DEVELOPMENT OF ARC-FAULT CIRCUIT-INTERRUPTER REQUIREMENTS FOR PHOTOVOLTAIC SYSTEMS

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ABSTRACT

Photovoltaic systems, which typically consist of an array of PV modules, are often associated with buildings, where the PV system components can either be mounted to the building, such as on the roof, or integrated into the building structure. The 2011 edition of the National Electrical Code® (NEC®) will require all PV systems with DC circuits operating at 80 volts or greater on a building to be protected by a listed Arc-Fault Circuit Interrupter (AFCI), PV type, or other system components listed to provide equivalent protection.

In response to this new NEC requirement, Underwriters Laboratories Inc. (UL) has developed the 1st Issue of the Outline of Investigation for Photovoltaic DC Arc-Fault Circuit Protection, designated Subject 1699B. This new Outline includes requirements for listing PV arc-fault circuit interrupters (PV AFCIs), arc-fault detectors (AFDs), and associated interrupting devices (IDs). These requirements will also address inverters, converters, and charge controllers with integral AFCI protection. In addition to using existing requirements from the UL1699 Standard for Arc-Fault Circuit-Interrupters for residential (AC) arc-fault protection developed in the 1990s, this new Outline includes special DC arc fault detection tests that were developed from more recent research.

This paper presents the feasibility of DC arc fault protection in PV systems, and the development of the safety requirements for this protection. It will also address the various types of arcing faults in PV systems, and the challenges for arc fault detection schemes in being able to respond to this arcing and mitigate the risk of fire ignition.

INTRODUCTION

Photovoltaic modules are tested for safety and performance using the UL 1703 Standard for Flat-Plate Photovoltaic Modules and Panels [1] and the International Electrotechnical Commission (IEC) IEC 61730 Photovoltaic (PV) module safety qualification [2]. Field experience has shown that electric arc fault failures due to PV wiring and system components can lead to fires. The Solar America Board for Codes and Standards has identified AFCI technology as a possible protection device for PV modules and systems against the unwanted effects of arc faults. This issue has also been discussed by IEC TC 82 (solar photovoltaic energy systems), and a DC arc detector was considered to be incorporated within PV systems when it becomes available. However, products for DC arc fault detection are now being developed and tested to demonstrate their effectiveness in arc detection and mitigation strategies. One recent collaborative testing effort with Eaton Corporation and Sandia National Laboratories is demonstrating the effectiveness of PV arc detection testing with a wide range of PV systems and topologies [3]. In addition, some DC arc-fault protection devices were proposed for automotive systems and aerospace systems, and they may be adapted for PV systems [4, 5].

In the U.S., the NEC [6] is the main building code for protecting people and property from the hazards of electricity. The 2011 edition of the NEC now requires that all PV systems with DC circuits operating at 80 volts or greater on a building to be protected by an AFCI, PV type, or other system components listed to provide equivalent protection. This system shall detect and interrupt arcing faults resulting from a failure in the intended continuity of a conductor, connection, module, or other system component in the direct current PV source and output circuits.

In response to this new NEC requirement, UL formed a PV AFCI Working Group to assist in the development of these requirements for the PV AFCI. This working group consisted of AFCI manufacturers, PV and inverter manufacturers, as well as representatives from government labs and PV consultants. As a result of this group's efforts, the 1st Issue of the Outline of Investigation for Photovoltaic DC Arc-Fault Circuit Protection, designated Subject 1699B, was published in April of 2011 [7].

TYPES OF DC PV ARCING FAULTS

Arcing is defined as a luminous discharge of electricity across an insulating medium. The length of time that continuous arcing occurs in an AC system is typically shorter than in similar DC systems because the arc generally cools and may extinguish when the current passes through a zero level during the normal sinusoidal cycle. In DC systems, however, the current remains relatively constant and does not go through a zero level. Thus the DC arc is more readily maintained over relatively large gaps in time. This arcing condition can lead to an electrically caused fire by exposing near-by combustible material to the energy generated by the arc. This energy can be sufficient to cause wire insulation to pyrolyze and produce combustible gases, which can readily be ignited.

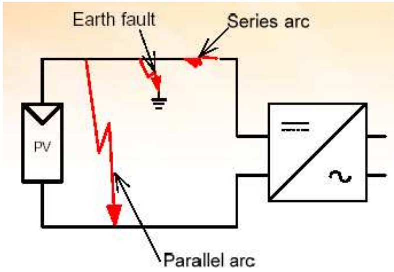

Figure 1. Series arc fault and parallel arc fault in PV systems.

DC arc faults in PV systems can be classified into two types: series and parallel arc faults, relative to their current path location in the electrical circuit as shown in Figure 1. When one of the current-carrying paths in series with the load is unintentionally broken or opened, a series arc fault can be created. Some examples of this are poor connections between cells, plugging and unplugging connectors at junction boxes, or breaks in wires. In general, a series arc fault has less energy than a parallel arc fault, but it has a much higher probability of occurring due to the large number of connections in PV systems. Figure 2 shows a module bus bar that was purposely cut for demonstration purposes to puncture the insulation foil and create a fire hazard.

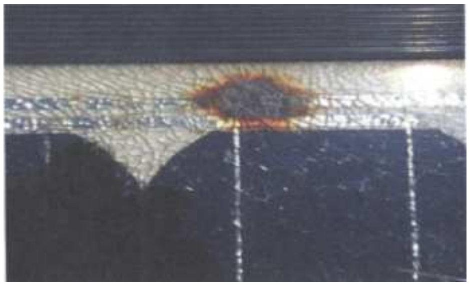

Figure 2. Example of fire hazard from damaged bus bar.

Junction boxes can also fail and lead to a fire hazard from arcing at the box and electrical ignition of the module. When there is an unintentional conducting path between two conductors of opposite polarity or between an ungrounded conductor and ground, a parallel arc fault can be created. In general, a parallel arc fault is due to a breakdown in insulation by occurrences such as mechanical damage, aging, or rodent damage. It is obvious that a parallel arc fault can be more dangerous than a series arc fault because the entire system voltage and current are potentially available to supply this fault energy. An earth fault (ground fault) is another example of a parallel arc fault. Figure 3 shows damage from arcing to the grounded metal frame of a PV module.

Figure 3. Arcing to grounded metal frame.

SERIES ARC FAULTS IN PV SYSTEMS

Aged PV systems may be observed where electrical deterioration would first be seen as a failure in electrical connections, either in the exposed system wiring or in circuits internal to the modules, such as at the solder bonds to a cell. Because PV systems are often treated as being very reliable and thus requiring less maintenance, this inevitable deterioration may go unnoticed for some time. The severe thermal cycling that results from exposure to the outdoor environment could result in a series arc fault at these break points.

A series arc can occur in a PV system when the continuity of a connection or conductor is compromised while the DC current is being generated by the system. Any intermittent connection or switches in the DC circuit has the potential for producing a DC arc fault. These connections may include soldered joints within the module, compression type wire connections, or the actual connectors that are commonly used on the wire leads attached to PV modules.

PV AFCI FOR FIRE PROTECTION

The NEC presently requires 120 Volt AC AFCI devices to protect against fires caused by arcing faults in many dwelling unit electrical branch circuits. These AFCIs have been available since about year 2000, and are tested to the UL1699 Standard for Arc-Fault Circuit-Interrupters [8]. These residential AFCIs are typically incorporated as part of the circuit breaker in a building's electrical service panel where they can continuously monitor current flow in the circuit. They use unique current and voltage sensing circuitry to discriminate between normal and unwanted arcing conditions. Once an unwanted arcing condition is detected, the control circuitry in the AFCI trips the internal contacts, thus de-energizing the circuit and reducing the potential for a fire to occur [9]. The NEC requires AFCIs for all branch circuits in finished rooms and areas of dwelling unit buildings, except for the kitchen and baths. An international workshop in Switzerland in 2007 focused on arcing in photovoltaic

DC arrays, the potential dangers, and some potential solutions [10].

For PV systems, the most likely arc fault to occur is a series arc because of the large number of series connections in an array and the fact that thermal cycling and aging can lead to a poor electrical connection over time. PV AFCI protection integrated into an inverter can also be realized, and in many cases that may be suitable to detect series arcs in a faulted PV array, as series arcs may be extinguished by shutting down the inverter.

Parallel fault arcing protection requires the AFCI to be located between the source (e.g. PV module) and the fault. Previous studies suggest that parallel arcing involves significant changes in the current at the primary side of the inverter or converter, and therefore is easily detectable. This is in contrast to a series arc that cannot be easily detected by simple low frequency analysis of the voltage and current signals due factors such as the specific characteristic I-V curve of the photovoltaic modules [11].

Protection of the wiring to the inverter could require the AFCI(s), for example, to be located in the combiner box(es), with at least one AFCI per string. If the arcing is between the positive and negative conductors, or is an earth fault on a grounded array, then opening the inverter may in fact make the arcing condition worse by allowing more current to backfeed the arc.

In the laboratory, an arc generator can be used to produce series arcing as shown in Figure 4. A typical arc generator can consist of two electrodes, such as copper rods approximately 6 mm diameter, that can be separated by using a lateral adjustment means. In the Subject 1699B requirements, a plastic material tube is placed over the electrodes to represent a surface path for arc tracking, such as may occur within wire or connector insulation. A small tuft of very fine steel wool is then placed inside the tube just sufficient to bridge the final gap between the electrodes and trigger the arcing event when the test voltage is applied. The moveable electrode is then moved into the opposite end of the tube, and adjusted to a given gap distance from the stationary electrode. When voltage is applied, the steel wool burns open very quickly and triggers an arc across the electrode gap. Various circuit characteristics, such as arc voltage, arcing current, and arc power (Watts) can be adjusted for the specific arcing event test. For the research that led to the arcing test requirements in Subject 1699B, the circuit was controlled to apply power for different time intervals, and observations were made regarding the burn through and ignition of the tube material. Various tube materials, such as polycarbonate and nylon were used as representative of connector insulation materials.

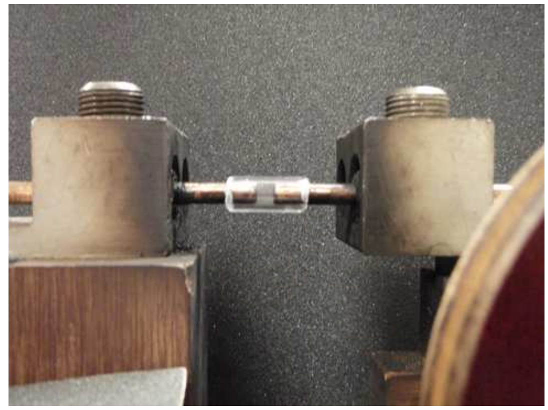

Figure 4. Laboratory arc generator.

Figure 5 shows an example of the results of a test with an arc generator in a circuit using a string of four PV modules in series, and having a total string voltage of 170 Volts DC, and a short circuit current of 7.5 A. The electrode gap was 3 mm. The top trace in Figure 5 shows the arc voltage, which was an average of 26.5 V. The center trace shows the string voltage, and the bottom trace is the string current. This test was conducted for two seconds, and the average arc power was 168 Watts. The concentrated power of the arc can reach temperatures that will pyrolyze insulating polymers and release hydrocarbons that can be ignited by the arc. An arc that burns through insulation can also easily ignite other foreign materials that may be found near or under PV modules, such as dry leaves and animal nesting materials.

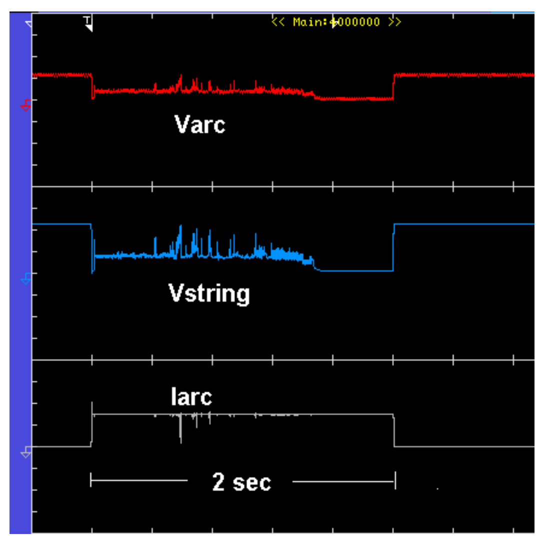

Figure 5. Results of arc generator test.

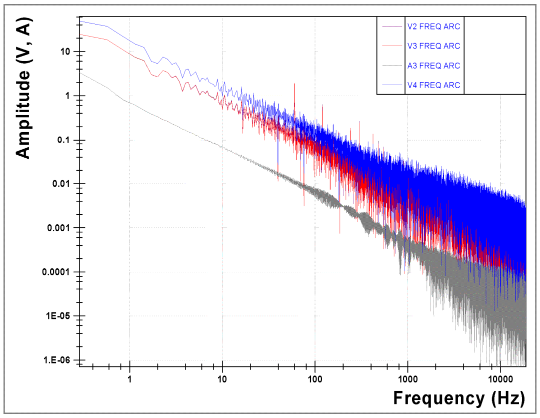

Figure 6. Spectra of arc fault waveforms shown in Figure 5.

The output from a string of PV modules is most often a very pure DC voltage. This can be seen from the trace of the string voltage in Figure 5 before and after the two-seconds of arcing. When arcing occurs, significant wideband noise occurs as can be seen in Figure 6 in the frequency spectra of these arcing waveforms. As can be seen in Figure 6, the voltage and current spectra show an inverse relationship to frequency, which is characteristic of the "pink noise" generated during electrical arcing [12]. This behavior closely resembles that which is observed during AC arcing, with the omission of the 50/60 Hz component and the resulting harmonics from the periodic striking of the arc. In the absence of an arc, the current spectrum does not show this 1/*f* relationship, and the voltage spectra only exhibit spectral components from external interference (such as 60 Hz pickup from the unshielded wiring in the array). Such characteristics were leveraged during development of the Subject 1699B test program for the PV AFCI.

ARC FAULT DETECTION TEST

The requirements in Subject 1699B include both Type 1 and Type 2 AFCI devices. A Type 1 device is intended to detect or interrupt series arcing faults only. A Type 2 device is intended to detect or interrupt both series and parallel arcing faults. For that reason, Subject 1699B includes both series and parallel arcing tests. The research that led to the Subject 1699B arc fault detection tests identified and characterized the various forms of arcing that can occur in PV wiring systems, and how quickly the AFCI must trip to prevent a fire once the arcing begins to occur.

To develop the arcing tests in Subject 1699B, a design of experiments (DOE) was conducted to investigate the influence of several test parameters and their effect on arc energy and insulation burn-through. The actual arcing tests involved using an arc generator as shown in Fig. 4 to produce the desired arcing. The arcing across the generator's electrode gap is produced at various power levels ranging from 300 to 900 Watts. To obtain this arcing power, the electrode gap can be adjusted to produce the desired arcing voltage, and by connecting the arc generator to a suitable power source, such as a PV array, the desired arcing current can be obtained.

With the PV AFCI device in the test circuit, connected in series or parallel as appropriate for the device or test, the AFCI must detect or interrupt the arcing before the arc energy exceeds 750 Joules, or two seconds, whichever is less. The 750 Joule requirement came from several experimental tests with the arc generator and a 1.6 mm thick polycarbonate tube to determine the arc energy level at which burn through of the tube material might occur. Using this test set-up, over 80 arcing experiments were conducted with arc energy varying from 250 – 2000 Joules, and arcing times from 1 to 4 seconds. As a result, 22 of these experiments produced burn through of the tube material, and none of these were at less than 750 Joules. The cumulative distribution function for this data showed that at the 750 Joule threshold there was only a 5% probability for burn through. See Figure 7 for a cumulative distribution summary of this data.

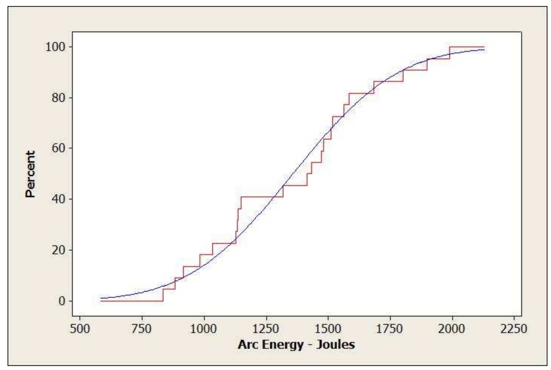

Figure 7. Cumulative distribution of experimental data where burn through was observed.

In addition to arc fault testing to demonstrate that the AFCI can protect against the hazards of an arcing fault, AFCI testing must also demonstrate that AFCI devices will not be unduly susceptible to unwanted tripping because of other PV components or circuit characteristics that could cause a false trip. For example, the input current characteristics of a typical inverter under some conditions may look like an arcing waveform to the AFCI. Another concern is with the possible inrush current peaks that may occur during the initial system turn-on when the inverter capacitors charge. Another unwanted trip condition is based on the contact arcing during DC disconnect switch operation. This PV AFCI testing will demonstrate that representative devices of each rating will not trip under these conditions.

Operation inhibition describes the condition where other components or circuit characteristics prevent the AFCI from functioning when actual arcing is taking place and the AFCI should be operating. Testing is performed to confirm that normal operational conditions and loads do not prevent the AFCI from responding to an arcing event. Masking from inverters or multiple strings in parallel, and from line impedance, can be some causes of operation inhibition.

CONCLUSION

PV systems are very unique electrical systems designed to produce electric power in hostile outdoor environments. Degradation of insulating materials and deterioration of electrical connections may be the most serious problems creating series or parallel arcing faults, which can result in fire damage originating in PV system components and wiring. A new concept called a PV AFCI is proposed to detect and interrupt arcing faults resulting from a failure in the intended continuity of a conductor, connection, module, or other system components in the direct current PV source and output circuits. This device could be an appropriate protection means to mitigate theses electrical fires. UL has recently developed requirements for the PV AFCI in the form of an Outline of Investigation, designated Subject 1699B. This Outline consists of construction and test requirements for DC arc fault detection to meet new NEC requirements for listed PV AFCI protection.

ACKNOWLEDGMENT

This work was supported by UL's Advanced Energy Safety R&D Center Project (AESC), Multinational Innovative R&D Centers in Taiwan Program, Taiwan Ministry of Economic Affairs (MOEA). Funding for this research work was also provided by the Department of Energy's Solar America Board for Codes and Standards (Solar ABC's) with New Mexico State University as the Prime Recipient of the Solar America Initiative grant.

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