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PV Ground Fault Protection Devices, *National Electric Code* Section 690.5 and Violations of NEC 250 and UL/IEC Listing/Registered Equipment Requirements

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Summary:

This paper documents the issues raised by the incorporation of a Over Current Protection Device between DC Return and Earth Ground as required by NEC 690.5 (based on 2005 and later) which violates requirement of Earth Grounding of non-isolated systems > 50 VDC [690.41] and violates “Systems that do not have one of the current-carrying conductors grounded must have disconnects and overcurrent devices in all of the ungrounded conductors [240.20, 690.13]” [John Wiles; PV-NEC-V-1.91.pdf].

This condition is present every time the GFP “trips” or if untrained users use GFP Breakers as an Array disconnect.

The use of a Over Current Protection Device as a “fault current sensor” between DC Return and Earth Ground will cause systems to violate Earth Ground Referenced Voltage design requirements that are typically required for non-isolated systems that use ELV (Extra Low Voltage) and SELV (Safety Extra Low Voltage) definitions for sending earth referenced communications signals (RS-232, USB, RS-485, etc.) and can present voltages upwards of 150 VDC and uncontrolled current potentials of 100’s to 1,000’s of Amperes throughout numerous DC electrical interconnections in Listed/Recognized Devices/Systems.

There is an absolute risk of equipment damage, fire, injury, death, and lawsuits if DC Ground Fault Protection as defined by NEC 690.5 and implemented by multiple commercial products and installations. All existing installations with NEC DC GFP installed shall be upgraded to a permanent (and appropriately rated) solid connection between DC Return and Earth Ground for all Earth Referenced DC PV Systems to reduce fire and shock hazards. First hand reports from multiple individuals in the Solar PV industry are already recommending that NEC DC GFP not be installed unless required by inspectors because it is understood that NEC DC GFP is unsafe.

NEC DC GFP must be removed from existing code requirements and any power systems that have NEC DC GFP installed must have Earth Ground to DC Return Bus permanently connected per NEC grounding requirements.

Introduction:

I have, over the last few years, been volunteering on a solar power discussion forum (http://www.wind-sun.com/ForumVB/ as user "BB.") where, among other things, we help people to safely design and install their Off Grid (and Grid Tied) Solar PV Systems.

In reviewing documentation and literature from various sources [NEC, Outback, John Wiles' "Photovoltaic Power Systems and the *2005 National Electric Code*: Suggested Practices"], I came across a circuit that has been used to interrupt Earth Faults in DC Power Circuits. For the sake of this paper, I will call it the NEC DC Ground Fault Protection circuit (NEC DC GFP).

From my experience designing various computer systems, both AC and -48 VDC powered, I came to have great appreciation for having an Earth Ground Reference and Double Isolated Power Supplies when designing for a larger multi-system environment to reduce the chances of shock and fire hazards when complying with the NEC (National Electric Code), UL 1459 2nd Edition, and various IEC and Bellcore/Telcordia (AT&T) requirements.

From several discussions on the Wind-Sun and Midnite Solar forums, I have been trying to educate our participants on the safety implications of installing NEC DC GFP system and to make their own decision if they should "violate code" and not implement the "GFP system".

During these discussion (and from personal communications) I have found that (at least a small number) of Solar PV System Vendors and at least one Manufacturer are also recommending not to install NEC DC GFP because of safety concerns.

Bob and Robin Gudgel from Midnite Solar have asked me to document in detail my explicit reasons why NEC DC GFP is an absolute safety nightmare when implemented. I would be terribly surprised if there have been no ground fault failures that have not resulted in equipment damage, overheated cables, or human shock.

It is only a matter of time before there is a fire, injury, or death (and following lawsuits) that are the result of "normal fault protection operation" of the NEC DC GFP system.

There is no way (that I can see) that the NEC DC GFP can be adjusted to be made safe. Existing installations must be modified/updated to bypass/remove the DC GFP ground fault detector (typically a OCP) to restore previous levels of fire and personnel safety that were present before NEC DC GFP was implemented.

Robin & Bob Gudgel and Ryan Stankevitz have also provided me with technical support and review of this document to ensure I have properly represented the issues.

Contents of this Document:

Following this section, there are four drawings which graphically represent:

- Typical NEC DC GFP installation.
- Three NEC DC GFP fault scenarios.
- Recommended fix for existing and new installations.

NEC DC Ground Fault Protection as Designed:

What I found when researching the NEC DC GFP solution was that it was implemented with a ground fault current sensor (a Over Current Protection Device inserted between DC Return and Earth Ground).

The inserted Over Current Protection Device was typically a Circuit Breaker, or Fuse + electronic circuit, or PTC + electronic circuit. This OCP would sense DC (or AC) current flows which exceeded ~0.5 to 5 Amperes into Earth Ground.

The “tripping” of the OCP would then be used to Signal or Switch off current flow between a Solar PV Array and a DC Solar Charge Controller (or Grid Tied / Utility Interactive Inverter). Some vendors would “inhibit” the Charge Controller or Inverter as another method to satisfy the requirements.

Convention:

For the rest of this paper, I will assume a Negative Ground Referenced DC Power Bus. The issues, however, are identical if implemented in a Positive Ground Environment.

The Problem:

When there is a Positive Power Bus to Earth Fault anywhere in the DC Power System (Solar Array, Solar DC Charger Bus, Battery Bus, etc.), There will be an excessive current flow forced through the NEC DC GFP OCP. This excessive current will “trip” the OCP and un-reference the DC Return (or Negative) Power Bus.

Because every implementation I have seen (a small subset on my part) of the NEC DC GFP only interrupted one side of the DC Power Bus, this left the Negative DC Bus floating with uncontrolled, and very likely, hazardous voltage/current potentials.

Effectively, the Positive Earth Fault has become the “new” Earth Reference in the DC Power System.

Fault Tree (one example):

For this document, I will assume worst case fault conditions and worth case fault locations (within reason).

1. Assume a near zero ohm short between the Positive Solar PV Array Bus and Earth Ground.
2. Causes current flow between DC Return and Earth Ground through the NEC DC GFP OCP "sensor".
3. NEC DC GFP OCP opens which un-references the Common Negative DC Bus (DC Return).
4. Effectively, the Positive Solar PV Array Terminal is now Earth Ground Referenced (via fault)
5. DC Return/Negative Bus is now Referenced to –Voc of Solar Array (up to -150 VDC in a typical medium sized PV system) and has upwards of 80 Amperes of available current (Isc of Solar Array).
6. Following standard NEC practice for Ground Referenced designs, no OCP (Over Current Protection Devices) have been installed in the Negative DC Return Bus.
7. What was Earth Ground Referenced now Exceeds ELV (Extra Low Voltage) definitions in NEC/NRTL requirements and the lack of OCP in the Negative DC Bus will allow 80 amps (in this Fault) to flow through all Negative DC Bus paths (including 14 AWG and smaller DC branch power and signaling circuits, if present).
8. Subsequent faults between DC Negative Bus and Earth Ground be could cause fusing of DC Negative Branch or communications signaling wiring. Violation of [240.20, 690.13]
9. Would also cause excessive voltage and current flow to equipment that uses Earth Ground for signaling reference (external computers, battery monitor, data logging equipment, etc.).

Conclusion:

Because, as designers, we are required to meet the definition of Separated or Safety Extra-Low Voltage (SELV) [http://en.wikipedia.org/wiki/Extra-low_voltage] in most low voltage DC systems:

> IEC defines an SELV system as "an electrical system in which the voltage cannot exceed ELV under normal conditions, and under single-fault conditions, including earth faults in other circuits".

The NEC DC GFP as currently designed and implemented does not comply with these other safety requirements.

And when implemented at the system level, standard industry Ground Referenced Design Practices will improperly assume that DC Return when Earth Referenced should never deviate from near Zero Volts. And in no case, will ever exceed ELV/SELV values.

If NEC DC GFP operates as designed when presented with a single Ground Fault on the Power Bus, it can cause unacceptable hazardous energy to be present as the DC GFP Detector is designed to be the weak link in the typical current path.

If there is a permanent ground between Negative DC Return and Earth Ground, then any excessive current flow will either be limited to safe levels by design (PV Solar Array NEC Cabling Design requirements or will trip one or more OCPs on the Positive Power Bus any current that exceeds the OCP ratings.

Appendix A (earth fault scenario figures):

The following figures document how the NEC DC GFP Earth Fault Detection Element causes non-compliant and functionally dangerous conditions as the result of normal 1 fault scenarios.

There are four drawings which graphically represent:

- Typical (minimum configuration) NEC DC GFP installation.
- Three NEC DC GFP fault scenarios (note: fault voltages/current availability are with respect to Earth Ground on drawings)
- Recommended fix for existing and new installations.

These five drawings do not document the subsequent failures/faults/safety issues that are created by the initial NEC DC GFP fault trip lifting “safety ground” (earth ground).

Also note that in all 3 fault scenarios, the Earth Fault Current will always be interrupted by the NEC DC GFP ~1 Ampere “fault detector” breaker (OCPD).

The Single Pole Ganged Breaker in the DC Power Line from the Solar PV Array to the Solar Charge Controller is either redundant or provides no function in turning off the Earth Fault Current.

#1 NEC DC GFP (ground fault protection) generic system setup using an external dual ganged 1A/100A GFP breaker on the PV + side of a MPPT Solar Charge **Controller.**

I will make some quick assumptions here—May not be an "optimal" solar PV system with MPPT controller, but demonstrates the upper limits of the issues I see.

- Voc-cold-array = ~150 VDC
- Isc-array = ~80 amps
- 48 volt battery bank >> 100 AH
- 80 amp continuous rated panel input Isc-array for MPPT
- 80 amp continuous rated output Ibatt for MPPT
- Assume generic MPPT type charge controller with 150 VDC / 100 Amp maximum PV Array input and 100 amp breaker (80 amp continuous) DC output to battery bank--~12-48 nominal battery voltage.
- Assume 1 amp Ground Fault Detection breaker between DC Return and Earth Ground. Assume 100 Amp Ganged Breaker (with 1 amp GFP Detector Breaker) which turns both 1 amp and 100 amp breakers off.
- Assume DC Negative Bus is ground referenced via A) 1 amp breaker (NEC DC GFP) or B) Solid Earth Ground Bond (as recommended this report).
- Assume thick lines are rated for 100 amps for power bus or 6 AWG minimum for earth grounding.
- Assume thin lines are rated for 15 amps (load) or 1 amp (GFP Det Brkr)

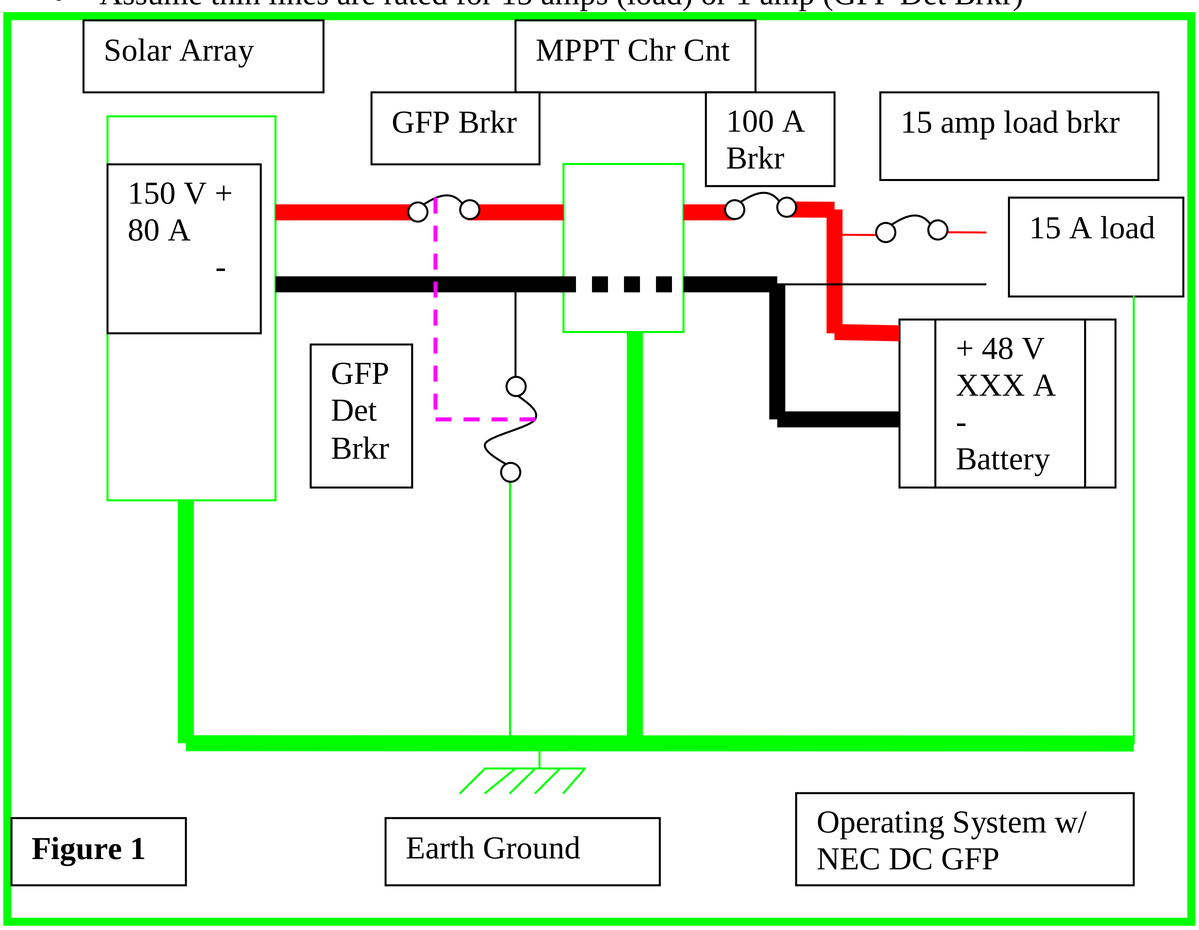

Figure 1

#2 Insert Ground Fault between GFP Brkr and MPPT controller.

Fault causes current flow between +Array to MPPT Case, to Earth Ground, through GFP Det Brkr, to –Array. Causes Det Brkr to open, which opens GFP Breaker.

This is an “unknown behavior” failure… I do not know how a MPPT controller will behave in this situation, but this fault may be benign if MPPT does not pass + bus current. It does leave the Power Bus ungrounded (floating). Has other system related issues but pass for now as this would be a lot of discussions of things we don’t care about right now.

If I was wearing my “design for worst case assumptions”, I would assume +Vpanel to +Vbattery is a dead short. This becomes the same failure and raises the same issues as in Figure #4.

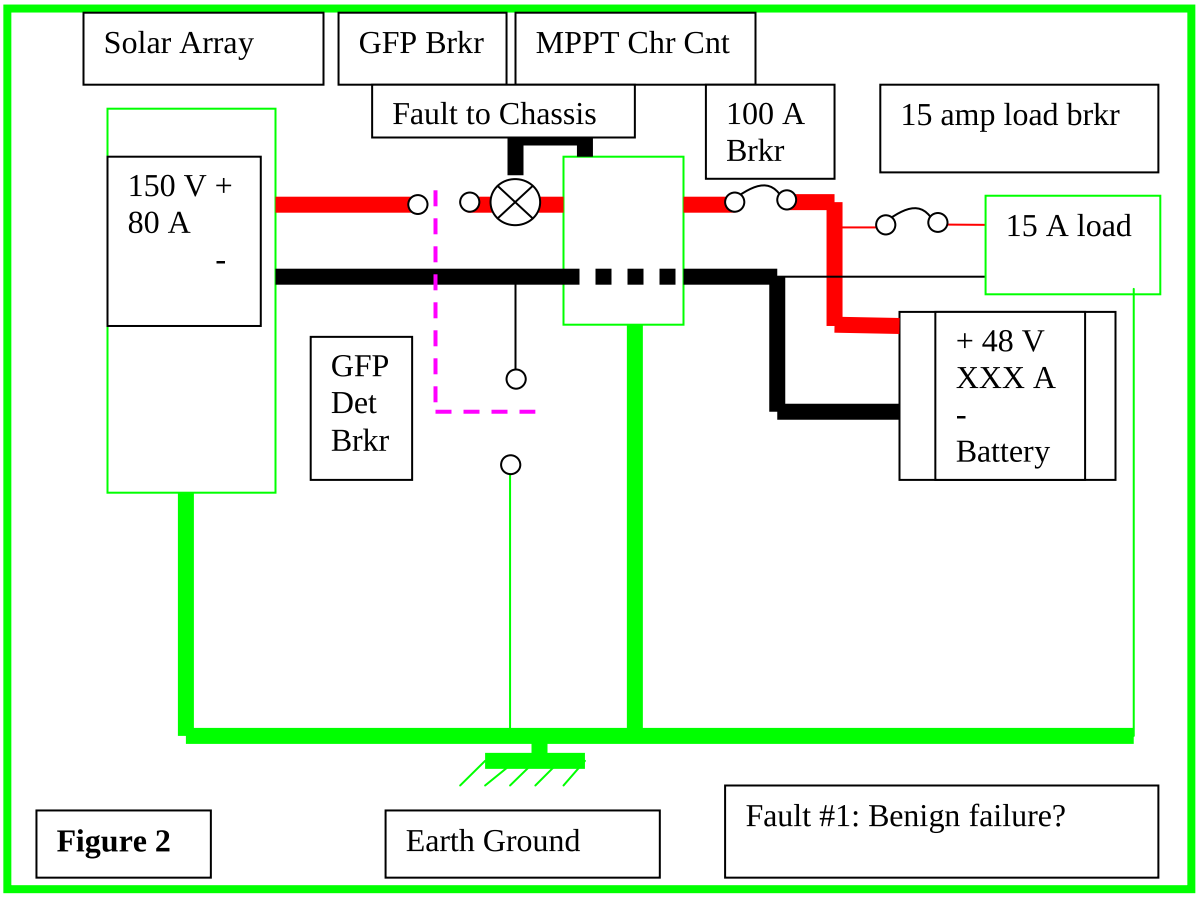

Figure 2

#3 Fault between GFP Brkr and +Varray to Solar Panel Frame (earth grounded per code).

We have current flow from +Varray through Panel Frame to Earth Ground to GFP Det Brkr to –Varray. Causes GFP breakers to open. This will normally not cause Array series fuses or any other + side protective devices to open… Weak link is DC GFP Detector.

Now, during daylight hours, the +Vpanel is at zero volts (relative to earth ground) and –Vpanel is at -150 VDC with 80 amp Isc available.

Assuming –Vpanel hard connects to –Vbattery through the MPPT charge controller, the –Vbatt is now at -150 VDC. Well outside of the ELV rating for UL 1459 (or whatever are the current/appropriate specs today—I am out of that loop for decades). +Vbattery is at 150V-48V=-102Volts.

If there is a fault at "15 A Load" between –Vbatt and Earth Ground, there will be ~-150 Volt potential and 80 amps through the 14 AWG return wire which has no Over Current Protection Devices in the entire path from Array to load and back through earth return and is simply limited to Panel's Isc.

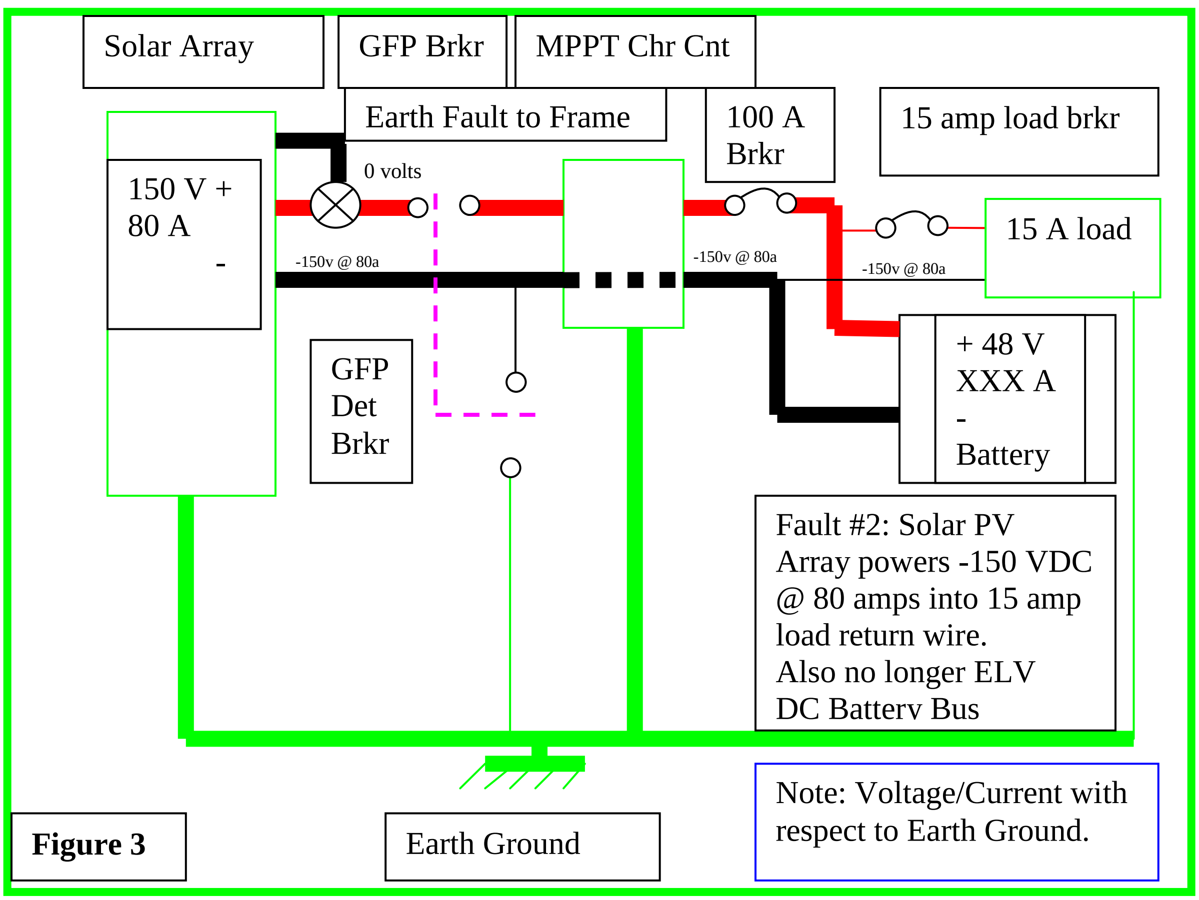

Figure 3

#4 Fault somewhere on +Vbattery bus

Assume in this case wiring between charge controller and 100 amp breaker GFP Brkr and MPPT controller chassis ground.

Current flows from +Vbattery through 80 amp breaker, to MPPT case, to Earth Ground through GFP Det Brkr to –Varray/-Vbattery. Causes GFP breakers to open.

At this point, +Vbattery becomes 0 VDC (earth reference). And –Vbattery becomes -48 VDC with 100 Amps of available current (because I choose to short after 100 amp breaker in this example).

At this point, the maximum current anywhere in the DC return path is defined by where the Earth Fault occurs on the positive bus. An earth fault will not cause any Positive distribution Over Current Protectors to trip as the "weak link" is the 1 amp GFP Det Brkr.

If there is a fault at "15 A Load" between –Vbatt and Earth Ground, there will be ~-48 Volt potential and 100 amps through the 14 AWG return wire which has an undefined (100 amps in this example) protection devices in the path from +48Vbattery through earth grounding, then to load (chassis and DC return) and back through DC return bus (mixed AWG) to battery.

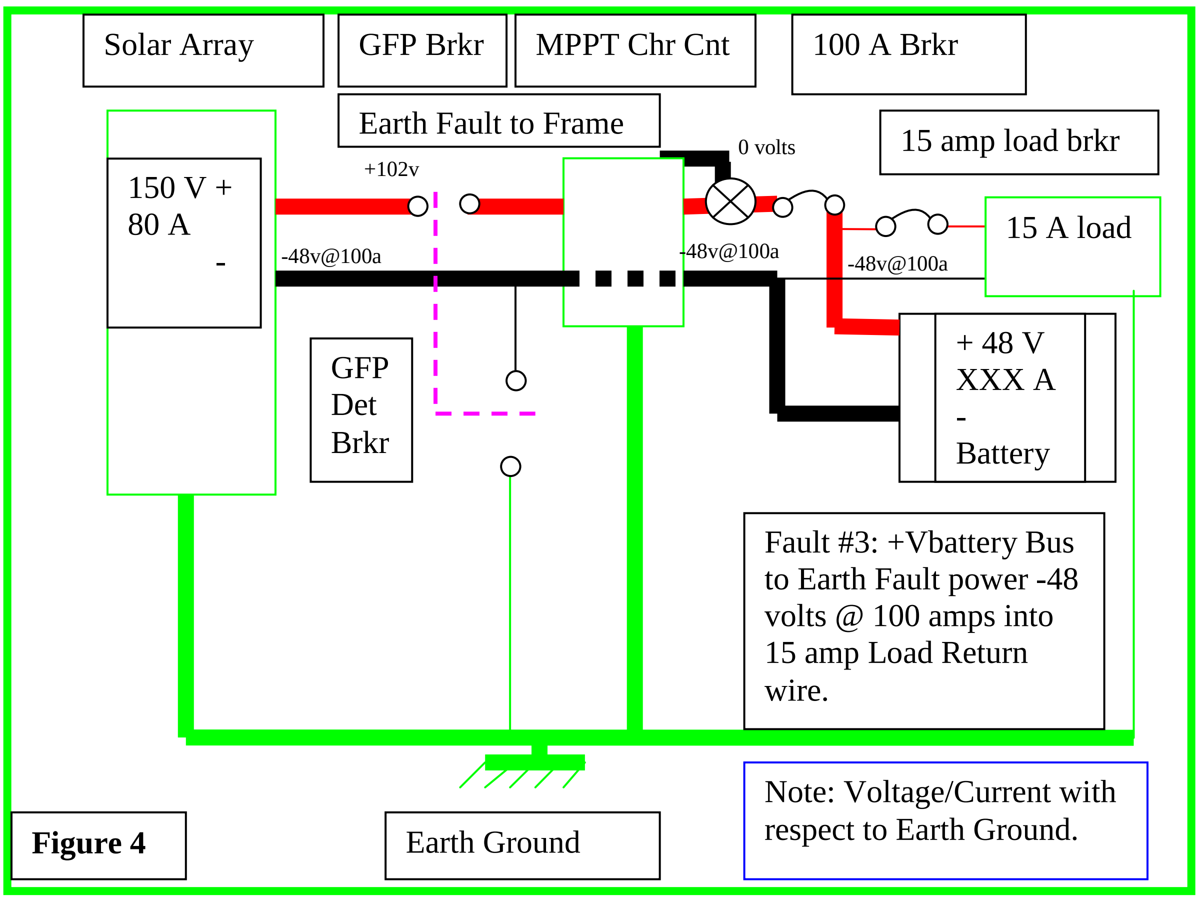

Figure 4

#5 Proposed Fixed / Proper Method of DC grounding for all systems:

1. NEC DC GFP may be left in or taken out—Does not matter from safety point of view (recommend disabling detection circuit as it causes multiple DC Earth Grounds).
2. Hard Earth the Negative DC bus per normal code requirements.

Assuming ARC Fault protection as implemented per NEC DC GFP is not "important" as it offers rather limited protection vs all other ELV/Excessive unprotected current flow resulting from "proper" operation of DC GFP system and Single Earth Faults which will cause true fire and ELV/SELV hazards.

All initial faults will still limit current to design maximum (Isc of array, or appropriate circuit breakers/wiring gauges per NEC).

- Initial faults will either continue current flow safely (+Vpanel to earth/ground/battery ground faults). May be "hot spot" at point of fault. But that would be true of multiple other faults that NEC DC GFP did not protect against.
- All other +Vbattery Faults will be limited by their appropriate Main/Distribution Breakers.
- Varray may not be ELV… But all DC Power Bus +/-/Earth reference voltages will never exceed Vbatt under normal operation.
- All circuits that use Negative DC bus for "ground reference" (i.e., RS-232, USB, and other non-isolated circuits) will never be above or below Earth/-DC power (all will be near zero volts except for voltage drops caused by current flow).
- Any other devices that use Earth Ground as a reference (i.e., computers with comm. Ports, etc.) will also never see Vpanel or Vbattery voltage differences between Earth Ground and DC ground reference from PV system DC Power Bus.

All subsequent faults will still be safe and meet NEC/IEC/etc. safety requirements.

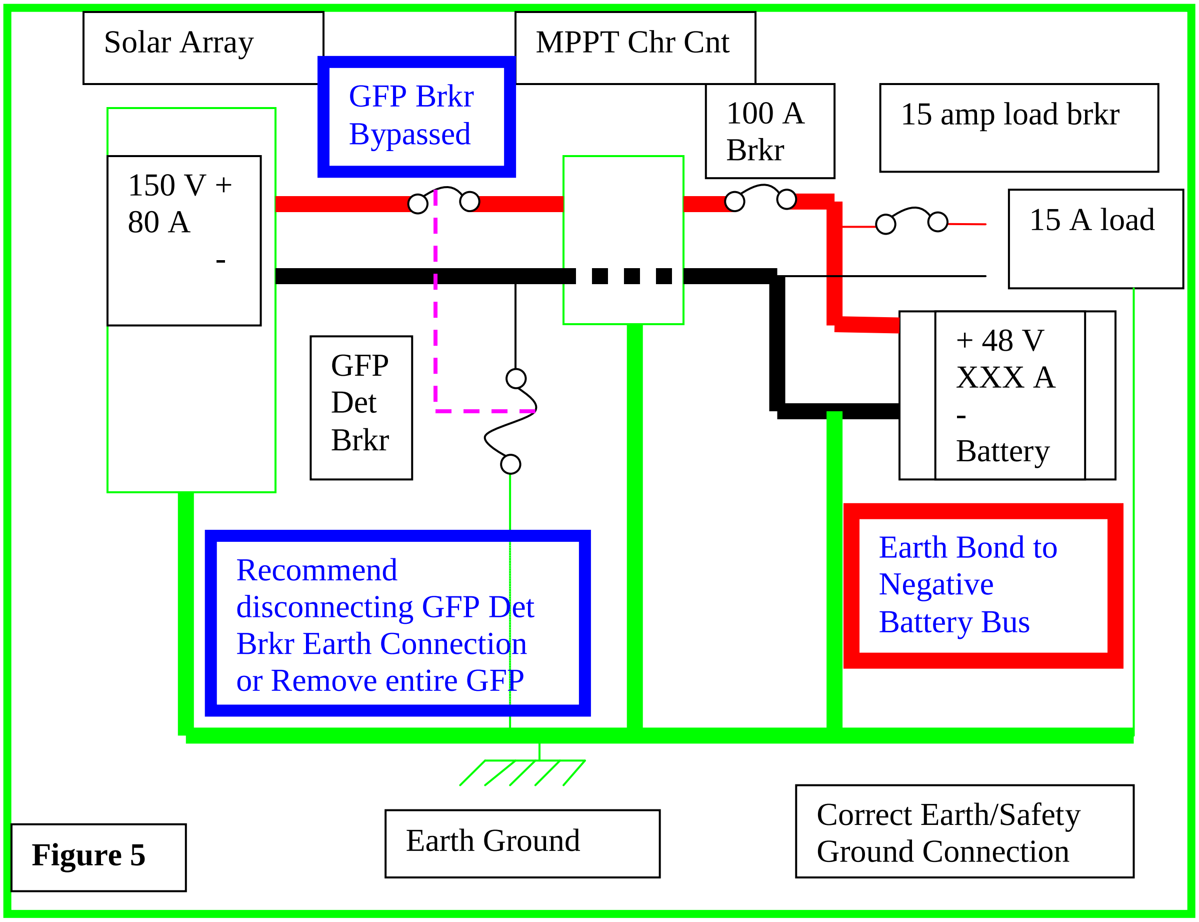
Solar Array
MPPT Chr Cnt
GFP Brkr Bypassed
100 A Brkr
15 amp load brkr
150 V +
80 A
-
15 A load
+ 48 V
XXX A
-
Battery
GFP Det Brkr
Earth Bond to Negative Battery Bus
Recommend disconnecting GFP Det Brkr Earth Connection or Remove entire GFP
Earth Ground
Correct Earth/Safety Ground Connection

Figure 5

Appendix B (implications to other connected equipment):

There are other failure mechanisms with other common devices (such as non-isolated MSW 120/240 VAC off-grid Inverters) that I have not addressed in the previous figures—but these devices also are subject to the similar safety issues with the NEC DC GFP system.

These subsequent hazards and faults are caused by the presentation of non-ELV / non-SELV voltage and uncontrolled energy on what would normally be the Ground Referenced Power Bus/Cabling.

This unsafe energy present on the "White" NEC defined DC Return Bus Ground Referenced conductor can cause fire, shock, injury and death via accidental/faulted contact with the now energized conductor is one violation of NEC.

Another violation on non-isolated system/devices that use the DC Power Bus; most engineers/systems assume that the DC Return (negative or ground return power bus in this set of examples) can be used as a reference level for inter device communication and as a current return to supply small amounts of power to external devices (repeaters, cooling fans, etc.).

The presence of 100's of volts and 10's-1,000's of Amperes on what, according to NEC and various NRTL requirements should be at Zero Voltage Potential with respect to Earth Ground is nothing that any equipment design engineer, manufacture, or NRTL agency foresaw as an environment where such non-isolated product would be placed.

At this point, every Solar Renewable System that has implemented the NEC DC GFP system is just one Power Bus to Earth Fault away from energizing what historically has been a non-hazardous, touch safe zone.

The one single DC Power Bus to Earth Fault will either immediately cause small signal and low power interconnect cables to overheat/fail, or energize conductors/exposed metal to energy levels that would never have been expected or allowed by NRTL agencies.

The actual voltage and current levels presented depend on a whole host of variables and cannot be defined/qualified by likely Power Bus to Earth Faults. The actual hazards are related to individual installations, including solar array ratings, battery bank voltage, OCP ratings in DC Power Bus, equipment connected to bus, use of non-isolated communications circuits, use of high power non-isolated devices (MSW—Modified Square Wave—Inverters) etc.

There is no way for untrained personnel to evaluate individual installations for risk provided by NEC DC GFP. And these risks may change over time as systems are reconfigured, repaired and upgraded in the field.

Appendix C (Arc Fault Implementation):

Midnite Solar has implemented Series Arc Fault on their new “Classic” MPPT Charge Controller.

On a “per device” Arc Fault detection / Current inhibit implementation; Midnite believes that this function addresses a common form of failure in Solar Arrays and Output Wiring. Detection and interruption of Series Arc Faults (poor/corroded power connections, improper use of high flex/fine “welding cables” and inappropriate binding hardware, etc.) has replaced the need for the NEC DC GFP System [per Robin Gudgel].

Series Arc Faults (poor connections in current path) are much more common and are serious fire hazards in their own right. Prior to the release of SAF protection, there has not been any effective method to address reports of solar array/wiring fires from otherwise properly installed and operating system where water and age has degraded electrical bonds in the array wiring. Implementing Series Arc Fault protection actually provides a real improvement in fire safety on existing and new installations without requiring any changes to the existing branch wiring or solar panels/arrays (no boxes/fire resistant protection of electrical connections, no additional fire barriers for rear of solar panels, etc.).

None of these real improvements in fire safety can be matched by the existing NEC DC GFP circuitry.

NEC DC GFP cannot detect series arc faults and therefore cannot interrupt an in process series arc fault. And cannot detect/prevent mill-amp level differential current flow for either fire or shock safety (as in AC GFI implementations with simple differential current transformers). So it does not address shock hazards either (and actually increase shock hazards in proper operation).

Because no Solar RE NEC DC GFP implementation has two pole current interruption (as required for isolated power systems) and does not require the implementation of Common Trip (Shunt Trip) two pole circuit breakers on each and every possible power source in Renewable Energy DC Power System (solar panels, wind turbines, battery banks, AC coupled inverters, both Power and Return of Branch Circuits, etc.)—There is no reasonable reason for NEC 690.5 to require (or even allow) NEC DC GFP.

Combining the higher likelihood of Series Arc Faults, the ease and low cost to implement SAF detection and current transfer inhibit versus the low frequency and serious safety flaws in NEC DC GFP implementations—Midnite Solar’s implementation of Series Arc Fault detection and current interruption has eliminated even the need for a DC GFP protection system as currently deployed [per Robin Gudgel, Midnite Solar].

If DC GFP where to be required/re-defined to provide similar protection as AC Ground Fault Interrupter protection using currently available hardware and appropriate safety requirements, it would add ~$300-$400 (or more) per device. Also such a protective device would have to be an external device as it would be too physically large/bulky to be made internal to most products (such as a DC solar charge controller) [per Bob Gudgel, Midnite Solar]

Appendix D (Grid Tied / Utility Interactive Inverter Implications):

I have much less information regarding how the NEC DC GFP circuitry used in Utility Interactive (aka Grid Tied) inverters behaves and will affect overall safety.

For most users, the 120/240 VAC power is the output they are exposed to in normal operation and roof wiring is not normally accessed by end users.. Branch Circuits are required to meet NEC (or equivalent) and therefore the addition of NEC DC GFP probably has little impact here.

However, many of these UI/GT Inverters do have various communication and low voltage interconnect buses—A warning to Manufacturers to perform an engineering review for the implications of reversing Negative vs Positive Grounding and common mode offset by ~600 VDC in the event of certain Solar Array to Earth Faults through their NRTL Listing Agency(ies) should be considered.

Many newer UI/GT Inverters have the ability to operate either as Negative or Positive Earth Grounded Solar Arrays (Sun Power out of Germany requires Positive Grounding of the solar array for optimal operation).

The configurable Positive/Negative earth grounding leads to even more confusion with the implications of Positive / Negative Ground Reversals on the Solar Array wiring. It could lead to errors by service and emergency personnel as to the meaning of “White” and Black/Red/other colors (White being defined as Ground Referenced).

Service personnel need to be trained to understand how to service systems where Earth Ground Reversals could occur (depending on exact NEC DC GFP implementation—may be vendor dependent).

For emergency/first responders, they should (already) be trained to assume that all circuits may contain hazardous voltage and energy (whether solar arrays or DC battery banks).

Appendix E (Fire / First Responders Implications):

As in Appendix E, I do not believe that ground reversal creates an unusual hazardous condition for emergency personnel.

The larger hazard is the use of "Hot Sticks" and other "live circuit" detectors that usually use capacitive coupling of 50/60 Hz voltage are not capable of detecting the presence of DC voltage/energy (solar arrays and battery banks).

One possible requirement would be the use of "Emergency Stop" buttons and shunt trip circuit breakers/inhibit input from all energy sources (solar charge controllers, battery banks, etc.) as sometimes used in large industrial installations.

Other than to acknowledge those options, which exist, are superior to the NEC DC GFP system for safety of emergency personnel—No further discussions will be provided in this paper.

Appendix F (Why Bonded DC Return to Earth Ground is Critical for Safety):

A compendium of why I believe that Bonded DC Return to Earth Ground is virtually mandatory for all non-isolated DC Power Systems (solar PV and all others) both from a safety and product integration point of view.

From my past experiences, working with DC and AC powered communications systems, I had always believed that that Earth Bonded DC Return was a critical piece of the engineering requirements to build a safe and compatible system. Towards that end, I have created this list document the major reasons why inserting a low current OCPD between DC Return and Earth Ground is unthinkable from my experience as a system designer.

We needed a positive connection to a "reference voltage" to ensure that the power buses did not exceed designed ratings (i.e., a nominal -48 volt, positive ground) in any single fault condition. Earth Ground was that reference that all others connected to (frame grounds, plumbing, building frames, etc.). And this carried through system interconnects (both power and signaling).

I have also included how Series Arc Detection and Interrupt will eliminate the need for NEC DC GFP in virtually all cases.

Note, there is one fault that NEC DC GFP works on that no other proposed DC GFP system for PV Array Power to Earth Faults can detect and interrupt—Including any that I can think of at this time.

Because PV Solar Arrays are Current Sources with cabling and OCPD designed to be 1.25x the maximum short circuit current—There is no other way to detect and interrupt a Solar Array Positive to Earth Fault (if Negative Ground as an example), short of complex active current monitoring. The detecting Earth Fault current flow by using a Fuse or Circuit Breaker is an interesting concept—but the hazards raised by using a low amperage OCPD between DC Return and Earth Ground overwhelm any advantages provided by the current NEC DC GFP design.

Reasons for Bonded DC Return to Earth Ground:

Based on my engineering experiences, the bonded DC Return to Earth Ground has been a fundamental design assumption for both product safety and system level compatibility.

- Bonded Ground ensures that the DC Return cannot exceed Local Earth Potential by more than a few volts.
- Line Crosses: For areas with 12.5kV / 25 kV distribution, a fallen line onto a roof can energies solar panels and their wiring. We Earth Ground Solar Panel Frames to prevent the metal from becoming energized (for any reason—such as trees knocking power lines on home/solar array). Earth Bonded DC Return prevents DC Power Bus from going outside of defined limits.

- Any DC Power Fault to Earth Ground should have an Earth Ground/DC Return connection sufficient to ensure that enough current flow to trip the OCPD on the DC Power Line (note does not apply to PV Array as it is a current source).
- Any accidental DC Power Bus to Earth Metal will trip OCPD—Typically a Branch Circuit Breaker in DC Power Line. (again, not PV Array faults)
- Assuming 50% of Earth Faults may occur in DC Power and 50% may occur in DC Return wiring/bus/etc.... A single Fault will either trip a OCPD (Power to Earth Fault) or Nothing (Return to Earth Fault). Or, in the case of PV Power Fault, continue to pass rated current through all current paths. (PV Array Earth or Line to Return Faults will not trip OCPD—a problem).
- Any initial DC Power Bus Fault (line to return, line to earth, and return to earth) leaves system in stable and "safe" condition. Any subsequent fault will behave as expected.
- DC Bus Systems have been assumed to be Earth Referenced for a ~Century (starting with early Telephone Equipment?).
- Non-Isolated DC Communications Circuits are prevalent across multiple industries and interfaces (RS-232, USB, Disk Drive Interfaces, Data Logging, etc.). To define a DC Power System to have Earth Referenced DC Return "sometimes", and at other times to "Invert" the Ground Reference (i.e., from negative to positive ground), and/or inject 10's-100's of volts with 10's-1,000's of Amperes into the Ground Reference "breaks" every non-isolated communications interface there is.,
- All Single Fault Conditions result in stable and easily controlled/identified fault states... For example, a tripped circuit breaker or blown fuse. All other portions of the DC Power System remain intact and operational (per design). No excessive voltages or current present anywhere in the DC Power System.
- No "DC Return" Branch Circuits are energized with non-zero voltage with respect to Earth Ground.
- No "DC Return" Branch Circuits are capable of sourcing/sinking current with respect to Earth Ground (i.e., DC Return to Earth Faults are non-events).
- No "DC Power" Branch Circuit has a voltage other than Zero or DC Bus System Voltage relative to DC Return or Earth Ground.
- No NEC DC GFP disconnects will be tripped based on Faults elsewhere in the DC Power System (i.e., a Battery Bus to Earth Fault will not trip the PV Array Disconnect).
- A single ~1 Ampere Earth Fault anywhere in the DC Power System will not require that 100% of all possible Power Sources (PV Array, Battery Bank, Battery Chargers, Inverters, Wind Turbines, etc.) be equipped with Two Pole disconnects which need to be all switched off for "safety" if NEC DC GFP is tripped (i.e., the need to turn off every possible DC Power Source for a single 1 amp fault).

Existing practices are no longer safe with NEC DC GFP system:

- Example: DC Battery Monitoring Shunts are installed on "Ground Referenced" side of battery bus. Large exposed shunt current sense leads that were very near Earth Ground can now be at 12-48 volts to as much as 150 VDC or more (earth ground reference) with tripped GFP due to ground reference inversion and solar PV array offset voltage (or other sources). Monitoring equipment will need to be redesigned for safety.
- Remote Meters/Displays/Buttons/Sensors for Solar Charge Controller, AC Inverters, AC Battery Chargers, Generator Auto-start Interfaces, etc. are designed with DC Return at Ground and DC Power to not exceed Vbatt Ratings. Now, cabling and electronics need to be designed to be safe at 150 VDC (or more) with NEC DC GFP tripped due to documented fault conditions.

Reasons no Earth Bond to DC Return is bad for safety:

With an OCPD between DC Return and Earth Ground "tripped", there is no other connection or device controlling DC Return to Earth Potential.

In some fault cases, the initial fault will trip the NEC DC GFP "detector" and leave the DC Bus energized and off set from Earth Ground with hazardous energy (voltage and/or current) and put the DC Power Bus in an unknown state (depends on equipment, where fault occurs, etc.).

There may be injuries/death from touching the, what should be nominal 0V / Battery Voltage level voltages.

The impressed voltages may be DC or AC with DC offset (need to check for both "unusual" AC and DC voltages on battery bus).

For equipment that uses DC Return as a reference voltage, may cause unsafe current flow in connected support equipment (battery monitors, data loggers, computers).

May cause dangerous voltages/energy to be impressed on connected support equipment (for example, a battery powered portable computer could have metal chassis/signal ports energized to 150-600 Volts with respect to earth ground).

And subsequent faults may be unprotected by OCPD (positive/negative ground inversion removes OCPD from current source/sink branch wiring paths). Leading to Fire, injury, or death.

Multiple Sources of Energy in Solar PV DC Systems—Not only the PV Array:

- Faulted PV Array can provide new ground reference (tripped NEC DC GFP detector). Voltage is based on installation specifications (12v-600 VDC, roughly 0-100 Ampere fault current ratings for “home sized” PV arrays)
- Faulted Power Bus of DC Battery Bank same neg/pos ground inversion and voltage/current based on DC system specifications and exact point of DC Power to Earth fault (12-48/60 VDC. 100's to 10,000's of Amperes of fault current)
- There are other devices which will produce very non-intuitive fault conditions… For example a standard MSW inverter (100’s to 1,000’s of Watts) is usually a non-isolated design. If there is a Earth Faulted 120 VAC output Line conductor faulted to Earth—this will cause the Inverter to “Earth Fault” the DC Battery Bus and trip the NEC DC GFP OCPD “detector”. This small 1 amp breaker will open and “float the DC Power Bus” and (I think) inject common mode AC onto the DC Battery Bus (roughly equal to MSW ~120-240 VAC wave form?) at high currents (in a bonded DC Return / Earth system, enough to trip a OCPD on the DC branch circuit for the inverter or possibly the AC output OCPD).
- Earth's Electric Field... ~100's of volts per meter (clear air). Small current but can charge ungrounded metal to 100's and even thousands of volts. Many devices have capacitors/capacitance relative to earth ground (metal conductors, filter capacitors, etc.). Sufficient stored energy for high energy discharges (injury/death/ignition source). When NEC DC GFP is tripped, there is no defined path to bleed off currents that tend to charge elevated/insulated metal structures (radio towers, PV Arrays on Roof, etc.). Over time, static charges could build up and provide substantial shocks in clear weather.
- Lighting / Thunderstorms will increase Earth's electric field to hazardous voltages and currents. Ideally, need to shunt current/voltage from nearby lightning strikes to ground. With DC Return to Earth Ground open—Another path will need to be found. Nearby strikes could “false” trip NEC DC GFP detection system. Again, leaving elevated voltage levels on “floating” DC Power Bus (and Array).

Voltage Limit for Solar RE DC Power Bus is set by “air gap” and other unintentional, and intentional, arc gaps in system “devices”.

- With NEC DC GFP “detector” tripped, an air gap of 1/4” to 3/8” (300vdc / 600 vdc) which means a Nominal Minimum breakdown voltage (assuming ~50 volts per 0.001 inch) of ~12,500 volts (1/4”) or ~18,750 volts (air gap per UL 1741).
- Delta Lightning Suppressors ~ 7,000 VDC
- Other unintentional spark gaps (capacitors, fuses/breakers, physical construction, and insulator punch through) will most likely be the first fail.

- Unintentional Voltage Clamping can reduce safety (insulation punch through, carbon tracks, welded contacts, etc.).
- Series OCPD are not rated to "interrupt" either static charge or lightning energy levels. Will not (intentionally) limit high voltage (and associated current) brought into building.
- Lifted DC Return Earth Ground (via tripped NEC DC GFP OCPD detector) allows hazardous voltages to be present in DC Power System (when tripped). It would seem like this would require service personnel to manually earth ground the DC Return any Solar RE Power System prior to service as system is "armed" to present unsafe voltage and current levels throughout DC Power System in the event of any single earth fault (no matter the cause). Service personnel manually bonding DC Return would disable NEC DC GFP system during service.

After initial DC Power to Earth Fault, system can be left in unstable condition

- Possible Negative / Positive Earth Ground reversal
- Earth Ground to DC Return path open allowing DC Return to float relative to ground
- PV Array can drive DC Return to 12v, 24v, 48v, 60v, 150 VDC, 300 VDC or even 600+ VDC depending on location of fault.
- NEC DC GFP is "assumes" that Ground Fault was in PV Array. Any Ground Fault in the system will give same indication as PV Array fault (DC Power Bus, MSW Inverter AC Ground Fault, non-isolated DC communications gear GF, AC Battery Charger GF, Battery Bus GF, etc.).
- DC Return Bus may be energized with amps, 10's, 100's, or even 1,000's of Amperes depending on location of Ground Fault
- PV Array Disconnected even though fault may not be in Array.
- Assuming 50% of Earth Faults may occur in DC Power and 50% may occur in DC Return wiring/bus/etc.... A single Earth Fault will either trip 1 amp OCPD detector (Power to Earth Fault) or bypass 1 amp OCPD detector (Return to Earth Fault) and render the NEC DC GFP system inoperative with no indication or passive method of detection/monitoring/reporting.
- In off-grid installations it is very common that the consumer shorts out the DC-GFP. They ground the battery negative. This happens a lot! The NEC DC-GFP is rendered inoperative. [per Robin Gudgel]
- NEC DC GFP system is unsafe to service while live. Either entire system needs to be shut down or manually Earth Grounded prior to service for safety.

Understanding of NEC DC GFP is not correct.

- Existing Single Pole PV Ganged OCPD is redundant. In only one specific failure (see Figure #2) where the "100 amp" OCPD Trip MAY stop PV Power to Earth Ground current flow.
- Existing 1 amp NEC DC GFP detection Breaker/Fuse is responsible for interrupting Ground Fault Current.
- Proposed two pole Solar Array Disconnect will only be a primary Earth Fault Disconnect in one very specific Earth Fault location (PV Array). Otherwise, 1 amp NEC DC GFP OCPD will be the primary or only device interrupting Earth Fault Current for any and all DC Power / PV Array Power to Earth Faults.
- Earth Faults from other sources (for example a Computer Logger with earth referenced Line Cross to Communications Interface) can "inject" >1 amp of Earth Fault current into NEC DC GFP system and cause Earth Fault which would disconnect PV Array.
- NEC DC GFP is not an Arc Fault Sensing Interrupt for PV Arrays. NEC DC GFP does not interrupt any Series Arc Faults. Midnite (and others?) currently have product with the ability to detect and SAFELY interrupt Series Arc Faults in Soalr Array Cabling.
- There are "redundant" circuit breakers in the PV Power input to solar charge controllers. One is ganged to the 1 amp pole. There is supposed to be a second breaker in series with the high current DC-GFP breaker so [the service personnel/end users] do not unground the system when turning off the array. … People are always using the DC-GFP breaker assembly as their PV disconnect. They see the second disconnect in series and do not understand why, so they do not put it in. [per Robin Gudgel] This lifts the Earth Ground from the DC Power System.

NEC DC GFP is not understood by UL/NRTL's either:

At this point in time, there appear to be several major holes in the NRTL Listing of product with respect to NEC DC GFP and the system implications (common mode voltage offsets, inversion of Positive/Negative Ground Reference, and uncontrolled (no OCPD in DC Return when pos/neg ground reference inverted).

It appears that NRTL inspections assume standard DC Ground that is "tied" to Earth Ground.

And that they do not look for non-isolated communications/monitoring/logging interfaces and what the implications of a single Earth Fault with the NEC DC GFP:

- UL or ETL does not test for this. They pretty much do not test the communications lines at all. They certainly would not test for high voltage on the bat neg or PV neg line. [per Robin Gudgel]

Warning Label is not very helpful:

And the required warning label is actually wrong as in normal operation the circuit conductors are Earth Referenced by the ~1 amp OCPD detector. Depending on present state of the NEC DC GFP, the conductors may be Earth Referenced (as designed), or inverted Earth Reference (colored are now Earth Referenced and White is energized upwards of 150 to 600 VDC depending on array), or may be floating/soft referenced.

And in some cases, (AC output earth faulted but still operating MSW Inverter as an example), there may be AC voltage/current present too.

And has very little information that would inform a service person or end user on how to proceed:

WARNING

ELECTRIC SHOCK HAZARD. THE DIRECT
CURRENT CIRCUIT CONDUCTORS OF THIS
PHOTOVOLTAIC POWER SYSTEM ARE
UNGROUNDED BUT MAY BE ENERGIZED
WITH RESPECT TO GROUND DUE TO
LEAKAGE PATHS AND/OR GROUND FAULTS.

Reason for Earth Fault Breaker/Fuse/Detection (via NEC DC GFP):

I do understand that this method of NEC DC GFP was created to solve a very real problem… If a PV Array Power Lead shorted to Earth Ground—This would not cause any OCPD to trip anywhere in a DC Power System not equipped with NEC DC GFP.

- Solar array is current mode device. Not enough current to cause OCPD to trip using “traditional” code for PV Power to Earth Fault.
- Any other method for detecting unbalanced current flow in DC circuits is difficult and expensive vs the simple current transformer used for AC ground fault protection.
- Present NEC DC GFP 1 amp OCPD can stop Earth Ground Fault current from PV (or any DC Power) by itself.
- Proposed NEC DC GFP 1 amp OCPD can stop current from PV Earth Fault protected by ganged two pole breaker. Other Earth Ground Fault currents will still only be interrupted by the ~1 Amp rated NEC DC GFP Earth Fault Detection OCPD.

Reasons for Arc Fault Detection/Protection (with Earth Bonded DC Return):

NEC DC GFP is not capable of the following:

- Series Arc Detection and Interrupt stops true Arcs.
- Series Arc Detection and Interrupt inhibits current flow in power (or load) circuit in Arc Fault.
- SADI is expandable beyond the core system. Lends it self very well to Branch circuitry monitoring and control. Applies to both Power Sources, Loads, and bi-directional devices (understand that Arc Fault is currently only required on PV Arrays > 80 Volts).
- Scalable beyond small systems and is not susceptible to scaled up normal leakage currents which would can false trip NEC DC GFP.
- SADI isolates subsystem where fault occurs.
- SADI is independent of current flow... Low or high current arcs are detected and interrupted
- SADI does not require shutting down entire DC Power System because of 1 fault to maintain safety (except for Grid Tied Inverters with single array inputs).
- SADI does not make DC Power System Unsafe with any defined single fault scenario.
- SADI can be added to new products and does not compromise safety with existing/grandfathered equipment and practices.
- SADI is flexible—Can be implemented with Standard OCPD hardware, or can be implemented in non-traditional ways (inhibiting switching power supplies in Solar Charge Controllers, AC Inverters, Battery Chargers, etc.).
- SADI is not disabled by single system faults (line to return, line to earth, and return to earth).
- SADI is not disabled by customers/end users who frequently jumper Battery Negative to Earth Ground [per Robin Gudgel].
- SADI protects entire series connected DC Power to DC Return path.

Appendix G (reference documentation and acknowledgements):

I wish to thank several companies here for their support of open communications by hosting public forums where technical discussions can be held regarding Renewable Energy systems.

The first here are the discussions regarding NEC DC GFP (that I am aware of). I started here as a poster and am currently a volunteer moderator in the Wind-Sun.com forum.

Hosted by Northern Arizona Wind & Sun, a Solar RE Retailer/Wholesaler.

September 2007: http://www.wind-sun.com/ForumVB/showthread.php?t=1298
February 2010*:* http://www.wind-sun.com/ForumVB/showthread.php?t=6918
March 2011: http://www.wind-sun.com/ForumVB/showthread.php?t=10650

The following discussion is hosted by Midnite Solar (Robin and Bob Gudgel Founders).

One of our posters from the Wind-Sun.com forum asked about NEC DC GFP and I suggested that he post his questions forum on Midnite Solar's forum as this was a question specifically about their recently released "Classic" MPPT Solar Charge Controller (Maximum Power Point Tracking).

March 2011: http://midnitesolar.com/smf_forum/index.php?topic=142.0

Bob Gudgel entered the discussion in the above link and he worked with me to understand my concerns with the dangers behind the NEC DC GFP implementation.

Poster "Kent0" also provided a nice drawing to document one of the fault conditions.

I would like to thank Ryan Stankevitz from Midnite solar. He (along with Tom Carpenter from Midnite Solar) helped by reviewing my initial and subsequent drafts/drawings.

Ryan also tested my several Earth Fault Scenarios (although he did not go so far as fusing the DC Return 14 AWG wire—that was a bit more than he wanted to demonstrate on his system).

And a big thank you to John Wiles for his PV NEC Suggested Practices document which helped me to understand the reasoning and implementation of the NEC DC GFP:

http://www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/PVnecSugPract.html

-Bill Baldwin 2011
San Mateo California