

SIZING FUSES FOR PHOTOVOLTAIC SYSTEMS PER THE NATIONAL ELECTRICAL CODE®

PHOTOVOLTAIC PROTECTION NOTE 5

INTRODUCTION

Properly sizing fuses for photovoltaic (PV) systems is critical for the safe, reliable and long-term operation of this renewable power source. Unlike typical electrical power distribution and control applications, fuses in photovoltaic systems are subject to unique conditions. Prolonged exposure to elements of the environment can produce abnormal ambient temperatures, which in turn affects fuse performance, conductor selection and sizing. Also, unlike traditional circuits which are normally sized based on continuous loads, PV modules produce continuous currents, leading to additional considerations when sizing fuses. Taking these conditions into account, a unique method for sizing fuses in PV systems is necessary. The following paper will first determine when fusing is required and secondly will outline a five step process for sizing fuse ampere ratings for photovoltaic applications according to the 2017 NFPA 70, *National Electrical Code (NEC)*.

WHEN TO FUSE, WHEN NOT TO FUSE

The requirement to protect photovoltaic systems from overcurrent conditions is defined in Article 690.9(A) of the NEC. Fuses are required to protect cables and PV modules from line-line, line-ground and mismatch faults. The sole purpose is to prevent fire and safely open a faulted circuit if an overcurrent event were to occur. However, there are some situations where fusing is not required and is defined by the following:

- **Single Series String (fusing not required)** Article 690.9(A), exception a, states that for PV module or PV source circuit conductors where there are no external sources connected (such as parallel connected source circuits, batteries or backfeed from inverters) fusing is not required. This case is true as long as the connecting cables are rated at $1.56 \times I_{sc}$ or higher.
- **Two Strings in Parallel (fusing not required)** Article 690.9(A), exception b, states that fusing is not required if the short-circuit currents from all sources do not exceed the ampacity of the

POINTS OF INTEREST

- The requirement to protect photovoltaic systems from overcurrent conditions is defined in Article 690.9(A) of the NEC. Fuses are required to protect cables and PV modules from line-line, line-ground and mismatch faults
- The following equation can be used to properly size string and array type fuses for photovoltaic source circuits and photovoltaic output circuits, where I_{rated} is the desired fuse nameplate ampere rating, I_{sc} is the PV module rated short-circuit current or the sum of parallel PV module rated short-circuit currents, and K_f is the temperature de-rating coefficient (if required):

$$I_{rated} = \frac{I_{sc} \times 1.56}{K_f}$$

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conductors or the maximum overcurrent protective device size specified on the PV module nameplate. In this scenario, each string of modules can produce a maximum circuit current of $1.25 \times I_{sc}$. As long as the connecting cables are rated at $1.56 \times I_{sc}$ or higher, the combined circuit fault current is not large enough to cause damage to the cabling or modules, thus fusing is not required.

- **Three or More Strings in Parallel (fusing required)** In this scenario, a fault in one string will be subjected to the maximum circuit currents of all other connected strings, with each string delivering $1.25 \times I_{sc}$ under worst-case conditions. The combined fault currents will be larger than the withstand rating of the installed wiring sized at $1.56 \times I_{sc}$ as well as the series fuse rating of the PV modules. Under this fault condition, both the conductors and PV modules would be subject to damage, therefore, fusing is required by code.

FIVE STEPS TO SIZING FUSES FOR PHOTOVOLTAIC SYSTEMS

The following steps should be used for sizing string and array type fuses for photovoltaic source circuits and photovoltaic output circuits per the 2017 *National Electrical Code*.

- Step 1: Determine maximum circuit current
- Step 2: Determine the nominal fuse ampere rating
- Step 3: De-rate fuse due to abnormal ambient temperature (if required)

- Step 4: Determine fuse nameplate ampere rating
- Step 5: Verify fuse will protect conductors

This paper will analyze each step in detail and provide a summary calculation in the summary section. To better understand the terms used in the forthcoming calculations please reference Figure 1, which is a simplified schematic of a typical grid-connected PV system with three or more strings connected in parallel. I_{1+} through I_{n+} represent PV source circuits and I_{PV+} represents a PV output circuit. The definitions for PV source circuit and PV output circuit will be presented in Step 1.

Step 1: Determine Maximum Circuit Current (Continuous Current)

The short-circuit current (I_{sc}) of a PV module can fluctuate based on sunlight intensity, varying from its nameplate rating. Nameplate ratings of PV modules are calculated by the module manufacturer under Standard Test Conditions (STC), where irradiance equals 1000 W/m^2 and module temperatures are 25°C . For conditions where sunlight irradiance is higher than STC, I_{sc} will be higher than nameplate. Vice versa, for conditions where sunlight irradiance is lower than STC, I_{sc} will be lower than nameplate¹. We will calculate the extreme-case (worst-case scenario) maximum circuit current output, which is a value that accounts for normal and expected values of

¹ On a similar note, not discussed in this paper, PV module open-circuit voltage (V_{oc}) will fluctuate based on temperature

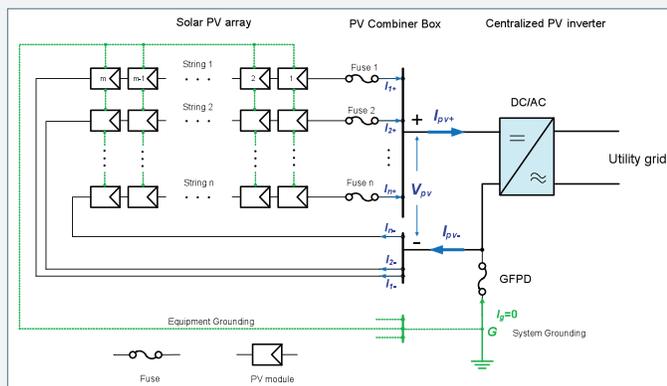


Figure 1: Schematic diagram of a typical grid-connected PV system under normal conditions

| SOLAR MODULE | | |
|--|----------------|---|
| THE ELECTRICAL CHARACTERISTICS ARE WITHIN ± 10 PERCENT OF THE INDICATED VALUES OF I_{sc} , V_{oc} , AND P_{max} UNDER STANDARD TEST CONDITIONS (IRRADIANCE OF 1000 W/m^2 , AM1.5 SPECTRUM AND CELL TEMPERATURE OF 25°C) | | |
| MAXIMUM POWER | (P_{max}) | 185.0 W |
| OPEN-CIRCUIT VOLTAGE | (V_{oc}) | 44.9 V |
| SHORT-CIRCUIT CURRENT | (I_{sc}) | 5.75 A |
| MAXIMUM POWER VOLTAGE | (V_{pmax}) | 36.21 V |
| MAXIMUM POWER CURRENT | (I_{pmax}) | 5.11 A |
| MAXIMUM SYSTEM VOLTAGE | | 600 V |
| FUSE RATING | | 10 A |
| FIRE RATING | | CLASS C |
| FIELD WIRING | | COPPER ONLY 14 AWG MIN. INSULATED FOR 90°C MIN. |
| SERIAL NO. | | |

Figure 2: Example of PV Module Nameplate

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sunlight irradiance that exceed the standard rating value of 1000 W/m². Figure 2 illustrates an example PV module nameplate. Notice the reference to the Standard Test Conditions and the indicated value of I_{sc} which will be used in the Step 1 calculation.

For our calculations, per the NEC, PV system currents are considered to be continuous. The term continuous is defined as more than three hours in duration, hence maximum circuit current is sometimes referenced by industry experts as the continuous current. PV source circuits are defined as conductors between modules and from modules to the common connection point in a DC system². PV output circuits are defined as circuit conductors between the PV source circuit and the inverter or DC utilization equipment³.

For PV source circuits, NEC Section 690.8(A)(1) states that the maximum circuit current (I_{max}), or continuous current, is defined as 1.25 multiplied by the PV module rated short-circuit current (I_{sc}) or the sum of parallel PV module rated short-circuit currents.

For PV output circuits, NEC Section 690.8(A)(2) states that the maximum circuit current (I_{max}), or continuous current, shall be the sum of parallel source maximum circuit currents as calculated in 690.8(A)(1). Therefore, for n strings, the equation for determining the maximum circuit current (I_{max}) is:

$$I_{max} = (I_{SC1} + I_{SC2} + I_{SC3} + \dots + I_{SCn}) \times 1.25$$

Step 2: Determine the Nominal Fuse Ampere Rating

NEC Article 690.9(B)(1) states that overcurrent protection devices (OCPD) shall carry not less than 125 percent of the maximum circuit current (I_{max}), or continuous current, as calculated in 690.8(A), Step 1. In other words, the OCPD cannot be loaded to more than 80% of its nameplate ampere rating continuously. This is a required factor of safety. By code, conductors are not loaded to 100%; the same concept applies to fusing. Therefore, by using the maximum circuit current (I_{max}) calculated in Step 1, the following equation for determining the nominal fuse ampere rating (I_n) is:

$$I_n = I_{max} \times 1.25$$

Step 3: De-rate Fuse Due to Abnormal Ambient Temperature (if required)

Fuse nameplate ampere ratings, like PV modules, are calculated by the fuse manufacturer under Standard Test Conditions, where ambient temperatures are 25°C. For operating temperatures greater than 40°C (104°F), the manufacturer's temperature correction factors shall apply. Fuses are thermal devices; prolonged exposure to ambient temperatures higher than 40°C will accelerate the fuse element melting time and may lead to nuisance trips at current values lower than the fuse nameplate rating. Vice versa, prolonged exposure to ambient temperatures less than 0°C will impede the fuse element melting time. Mersen provides the following recommendations:

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1. If fuses are installed where temperatures exceed 40°C, attempt to install them in the shade, or covered from the sun. This will mitigate the exposure to heat and correction factors may not need to be applied.
2. If temperatures exceed 40°C, and option 1 is not available, verify the duration of the high-temperature exposure. If high-temperature exposure is 2 hours or less correction factors may not need to be applied.
3. Worst-case scenario, if the fuses are operating in outdoor environments and there is exposure to direct sunlight and sustained temperatures exceed 40°C then a correction factor may be applied to prevent nuisance openings. In this scenario, a recommended fuse de-rating chart is provided by the fuse manufacturer and shown in Figure 3. First, determine the proper temperature de-rating coefficient (K_f) by identifying the sustained ambient temperature that the fuse will be exposed to on the horizontal axis. From that point, follow the graph vertically until you intersect the de-rating curve. From this intersection point follow the graph horizontally until you intersect the y-axis. This value on the y-axis is the temperature de-rating coefficient (K_f). Divide the nominal fuse ampere rating (I_n) calculated in Step 2 by the de-rating coefficient to determine the de-rated ampere rating of the fuse (I_{rated}). For ambient temperatures equal to 25°C, $K_f = 1$.

$$I_{rated} = \frac{I_n}{K_f}$$

Note: If de-rating is applied, the nameplate rating of the selected fuse must not exceed the ampacity of the conductors it is protecting or for PV source circuits; the maximum series fuse rating from the module nameplate.

Step 4: Determine Fuse Nameplate Ampere Rating

If the de-rated ampere rating of the fuse (I_{rated}) is not a readily available fuse ampere rating, Section 690.8(B) permits selecting the next highest available rating. For example, if the fuse ampere rating is calculated to be 13.5A, a 15A fuse should be used as it is the next highest available ampere rating. Readily available photovoltaic fuse ampere ratings may include 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 110, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500 and 600A.

Step 5: Verify Fuse will Protect Conductors

The fuse nameplate rating, after any corrections for conditions of use (Steps 3 and 4), must be less than or equal to the ampacity of the conductor selected. If not, then the conductor size must be increased in order to ensure safety.

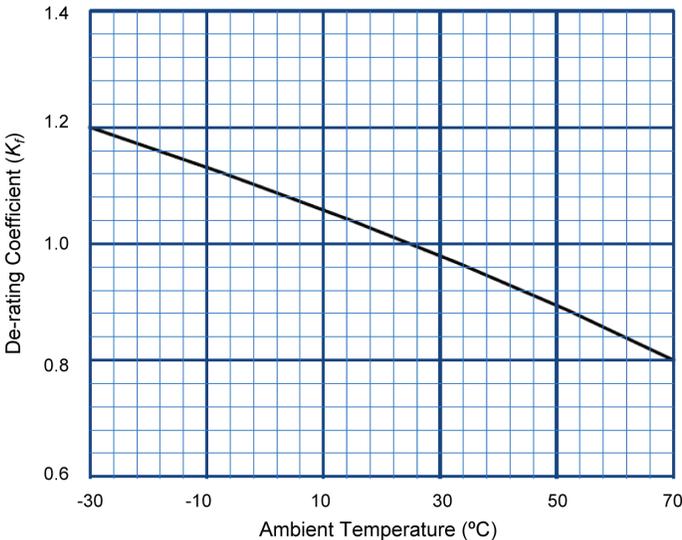


Figure 3: Mersen De-Rating Chart for Abnormal Ambient Temperatures

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SUMMARY

To summarize steps 1 through 5, the following equation can be used to properly size string and array type fuses for photovoltaic source circuits and photovoltaic output circuits, where I_{rated} is the desired fuse nameplate ampere rating, I_{sc} is the PV module rated short-circuit current or the sum of parallel PV module rated short-circuit currents and K_f is the temperature de-rating coefficient (if required):

$$I_{rated} = \frac{I_{sc} \times 1.56}{K_f}$$

If the desired fuse nameplate value (I_{rated}) is not a readily available nameplate rating, you are allowed to select the next highest available rating. The final calculated fuse nameplate rating must be less than or equal to the ampacity of the conductor selected, if not then the conductor size must be increased.

Example

Let's use the example PV module nameplate referenced in Figure 2. The rated short-circuit current (I_{sc}) of our PV module is 5.75A with a maximum system voltage of 600V. Let's also say that the ambient temperature of our example installation is 50°C. By using the de-rating chart and 50°C as our ambient temperature on the x-axis, we can calculate our de-rating coefficient (K_f) to be 0.90. When applying the summary equation we get the following:

$$I_{rated} = \frac{5.75A \times 1.56}{0.9} = 9.97A$$

In this example, 9.97A is not a readily available fuse ampere rating. The code allows us to use the next available fuse ampere rating, which is 10A.

REFERENCES

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ADDITIONAL RESOURCES

- Photovoltaic Protection Note 1: Ground Fault Analysis and Protection in PV Arrays
- Photovoltaic Protection Note 2: Line-Line Fault Analysis and Protection in PV Arrays
- Photovoltaic Protection Note 4: UL 248-19: Photovoltaic Fuses

These and other Tech Topics are available on ep.mersen.com.