Disasters Happen

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Accidents happen—and, if they involve your PV system or one that you installed, they can be a disaster when you or the qualified installer is forty miles away down a muddy road.

- The daily cycling of the currents cause connections to loosen.
- Nails are driven into walls and into cables.
- Metal tools are dropped across terminals.
- Aging batteries go into thermal runaway.
- Birds and animals chew on insulation.
- Structures shift and damage hidden cables.
- Sunlight ages and hardens cable insulation.
- Well pumps lock up.
- Generators and PV arrays develop ground-faults.

This Code Corner and the next will discuss how to implement the requirements of the National Electrical Code ® (NEC ®) that will help to keep accidents and incidents like these from becoming disasters. Overcurrent protection will be covered in this column and disconnects in Home Power 53.

Definitions of Overcurrents

Overcurrents in electrical system wiring can be of two types. Overload currents are represented by sustained currents in the 2-6 times normal range caused by partial faults in the insulation of conductors and circuit overload problems like stalled pump motors. These currents can cause long-term deterioration of the cables from overheating. The overheating is generally not sufficient to cause fires initially, but may damage the cables and surrounding building materials.

When uninsulated conductors or conductors with damaged insulation come into contact (positive to negative), a short circuit occurs and currents can flow that are many times the ampacity (current-carrying capacity) of the conductors. Partially damaged insulation may allow high currents to flow even if there is not a direct, low-resistance short circuit. In most PV systems, the batteries are the source of very high currents and can deliver thousands of amps into short circuits. These high currents in short circuits create heat which can cause further system damage and fires as insulations melt and then ignite.

NEC Requirements

The National Electrical Code requires that every current-carrying conductor in an electrical power system be protected by overcurrent devices. The devices are either fuses or circuit breakers and act to interrupt the flow of current when subjected to sustained overload currents or short-circuit currents.

The overcurrent devices are normally located in the circuit in the ungrounded conductor nearest the source of the potential overcurrent. If the circuit is ungrounded, then overcurrent protection is required in both conductors of a circuit. In PV systems, sources of high current are the PV modules, the batteries, backup generators, and the utility grid when used. If a circuit can be subject to overcurrents from two sources, there may be a requirement for overcurrent protection for that circuit near both sources.

Conductor ampacity (See Code Corner, Home Power 51) plays a major role in determining the need for and location of overcurrent protection. PV modules generate limited currents (compared to batteries and other sources). The module and array cables are typically sized to handle these module currents without overcurrent protection. This means that when delivering the maximum current possible from the modules into a short circuit, the cables connected to the PV array are operated at less than their ampacity under all conditions. In some designs with large (over 1 kW) arrays, overcurrent devices may be needed in the module wiring.

These same cables are usually connected to the battery system and they are not, by any means, sized to handle short-circuit currents from the battery. For this reason, overcurrent protection is needed near the battery end of the PV array wiring to protect these cables, should a fault or short circuit occur near the modules. While many PV systems use blocking diodes to stop the flow of battery current into the PV array at night, these blocking diodes cannot be relied upon to protect the wiring from short-circuit currents. When these diodes fail, they usually fail in a shorted mode and allow current to flow freely in both directions.

Although the battery-to-inverter cables are very large and sized to handle the normal operating currents in those circuits, they are not large enough to carry the battery short-circuit currents if a fault occurs near the inverter. Overcurrent protection is also required in this circuit.

Branch Circuit or Supplemental Devices
Within the two types of overcurrent devices (fuses and circuit breakers) there are two categories of devices that are established by standards written by Underwriters Laboratories (UL). The first category is the listed branch-circuit rated device. This category of overcurrent device is the more robust of the two categories and is acceptable for use in all locations in a PV system. Fuses that are listed for branch-circuit use are called "class" fuses and have class designations of T, H, RK5, RK1, CC, and the like. Circuit breakers that are used in load centers like those produced by Square D, Siemens, General Electric, and others are listed as branch-circuit-rated devices.

The other category of overcurrent device is known and listed by UL as a supplemental device. It is called a supplemental device because it is generally installed inside a piece of electronic equipment which is connected to a circuit that is protected elsewhere by a branch-circuit-rated device. In PV systems, listed supplemental overcurrent devices are allowed only in the circuits to the PV array or modules. Fuses known as midget fuses are one of the few supplemental fuses that are listed by UL with the necessary direct current (DC) ratings. Some listed supplemental circuit breakers such as those made by Heinemann and Airpax are available, but they do not plug into commonly available load centers and must be installed in custom enclosures.

DC Ratings are Needed
In all cases (fuses or circuit breakers and supplemental or branch circuit), all overcurrent devices used in PV systems should be listed by UL and rated for operation on direct-current (DC) circuits at the appropriate voltage and current. Many fuses and circuit breakers are not suitable for DC, even though they may be class type fuses or branch-circuit-rated circuit breakers.

Automotive fuses are not suitable for use in PV systems even though they are used in DC systems on automobiles. They are not tested for use in non-automotive applications and do not have the proper interrupt ratings (discussed below). In a similar vein, devices with only ac ratings (particularly the small ac-only rated, glass supplemental fuses) should not be used. AC-rated devices cannot effectively interrupt the direct currents and extinguish the long-lasting, continuous arcs that are associated with direct currents.

Most DC-rated devices have the ratings printed directly on the body of the fuse or circuit breaker. If there is any question, the manufacturer can provide the DC ratings as established by the UL listing—if there has been a DC rating established at all.

Interrupt Ratings
Particularly important in DC circuits with batteries is the interrupt rating of the overcurrent device. The high short-circuit current capabilities of batteries impose rather strenuous requirements on overcurrent devices that must interrupt fault currents from these batteries. The DC interrupt rating for a device that is rated for both DC and ac operation will be far smaller than the ac interrupt rating because of the difficulty in interrupting the direct current flow under both normal and fault conditions. Many DC-rated overcurrent devices have interrupt ratings in the 3000-5000 amp range, which is significantly lower than the tens of thousands of amps that the batteries on a typical PV system can deliver into a short circuit. Supplemental overcurrent devices usually, but not always, have lower interrupt ratings than branch-circuit rated overcurrent devices. The DC interrupt rating should also be printed on the device.

Current Limiting
Since many overcurrent devices have interrupting ratings that are inadequate, a current-limiting fuse can be installed in the same circuit. These fuses act to open a circuit so fast that the short-circuit currents are not allowed to build up to a high level. The current starts to rise to a peak value, but the quick-acting, current-limiting fuse holds it to a value that can be safely handled by other overcurrent devices on the same circuit.

For example, the common Square D residential QO series of circuit breakers has a DC interrupt rating of 5000 amps at 48 volts DC. Since these are low in cost and readily available, they are frequently selected for PV array combiner circuits and DC load centers. They are perfectly satisfactory for this use, when they are connected to the battery through a current-limiting fuse. While the fuse and its required disconnect switch are somewhat expensive, they do allow the use of the inexpensive Square D circuit breakers.

There are no UL-Listed, branch-circuit rated, DC, current-limiting circuit breakers — the mechanical delays inherent in circuit breakers prevent them from acting fast enough. There are some supplemental European circuit breakers that may eventually be listed in the U.S. as supplemental current limiting devices.

In some cases, a current-limiting fuse is not needed to protect a circuit breaker in a battery circuit. Overcurrent devices protect the cable and, when required, other current devices with inadequate interrupt ratings. Some DC-rated, UL-listed, branch-circuit-rated circuit breakers have interrupt ratings of 20,000-25,000 amps. This rating is similar to the interrupt rating on some DC-rated fuses. If this circuit breaker is the only overcurrent device in a circuit, then it can protect the conductors and itself without the addition of a current-limiting fuse. A common use is a DC-rated circuit breaker protecting the conductors between the batteries and the inverter. It would have an overcurrent rating in the range of 100-300 amps (based on the inverter input current and the cable size) and also have an interrupt rating of 25,000 amps to deal with fault currents.

Current Ratings

The overcurrent devices used to protect PV module and array conductors should be rated at less than the ampacity of the cable (or the next higher standard value), and that rating should be at least 156% of the rated short-circuit current from the module or array. This rating will comply with the requirements established by UL and the NEC.

Overcurrent devices on other dc-load circuits should be rated at 125% of the continuous steady-state currents and, as before, always be rated less than the conductor ampacity.

The overcurrent device for the conductor between the battery and the inverter should be rated based on 125% of the inverter input current calculated at full rated ac-power output and the lowest battery voltage. The inverter efficiency should also be used. See Code Corner in Home Power 48 for an example of this calculation.

Voltage Ratings

Overcurrent devices used to protect PV module and array wiring should have a voltage rating of at least 125% of the system open-circuit voltage. The common Square D QO circuit breaker with a 48-volt rating can be used in 12-volt systems that have a 22-volt open-circuit voltage (125% of 22 is 27.5 volts), but not on 24-volt PV systems that have an open-circuit voltage of 44 volts (125% of 44 is 55 volts). Circuit breakers such as the Heinemann units have either a 65-volt or 125-volt DC rating depending on the particular unit and the interrupt rating. Many DC-rated fuses have a DC voltage rating of 125 volts, although some are rated as high as 700 volts.

Cold Fuses

Whenever a fuse is used as an overcurrent device, there should be provisions in the system to disconnect both ends of the fuse from all sources of voltage for servicing. These provisions will normally mean that there will be disconnects between the battery and the current-limiting fuses located on each ungrounded battery conductor. Other disconnects (discussed in the next Code Corner) for the PV, generator, and inverter should suffice to remove voltages from the other end of the fuse.

Summary

Keep your system from becoming a disaster — install the appropriate overcurrent devices. Overcurrent devices are required to protect the ungrounded conductors of most PV systems. They should be listed to UL Standards and have the appropriate DC voltage, current, and interrupt ratings. Current-limiting fuses are required on most battery circuits. Disconnects will be required for most fuse installations.

Access

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An NEC Article 690 Task Group, chartered by NFPA, is working on the 1999 NEC with a Technical Review Committee from the Solar Energy Industries Association (SEIA). Those wishing to actively participate should contact Ward Bower at Sandia National Laboratories • 505-844-5206

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