Flex is Out and the Dodo Diode Isn't Dead

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The news is not good, but please don't shoot the messenger. First, an electrical inspector has pointed out that the very popular flexible non-metallic conduit should not be used with PV modules. Second, although some system designers have said that the blocking diode is as dead as the extinct Dodo bird, there may be good reasons for using diodes or fuses in all systems.

Flexible Conduit

Liquidtight flexible nonmetallic conduit as described in Section B of Article 351 of the National Electrical Code (NEC) is often used for containing the wiring from PV modules to nearby junction boxes. This flexible, light-weight, gray plastic conduit is widely available in building supply stores and electrical supply houses in both precut and bulk lengths. The conduit cuts easily with a knife and the termination fittings are easy to install.

Unfortunately, this type of conduit is listed by Underwriters Laboratories (UL) for use at 70 or 80°C when dry and only 60°C when wet. NEC Section 351-23 (b) (2) states that this conduit may not be used where any combination of ambient temperatures and conductor temperatures are in excess of that for which the conduit is approved.

Conduit attached to PV modules is in an exposed location and wet-rated conductors must be used in all conduit that is exposed-see Definitions (location) in the NEC and NEC Handbook. Most PV modules are listed for use with 90°C conductors because junction-box and back-of-module temperatures can exceed 70°C. For these reasons, the conductors used in the installation of PV modules must have a 90°C insulation rating when wet. Typical cables are THWN-2, RHW-2, and XHHW-2 all having a 90°C insulation rating.

With 90°C cables, high ambient temperatures (70°C+), and possible wet conditions, the NEC says that the liquidtight flexible nonmetallic conduit marked 70°C dry/60°C wet cannot be used. UL is considering revisions to UL Standard 1703 that might require that either the listed PV module or the instructions for the listed module state that the use of this conduit is unacceptable. The flexible nonmetallic conduit can deform at high temperatures and reduce the internal area (needed to maintain the ampacity of the conductor), or the deformation and water can cause the fitting on the end of the conduit to come loose from the conduit.

Alternatives that can be used for PV module connections include liquidtight flexible metal conduit, ridged nonmetallic conduit (PVC), and several of the metal conduits. In addition, where conduit is not needed, outdoor-rated, exposed (not in conduit) single-conductor cables may be used. While these alternatives are, in some cases, more expensive or more difficult to use, they will ensure that the cables are adequately protected and that the protection will not fail due to high temperatures or wet conditions.

The Dodo Diode and The Series Fuse

Each PV module listed to UL Standard 1703 by a recognized testing laboratory is marked with the maximum current value of a series fuse intended to protect the module from overcurrents that may be forced through the module under fault conditions. The NEC requires that all instructions and labeling provided with listed modules be followed. This fuse requirement is in addition to other NEC system requirements to provide proper overcurrent protection for all conductors.

As PV system designs have matured over the last ten years, there has been a divergence of the design and installation practices between high-voltage (over 50-volts) and low-voltage systems. High-voltage systems, usually utility-interactive, have always employed blocking diodes and overcurrent protection for each string of series-connected modules. This NEC-required overcurrent device usually has been sized to provide overcurrent protection for the conductors in the series string and has been generally near the value of the required series fuse (required by UL Standard 1703) used to protect the PV module.

In low-voltage systems, system designers have been very concerned with power losses and voltage drops in these mostly stand-alone, battery-charging systems. Blocking diodes went the way of the dodo bird as designers found that the daytime losses through the diode exceeded the very low losses associated with night-time reverse current flow through the modules when the diode was removed. Many of these systems, but not all, have charge controllers without blocking diodes that disconnect the battery at night. There are many systems that do not employ charge controllers at all. Other charge controllers respond only to battery voltage and do not prevent reverse current flow from the batteries into the modules. Although overcurrent protection is usually provided for the conductors in the system, the rating of these overcurrent devices may be many times the value needed for the PV module protective fuse. Typical conductors used for module and array wiring have an ampacity several times that required by the individual module or module strings, and the overcurrent device is rated at these higher values to protect the conductors from backfeed currents from the batteries. Thus, in common practice, when a module fuse or blocking diode is not used, the module has insufficient overcurrent protection. On typical 12 and 24-volt systems, as much as 1000 watts of PV modules may be connected to a single source circuit without blocking diodes or module overcurrent protection.

Simulations

Simulations were run by David King at Sandia National Laboratories. The simulated 36-cell PV modules were equipped with bypass diodes around every 18 cells, but no blocking diode or series fuse. Two modules were connected in series to charge a simulated 24-volt battery. Various fault conditions were simulated.

First, a ground fault was simulated in the wiring between the PV modules. The battery voltage forced a reverse current of 7.5A through the first module, dissipating 198W in the module. The result was dynamic where the module heated up, its resistance to current flow decreased, the reverse current increased, and power dissipation increased until thermal equilibrium or an open circuit occurred. At 60°C module temperature, the simulated reverse current was 10.8A (285W). If a single string of 18 cells remained in the circuit, as might happen if a ground fault occurred at a bypass diode termination in the module junction box, over 50A of reverse current passed through the cells and 1350W were dissipated. A ground fault internal to the module (cell interconnect to frame or other grounded surface) was simulated leaving a single cell in the circuit. This case would be catastrophic with hundreds of amps of reverse current flowing through the single cell. In each of these cases, the simulated fault current from the battery would have been high enough to cause damage to the PV module. These simulated failure modes were verified with tests on PV modules and PV cells.

Test Results

A typical 40-watt, 33-cell, glass/Tedlar, 12-volt PV module was tested in a manner that might duplicate the conditions created by a ground fault in the series interconnecting cable between two such modules in a 24-volt PV system. This conceptual PV system had a number of parallel module strings and/or a battery bank capable of back feeding the array. A PV-charged battery bank at 26.5 volts was connected to the test module-positive-to-positive and negative-to-negative. Initial reverse current flow was 18.5A (490W). The module was shaded. Over the next 45 minutes, the cell temperatures went from 28°C to well over 200°C as the current increased to 39A (1034W). Bubbling of the encapsulant and some smoke were noted around the cells backed by the junction boxes (less heat radiation to the rear of the module in these areas). The Tedlar backing delaminated in a non-uniform manner from the rear of the module in areas where the cell temperatures were the highest. Forty-six minutes into the test, the PV module developed an open circuit, probably due to solder bond failures on the cells in front of the junction boxes. Although no flames were evident, the Tedlar was significantly discolored and the module was damaged beyond repair.

To evaluate a more severe situation, a similar test was conducted on a series string of nine silicon PV cells where the negative connection of the laminated string was connected to battery ground simulating a ground fault that could occur in an aluminum-backed module or a thin-film module laminated to a steel roofing panel. In this situation, the battery voltage (26.5V) was applied across the cell string. The reverse currents of more than 100 amps quickly caused the string of cells to develop an open circuit as the internal solder bonds melted. Tests on strings of 18 cells in series also resulted in open-circuited modules.

In no case was fire evident, but module temperatures in these tests were over 200°C (392°F) which could possibility start fires in dried leaves, grass, or even bird nests behind modules.

Solutions

Wiring the PV array to the requirements of the NEC with the correct size cable and the proper overcurrent protection for that cable will help to reduce the magnitude of the problem. Such wiring will limit the magnitude of potential backfeed current from parallel strings of modules or from the battery. Even with NEC-compliant wiring and overcurrent protection, the backfeed currents described above are sufficient to damage PV modules. Adherence to the markings on listed for a series fuse for each module or string of modules is necessary to provide full protection.

Fuses, while meeting all NEC and UL requirements, can present problems. Numerous fuses (one per module in 12-volt systems) installed in 12, 24, and 48-volt systems may pose significant operational and maintenance

(O&M) costs to the PV system. A few out-of-sight-out-of-mind, failed fuses installed in PV module junction boxes may never be replaced until the system fails entirely.

Although blocking diodes are not tested or listed as overcurrent devices, they do, in fact, prevent reverse currents from flowing. While diodes can fail in a short-circuited manner, they may prove to be more reliable than fuses in this application. Diodes, if considered by a modified UL Standard 1703 and the NEC as a required integral part of the PV module, could be the solution to this problem. Diode losses in low-voltage, battery-charging systems would have to be addressed. A modification to UL-1703 could require that blocking diodes be installed in each PV junction box on 12-volt systems and in one junction box per module string on higher voltage systems. Equivalent protection provided by fuses or other means could also be allowed.

It is suggested that blocking diodes or series fuses be installed on all systems. In a 12-volt system, each module needs a blocking diode or fuse. On 24 and higher voltage systems, each series string of modules needs a diode or fuse. The diode should have a current rating at least 1.56 times the short-circuit current rating of the module or string of modules. Electronic parts suppliers can supply silicon power diodes at low cost. At least a 400-volt diode should be used on a low-voltage PV system to provide some degree of surge protection. For example, Digi-Key Corporation (800-344-4539) has 6-amp, 400-volt diodes available at about $6.50 for 10 diodes (part # GI754CT-ND). The diode or fuse should be installed in series with the positive output of the module or string of modules. The band on the diode should point toward the positive battery terminal. The diode can usually be installed in the module junction box using the spare terminal (if any) provided.

DC rated, UL-listed fuses such as the Littelfuse KLK-D are available that are rated at 600 volts and various current levels. They are about $6-7 each and require a fuse holder. They are probably too large to mount in a module junction box. They do not, however, have the voltage drop and power loss associated with the blocking diode. Type ABC fuses from Bussmann may be a little cheaper and also have a DC rating. Fuses can be ordered from the larger electronic supply houses like Digi Key, Newark, and Allied. The ampere rating of the fuse should match the fuse size marked on the back of listed modules. If the modules are not listed and have no marking suggesting the proper fuse size, then the fuse size should have an ampere rating of about 1.56 times the module short-circuit current.

Your Failed Modules

It is suspected that ground faults described above may be more common than previously realized. These faults may have caused modules to fail for no apparent reason. The Southwest Technology Development Institute and Sandia National Laboratories are interested in examining failed modules that may have failed for the reasons described below. Anyone having modules that have failed for unknown reasons should contact me at the address below. Please be prepared to provide a description of the system where the modules were installed and the type of module including all information from the back of the modules and the stamped production date code. If the modules are types that are of interest, we may be able to provide a limited number of new modules at no cost in exchange for the failed modules.

Conclusions

It is evident from the simulations and actual tests that PV systems without protective module fuses or blocking diodes on each module or string of modules can be subject to extensive damage in ground-fault situations. Systems that have the capability to generate reverse currents in excess of the values indicated by the required protective fuse on a PV module can cause damage to the PV modules and may cause fires. PV systems that are ungrounded or systems that have insufficient sources of current would not be subject to this problem. The installation of fuses and/or blocking diodes in each module (12-volt system) or string of modules (24-volt and higher systems) appears to be the only solution to this serious problem.

Questions or Comments?

If you have questions about the NEC or the implementation of PV systems following the requirements of the NEC, feel free to call, fax, email, or write me at the location below. 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-AC04-94AL8500. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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