

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.

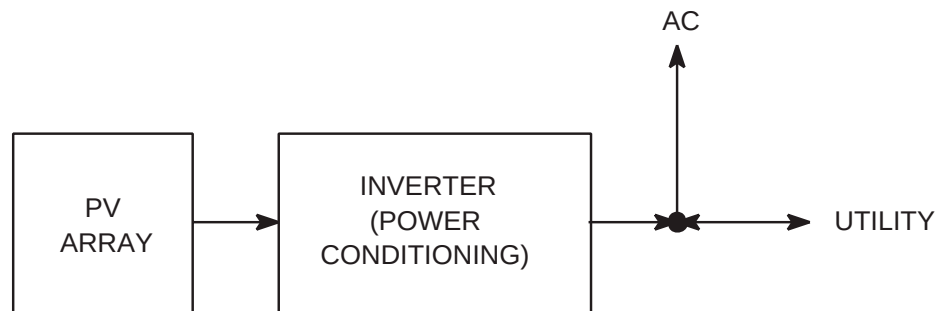
IEEE Std 928-1986 (Reaff 1991), IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems.

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.



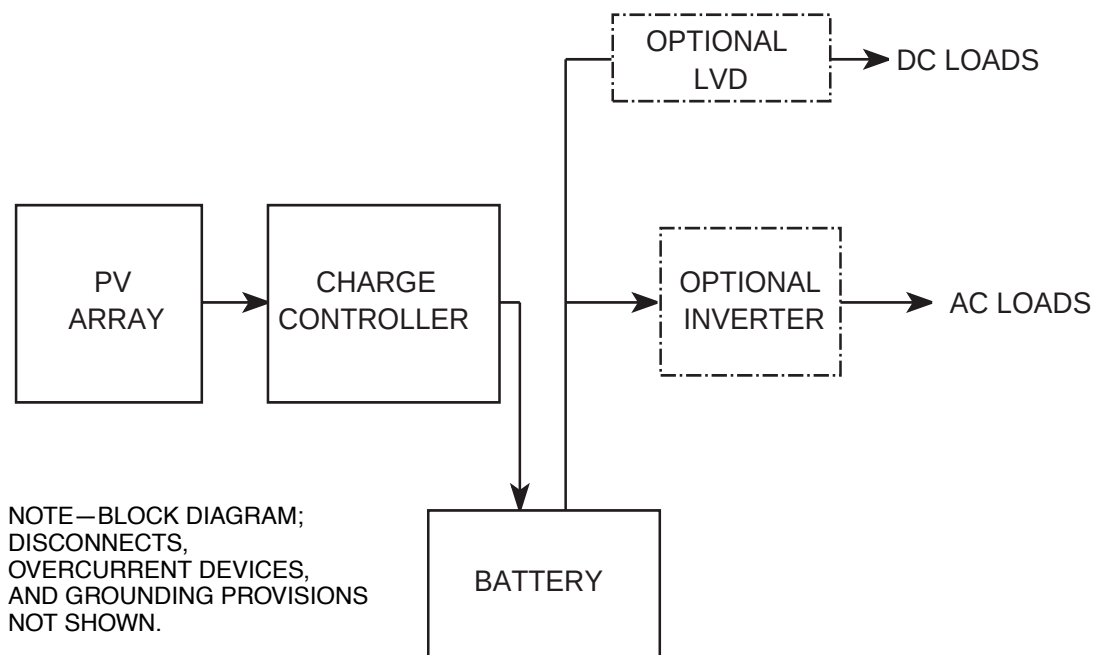
NOTE—BLOCK DIAGRAM;
DISCONNECTS, OVERCURRENT
DEVICES, AND GROUNDING
PROVISIONS NOT SHOWN.

Figure 1—Example of utility-intertie system

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

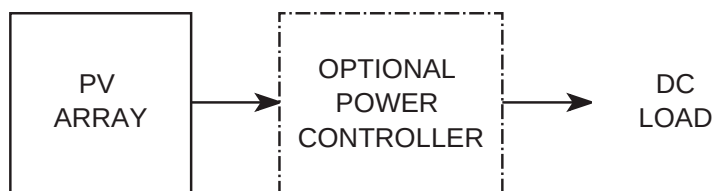
- Stand-alone (PV plus storage) (Figure 2);
- Direct-connected (PV-to-load with no storage) (Figure 3);
- Hybrid (PV and other optional renewable energy source plus non-renewable backup generator) (Figure 4).

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

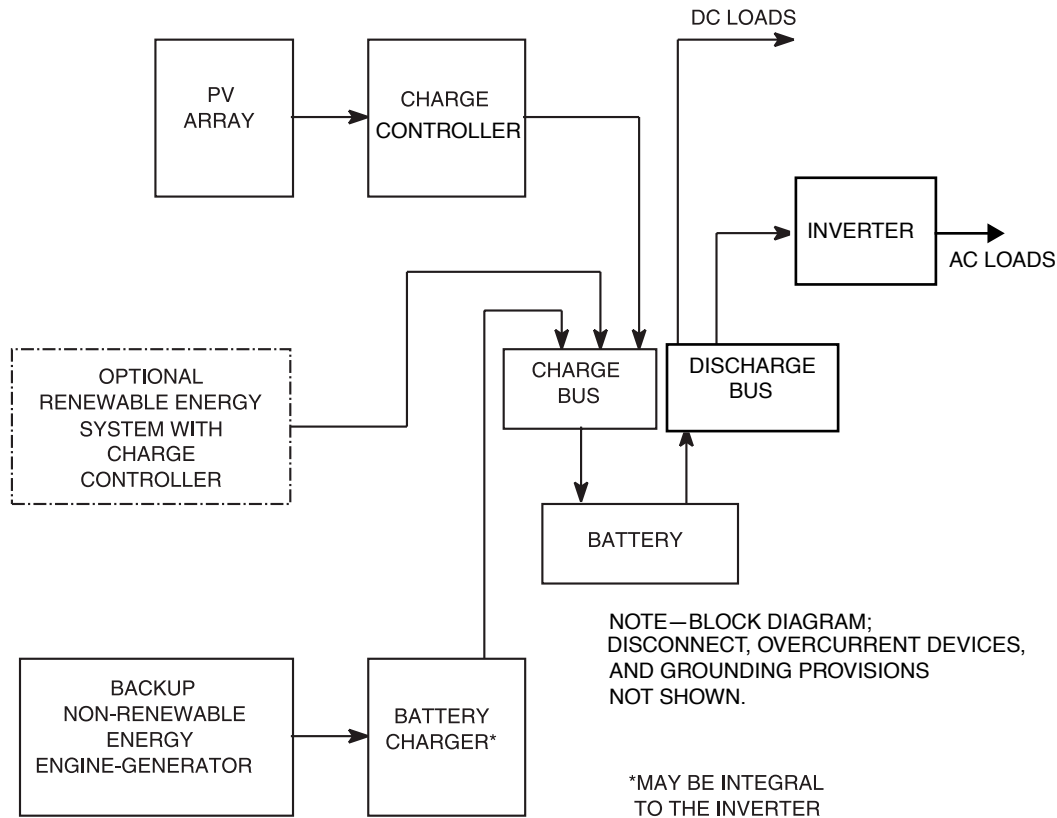


Figure 4—Example of one type of hybrid PV system

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.

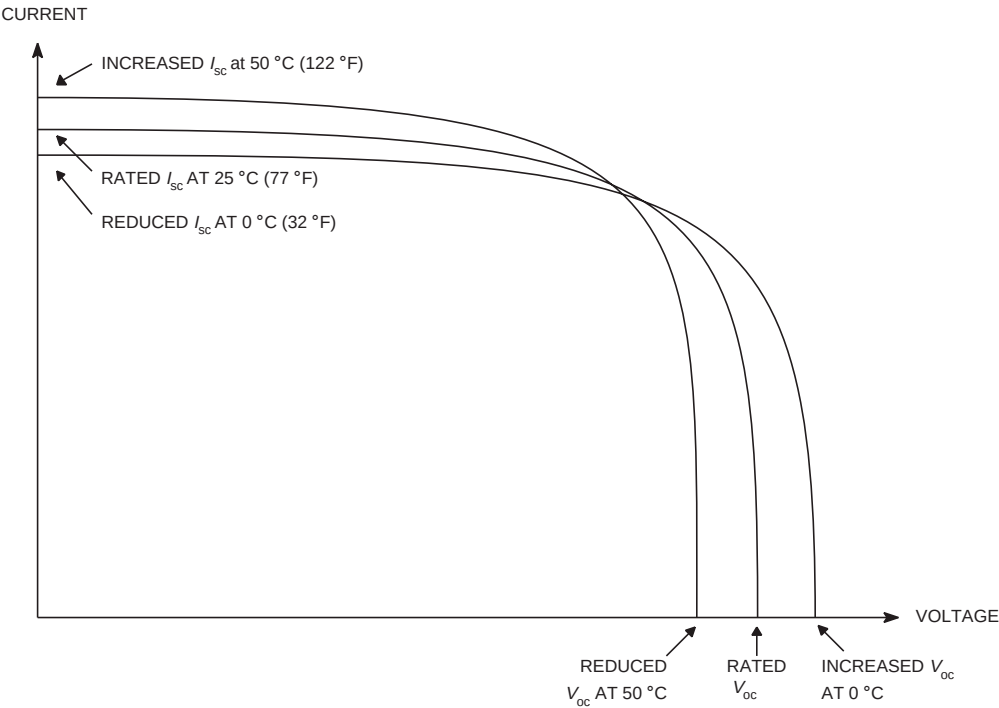


Figure 5—Effect of temperature on PV module parameters

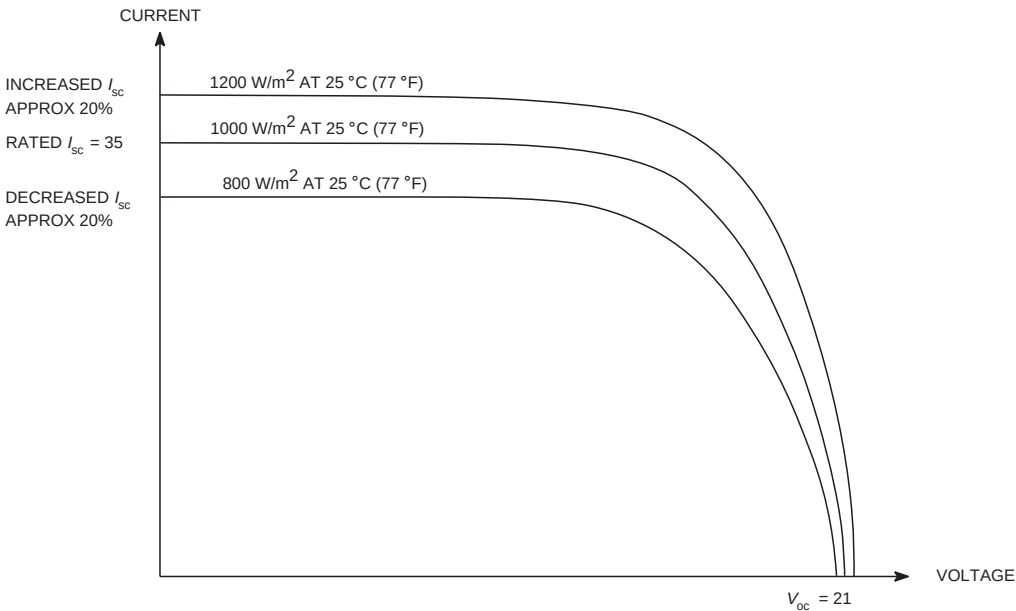


Figure 6—Effect of irradiance on PV module parameters

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.

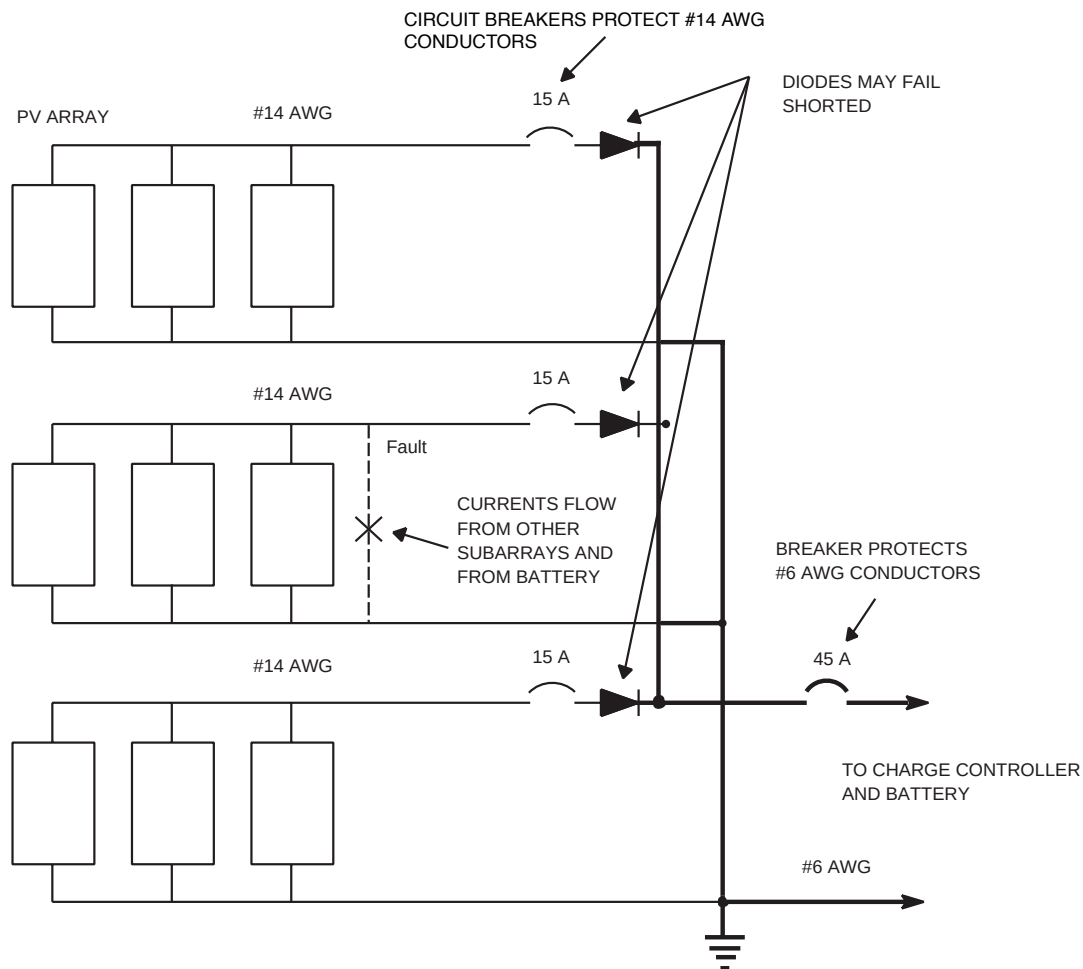


Figure 7—Overcurrent protection and fault in module wiring

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.