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INVESTIGATION OF GROUND-FAULT PROTECTION DEVICES FOR PHOTOVOLTAIC POWER SYSTEMS APPLICATIONS*

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ABSTRACT

Photovoltaic (PV) power systems, like other electrical systems, may be subject to unexpected ground faults. Installed PV systems always have invisible elements other than those indicated by their electrical schematics. Stray inductance, capacitance and resistance are distributed throughout the system. Leakage currents associated with the PV modules, the interconnected array, wires, surge protection devices and conduit add up and can become large enough to look like a ground-fault. PV systems are frequently connected to other sources of power or energy storage such as batteries, standby generators, and the utility grid. This complex arrangement of distributed power and energy sources, distributed impedance and proximity to other sources of power requires sensing of ground faults and proper reaction by the ground-fault protection devices. The different dc grounding requirements (country to country) often add more confusion to the situation. This paper discusses the ground-fault issues associated with both the dc and ac side of PV systems and presents test results and operational impacts of backfeeding commercially available ac ground-fault protection devices under various modes of operation. Further, the measured effects of backfeeding the tripped ground-fault devices for periods of time comparable to anti-islanding allowances for utility interconnection of PV inverters in the United States are reported.

INTRODUCTION

Photovoltaic power systems may experience unexpected ground faults on either the dc or ac side of the inverter. Sometimes stray leakage currents associated with the PV modules, the PV array, wires, terminal blocks, surge protection devices and conduit can become large enough to look like a dc ground-fault in PV systems. The National Electrical Code® (NEC®) has required the use of dc ground-fault protection devices for PV systems installed on dwellings in Section 690-5 since 1987. [1] The NEC states "Roof mounted dc photovoltaic arrays located on dwellings shall be provided with dc ground-fault protection to reduce fire hazards." The trip levels associated with these dc ground-fault protection devices are generally set at levels to protect against danger of fire rather than for personnel protection. The fault trip levels are generally around 0.5A for available devices.

Section 690-6 for alternating current (ac) PV modules was added to the 1999 edition of the NEC. It states "690-6(d) Alternating-current module systems shall be permitted to use a single detection device to detect only ac ground faults and to disable the array by removing ac power to the ac module(s)." This provides for installation of single and multiple ac PV modules and permits the use of a single ground-fault device to protect multiple ac PV modules. This article does not specify whether the ground-fault protection device for the ac PV module is to be rated for fire or for personnel protection nor does it mention that commercially available hardware is not rated to be backfed.

This paper focuses on the ground-fault issues associated with ac PV systems and ac ground-fault devices. Normal ground-fault trips on a properly installed (non-backfed) ground-fault device on a branch circuit disconnects the trip coil in the GFCI from the line power in less than one cycle. If the device is being backfed with a PV power source such as an ac PV module, the power now passes from the load side to the line side of the ground-fault device. When most ground-fault devices are tripped, and the backfeed is present, the trip coil remains energized through associated internal circuitry and remains connected to the inverter. It can remain energized as long as the inverter continues to operate. Test results and operational failures resulting from backfeeding many of the commercially available ac ground-fault protection devices in a tripped state are described. This data provides substantiation for the need to clarify existing NEC requirements for ac ground-fault protection for the ac side of ac PV module systems, and the permitted uses for the hardware.

GROUND-FAULT SAFETY REQUIREMENTS

The NEC requirement for dc ground-fault protection is based on fire protection as opposed to the ac anti-shock personnel protection that is commonly required for outdoor locations, kitchens, garages and bathrooms. The first dc devices to be used in PV systems were custom designs that were not listed or certified. [2] The dc ground-fault protection may now be obtained as separate listed devices or is now included in some utility-interactive inverter designs.

The new Section 690-6 in the 1999 NEC permits the use of a single ground-fault device on the ac circuit to detect ac ground faults and in turn disable an ac PV module by removing the ac power to the integrated inverter. Although Section 690-6(d) is permissive and not a requirement to use the ac ground-fault protection, other

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parts of the code do require ground-fault protection for devices and receptacles in outdoor and wet locations, and that presents a set of confusing and conflicting requirements. Some PV installers have interpreted the NEC to permit the use of ground-fault circuit interrupters (GFCIs), used for personnel protection, to meet the ground-fault device requirement. However, the low trip levels of GFCIs (4-6 mA) have been found to result in false trips due to electromagnetic interference (EMI) filter leakage with some inverters. There have also been other interpretations by PV installers that ground-fault protection (GFP) devices (used for equipment protection) may be used to meet the NEC requirement. Both types of devices have been used in PV installations, but neither of the device types is listed to be backfed by another source of power as in applications using ac PV modules to feed power into the electrical grid. [3]

DC Ground-fault Protection Hardware

Ground-fault protection hardware for PV arrays is now commercially available as separate devices for low-voltage systems (48-V or less) or may be integrated into the dc-to-ac utility-interactive inverters used for PV applications. The need for dc ground-fault protection is based entirely on fire prevention and the requirement generally applies only to roof-mounted PV arrays on dwellings. The commercially available dc ground-fault protection hardware has been designed to have power applied from both the PV array side and the inverter side and to satisfy the requirements of the NEC. [2,4]

AC Ground-fault Circuit Interruption Devices for Personnel

There are several types of ac ground-fault protection devices that are commercially available. The anti-shock ground-fault circuit interrupters (GFCIs) are used to prevent shock and electrocution. They are designed to measure leakage currents (4-6 mA) to ground on the load side and then to disconnect the power within one cycle of ac power. [5,6] These devices are designed as either a circuit breaker for installation in a distribution panel or as a receptacle. Some of the devices are marked "do not backfeed" but even those with no marking are not rated or listed by an independent laboratory to be backfed.

The circuit breaker type of anti-shock GFCI installed in the service entrance panel is designed to protect an entire branch circuit from ground faults and also to act as overcurrent protection. The other type of anti-shock GFCI is the more familiar unit found in bathrooms, kitchens and garages in dwellings. They are receptacle-type GFCI devices and they may protect an entire branch circuit, a portion of the circuit or a single receptacle from ground faults. Figure 1 shows some of the receptacle GFCI (personnel protection) devices tested. None of these receptacle-type GFCI devices are rated or listed to be backfed.

AC Ground-fault Protection Devices for Equipment

Ground-fault protection (GFP) devices (a separate category of ground-fault protection) are designed to protect equipment from ground faults as well as to provide overcurrent protection. They are set to trip at higher levels of ground-fault current and to provide for equipment and fire protection <u>only</u>. The trip currents on the commercial devices tested were marked to be 30 mA. Figure 2 shows some of the circuit breaker GFP (equipment protection) devices tested. The devices tested were single-pole and rated at 120 Vac.

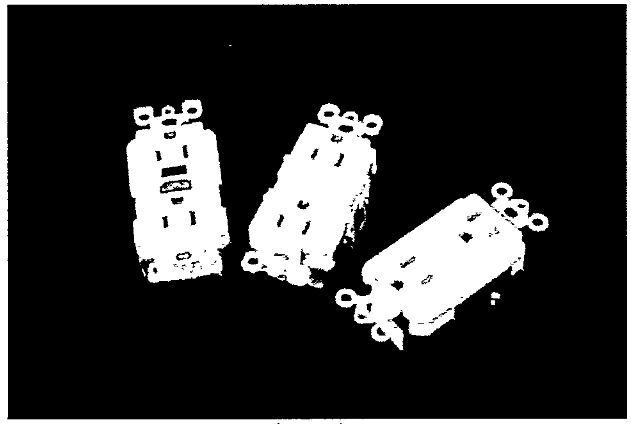

Figure 1. Receptacle GFCI devices.

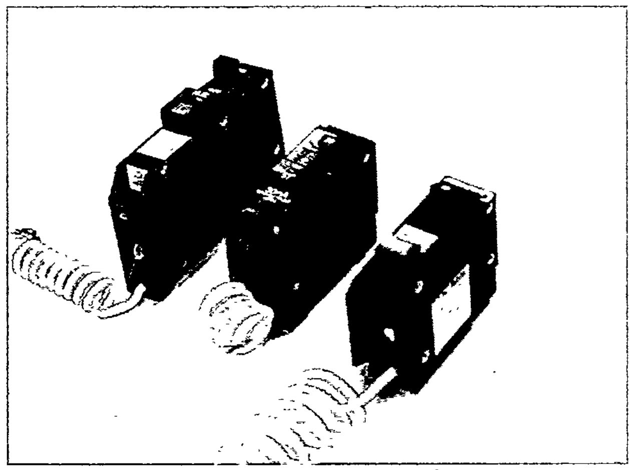

Figure 2. Equipment GFP devices tested.

Anti-islanding Requirement for AC PV Modules

Inverters in PV systems and ac PV modules, including those where GFCI or GFP devices may be used, are required by the NEC to be listed for the purpose. Generally that means the inverter will be listed (tested and evaluated) according to the Underwriters Laboratories Standard for Safety for Static Inverters and Charge Controllers for Use in Photovoltaic Power Systems (UL1741). [7] The IEEE Std. 929-2000 "Recommended Practice for Utility Interface of Photovoltaic (PV) Systems" may also be applied by the local utility as an interconnection criterion. [8] Both documents have been coordinated to specify and test for minimum run-on (continuing operation after disconnection from the utility) times for inverters when the utility is disconnected or out-of-specification. In addition to response times for out-of-voltage tolerance there is an islanding protection section that addresses the response that listed (non-islanding) inverters must exhibit when exposed to an islanding condition.

Typically an islanding condition may exist when the utility is suddenly disconnected and the remaining load on the inverter is nearly balanced to its output power. [9] Tests in UL1741 and IEEE Std. 929-2000 add a tuned LC (inductive and capacitive) circuit in parallel with the balanced resistive load. [10] The total RLC circuit has a quality factor (Q) of 2.5 that tends to hold the resonant frequency near 60 Hz. Inverters meeting the standard are able to detect the islanding condition described above and disconnect within 10 cycles if the load is less than 50% or greater than 150% of the output power of the inverter and the power factor is less than 0.95 (leading or lagging). If the load is balanced within the 50% limits and the power factor is greater than 0.95 then the inverter must disconnect within 2 seconds when the test circuit has a quality factor of 2.5 or less.

LOADS REPRESENTED BY GFCI AND GFP DEVICES

Tests conducted showed that all circuit breaker type GFCI and GFP devices are constructed so that the trip coil for the device is connected on the load side of the circuit. Tripping on a normal (non-backfed) branch circuit disconnects the trip coil in the GFCI from the line power within one cycle. If the device is being backfed with a PV power source such as an ac PV module, the power now flows from the load side to the line side of the device. When tripped, the trip coil remains energized through associated circuitry and remains connected to the inverter. It can remain energized as long as the inverter continues to operate.

It was found that some of the trip coils and electronic circuits in the various GFCI and GFP models exhibited resistive loads drawing between 100 W and 300 W. That is exactly the same range of power found in either single or multiple ac PV modules, thus increasing the probability of islanding. Even short-term power levels in this range, when confined to the small size of ground-fault protection devices, can result in destruction of the circuit or the trip coil. It was found that many of the trip circuits in tripped circuit breaker ground-fault protection devices would be destroyed in 2-3 seconds of run-on by an inverter.

TESTS CONDUCTED UNDER ISLANDING CONDITIONS

Commercially available GFP and GFCI devices [6] were tested using the circuit shown in Figure 3. The test setup allowed for a wide range of backfeed operations of the ground-fault devices. Note that the devices are designed for current flow from the "line" to the "load." With a PV system, the current will flow from the "load" to the "line" meaning the device is backfed. The inverter simulator had output characteristics similar to a voltage-sourced power producer with controllable power out and run-on time adjustments. The power output was adjustable to match loads presented by the ground-fault devices or to show the effect of higher and lower backfeed currents after the ground-fault protection tripped. The time for run-on was easily adjusted from approximately 40 milliseconds to hours in 10-ms steps using the electronic timer/counter. Other features included the ability to adjust the magnitude of a ground fault current, along with a protective fuse for direct short ground faults.

The GFCI devices or the GFP devices under test were tripped by an adjustable ground fault current and the timer was triggered at the same instant. The timer/counter then adjusted the length of time the inverter simulator would backfeed the ground-fault protection under test. Ground-fault circuit breaker devices were subjected to a full range of run-on times until the trip circuit failed.

Voltage and current waveforms and the times-to-failure were recorded with a digital oscilloscope. Some tests with receptacle type GFCIs required that the oscilloscope be isolated from ground because the NEUTRAL line was

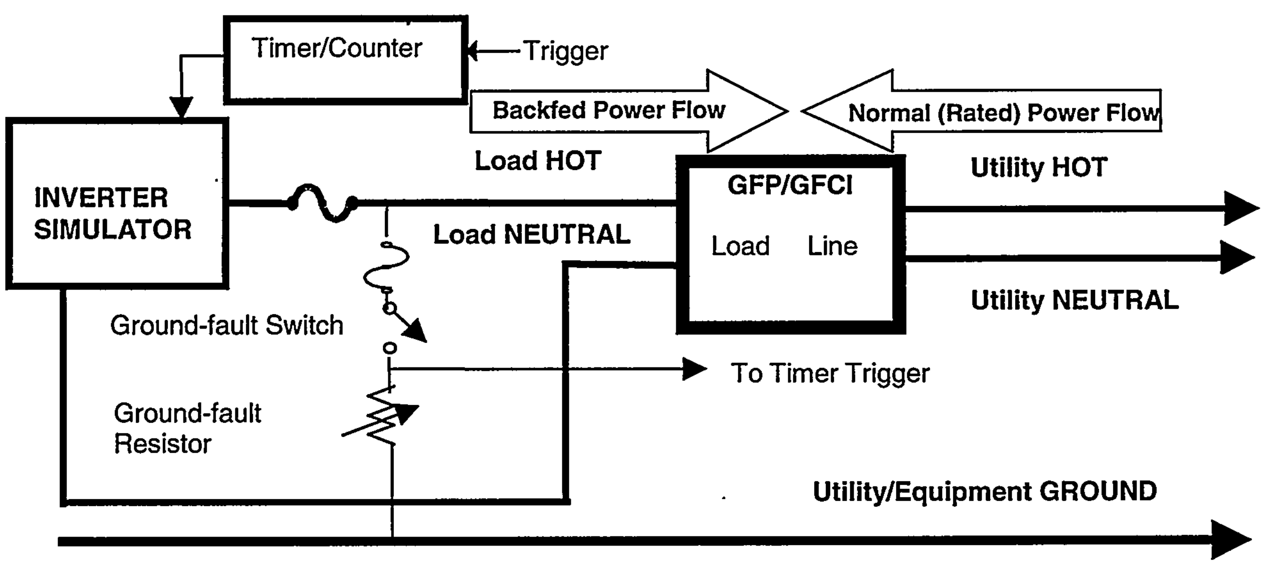

Figure 3. Ground-fault device test set-up.

interrupted when the device tripped. This also required that a high resistance load be applied from the load HOT terminal to the load NEUTRAL terminal of the device.

All of the ground-fault devices reacted to specified fault levels and disconnected (tripped) in less than one cycle. The current drawn by the ground-fault hardware from different manufacturers, however, varied widely. Each type of circuit breaker ground-fault device was tested with increasing run-on times after tripping until failure or until no further changes were observed. The trip circuit in most circuit breaker-type devices failed after 2-3 seconds of simulated inverter run-on. All devices with failed trip circuits were capable of being reset after failure, but none continued to function as a ground-fault protection device. Note that the only way a customer would know if the device was damaged, would be to press the test button on the device and observe a trip. All devices were labeled to be "tested" on a monthly basis.

RESULTS OF BACKFEED TESTS ON GFCI AND GFP DEVICES

Voltage and current waveforms, up to and after the occurrence of a ground fault, were recorded. The waveforms reported in this paper include the voltage across the load terminals (load HOT to load NEUTRAL) of the ground-fault device and the current flowing into the load (HOT) terminal of the device. Fault current supplied by the inverter simulator was not measured. The waveforms show disturbances caused by ground faults, reaction time of the ground-fault device, current drawn by the ground-fault device following a ground-fault, simulated inverter run-on and inverter disable reactions.

The following set of waveforms shows the wide variety of reactions and trip circuit loads represented by the tripped ground-fault devices.

It is evident in Figure 4 that the current supplied by the simulated inverter before the fault and after the fault was very nearly the same (matched load) and represented approximately 250 W. The device tripped in less than one cycle (about 8ms) with a clean transfer of power, first flowing to the grid and then to the internal circuit and trip circuit and coil of the GFP. The current and voltage waveforms showed no perceivable perturbations. The inverter run-on time for this test was 200 ms. As the run-on time was increased, internal heating of the ground-fault device resulted in a gradual decrease in current drawn during run-on (also shown in Figure 4) until the device's trip circuit failed after approximately 2 seconds of run-on. Each ground-fault device was tested to failure or until it was evident there were no further changes taking place. The time-to-failure typically ranged from 2 to 5 seconds.

The UL1741 and IEEE Std. 929-2000 requirement allowing for a 2-second balanced-load disconnect time presents a dilemma for using these circuit-breaker devices in the backfed configuration. Some ac PV modules or combinations of ac PV modules operate in the 100-300 W range where some ground-fault devices may present a matched load to the PV system output. Note that even though the inverter meets the standards, the balanced load (represented by the trip circuit of the ground-fault protection) maximizes the allowable run-on time.

Figure 5 shows waveforms measured on an equipment-type (30 mA) ground-fault protection device where the current drawn by the device after tripping appeared to be a rectified current. This particular waveform depicts a condition where the current supplied by the inverter simulator to the utility grid is approximately twice the value drawn by the tripped ground-fault device. The device tripped in less than one-half cycle and the run-on time for this test was 55 ms.

Figure 6 shows the waveforms measured on a circuit breaker-type personnel protection (5 mA sensitivity) GFCI.

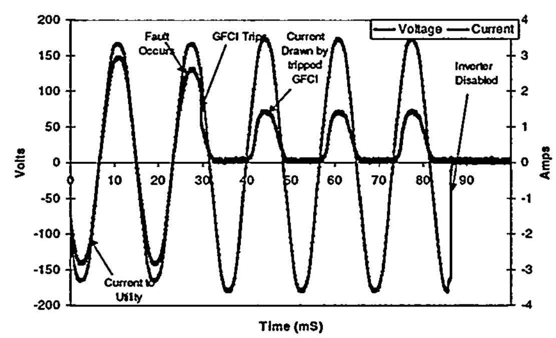

Figure 5. Backfed current in a tripped ground-fault device that rectifies backfed current.

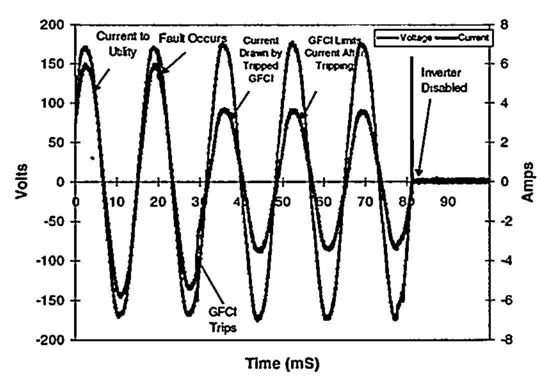

Figure 6. Backfed current through a tripped ground-fault device where the GFD limits the current from the inverter.

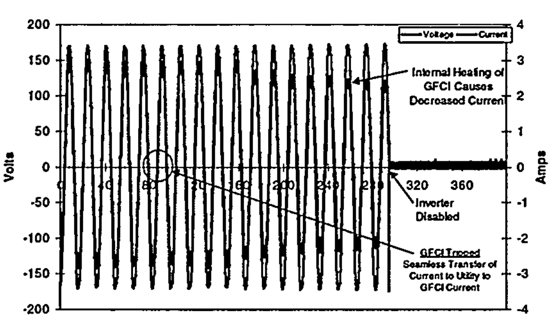

Figure 4. Backfed current into a tripped ground-fault device where the trip-circuit load matched the output of the simulated inverter.

Note that all of the personnel-type GFCIs exhibited a range of waveforms and reactions similar to the equipment protection GFPs. This waveform represents a 50 ms run-on by the simulated inverter.

The receptacle-type GFCI devices were also tested.

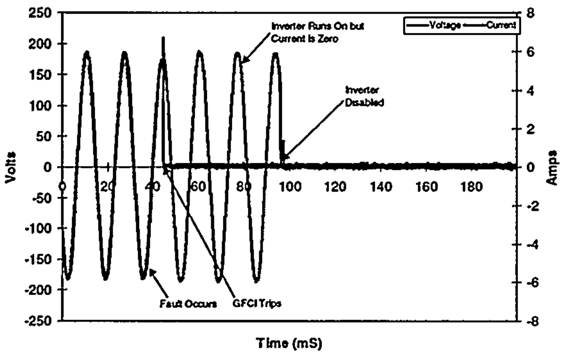

Figure 7. Backfed current with a receptacle-type ground-fault circuit interrupter device.

Figure 7 shows the current waveform from the simulated inverter is terminated when the device was tripped. Note that no current is drawn once the GFCI trips because the receptacle-type devices open both the neutral and hot lines when tripped and that effectively disconnects the trip coil from the load terminals of the simulated inverter circuit. There was no indication the receptacle type devices would ever fail because of islanding. This design (with higher trip points) would be a good candidate to provide ground-fault protection for PV applications such as ac PV modules except the NEC does not allow any receptacles on the dedicated circuit from an ac PV module. Also, the device would have to be listed to be backfed.

The NEC states "690-64. Point of Connection.
The output of a photovoltaic power source shall be connected as specified in (a) or (b).
(a) Supply Side. A photovoltaic power source shall be permitted to be connected to the supply side of the service disconnecting means as permitted in Section 230-82(5).
(b) Load Side. A photovoltaic power source shall be permitted to be connected to the load side of the service disconnecting means of the other source(s) at any distribution equipment on the premises provided that all of the following conditions are met.
1. Each source interconnection shall be made at a dedicated circuit breaker or fusible disconnecting means."
Additionally, Article 690-64(b) requires that
"3. The interconnection point shall be on the line side of all ground-fault protection equipment.
Exception: Connection shall be permitted to be made to the load side of ground-fault protection, provided that there is ground-fault protection for equipment from all ground-fault current sources.
5. Equipment such as circuit breakers, if backfed, shall be identified for such operation."

Fielded PV systems have also demonstrated that the low trip levels (4-6 mA) of these GFCIs have been found to cause nuisance trips because of current associated with electromagnetic interference (EMI) filters in the inverters. They are an unacceptable option for ac ground-fault protection for ac PV modules.

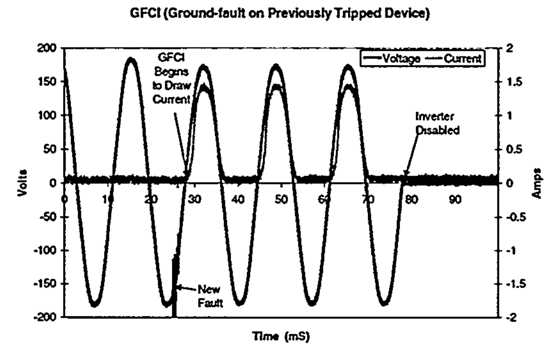

Figure 8. GFCI reaction to backfeed voltage when a new fault occurs.

NEW ISSUES AND CURRENT WORK

Utility-interactive Inverters that become Stand-alone on Utility Outages

It was observed during these tests that once the power had been removed from a tripped circuit breaker-type ground-fault device, and then reapplied, the trip circuit would draw no current. This feature could save the device from destruction should a renewable energy system try to restart repeatedly. Listed utility-interactive inverters for PV systems shall not try to restart unless the utility voltage is present and within specifications for two minutes.

New inverters are available today, however, that can also operate independently of the utility grid to supply loads in the event of utility outages. If the tripped circuit breaker-type ground-fault device were to remain in the circuit, the stand-alone inverter output could continue until the internal ground-fault device circuitry was destroyed. Figure 8 shows the reaction to the occurrence of a fault on a device that is already in the tripped state. This waveform also represents a simulated inverter run-on of 50 ms.

Arc-fault Circuit Interrupters (Future Requirements?)

Arc-fault circuit interrupters are emerging as a new safety device that can detect arc-types of faults or loose connections in a branch circuit. [12] The NEC now contains a requirement for using these devices in bedroom branch circuits in residential dwellings. The effective date for the new requirement is set for January 1, 2002. Some circuit breaker-type devices are now commercially available and two devices were tested. No receptacle-type AFCI devices could be purchased for these studies. The circuit breaker devices are not rated for backfeeding, but tests showed less potential for destroying the AFCI after tripping than with the circuit breaker-type ground-fault protection devices.

Other issues that need to be addressed as devices emerge include AFCI immunity to high frequency switching inverter waveforms and reactions of the devices to ground faults. The test results showed that the devices tested offered neither personnel nor equipment ground-fault protection. The devices did trip with ground faults greater than approximately 0.5 A, and after tripping would draw intermittent but periodic current when backfed.

Proposed Changes for the 2002 NEC

Several changes related to the use of ground-fault devices in PV applications have been proposed for the 2002 NEC. On the dc side, the proposed new language states:
690-5. Ground Fault Protection. Roof-mounted dc PV arrays located on dwellings shall be provided with dc ground fault protection to reduce fire hazards." Additionally, 690-5(c) would read
(c) Labels and Markings. Labels and markings shall be applied near the ground-fault indicator at a visible location stating that if a ground fault is indicated, the normally grounded conductors may be energized and ungrounded."

On the ac side for ac PV modules, the permissive language to permit the use of a single detection device to detect only ac ground faults and to disable the array by removing ac power to the ac modules remains. Work is continuing to show that no devices exist to meet this permissive language and that the language creates confusion.

CONCLUSIONS

The NEC currently has a permissive requirement for using a ground fault device for use with ac PV modules. A dilemma exists for the use of ac ground-fault devices with ac PV modules. Although not specifically required by the NEC, a combination of interpretations for wet locations where ac PV modules may be installed, and permitting the use of a single detection device for multiple ac PV modules in Article 690-6 have suggested that the ground-fault protection devices are required when installing ac PV modules. The tests conducted showed that even a short-term reverse power applied to ground-fault devices in a tripped state rapidly results in destruction of its trip circuit. These tests confirmed that circuit-breaker-type GFCI devices being sold today should not be backfed even if inverters are listed with a maximum of 2 seconds run-on with a matched load. They were found to be unsuitable for the PV ground-fault application in a backfed configuration. The receptacle-type GFCI was found to open the load NEUTRAL and remove the trip coil and circuitry from the backfeeding PV power source. However, they violate other NEC requirements against backfeeding and inserting receptacles in the dedicated PV branch circuit. The tests showed there are currently no devices available that meet the Article 690-6 requirements for ac PV modules and that the permissive language only serves to confuse users and inspectors. Changes are necessary to alleviate the dilemma and have been proposed for the 2002 edition of the NEC.

ACKNOWLEDGEMENTS

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