To Fuse or Not to Fuse?

by John Wiles

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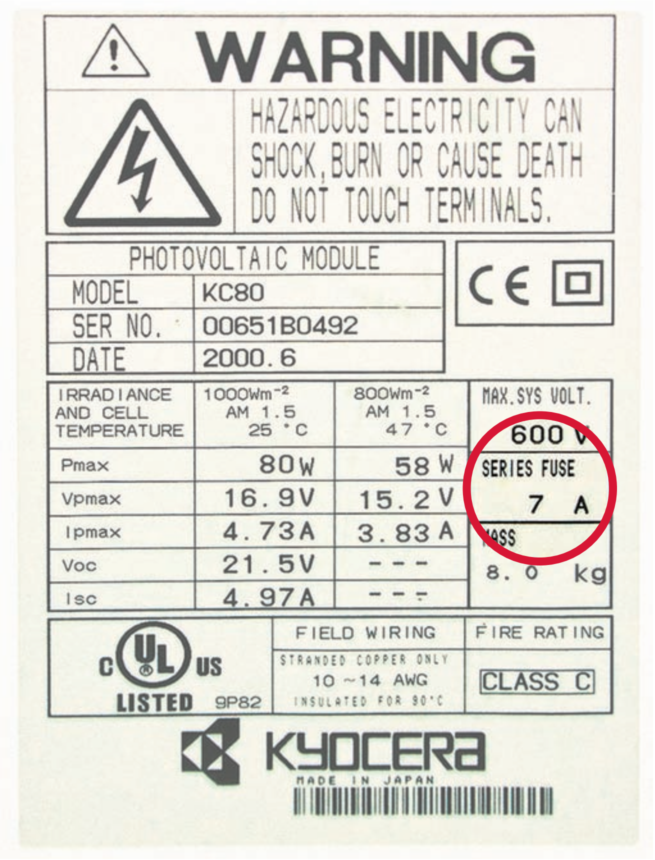
Most people agree that the *National Electrical Code (NEC)* improves with each edition. However, photovoltaic technology is still evolving, with new equipment, new wiring procedures, and new installation requirements being developed constantly. With these changes, and more inspectors and installers coming into the field every day, questions are bound to arise.

Some procedures and best approaches continue to stump both old timers and newcomers alike. The question of when to use overcurrent devices, such as fuses or circuit breakers, in direct-current circuits between PV modules and utility-interactive inverters is one in particular that plagues PV pros, since the solution is not directly found in the *NEC* but must be evaluated on a case-by-case basis.

Before answering this question, we first should address the issue that properly rated fuses and circuit breakers are functionally equivalent for this application, and are collectively known as overcurrent protective devices (OCPDs). This is true even though the required label on the back of certified/listed PV modules says "fuse."

In general, PV arrays operating at DC voltages above 150 volts (cold-weather, open-circuit voltage) may use fuses, and those operating below this voltage may use either fuses or circuit breakers. These applications are due to the ratings, availability, and cost of the different devices.



This PV module label states the maximum series fuse size.

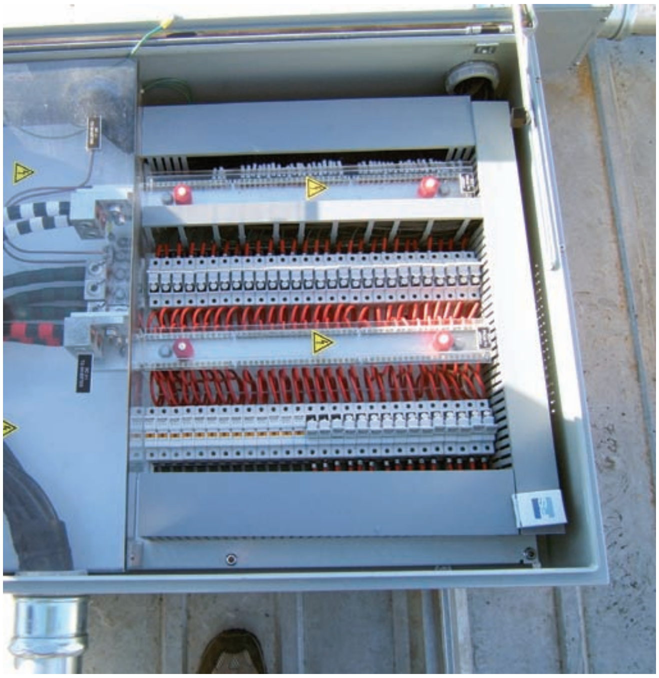
Protecting the Conductor

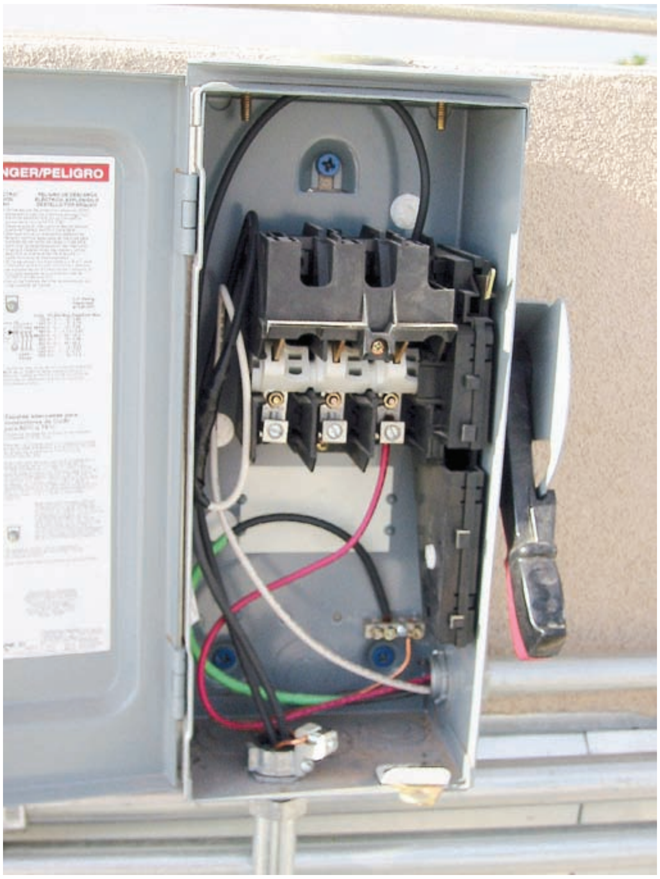
The *NEC* requires that, in most electrical systems, every ungrounded circuit conductor be protected from overcurrent that might damage that conductor. OCPDs provide that function. However, smaller utility-interactive PV systems may not need OCPDs in the DC circuits connected to the PV modules.

PV modules are current-limited devices, and their worst-case, continuous outputs, according to *NEC* Section 690.8(A)(1), are 1.25 times the rated short-circuit current (Isc). An exception in Section 690.9(A) allows conductors (typically rated at 1.56 times Isc) to be used with no OCPD where there are no sources of external currents that might damage that conductor.

However, if there are external sources of current that can potentially damage the internal module conductors, Underwriters Laboratories (UL), in its safety standard for modules (UL Standard 1703), has established that modules must have an external series OCPD. The *NEC* outlines protection for the wire, while the UL standard addresses protecting the module. Without an OCPD, the module can be damaged if reverse currents are forced through the module (due to an external or internal fault) in excess of the values of the maximum series fuse marked on the label on the back of the module.

External sources of current vary from system to system. They can originate from modules or module strings paralleled to the module of interest; from batteries backfeeding through charge controllers; or from utility currents backfeeding through utility-interactive inverters. (Note that the scenarios discussed below apply only to batteryless, utility-interactive PV systems.)





Above: A commercial-scale combiner box.
Right: An unfused DC PV disconnect, suitable for a single- or two-string grid-tied system.

Utility-Interactive Inverters & Utility Backfeed Currents

Most smaller utility-interactive inverters (10 KW or less) are designed so that they cannot backfeed current from the utility into array faults. These inverters have a maximum utility backfeed current of 0 amps. Although tests for abnormal operation and backfeeding exist, these tests do not rule out possible backfeed during an inverter's normal operation. Certification, usually in the form of a technical bulletin or technical specifications from the manufacturer, that the inverter cannot backfeed into an array fault under normal operation should be obtained from the inverter's manufacturer.

If the inverter can backfeed utility currents into the DC PV wiring, the *NEC* requires that an OCPD be installed in series with the output of all strings (or modules) to protect the cables and the modules from reverse currents. Inverters that have a maximum utility backfeed of something other than 0 A may be inverters larger than 10 KW or those designed for transformerless or bipolar operation. In cases where there are fused combiner boxes mounted at the array, an OCPD may also be needed at the inverter input, since the inverter can be a potential source of overcurrent. This OCPD will have a minimum rating based on the number of strings connected in parallel on that circuit and the short-circuit current of each string. This OCPD is sized to allow maximum forward currents from the array (all strings of modules) to pass through without interruption and to keep the overcurrent device from operating at more than 80% of rating.

Faults & Parallel Strings

The most common backfeed situation occurs in systems where there are multiple strings of modules connected in parallel. In the event of a fault, nonfaulted strings may be able to supply sufficient overcurrents (through the parallel connection) to damage either the conductors or the modules in the faulted strings. The inverter, for this example, has not contributed to the fault currents.

Fault currents can increase the normal current being carried in wires and modules. So the basic question becomes: How many PV modules or strings of modules can be connected in parallel and still meet *NEC* and UL requirements (marked on the back of each module) before an OCPD is needed on each module or string of modules?

UL requirements marked on the modules are based on the reverse-current tests described, which stipulate a maximum value for the OCPD. Section 110.3B of the *NEC* requires that installers follow the manufacturer's instructions and labels. However, lesser values can be used as long as they meet the *NEC* requirement of being 1.56 times the module short-circuit current (1.56 Isc) to protect the conductor associated with the module or string of modules (Section 690.8A and B).

In a few cases, module manufacturers have not met the code requirements, and the value of the module OCPD marked on the back of the module is less than 1.56 Isc. This poses a code conflict (110.3(B) vs. 690.8,9) and is an issue for UL to rectify.

String Scenarios

Assuming batteryless grid-intertie with an inverter that is certified not to backfeed via the AC source, let's examine some scenarios.

One string of modules. In a one-string system, no fusing would be required because no external sources of overcurrent exist. An unfused DC PV disconnect would be used on this type of system. The maximum series fuse rating that is marked on the back of the module is at least 1.56 Isc, and there are no sources of external currents that could damage the modules or the connecting cables (also rated at 1.56 Isc or higher).

Now let's look at a PV system with multiple strings of modules connected in parallel. Keep in mind that we are not determining the *rating* of any required OCPD; we are merely making some calculations that determine *whether or not* an OCPD is needed on each string of modules.

Two strings in parallel. Consider two modules or two strings of modules connected in parallel, then connected to the inverter input. Each string of modules can generate a maximum of 1.25 Isc. If a fault occurs in one string, the second unfaulted string can try to force 1.25 Isc amps into the faulted string. However, the modules in the faulted string can withstand currents up to at least 1.56 Isc or higher (if their marked series fuse rating is higher), and the conductors have an ampacity of at least 1.56 Isc or greater. Therefore, with only two strings of modules, no currents exist in the PV array that can damage the modules or the wiring—and no OCPDs are required.

Three strings in parallel. Now consider a system with three strings of modules connected in parallel. A fault in one string could see currents from the two other unfaulted strings. Each of these unfaulted strings could deliver up to 1.25 Isc under worst-case conditions for a total of 2.5 Isc (2 x 1.25 Isc). Suppose that the module manufacturer had the value of the maximum series fuse marked on the back of the module of exactly 1.56 Isc and the wiring was sized at exactly 1.56 Isc. The currents from the two unfaulted strings at 2.5 Isc would be far greater than the series fuse rating of the module and the ampacity of the conductors, risking damage. In this case, fuses in all three strings at a minimum value of 1.56 Isc would be required.

However, module manufacturers usually do not specify a marked maximum fuse value of *exactly* 1.56 Isc. Typically, the module will pass the UL reverse-current tests at a higher current, such as 15 amps. As an example, let's take a module that has an Isc of 5 amps and a marked value of the maximum series fuse of 15 amps. To protect the conductors, the interconnecting conductors between the modules must also have an ampacity of 15 amps, after the appropriate derating for conditions of use have been applied. In a system with three series strings of this module, the two unfaulted strings could deliver 12.5 amps (2 x 1.25 x 5). Since this current is less than the 15-amp ampacity of the conductors and is also less than the 15-amp maximum series fuse requirement marked on the back of the module, no fuses are required because no damage can be caused by overcurrent. The actual conductor ampacity would not have to be 15 amps but would have to be at least 12.5 amps after derating for conditions of use.

Determining Fuse Requirements

Series Strings	15 A Series Fuse		20 A Series Fuse
	5.0 A Isc	8.0 A Isc	1.5 A Isc
2	1.25 x 5 x 1 < 15	1.25 x 8 x 1 < 15	1.25 x 1.5 x 1 < 20
	No OCPD	No OCPD	No OCPD
3	1.25 x 5 x 2 < 15	1.25 x 8 x 2 > 15	1.25 x 1.5 x 2 < 20
	No OCPD	OCPD Required	No OCPD
12	OCPD Required	OCPD Required	1.25 x 1.5 x 11 > 20
			OCPD Required

In another example, let's look at a module rating of 8 amps Isc with the module wiring and module fuse rating still at 15 amps. The two unfaulted strings could send up to 20 amps (2 x 8 x 1.25). Because this exceeds the conductor ampacity and the ability of the module to withstand reverse currents, fuses would be required in each string of modules. The OCPD must be at least 1.56 Isc—in this case, 12.48 amps (1.56 x 8) and not more than 15 amps. A 15-amp OCPD would normally be used.

Modules with low Isc and high series fuse ratings. Some modules have a low short-circuit current and a high maximum series fuse rating. A module with a 1.5-amp Isc and a 20-amp maximum series fuse can have up to 11 strings of modules in parallel without any OCPD.

The bottom line is that when more than two modules or strings of modules are connected in parallel, a calculation should be done to see if an OCPD is required in each string. When three strings of modules are connected in parallel without fuses, the conductor ampacity may have to be greater than the normal 1.56 Isc, as described in *NEC* 690.9(A), exception (b). For a slightly more technical approach to these requirements and calculations, see Appendix J in *PV Power Systems and the 2005 NEC: Suggested Practices* manual (see Access).

Access

John Wiles (jwiles@nmsu.edu) works at the Institute for Energy and the Environment, which provides engineering support to the PV industry and a focal point for code issues related to PV systems. As an old solar pioneer, he lived for 16 years in a stand-alone PV-powered home—permitted and inspected, of course. This work was supported by the United States Department of Energy under contract DE-FC 36-05-G015149.

Photovoltaic Power Systems and the 2005 National Electrical Code: Suggested Practices by John Wiles • www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/PVnecSugPract.html

PV Systems Inspector/Installer Checklist and previous *Code Corner* articles • www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/Codes-Stds.html