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Degradation analysis of 28 year field exposed mono-c-Si photovoltaic modules of a direct coupled solar water pumping system in western Himalayan region of India

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ABSTRACT

It is important to understand photovoltaic (PV) module degradation for the design of PV systems. In the present study results of degradation in mono-crystalline-silicon PV generator of a solar water pump after 28 years of outdoor exposure at a western Himalayan location in the Indian state of Himachal Pradesh, are presented. The main objective is to study the impact of PV degradation on solar pump performance, reliability and life-expectancy under field conditions. Main defects observed in PV modules are encapsulant discolouration, delamination, oxidation of front grid fingers and anti-reflective coating, glass breakage and bubbles in back sheet. Hot spots are identified using thermal imaging and degradation is quantified by measuring PV parameters under indoor and outdoor conditions. Sun simulator is used to test degraded modules under standard testing conditions. Average power degradation of PV generator is found to increase 1.4% per year which is reasonable considering materials and technology used about three decades ago. The open circuit voltage is found to show an average increase of 2.8% requiring further experimental investigations. The study has relevance in improving the performance and life-expectancy of PV based systems beyond the warranty period of 25 years by replacing most degraded modules. Follow up research areas are also identified.

1. Introduction

Long-term reliability of PV modules is required to make PV technology a commercially viable option for energy production. Reliability of PV modules can be assessed by understanding degradation phenomenon and degradation mechanism during the outdoor operation. Studying degradation is of utmost importance as it helps in developing adequate qualification standards and specifications for PV modules with appropriate warranty periods. Most PV degradation studies are generally carried out through indoor accelerated ageing experiments. In such studies, stress or a combination of stresses are applied to reproduce the identified degradation mechanism in shorter periods of time. Finally, based upon accelerated ageing tests, qualification standards are developed. At present, the qualification testing of PV modules is carried out as per International Electro Technical (IEC) standards [1,2]. The main objective of the qualification tests is to reproduce the identified degradation mechanisms quickly in the intended environment. Quality standards developed through accelerated-ageing tests have helped considerably to improve reliability and durability of PV modules in recent years. However, it is not possible for accelerated tests alone to replicate various possible degradation mechanisms in PV modules occurring during real-time field exposure. Under the real outdoor exposure, stresses like radiation, temperature, humidity, wind and operating voltage are experienced together, whereas during accelerated qualification tests these stresses are applied as per predetermined sequence, which need not necessarily result in generation of same type of defects. Another approach to study the degradation is to carry out long term outdoor exposure of small PV arrays; perform experimental measurements to evaluate various performance parameters to identify degradation.

In the present study, degradation analysis of 28 year field exposed mono-crystalline silicon (mono-c-Si) PV generator of water pumping system is carried out. The system is installed at the

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outdoor photovoltaic research facility of Centre for Energy and Environment, National Institute Technology, Hamirpur (NIT-H), India. The objective of the study is to understand the impact of PV degradation on water pump performance under actual field conditions, the life-expectancy and reliability of mono-crystalline-Si based PV systems. A detailed analysis is done through a comprehensive test campaign which involves visual inspection, infrared imaging, and I–V characteristics measurement using Sun simulator to understand the degradation mechanism. The results obtained are compared with the manufacturer data sheet parameters and deviation between initial values and experimental results are presented.

The paper is organized as follows: an overview of the degradation studies is presented in Section 2; solar PV water pumping system is described in Section 3; methodology of PV modules degradation analysis is explained in Section 4; results are discussed in Section 5 and conclusions are drawn in Section 6.

2. Overview of PV module degradation studies

A number of long term field testing studies of crystalline silicon (*c-Si*) PV modules, have been carried out to understand PV module degradation mechanism. There are number of modes and mechanisms of PV module degradation like corrosion and electromigration in the contact layers and interconnects. The contact degradation results in increase in series resistance whereas interconnect degradation can affect both series and shunt resistance. Most commonly used encapsulant material in photovoltaic application is EVA, its discolouration and stability have received significant attention for improving the performance and durability of PV modules. In order to quantify the adhesive strength of EVA, a destructive procedure of obtaining samples from field aged *c-Si* modules was developed at Florida Solar Energy Centre [3]. The adhesive shear strength is measured by measuring the peak torque while extracting the sample. The results of the study indicated that adhesion shear strength is weaker at EVA/solar cell interface than Glass/EVA interface and after 7 years of outdoor exposure, the shear strength is only 20% of unexposed module samples. Several researchers have reported the degradation in performance due to EVA browning because of ultraviolet exposure and oxidation resulting in loss in the transparency and photon availability [4–6]. Water penetration through the laminated edges and back sheet of PV module is another driving force for many degradation mechanisms. Mon et al. [7] at Jet Propulsion Laboratory, USA, studied water module interaction and suggested that thin-film PV modules are more prone to water penetration than mono-*c-Si* or multi crystalline (*multi-c-Si*) modules because the thin-film active material is located at the encapsulant/substrate interface, whereas *c-Si* and *multi-c-Si* are surrounded by the encapsulant on all sides. Recent studies about the moisture intrusion in PV modules deployed in the field show that moisture penetration results into delamination and reduces the active area of the module [8,9]. Most of these degradation studies are carried out on field-aged failed modules. Studies reported on healthy field-aged modules which can provide the data of satisfactory performance of PV technology in the field through evaluation of the degradation rate are very less. Thus, in order to define degradation rates, authors around the world have recently started studying performance of different technology modules under different climatic conditions. Carr et al. [10] at the Australian Cooperative Research Centre Perth, Australia evaluated the performance of five different technology PV modules from seven different manufacturers for 16 months of outdoor operation. The results of the study indicate that mono and multi-crystalline silicon PV modules show 2% per year power reduction where as amorphous and CIS solar modules exhibited a significantly higher power reduction. Raghuraman et al. [11] evaluated performance of forty four modules from eight different manufacturers and three different technologies in Mesa, Arizona under hot-arid climatic conditions for 2.4 years–6.7 years. Mono-crystalline and multi-crystalline silicon modules exhibited low power degradation (approx 0.5% per year) while amorphous silicon (*a-Si*) multi-junction modules degraded comparatively more (1.16% per yearly). Marion and Adelstein [12] at Solar Energy Research Facility (SERF) reported the performance of two PV systems installed on the roof top of SERF building from 1994 to 2002. Each PV system consists of 140 modules. Results indicated that performance of both PV systems is reducing at a rate 1% per year. The reduction in the performance is regarded as an effect of ageing. A study on power degradation of crystalline silicon PV modules is presented jointly by the Japan Quality Assurance Organization and Solar Techno-Centre [13]. Modules were operated outdoors for 10 years in Hamamatsu (Japan) and average power reduction was found to be 6.2%; however about 10% of the PV modules have suffered power reduction of more than 10%. Another interesting work carried out is by Dunlop and Halton [14] at the Institute for Environment and Sustainability, Italy, studying the performance of 40 silicon (poly and mono) crystalline PV modules with different encapsulations and from six different manufacturers operating for 20–22 years in the field. Modules encapsulated with silicone sealant showed average power degradation of 6.4% while modules encapsulated with EVA and a Tedlar aluminium back sheet exhibited 14.8% mean power degradation in 22 years. Realini et al. [15] analyzed the performance of a 10 kW PV system consisting of *c-Si* PV modules installed at Lugano, Switzerland after 21 years of operation and after analysis 0.5% per year power degradation is reported. Jordan and Kurtz [16] recently reviewed the degradation rates from the field testing studies carried out during last 40 years and concluded that the average power degradation rates distribution is found to be 0.8% per year. Sastry et al. [17] studied the performance degradation of mono-*c-Si* PV modules supplied by eleven manufacturers for a period of 10 years at the Solar Energy Centre (SEC), India. These modules were tested in five groups: group-1 IEC 51215 qualified modules showed average degradation of 8%, group-2 modules were not qualified as per IEC standard and showed average degradation of 10%, group-3qualified modules showed average degradation >28%, group-5 consisted of failed modules which were repaired and made functional. The degradation in the output power of modules qualified under IEC 61215 standard was found to range from 5 to 16.5% whereas the modules not qualified under the IEC 61215 standard, were found to range from 17 to 33% after 10 years and found that even the well qualified modules have degraded more than the expected levels. In another study Sastry et al. [18] concluded that Cd-Te and *mono-c-Si* solar cell technologies are found to be more resilient to degradation than *a-Si* modules; degradation in hot-humid climate occurs primarily due to moisture ingress that causes delamination and electrochemical degradation of contacts of cells. In this study, sampled *mono-c-Si*, CdTe, CIS, *a-Si* double and triple junction modules from the test beds of SEC were tested after field exposure of more than 10 years using electrical, thermal, and electro-luminescence techniques.

Sharma and Chandel [19] in a detailed review on the degradation of photovoltaic technologies emphasized the need for developing site specific qualification standards and highlighted the efforts being made for the creation of a comparative rating system to make qualification standards more quantitative. Despite the progress made in this area, further research is needed to establish stringent quality standards to ensure the module life time of 30 years.

Sharma et al. [20,21] studied the performance and degradation of *a-Si*; HIT and *multi-c-Si* module arrays installed at Solar Energy