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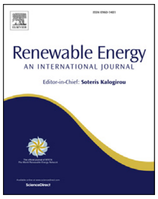

A comparative investigation on in-situ and laboratory standard test of the potential induced degradation of crystalline silicon photovoltaic modules

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ABSTRACT

Potential induced degradation (PID) is one of the genuinely critical concerns of a sustainable power generation from a PV system. Generally, the PID behavior of a PV module is tested in the laboratory according to the IEC standard before installation into a plant. On the other hand, an electroluminescence imaging is a reliable technique to identify the different types of PV cell defects which cause the degradation of the PV modules. The aim of this research is to investigate the PID behavior of similar PV modules in both the real on-site test and the laboratory standard test conditions. This will facilitate the outcome of the tangible indoor PID test results with more ease and reliability. It has been observed from the EL images of the on-site degraded PV module that a performance degradation happens due to different types of PV cell defects, such as, localized shunting, cracks, front contact grid interruptions, etc. The maximum power versus EL mean intensity shows a linear relationship which predicts the quantitative performance analysis of a PV module from an EL imaging process. The PID of a PV module has been found in a negative voltage stress condition in both the on-site and the laboratory tests. The shunt resistance gradually decreases as a consequence of the negative voltage stress only. The on-site degradation levels of the $P_{\max}$, V_{oc}, $I_{sc,}$ and FF are 46.5, 7.15, 30.4, and 17.35% respectively after a duration of nearly 11 years of a negative voltage stress generated from a 240 V string size. In a laboratory PID test, the $P_{\max}$, V_{oc}, $I_{sc,}$ and FF are degraded due to a negative voltage stress with a value of 6.83%, 1.9%, 1.5%, and 3.5% respectively.

1. Introduction

Energy harvesting from natural resources has an ever growing role in the global energy supply, an important aspect of which is the development of a system with a conductively low environmental negligible contagion and in this aspect, photovoltaic (PV) solar system is one of the most promising systems ever devised due to its low environmental impact [1]. The number and size of the PV plants are in increasing trend by virtue of the favourable PV module price since last decade [2]. With the increase of the PV plant capacity, the number of solar panels connected in series has to be accordingly increased in order to mobilize a higher system voltage which, incidentally, has numerous advantages, such as, firstly, it gives a lower loss of yield and produces an efficient power transmission, reducing the balance of system (BOS), installation and maintenance cost [3]. This system voltage has been gradually increased from 600 V to 1000 V and recently the system voltage has reached as high as 1500 V between the two terminals of a string [3]. In order to make the PV technology a cost-effective entity, the durability and reliability of PV power plants with a constant generation of electricity for a long lifespan (over 20–25 years) are crucial aspects which need vigorous researches for further improvement [4]. Researchers, manufacturers, and investors are now focusing their attentions on the reliability and sustainability issues of the PV module, in one way or another. An early degradation of the PV module in a PV power plant is due to the voltage stress generated from a large string size known as a potentially induced degradation (PID) which creates a very high concern and a

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Abbreviation

EL	Electroluminescence
EVA	Ethylene vinyl acetate
G	Incident irradiation (W/m^2)
$\hat{I}_{LC}$	Normalized wet leakage current
$I_{LC\_After\_PID}$	Wet leakage current of PV module after PID stressing
$I_{LC\_Before\_PID}$	Wet leakage current of new PV before PID stressing
LID	Light induced degradation
PID	Potential induced degradation
PV	Photovoltaic
p_{sc}	Packing factor of solar module
R_{sh}	Shunt resistance
STC	Standard test condition
t	Aging period
T_a	Ambient temperature (°C)
T_b	Tedlar back surface temperature (°C)
T_{sc}	Solar cell temperature (°C)
T_m	Module temperature
U_{sca}	Heat transfer coefficient through glass cover from module top surface to ambient (W/m^{2}K)
U_t	Heat transfer coefficient from module top surface to back surface (W/m^{2}K)

Greek letter

τ_g	Transmissivity of glass
α_{sc}	Absorptivity of solar module
η_{sc}	Electrical efficiency of solar module
γ	Temperature coefficient of Pmax

challenging issue all over the world. Recently the PID has been considered as the key concern to reduce the module reliability as it could lead to a catastrophic failure of the PV module especially under a large string size [5]. Singh, Schmidt and Libby [6] had done a literature study and risk analyses on a PID and the authors reported that the degradation extent of the PV modules was due to the PID's variabilities from 20% to 80%. The PID characteristics of a PV module depend on the module which consists of the component materials, such as, the type of cell, EVA, and glass materials, etc. [7]. A large number of researches on the investigation of PID on different types of PV module component materials are available in the literature, such as, crystalline silicon (c-Si) (both p-type and n-type) [8,9], amorphous thin film silicon (a-Si) [10], silicon hetero junction (c-Si/a-Si) [11], copper indium gallium selenium (CIGS) thin film [12], cadmium telluride (CdTe) thin film [13] and organic PV cell [14], etc. However, to understand the real feature of the PID behavior of a PV module, it is prudent to use the on-site testing which is also the superior way. Nonetheless, it is to be carefully noted and considered that the on-site module testing is quite time consuming and takes several years to perform before a reliable result can be realised [15]. Generally, the laboratory PID test is a sufficiently good alternative and the PID effect is usually studied in the environmental chamber. Thus, testing the PID performance of PV modules before installation into the power plant is an essential task which is normally conducted according to the International Electrotechnical Commission (IEC) standard test condition titled as IEC TS 62804–1:2015 [16]. Different PV module manufacturers give a PID proof warranty on their modules by testing in accordance with the IEC 62804 test standard. Nevertheless, the correlation between the laboratory PID test standard and the on-site PID behavior of a PV module has not been well assessed as yet. Some of the researchers have tried to establish the correlation between the laboratory PID test and the on-site PID test. For example, Koentopp et al. [17] reported a comparative literature between the laboratory PID test and the on-site PID progression test through a shunt resistance (R_{sh}) measurement in Thalheim, Germany. Authors have mentioned that the PID recovery rate plays an important role in the on-site PID progression. It is also found that the PV module having a higher recovery rate in the laboratory shows a lower PID progression in the on-site. The time-dependent R_{sh} progression curve shows exponential characteristics [18]. Recently, a study regarding a on-site PID prediction of crystalline silicon PV based on an accelerated laboratory PID test of a 4-cell mini module has been done in Busan, South Korea [19]. Authors have reported that the predictive PID rate is analogous to the real PV plant PID rate after 3 years of on-site operation. Although there are some reports on the correlation between the chamber test and the filed PID results, nonetheless these are not sufficient to correlate test results with a PID durability in specific climates. However, a comparative investigation between a laboratory PID IEC standard test (Method B: Al foil test) and a long-time filed PID of the same PV module operated in the real on-site for several years is very seldom found in the literature.

On the other hand, the performance testing of PV modules with electroluminescence (EL) imaging has picked up a growing related interest in recent years due to its quick and spatially resolved defect detection possibilities [20] such as, detection of recombination, resistive and optical losses of PV cells/modules, for instance, low diffusion lengths [21], high series resistance [22] and shunts, etc. [23] by the EL imaging process has been already reported. In general, the EL image intensity is an outcome of the emission of light as a consequence of a forward voltage biasing to the PV module, which is the reciprocal of performance of a solar cell under a light illumination that is the generation of electricity from a light source [20,24]. The correlation between different parameters of a PV module performance and an EL emission intensity has been previously reported by different researchers [25–27]. Furthermore, an experimental investigation has been done to establish a correlation between the maximum power and the EL image intensity of a PV module. In addition, a high voltage stress leakage current has been identified as one of the major driving factors behind the PID. It has been observed that the amount of leakage current is maximized under a wet surface condition leading to a higher PID in the on-site [28]. Lin et al. [29] reported that the PV modules having a higher wet leakage current showed higher power losses during the PID testing. Reid et al. [30] reported that the stability of a volume resistivity during a long-term aging of the PV modules was also very important to ensure a long-term resistance to the PID effects. Authors measured the wet leakage current of the 60-cell modules after 3000 h of damp heat aging at 85 °C and 85% relative humidity. A higher grade encapsulant EVA showed a very high insulation resistance and a low wet leakage current and the module showed a high PID about 1% only. On the other hand, a lower grade EVA showed a high wet leakage current and the PID happened at about 45%. Therefore, the wet leakage current test has a significance in the PID testing process. The impact of both the on-site and the laboratory PID stress on the wet leakage current behavior of PV module has also been investigated in this research.

Finally, the objective of the research is to investigate the PID behavior of the same PV module in both the laboratory and the on-