Photovoltaic Module Grounding: Issues and Recommendations

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- Solar ABCs grounding review team including:
  - John Wiles, Brian Wiley, Mike Coddington, Michael Sheehan, Bill Brooks, Howard Barikmo
  - Carl Lenox, John Mead
  - Others from Solar ABCs Steering Committee and stakeholders

Study Objectives

- Address two key issues:
  - There are a limited numbers of approved (listed) grounding methods, despite a wide variety of installation methods for grounding module frames.
  - Lack of confidence in existing approved grounding methods, due largely to failures in the field from loss of mechanical integrity, installation error, and damage from corrosion.
- Specific Issues/Consequences:
  - Onus of defining acceptable methods and components fell on module manufactures via UL 1703.
  - Grounding equipment suppliers must have their components/methods included in module installation manual
  - Violations, misinterpretations, and errors in the above.
  - Well-engineered grounding measures using methods or component systems that together were not listed or had no reasonable process for certification through UL 1703.

Study Outline

- Address gap in requirements and methods for reliable grounding of PV module frame and mounting components
- Preliminary "lay-of-the-land" Report (BEW) - Published 3/2011
  - Summary of existing conditions, problem statement
  - Survey of existing issues and experiences from stakeholders
- UL interim test development (UL) – Released 6/2011
  - Preliminary testing on corrosion, degradation using methods that go beyond those in existing UL 1703 standard.
- Final report (BEW/UL) - Published 4/2012.
  - Update on relevant standards
  - Recommendations for a set of tests/methods to incorporate into existing/new standards
  - Additional analysis of safety thresholds and objectives for proper module grounding

Definitions

- The terms “ground,” “grounding,” and “grounded” are used to describe the connections to module frames that are the primary focus of the study.
- There is a distinction between “grounded” and “bonded.”
- Article 100 of the 2011 National Electric Code (NEC) defines these terms as follows:
  - Grounded: Connected to ground or to a conducting body that extends the ground connection.
  - Bonded: Connected to establish electrical continuity and conductivity.
- Much of the scope of this study focuses on the bonding of frames to other parts or conductors that are then grounded. The reports use the more general “grounding” term to describe both bonding and grounding unless bonding is specifically called out.

Scope

- Focus is on grounding of conventional module frames
- Report does not specifically address:
  - AC modules or other module integrated or attached electronics
  - Grounding/bonding of support structures
  - System level equipment and electrode ground issues
  - Lightning protection
- System level grounding issues specifically related to the NEC are being addressed in upcoming Solar ABCs study by John Wiles.

Update on Applicable Standards

- UL 1703: *Flat-Plate Photovoltaic Modules and Panels*
  - Still a "primary" standard for module grounding and devices.
  - Multiple changes through Standards Technical Panel (STP)
  - Move towards more categorical evaluation of ground means
- UL 467: *Grounding and Bonding Equipment*
  - General ground component testing.
  - Not allowed for PV module connection evaluation per UL CRD
  - Briefly considered revising to qualify PV grounding components
- UL 2703: *Rack Mounting Systems and Clamping Devices for Flat-Plate Photovoltaic Modules and Panels*
  - New standard created to address PV module mounting systems
  - Ability to certify individual components as well as panelized apparatus

Enhanced Current Tests

- Recommendations from ad-hoc group focusing on UL 1703's grounding/bonding section:
  - Bond path resistance: Existing low-current (30A) test based on string fuse and leakage current.
  - Bonding devices, two high current tests:
    - 4-6 s test, current per UL 467 (based on size of largest allowed ground conductor, e.g. 750 A for #10 AWG.)
    - 5000A until fuse blows
  - Grounding means shall not crack, break, or melt
- Largely implemented in UL 2703 Draft

Environmental and Accelerated Aging Tests

- Section 35: Temperature Cycling Test
  - 200 cycles various, from -40 to +90C
- Section 36: Humidity Test
  - 10 Cycles humidity-freeze
- Section 37: Corrosive Atmosphere Test
  - Salt spray and moist carbon-dioxide/sulphur dioxide
  - *Exception: A specimen constructed of materials such as plastic, 300 series stainless steel, or aluminum, which are inherently resistant to atmospheric corrosion need not be tested.*
- *Bonding Path Resistance tests are repeated after environmental exposure tests*

UL 2703 Activities

- Surge of UL 2703 grounding and bonding applications and listings
- Component success generalizations:
  - 300 Series stainless steel passing well (16% Cr min, Austenitic chromium-nickel alloys)
  - 200 Series stainless is hit or miss (austenitic chromium-nickel-manganese alloys)
  - 400 Series stainless generally not passing (ferritic and martensitic chromium alloys)
  - ASTM A690 or better galvanized steel doing well (with Atmospheric Corrosion Resistance for Use in Marine Environments)
  - A660 and below galvanized steel not as well, with exceptions
  - Zinc thickness more relevant than galvy method (electroplating or hot-dipped), but hot dipped generally better

UL 2703 Activities

- Connections applying torque force anecdotally faring better than just direct force, but not as a rule
- Varying thickness of module frame anodization catching applicants off-guard (device not penetrating successfully).
- Device failures generally occur in bonding resistance or short-circuit tests after environmental conditioning tests
- Several proposed solutions have conflict with NEC 250.8 (see next slide)

2008 NEC 250.8
Connection of Grounding and Bonding Equipment

- (A) Permitted Methods. Grounding conductors and bonding jumpers shall be connected by one of the following means:
  - (1) Listed pressure connectors
  - (2) Terminal bars
  - (3) Pressure connectors listed as grounding and bonding equipment
  - (4) Exothermic welding process
  - **(5) Machine screw-type fasteners that engage not less than two threads or are secured with a nut**
  - **(6) Thread-forming machine screws that engage not less than two threads in the enclosure**
  - (7) Connections that are part of a listed assembly
  - (8) Other listed means
- (B) Methods Not Permitted. Connection devices or fittings that depend solely on solder shall not be used.

Section 250.8 has been revised by deleting the specific prohibition of sheet metal screws since **there are many other types of screws that also are prohibited, such as drywall screws, self--tapping tech screws with less than two threads into an enclosure and similar screws that may not provide an acceptable ground return path.** Connections that are part of a listed assembly, where part of the listing process, are acceptable since the grounding connections have been tested. Machine screws with at least two threads or secured with a nut are acceptable, and any self-tapping screw, where at least two threads are formed, are acceptable. Section 250.8 has been changed into a list format for ease of use.

Accelerated Aging Tests

Evaluate long-term effectiveness of different module grounding methods:

1. copper connections via screw/washer/nut assemblies
2. lay-in lug assemblies
3. grounding clips

Install and age separately using:

1.IEC 61215 damp heat tests

2.IEC 60068-2-11 salt mist tests (similar to ASTM B117)

…With and without current cycling, anti-oxidant compound

ACCELERATED AGING TESTS ON PV GROUNDING CONNECTIONS

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ABSTRACT

As many contemporary Photovoltaic (PV) Power systems being installed are designed to produce significant amount of electricity and claimed to operate for 25 years or more, appropriate grounding on PV modules to reduce or eliminate shock and fire hazards becomes a critical issue under high electricity output and long-term use. Although some PV manufacturers have provided technical bulletins to suggest grounding products and methods, not all of them have been carefully evaluated and reviewed by the certification/listing laboratories. In this paper, different types of PV grounding connectors were collected, installed and put into accelerated environmental test chambers. The effects of current cycling, assembly force, anti-oxidation coating application on grounding reliability were evaluated. The grounding failure modes and mechanisms are also discussed in this paper.

INTRODUCTION

Photovoltaic (PV) power systems being installed today are normally designed to produce significant amounts of electricity over an expected operating life of more than 25 years. The high electrical output and long-term reliable performance necessitate robust grounding systems for PV systems to minimize accidental electric shock and fire hazards.

In late 2007, UL issued an Interpretation of UL 1703 on the topic of module field grounding. The Interpretation clarified that the module instruction manual must specify the grounding methods and materials to be used for external field-made grounding connections. These methods and materials are evaluated as part of the module Listing process and will apply to all existing Listed modules and their instructions as they come up for review [1].

A good connection between the grounding hardware and the module frame is essential for a grounding system to function properly. Typically PV manufacturers use copper-alloy for electrical connections and aluminum-alloy for the module frames. The anodization on the aluminum-alloy surfaces is able to provide an oxidized layer to minimize further corrosion of the frames. However, while the anodization of the aluminum-alloy surfaces creates an oxidized layer that minimizes frame corrosion, it also generates a high electrical resistance reducing grounding effectiveness. To overcome this design issue, the grounding hardware must penetrate through the anodization layer to create a direct electric connection. This is normally achieved by one of the following approaches: (1) Installing a self-tapping or self-drilling fastener through the frame, (2) using a stainless steel star (toothed) washer held against the frame by a bolt or nut, or (3) attaching a Listed lug (see Fig. 1) to the marked grounding points after appropriate surface preparation has been accomplished [2] [3].

The differences in these grounding approaches may result in significant performance differences over the course of the product service life. Therefore further study is needed to address the long-term effect and reliability of these different grounding installations.

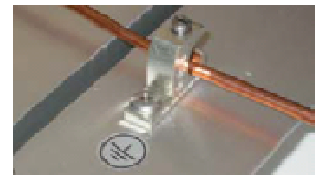

Figure 1 Lay-in lug Listed for direct burial (DB) and outdoor use.

OBJECTIVE

The objective of this study is to investigate the long-term effectiveness of different PV grounding devices under simulated harsh environmental conditions. By measuring the contact resistance at the junction between connectors and aluminum frames, this scope of this study includes examining the following grounding techniques:

- Attaching lay-in lug to aluminum frame with a lock-nut penetrating the aluminum surface.
- Removing anodization on the aluminum frame and then attaching lay-in lug directly to it. An anti-oxidant compound was applied between the lug and aluminum surface.
- Grounding copper wire to aluminum frame using thread-cutting screw and cup washer.
- Attaching lay-in lug to aluminum frame with a teeth washer laid between the lug and aluminum surface
- Using grounding clips assembly consists of a slider, base, and thread-cutting screw.

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Aging Tests - Salient Results

- Under damp-heat condition, R remained low (<0.05Ω) almost no change over 20 weeks.
- Under salt mist condition most samples corroded severely failed (> 10Ω) in weeks,
- Samples using the anti-oxidant coating lasted longer before failing.
- Lay-in lug with washer (D) and grounding clips (E) with compound lasted > 20 weeks
- Current cycling did not have a significant impact
- Proper torque on the connections improved the performance.
  - Under-torqued connections failed 5 times sooner

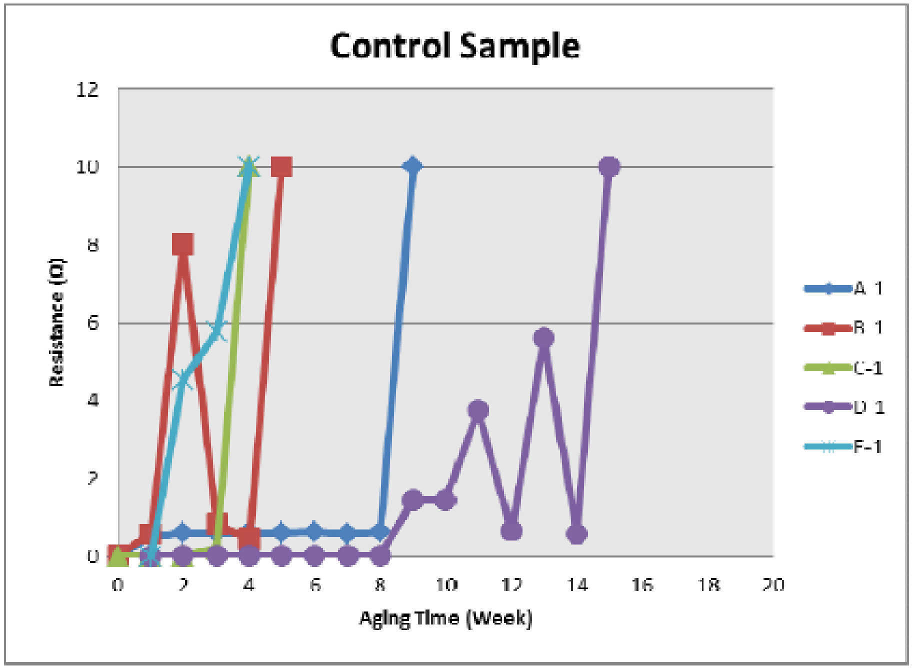


Figure 4 Resistance change for all No.1 connectors under salt mist aging

Corrosion Testing Issues

- IEC 60068-2-11 salt mist tests (similar to ASTM B117)
- Interpret with Caution: Corrosion mechanisms induced by the B117 tests are known to often differ from those found in the field.
- Attempting to accelerate galvanic corrosion is particularly problematic.
- ASTM reference on corrosion tests and standards states
  - "Accelerated testing to get a result in a shorter time period than would be possible naturally should be avoided whenever possible, because the mechanism of galvanic corrosion can change if the rate is altered significantly." (Baboian, 2005).

- IEC 61701 Ed.2: "Salt mist corrosion testing of photovoltaic (PV) modules"
  - More nuanced set of tests with different levels of severity to choose from depending on the environment one is testing for.
  - Better reflects processes seen by PV modules
  - Applicable regardless of frame material.
  - Based on IEC 60068-2-52 rather than IEC 60068-2-11, more widely used in the electronic component field.
  - Testing sequence combines a salt fog exposure followed by humidity storage under controlled temperature and relative humidity conditions.
  - Different testing sequences are considered for the PV module technology involved: crystalline silicon, thin-film and concentrator photovoltaic (CPV) modules.

Safety Objectives for Proper Module Grounding

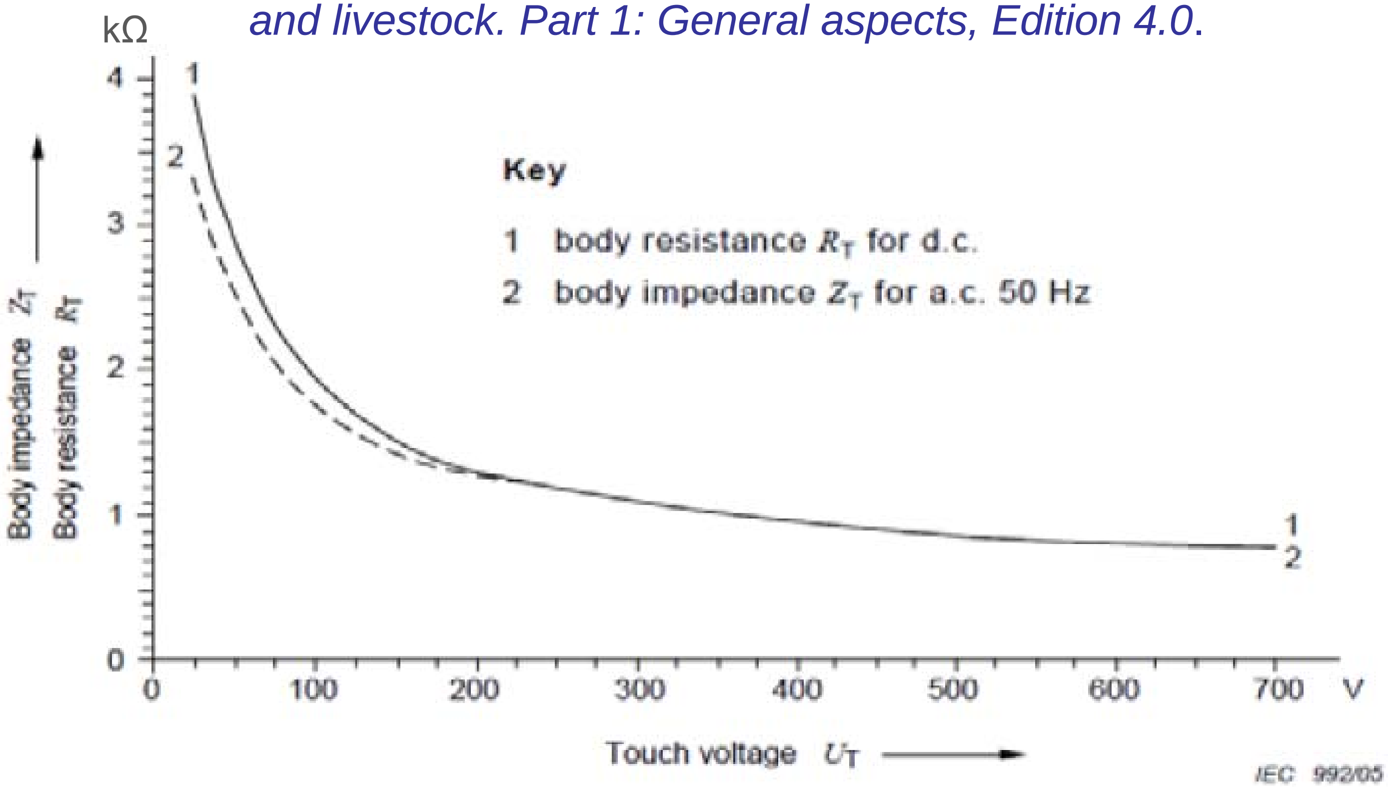
- Basic concepts of the impact of electricity on the human body
  - DC impedance and current thresholds
  - Potential danger to personnel presented by improperly grounded module frames.
- Module frame fault scenarios
  - Guidance for determining adequate conductivity of the grounding system and frame connections that carry fault current.
- Systemic methods of module grounding and how well they address safety in the event of the faults.
- Generalized design criteria using National Electrical Code principles.
- The current test regimes recommended for certification should adequately address safety issues such as touch safe voltages and currents.

Safety Aspects of Module Grounding

Human voltage and current thresholds

- Example graph of body resistances to AC/DC voltages
- DC slightly safer resistance at lower voltage
- Values are for 50th percentile of population
- UL benchmark uses 5th percentile, ~45% lower values

From IEC/TS 60479-1: *Effects of current on human beings and livestock. Part 1: General aspects, Edition 4.0*.



Safety Aspects of Module Grounding

Human voltage and current thresholds

- Zones indicate DC current level and duration impact on body
- DC-3 (beginning at Curve b) and DC-4 potentially harmful or fatal
- C curves represent sufficient currents to cause ventricular fibrillation at various population percentiles
- 30 mA threshold applicable for DC

From IEC/TS 60479-1

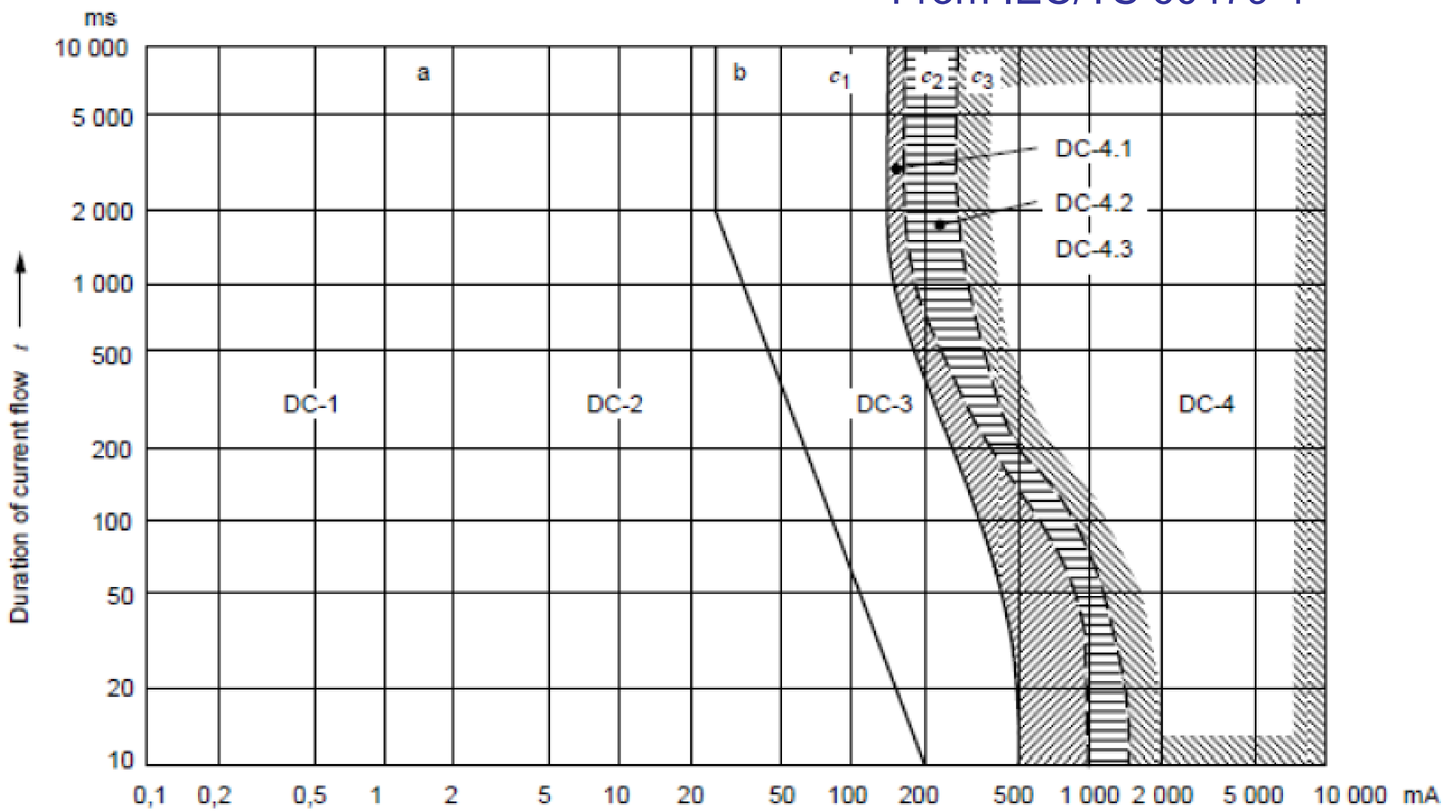


Figure 3: DC Time-Current Curves and Zones Defining the Typical Impact on Human Beings (IEC, 2005)

Safety Aspects of Module Grounding

Human voltage and current thresholds

DC Current Thresholds for Various Physiological Effects in Humans (UL, 1999)

Physiological effect	Ordinary DC limit	DC limits for situations restricted to adults only
Startle reaction	2.0 mA	2.0 mA
Inability to let go	30 mA	40 mA
Ventricular fibrillation	80 mA	240 mA
Electrical burns	70 mA	70 mA

Key: milliampere (mA)

AC Current Thresholds for Various Physiological Effects in Humans (UL, 1999)

Physiological effect	Ordinary 60-Hz limit	60-Hz limits for situations restricted to adults only
Startle reaction	0.5 mA	0.5 mA
Inability to let go	5.0 mA	6.0 mA
Ventricular fibrillation	20 mA	105 mA
Electrical burns	70 mA	70 mA

Key: milliampere (mA), hertz (Hz)

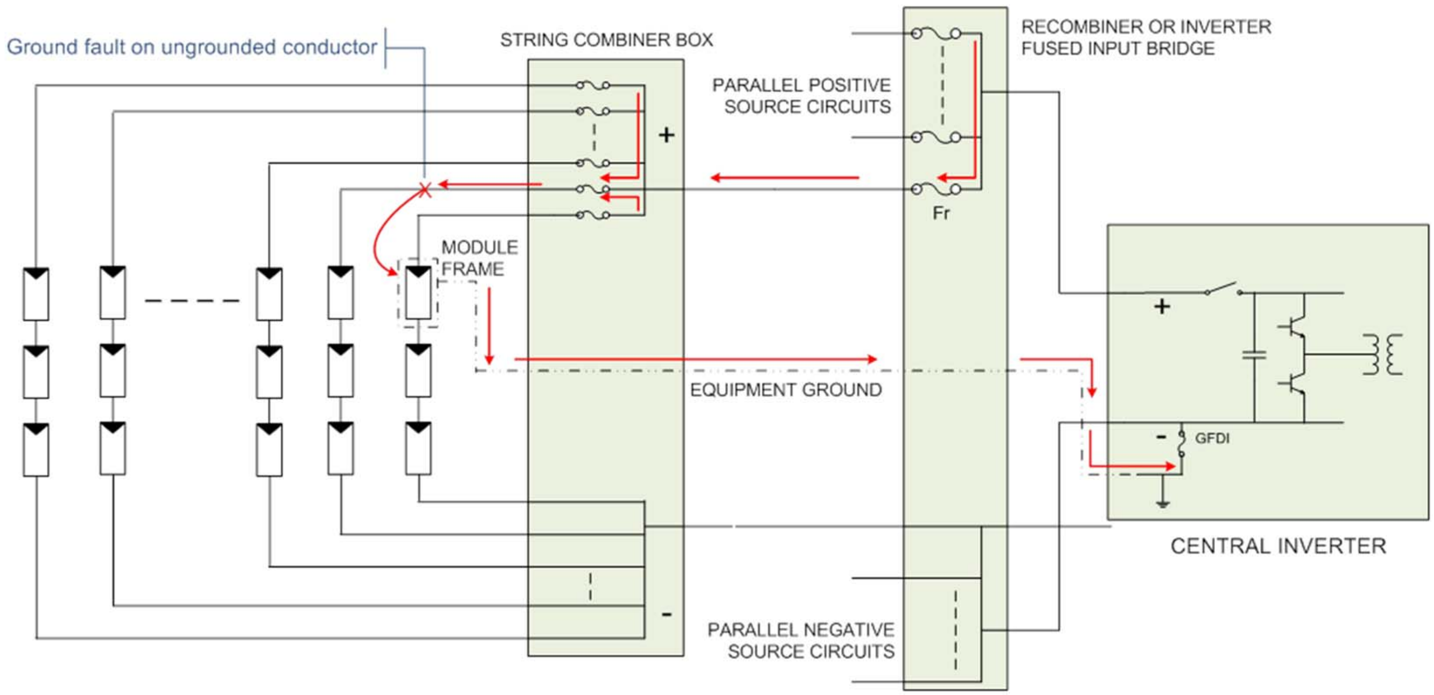
Module Frame Fault Scenarios

- Lightning
- Ground faults (live DC circuit connection to frame)
- Leakage current
- Faults from external sources, such as AC circuit.

- Grounding circuit requirements:

Module frames “shall be connected together and to the supply source in a manner that establishes an effective ground fault current path” [250.4(A)(3)]. An effective ground-fault current path is electrical equipment and wiring that “shall be installed in a manner that creates a low-impedance circuit facilitating the operation of the overcurrent device,” and “shall be capable of carrying the maximum fault current likely to be imposed on it...” [250.4(A)(5)]

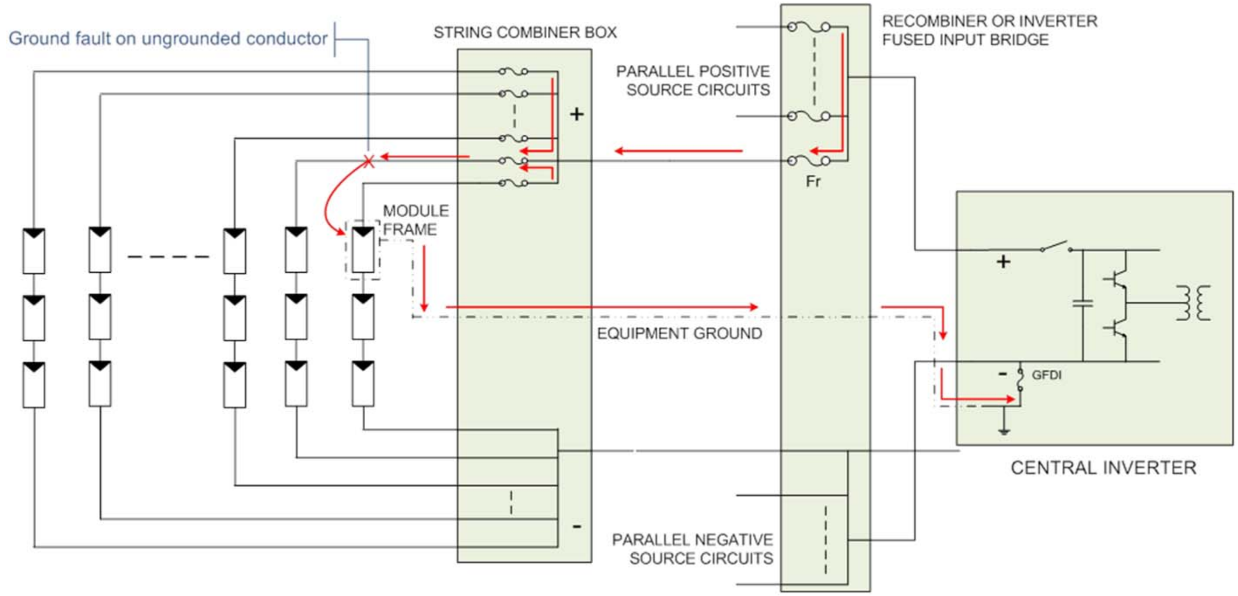
DC string fault to grounded module frame



- Fault current from entire array present on module frame until GFDI fuse (e.g. 5A) or string fuse (e.g. 15A) blows.
- Fault current levels dependent on fault impedance and ground circuit impedance .. may delay OCPD operation, create unsafe voltages

Example scenarios for shock hazard

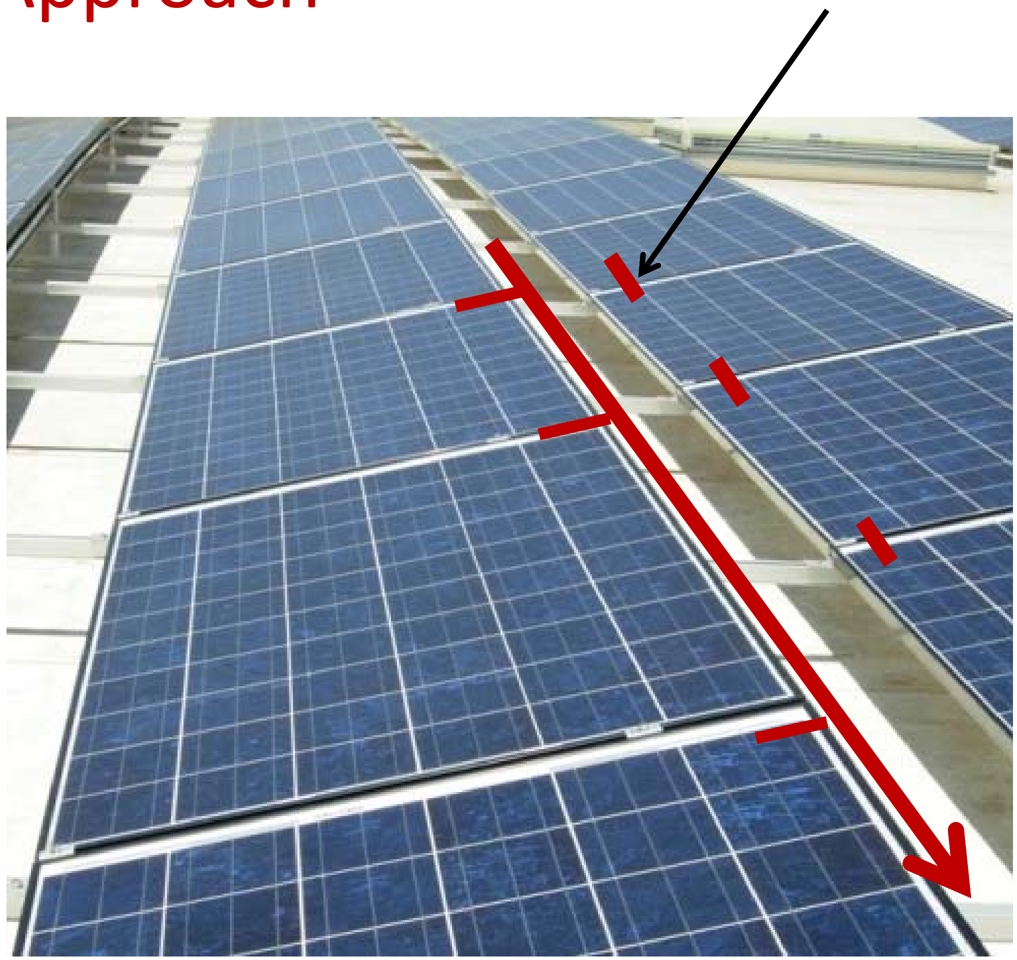
- Poor, high-impedance frame connection to ground circuit
- Large array (current capacity)
- Low body resistance value
- Low resistance between body and return path to ground (e.g. touching combiner box).



- In this case, a person touching the faulted module frame becomes a primary path for fault current, e.g. 300V/1kOhm or 300 mA.
- 2 Ohm ground connection and 15A fault current creates 30V -- 30 V/1 kOhm = 30 mA

Frame Grounding Approach

- Frames bonded to EGC conductor or support
- Frames bonded together with single ground circuit path (up to 0.1 Ohm per connection, as permitted by UL 1703).
- Frames bonded together with multiple circuit paths (effectively a contiguous sheet, very low ground resistance)



Recommendations for Design and Installation Related to:

- Listings and instructions
- Equipment selection
- Torqued connections
- Proper handling of and installation of equipment
- Proper sequence and orientation of components
- Avoidance of dissimilar metal combinations
- Other aspects to reduce corrosion risk
- Storage of components prior to installation

Conclusions and Follow-Up

- UL 2703 is resolving many of the problems identified at the outset of this study
  - Testing more specific for grounding components
  - Better process for component manufacturers
  - Trends towards generalized methods rather than entirely module-specific.
  - Issues remain of course…
- Accelerated aging (corrosion) tests evolving, looking for consensus
  - Possible adoption of IEC 61701 Ed.2 or similar methods, under review by UL STP.
- Field knowledge, training and diligence always required