
Ground Fault Protection Improvement Study

Greg Ball
DNV-KEMA

Solar ABCs Stakeholder Meeting
July 11, 2013
San Francisco, CA



Study Authors

- Bill Brooks – Brooks Engineering
- Andy Rosenthal – New Mexico State University
- Jay Johnson & Jack Flicker – Sandia National Labs
- Greg Ball – DNV KEMA

Significant contribution and support from:

Mark Albers – SunPower

John Wiles – NMSU

Tim Zgonena – UL

Southern California Edison

Duke Energy



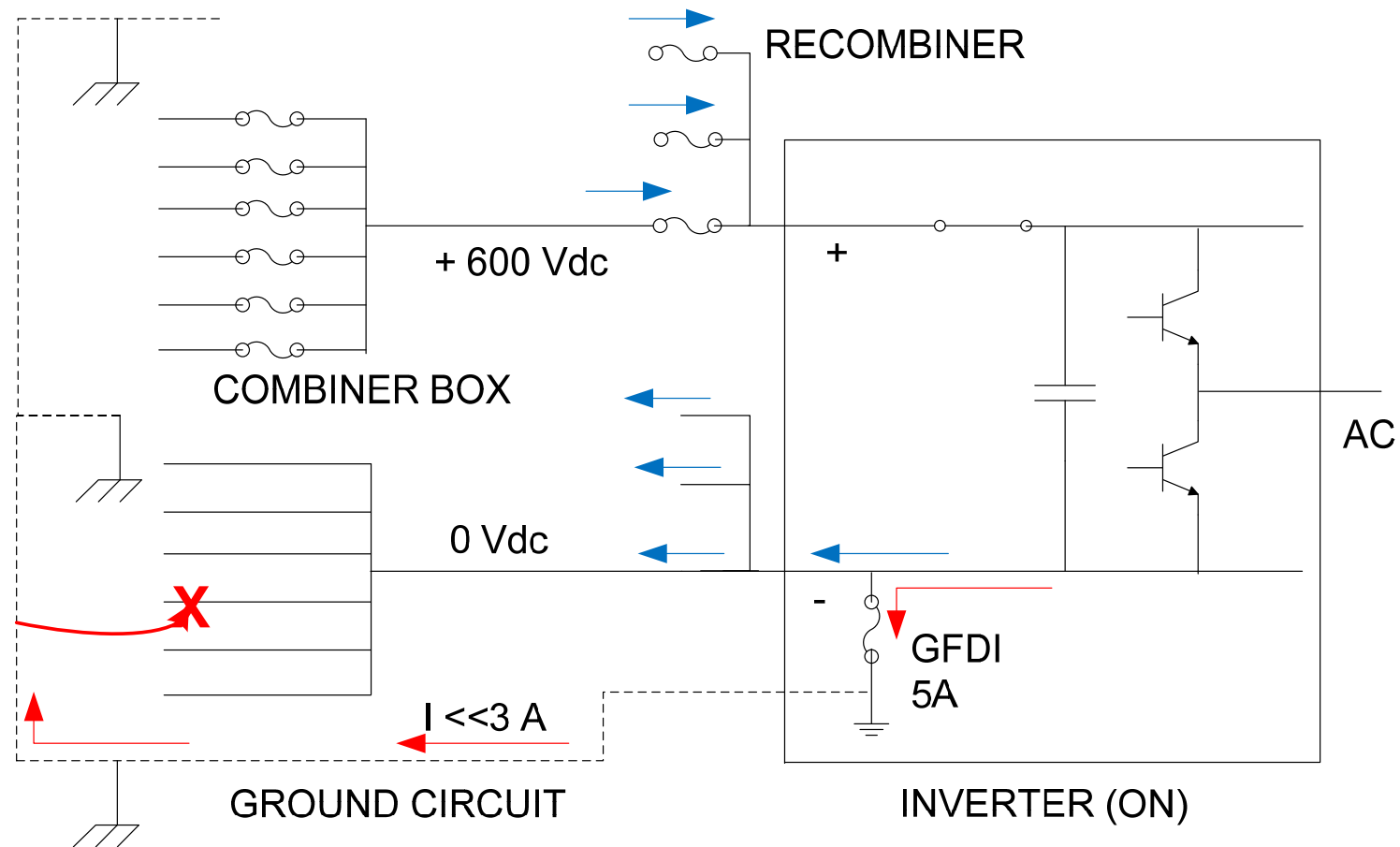
Why improve ground fault protection?

- Notable rooftop fires (e.g Bakersfield, Mt. Holly, NC) originated with undetected ground faults
- Analysis of faults reveal a “blind spot” in grounded PV arrays – faults on the grounded conductors
- Existing ground fault protection (fuse in inverter) generally oversized
 - Designed for *ungrounded* conductor faults
 - Conservative assumptions of leakage current to avoid nuisance trips
- Ground faults not causing these problems in Europe and elsewhere where ungrounded (floating) systems are the norm
- The problem is not going away, and will be more prevalent with aging systems



Grounded conductor “blind spot” fault

Below GFDI rating, goes undetected indefinitely



Solar ABCs study objectives

- Characterize leakage currents and impedances in existing, large PV arrays ($\geq 100\text{kW}$)
- Characterize the performance of their existing ground-fault detection when simulated faults are introduced.
- Develop models of arrays under fault conditions
- Investigate alternatives for improved detection/protection
 - Minimizing allowable ground fault current
 - Minimizing nuisance tripping
- Develop a consensus-based set of recommendations for:
 - Retrofitting existing systems
 - Functional requirements for new systems



Field Test Program Overview

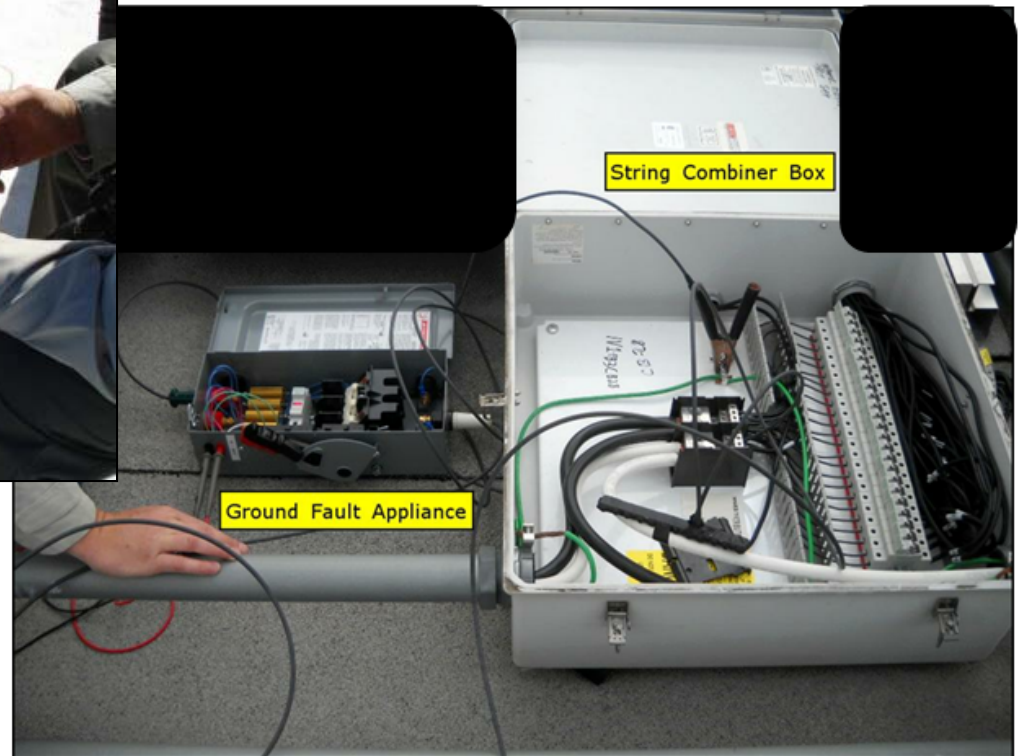
- Sites selection criteria (in order of decreasing importance):
 - Variety of inverter types
 - Rooftop and ground mount
 - c-Si and thin film
 - Geographic/climate variety
- Tests conducted:
 - Megger conductors and array to check for existing faults
 - Use differential current device to measure background DC leakage current
 - Measure the impedance of a typical array's Equipment Grounding Conductor
 - Use oscilloscope to characterize AC component in ground connection
 - Introduce controlled ground faults to characterize fault current and detection capabilities
- Tests performed at the following sites:
 - Sandia National Laboratories ,Albuquerque, NM (March 2012)
 - Fontana, CA (May 2012)
 - Union City, CA and Fresno, CA (June 2012)
 - Solar ABCs gratefully acknowledge the support of Duke Energy, Southern California Edison, and SunPower Corp. with the field testing program

Ground-fault test equipment



Ground-Fault Tester
10, 5, 1 and 0 Ω settings

Megger testing of cables
with and without modules
in circuit. 50 and 500 V settings.
Results unremarkable



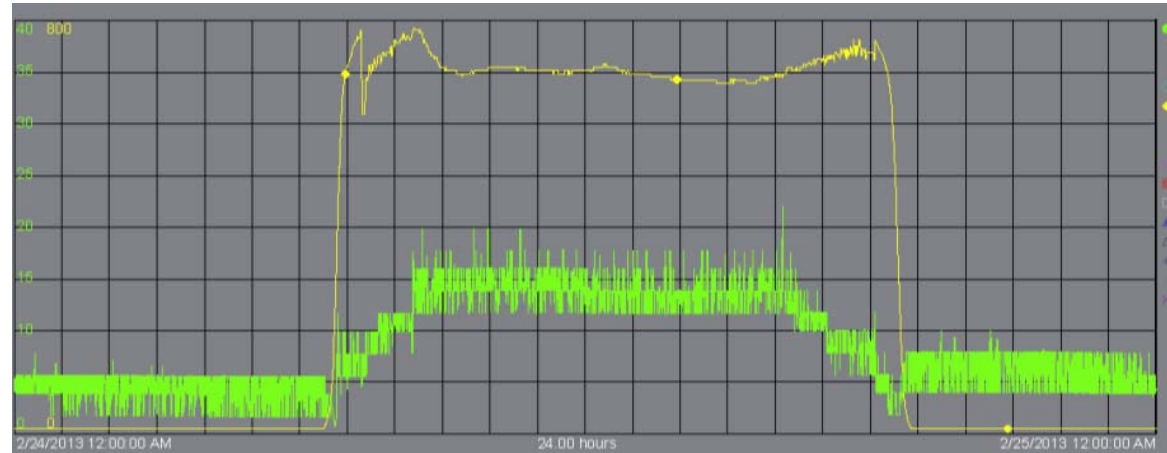
General Results

- Twelve inverters from eight different manufacturers were tested
- **In every case**, inverters operated normally in the presence of some or all of the introduced ground faults
- Background DC leakage currents measured in large arrays found to be generally very low (~5-10 mA range or less, measured at inverter)
 - Some evidence that leakage currents can be higher in other systems
- AC component in ground circuit not well characterized due to measurement noise
- Low ground system resistances on healthy systems ($< 1 \Omega$)
- Introduced ground fault currents measured from mA to 3+ Amps depending on system and fault impedance
- Residual current detector monitoring shows excellent capabilities for detecting grounded conductor faults in 10' s of mA range
- RCD' s set to trip at 60 mA not causing nuisance trips (and have detected and enabled correction of two high impedance faults that could have led to fires)



Additional Findings from SunPower and Duke Energy

- SunPower recorded RCD data from 2 sites
- Ramps to 7-10 mA as sun comes up
- Increasing to 15 mA with irradiance
- Infrequent spikes (~50 mA)
- Nuisance trips mitigated by as low as 1 second averaging, 100 mA setting
- Duke Energy rooftop systems retrofitted with RCDs
- Trip setting 60 mA, typical ground currents in 20-50 mA range
- New faults have since been detected and repaired
- Night time elevated ground currents recorded, correlated with lightning activity. Averaging (e.g. 1 or more seconds) can be used to avoid nuisance trips.

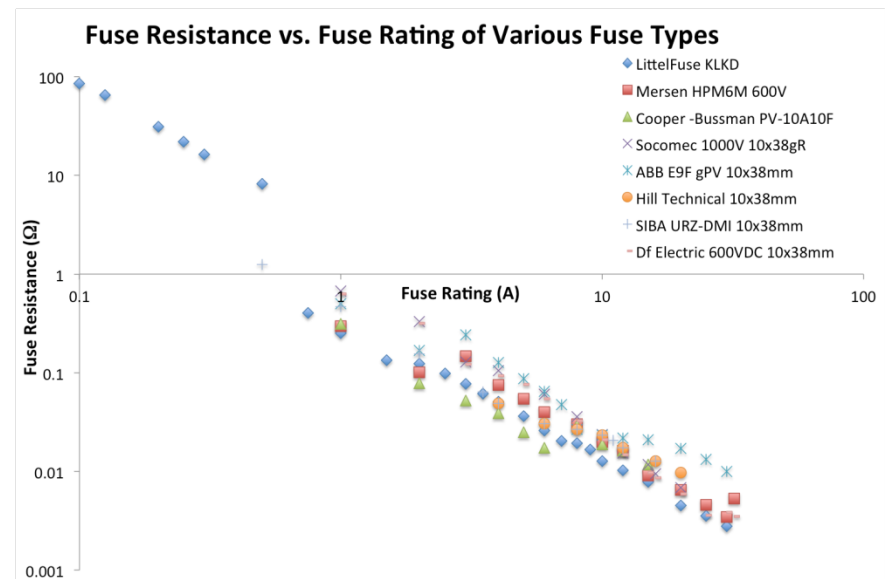
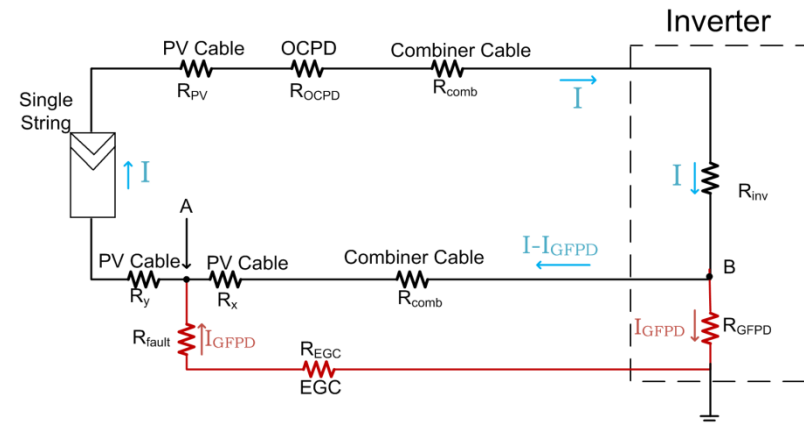


Ground Current for Typical Clear Day: Approx. 15 mA



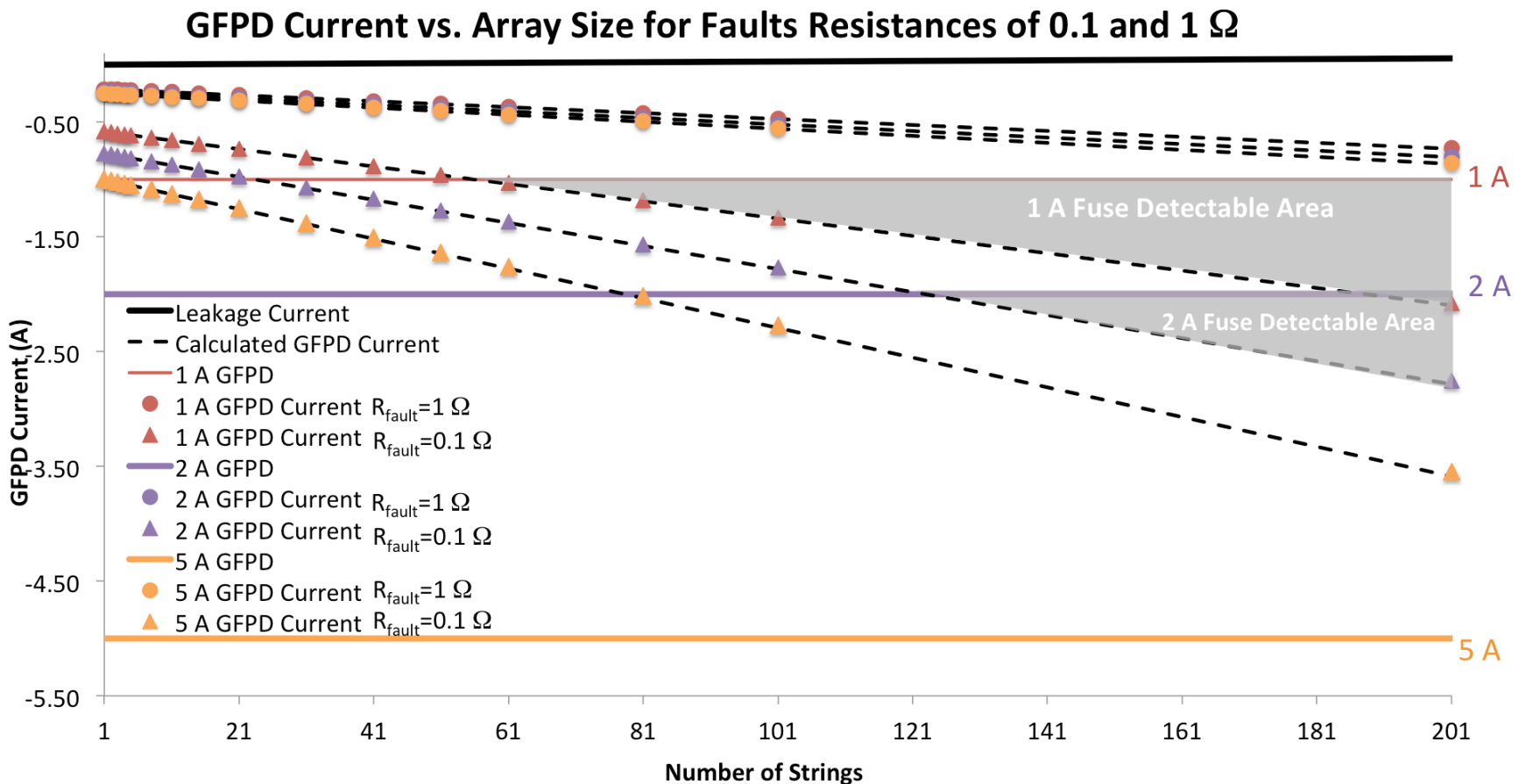
Fuse Internal Resistance

- Contrary to popular belief, continuously reducing the GFDI fuse rating does **NOT** increase the number of ground faults that are detected!
- **WHY?!** After the ground fault, there are two paths the current can take:
 - Normal PV conduction path
 - Fault path through the GFDI
- The high internal resistance of the fuse reduces the current through the GFDI path and it does not clear!



Detection Ranges for GFDI Fuses

- Only 1 A and 2 A fuses can detect blind spot faults.
 - The 1 A fuse needs 56 strings to trip and the 2 A fuse needs 124 strings to trip.



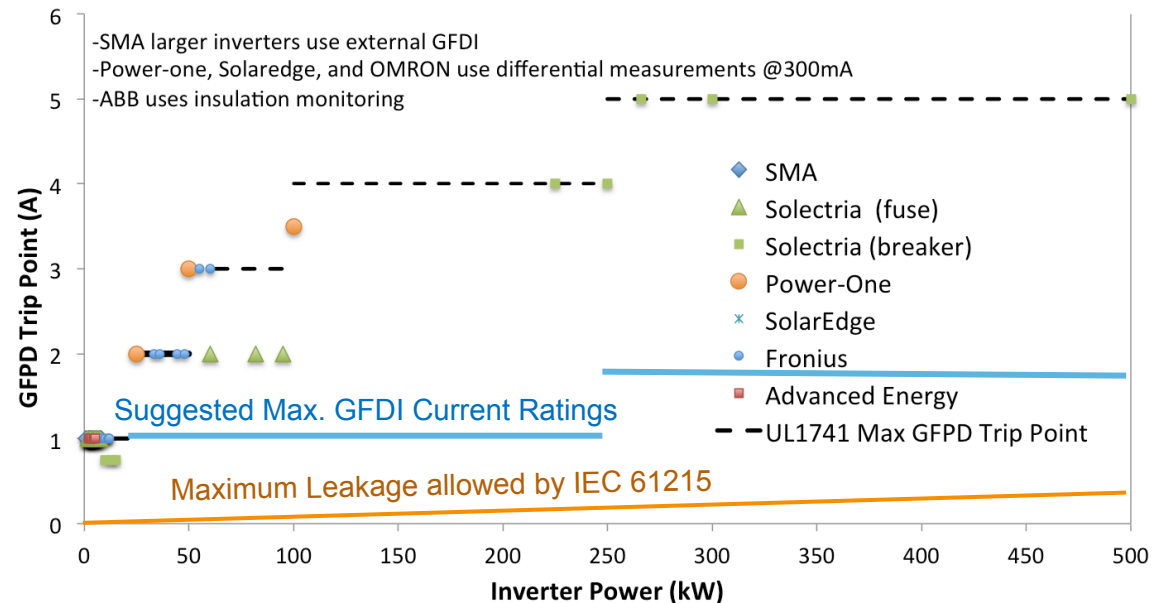
Modeling Recommendations

- Based on the modeling results, reducing GFDI fuses to 1 A for all 600 V installations below 250 kW will increase the detection window for blind spot ground faults.
 - Higher voltage and power installations may require a 2 A fuse.
 - Note: It is likely a 1 A GFDI fuse at Bakersfield and Mt. Holly would have tripped on the first blind spot ground fault.
- More research is needed to verify fuse rating reductions do not cause nuisance trip issues in the case of lightning or array transients.

UL 1741 maximum allowable ground fault trip ranges

Device DC Rating (kW)	Max. Ground-Fault Current Detecting Setting (A)
0-25	1
25-50	2
50-100	3
100-250	4
>250	5

GFPD Trip Point vs. Size of Various Inverter Manufacturers



Summary of recommended mitigation methods

Enhanced ground fault monitoring

- Residual current monitoring
- Residual current monitoring with trip
- Electronic sensing in ground circuit
- Isolation monitoring

Sensitized overcurrent protection

- Reduce fuse size in ground fault circuit

Other systemic measures

- Targeted annual O&M practices
- Arc-fault detection

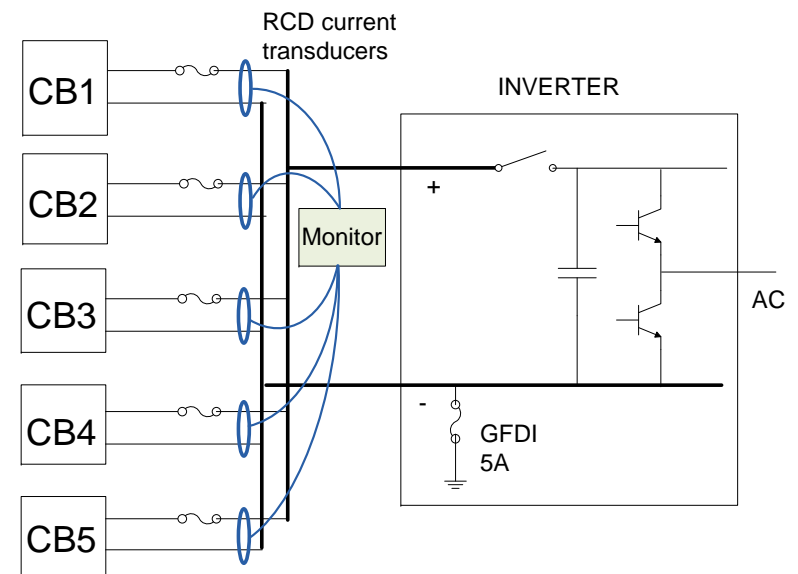
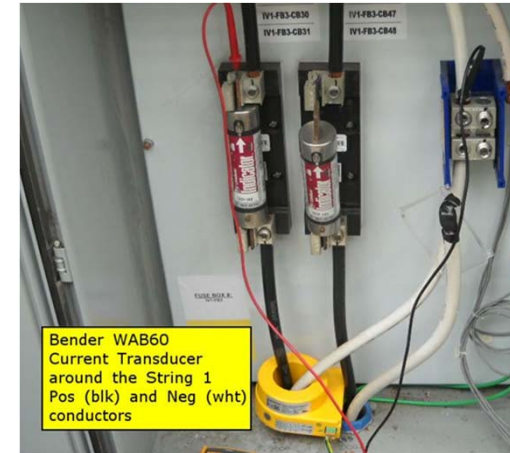
Shown in authors' order of preference for effectiveness and value
Modifications by qualified personnel only and must involve equipment manufacturers!

Method 1: Residual current measurements

With alarm

Installed at inverter entrance on positive and negative feeder circuits

- **Effect:** Major increase in the sensitivity and flexibility of ground fault detection/mitigation
- **Pros:**
 - Proven method for detecting blind spot conditions
 - Alarm gives operator options for response; reduces impact of false trips
- **Cons:**
 - Requires rewire of array conductors through current transducers, and monitor interface
 - Does not interrupt the fault current.
 - May require installation of a new enclosure to access existing conductors
- **Cost:** Moderate to high
 - Possible to run multiple circuits through single CT

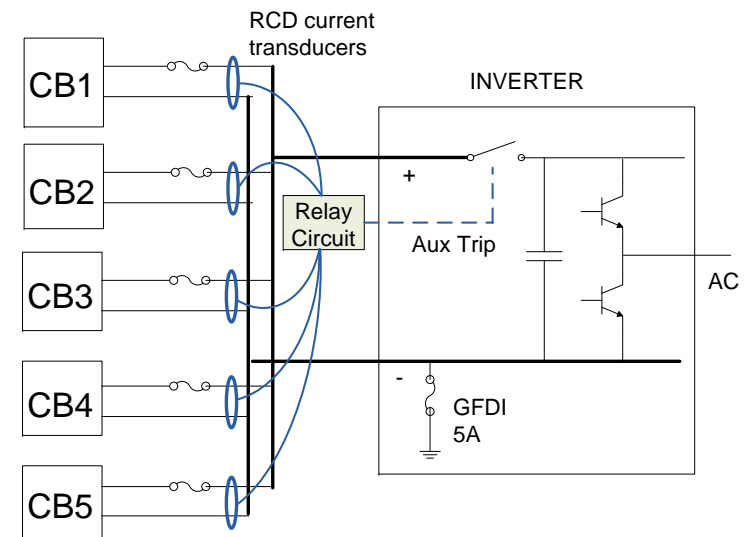


Method 2: Residual current measurements

With auxiliary trip

Similar to method 1, except relay is used to trip inverter off via E-stop, auxiliary trip, or shunt-breaker

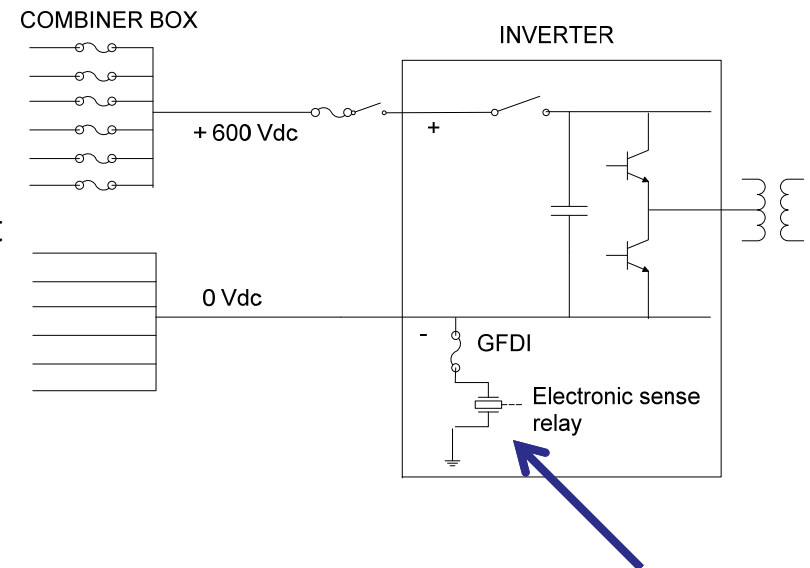
- **Effect:** Major increase in the sensitivity of ground fault detection and interruption
- **Pros:**
 - Proven method for detecting blind spot conditions.
 - Interrupts fault current under blind spot condition
 - Data averaging can mitigate false trips caused by lightning or other transients
- **Cons:**
 - Requires rewire of array conductors through CTs, possible add'l enclosure.
 - Nuisance trips possible
 - Inverter trip wiring could have certification/warranty implications
- **Cost:** Moderate to high
 - Possible to run multiple circuits through single CT



Method 3: Electronic current sense relay in ground circuit

High accuracy sensing is installed in series with ground fault fuse or breaker circuit. Shunt or specialized CT required. Applicable for larger inverters.

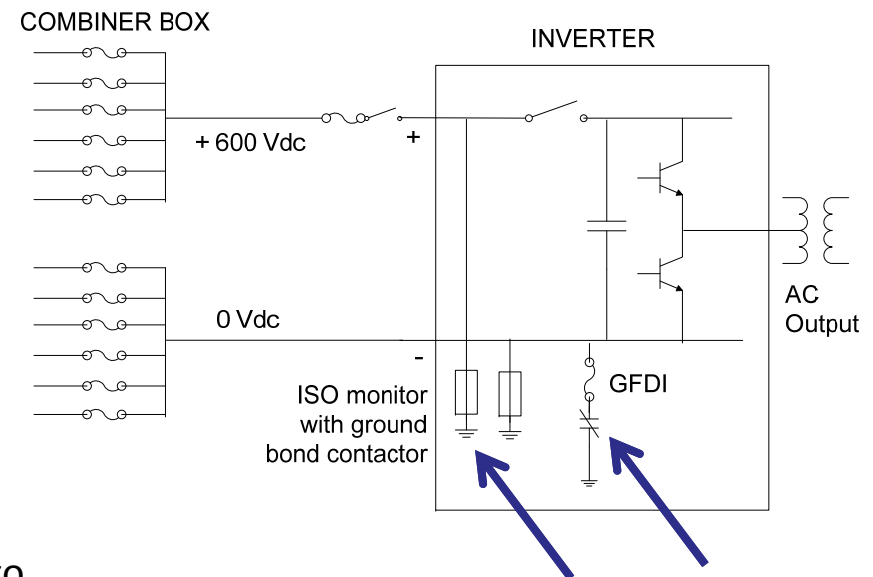
- **Effect:** Major increase in the detection sensitivity and mitigation flexibility (~100 mA sensitivity)
- **Pros:**
 - Relays can be programmed to trigger on current and duration levels
 - Can be coordinated with auxiliary trip
- **Cons:**
 - Requires rewire of ground fault fuse circuit
 - False trips possible
 - May impact inverter certification – must have approval from manufacturer.
- **Cost:** Moderate
 - Possible inverter manufacturer retrofit



Method 4: Isolation monitoring with periodic check

Install isolation monitor, implement periodic checks

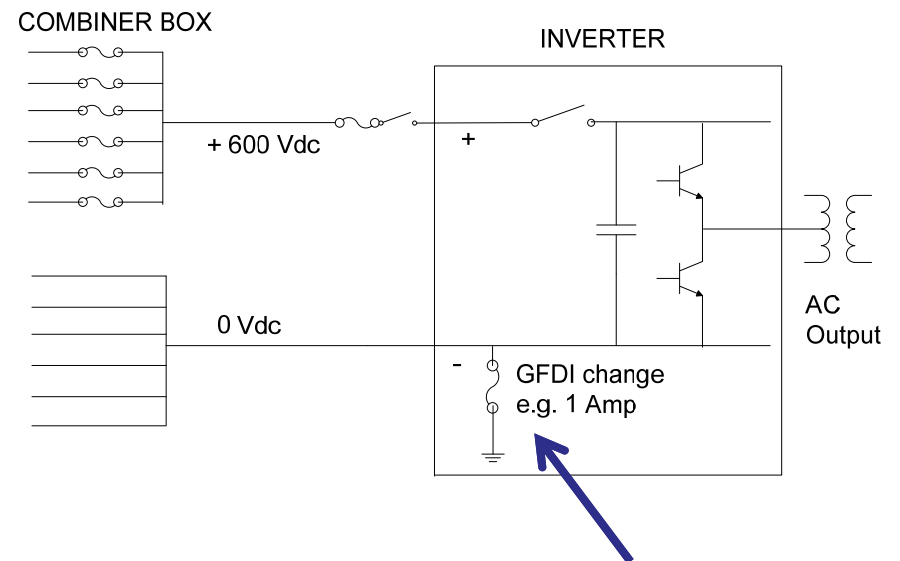
- **Effect:** Capable of detecting low insulation conditions and ground faults on either pole
- **Pros:**
 - Proven method for detecting blind spot fault conditions. (Similar to international non-isolated system protection)
 - Prevents inverter start up until faults are corrected
 - Consistent with evolving UL and IEC standards
- **Cons:**
 - More significant changes needed in inverter to implement monitoring, logic control and ground bond contactor
- **Cost:** High (in most cases)
 - Involves inverter manufacturer retrofit



Method 5: Reduce fuse size in ground fault circuit

Replace fuse.

- **Effect:** Minor increase in the sensitivity of ground fault detection. ~10x less sensitive than Methods 1-4.
- **Pros:**
 - Easy, inexpensive retrofit
- **Cons:**
 - Not as sensitive as electronic ground current monitoring
 - May conflict with other inverter functionality
 - May impact inverter certification
 - May result in nuisance trips
- **Cost:** Low



Method 6: Targeted operations and maintenance practices

Routine visit by qualified personnel to perform tests

- **Effect:** Capable of identifying blind spot faults
- **Pros:**
 - O&M can find undetected faults and degraded insulation
 - Annual operation and maintenance inspections are useful for many reasons beyond the blind spot.
- **Cons:**
 - Requires routine visit by technicians to perform tests.
 - Faults that occur between inspections may still go undetected.
 - Not a blind spot cure
- **Cost:** Moderate, but recurring



Method 7: Use of arc-fault detection

Series arc fault current interrupters (AFCIs) installed in contactor combiner boxes or at inverter feeder input circuits

- **Effect:** Can isolate circuits when arc is detected
- **Pros:**
 - Isolating strings when arc is detected may lessen any fault severity
 - May isolate 2nd dangerous fault that follows a blind spot fault (becomes series arc).
 - Detects other fire-causing faults
- **Cons:**
 - AFCI may not be able to detect blind spot faults
 - Series AFCIs are not evaluated for response to arcing faults to ground.
 - Limited commercial availability of proven equipment
- **Cost:** High (expected)

