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Photovoltaic ground fault detection recommendations for array safety and operation

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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 (R_{iso}) 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.

1. Introduction

A PV array ground fault is an electrical pathway between one or more array conductors and earth ground. Such faults are usually the result of mechanical (Wills et al., 2014), electrical, or chemical degradation of photovoltaic (PV) components, or mistakes made during installation. Fault types are defined by the location in the array and the impedance of the fault and can vary widely in the severity of their impact on array operations depending on these two factors. In order to protect the array during a ground fault event, a ground fault protection device (GFPD) is used to detect ground fault currents (Wiles, 2012). If the GFPD or another device also interrupts the fault current, the protection system is called a Ground Fault Detector/Interrupter (GFDI). The 2014 National Electrical Code (NEC) 690.5 specifies ground-fault protection requirements for grounded direct current (DC) photovoltaic arrays while NEC 690.35 defines the requirements for ungrounded systems (National Fire Protection Association, 2014). Both of these sections requiring ground faults are detected and their presence is indicated.

Recently, a detection limitation, or "blind spot", in traditional fuse-based ground fault protection systems was identified for DC-grounded, AC-isolated PV systems that are most common in the United States (Brooks, 2011a,b). The historical fire events presented in Brooks (2011a,b) have highlighted the incomplete protection provided by ground fault fuses in grounded arrays in the United States. Fortunately, in ungrounded, non-isolated, and hybrid systems, the ground fault blind spot does not exist (Ball et al., 2013).

Historically, the ground-fault detection blind spot has caused multiple latent ground faults, in which a fault persisted for an extended period of time undetected, and ultimately resulted in a PV fire (Brooks, 2011a,b). Latent ground faults can either be grounded conductor-to-ground faults (Fig. 1) or high-impedance ground faults on ungrounded conductors. The initial ground fault is generally not a fire hazard, but will remain latent because the fault current is too low to trip the inverter's GFPD fuse. At this point, the equipment grounding conductor (EGC) is energized and could represent a shock hazard resulting in injury, but does not possess enough current to cause a fire. However, if a second ground fault occurs in the array, fault current, which may be large, will bypass the interrupting device and the ground-fault protection system will not function as intended to prevent a fire. Fig. 2 shows the damage caused by the ground fault detection blind spot when two ground faults occur. Field experiments have further confirmed the existence of the ground fault detection blind spot (Ball et al., 2013).

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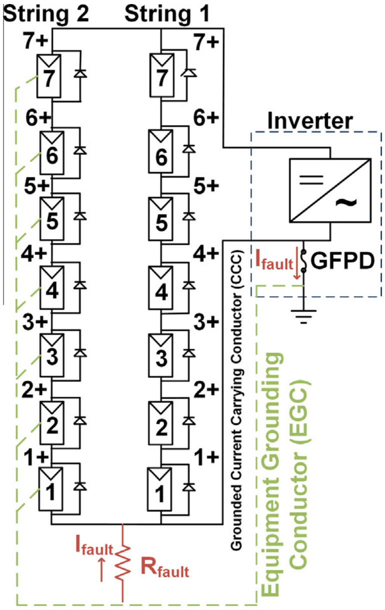

Fig. 1. Schematic for a DC-grounded PV array with two strings and a GFDI. The path of a ground fault on the negative current carrying conductor is denoted in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

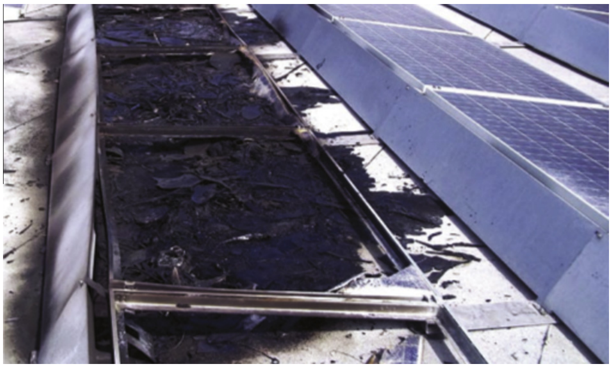

Fig. 2. A blind spot in a listed inverter's fuse-based ground-fault protection scheme resulted in this fire damage.

This paper summarizes a three-year research program at Sandia National Laboratories to improve PV ground fault fire protection in the United States and presents suggested changes to national and international standards for four ground fault technologies. Specifically, we investigated the risk of ground faults in systems with different ground fault protection schemes and present recommendations for trip thresholds for fuse-based GFPD systems and three technologies that have not been regularly used in the United States, but were recommended by the Solar ABCs steering committee (Ball et al., 2013) for inclusion in future PV systems:

1. Replacing the rated fuse with a lower rating
2. Isolation monitoring (R_{iso})
3. Residual current detection (RCD)
4. Current sense monitoring/relay (CSM/R).

Using numerical SPICE and analytical models as well as historical data from the field, each of these methods is discussed along with the basis for proper thresholding below. The thresholds were selected carefully to minimize the risk of unwanted tripping while maintaining the largest sensitivity for ground fault detection—*i.e.*, protecting against the largest range of fault impedances and locations.

In Section 2, a numerical SPICE simulation tool for faults on PV arrays is introduced and validated with real PV ground faults. This SPICE tool is used to calculate ground fault currents through GFPD fuses as well as demonstrate that reduction of GFPD size does not eliminate the ground fault detection blind spot. Section 3 presents historical data of RCD and CSM measurements for a variety of utility and residential scale systems. These results are used to determine appropriate trip thresholds. In Section 4, an analytical basis for R_{iso} measurements is presented. This basis is then used to define the appropriate R_{iso} trip threshold as a function of array size to balance safety with unwanted tripping events. In this work, a combination of historical data, analytical analysis, and simulations shows that not all ground faults can be effectively detected; however, trip thresholds are developed that maximize the detection window for each detector type.

2. Fuse-based GFPD

The majority of the PV installations in the United States are DC-grounded systems with GFPD fuses. When a ground fault occurs in the system, the fault current travels through the fuse and trips it, if the current magnitude is large enough. In this section, we discuss the challenge of using this technology for certain ground faults and recommend new fuse ratings to improve the number of detectable ground faults.

From a GFPD fuse detection standpoint, the worst-case is when the fault location is on the grounded current carrying conductor (CCC), so this case is studied in detail below. In general, due to the non-linear nature of PV modules, the fault current for a fault located somewhere mid-string does not have a non-transcendental solution. However, when the fault exists at either of the CCCs, the fault acts as a current divider and an analytical solution is possible. In the following section, the fault current for a fault located at the grounded CCC (a blind spot fault scenario) is briefly presented (a full derivation is described at length in Flicker and Johnson (2013a,b,c)). This analytical solution is corroborated by the validated SPICE simulations described earlier and used to determine the efficacy of replacing the listed fuse rating with a more sensitive type in order to close the ground fault blind spot.

2.1. Analytical model of system with fuse-based GFPD

To model current flow during a ground fault, the internal resistances of the conductors and the GFPD must be included because the current division between the fault path and the intended conduction path is heavily dependent on small internal resistances of the conductors.

Underwriters Laboratories 1741 Ed. 2 (2010) mandates the maximum sizing of these protection devices based on the array size (Underwriters Laboratories 1741, 2010). It is possible to install a lower rated fuse than mandated by UL 1741, though retrofitting fielded systems by replacing the fuse may invalidate the nationally recognized testing laboratory (NRTL) listing. In the ideal case, fuse ratings could be decreased freely without affecting the GFPD current; however, in reality, the fuse impedance depends on fuse ampere rating and thus affects the fault current. Fig. 3 shows a graph of fuse resistance vs. fuse rating for a number of 10×38 mm style fuses from multiple manufacturers.

The resistance of the fuse is inversely related to the fuse rating, so fuses with low trip ratings can have significant resistances. For example, the 0.1 A LittelFuse KLKD fuse has a resistance of 85.5 Ω (Fig. 3). Such large resistances have significant effects on