed by the NEC in 1/0 and larger gages). The ampacity would be 280 A (derated by 20% from 350 A because four conductors are in the conduit; see NEC Table 310-16, Note 8).

Conductors rated at 75 °C (167 °F) should be used because commonly available fuses and circuit breakers at these current levels may only be used with conductors up to 75 °C (167 °F). The use of conductors rated at 90 °C (194 °F) or higher at full ampacity is not permitted by the NEC [unless derated to 75 °C (167 °F operation)] and may cause failure of connected fuses and/or circuit breakers.

The 267 A from Equation (D.1) is not a standard rating for overcurrent devices, and the NEC would allow the use of a 300 A circuit breaker or fuse to protect these cables. Although not specifically mentioned in the NEC, a 250 A original equipment manufacturer (OEM) time-delay breaker might also be used.

A 250 A breaker with a normal, curve-1-delay function would carry 312 A for at least 2 min and as long as 18 min (tolerance specification). When the normal operating tolerances of circuit breakers and fuses are considered, a 250 A device might carry 267 A for an indefinite time. The actual current in the circuit at full power is 214 A ($4000/0.85/22$) and a 250 A OEM breaker is generally rated at 100% (instead of 80%) continuous duty.

Where commercial, industrial, or three-phase motors are used (relatively rare in stand-alone applications), surge currents due to motor starting may be used to calculate the cable ampacity and the fuse or circuit-breaker ratings. Both fuses and circuit breakers generally have the necessary time delays built in to handle overcurrent surges from standard single-phase motors without difficulty. Some fast-acting (non-time delay) fuses may not be able to handle the larger or longer surges, and the fuse manufacturer's literature should be consulted.

While the calculated cable sizes provide the needed ampacity, voltage drop considerations on stand-alone systems may indicate that larger cable sizes should be used. At 267 A, the voltage drop in 4.8 m (16 ft) [2.4 m (8 ft) one way] of two paralleled #2/0 AWG cables would be about 0.206 V. Starting a large well pump motor results in four times as much surge current and the voltage drop would be 0.8 V. At low battery voltages, this may cause the inverter to shut down in the low-voltage disconnect mode.

Figure D.1 shows the combined protective devices and cable sizes associated with the battery for a grounded, 24 V PV system with a maximum 80 A PV charging current, an 80 A dc load current, and the 4000 W inverter.

D.2 Caution

Some caution should be exercised in using high-current fuses with cables that have an ampacity less than the overcurrent rating of the fuse. A 400 A fuse requires that at least a 600 kcmil cable be used. At 75 °C (167 °F), this cable has an ampacity of 420 A. Two 250 kcmil cables may also be paralleled for an ampacity of 408 A (derated by 20% from 510 A for more than three cables in a conduit). Using smaller cables (with less ampacity) than these would indicate that the fuse cannot protect the cables from overloads.

While welding cables are frequently specified and used in inverter-to-battery wiring, many inspectors will not allow these cables. They have no recognized ampacity ratings, are frequently not tested or listed, and the insulation may not be suitable for use in conduit. The temperature rating of welding cables may be as high as 105 °C (221 °F), which works well with the high-temperature terminals on welding machines, but not with the 60–75 °C (140–167 °F) terminals on batteries or overcurrent devices. The NEC acknowledges the use of welding cable connected to welding machines, but only in welding cable trays.

Flexible, building-type cables (USE-RHH-RHW) are available from a number of manufacturers and should be used in these applications since they meet all NEC requirements.

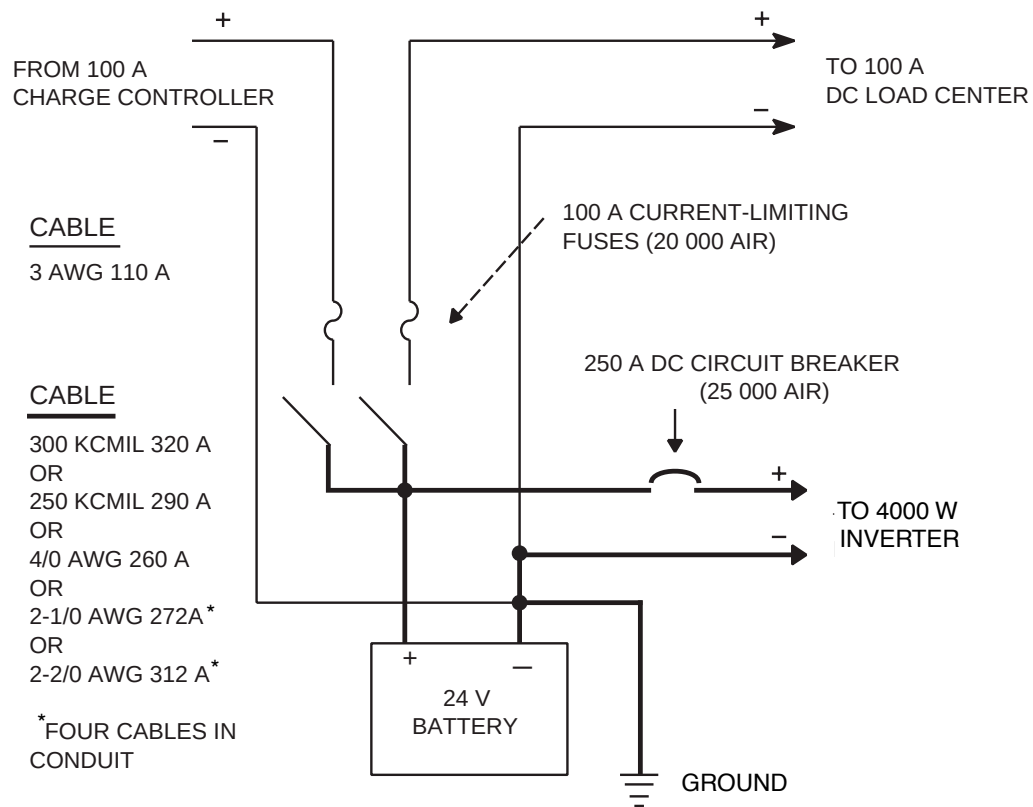


Figure D.1—Typical battery wiring

Annex E

(informative)

Overcurrent devices for module wiring

DC-rated fuses and circuit breakers are not as widely distributed as ac fuses and circuit breakers. AC breakers depend on the zero crossing of the current to interrupt the arc. The arc that forms when a dc circuit is opened is hard to extinguish and may destroy ac-only rated circuit breaker or contactor devices in a short period of time. AC fuses may not blow or clear with dc current.

E.1 Types

In the array circuits, the NEC allows supplementary overcurrent devices to be used. These are the small circuit breakers or small glass or ceramic-bodied fuses used inside electronic equipment, which provide protection above and beyond that provided by the main branch-circuit fuse or circuit breaker. Many supplemental overcurrent devices are listed only for ac operation. DC-rated, listed fuses in the midsize [10.3 × 38.1 mm (13/32 in × 1-1/2 in)] are available. There are also small, supplemental dc-rated, listed, supplemental circuit breakers available from several manufacturers.

There are *UL-recognized* (as opposed to *UL-listed*) overcurrent devices on the market that are built to the manufacturer's specification rather than to a UL standard. The performance of these devices may be less robust than the performance of a fully listed device. They are intended for factory installation in equipment where the limitations of use are known to the manufacturer and where their use meets the limitations determined by the UL.

The use of overcurrent devices listed for branch circuit use (Class R, K, CC, H, L, and T fuses and listed circuit breakers) will provide greater protection and durability than supplemental overcurrent devices. The construction of these devices also offers better performance through lower voltage drops due to heavier internal construction. UL standards and manufacturer's data for each of these fuse types give specific details.

Glass or plastic automotive fuses are *not* considered supplementary fuses, are rated only to 32 V, and are not tested or listed by the UL for supplementary use. They *should not* be used in PV systems.

The NEC requires that the fuses have switches on both input and output circuits to remove all sources of voltage prior to servicing. This requirement, plus the need for dc-rated switches and disconnect devices, indicates that circuit breakers may provide greater performance at lower cost. Commonly available residential circuit breakers are UL listed for operation at 60–70 A and 48 V dc; data are available from the manufacturers. Because the PV array open-circuit voltages times 125% N (N for normal operation) should be used when specifying components, these breakers can be used for 12 V (V_{oc} of 22) systems. Small load centers are available that hold these breakers.

Figure E.1 illustrates the overcurrent protection and disconnects required for a small, ungrounded PV system with no inverter. Both fused disconnects and circuit-breaker systems are shown. Disconnects and overcurrent devices are required in only the ungrounded conductors. In these ungrounded examples, two-pole disconnects and overcurrent protection are shown for the PV source circuits.

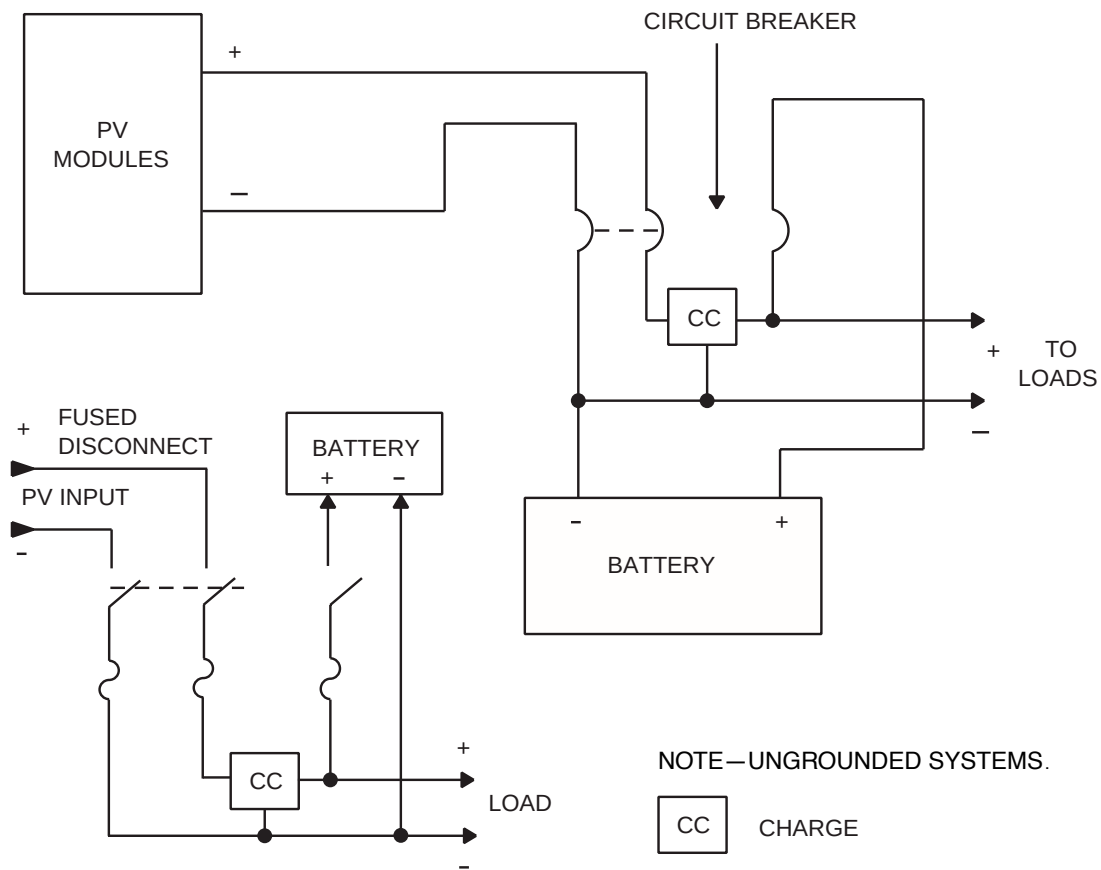


Figure E.1—Typical overcurrent protection for the small system

Small midget-type fuses (supplemental fuses rated up to 30 A at 600 V dc) mounted in pull-out fuse holders can provide low-cost overcurrent protection for the PV source circuits. Some of these pull-out fuse holders, particularly for the larger, branch-circuit-rated fuses, are load-break rated. Figure E.2 shows a portion of a large system with midget fuses in pull-out holders in several locations coupled with higher current, Class T fuses in pull-out fuse holders and a final circuit breaker for the PV disconnect function. Wiring is in conduit, conductors are temperature rated at 90 °C (194 °F), module conductors are derated for 70 °C (158 °F) ambient temperature, and conductors and overcurrent devices are sized to 156% of the short-circuit current.

E.2 Rating

Conductors should be sized based on the PV module or array short-circuit current at 125% N and 125% E factors (E for equipment limitations) plus temperature deratings. The rating of the overcurrent device is then based on the ampacity of the conductor. When the calculation yields a nonstandard value for the rating, the NEC allows the next larger standard size to be used—up to 800 A.

In all cases, the dc ratings of the fuse, as listed against the appropriate UL standard, should be plainly marked on the fuse.

The overcurrent device should be located nearest the source of the overcurrents; this is usually in the combiner box near the charge controller on stand-alone systems or near the inverter on utility-intertie systems.

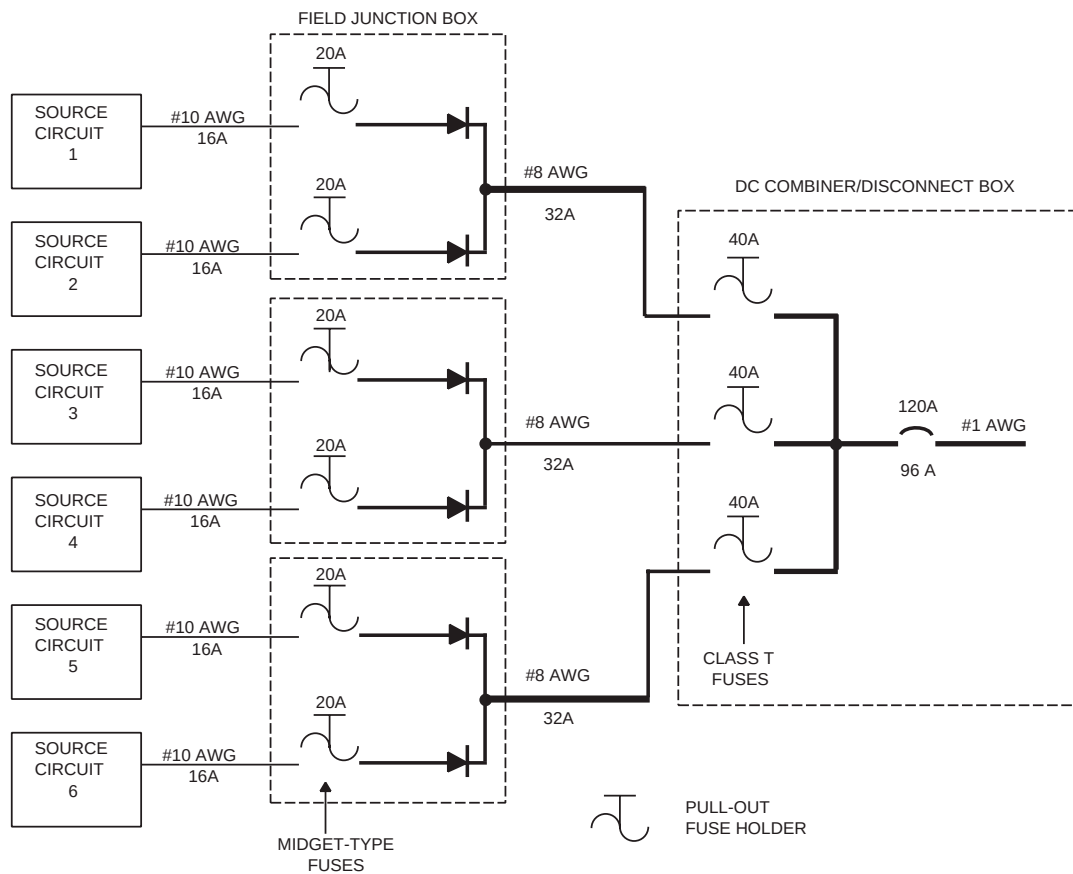


Figure E.2—Example of array wiring overcurrent protection

Annex F

(informative)

Disconnecting devices—locations

There is usually one location in a system where the majority of the equipment are connected and grouped. The NEC requires that all the disconnects for all sources of power be grouped (visible and reachable from one location), and that all can be opened with no more than six motions of the hand. Safety, combined with this requirement, may dictate that some circuits have more than one disconnect.

On grid-connected systems, the inverter is best located near the service entrance point for the building or facility. A location close to the service entrance disconnect allows the ac inverter disconnect to be grouped with the PV disconnect, and allows both to be near the service disconnect. Figure F.1 shows the location of these disconnects.

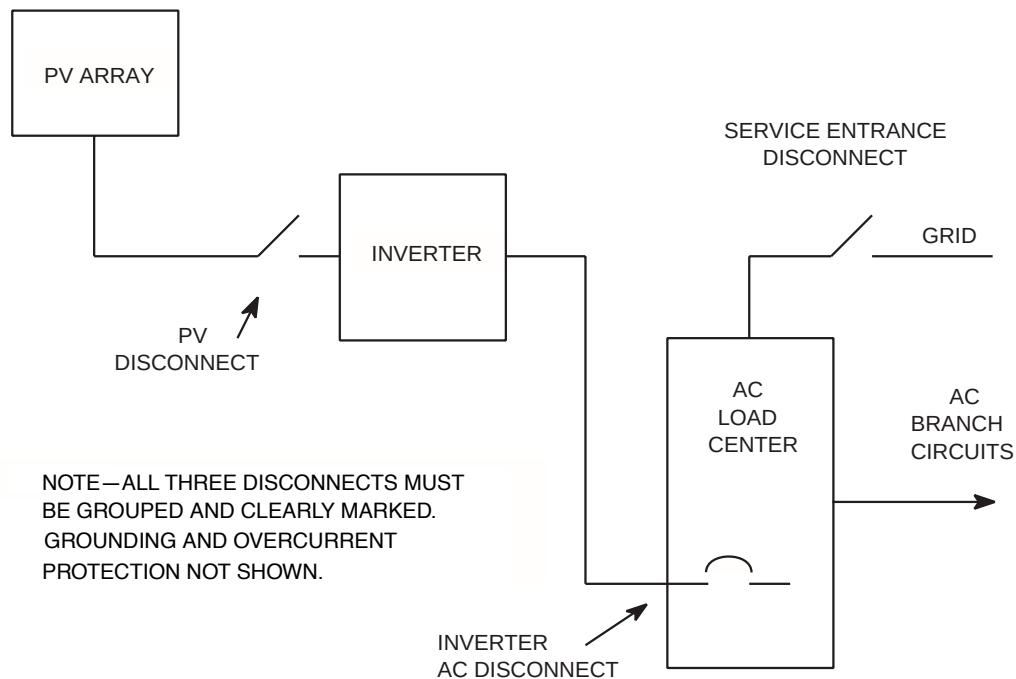


Figure F.1—Example of disconnects for grid-tied PV system

In a stand-alone system, the central location for disconnects is usually at the inverter/battery location. These two pieces of equipment are generally located near each other to minimize the length of large, high-current cables between them. Wiring from the rest of the system converges on this central location. In stand-alone systems with batteries, back-up generators, other power sources, and possibly utility-grid back-up, the disconnect situation becomes more complex. One of the many possible configurations for disconnects is shown in Figure F.2.

In many systems—both grid-connected and stand-alone—the equipment is dispersed from the central location. Dispersed equipment locations, NEC requirements for overcurrent protection, and the grid-connection point may dictate more than one disconnect for each power source.

For example, in a grid-tied system, the PV array may be on the top of a multi-story building, the inverter on the top floor, and the service entrance disconnect in the basement. This layout would necessitate two ac disconnects for the system. One would be positioned near the inverter and the other near the service entrance disconnect.

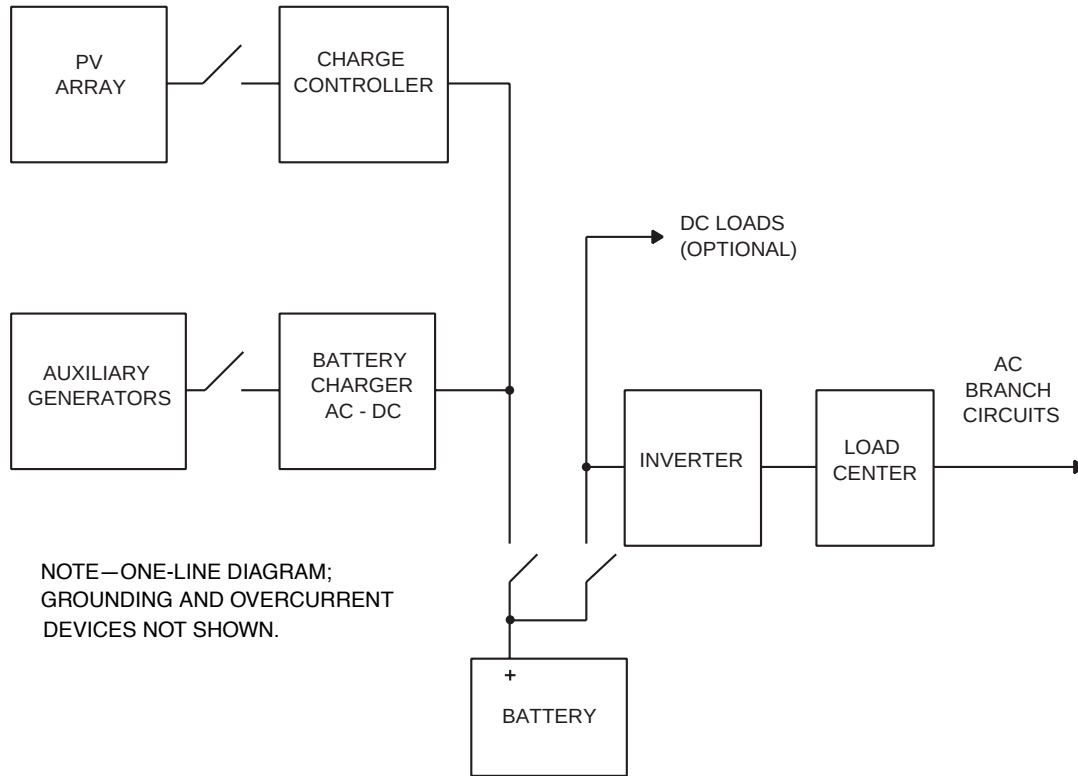


Figure F.2—Example of stand-alone PV-hybrid disconnects with external battery charger and all ac loads handled by inverter

In a stand-alone system, with a motor-generator outside, the batteries in a separate building, and the inverter remote from both or either, several disconnects might be needed to ensure system safety and code compliance.

Figures F.3 and F.4 show variations on equipment configuration. In Figure F.4, the requirement to group the disconnects for all sources of power and the remote location (from the batteries and the inverter) of the generator and the PV array may dictate that these two sources each have two disconnects—one located near the device and one grouped with the other disconnects. The disconnects near the source resemble the disconnects mounted near outdoor air conditioning compressor/condenser systems. Furthermore, newer inverters with generator support functions may operate in parallel with generators, thereby requiring at least an over-current device (with a switch) at the inverter end of the generator to inverter cable.

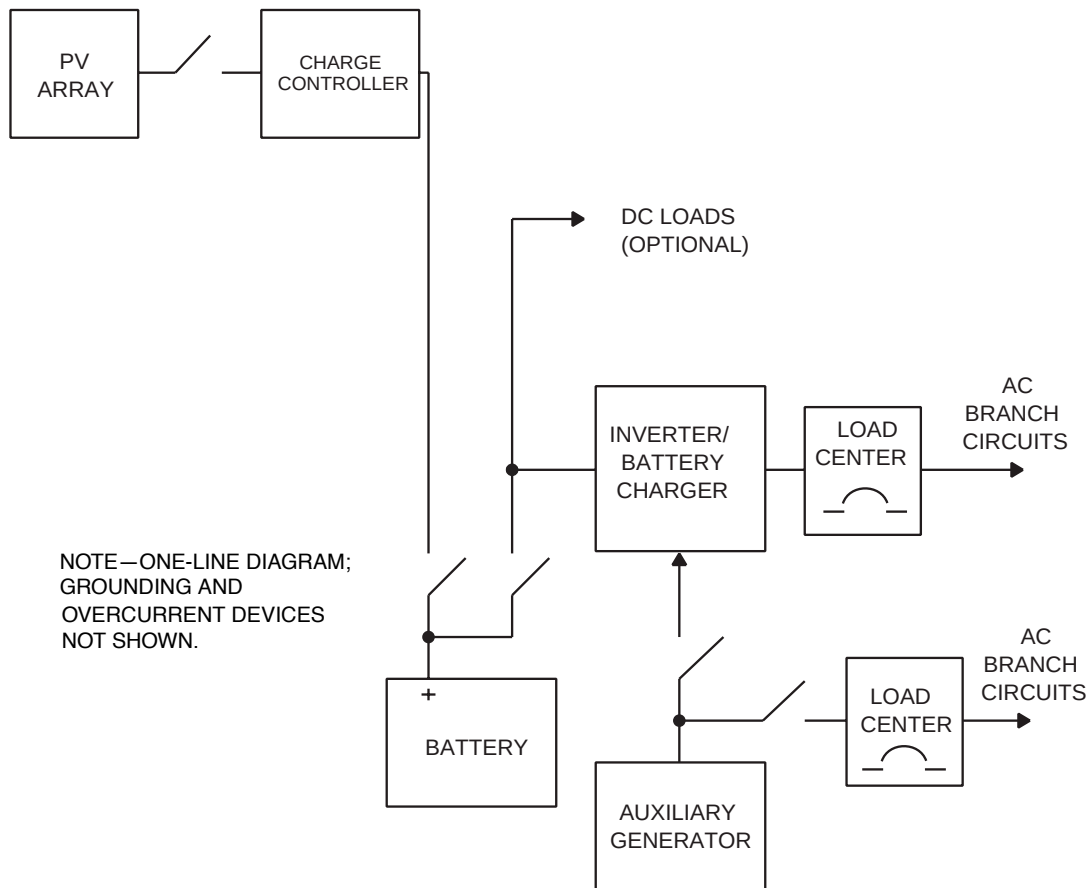


Figure F.3—Example of stand-alone PV-hybrid disconnects where the inverter includes a battery charger and the inverter and generator supply ac loads

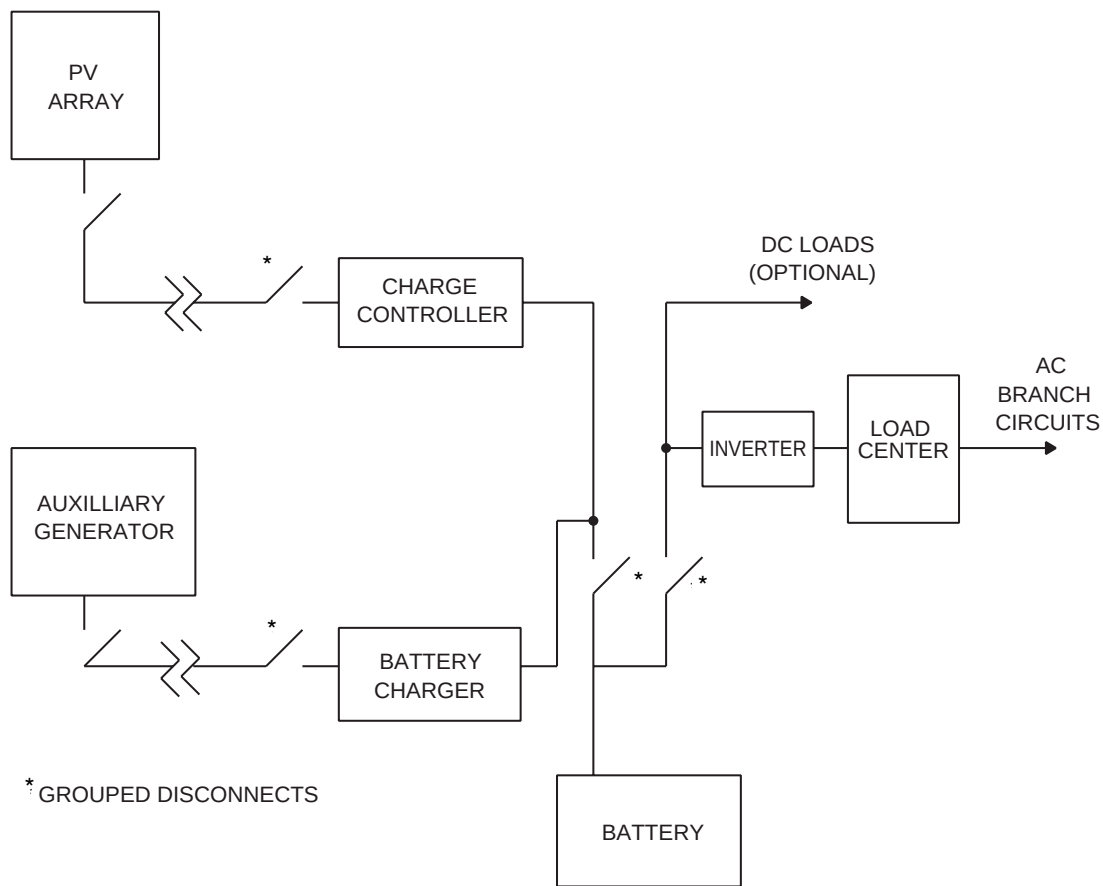


Figure F.4—Example of disconnects for remotely located power sources

Annex G

(informative)

Grounding details

G.1 Equipment grounding

The NEC requires that the exposed metal surfaces of all equipment operated during the production and use of electrical power be grounded. The NEC does not make any exceptions for low-voltage systems, and systems less than 50 V are specifically addressed. The equipment requiring grounding may range from power sources (metal frames on PV modules, cases on wind and hydro generators, and support structures) to the appliances that provide useful work (pump housings and the cases on blenders). The double-insulated configuration, which does not require the equipment-grounding conductor, is allowed only in end-use consumer-type appliances and is not used in power generation and distribution equipment.

While it is common practice to run an equipment-grounding conductor from the PV module frame to the central ground rod located near the batteries, better lightning and surge protection would dictate that ground rods be placed as near as practical to the lightning-prone metal surfaces (PV array frames and wind machine towers). The effect of lightning-induced surges is then minimized. To meet the code, these ground rods should be bonded to the main ground rod. Separating the equipment-grounding conductor from the current-carrying conductors will minimize induced surges from nearby lightning strikes, and separation is allowed in dc systems but not ac systems. Annex K provides additional information on surge suppression.

Exposed metal surfaces of switch boxes, fuse holders, charge controllers, inverters, and battery boxes should be connected to the equipment-grounding conductor. When equipment is found that does not have a provision to attach the grounding conductor, the equipment manufacturer should be consulted on the location of the connection, and whether case (and negative conductor) grounding may affect the performance or the warranty.

The size of the equipment-grounding conductor should be based on the size of the overcurrent device protecting the conductors between any two pieces of equipment. The NEC gives details in Table 250-95—for example, a circuit fused at 30 A would require a #10 AWG equipment-grounding conductor, and a 400 A fused circuit would require a #3 AWG equipment ground. If the current-carrying conductors are oversized to decrease voltage drop, then the code requires that the equipment-grounding conductor be increased in size proportionately (circular mills or cross-sectional area). Pressure-type lugs are required by the NEC for conductors greater than #10 AWG; a large wire under a screw is not considered safe by UL standards.

Bare, uninsulated conductors or conductors with green insulation should be used for the equipment-grounding conductors.

The actual connections may be daisy-chained from one piece of equipment to the next and then to the ground rod as is done in ac practice. They may also be individually connected to a common point and then to the rod. Separate multiple connections to the ground rod (each with a separate clamp) are allowed.

G.2 System grounding

Grounding one of the current-carrying conductors is required by the NEC if the no-load or open-circuit voltage in the system exceeds 50 V. Below that voltage, system grounding is optional. A bipolar system at any voltage should have the array center-tap conductor grounded.

The negative conductor is the most commonly grounded conductor in renewable energy systems. Many telephone and telecommunications systems require a positive ground. If dc-powered by the PV system, a dc-dc isolator may be used so that the PV system can have a negative ground and the telephone system can have a positive ground. If the only load on the system has a positive ground, then the entire system can be positively grounded.

G.3 Continuity of grounded conductor

The manufacturer of the particular equipment (inverter, charge controller, etc.) is the best source of information on equipment connections in a grounded system. Current-carrying conductors that are grounded should have white colored insulation and should be electrically continuous throughout the entire system from power source to load. That generally means no switches, no relays, no fuses, and no semiconductor power processing in the negative (grounded) lead (a common practice in charge controllers and some peak-power trackers).

An electrical inspector expects that all conductors colored white will be at the same potential above ground—i.e., near 0 V. When there are switches, relays, or transistors inside charge controllers in the negative, grounded lead, these devices violate the continuity of the grounded conductor and may create an unsafe condition.

Although most current-measuring shunts are installed in the grounded conductor, to do so presents the possibility that the shunt may be bypassed by inadvertent multiple grounding connections. Some engineers are installing shunts in the ungrounded conductor to avoid this potential problem. A properly designed shunt with the same or greater ampacity than the conductor is considered to be the same as a conductor.

G.4 Single-point connection

In a grounded system, there should be only one connection between the grounded conductor and the grounding electrode. If there is more than one connection (either intentionally or unintentionally), parallel paths for current flow may exist, and this is not allowed by the NEC. Currents may flow in the grounded, current-carrying conductors and in the uninsulated equipment-grounding conductors.

The NEC requires that the dc system-grounding electrode conductor between the negative conductor and the ground rod should be as large as the largest current-carrying conductor in the system—even if that happens to be a #4/0 AWG battery cable. Under some circumstances, the grounding electrode conductor may be reduced to a #6 AWG conductor. NEC Section 250-93 provides the details.

G.5 Location of system ground

The ac system has the single point system ground normally located in the ac load center where the ac neutral is bonded to the equipment-grounding conductors, and both are then connected to the grounding electrode.

Article 690 of the NEC requires that the point of ground connection to the negative conductor be on the PV output circuits and suggests in a fine-print note that a connection closest to the array should minimize surge problems. Following this suggestion would make the PV disconnect switch enclosure the logical place to make the connection. On a direct-connected (no batteries) system, this is the ideal place. On a system with batteries and large cables, the negative battery terminal or negative inverter terminal might be a better location, since the heavy grounding cable can be connected to the heavy conductor between the battery and the inverter. Grounding at this location may also help to reduce electromagnetic interference (EMI) from the inverter. Figure G.1 shows two possible locations for connecting the grounding electrode conductor.

For utility-intertie inverters with the case connected to the negative dc input terminal, the system ground connection *should* be made at this point. To do otherwise would create the parallel current paths discussed in Annex H and not allowed by the NEC.

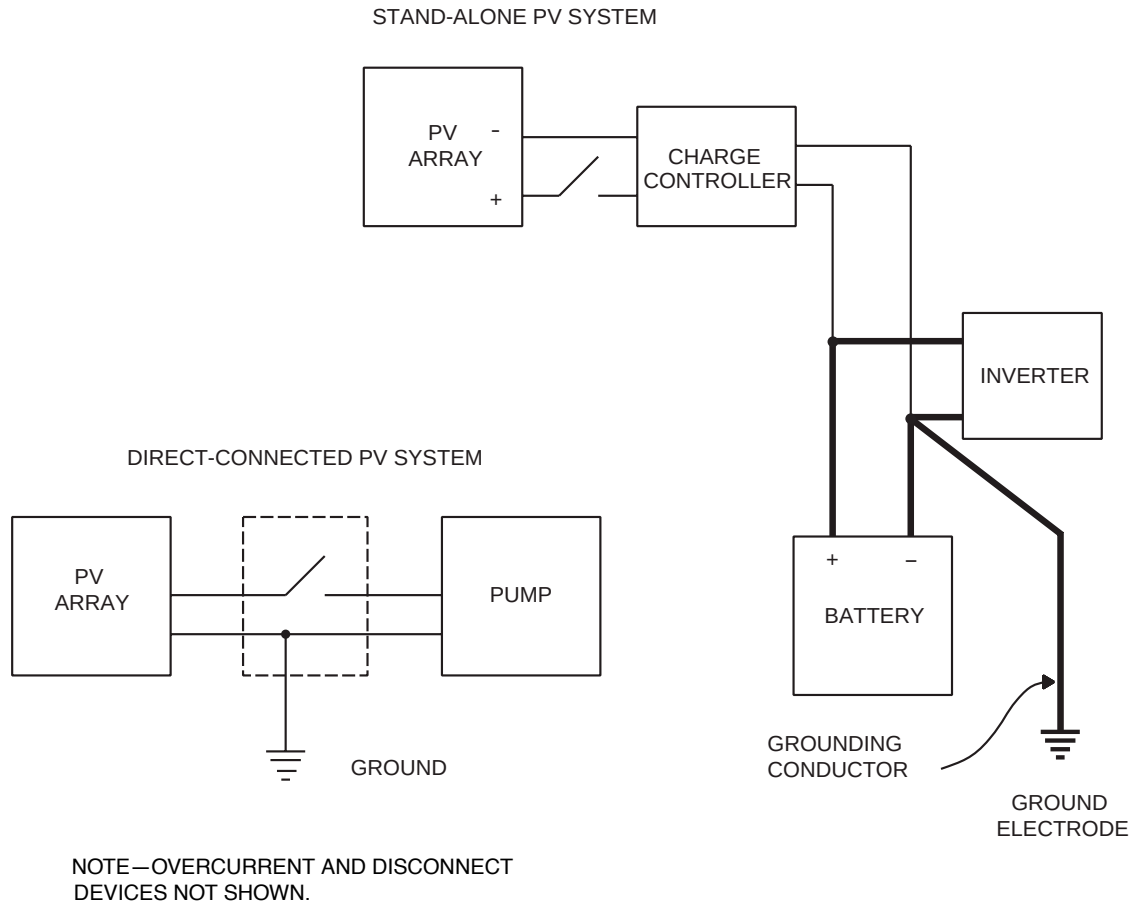


Figure G.1—Example of location of grounding electrode conductor

Annex H

(informative)

Grounding problems and solutions

H.1 Grounding conductors—safety

The equipment-grounding conductors in a system may be insulated or uninsulated (bare) conductors that are grounded. They are intended to carry currents only during fault conditions and are meant to protect personnel from dangerous voltages during faults. When these equipment-grounding conductors are improperly connected, currents flow in these bare conductors during non-fault conditions, which may pose safety problems. When currents flow in these conductors, shock hazards may exist, and equipment damage is possible. Significant electrochemical corrosion may occur in especially damp locations from small currents flowing for long periods of time. Electronic equipment such as TVs, stereos, computers, radio telephones, and PV instrumentation and control systems may not work properly because ground potentials exist.

Improperly connected PV systems may allow currents to flow in these equipment-grounding conductors. With the available equipment (which may have connections to chassis not allowed by UL standards), it is sometimes difficult to avoid these currents. The NEC specifically prohibits connections that result in ground currents and requires that actions be taken to eliminate them. Extra connections to ground should be avoided.

H.2 The equipment

H.2.1 Load centers

An uninsulated copper or aluminum bus bar is installed in most standard ac residential load centers (circuit-breaker enclosure). This bus bar is fastened (electrically connected) to the load center enclosure. All neutral (white insulation) conductors and all equipment-grounding (bare) conductors are connected to the bus bar, and it, in turn, is connected to the grounding electrode or grounding system. This load center internal connection represents *one* connection between the neutral and equipment-grounding (grounding for short) conductors. It is the preferred location for the single system connection between the grounded conductor and the grounding system.

H.2.2 Inverters with and without receptacles

The PV inverter with hard-wired and receptacle outlets should have the neutral connected to the grounding conductor to provide safety for plug-in loads. This represents a second connection between the neutral and grounding conductors. If the inverter is connected to the load center, as described above, there will be two connections between the neutral and the grounding conductors. These two connections place the wires (neutral and equipment grounding) in parallel and allow currents to flow through both—an unsafe situation.

Most inverters with no receptacle outlets have a floating neutral that is not connected to the grounding conductor. When connected (hard wired) to the load center, they work properly and no objectionable currents flow in the grounding conductor.

Standby inverters with receptacle outlets should make the internal bonding connection between neutral and ground when operating as the ac source in the stand-alone inverting mode. When transferring ac power through the inverter (internal transfer switch) from a backup source (such as the grid or an ac generator) to the load, the connection may pose problems. In either case, the internal connection will create parallel paths if the inverter is connected to the load center containing an internal connection, and unwanted ac currents will flow through the equipment-grounding conductors.

Still other inverters have an internal relay that opens the connection between the neutral and grounding conductors when an external power source is used for battery charging. This configuration presumes that the external generator or power source has the necessary ground connection. It also presumes that there is no load center connected that has the internal bonding connection. Some UL standards (marine and RV usage) allow this relay and may even require it, although it may not be a good solution in all installations.

H.2.3 Generators

Most standby generators used in smaller, hybrid PV systems are less than 6 kW and have receptacle outlets and sometimes hard-wired outputs. For safe use of plug-in loads, the neutral and grounding conductors are frequently (but not always) connected internally. This third connection provides another parallel path when the generator is connected to either the load center or the inverter. Generators with only hard-wired outputs may have an optional neutral-to-ground connection at the wiring panel. Some generators do not connect the neutral to the grounding conductor, and the neutral floats all of the time.

Figure H.1 demonstrates some of the possible redundant connections (bonds).

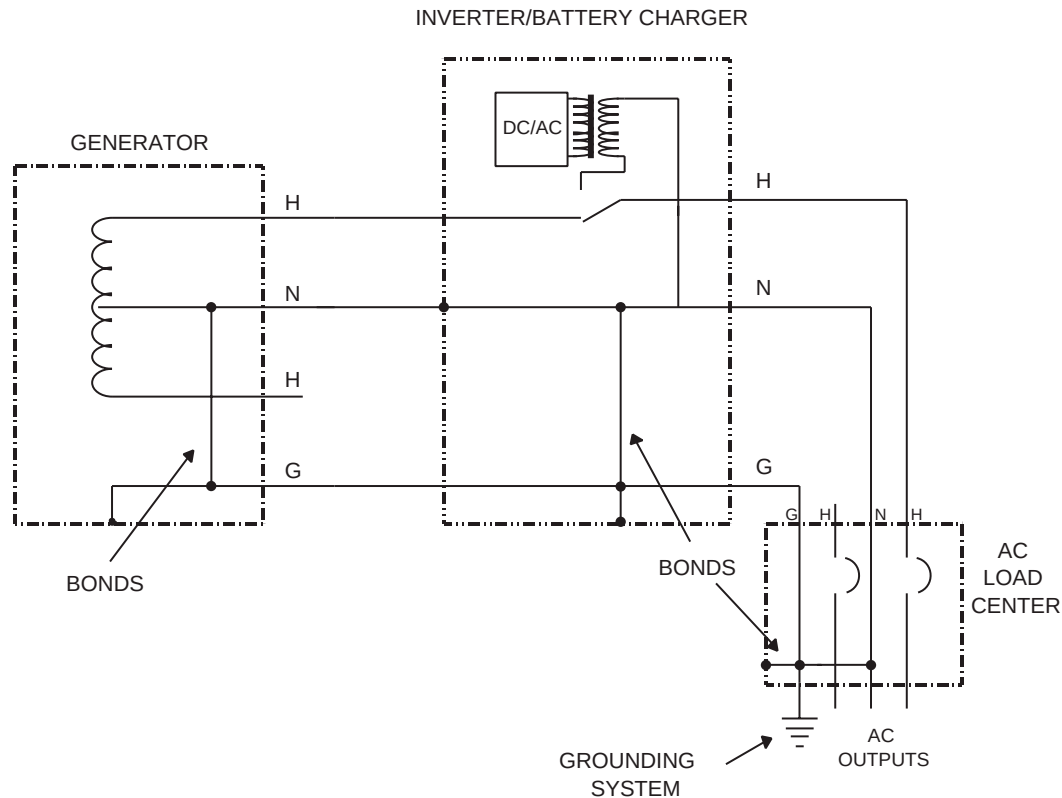


Figure H.1—Multiple redundant grounding connections

H.3 Solutions to grounding problems

Because the equipment that is used in PV systems may not be standardized, and frequently is designed for other purposes (e.g., construction generators), it is difficult to generalize about all possible solutions to grounding problems.

In a stand-alone PV system that provides ac power to a residence, the most durable hardware will be the ac load center. The load center is most likely to be the piece of equipment that will not break and will always be in the system when generators or inverters are down, disconnected, or otherwise not available to the system. The ac load center is also the place where standard residential and commercial systems have the ground/neutral bond, and installers and inspectors are accustomed to it being in that location.

The ac load center should be the single piece of equipment that contains the single connection between the neutral and equipment-grounding conductor. If the connection in the load center is used, there should be no connection in the inverter or in the backup generator. This may require modification of existing inverters and generators. The modifications are best done by the manufacturer.

H.4 Equipment design

In new systems, the equipment (generators and inverters) may be ordered with the required internal configuration that does not require modification. UL is developing a standard (Draft 1741) on PV inverters that should address these issues and should require these devices to be either stand-alone devices with GFCI outlets or hardwired devices to be used with load centers.

H.4.1 Inverters and generators

Inverters and generators that have hardwired outputs only, and that do not have an internal connection between the neutral and grounding conductors, should be used in PV systems. *These devices become part of a permanent installation and the generator and inverter lose any portable, stand-alone capability they may have had unless specifically designed for both applications.* When modified for hard-wire connections and then used as stand-alone devices, there is no longer any return path in the grounding system to trip the overcurrent device when ground-faults occur.

The inverter or generator ac *output* may be hardwired to the transfer switch or the load center with conduit as appropriate.

The load center should have the necessary internal bond between the neutral and ground. Since the ac branch circuit (even if it is just the ac output of the generator) needs overcurrent protection, this load center may be only a single circuit breaker in small systems. The ac system is also grounded in this load center.

One connection between the neutral and grounding conductors is allowed by NEC. That connection should be in the load center, where it normally resides and where the inspector expects to find it. The inverter and generator are hardwired into the system and *can no longer be safely used by themselves*. The load center makes the safety ground connection for the entire system. The ac system-grounding conductor for the grounding electrode goes from the load-center bus bar to the ground rod, just as it does in a conventional ac-only system. If either the inverter or generator is removed for repairs, the ac system remains safely grounded.

Annex I

(informative)

Battery connections

I.1 Sizing

When an attempt is made to minimize the size of the conductors used for wiring battery banks, the voltage drop in the connections and wiring between cells is frequently overlooked. The ampacity calculations are straightforward, but voltage drop calculations are more difficult because the cable and terminal connection resistances are not always known. The problem is further compounded when the lengths of the cables between each cell or battery string in a parallel battery system and the charging source are not equal.

Unequal battery or cell charging may result in over- or undercharging of portions of the battery bank. Overcharging may cause excessive water loss and hydrogen gas evolution which, in turn, may damage batteries and present the possibility of fires and explosions. Undercharging may result in sulfation and loss of battery capacity, which can lead to loads not receiving power when needed.

Figures I.1 and I.2 show cable connections that usually result in all batteries (or cells) receiving equal charge and discharge currents.

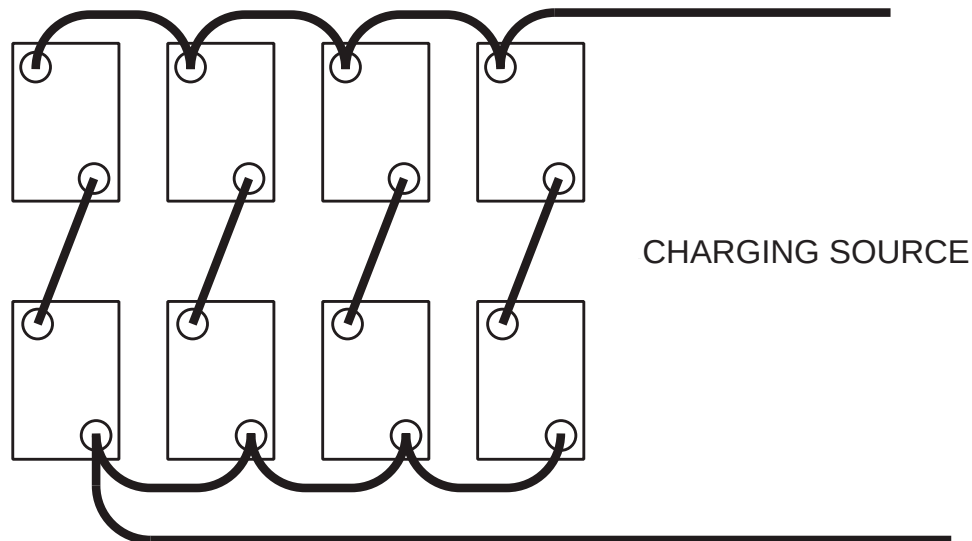


Figure I.1 — Battery connections—equal voltage drops

In Figure I.1, a diagonal connection scheme is used to equalize the voltages. In Figure I.2, equal length conductors are connected between each series string of batteries and a common, low-resistance bus bar or connector. These diagrams assume that good, low-resistance connections are made with corrosion control and periodic cleaning as needed.

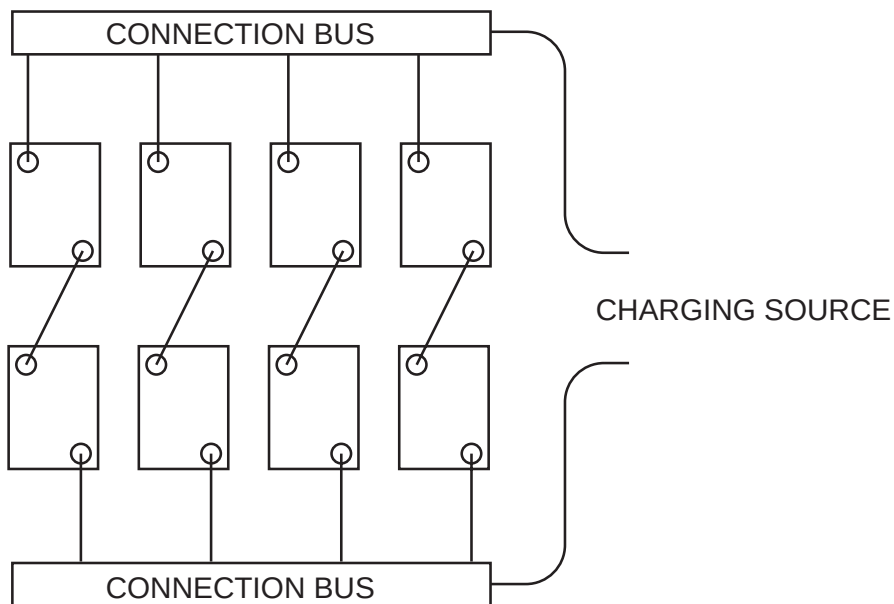


Figure I.2—Battery connections—equal length cables

Figures I.3 and I.4 show cable connections that may result in batteries (or cells) at locations C and D being undercharged with respect to batteries (or cells) at A and B.

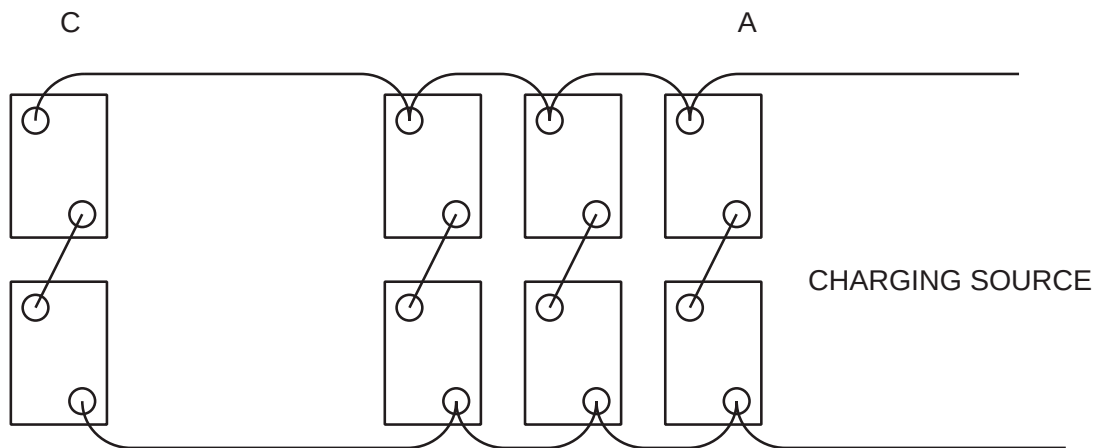


Figure I.3—Battery connections—excessive length

If the battery cables are oversized (above ampacity requirements) to account for momentary surge-current voltage drops, then any of the connection diagrams should work as long as the voltage drops are kept below guidelines established by the battery manufacturers.

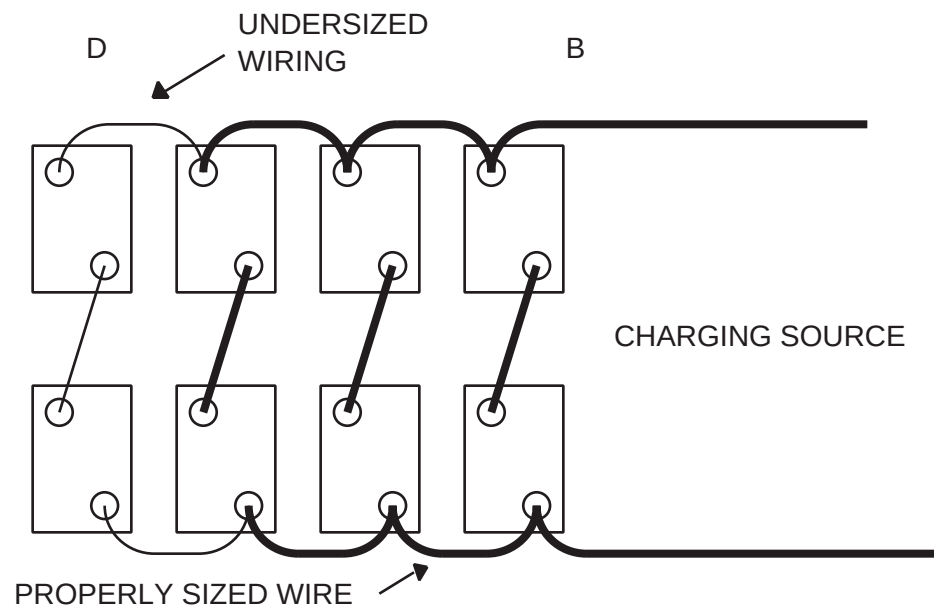


Figure I.4—Battery connections—excessive resistance

Annex J

(informative)

Battery safety considerations

J.1 Safety considerations

The most commonly used batteries in the PV systems are flooded lead-acid batteries and valve-regulated lead-acid batteries (VRLA). The safety considerations below address only these two types of batteries and may not be applicable to other less commonly used types of batteries.

The battery is an electrochemical energy storage device that contains dilute sulfuric acid. It is capable of generating explosive mixtures of oxygen and hydrogen gases. Batteries are also capable of short-circuit currents of up to several thousand amperes. It is prudent to be aware of the potential hazards associated with the application and use of batteries and to take appropriate precautionary measures in the design of the photovoltaic system, the facility, and maintenance procedures.

Federal, state, and local building, electrical, and fire-safety codes should be consulted to determine requirements related to the safe installation of lead-acid battery systems. The battery manufacturer should be consulted for recommendations on installation and maintenance. Seismic certified battery racks may be needed in certain areas.

Flooded lead-acid batteries will evolve oxygen and hydrogen gas as a normal result of charging and the amount of gas evolved increases as the batteries are overcharged. VRLA batteries are designed to contain and recombine these gasses, but venting occurs during high levels of overcharging that exceed the design parameters. Some venting of hydrogen may occur in a VRLA battery as the battery ages.

Levels of hydrogen gas in air from 4% to 96% are explosive, should ignition occur. The battery should not be installed in a closed (sealed) container, nor should potential sources of ignition be allowed in the vicinity of the battery. Adequate ventilation should be provided to prevent an accumulation of hydrogen exceeding 2%. The top of the battery enclosure should be designed to eliminate areas where pockets of hydrogen gas can be trapped. It should be assumed that there is always a potentially explosive mixture of oxygen and hydrogen gas within the cell; so each cell should contain some type of spark-arresting vent system. The cells should not be vented to a common hydrogen venting manifold to the outside. If gases in the plumbing ignite, they could ignite the gases in the individual cells.

Vented cells are sometimes equipped with catalytic vents that recombine the evolved oxygen and hydrogen gas and return the resulting water to the electrolyte. These catalytic vent caps should be sized for the ampere-hour capacity of the cell. They require periodic inspection and maintenance to assure continued operation. Whenever a charge equalization occurs, these caps should be removed and replaced with conventional, flame-arresting vent caps, since the excessive gassing that occurs may result in shortened cap life.

Electrolyte in the battery is electrically conductive, corrosive, and harmful to the eyes and skin. Spilled electrolyte and electrolyte leaking from cracked containers can produce ground faults that can result in personnel shock hazards or fires from shorted cells. Related equipment should contain ground-fault detection circuitry to alert the user to this hazard. Spilled electrolyte should be handled in accordance with the appropriate local, state, and federal regulations covering the installation. A leaking battery cell must be either removed from the system or, if possible, repaired to eliminate the hazard. Damaged batteries and those replaced as a result of maintenance actions should be disposed in accord with the applicable regulations. The facility should contain appropriate eye wash facilities and a spill kit for electrolyte neutralization and cleanup.

VRLA cells have the electrolyte immobilized either in a gel or an absorbent glass mat and, as a result, do not require the same degree of spill protection appropriate for vented cells. Also, they have the capability of recombining the oxygen and suppressing the generation of hydrogen. VRLA batteries will release hydrogen gas if severely overcharged, and similar precautions taken with vented cells should be incorporated in VRLA systems if the possibility of significant overcharging exists.

The VRLA battery oxygen recombination cycle is an exothermic reaction that generates heat. This type of battery has the potential for thermal runaway, wherein it generates heat at a rate faster than it can be dissipated. This can result in deformation of the case and significant emission of gases. When thermal runaway occurs, it is typically the result of extended overcharging, which can be the result of shorted cells, coupled with an elevated temperature of the battery environment and an inadequately ventilated battery enclosure. Thermal runaway can be prevented or arrested by appropriate charging-voltage control including temperature compensation, spacing of the individual batteries to allow for adequate air circulation, adequate ventilation of the battery enclosure, and appropriate periodic maintenance. To arrest thermal runaway, circuitry can be included to disconnect the battery from the charging source should the battery temperature rise significantly above the ambient temperature. IEEE Std 1189-1996 [B1]⁶ provides more detail regarding thermal runaway and its mitigation.

J.2 Summary of equipment and facility safety precautions

The battery system presents significant electrical, chemical, and fire hazards that can be minimized through appropriate facilities and battery system design and application. The design and application should consider the following:

- a) Federal, state, and local building, electrical, and fire-safety codes as well as industry standards;
- b) Appropriate spacing of batteries in an enclosure that provides for adequate ventilation to prevent hydrogen accumulation, and that allows for heat dissipation from the cells;
- c) Short-circuit protection and individual wiring to a common tie-point for each parallel string;
- d) Spark arresting vents for the batteries;
- e) Temperature compensation of the charging voltage;
- f) Charging current interruption in the event the battery temperature should rise significantly above the ambient temperature or should the battery temperature exceed the maximum charging temperature recommended by the battery manufacturer;
- g) Insulation of battery mounting surfaces to minimize the possibility of ground faults and incorporation of ground-fault detection circuitry; use of non-conductive battery cases; and grounding of metal support stands and enclosures for personal safety;
- h) Battery maintenance practices consistent with manufacturer's recommendations to remove spills or accumulated electrolyte;
- i) Battery case compatibility with cleaning compounds;
- j) Appropriate personal safety equipment, such as spill kits and fire protection equipment;
- k) Insulated tools for installation and maintenance.

J.3 Summary of personal safety precautions

Batteries should only be handled by experienced personnel familiar with the associated risks. Batteries present personnel safety risks as related to their electrical capabilities, potential to evolve explosive gases, and acidic electrolyte. To minimize any personal safety risks, the battery handler should consider the following items prior to handling and maintaining the batteries:

⁶The numbers in brackets correspond to those of the bibliography in Annex M.

- a) Proper facility and personal safety equipment—in place and operational;
- b) Full eye protection, rubber gloves, and an apron to protect the eyes and skin from caustic electrolyte;
- c) Self-grounding through the use of metal grounded objects to discharge any accumulated static charge;
- d) Flames, sparks, or other potential sources of ignition in the battery area;
- e) Insulated tools in the area of the battery;
- f) Proper battery handling equipment;
- g) Removal of metal hard hats and jewelry including watches, rings, and chains;
- h) Appropriately rated disconnects—opened prior to replacement of any cells or inter-cell connections;
- i) Industry standard electrical safety practices.

Annex K

(informative)

Surge and transient protection

K.1 Lightning strike protection

Direct and nearby lightning strikes can induce currents and voltages that cause damage to PV modules, inverters, charge controllers, batteries, and other components in the renewable energy system and to the connected load devices. Commercial surge suppression devices are available, but there are no absolute guarantees on methods of preventing lightning damage. There are good engineering practices that should be applied that may reduce the probability of damage from lightning strikes. They have been used for years by radio and TV stations, ham radio operators, remote communication systems, the utility companies, and others. More protection is provided by combinations of protection methods. The cost increases as the degree of protection increases. Refer to the IEEE Surge Protection Standards Collection [B2] for more information.

Although there is little that can be done to protect the renewable energy system from a direct lightning strike, systems can be reasonably protected from surges induced by nearby lightning strikes.

K.2 Grounding for surge and transient suppression

Lightning travels between or from charged clouds to earth or vice versa. The strike occurs when the potential difference between the cloud and the earth exceeds the dielectric strength of the intervening air. Normally, nonconductive objects, such as trees and houses, may serve as conductors to channel the charges and reduce the resistance between the cloud and earth. If the charge is dissipated before the potential increases to breakdown voltage, the lightning strike does not occur.

A tall, metallic structure that is adequately grounded can usually protect an area around its base that has a diameter equal to $1/3$ the height of the pole or structure (this area is called the cone of protection). Therefore, a tall, grounded, metal pole directly behind a PV array (on the north side in the northern hemisphere) may protect the array frame from direct strikes.

These suggestions on surge suppression assume that the PV installation complies with the NEC. The NEC requires that all exposed metal surfaces containing energized conductors be grounded with an equipment grounding system regardless of the nominal system voltage. Systems with PV open-circuit voltages below 50 V are not required to have one of the current-carrying conductors grounded (the system ground). Any system with ac voltages over 50 V should have the neutral grounded (a system ground).

Some inverters do not have isolation between the ac and dc sides, so grounding the ac neutral also grounds the dc negative. Other inverters have the case (which should be grounded) connected to the negative input, which grounds the negative current-carrying conductor when the case is grounded.

Indirect strikes near the PV system may induce surges in the PV modules and in all conductors of the PV system and any other conductors connected to the load. Direct or close strikes on telephone and power lines even miles away may put large surges on these lines leading to the site. The techniques outlined in K.3 through K.8 may reduce the effects of lightning-induced surges on the PV system.

K.3 Equipment grounding

In areas of high lightning activity, the NEC requirements should be augmented to include recommended lightning-protection wiring methods and protection devices. A conductor larger than that recommended by code (not less than #10 AWG) should be fastened to each metallic module frame with a self-threading, stainless-steel screw. Provisions for this connection are found on all modules listed to UL 1703-1993. The other ends of these conductors should be connected to a single point on the array frame or rack—again with another self-threading, stainless-steel screw or with a stainless-steel bolt in a drilled and tapped hole. From this point, a #6 AWG or larger copper conductor should be run directly to the nearest earth-grounding electrode where it is connected to the lowest resistance-grounding electrode that can be afforded. The minimum length for ground rods required by the NEC is 2.4 m (8 ft). A UL-listed clamp should be used to make the connection. A steel well casing, drilled and tapped for connections, can be used for the ground rod.

The NEC requires that the resistance between the ground rod and the earth be no greater than 25 Ω . If the value exceeds this (as measured with an earth resistance tester), then additional ground rods should be added to the system.

In dry areas, lightning protection specialists have found that several ground rods spaced 6–15 m (20–50 ft) apart in a radial configuration bonded to the central rod may be effective. Buried copper water plumbing may also serve to improve the grounding system. Pipe or copper wire (#2 AWG or larger) can be buried in trenches 30–46 cm (12–18 in) deep in a radial grid. All grounding members should be connected or bonded to the central ground rod with heavy, bare conductors buried underground. Direct-burial, UL-listed grounding clamps or exothermic welding should be used for all connections. *Soldering should never be used.* These devices and connections are described in engineering texts on the subject.

Ground rods that contain chemicals to increase the soil conductivity are available from several sources.

On systems that should be grounded, the 1996 NEC requires that the conductor from the grounded current-carrying conductor (usually the center tap or negative lead in a dc system) to the main ground rod be unsplined. It may be as small as #6 AWG in some cases, but larger sizes may provide better surge protection.

K.4 Conductor shielding

Conductors between the PV array and the charge controller or inverter may be routed in metallic conduit to minimize the pickup of induced surges. Routing cables underground also helps to minimize the unwanted induced surges.

Minimizing the size of any circuit loop (lowering the inductance) may also serve to reduce the magnitude of induced transient voltages. Where practical, twisting the conductors of a circuit not only minimizes surge pickup, but also reduces the radiation of undesirable signals.

K.5 Inductors and surge transmission

After a surge is impressed on an electrical conductor, the transmission of this surge may be attenuated or restricted by placing an inductor in the line. Running the conductors from the PV array to the load in grounded metal conduit increases the inductance on these lines and shields them from much of the initial surge pickup. It also attenuates the surges that do get induced. The conductors from the array can be coiled in a loop about 15–30 cm (6–12 in) in diameter, forming an inductor. Five to ten turns should be used in the loop, and the conductors should be tightly held together. This coil could be placed at a location near the entrance of the load building, in a metal box with conduit to and from the box.

K.6 Array disconnect

All systems should have a PV disconnect switch (NEC requirement). This switch has two poles on ungrounded systems and one pole on grounded systems. In an attended system, this switch may be left open when lightning storms are nearby. The 6–12 mm (1/4–1/2 in) gap in the switch provides some protection from surges when open, but a large surge may jump the gap.

K.7 Surge arrestors

Surge arrestors are available in a number of sizes. Generally, the greater the discharge capability the better. These surge arrestors can be connected at both ends of the array-to-controller wiring to bleed surges to ground or absorb them internally. Small quarter-sized units [metal oxide varistors (MOVs)] may be mounted at module junction boxes and inside electronic equipment like inverters and charge controllers. These MOVs should have a clamping voltage above the maximum PV open-circuit voltage. Large units (the size of a frozen orange juice can), which may absorb far more energy from surges, may be mounted on the conductors entering the house or controller box. These units are used to protect 120/240 V service entrances on residences and deep-well pumps. They contain silicon oxide and are sometimes known as silicon oxide varistors (SOVs). Although rated at voltages higher than the typical 12, 24, 36, or 48 V PV system, they may be used to limit the voltage rise to a more manageable level. They are available from many electric supply houses. These units should be connected positive to negative, positive to ground, and negative to ground. In the smaller MOV two-wire units, three separate devices should be used. The larger SOV units have three wires. One is connected to the positive conductor, one to the negative conductor, and one to ground.

Gas discharge tubes and other types of surge arresting devices are available from companies specializing in these technologies. Gas discharge tubes should be fused in dc systems since, once a gas discharge device establishes an arc, the arc will not extinguish unless current is reduced to zero. It is beyond the scope of this guide to define specific device types and their applications.

K.8 Utility and phone lines

If grid power (as a backup or utility intertie) or hard-wired telephone lines serve the load, surge suppression should also be placed on these lines. The large surge arrestors described above may be used on the utility power lines, and special telephone arrestors are available from a number of sources. A single-point ground for all electrical circuits in a facility is recommended by lightning protection specialists.

Annex L

(informative)

References to the NEC

L.1 Applicable sections of this guide to the 1996 NEC

The section numbers listed in Table L.1 and the references to the applicable sections of the 1996 NEC are presented as a guide that can be used for installing PV systems in jurisdictions where the NEC is mandated and enforced. The NEC should be consulted in its entirety for a comprehensive understanding of its contents. Standards from UL are also referenced.

Table L.1—Applicable sections of this guide to the 1996 NEC

Section	Reference NEC section or UL standard	Section	Reference NEC section or UL standard
6.0	Article 300 and 690-D	7.2	110-9, 690-7, and 690-9
6.1	690-31(a)	7.3	690-9 FPN, UL 198B-1995 [B3], UL 198C-1986 [B4], UL 198D-1995 [B5], UL 198E-1988 [B6], UL 198F-1995 [B7], UL 198G-1988 [B8], UL 198H-1988 [B9], UL 198L-1995 [B10], UL 198M-1995 [B11], and UL 489-1991 [B12]
6.1.1	310-13 FPN, 318-11, 340-4, 340-5, 340-7, Table 400-4, 400-6(b), 400-7(a)(10), 402-5, 630E, 690-31(b), and UL Marking Guide, Wire, and Cable [B13]	7.4	110-9, 240-11, 690-7, and 690-8
6.1.2	Table 310-16, Table 310-17, and 690-8	8.1	230-71, 230-72, 422-25, 690-13, and 690-15
6.1.3	110-14(c), 310-10, Table 310-16, and Table 310-17	8.2	690-7, 690-7(c), 690-8, and 690-17
6.2	200-6(a)(b), 210-5(b), 215-8, 300-15(b)	8.3	690-17
6.3.1 ⁴	300-3(a), 310-3, 310-4, 310-9, Table 310-16 (Note 8), Table 310-17 (Note 8), 339-3(b)(5), 400-8, 630E	8.4	384-16(f) and 690-64(b)(5)
6.3.2	300-3(a), 300-3(b), 300-4, 310-10, Table 310-16 (Note 8), and Table 310-17 (Note 8)	9.2	690-41
6.3.3	690-8	9.3	250-21
7.0	690-9	9.4	690-5

L.2 Applicable section of the 1996 NEC to this guide

Table L.2 presents a reverse cross-reference from the NEC to this guide.

Table L.2—Applicable sections of the 1996 NEC to this guide

NEC section or UL standard	Reference document section	NEC section or UL standard	Reference document section
110-9	7.2 and 7.4	400-7(a)(10)	6.1.1
110-14(c)	6.1.3	400-8	6.3.1
200-6(a)(b)	6.2	402-5	6.1.1
210-5(b)	6.2	422-25	8.1
215-8	6.2	630E	6.1.1 and 6.3.1
230-71	8.1	690-5	9.4
230-72	8.1	690-7	7.2, 7.4 and 8.2
240-11	7.4	690-7(c)	8.2
250-21	9.3	690-8	6.1.2, 6.3.3, 7.4, and 8.2
Article 300	6.0	690-9	7.0 and 7.2
300-3(a)	6.3.1 and 6.3.2	690-9 FPN	7.3
300-3(b)	6.3.2	690-13	8.1
300-4	6.3.2	690-15	8.1
300-15(b)	6.2	690-17	8.2 and 8.3
310-3	6.3.1	690-D	6.0
310-4	6.3.1	690-31(a)	6.1
310-9	6.3.1	690-31(b)	6.1.1
310-10	6.1.3 and 6.3.2	690-41	9.2
310-13 FPN	6.1.1	690-64(b)(5)	8.4
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Annex M

(informative)

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[B4] UL 198C-1986, High-Interrupting-Capacity Fuses, Current-Limiting Types (DoD).

[B5] UL 198D-1995, Class K Fuses.

[B6] UL 198E-1988, Class R Fuses (DoD).

[B7] UL 198F-1995, Plug Fuses.

[B8] UL 198G-1988, Fuses for Supplementary Overcurrent Protection.

[B9] UL 198H-1988, Class T Fuses (DoD).

[B10] UL 198L-1995, D-C Fuses for Industrial Use.

[B11] UL 198M-1995, Mine-Duty Fuses.

[B12] UL 489-1991 Molded-Case Circuit Breakers and Circuit-Breaker Enclosures (DoD).

[B13] UL Marking Guide, Wire, and Cable.