Ogling Overcurrent Devices

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In the *Code Corner* column in *HP84,* I looked at some general characteristics of overcurrent devices. In this column, I'll examine where overcurrent devices (fuses and circuit breakers) should be used, and how to size them. First, let's look at what short circuits are, and where overcurrent devices may not be required.

Short Circuits

We normally think of a short circuit as a very low-resistance, hard contact between two conductors. However, a short circuit can be any unwanted connection between two conductors or a conductor and a grounded surface. That connection could be a low-resistance connection, but it may also be a higher-resistance connection that will still allow damaging current to flow.

Short circuits are also called faults. A line-to-line fault occurs between two conductors of a circuit. A ground fault occurs between an ungrounded conductor and a grounded surface. Faults may result in low currents (high resistance) or high currents (low resistance).

Where Is Overcurrent Protection Not Required?

Before we look at where overcurrent protection is required, let's examine systems where it is not required. First, we must remember that we are protecting conductors from overcurrents. The circuit conductors in most power systems are sized to carry 125 percent of the continuous load currents. In the case of PV source and output circuits, this continuous current is 156 percent of the module short-circuit current.

PV modules and arrays can put out more current than the rated short-circuit current. This can happen every day around solar noon because then the sun is frequently brighter (greater insolation) than the standard value of 1,000 watts per square meter. This requires an additional 125 percent factor for PV source and output circuits. The two 125 percent factors combine to yield 156 percent (1.25 x 1.25 =1.56).

If the power sources in the system can provide power in excess of 125 percent of the continuous currents, there is probably a need for overcurrent protection. Some of these power sources might be the utility grid, batteries, large PV arrays, generators, and other energy sources or storage devices.

One type of PV system may not need any overcurrent protection. This is the direct-connected PV system, without batteries, using only a single string of series-connected modules or a single module. All of the wiring between the modules and the load is sized at 156 percent of the module short-circuit current (Isc). In this system, no battery or other source of energy can provide high overload or short-circuit currents, so the conductors are safe for these currents. No overcurrent protection is needed. A direct-connected, PV-powered water pumping system is an example of such a system.

A means of disconnect, such as a pull-out switch, is required. This allows the load and any electrical controls to be electrically isolated from the array for servicing. If the system has a controller that boosts current, an overcurrent device may be needed in the wiring to the load, unless that wiring is sized at least 125 percent of the maximum available current that can be supplied by the controller to the load.

Normally, overcurrent protection is not allowed in conductors that are grounded. If a fuse or breaker were used in a grounded conductor and that device opened (due to an overcurrent situation), the normally grounded conductor might become energized (hot) and pose a safety hazard. In the U.S., with our grounded electrical systems, the white marking on a conductor indicates that the conductor is grounded. This means it has no potential difference (voltage) with respect to other grounded conductors or surfaces. When such a marked conductor is accidentally allowed to become ungrounded or even carry voltages above ground, it may damage equipment or harm people.

Only in the case of load circuits is the use of an overcurrent device allowed in a grounded conductor. It is allowed only when the device is one pole of a ganged, multipole circuit breaker that disconnects all conductors of a circuit when it trips.

Where Are Overcurrent Devices Required?

In systems that have sources of available energy that can deliver currents that exceed the ampacity of the conductors, overcurrent protection is required for all ungrounded conductors. Medium-to-large PV arrays that have more than one string of modules connected in parallel would be such a source.

Conductors in most power systems are sized at 125 percent of the continuous currents they are expected to carry. So it doesn't take much of a source to provide sufficient overcurrents to damage these conductors. Batteries can provide tens of thousands of amps into short circuits. Utility grids can also deliver tens of thousands of amps. With conductors rated to carry from a few to several hundred amps, it is easy to see how they could be damaged.

Again, PV source and output circuit conductors are sized to carry 156 percent of the module short-circuit current. But two or three parallel strings of modules can deliver currents in excess of the ampacity of the rating of the string conductors when a short circuit occurs.

The *National Electrical Code (NEC)* allows 12 volt and some 24 volt PV systems to be ungrounded. A grounded system is defined as an electrical system where one of the circuit conductors is grounded. Of course, an equipment-grounding system and a grounding-electrode system are required on all PV systems at any voltage.

Ungrounded systems require overcurrent protection in both of the ungrounded conductors of each circuit, which may increase the cost and complexity of the system. Faults can occur in either of the ungrounded conductors to ground or between the two conductors. So the *NEC* has always required overcurrent protection (and disconnects) in all ungrounded conductors for safety and for fire hazard reduction.

Another requirement for overcurrent protection has to do with protecting a PV module from reverse currents. Modules have internal connections between the cells that have a certain ampacity. As part of the module testing and listing process, the maximum value of reverse current that the module can withstand under fault conditions is determined. The value of the required series fuse is marked on the back of the module.

This overcurrent device (it may be a circuit breaker) is only indirectly required by the *NEC* through the code requirement that all instructions furnished with a listed product be followed. Only one of these series protective overcurrent devices is required per series strings of modules, and it should be located at the end of the string that is most distant from the ground connection (usually the positive end).

To provide maximum protection for the longest runs of conductors, overcurrent devices are required to be located at or very close to the source of any potential high short-circuit or fault currents.

Battery Circuits

Suppose that a specific battery can deliver a maximum of 320 amps continuously to an inverter under normal operations. The cable from the battery to the inverter would have an ampacity of 400 amps (125 percent of 320). It would be protected with a 400 amp overcurrent device. From an overcurrent protection standpoint, it would be ideal to locate the overcurrent device at the positive terminal of the battery. However, battery acid, hydrogen gas, and sore backs from bending over to check the device preclude the installation this near the source.

Although the *NEC* does not specify the distance, it is generally agreed that a distance of 4 to 5 feet (1.2–1.5 m) from the battery enclosure to the disconnect/ overcurrent protection is acceptable. Power centers are listed by the testing organizations with 4 to 5 feet of cables between the main disconnect and the battery. Of, course, these unprotected cables should be of high quality and should be physically protected by installing them in conduit.

If the inverter also serves as a battery charger, it may also be considered as a source of potential fault currents into these same battery-to-inverter cables. In many cases, however, the maximum continuous inverter charging currents are less than the currents the inverter draws when acting as an inverter. If this is the case, the cables have been sized for the higher currents, and no overcurrent protection is required at the inverter end of these cables.

If, on the other hand, the inverter can provide battery charging currents that are as high or higher than the ampacity of the cable, an overcurrent device must be located at the inverter end of the cable. This would be particularly true if the cables were longer than the 4 to 5 feet mentioned above. In many systems, a single circuit breaker, located adjacent to the inverter, provides some degree of overcurrent protection and serves as the battery disconnect.

In other systems where the inverter and batteries are located in two different rooms or more than 4 to 5 feet apart, a disconnect and an overcurrent-protection device may be required at both ends of the battery-to-inverter cable. In a grounded system, the devices are located only in the positive conductor (assuming a negative grounded system). There would be no disconnects or overcurrent protection located in the grounded conductor.

Since batteries can deliver very high currents into faults, overcurrent devices in these circuits must have high interrupt ratings. Typically, current-limiting fuses have sufficient interrupt ratings (20,000 amps or higher) to successfully open under fault conditions. High-quality circuit breakers by Heinemann, AirPax, and others also have the necessary high interrupt capabilities (25,000 amps) for use in these circuits. Current-limiting fuses should be used when downstream switchgear, overcurrent devices, and other components that might be involved in the fault have insufficient interrupt ratings to withstand the short-circuit currents at their locations in the circuit.

PV Module Circuits
Any time circuits are combined in parallel, such as in module combiner boxes, the conductors normally change size because the output circuits must handle higher currents than the input circuits. As the conductors change size (and ampacity), the overcurrent protection must change to match the new ampacity.

Let's look at a system with four PV module source circuits with a module Isc of 4 amps. The value of the maximum module protective fuse marked on the back of the modules is 15 amps. The conductors in this module source circuit must have an ampacity of at least 1.56 times the short-circuit current (1.56 x 4). This is 6.24 amps (let's round this up to 7 amps) after any temperature or other derating.

Each of these PV source circuits is fed into a fused combiner box, and 8 amp fuses are used in each circuit, since 7 amp fuses are hard to find. If we are using 8 amp fuses, the cable ampacity after deratings must be at least 8 amps. Since 8 amps is less that 15 amps, these fuses can also serve as the module protective fuses while providing overcurrent protection for the cables.

What is the source of potential overcurrents? In this case, the currents may come from the battery, or from any three of the other source circuits feeding currents into a fault in the fourth source circuit. For this reason, the fused combiner box is located where the module strings come together, and where the combined outputs require a larger output cable from the fused combiner box.

This location may be near the modules, which allows the use of short, small module interconnection wiring, but requires longer, heavier fused combiner box output conductors. It may also be located near the charge controller. This requires longer, small module interconnections, but allows a short output cable. Voltage drops, conductor costs, and physical limitations will determine where the fused combiner box is installed.

The output cable must have an ampacity sufficient to handle the combined outputs of all four module source circuits. In this case, it would be 24.96 amps (4 x 1.56 x 4), which we'll round up to 25 amps. A fuse or circuit breaker at the input to the charge controller is required to provide overcurrent protection for this cable from potential overcurrents from the battery. The size of the fuse would be equal to or less than the ampacity of the cable it was protecting, and must be at least 25 amps (again, 4 x 1.56 x 4).

Figure 1 shows module source circuits combined into subarrays and then into a full PV array, using fuses and circuit breakers. Each overcurrent device is rated to carry continuous currents at only 80 percent or less of the rating. Temperature and other deratings for the conductors are not shown.

Figure 1

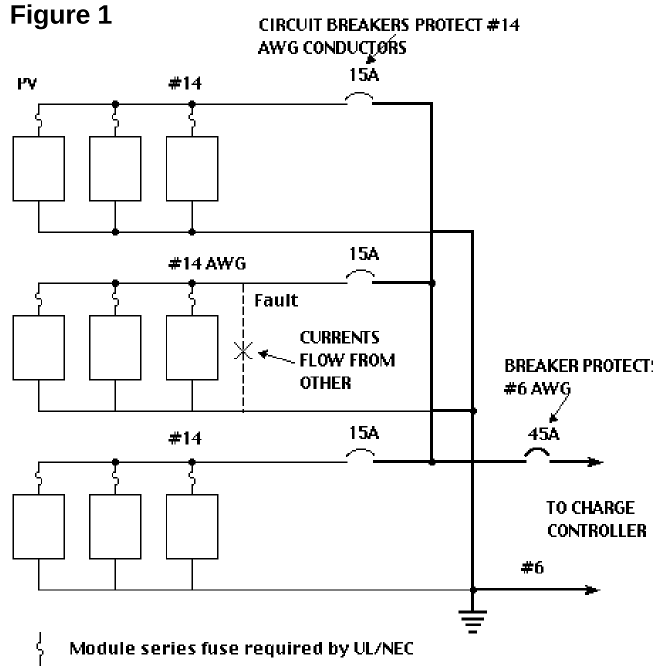
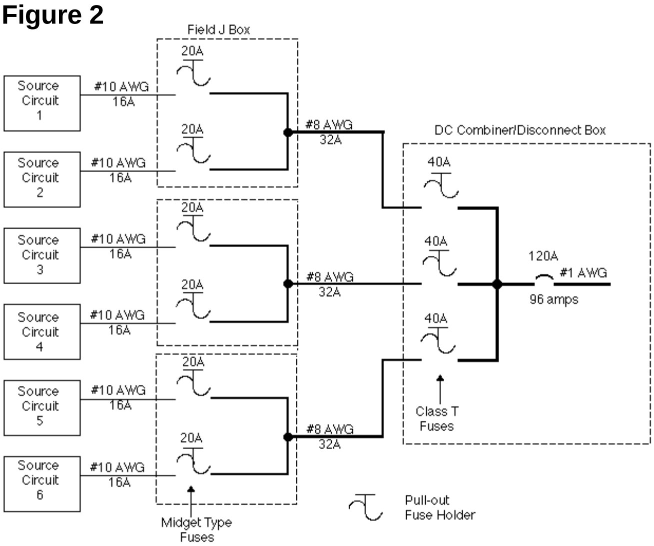


Figure 2 shows a slightly more complex system to further demonstrate the concepts. The currents shown are 1.25 Isc for each circuit, and that represents the continuous current in that circuit. The circuit breakers are increased another 125 percent above this value to ensure that they are operating at only 80 percent of rating on a continuous basis. The figures show how PV source circuits combine, and how the overcurrent devices must increase in size to handle the combined currents and protect the larger conductor wire sizes.

Summary
Overcurrent devices are normally required to protect all ungrounded conductors from current levels exceeding the rated ampacity of the circuit. Either fuses or circuit breakers may be used, depending on the application. The overcurrent devices are rated at or below the ampacity of the conductors being protected, and are

Figure 2



normally sized to carry currents at only 80 percent of rating. In the next *Code Corner,* I'll look at additional requirements for overcurrent devices.

Questions or Comments?

If you have questions about the *NEC,* or the implementation of PV systems that follow the requirements of the *NEC,* feel free to call, fax, e-mail, or write me. Sandia National Laboratories sponsors my activities in this area as a support function to the PV industry. This work was supported by the United States Department of Energy under contract DE-FC04-00AL66794. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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