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Degradation of mono-crystalline photovoltaic modules after 22 years of outdoor exposure in the composite climate of India

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ABSTRACT

The understanding of degradation modes and mechanism is very important in order to ensure the lifetime of 25–30 years of PV modules. In the present study, degradation analysis of 90 mono-crystalline silicon PV modules installed on the rooftop of the guest house of National Institute of Solar Energy (NISE), Gurgaon has been carried out after 22 years of outdoor operation in a composite climate of India. A comprehensive analysis has been carried out through visual inspection, thermal imaging, *I-V* characteristic and insulation resistance measurement as well as rate of degradation has been calculated. The defects in bus bar, cell inter-connection ribbon, string inter-connection ribbon and chalking in back-sheet are found to be most frequently observed defects. Hot spot in solar cell, burn mark and delamination in back-sheet are also observed in some PV modules. The average power degradation rate of 90 PV modules over period of 22 years has been found to be about 1.9%/year with maximum rate of power degradation 4.1%/year and minimum is 0.3%/year. Insulation resistance measurement of all the modules both in dry and wet condition showed that only 9 modules have shown insulation resistance <400 MΩ. The study addresses the degradation mechanism in order to assess the safety issues related to the large scale PV plants in Indian climatic condition.

1. Introduction

Converting Sun light to electricity using Photovoltaic (PV) technology is one of the most promising ways to achieve the rapidly increasing global electricity demand with pollution free environment. Photovoltaic industry has grown at an extraordinary pace in the past two decades. PV industry has grown from few MW to 183 GW installed PV capacity as on 07 December, 2015 worldwide (FISE, 2015). The PV system installation in India has increased after the launching of Jawaharlal Nehru National Solar Mission (JNNSM) by Government of India in December 2009 (Jawaharlal Nehru National Solar Mission, 2010). The installed capacity of PV system in the country till March 2015 is 4.86 GW (MNRE, 2015). At present, the main challenge faced by PV industry is to make PV generated electricity cost effective. In this context long term performance and reliability of PV module is of utmost importance. The long term reliability of PV modules is assessed through qualification standards developed by International Electro-technical Commission (IEC). These tests have helped a lot the PV industry to identify/eliminate the infant failure and ensure the quality of PV module. There are reports that qualified modules have survived for more than 20 years (Polverini et al., 2013). At the same time there are reports that even the well qualified modules have failed or degraded more than their expected levels (Sastry et al., 2010). Therefore it is now broadly thought that present qualification standards are not adequately addressing the actual outdoor conditions. Therefore it is important to study the behavior of PV modules in actual outdoor conditions to understand their performance, generation and growth of defects for their long term reliability.

The long-term reliability of the PV module can be studied from the degradation mechanism in outdoor operating conditions. The reliability issue and performance degradation may be caused by packaging materials, semiconductor degradation, solar cell interconnection, adhesion losses (Quintana et al., 2002; Shrestha et al., 2014). Som and Al-Alawai (1992), have studied an effect of degradation on (i) mono-crystalline silicon based PV modules and (ii) multi-crystalline silicon based PV modules. They observed that mono-crystalline PV modules degraded fast in comparison to multi-crystalline in one year due to severe corrosion. The correlation of the visual defects and the shifts in the electrical parameters was analyzed by Sanchez-Friera et al. (2011). Further it was reported that glass weathering, delamination at the cell-EVA interface and oxidation of the antireflective coating and the cell

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Nomenclature

I	current (A)
V	voltage (V)
P	power (W)
P_s	net present cost, R_s
n	number of years
$F_{CR,i,n}$	capital recovery factor
$F_{SR,i,n}$	sinking fund factor
i	Rate of interest, %

Abbreviation

PV	photovoltaic module
EVA	ethyl vinyl acetate
HIT	hetro junction intrinsic thin layer
c-Si	crystalline silicon
Mono-C-Si	mono crystalline silicon
MPPT	Maximum power point tracking
STC	standard test condition
IEC	International Electro technical Commission
JNNSM	Jawaharlal Nehru National Solar Mission
MNRE	Ministry of New and Renewable Energy
IR	infrared
UAC	uniform end of annual cost, R_s

Subscript

sc	short circuit
oc	open circuit
Max	maximum power point at reference value
ARC	alternate reporting condition
MP	maximum power point
M	PV module
T	tilted surface

Greek letters

β	temperature coefficient

metallization grid were the most frequently occurring defects. Sakamoto and Oshiro (2003) found 0.5%/year power degradation in c-Si PV modules after 10 years outdoor exposure. They have concluded that reason behind it is delamination between cell and EVA and metallization of solder bond. Kuitche et al. (2014), found that the solder bond failure and encapsulate discoloration are dominant failure modes of crystalline silicon PV module under hot desert climatic condition. Typical performance losses in large field deployed, large-scale system ranging from 1% to 10%/year are given quantitatively, and qualitative reports of EVA discoloration are summarized with respect to ultraviolet world-wide location and site dependence (Czanderna and Pern, 1996). Tamizhmani and Kuitche (2014), explained the different failure mode, failure causes and failure mechanism of PV module for different climatic conditions. The average peak power decay/year in composite climate has been found to be 14.6% in a-Si array modules, 1.7% in poly-C-Si array modules and 1.5% in the HIT array modules respectively, which corresponds to loss in either short circuit current or fill factor or both (Sharma et al., 2013). Polverini et al. (2013), reported 4.42% an average performance decay of 70 polycrystalline silicon PV modules installed in the Ispra, Northern Italy after 20 years outdoor exposure. Alshushan and Saleh (2013), reported that after 30 years, the average peak power degradation of crystalline silicon PV modules were found to be 13.86% of initial value for the modules installed in Libya. Dunlop and Halton (2006) studied the performance of 40 crystalline silicon (mono and multi) PV modules after 20–22 years field exposure. They concluded that module encapsulated with EVA and a Tedlar aluminum back sheet exhibited 14.8% mean power degradation while module with encapsulated silicon sealant showed average power degradation of 6.4%. Realini et al. (2001), reported 0.5%/year power degradation of 10 kW PV system of c-Si PV modules installed at Lugano, Switzerland after 21 years operation. Ndiaye et al. (2014), reported that after few years operation of c-Si PV module in tropical climate Dakar, Senegal, the highest loss in the maximum power output was 0.22%/year to 2.96%/year. However, the open-circuit voltage was not degraded. Oxidation of the antireflective coating, cell metallization grid, glass weathering and delamination at the cell-EVA interface were found to be most frequently occurring defects. The 11.5% degradation was found in peak power which was totally due to the short circuit current (Jordan and Kurtz, 2013).

Study about the degradation of PV module in real outdoor condition in India is not very much prominent because of lack of comprehensive performance information. The degradation mechanism depends upon the operating environmental condition. India has six different climatic zones, therefore analysis of degradation mechanisms throughout the country are very difficult task (Grid Interactive Solar Power, 2013). Sastry et al. (2010), has reported about the performance degradation of mono-C-Si in Indian climate after 12 years of outdoor exposure for the modules manufactured by 11 different Indian manufactures. They have reported that 5–16.5% degradation was found to be in output power in those modules whose module qualified under IEC 61215 standards after 10 years. 17–33% degradation was found to be in output power in those modules whose module not qualified under IEC 61215 standards after 10 years.

The previous studies revealed that even the well qualified modules have failed or degraded more than the expected levels and suggested that there is a need to review the PV qualification standards especially for Indian climatic conditions. Chandel et al. (2015) reported that after 28 years outdoor exposure of mono-C-Si PV modules for western Himalayan region of Indian climate that have 1.4%/year average power degradation for PV generator. It is due to encapsulate discoloration, delamination and oxidation of front grid finger, anti-reflecting coating and bubbles in back-sheet.

The main focus of the study is on the defects observed in a roof mounted PV system under composite climatic conditions which are reported and will be useful for the current studies being undertaken to identify various defects under Indian climatic conditions and are going to provide valuable inputs for any modifications in IEC standards which are being considered seriously. The results presented in this study are of significance in this context of quality and problems faced in field installed PV modules as such the results are of importance for further follow up. Also such degradation studies have not carried in detail in different parts of India except at location in Gurgaon at the Solar Energy Centre now named as National Institute of Solar Energy. Further PV industry has started finding applications worldwide in all climatic zones with various configurations. Efforts are underway toward making qualification tests more quantitative by creating a comparative rating system for various conditions encountered by the PV module in the field worldwide Keeping in view this there is a need to have