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PV module degradation analysis and impact on settings of overcurrent protection devices

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ABSTRACT

Degradation of photovoltaic (PV) modules is inevitable regardless of the size of a PV plant. While it is understood that degradation leads to a reduction in power generation, the effects of module degradation on PV plant protection system remains somewhat unclear. Considering that most of the PV plant protection system settings are based on modules in good conditions without degradation, it is imperative to evaluate the effect of module degradation on fault detectability by conventional protection infrastructure to ensure safety and reliability of PV plants. The purpose of this paper is to investigate the relationship between the levels of module degradation and PV plant faults including fault current levels, fault locations and types of faults. An experimental setup comprising of 16 modules of varying degradation levels is used to generate multiple short circuit fault scenarios. The results indicate that degradation results in a decrease in string current, which may lead to an increased likelihood of fault undetectability using conventional protection settings.

1. Introduction

In recent years, there has been remarkably rapid growth in large-scale solar photovoltaic (PV) power plant installations around the world. Most of these installations are of multi-MW capacities, ratings and consequently, comprise of thousands of modules spread over hectares of land. Monitoring this large number of modules individually is cumbersome, costly and often impractical. Investigations have shown that the PV modules may suffer premature degradation due to several factors such as long outdoor operation, lack of maintenance, enclosure problems, thermal cycling, grounding problems and corrosive environments (Munoz et al., 2011; Djordjevic et al., 2014). The phenomenon of module degradation is inevitable in any PV system. A study performed by NREL indicates that module degradation rates can be as high as 4% per year while the average degradation rate is estimated to be a 0.8% per year reduction in power output (Jordan and Kurtz, 2013). However, these degradation rates can vary substantially from string to string and module to module even within the same array. Besides reduction in solar power generation, the overall effect of the presence of a degraded module in a string and associated fault detection must be carefully understood.

The phenomenon of degradation becomes particularly important when it is associated with faults. These faults are inevitable in any PV system, but their detection is based on certain settings of protection devices. The main purpose of PV system protection devices is to protect against overcurrent and grounding faults. In particular to prevent catastrophic failure, possible fire and protect modules from degradation. Commonly used overcurrent protection devices (OCPD) and ground fault protection devices (GFPD) include fuses and circuit breakers that are generally used for each individual string in PV systems (Calais et al., 2008). The Australian Standard AS/NZS5033 Installation of PV arrays (Standards Australia, 2014) recommends fuses to protect both PV modules and cabling in the case of fault occurrence. Furthermore, to select a protection device setting, (Haeberlin, 2007) recommends that a single OCPD (fuse) rating for a string should be between 1.4 and 2.4 times the short circuit current (I_{sc}) (Standards Australia, 2014). These settings are based on ideal PV module ratings (without degradation) and do not take into account variations in current levels after modules undergo a certain level of degradation.

PV degradation is the gradual deterioration of module component characteristics which may affect its ability to operate within the limits of acceptable performance (Ndiaye et al., 2013). A degraded PV module can do its primary function of generating electricity from sunlight, but with a lower power output. However, the degraded state of the module can be more problematic when it exceeds a critical threshold of degradation (Charki et al., 2012). The degradation of a PV module can be classified into their signs, mechanisms, and types. The PV module performance can be degraded due to several factors such as temperature, humidity, ultraviolet (UV) exposure and mechanical damage (Suleske et al., 2011; Osterwald et al., 2002; Dhoke and Mengede, 2016;

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Munoz et al., 2011). Each of these factors may generate one or more types of module degradation such as discoloration, delamination, corrosion, and breaking or cracking of cells (Munoz et al., 2011; Jordan et al., 2012). These types of PV degradation, particularly deterioration of packaging material, loss of adhesion, bad interconnects between cell and modules, degradation due to moisture intrusion, degradation of semiconductor device, cracked cells and hot spot formation (Dyk and Meyer, 2000), lead to a decrease in the shunt resistance (R_{sh}) or an increase in series resistance (R_s) (Macabebe and Van Dyk, 2008; Meyer and Dyk, 2004). As a result of this variation in resistance, once modules undergo degradation, their associated current levels are expected to deviate. The associated lowering in fault current levels can lead to the non-detection of severe faults for prolonged durations as *hidden* faults. In such situations, degradation may render the original protection settings inadequate, resulting in undetectability of a fault leading to rapid and cascaded failures of modules in strings (Flicker and Johnson, 2013). Therefore, it is essential to analyze and understand the relationship between degradation and expected fault current levels to ensure that degradation will not accelerate the module failures due to faults remaining hidden.

The limitation of existing protection devices to efficiently detect faults in PV systems is identified in literature. The non-detection can range from infrequent but severe catastrophic faults such as ground faults, line-line faults and arc faults (e.g. (Alam et al., 2015)) to frequent but incipient hidden faults (see e.g. (Zhao et al., 2013)). Furthermore, low irradiance levels can substantially contribute to reduction in fault current levels and keep faults hidden (Zhao et al., 2011). Besides fault detection, the fault location can be challenging as the faults can occur in PV modules, junction boxes, combiner boxes, PV module wiring and PV string all of which can result in overcurrent within a PV array (Hariharan et al., 2016). The protection threshold settings of existing overcurrent protection devices are defined in terms of good modules. Nevertheless, all modules undergo some level of degradation over time. It is understood that as the modules undergo degradation, the current production drops. Therefore, there has to be a corresponding drop in fault current levels even in ideal irradiance conditions. Faults in PV systems with significant degradation levels can be a major problem because, if degradation contributes to non-detection of faults then this may lead to further accelerated degradation of degraded modules. This is because the degraded modules can be forced into reverse bias and dissipate power or force a bypass diode to engage with the loss of the entire module's power (Laukamp et al., 2013). PV cells in a module can dissipate power during reverse current flow which represents a danger of hot spot heating (see Fig. 1(a)).

The purpose of this paper is to gain insight into the relationship between degradation levels and magnitudes of line-line faults and string currents. Many large-scale PV systems are susceptible to line-line faults because string cables are usually grouped together and passed through the backside of module mountings into raceways as shown in Fig. 1(b). These cables are grouped together and if exposed to physical damage may get short circuited and create line-line faults. This research discovers that line-line (intra-string and cross-string) faults with a degraded module in a string generate significantly lower string current which may not be detected by a protection device connected at the end of the string. An experimental setup of sixteen PV modules with different degradation levels and monitoring devices is developed to create and analyze different line-line faults.

The rest of this paper is organized as follows. Section 2 describes the fundamental background of PV systems, particularly on the PV array (DC side). Section 3 gives an in-depth degradation analysis and evaluation of module degradation factor. Section 4 studies the degradation impact on different fault scenarios. Section 5 provides the results of the different fault experiments followed by discussion. Finally, the main conclusions are summarized in Section 6.

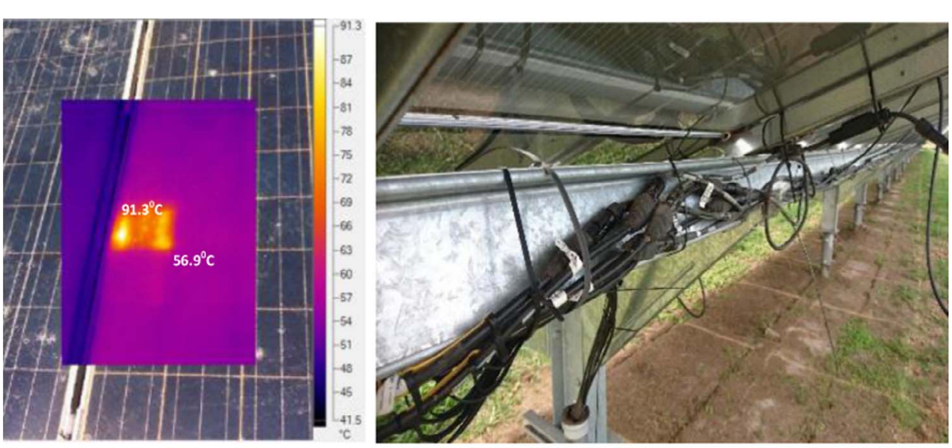
2. PV system description

2.1. PV system configurations

PV is a modular and scalable technology that can be built and extended incrementally. Fig. 2 shows a typical configuration including PV modules, a combiner box, protection devices and an inverter. The protection devices included in Fig. 2 are an OCPD, a GFPD and a surge arrestor. This choice is consistent with The University of Queensland's (UQ) existing Aurora inverter based PV systems. PV arrays can be arranged in a variety of series and/or parallel combinations to match the desired voltage and current specifications. As shown in Fig. 2, a number of PV modules can be connected in series to build a string, and the connection of multiple strings results in an array. In small-scale PV plants, strings are usually connected directly to inverters. On the other hand, in large-scale systems, the strings are connected to inverters through a combiner box. For example, at UQ Gatton 3.26 MW Solar Farm, each inverter is connected to 480 strings and each string comprises 15 PV modules. Consequently, it can be extremely difficult to detect any malfunction in any string/module in large-scale systems and once detected it can be extremely difficult to precisely locate and identify the fault. Protection devices such as overcurrent and grounding are essential in PV systems to protect PV modules and components from failure or fire hazards.

2.2. PV system protection devices

According to AS/NZS 5033 (Standards Australia, 2014), two types of protection devices are recommended in PV systems, namely,



(a) (b)

Fig. 1. Hotspot on a PV module captured by thermal camera showing different temperatures in same module due to degradation (a), Grouped string cables at backside of PV modules in large scale PV plant (b).