PHOTOVOLTAIC FUSE SIZING

How to Calculate Fuse Sizes for Photovoltaic Installations

TECHNICAL PAPER

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Introduction

Every photovoltaic (PV) power application must use fuses that are properly sized to its system. When you use the incorrect fuse size (or a standard non-PV fuse), you put the system's reliability and safety in jeopardy. Due to the explosive growth in PV system power, understanding how to properly size a fuse for a PV application is essential.

This paper provides insight into how fuse sizes affect PV applications, and how to calculate the correct fuse size for PV equipment. This paper will go over NEC's method for how to size a fuse to a PV system. There are other methods, such as that found in IEC 60269-5-19, Low-voltage fuses - Part 5: Guidance for the Application of Low-Voltage Fuses. If you are interested in using a different method, contact the Littelfuse Techline.

Acronyms

AC	alternating current
DC	direct current
IEC	International Electrical Code
NEC	National Electrical Code
PV	photovoltaic
MPPT	maximum power point tracking

Why PV Installations Require a Specific Type of Fuse

Fuses can only provide proper protection against reverse currents and circuit faults (which can cause personnel injury, power outages, equipment failure, and property damage) if they are the correct size for the system. The maximum circuit current and system voltage are important factors to determine which fuses can protect these systems.

PV applications require fuses that can protect against overcurrents, reverse currents and short circuits, against which standard fuses would not provide adequate protection. Therefore, you must use fuses that are specifically designed for PV installations.

Solar Applications

A Central Inverter
600-volt to 1500-volt Fuses
Power Distribution Blocks
Dc Earth Leakage/Gound-Fault Relays
Varistor Products
Surge Protective Devices
1000-volt to 1500-volt High-Speed Semicondutor Fuses
Temperature Sensors

B String Inverter
600-volt to 1000-volt Fuses
Touch-Safe Fuse Holders
Power Distribution Blocks
Varistor Products
Surge Protective Devices
Dc Disconnect Switches
Temperature Sensors

C Wiring Harness
1000-volt to 1500-volt In-Line Fuses

D Small Inverter
TVS Diodes/SCRs
Varistor Products
Temperature Sensors

E Micro Inverter & Solar Shingles
TVS Diodes/SCRs
Varistor Products
Temperature Sensors
86-volt Surface-Mount Fuse

F Combiner Box
1000-volt to 1500-volt Fuses
Touch-Safe Fuse Holders
Power Distribution Blocks
Surge Protective Devices
Dc Disconnect Switches

G Array Combiner
1000-volt to 1500-volt Fuses
Fuse Blocks
Touch-Safe Fuse Holders
Surge Protective Devices
Dc Disconnect Switches

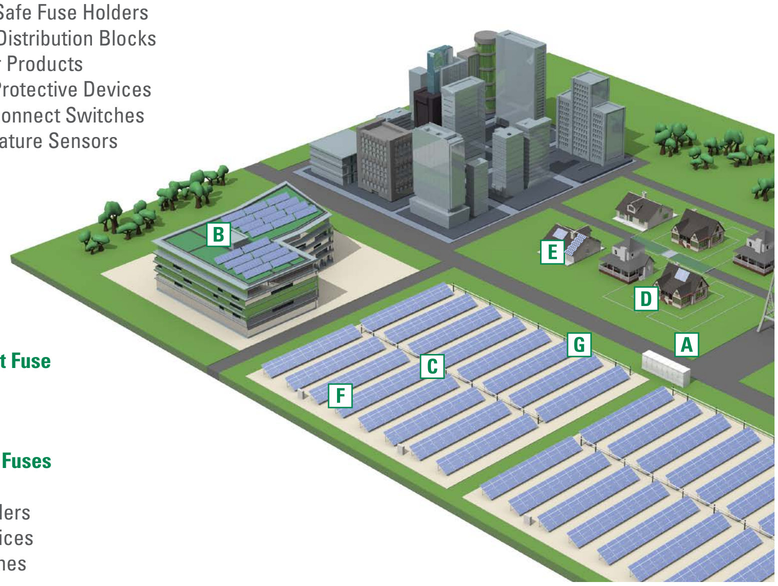

FIGURE 1. Fuse locations in a standard PV application.

As shown in **Figure 1**, PV fuses protect

- Central inverters,
- Small inverters,
- Micro inverters,
- String inverters,
- Wiring harnesses,
- Combiner boxes, and
- Array combiners.

Why PV Applications Specifically Require PV Fuses

Due to the unique conditions of PV installations, PV fuses have three characteristics that are unnecessary in non-PV applications:

- A higher dc voltage rating
- The ability to withstand harsh, fluctuating temperature changes
- Improved current cycling

A Higher Dc Voltage Rating

Before PV power became a significant source of utility energy generation, most low-voltage dc systems used 300 V dc and below. The physical size of most PV installations has grown immensely since then, and in turn, so has the amount of power these systems generate.

PV fuses are currently required to have voltage levels between 450 V dc and 1500 V dc, which enables them to protect higher power modules. This increase in system voltages is intended to minimize any power loss associated with long conductor runs.

The Ability to Withstand Harsh, Fluctuating Temperature Changes

PV fuses can operate in a wide temperature range, from an extreme cold of -40 °C to an extreme heat of +90 °C. In some regions, PV power systems need to function where extreme temperature variations occur in repeated daytime or nighttime cycles. Therefore, the thermal cycling capability of PV fuses is important to these systems' safety and long-term reliability.

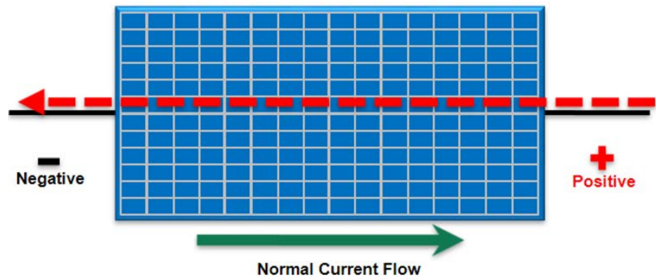

FIGURE 2. Reverse overcurrents occur when power flows back from the circuit to its source.

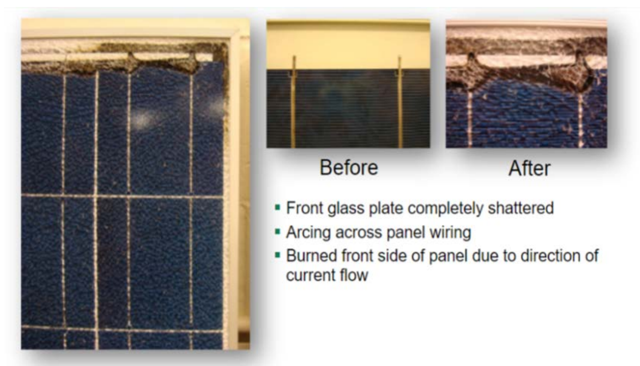

FIGURE 3. Polysilicon panel failures include glass destruction, arcing and burning of panels

Improved Current Cycling

PV panels and circuits are subject to inconsistent current levels when sunrise, sunset, clouds, and stormy weathercause fluctuations in power generation. Under these weather conditions, the inconsistent current levels create current cycling, which non-PV fuses are neither designed for nor tested to protect against. Using non-PV fuses under these weather conditions would therefore create nuisance tripping.

Standard fuses also do not provide sufficient protection against periods of low-overload currents, which are more typical in PV applications than in non-PV applications. PV fuses can eliminate reverse currents and short circuits that would otherwise lead to overheating during low-overload fault conditions.

Therefore, only fuses designed for PV systems may be used in these applications. The result is better longevity, reliability, and safety for the PV power equipment.

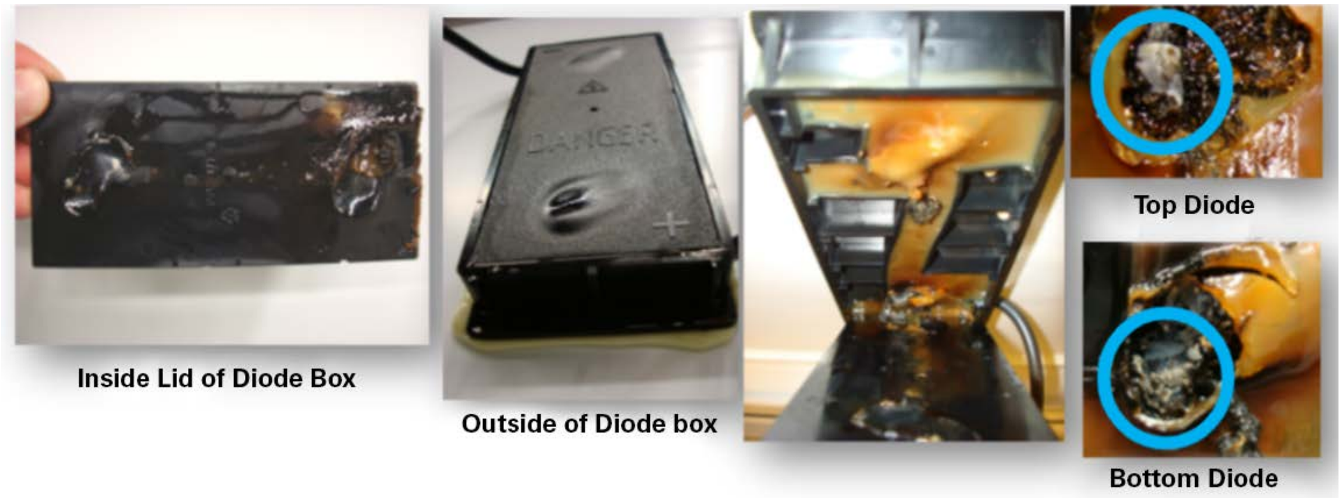

FIGURE 4. Thin-film panel failures result in heat damage to thermal gel and blocking diodes

PV Panel Failure

What Causes Failure in PV Panels

Reverse overcurrents are one of the primary causes of PV panel failure. An overheated PV panel caused by a lack of fuse protection is subject to melting, arcing, fire, and heat-damaged equipment and property.

How Reverse Overcurrents Occur

The green arrow in **Figure 2** indicates the normal flow of power. The red arrow shows the reverse current flow when an electrical fault occurs. In these conditions, unrestricted current will cause overheating to wires, equipment, and potential damage to associated property.

How Reverse Overcurrents Affect Different Types of PV Panels

The most common types of PV panels include thin-film, polysilicon and mono-silicon panels. Due to their respective material construction, each is impacted by reverse overcurrents differently.

Polysilicon PV Panel Failure

In **Figure 3,** heat from a sustained overload current caused the polysilicon panel's front glass to shatter and the panel wiring to burn. This type of incident can lead to an electrical fire, which can be destructive to equipment and deadly to any person who is present at the time of the incident.

Exception for Crystalline Silicon Modules

For crystalline silicon modules, rather than using the ambient temperature correction factor formula, refer to NEC table 690.7(A) (see Table 690 below) to determine these values at different temperature ranges.

TABLE 690.7 (a) voltage correction factors for crystalline and multicrystalline silicon modules

CORRECTION FACTORS FOR AMBIENT TEMPERATURES BELOW 25 °C	
AMBIENT TEMPERATURE (°C)	FACTOR
24 to 20	1.02
19 to 15	1.04
14 to 10	1.06
9 to 5	1.08
4 to 0	1.10
-1 to -5	1.12
-6 to -10	1.14
-11 to -15	1.16
-16 to -20	1.18
-21 to -25	1.20
-26 to -30	1.21
-31 to -35	1.23
-36 to -40	1.25

Thin-Film PV Panel Failure

As shown in **Figure 4**, a sustained low overload current caused the thin-film panel's thermal gel to overheat, which deformed the diode box. The diodes were still somewhat functional, but had there been a sustained current, then the diodes would have been destroyed beyond function and there could have been a fire. The panel became unusable as a result.

Mono-Silicon PV Panel Failure

In **Figure 5**, a sustained reverse current burned the back part of the panel. An overcurrent caused arcing across the panel cells, and the blocking diodes were destroyed from overheating.

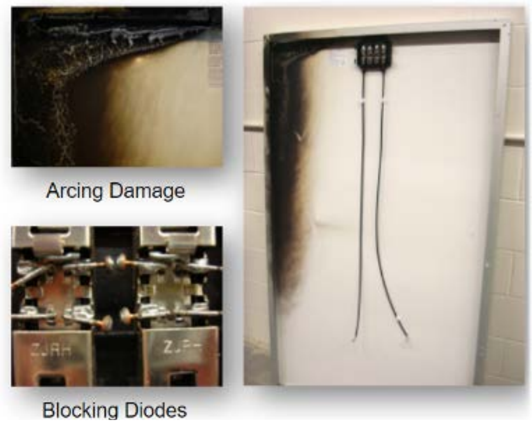

FIGURE 5. Mono-silicon panel failures include arcing, burning and diode destruction.

Fuse Sizing

You can calculate the correct fuse size by using the following steps. This formula ensures the fuse is sized for the optimal protection and energy efficiency.

Step 1

Determine the Maximum System Voltage

Normally, the maximum system voltage is provided by the module manufacturer on the label (or nameplate) or the data sheet.

If the manufacturer did not provide the module's maximum system voltage, then you must calculate the ambient temperature correction factor using the formula:

$$T_{atcf} = 1 + \frac{(T_{stc} - T_{lat}) \times T_{voc}}{100} \qquad (1)$$

where:

T_{atcf}	Ambient temperature correction factor.
T_{stc}	Standard testing conditions temperature (25 °C).
T_{lat}	Lowest expected ambient temperature (°C).
T_{voc}	Open circuit voltage temperature coefficient (%/ °C).

The ambient temperature correction calculation compensates for potential variations that are caused by climatic or other weather conditions.

After you calculate the ambient temperature correction factor, determine the maximum system voltage with the formula:

$$V_{SYS} = N \times V_{oc} \times T_{atcf} \qquad (2)$$

where:

V_{SYS}	Maximum system voltage.
N	Number of modules in the string.
V_{oc}	Open-circuit voltage.
T_{atcf}	Ambient temperature correction factor, which was calculated using formula (1).

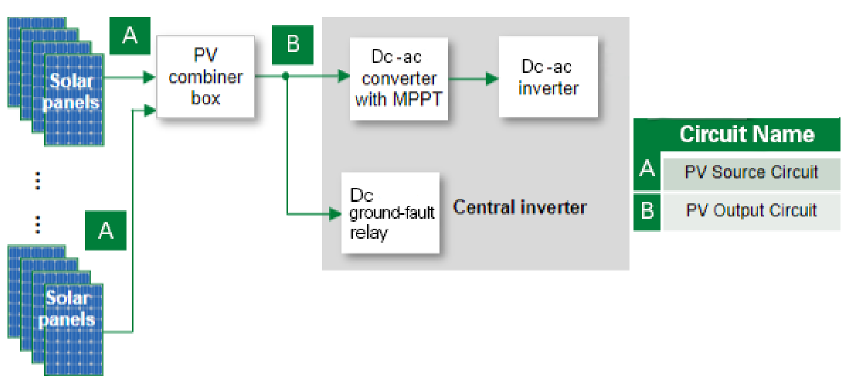

FIGURE 6. The formulas for fuses in the source circuit (A) and the output circuit (B) are different.

The fuse voltage must be equal to or greater than the determined voltage using (2). You can determine the next highest standard fuse rating with NEC 240.4(B).

Step 2

Determine the Maximum Circuit Current

The formula to determine the maximum circuit current is different for fuses located in the PV source circuit versus fuses in the PV output circuit (see **Figure 6**).

PV Source Circuits

In a source circuit, the maximum circuit current is 125 % of the short-circuit current of the module (as per NEC 690.8(A)(1)). This is to correct for the increased current output of modules around solar noon. (In field-installed conditions, PV modules are known to generate short-circuit currents higher than the rated short-circuit for more than three hours near solar noon.)

To determine the maximum circuit current for fuses located in PV source circuits, use the formula:

$$I_m = 1.25 \times I_{sc} \tag{3}$$

where:

I_m	maximum circuit current.
I_{sc}	string short-circuit current.

When the irradiance (the heat flux density, which is measured in watt per square meter) is higher than the standard testing conditions, the module or the string short-circuit current (I_{sc}) will also be higher than the standard testing conditions.

When the irradiance is lower than the standard testing conditions, the short-circuit current will also be lower.

PV Output Circuits

NEC 690.8(A)(2) says that the maximum circuit current shall be the sum of a parallel source circuit as calculated in 690.8(A)(1).

If we consider ***N*** strings, this implies:

$$I_m = 1.25 \times (I_{sc1} + \dots + I_{scN}) \tag{4}$$

where:

I_m	maximum circuit current.
I_{sc1}	string #1 short-circuit current.
I_{sc}	string short-circuit current.
N	number of modules in the string.

For fuses in the output circuit, with N source circuits in parallel, the maximum circuit current will be 125 % times the sum of all the short-circuit currents of the source circuits.

Step 3

Determine the Fuse Amperage

For safety and longer product life, fuses should not continuously carry currents that are more than 80 % of their current rating. NEC 690.9(B) says the current rating (I_n) of PV fuses should be at least 125 % of the maximum circuit current (I_m) calculated as defined in 690.8(A).

MODEL TYPES AND RATINGS AT STANDARD TEST CONDITIONS (1000 W/M², AM 1.5, 25 C)[2]								
NOMINAL VALUES		**FS-6420 FS-6420A**	**FS-6425 FS-6425A**	**FS-6430 FS-6430A**	**FS-6435 FS-6435A**	**FS-6440 FS-6440A**	**FS-6445 FS-6445A**	**FS-6450 FS-6450A**
Nominal Power3 (-0/+5%)	P_{MAX} (W)	420.00	425.00	430.00	435.00	440.00	445.00	450.00
Efficientcy (%)	%	17.00	17.20	17.40	17.60	17.80	18.00	18.20
Voltage at P_{MAX}	V_{MAX} (V)	180.40	181.50	182.60	183.60	184.70	185.70	186.80
Current at P_{MAX}	I_{MAX} (A)	2.33	2.34	2.36	2.37	2.38	2.40	2.41
Open-Circuit Voltage	V_{OC} (V)	218.50	218.90	219.20	219.60	220.00	220.40	221.10
Short-Circuit Current	I_{SC} (A)	2.54	2.54	2.54	2.55	2.55	2.56	2.57
Limiting Reverse Current	I_R (A)	5.00						
Maximum Series Fuse	I_{CF} (A)	5.00						

FIGURE 7. Sample solar module datasheet.

$$I_n = 1.25 \times I_m \quad (5)$$

where:

I_n current rating.

I_m maximum circuit current.

Use formula (6) to calculate the current ratings for the fuses located in the PV source circuit, and formula (7) for the fuses located in the PV output circuit.

PV Source Circuit

If the fuse is in a PV source circuit, use the formula

$$I_n = 1.56 \times I_{sc} \quad (6)$$

where:

I_n current rating

I_{sc} string short-circuit current.

PV Output Circuit

If the fuse is in a PV output circuit, use the formula

$$I_n = 1.56 \times (I_{sc1} + \ldots + I_{scN}) \quad (7)$$

where:

I_n current rating

I_{sc} string short-circuit current.

N number of modules in the string

Step 4

Determine the Fuse's Temperature De-Rating

If a fuse is to be installed in ambient temperatures that are higher than the standard testing condition, then a de-rate factor, which is provided by the fuse manufacturer on a fuse rerating curve, must be applied accordingly.

If the manufacturer has not provided the de-rate factor, deduce it from the rerate curve then use the formula

$$T_{df} = \frac{de-rate\,\%}{100} \quad (8)$$

where:

T_{df} de-rate factor.

and then: $$I_n = 1 + \frac{(1.56 \times I_{sc})}{1 - T_{df}} \quad (9)$$

where:

I_n current rating.

I_{sc} string short-circuit current.

T_{df} de-rate factor.

Step 5

Determine the Fuse Size

If the current rating is not a standard fuse ampere rating, choose the next highest standard fuse rating according to NEC 240.4(B).

Fuse Sizing Exercise for PV Applications

In this example, we will use information obtained from a solar module datasheet and apply the formulas that were outlined in the previous section (see **Figure 7**).

In this example, let's assume each string is made up of six 450-watt modules in series and the lowest expected ambient temperature in the installation location is -15 °C.

Step 1 Exercise for PV application

Determine the Maximum System Voltage

Since the manufacturer did not provide the maximum system voltage, we will first determine the ambient temperature correction factor using formula (1).

Using the datasheet information given in Figure DATASHEET, we know the voltage temperature coefficient (T_{VOC}) is -0.28 %/ °C

$$T_{atcf} = 1 + \frac{(25\,°C - (-15\,°C)) \times 0.28\,\%}{100} \quad (1)$$

$$T_{atcf} = 1.112$$

Based on (1), the voltage ambient temperature correction factor (T_{atcf}) is 1.112.

Now that we have the voltage ambient temperature correction factor, we can use it to determine the maximum system voltage (V_{SYS}) using formula (2).

where:

N	6 modules
V_{oc}	221.1
T_{atcf}	1.112

therefore,

$$V_m = 6 \times 221.1 \times 1.112 \quad (2)$$

$$V_{SYS} = 1475.18 \text{ V}$$

Based on (2), the maximum system voltage is 1475.18 V.

Since the current rating (I_n) factor does not equal the typical fuse ampere rating, we will use the next highest standard fuse rating according to NEC 240.4(B), which is 1500 V dc.

Step 2 Exercise for PV application

Determine the Maximum Circuit Current

For the 450-watt module, the string short-circuit current (I_{sc}) is 2.57 A. The fuses will be located in the PV source circuit, so we will use (3) to determine the maximum circuit current (I_m).

$$I_m = 1.25 \times 2.57 \quad (3)$$

$$I_m = 3.2125$$

Step 3 Exercise for PV application

Determine the Fuse Amperage

To determine the fuse amperage, we will use (5).

where:

I_m	3.2125

$$I_n = 1.25 \times 3.2125 \quad (5)$$

$$I_n = 4.016$$

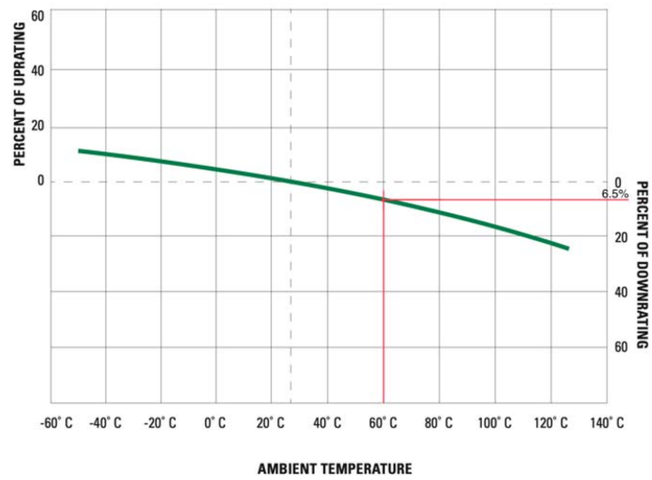

FIGURE 8. Percent of uprating and downrating according to ambient temperature.

Step 4 Exercise for PV application

Determine the Fuse's Temperature De-Rating

Assume the maximum ambient temperature is 60 °C. Then, we can use the fuse de-rate curve (see **Figure 8**) to determine the de-rate percentage, which is 6.5 %.

In this exercise, the fuse is going to be installed in ambient temperatures that are higher than the standard testing conditions. Since the manufacturer has not provided the de-rate factor (T_{df}), we will use (8) to find it.

where:

De-rate %	6.5 %

$$T_{df} = \frac{6.5\ \%}{100} \quad (8)$$

$$T_{df} = 0.065$$

Now that we have the de-rate factor, we can apply (9) to determine the fuse's temperature de-rating (I_n).

where:

I_{sc}	2.57
T_{df}	0.065

$$I_n = \frac{1.56 \times 2.57}{1 - 0.065} \quad (9)$$

$$I_n = 4.29 \text{ A}$$

Step 5 Exercise for PV application

Determine the Fuse Size

Based on (9), the fuse current rating (I_n) is 4.29 A. Because this is not a typical fuse rating, we will select the next highest fuse size according to NEC 240.4 (B), which is 5 A.

PV Fuse Exceptions

There are exceptions to the rules about the need for PV fuse protection:

- NEC (690.9) (A) says that overcurrent devices are not required for PV modules, PV source circuits, or dc-to-dc converter source circuit conductors when they have sufficient ampacity for the highest available current.
- Fuses are not typically needed when there are no external sources (such as in parallel-connected PV source circuits, energy storage systems, or in the backfeed from the inverters).
- When the PV source circuits or the PV output circuits have one or two strings of PV modules connected in parallel, fuses are not required.
- PV fuses are also not required when short circuit-currents from all of the combined sources does not exceed the conductor's ampacity.

For more information on PV system protection, please visit Littelfuse.com/solar

Definitions

Alternating-current (ac) photovoltaic (PV) module: A complete, environmentally protected unit consisting of solar cells, optics, inverter, and other components, exclusive of tracker, designed to generate ac power when exposed to sunlight.

Ambient temperatures: The air temperature immediately around the PV equipment, a factor measured both directly and mathematically to prevent equipment damage, especially with the overheating of metals and other materials that are contained in the PV equipment.

Array: A mechanically integrated assembly of module(s) or panel(s) with a support structure and foundation, tracker, and other components, as required to form a dc or ac power-producing unit.

Central inverters: The core of a PV system, the central inverter converts the dc output from PV panels into ac electricity. A central inverter also controls the PV array system. The central inverter is usually stationed near the main electrical service switchboard away from potentially harmful environmental conditions.

Circuit faults: The failure of PV power equipment to handle the volume or direction of available current.

Dc-to-dc converter: A device installed in the PV source circuit or the PV output circuit that can provide an output dc voltage and current at a higher or a lower value than the input dc voltage and current.

Dc-to-dc converter output circuit: Circuit conductors between the dc-to-dc converter source circuits(s) and the inverter or dc utilization equipment.

Dc-to-dc converter source circuit: Circuits between dc-to-dc converters and from dc-to-dc converters to the common connection point(s) of the dc system.

Direct-current (dc) combiner: A device used in the PV source and the PV output circuits to combine two or more dc circuit inputs and provide one dc circuit output.

Fuse amperage: The level of current a PV or other type of fuse is designed to handle.

Inverter: Equipment that is used to change voltage level or waveform, or both, of electrical energy. Commonly, an inverter (also known as a *power conditioning unit* or a *power conversion system*) is a device that changes dc input to an ac output. Inverters may also function as battery chargers that use ac from another source and convert it into dc for charging batteries.

Inverter output circuit: Conductors connected to the ac output of an inverter.

Label or nameplate: The factory designation of the maximum system voltage listed on a fuse product.

Low overload current: Occurs when a system imbalance permits the power to flow back from the circuit to its source.

Maximum circuit current: The total anticipated wattage in a PV system.

Maximum system voltage: The volume and level of power expected within a system. The maximum voltage of PV system dc circuits is the highest known voltage between two circuit conductors and any conductor and ground.

Micro-inverters: Micro-inverters connect to an individual PV panel with the role of converting dc into ac for general power usage.

Module short-circuit current (Isc): The amount of current generated when the positive and negative terminals of a module are shorted together.

Mono-silicon panel: A single-layer base material for PV equipment. Silicon serves as a light-absorbing construct.

Overcurrent: Any current in excess of the rated current of equipment or the ampacity of a conductor. It may result from overload, short circuit, or ground fault.

Panel: A collection of modules mechanically fastened together, wired, and designed to provide a field-installable unit.

Photovoltaic output circuit: Circuit conductors between the PV source circuit(s) and the inverter or dc utilization equipment.

Photovoltaic power source: An array or aggregate of arrays that generates dc power system voltage and current.

Photovoltaic source circuit: Circuits between modules and from modules to the common connection point(s) of the dc system.

Photovoltaic (PV) system: The total components and subsystem that, in combination, convert solar energy into electric energy for connection to a utilization load. A system typically involves a PV field to gather energy, a current system to collect and transfer power generated by the field, fuses to manage the flow and direction of that current, and a distribution network or storage system to make power available for current or future use.

Photovoltaic (PV) fuses: A fuse designed and installed to handle power fluctuations due to reverse currents, power overloads and high system voltage in specific applications. PV fuses prevent overheating by eliminating reverse overcurrents that occur during fault conditions.

Photovoltaic (PV) system dc circuit: Any dc conductor supplied by a PV power source, including PV source circuits, PV output circuits, dc-to-dc converter source circuits, or dc-to-dc converter output circuits.

Polysilicon panel: Used for the production of conventional solar cells. Polysilicon is made by refining metallurgical-grade silicon through a chemical purification process to deliver light-gathering properties.

Reverse overcurrent: Occurs when an electrical fault results in power flowing back toward the PV panel network, causing potential overheating to wires, equipment, and associated property.

Standard circuit protection devices: Standard circuit protection devices include non-PV fuses and circuit breakers.

Subarray: An electrical subset of a PV array.

Thermal cycling: Thermal cycling describes the rise and drops in temperature over a specific period.

Thin-film panel: A thin-film solar panel is made up of one or more thin layers of PV materials that are laid onto a substrate. They are often 300 times thinner than typical PV substrate.

Voltage open circuit: The maximum voltage available from a solar cell, which occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current.

Codes and Standards

Codes

National Electrical Code

NEC ARTICLE 690 Solar photovoltaic (PV) systems

International Electrical Code

EC 60269-5 Low-voltage fuses - Part 5: Guidance for the application of low-voltage fuses

IEC 60269-6 Low-voltage fuses - Part 6: Supplementary requirements for fuse-links for the protection of solar PV energy systems

Standards

UL and North American Standards

CSA C22.2 NO 248.19 Low-voltage fuses — Part 19: Photovoltaic Fuses

UL 2579 Fuses for Photovoltaic Systems

UL 248-19 Standard for Safety Low-Voltage Fuses – Part 19: Photovoltaic Fuses

International Standards

AS/NZS 5033 Installation and safety requirements for photovoltaic (PV) arrays

IEC 60269-6 Low-voltage fuses – Part 6: Supplementary requirements for fuse-links for the protection of solar PV energy systems

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