Ground Fault Detection in Solar Panel

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Abstract- *PV faults have caused rooftop fires in the United States, Europe, and elsewhere in the world. One prominent cause of past electrical fires was the ground fault detection "blind spot" in fuse-based protection systems discovered by the Solar America Board for Codes and Standards (Solar ABCs) steering committee in 2011. Unfortunately, while a number of alternatives to ground fault fuses have been identified, there has been limited adoption or historical use of these technologies in the U.S. Analytical and numerical SPICE simulations were conducted for a wide variety of ground faults and array configurations to understand the limitations of fuse-based ground fault protection in PV systems and determine proper trip settings for alternative GFPDs. Simulation results were compared with experimental measurements on arrays to validate the SPICE model as well as provide direction on proper thresholding of residual current detector (RCD), current sense monitor (CSM) and isolation monitor (Riso) devices based on historical fault current data. We argue the combination of simulation results with historical data indicates robust settings are possible for each of these technologies to minimize unwanted tripping events while maximizing PV fault detection.*

Keywords- photovoltaics, ground fault, SPICE, balance of systems, RCD, isolation resistance measurement, differential current measurement, photovoltaic leakage current

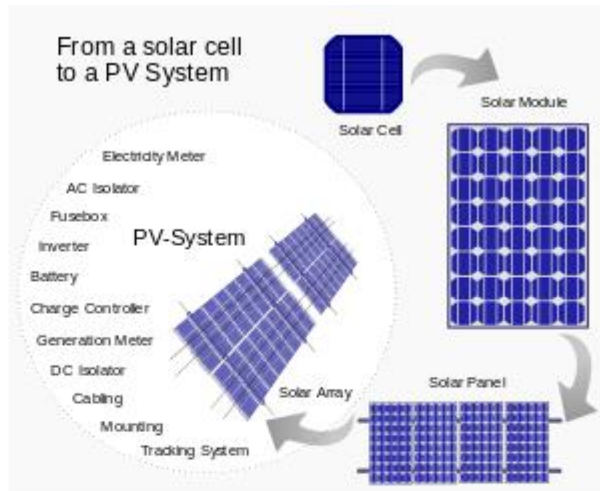
I. INTRODUCTION

The term **solar panel** is used colloquially for a photo-voltaic **(PV) module**.

A PV module is an assembly of photo-voltaic cells mounted in a frame work for installation. Photo-voltaic cells use sunlight as a source of energy and generate direct current electricity. A collection of PV modules is called a PV Panel, and a system of Panels is an Array. Arrays of a photovoltaic system supply solar electricity to electrical equipment.

The most common application of solar energy collection outside agriculture is solar water heating systems.

II. THEORY AND CONSTRUCTION



From a solar cell to a PV system

Photovoltaic modules use light energy (photons) from the Sun to generate electricity through the photovoltaic effect. Most modules use wafer-based crystalline silicon cells or thin-film cells. The structural (load carrying) member of a module can be either the top layer or the back layer. Cells must be protected from mechanical damage and moisture. Most modules are rigid, but semi-flexible ones based on thin-film cells are also available. The cells are connected electrically in series, one to another to a desired voltage, and then in parallel to increase amperage. The wattage of the module is the mathematical product of the voltage and the amperage of the module.

A PV junction box is attached to the back of the solar panel and functions as its output interface. External connections for most photovoltaic modules use MC4connectors to facilitate easy weatherproof connections to the rest of the system. A USB power interface can also be used.

Module electrical connections are made in series to achieve a desired output voltage or in parallel to provide a desired current capability (amperes) of the solar panel or the PV system. The conducting wires that take the current off the modules are sized according to the ampacity and may contain silver, copper or other non-magnetic conductive transition metals. Bypass diodes may be incorporated or used externally, in case of partial module shading, to maximize the output of module sections still illuminated.

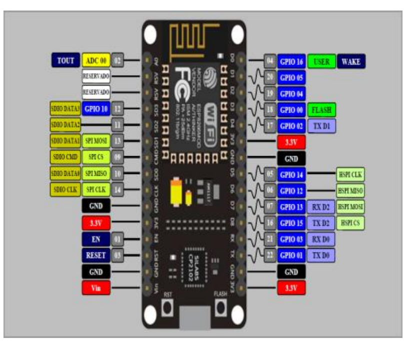
Some special solar PV modules include concentrators in which light is focused by lenses or mirrors onto smaller cells. This enables the use of cells with a high cost per unit area (such as galliumarsenide) in a cost-effective way.

Solar panels also use metal frames consisting of racking components, brackets, reflector shapes, and troughs to better support the panel structure.

Nodemcu

Introduction

General-purpose input/output (GPIO) is a pin on an IC (Integrated Circuit). It can be either input pin or output pin, whose behaviour can be controlled at the run time.



Where to use ESP8266-01

The **ESP8266** is a very user friendly and low cost device to provide internet connectivity to your projects. The module can work both as a Access point (can create hotspot) and as a station (can connect to Wi-Fi), hence it can easily fetch data and upload it to the internet making **Internet of Things** as easy as possible. It can also fetch data from internet using API's hence your project could access any information that is available in the internet, thus making it smarter. Another exciting feature of this module is that it can be programmed using the Arduino IDE which makes it a lot more user friendly. However this version of the module has only 2 GPIO pins (you can hack it to use upto 4) so you have to use it along with another microcontroller like Arduino, else you can look onto the more standalone **ESP-12** or **ESP-32** versions. So if you are looking for a **module to get started with IOT** or to provide internet connectivity to your project then this module is the right choice for you.

How to use the ESP8266 Module

There are so many methods and IDEs available to with ESP modules, but the most commonly used on is the Arduino IDE. So let us discuss only about that further below.The **ESP8266 module** works with 3.3V only, anything more than 3.7V would kill the module hence be cautions with your circuits. The best way to program an **ESP-01** is by using the FTDI board that supports 3.3V programming. If you don't have one it is recommended to buy one or for time being you can also use an Arduino board. One commonly problem that every one faces with ESP-01 is the powering up problem. The module is a bit power hungry while programming and hence you can power it with a 3.3V pin on Arduino or just use a potential divider. So it is important to make a small voltage regulator for 3.31v that could supply a minimum of 500mA. One recommended regulator is the LM317 which could handle the job easily. A **simplified circuit diagram for using the ESP8266-01 module** is given below

ESP8266 Development Platforms

Now, let's move on to the interesting stuff!

There are a variety of development platforms that can be equipped to program the ESP8266. You can go with Espruino – JavaScript SDK and firmware closely emulating Node.js, or use Mongoose OS – An operating system for IoT devices (recommended platform by Espress if Systems and Google Cloud IoT) or use a software development kit (SDK) provided by Espress if or one of the platforms listed on WiKiPedia.

Fortunately, the amazing ESP8266 community took the IDE selection a step further by creating an Arduino add-on. If you're just getting started programming the ESP8266, this is the environment we recommend beginning with, and the one we'll document in this tutorial.

This ESP8266 add-on for Arduino is based on the amazing work by Ivan Grokhot kov and the rest of the

ESP8266 community. Check out the ESP8266 Arduino GitHub repository for more information.

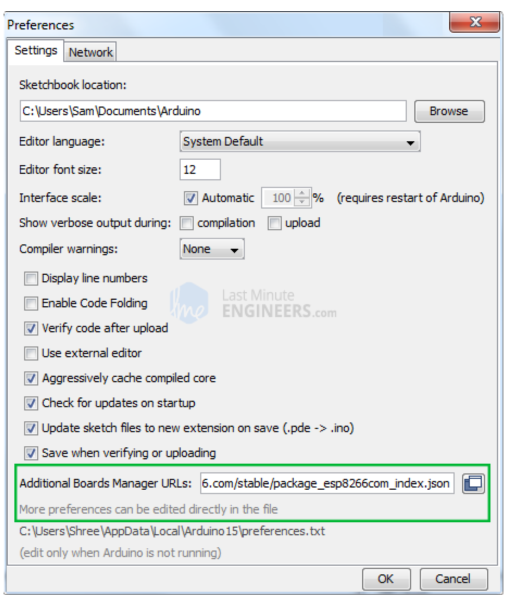
Installing the ESP8266 Core on Windows OS

Let’s proceed with installing ESP8266 Arduino core.The first thing is having latest Arduino IDE (Arduino 1.6.4 or higher) installed on your PC. If don’t have it, we recommend upgrading now.

Latest Arduino IDE

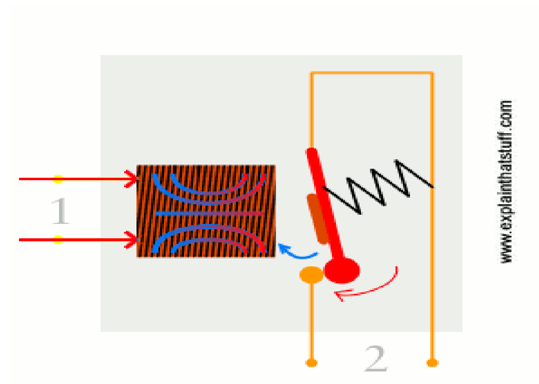
To begin, we’ll need to update the board manager with a custom URL. Open up Arduino IDE and go to File > Preferences. Then, copy below URL into the Additional Board Manager URLs text box situated on the bottom of the window: http//arduino.esp8266.com/stable/package_esp8266com_index .json

Hit OK. Then navigate to the Board Manager by going to Tools > Boards > Boards Manager. There should be a couple new entries in addition to the standard Arduino boards. Filter your search by typing esp8266. Click on that entry and select Install.



RELAYS

you might not realize it, but you're constantly on-guard, watching out for threats, ready to act at a moment's notice. Millions of years of evolution have primed your brain to save your skin when the slightest danger threatens your existence. If you're using a power tool, for example, and a tiny wood chip flies toward your eye, one of your eyelashes will send a signal to your brain that make your eyelids clamp shut in a flash—fast enough to protect your eyesight. What's happening here is that a tiny stimulus is provoking a much bigger and more useful response. You can find the same trick at work in all kinds of machines and electrical appliances, where sensors are ready to switch things on or off in a fraction of a second using clever magnetic switches called **relays**. Let's take a closer look at how they work!



What are relays?

A relay is an electromagnetic switch operated by a relatively small electric current that can turn on or off a much larger electric current. The heart of a relay is an electromagnet (a coil of wire that becomes a temporary magnet when electricity flows through it). You can think of a relay as a kind of electric lever: switch it on with a tiny current and it switches on ("leverages") another appliance using a much bigger current. Why is that useful? As the name suggests, many sensors are incredibly sensitive pieces of electronic equipment and produce only small electric currents. But often we need them to drive bigger pieces of apparatus that use bigger currents. Relays bridge the gap, making it possible for small currents to activate larger ones. That means relays can work either as switches (turning things on and off) or as amplifiers (converting small currents into larger ones).

How relays work

Here are two simple animations illustrating how relays use one circuit to switch on a second circuit.

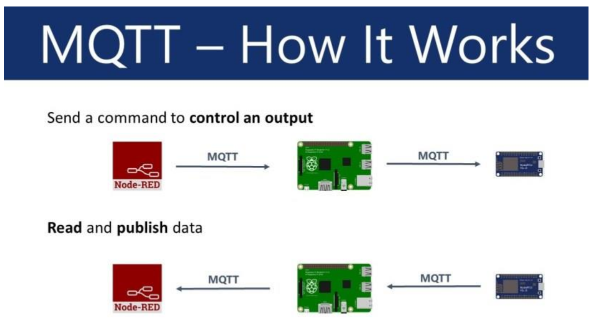
When power flows through the first circuit (1), it activates the electromagnet (brown), generating a magnetic field (blue) that attracts a contact (red) and activates the second circuit

- Differential protection relays: These trigger when there are current or voltage imbalances in two different parts of a circuit.
- Frequency protection relays (sometimes called under frequency and over frequency relays): These solid-

state devices trigger when the frequency of an alternating current is too high, too low, or both.

- What is MQTT and How It Works

In this article, we're going to introduce you to the MQTT protocol. MQTT stands for **M**essage **Q**ueuing **T**elemetry **T**ransport.



It is a lightweight publish and subscribe system where you can publish and receive messages as a client.

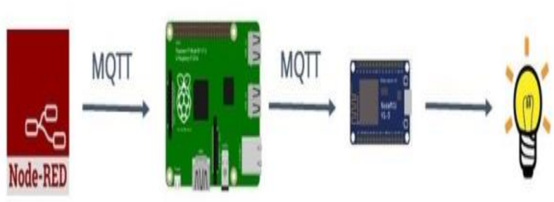
MQTT is a simple messaging protocol, designed for constrained devices with low-bandwidth. So, it's the perfect solution for Internet of Things applications. MQTT allows you to send commands to control outputs, read and publish data from sensor nodes and much more.

Therefore, it makes it really easy to establish a communication between multiple devices.

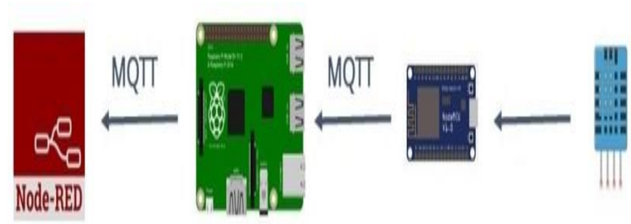
High Level Overview

Here's a quick high level overview of what MQTT allows you to do.

You can **send** a **command** with a client (likeNode-RED an **output**:



Or you can **read data** from a **sensor** and **publish** it to a client



In MQTT there are a few basic concepts that you need to understand:

- Publish/Subscribe
- Messages
- Topics
- Broker

MQTT – Publish/Subscribe

The first concept is the publish and subscribe system. In a publish and subscribe system, a device can publish a message on a topic, or it can be subscribed to a particular topic to receive messages

- For example **Device 1** publishes on a topic.
- **Device 2** is subscribed to the same topic as **device 1** is publishing in.
- So, **device 2** receives the message.

MQTT – Messages

Messages are the information that you want to exchange between your devices. Whether it's a command or data.

III. BLOCK DIAGRAM

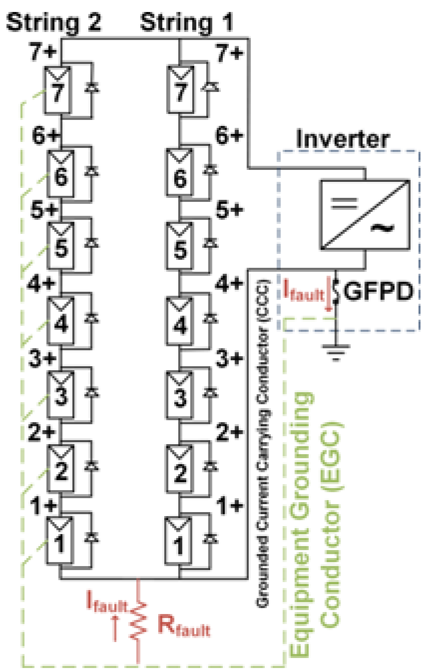


Fig. 1. Schematic for a DC-grounded PV array with two strings and a GFDI. The path of a ground fault on the negative current carrying conductor is denoted in red.

fuses and fault resistances of 0.1 and 1 □. Simulations with a 1 A (0.252 □), 2 A (0.125 □), and 5 A (0.0363 □) are shown as red, purple, and orange points, respectively. Triangles indicateafaultresistanceof0.1□whilecirclesrepresenta1□ resistance. Solid lines at 1, 2, and 5 A denote the fuse ratings with color corresponding to the fuse trip point. The GFPD current calculated by (8) is denoted by a dashed line for each set of fuse and fault resistances.

The GFPD current is linear with number of strings for all fuse ratings and fault resistances. For all arrays up to 201 strings, only the 1 A and 2 A GFPDs (at fault resistance of0.1□□ allow enough GFPD current to trip the fuse (shaded regions denote where I_{GFPD}>I_{trip}) The 1 A GFPD only detects the ground fault in arrays larger than 56 strings while the 2 A GFPD detects faults in arrays larger than 124 strings. The orange traces do not reach 5 A even for 201 strings, so a 5 A GFPD would never trip for a blind spot ground fault.

It is tempting to believe that decreasing the fuse rating will increase the number of detectable blind spot faults. However, the decrease in trip point is more than offset by the increased GFPD resistance, so fuses with low ratings will detect fewer faults to the grounded CCC. Fig. 11 shows the simulations results for 0.1 (green), 0.25 (purple), and 0.5 A (blue) GFPD fuse ratings at R_{fault} of 0.1 and 1 □. In each case, due to the increase in fuse resistance, the GFPD current is far too small to trip thefuses.

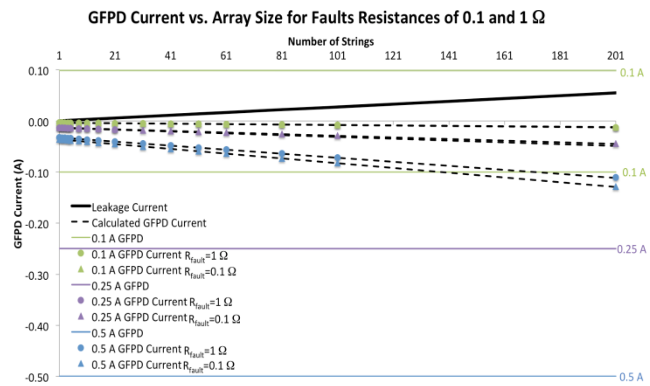


Fig. 11. Graph of GFPD current vs. array size for various GFPD and fault resistances.

The color of the line indicates GFPD resistance. Green traces denote 0.1 A (85.5 □), while purple and blue traces denote 0.25 A (22 □), and 0.5 A (8.16 □), respectively. Even though the fuses have low trip points, due to the increased fuse resistance, the GFPD current is below the fuse trip point and the blind spot window is increased.

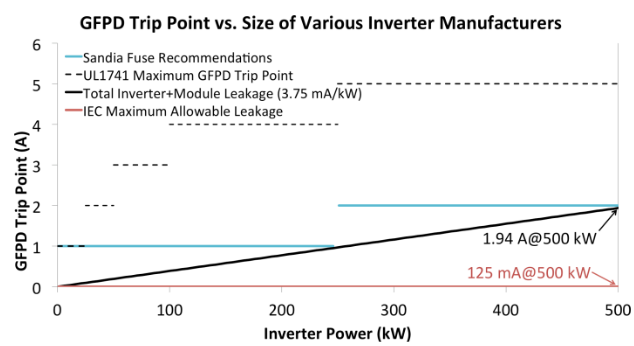


Fig. 12. Graph of GFPD current vs. array size for various GFPD and fault resistances. The color of the line indicates GFPD resistance.

As decreasing the fuse size is not an appropriate solution to the ground fault blind spot, other GFPD devices are necessary. The remainder of this paper offers suggestions for two alternative ground fault detection techniques with trip points validated with experimental results.

RESIDUAL CURRENT DETECTION/ CURRENTSENSE MONITORING

RCDs and CSMs are combined in this section because both operate on the principle of detection of stray current flows in the presence of a fault condition, and the current magnitude will be the same for either technology. CSMs operate by monitoring (via a current transformer) the current flow through the ground bond. Excessive current flow through the ground bond (greater than array and BOS component leakage) is assumed to be caused by a ground fault and, if the measured current is above a pre-set threshold, the CSM trips. RCDs operate by monitoring the differential current flow in the positive and negative CCCs–often inside the inverter. Current imbalance between the two CCCs above a preset threshold is assumed to be caused by a ground fault and trips the RCD. In non-AC-isolated systems with transformer less inverters, the fault current is fed from the AC side of the system as well, so the RCD can be installed on the AC side of the inverter. Fig. 14 shows a circuit schematic detailing the different installation positions of RCD and CSM devices.

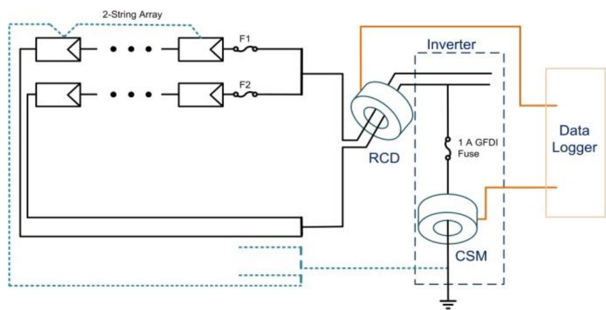


Fig. 14. RCD vs. CSM measurements on a PV array.

For both RCD and CSM, the trip threshold is freely selectable and, in either configuration, does not modify the conductive pathway being monitored. Rather, both solutions inductively measure current in the monitored pathway. This approach maintains the inverter certification listing even after retrofit by ensuring that the manufacturer's factory installed ground fault protection system functions exactly as originally evaluated by a NRTL.

The types of detectable ground faults for these solutions depend on the threshold used to define the presence of a fault. If this trip threshold is too low, there will be nuisance trip events resulting from module and BOS component leakage currents; but if the threshold is too high, higher impedance ground faults will go undetected. Both RCD and CSM methods could register array leakage as a type of fault, therefore, the generalized detection threshold must be set above the maximum leakage current in all unfaulted operating conditions (meteorological, topological, and electrical).

Test Case #1

To understand the influence of the meteorological conditions on RCD measurements, Sandia National Labs worked with a large, utility-scale PV operator to collect the system leakage values from 340 500 kW co-located inverters in a desert environment[24].

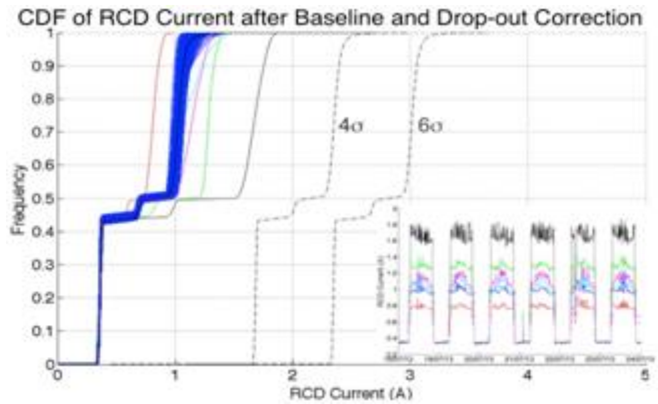


Fig. 13. CDFs corrected for baseline and data dropouts. Most of the CDFs are clustered together with a few outlier inverters with higher or lower leakages (shown in inset). Assuming a normal distribution, the +4□ and +6□ limits of the average CDF are shown as black dashedlines.

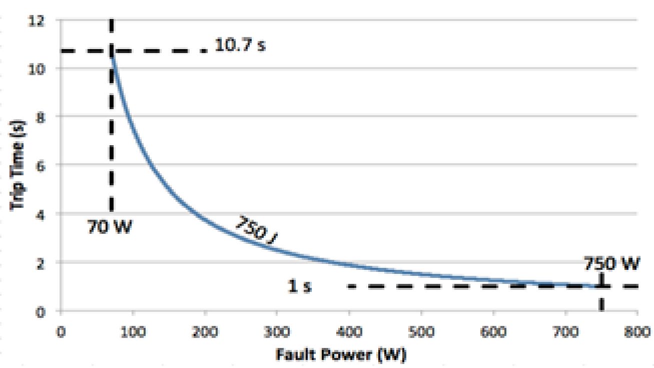
Test Case #1 Experimental

The RCD system leakages for each inverter were measured at one-minute intervals for over a year (1 January 2013 to 3 August 2014). In compliance with UL 1741, each inverter has a GFPD fuse rated at 5 A to protect against ground faults.This conservative threshold was chosen to maximize the detection of ground faults while eliminating unwanted tripping events due to electromagnetic interference (EMI), module/inverter leakage, and meteorological events (*i.e.* lightning).

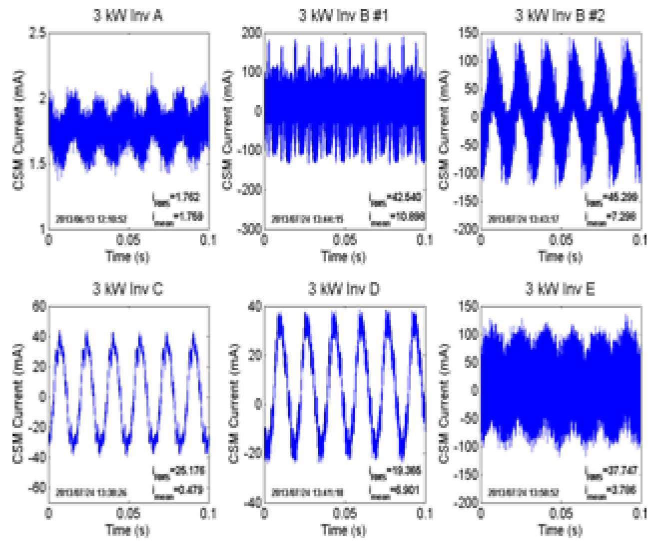
Test Case #1 Results

Fig. 13 shows the cumulative distribution functions (CDFs), corrected for baseline deviations and data dropouts of all 340 RCDs for the time period of data collection [24]. For a given CDF curve, a shift to the right indicates higher leakages in the inverter, possibly due to an incorrect baseline value or a high impedance ground fault. If the effect of data reliability is corrected (which could be done via simple, on-board programming), such as baselining the inverter leakage each night when the inverter is disconnected and eliminating repeated data due to dropouts, the CDFs of all 340 inverters are tightly distributed. All but five of the 340 inverters (colored in blue in Fig. 13) lie within a range of 1.14–1.51 A 99.99% of the time. The five inverters that act as outliers (CDFs are colors other than blue) demonstrate either higher or lower leakage values than the average (blue). TheRCD values over a six-day period of these outlier inverters along with a "typical inverter" (blue) are shown in the inset. The inverters corresponding to the magenta, green, and black curves show higher measured leakage values during the day while the red curve corresponds to a lower measured leakage value. It should be noted that, although the baseline (nighttime) value for each inverter is the same, the turn- off/turn-on values scale with the daytime leakage of the inverter, indicating that the increased or decreased RCD current may be due to a proportionality (gain) problem in the RCD rather than an actual increase of leakage in the inverter.

The 4σ and 6σ confidence bands of the average CDF of all the inverters (both "normal" and the five outlier inverters) is shown as dashed black lines in Fig. 13. Note that these curves represent RCD values that are exceedingly rare given the data population: $Pr(x \geq \mu+4\sigma) = 0.00317\%$ and $Pr(x \geq \mu+6\sigma) = 9.87\cdot10^{-8}\%$. These statistical metrics can be used to establish thresholding rules based on the requirements of the inverter manufacturer, O&M company, plant owner, or standards- making panel. For example, there is a 4σ confidence that 99.999% of measured leakage values are below 3.1994 A and a 6σ confidence that 99.999% of the RCD values are below 3.8616 A (Table I). A set point of without tripping the unit. After identifying excessive noise on the ground bond as the cause of unwanted trips at one site, the EPC resolved the problem by using a shielded CT in place of the standard version. We attribute the remaining unwanted trip events to disturbances on the AC grid and one faulty CSM CT.



To accurately set a proper threshold, the subsecond noise characteristics over the entire normal operating regime should be recorded using an oscilloscope and voltage/current probes. The maximum leakage, plus a margin (*e.g.* 50%) should be added to (10) to set an optimal threshold. For example, for inverter D in Fig. 16, the trip time curve shown in Fig. 18 should be shifted to the right by 60 mA (40 mA for noise plus 20 mA as margin). Due to the variability from unit-to-unit, this should be done to determine the correct trip point for everyunit.



ISOLATION MONITORING

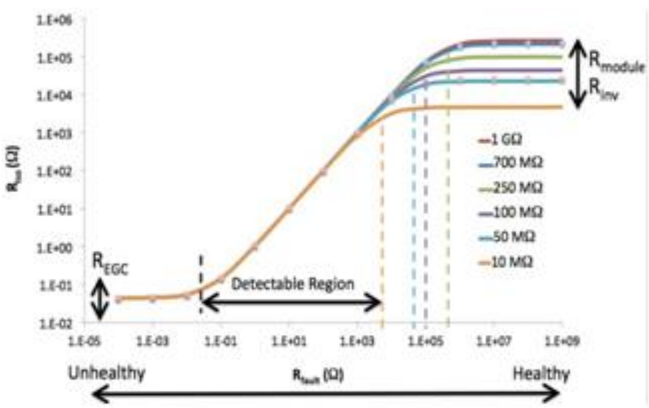
R_{iso} measurements are carried out on ungrounded systems (or grounded systems which are temporary disconnected from earth ground) by injection of a voltage pulse into one of the two CCCs (the non-pulsed CCC is left floating) of the PV system by an external power source. Neglecting array capacitance and noise sources, the ground isolation can then be calculated from the current draw on the power source, represented in (11). If the isolation is measured to be below a certain threshold, the isolation monitor trips.

From IEC 60364-4-42 [26], the maximum power that can dissipated safely through an enduring fault without risk of a fire is 70 W instantaneous power or an equivalent energy of 750 J. A maximum allowable energy value of 750 J makes it possible to formulate a trip time vs. fault power curve for any PV system, as shown in Fig. 17. Assuming a worse case, where the array is at V_{oc} and supplying all the current through the fault (which is impossible in practice, but does give an added safety factor), then the trip-time curve for a current sensing device (*i.e.* CSM or RCD) would be describedby:Thisprocessiscarriedoutwithbothpositiveandnegat ivepolarity pulses on one or both CCCs. The pulse polarity and CCC choice does not affect the measurement of the fault as long as there is sufficient illumination to forward bias the module photodiodes. In low illumination conditions, the pulse will travel through the bypass diodes. One pulse polarity will pass through the bypass diodes and measure the fault, as long as the pulse magnitude ($V_{applied}$) is large enough to overcome the voltage drop of the multiple bypass diodes in the array. The opposite pulse polarity will be blocked by the bypass diodes, possibly leading to anomalous R_{iso} readings, if this is not considered. The parasitic resistance of the bypass diodes will add slight position dependence in low-light conditions.

R_{iso} measurements are heavily influenced by the capacitance of the PV modules to ground. This means that, especially for larger arrays, the time period of measurement can be long and R_{iso} is not an appropriate method to quickly measure and prevent dangerous high-current faults from causing fires. However, when used with an additional detection device (*i.e.* fuse, CSM, or RCD), which operate on small time-scales, R_{iso} is effective at finding the existence of latent faults during a 'morning check' before the inverter begins to export power.

The detectable fault region of R_{iso} measurements depends on the threshold used to define the presence of a fault. Ideal detection thresholding maximizes the balance between system safety and uptime, and is essential to the performance and reliability of the PV array and the safety of those around the system.

Numerical Model



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