Blocking Diodes and Fuses in Low-Voltage PV Systems

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ABSTRACT

Instructions and labels supplied with listed PV modules and the requirements of the *National Electrical Code* (NEC)[1] dictate that a series fuse shall be used to protect the module against backfeed currents. Few of the hundreds of thousands of low-voltage (12, 24, and 48-volt) stand-alone photovoltaic (PV) power systems use series fuses on each module or string of modules. Tests and simulations at the Southwest Technology Development Institute (TDI) and at Sandia National Laboratories (SNL) have established that the absence of these fuses can pose significant fire and safety hazards even on 12-volt PV systems. If the system has sufficient backfeed voltage and current, it is possible that a ground fault in the wiring or inside a module can result in the destruction of a PV module.

INTRODUCTION

Each PV module listed to Underwriters Laboratories (UL) Standard 1703 [1] 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 or other unusual operating conditions. Section 110-3(b) of the NEC [2] requires that all instructions and labeling provided with listed products, including PV modules, be followed. This fuse requirement is in addition to other NEC system requirements that provide proper overcurrent protection for all conductors.

As PV system designs have matured over the last fifteen years, there has been a divergence of the design practices between high-voltage (over 50-volts) and low-voltage systems. High-voltage systems, usually utility-interactive, have always employed 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 (by UL Standard 1703) series fuse used to protect the PV module.

In low-voltage systems, system designers have been very concerned with power losses and voltage drops in these mainly stand-alone, battery-charging, and direct coupled systems. Blocking diodes were eliminated from the systems 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 under fault conditions.

Although overcurrent protection is usually provided for the conductors in the system, the rating of these overcurrent devices may be many times the size of 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 is not used, the module has insufficient protection from backfeed currents. On some 12 and 24-volt systems, as many as 1000 watts of PV modules may be connected to a single-source circuit without module overcurrent protection.

SIMULATIONS

To illustrate the situation of concern, the four-quadrant current-voltage (I-V) curve of a small array with two 36-cell silicon PV modules connected in series was simulated using PVSIM [3]. The modules were equipped with bypass diodes around every 18 cells, but no blocking diode or series fuse. The I-V (current-voltage) curve #1 shown in Figure 1 illustrates the array functioning correctly at 25°C charging a 24-volt (grounded) battery bank at an operating voltage of V_{op}=30 V.

The next four I-V curves illustrate the consequences of several hypothetical ground-fault failures of increasing severity. Curve #2 shows the results of a ground fault located between the modules. The battery voltage becomes the operating voltage for the module (V_{op}=26.5 volts) forcing the module to operate in the fourth I-V quadrant with a reverse current of 7.5A, dissipating 198W in the module. The result is dynamic where the module heats up, its resistance to current flow decreases, the reverse current increases, and power dissipation increases until thermal equilibrium or an open circuit occurs. At a 60°C module temperature, the reverse current would be 10.8A (285W).

Another failure, curve #3, is similar to the first except the module is not illuminated (simulated night time); the consequence is nominally the same with 210W dissipated in the module. Curve #4 shows the result 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. In this case, over 50A of reverse current flows through the cells and 1350W are dissipated. The final failure (curve #5) occurs with a ground fault internal to the module (cell interconnect to frame or other grounded surface) leaving a single cell in the circuit. This case would be catastrophic with hundreds of amps of reverse current flowing through a single cell.

A limitation of the simulation assumes that each cell is identical and that the reverse voltage distributes equally over each cell. The simulation also assumes distributed radiation of the thermal energy resulting from the equal power dissipation in each cell. In the PV modules, the cells are not identical, which results in unequal voltage distribution and power dissipation. The thermal radiation is modified by not only the unequal power dissipation, but also by the differing thermal conduction values represented by the module backing exposed to free air or covered by junction boxes. To verify the simulated failure modes and to determine the effects on actual modules, tests were conducted at the Southwest Technology Development Institute.

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 has a number of parallel module strings and/or a battery bank capable of back feeding the module. 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). 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. A second test was conducted on a similar module and the voltage, current, and temperature time profiles are shown in Figure 2.

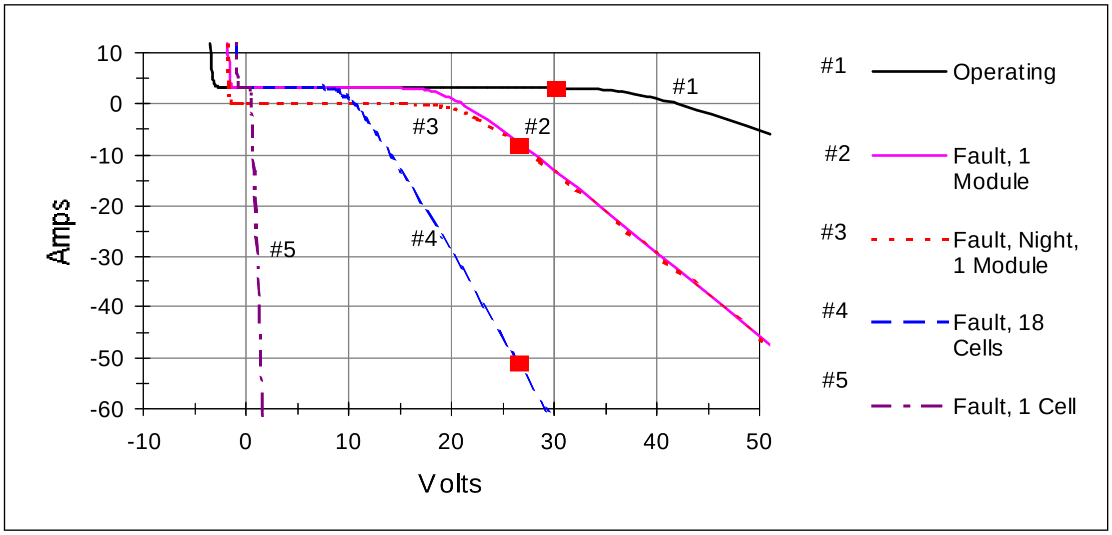

Fig. 1. Array Ground-Fault Simulation

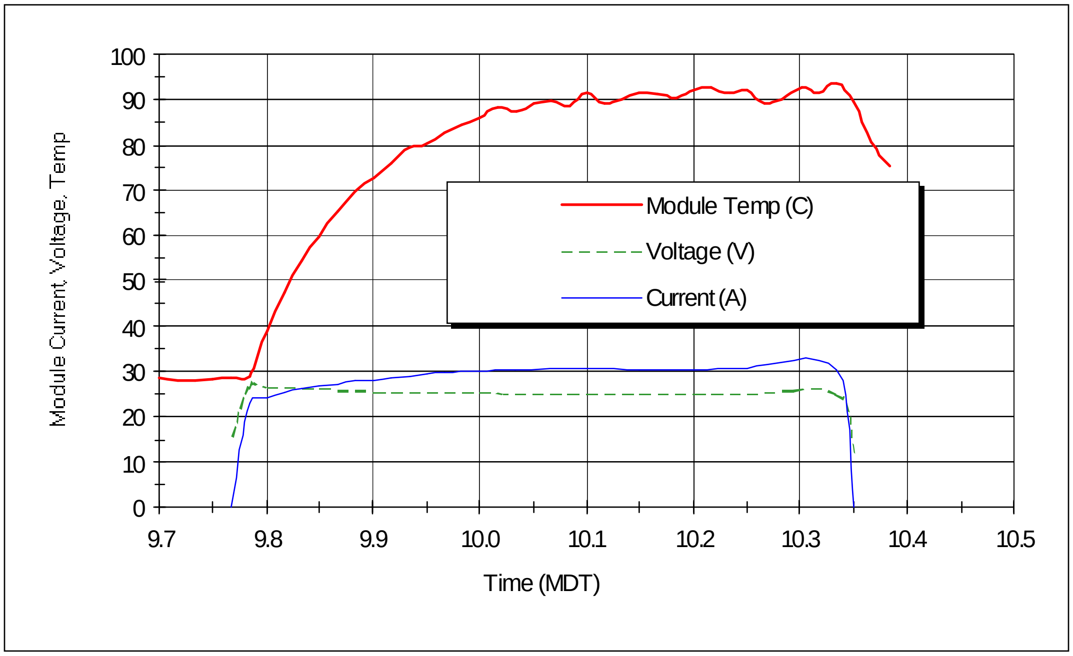

Fig. 2. 33-Cell Module

To evaluate a more severe situation, a similar test was conducted on a series string of 9 silicon PV cells. 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 (V_{op}=26.5V) was applied across the cell string. Infra-red video and data logged temperature measurements showed that the applied voltage quickly resulted in high temperatures and an open circuit in the string of cells.

The simulations and tests reveal that some sort of protection is needed for these back-fed currents. The NEC and UL Standard 1703 require that a fuse or other overcurrent device be used. This protection is for the module and not the interconnecting cables. The requirement is similar to a fuse in a stereo or television set that serves to protect the set from internal problems. In the TV set, however, the fuse is installed by the factory, not by the electrician wiring the house. In the case of the PV module fuse, the fuse is to be installed by the PV installer, electrician, or electrical contractor wiring the system.

DIODES

Blocking diodes can be used to prevent these reverse current flows. They are not, however, tested and listed as overcurrent devices, so they do not meet the requirements of the NEC or UL Standard 1703 for this purpose. UL Standard 1703 could be modified to require that a diode be installed in each module (12-volt systems) or series string of modules (24 and up) as an internal part of the module. Such a diode could be mounted in the module junction box and be bypassed or eliminated for the second and subsequent modules in each string. By modifying the UL Standard to require the inclusion of the diode, it would no longer violate the NEC to use the diode in this manner because it would no longer be used as an overcurrent device.

IMPACTS

Battery charging in hot climates generally dictates that 36-cell PV modules be used due to reductions in the module operating voltage as module temperature rises. Voltage drops due to series diodes or fuses and fuse holders may impose performance constraints on the performance of the system in battery-charging applications.

In cold or cool climates at battery charging voltages, an array of 36-cell modules would be operating to the left of the peak-power point. The addition of a blocking diode (with a 0.5 - 0.7 volt drop) to the module output would result in a minimal reduction in the current to the battery. In warmer and hot climates, where the module temperature climbs above the 40° - 50°C range, the modules (charging batteries) would be operating to the right side of the peak-power point. In this case, the addition of a diode or fuse would result in greater reductions in charging current. The use of fuses, with low-resistance connections, results in less voltage drop than the use of diodes.

Any voltage drop from a diode or fuse will have less impact on the system performance as the system voltage increases from 12 volts to 24 volts or 48 volts.

Both fuses and diodes represent added components. These components and their connections represent added complexity to the system and pose potential problems in maintenance and reliability.

Numerous fuses mounted in PV junction boxes would be out of sight and out of mind. One or two blown fuses could reduce the PV array output in a medium sized system without being noticed. Diodes may resist surges better than fuses, but they initially fail in a shorted mode. Shorted diodes would not be noticed and would not provide the desired module protection. Small, listed, dc-rated supplemental circuit breakers with auxiliary switches connected to an alarm circuit may be a solution that minimizes the performance impacts and the maintenance/operability issues.

Conclusions

Continued research is needed. 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 greater than the value of the required protective fuse on a PV module can pose fire and safety hazards. PV systems that are ungrounded or systems that have insufficient sources of back-feed currents would not be subject to this problem. Ungrounded systems could, however, have wiring faults that could duplicate the reverse currents from ground faults on a grounded system. The installation of overcurrent devices 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 safety problem.

Fuses may not be the best solution to the problem. Numerous fuses (one per module in 12-volt systems) installed in 12, 24, and 48-volt systems may pose significant O&M costs to the PV system. A few out-of-sight-out-of-mind, failed fuses installed in PV module junction boxes may not be replaced until the system fails entirely.

Although blocking diodes are not tested or listed as overcurrent devices, they can, 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 revised 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, circuit breakers, or other means could also be allowed.

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