The National Electrical Code® & PV Module Wiring Methods & Cables

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The National Electrical Code (NEC)®, updated and published every three years by the National Fire Protection Association (NFPA), is the most current and comprehensive electrical safety requirements document in the world. The 1996 NEC has just been published and work is already underway on the 1999 edition. Hundreds of volunteers work on a three-year cycle to review and update the NEC with the latest technology and methods of connecting electrical power systems. Representatives from the photovoltaic (PV) industry, academic institutions, the inspector community, Underwriters Laboratories, Inc. (UL), and the electric utility industry meet regularly to modify and update Article 690 of the NEC that deals with PV systems. Although Article 690 covers only nine pages in the NEC, about 90% of the remaining 1000 pages of the code also deal with aspects of PV installations. The NEC has been legislated into law by over 40 states and by most major cities in the United States. Paperback copies of the NEC are available for $25-35 at most electrical equipment distributors. The NEC and the hard bound NEC Handbook are available from NFPA (see access).

The NEC requires that all equipment be examined for safety. While the local electrical inspector (authority having jurisdiction, or AHJ) will inspect the field-installed wiring, the AHJ relies on the listing or labeling mark of an acceptable testing laboratory like UL or ETL to provide an indication that all equipment, conductors, and devices have been examined for safety. The listing mark ensures that the equipment has been tested to meet a number of appropriate safety standards relating to shock and fire hazards. Many inspectors will only inspect or approve systems that have been assembled with listed components. Insurance and Mortgage companies often require electrical inspections.

The inspector will be looking for the good workmanship required by the NEC. Installations that resemble other electrical power installations will be more readily accepted than those that use unconventional installation practices and equipment that does not resemble normal electrical supply equipment.

All listed equipment comes with labels and/or instructions that define the requirements (developed in conjunction with the requirements of the NEC) for installation and use of that equipment. Violations of these instructions or requirements may result in unsafe systems and equipment damage. The inspector, in many cases, will verify that these instructions have been followed. Almost all of the material that is printed on labels attached to electrical equipment has been placed there to meet a safety requirement. Much of the material found in equipment instruction and installation pamphlets and manuals is also mandated by safety requirements.

Safety vs. Performance

NEC requirements for PV installations and the requirements found on labels and in instructions for listed equipment, when followed, will generally result in a safe installation. While listing equipment to UL Standards and installing that equipment to NEC requirements does not guarantee high levels of performance, higher performance frequently is achieved. The required manner of sizing components, discussed below and in subsequent Code Corners, and the quality of listed equipment will generally result in PV systems that have higher levels of performance than systems that do not meet NEC requirements. Of course, it is possible to install a code-compliant system using listed equipment that has not been designed or adjusted properly.

PV Modules

PV modules are the major part of any PV system. While they are a relatively expensive portion of the system, they are durable, long-lasting, and nearly maintenance free. When exposed to sunlight, they will produce power for over twenty years. Since they must be mounted in exposed locations, the wiring that connects them to the rest of the system should be as robust as the modules themselves in order to achieve a safe, reliable, and durable installation. The NEC provides guidance in the installation of this wiring, and both the wiring methods and types of cables are covered in this Code Corner.

Safety — First, Last, and Always

PV modules are electrical power producing devices. Although the typical module produces only 40-80 Watts of power at a nominal 12 Volts, it still can pose a shock and fire hazard, especially in a system configuration, where the modules are connected in series and parallel for higher voltages and currents. It is not uncommon to see residential systems with PV arrays that can deliver

40-60 Amps at 24 Volts with charge controllers that are designed to handle over 100 Amps. In the larger commercial installations, PV source circuit voltages can be 600 Volts and higher.

It is strongly recommended that PV modules be covered with an opaque material during installation so that the terminals are not energized. Working at night and in other very low-light conditions can also lower the shock and fire hazards but at the expense of creating other hazards. Insulated tools and insulating gloves should be used if module wiring is accomplished on illuminated PV modules with live electrical contacts.

PV Module and Array Wiring Methods

The NEC outlines numerous wiring methods that are acceptable for connecting electrical equipment in the field. It does not cover the internal wiring of equipment since that wiring is viewed as part of the equipment listing process. Wiring methods include the following: 1) Use of multiple conductor cables with outer jackets (Types NM, TC, and UF), 2) Use of single conductor cables (RHW, RHH, THHW, etc.) in conduits (metallic and non-metallic), 3) Use of several other cable types under various circumstances that are delineated in the code. While PV modules may be connected using any of these "conventional" wiring methods, they may also be connected using single-conductor, exposed cables from module junction box to module junction box.

In all installations, the conductors must be properly attached to the PV modules with good electrical and mechanical connections. Following the manufacturer's instructions and using supplied materials will facilitate these connections. In many commercial installations, local codes (which supplement the NEC) require that conduit be used for all wiring. This means that modules designed for conduit fittings must be used. Some consideration might also be given to using either conduit or a multiple-conductor sheathed cable for any installation where the public has access to the wiring on the back of the modules. The conduit or sheathed cable provides an additional degree of protection from physical damage for the enclosed conductors over and above the protection afforded exposed, single-conductor cables.

Cable Types

While the NEC allows single-conductor USE, SE, and UF cable types to be used for module wiring, the best choice usually narrows down to a type USE-2 cable. It is a direct burial cable that is also sunlight resistant and has insulation with a 90°C (Celsius) temperature rating when wet. Standard USE-2 cable cannot be used inside a building (even in conduit) because it does not have the required flame retardant in the insulation. However, USE-2 is frequently additionally marked as type RHW-2 which indicates that it is also suitable for use inside buildings when routed through conduit.

SE cables are not commonly found in the single conductor configuration — they are usually available in cables with two exposed conductors and a bare cable for grounding. UF cable is suitable when manufactured as a multiple-conductor cable with jacket, but single-conductor UF cables are not commonly available and may have long-term durability problems in PV systems.

Since PV module wiring is normally confined to exterior locations, any exposed, single-conductor PV module wiring (such as USE-2) must be connected before or as it enters a building to one of the normal, "conventional" wiring methods. This must be done because exposed, single-conductor cables are not allowed inside buildings. USE-2/RHW-2 cable can be used for exposed, single-conductor module wiring and can then be installed in conduit for interior building runs. A roof-mounted, weather-proof junction box could also be used to provide a transition point between two different wiring methods.

A cable with an insulation rated for wet locations should be selected when using conduit in exposed (outdoor) PV installations. RHW, XHHW, RHW-2, and XHHW-2 are the best choices. Although THHW has a wet-rated insulation, there may be long-term durability issues associated with this cable when used in PV systems. Cables with a -2 marking indicate that the insulation has a 90°C temperature rating when wet. These types of cables are needed when connecting PV modules, because they operate at high temperatures as described below.

Cable Sizing — Ampacity

Ampacity is a term defined in the NEC that denotes the current-carrying capacity of a given conductor under a specific set of conditions. The ampacity of a conductor depends on the size of the conductor, the material of the conductor (copper or aluminum), the type of insulation (USE, XHHW-2, THHN, etc.), the type of insulation on the conductor, the mounting location (free-air/exposed or in conduit), and the ambient temperature. Tables 310-16 and 310-17 in the NEC provide details on the ampacity of various types of cables.

When a cable is installed according to the requirements of the NEC, it is designed to operate at least 20 years and still be safe. If the ampacity rating or operating temperature is exceeded for this cable, it may become unsafe in fewer years.

PV Module Rating and Operation
PV modules are rated under an illumination of 1000 watts per square meter with a cell temperature of 25°C (77°F) in a laboratory. However, when modules are exposed to actual outdoor operating conditions, the illumination may be 1150 W/m2 or higher on normal days, and the operating temperature may range from the lowest expected ambient temperature (-40°C or below with a strong winds) to 20-40°C above the highest expected ambient temperature (45°C ambient plus 30°C equals 75°C). The electrical output of the module (voltage and current) varies as these illumination levels and operating temperatures change. The output may be significantly different from the rated outputs marked on the back of the module.

PV System Design
The starting point for the balance of systems (BOS—cables, overcurrent devices, and disconnects) design is the rated module open-circuit voltage and short-circuit current printed on the back of the module. In order to meet NEC and UL requirements, the rated open-circuit voltage (Voc) must be multiplied by 1.25 to account for cold weather operation. This new voltage, called the maximum circuit voltage, will be used to determine the voltage rating of the module interconnection cable, array wiring, and other components. The rated short-circuit current (Isc) is multiplied by 1.56 to account for expected sunlight levels and NEC required 80% operating limits on cables and overcurrent devices. This circuit current is used to determine the ampacity of the cables and the rating of overcurrent devices and disconnect devices.

Temperature Deratings For Cables
Cables must be sized so that they can carry the circuit currents without exceeding the safety margins established by the NEC. The cable sizes are determined by the needed cable ampacity at the operating temperature of the cable.

Tables 310-16 (conduit installations) and 310-17 (free-air installations) provide ampacity figures for cables operating at 30°C (86°F). These tables also provide ampacity derating factors for cable operation at other temperatures. There is a possibility that PV modules on hot days with little wind may have junction box temperatures greater than 75°C. Temperatures in this range indicate that only cables with an insulation temperature rating of 90°C or higher should be used; cables with 75°C insulation have ampacities of zero when operated at temperatures above 70°C and are therefore not usable. When using 90°C conductors, even the 30°C ampacity values must be derated for the 75°C module operating temperatures. If modules are always operated in areas where the maximum ambient temperature is well below 45°C (113°F), then the module may operate below 75°C, and smaller ampacity derating factors may be appropriate. If the maximum ambient temperatures are above 45°C, then the module may operate at temperatures higher than 75°C and larger ampacity derating factors must be used. For equal current requirements, higher operating temperatures generally require larger conductor sizes.

Example: A number 10 AWG (American Wire Gage) USE-2/RHW-2 cable has an ampacity in free air of 55 amps at 30°C. When operated at 75°C, a factor of 0.41 is used to adjust the ampacity to 22.55 amps (55 x 0.41). If this cable is installed in conduit, the ampacity starts at 40 amps and is derated to 16.4 amps at 75°C. The Code Corner columns in *Home Power Magazine* issues 45-48 provide examples of these calculations.

The temperature derated ampacity of the cable selected for module interconnections must be greater than the circuit current (1.56 x rated Isc). The voltage rating of the cable must be greater than the maximum circuit voltage (1.25 x Voc). With single modules in the 40-85 watt power range, selecting and sizing an appropriate cable is a relatively easy task. When modules are connected in series and parallel for greater outputs, the cable sizes and ratings need to be determined for each circuit that can have differing currents and voltages. Examples can be found in the back issues of *Home Power Magazine* mentioned above. The NEC applies other restrictions on the maximum ampacity of cables, particularly number 10 AWG and smaller, and should be referred to for the necessary details.

Module interconnection cables and other array wiring that is not connected directly to the module junction boxes may operate at temperatures that are closer to ambient temperatures. In these cases, an appropriate ampacity derating factor should be used in selecting the proper cable.

Every conductor in an electrical power system, including PV systems, must be protected for overcurrents produced by overloads, short circuits, and unexpected failure-related currents. Even though the overcurrent device rating is chosen after the cable size is selected, the type of overcurrent device may influence the cable type and ampacity calculations. The next Code Corner will deal with overcurrent devices and with the calculations for rating them and how they affect cable ampacity.

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. Those wishing to actively participate should contact Ward Bower at Sandia National Laboratories • 505-844-5206

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