APPENDIX J: Fusing of DC PV Module Circuits in Utility-Interactive PV Systems

In most electrical systems, the *National Electrical Code (NEC)* requires every ungrounded circuit conductor be protected from overcurrents that might damage that conductor. Overcurrent protective devices (OCPD), either fuses or circuit breakers, provide that function. However, some of the smaller utility-interactive PV systems may not need OCPD in the dc circuits that are connected to the PV modules.

The *NEC* assumes that each ungrounded conductor is connected to some source of overcurrents that might potentially damage that conductor under fault conditions. This source could be a power supply, a utility service, or a battery that supplies currents in excess of the ampacity rating of the conductor. PV modules are current limited devices, and their worst-case, continuous outputs for Code calculations are 1.25 times the rated short-circuit current. An exception to Section 690.9(A) allows conductors to be used with no OCPD where there are no sources of external currents that might damage that conductor.

Additionally, Underwriters Laboratories (in UL Standard 1703) has established that modules must have an *external* series OCPD if *external* sources of current can damage the *internal* module conductors. The module can be damaged if reverse currents are forced through the module (due to an external or internal fault) that are in excess of the values of the maximum series fuse marked on the label on the back of the module. Again, if there are no sources of external currents that exceed this marked value, then no OCPD is needed to protect the internal module wiring.

External sources of current (apart from the module or series-connected strings of modules) vary from system to system. These currents can originate from modules or series-connected strings of modules that are connected in parallel to the module of interest, from batteries in the system, or from utility currents backfeeding through utility-interactive inverters.

In systems with batteries and charge controllers, the batteries are a very predominate source of currents and, generally, OCPD will be required on each module or series-connected string of modules. Generally, only one OCPD will be required to protect all modules connected in a single series string. A properly sized and located OCPD will protect not only the conductors, but also the modules from external overcurrents.

In utility-interactive systems, some inverter designs are capable of allowing current from the utility to flow backwards through the inverter into faults in the PV array. Systems using these types of inverters would typically require OCPD at the inverter dc inputs or OCPD on each string of modules or OCPD in both locations. Many of the smaller utility-interactive inverters (below about 6 kW) are designed so that they cannot backfeed currents from the utility into array faults. However, there are currently (1/7/07) no tests in the UL 1741 to validate the lack of backfeeding from the utility, so a manufacturer's certification should be obtained that the inverter cannot backfeed from the utility into an array fault.

The general case—most larger PV systems

The most common situation occurs in systems where there are multiple strings of modules connected in parallel. The non-faulted strings may be able to supply sufficient overcurrents (through the parallel connection) to damage either the conductors or the modules in the faulted strings. A basic question is: How many PV modules or strings of modules can be connected in parallel and still meet the *National Electrical Code (NEC)* and Underwriters Laboratories (UL) requirements (marked on the back of each module) before a OCPD is needed on each module/string of modules? UL marks the modules based on reverse-current tests. The *NEC* requires that the manufacturer's instructions and labels be followed. The intent of the module marking is to protect the conductors internal to the module at the marked level from reverse currents. This is a maximum value for the OCPD. Lesser values can be used as long as they meet the *NEC* requirement of 1.56*Isc to protect the conductor associated with the module or string of modules. In some cases, the value of the module protective overcurrent device 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.

Many installers of 12-, 24-, and 48-volt PV systems ignore the module OCPD requirement and connect modules/strings in parallel. Can it be done and how? Dave King at Sandia National Laboratories and I have smoked a few modules and determined that the module OCPD requirement is valid.

It is easy to see that in a one-string system, an OCPD is needed only when the inverter or battery is a source of overcurrents. No fusing would be required in a one-string system if there were no battery or inverter that could source overcurrents.

Consider ***n*** modules or strings of modules connected in parallel. The *NEC* requires that an OCPD be installed in the combined paralleled output of all strings (modules) to protect the cable from reverse currents from batteries and back feed of ac currents through an inverter. In this case, we are assuming that the inverter or the batteries are a potential source of overcurrents. The OCPD will have a minimum rating of 1.56*n*Isc amps. It is sized at this value to allow maximum forward currents from the array to pass through without interruption and to keep the overcurrent device from operating at more than 80% of rating.

Examine a circuit where there are ***n*** modules/strings connected in parallel. Place a ground-fault in one module/string. Examine the sources of fault current that would affect that module string. Let us ignore current from the faulted module/string itself since the wiring in that string is already sized to carry all currents generated in the string.

First, there is the back feed current from the battery or the inverter in those systems with these components. It is limited to the *NEC* required OCPD of 1.56*n*Isc. This current is added to the current from the remaining modules connected in parallel. In this case, the current is (n-1)*1.25*Isc. The 1.25 is required because of daily-expected irradiance values that are greater than the STC-rated Isc.

I-fault = 1.56*n*Isc + (n-1)*1.25*Isc

With a little algebra, the resulting fault current is:

I-fault = (2.81*n-1.25)*Isc amps. (Fault Current Equation)

Note that this equation does not account for rating roundup of the OCPD, so each system must be checked with the actual OCPD values.

If the module can pass the UL reverse current test at this I-fault value or greater and be so marked (the maximum protective series fuse on the label), then it is possible to parallel ***n*** modules/strings (pick your ***n***) without a series OCPD for each module/string.

For example, a PV module is rated at 60 watts and has a maximum series OCPD requirement of 20-amps, which is marked on the back of the module. The Isc for this module is 3.8 amps. Here are the required calculations and checks for two strings in parallel.

The paralleled circuit OCPD installed at the output of the two paralleled strings will be 2*1.56*3.8 = 11.8 amps. Assume a 12 amp OCPD is used since the *NEC* now requires module/string OCPDs in one-amp increments up to 15 amps; fuses are available in these values except there is a jump from 10 to 12 and then to 15. This OCPD will allow 12 amps of fault current to reach the faulted module/string from backfeed from a charge controller/battery or from the utility grid through a utility-interactive inverter. Another 1.25*3.8 = 4.75 amps will come from the parallel-connected module/string for a total of 16.75 amps. This is acceptable since this module is marked for 20 amps.

However, if we try to parallel three of these modules/strings, the fault current equation yields a fault current of 29+ amps that exceeds the 20-amp limit on the module. The single OCPD is 3*1.56*3.8 = 17.8 amps (since OCPDs at this rating are not common, a 20-amp OCPD must be used). The two parallel-connected modules contribute 2*1.25*3.8 = 9.5 amps for a total potential fault current of 29.5 amps. This is significantly above the maxim series protective fuse of 20 amps.

In most cases, it is not possible to parallel many more than 2 modules/strings with a single OCPD unless the marked maximum series OCPD is very large in relation to Isc for the module. Some of the thin-film technologies may be able to do this and that will be an installation benefit for them.

Questions about driving voltages to produce these currents? The faults can occur anywhere in the module/string so a fault involving a single cell could be the trouble spot, and driving voltages over 1 volt could produce the reverse currents.

What about currents generated within the faulted module string? In the portion of the module/string below the fault (toward the grounded end of the module/string), the currents flow in the forward direction toward the fault and may or may not cause problems. As far as the contribution to the fault current is concerned, the contribution only appears in the fault path/arc and does not affect the ampacity of the cable. Above the fault (toward the ungrounded end), the currents in that portion of the module/string appear to oppose the external fault currents that are trying to reverse the flow of current, but the string is reversed biased, and the external driving currents are flowing. Since the location of the fault cannot be controlled ahead of time, worst-case currents must be assumed.

The increased marking value of 20 amps on the example module allows for two modules/strings to be connected in parallel and it does make it easier for the installer to use a single OCPD with larger cable to meet both the *NEC*-required cable protection and the UL-required module protection with one large OCPD instead of a two smaller OCPDs plus a larger OCPD.

Conductor ampacity must also be addressed if modules are going to be paralleled on a single OCPD. The conductors for each string must be able, under fault conditions, to carry the current from the other parallel strings (modules) plus the current that may be backfed from the inverter or battery. In the case with ***n*** strings in parallel and a single OCPD in the combined output, the conductor ampacities would be as follows:

Each of the string conductors would have to have an ampacity of 1.25 (n-1)*Isc + 1.56 n Isc. If the equation is factored, the required ampacity becomes A=(2.81*n-1.25)*Isc. As before, OCPD roundup is not considered and the values should be recalculated with actual OCPD values. The combined output-circuit conductors would require an ampacity of 1.56*n*Isc .

Modern, small utility-interactive inverters

Many utility-interactive inverters on the market have redundant internal circuitry that prevents currents from being backfed through the inverter from the utility to faults in the PV array. This removes one source of currents in the above equation. With these products, it is possible to have two and sometimes more strings of modules in parallel with no OCPDs in the dc circuits. The inverter manufacturers should be contacted for information in this area. The above equations can be modified by deleting the combined-circuit OCPD and then solved to determine both the requirements for OCPDs and the necessary ampacity of the conductors.

In this case the current flowing through the forward fuse (n*1.56*Isc) is set equal to 0 (zero) or removed from the equation. In a system with ***n*** strings of modules connected in parallel, if one of the ***n*** strings develops a fault, the fault current is now reduced to:

I fault= (n-1) * 1.25 * Isc. For two strings in parallel, n=2 and the fault current becomes

I fault = 1.25 Isc.

The *NEC* requires that all PV wiring generally be sized at 1.56 Isc. The required module series protective fuse is nearly always greater than 1.56 Isc.

Therefore, in a system with two strings of modules connected in parallel, there are no sources of fault current that exceed the ampacity of the conductors or the requirements for a module protective fuse. No dc string or array fuses would be needed. *NEC* Section 690.9(A) Exception applies.

If there are more than two strings of modules connected in parallel, then the calculations outlined above will have to be made to ensure that (n-1) * 1.25 * Isc is less than the module series protective fuse value. If not, fuses should be used in each string.