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Effect of operating temperature on degradation of solder joints in crystalline silicon photovoltaic modules for improved reliability in hot climates

Osarumen O. Ogbomo[a,*], Emeka H. Amalu[b], N.N. Ekere[a], P.O. Olagbegi[c]

[a] School of Engineering, Faculty of Science and Engineering, University of Wolverhampton, WV1 1LY, UK
[b] Department of Engineering, School of Science, Engineering and Design, Teesside University, Middlesbrough, Tees Valley TS1 3BA, UK
[c] Mechanical Engineering Department, Faculty of Engineering, University of Benin, Nigeria

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ABSTRACT

Accelerated degradation of solder joint interconnections in crystalline silicon photovoltaic (c-Si PV) modules drives the high failure rate of the system operating in elevated temperatures. The phenomenon challenges the thermo-mechanical reliability of the system for hot climatic operations. This study investigates the degradation of solder interconnections in c-Si PV modules for cell temperature rise from 25 °C STC in steps of 1 °C to 120 °C. The degradation is measured using accumulated creep strain energy density (W_{acc}). Generated W_{acc} magnitudes are utilised to predict the fatigue life of the module for ambient temperatures ranging from European to hot climates. The ANSYS mechanical package coupled with the IEC 61,215 standard accelerated thermal cycle (ATC) profile is employed in the simulation. The Garofalo creep model is used to model the degradation response of solder while other module component materials are simulated with appropriate material models. Solder degradation is found to increase with every 1 °C cell temperature rise from the STC. Three distinct degradation rates in Pa/°C are observed. Region 1, 25 to 42 °C, is characterised by degradation rate increasing quadratically from 1.53 to 10.03 Pa/°C. The degradation rate in region 2 ,43 to 63 °C, is critical with highest constant magnitude of 12.06 Pa/°C. Region 3, 64 to 120 °C, demonstrates lowest degradation rate of logarithmic nature with magnitude 5.47 at the beginning of the region and 2.25 Pa/°C at the end of the region. The module fatigue life, L (in years) is found to decay according to the power function $L = 721.48T^{-1.343}$. The model predicts module life in London and hot climate to be 18.5 and 9 years, respectively. The findings inform on the degradation of c-Si PV module solder interconnections in different operating ambient temperatures and advise on its operational reliability for improved thermo-mechanical design for hot climatic operations.

1. Introduction

The annual electrical power consumption of the entire planet can be generated by the sun in just one hour (Harrington, 2015; Maehlum, 2013). Solar energy is abundant in addition to being clean, sustainable and renewable (Belward et al., 2011; Gujba et al., 2011). However, some parts of the world are still struggling to meet their energy needs. Photovoltaic module (PVM) systems are capable of harnessing and converting the immense energy of the sun into useful electricity. Unfortunately, PVMs have demonstrated low performance in hot climates because elevated ambient temperature conditions significantly influence their performance. The conditions include the intensity of solar radiation, cell temperature magnitude, wind speed and humidity (Dubey et al., 2013; Skoplaki and Palyvos, 2009a, 2009b). Normally, PV modules are designed to operate under standard test conditions (STCs) which are solar radiation of 1000 W/m^2, cell temperature of 25 °C, wind speed of 1 m/s and air mass (AM) of 1.5. Cell temperature of 25 °C is characteristic of European and other temperate climates. The operating conditions of PVMs in hot climate differ from STC and vary in different climatic zones (Eludoyin et al., 2014). High cell and ambient temperatures are considered critical to the reliability of PV solder interconnections.

This study focuses on hot climates with high ambient temperatures ranging from 25 °C to 45 °C which can force PV cell temperatures to increase to as high as 90 °C. Kurnik et al. (2011) in their outdoor testing of PV module temperature and performance under different mounting and operating conditions, reported that the temperature difference between ambient and module can be as high as 22 °C. The PV module has been described as a layered composite of different materials hence the different material combinations complicate stress distribution and concentration (Lenarda and Paggi, 2016; Ojo and Paggi, 2016a). Operations at high-temperatures increases the mismatch effect among

* Corresponding author.
E-mail address: O.O.Ogbomo@wlv.ac.uk (O.O. Ogbomo).

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crystalline silicon wafer, silver contacts, solder, copper ribbons and other component layers in the module occasioned by the differences in their coefficient of thermal expansion (CTE). In turn, the mismatch leads to thermo-mechanical induced fatigue loading of the interconnection in the PV module (Dubey et al., 2013; Kato, 2012). Consequently, PV modules operating in the hot climatic regions possess higher failure rates than those in temperate climates. Munoz et al. (2011), in their measurement of early degradation of crystalline silicon PV modules using visual inspection, I-V curve characteristics, thermal evaluations by Infrared imaging and electroluminescence, reported that early defects are caused by module operation in conditions that differ from standard test conditions.

Ferrara and Philipp (2012) in their study of the reasons for PV module failures, grouped them into intrinsic and extrinsic factors. Intrinsic factors are based on material properties while extrinsic factors are based on climatic stress factors and defective installations. Highlighted climatic stress factors which include solar irradiation, humidity, wind, high/low temperatures and temperature changes result in failure modes that can either be obvious to an observer or not. Obvious failures like discoloration, delamination, formation of bubbles and cracking of EVA showed no direct relation to power loss whereas, cell and interconnection breakage are responsible for the degradation of electrical performance of PV modules as well as reduction in fatigue life and lifespan. Solder interconnections perform structural and electrical functions in a PV module. Any degradation in the solder joint means the power generated by the PV cell cannot be accessed. Additionally, the solder joint holds the electrical components (i.e. PV cell, contact and interconnect ribbons) of PV modules together.

Ndiaye et al. (2013, 2014) buttressed on the economic importance of PV module fatigue life and lifespan. They indicated that in the choice of energy sources, consumers consider cost effectiveness and return on investment, so fatigue life and lifespan are determining factors. Further findings from their review of silicon photovoltaic module degradation in Senegal, includes identifying temperature and humidity as the most dominant factors responsible for all observed modes of PV module degradation of which interconnection breakage topped the list. They also reported that current literature on PV module degradation focuses on the degradation of the entire module and not on a single mode of degradation. They recommended that in the study of PV module degradation, one mode of degradation should be focused on at a time as this will provide better understanding and thorough research.

The majority of previous literature (Jordan et al., 2010; Jordan and Kurtz, 2013; Kurnik et al., 2011; Skoplaki et al., 2008; Ye et al., 2014) have studied the electrical power degradation of PV modules considering various component parts but have neglected the effect of solder joints degradation. The PV failure modes observed in field operations include delamination and discolouration of EVA, solder bond and ribbon degradation and cracking as well as burn marks (Bosco, 2010; Köntges et al, 2014). Other researchers which include Jeong et al., (2012); Zarmai et al., (2015) reported that the solder interconnection is the most susceptible part of the PV Module and responsible for over 40% of module failures. Chandel et al. (2015), in their degradation analysis of 28-year field exposed mono-c-Si photovoltaic modules directly coupled with solar water pumping system in western Himalayan region of India, reported that interconnection degradation is responsible for increase in shunt and series resistances which imply decrease in short circuit current and power output of PV Module. They further argued that contact and interconnection degradation are the primary degradation modes of PV modules operating in tropical climates - known for their hot and humid characteristics.

Fig. 1 presents a schematic showing the operation of a PV module in hot climate. The PV module functions to harness only the light energy of the sun into useful electrical power – which is the functional design. However, field operations in a hot climatic region exposes the module to both the heat and light energies of the sun. Such operation exposes the module to conditions outside its designed intents. The figure shows that the PV module converts the light energy into useful electrical power, but the unwanted heat energy impedes power generation and accelerates the interconnection degradation which leads to interconnection rupture.

The significant effect high temperature operation has on the electrical conductivity of the solder interconnection and thus power output of the entire PV module is buttressed in our previous study (Ogbomo et al., 2017). In that study, the performance of PV module contacts and interconnection technologies in tropical climate were scrutinised. At high temperatures, electrons in the material are thermally excited and energised thus, they vibrate and collide with one another. This activity increases the electrons' resistance to the flow as electric current and impedes the electrical conductivity of the material. This implies that as temperature increases, resistivity and electrical resistance increase. These relations are represented in Eqs. (1) and (2). As a result of the inverse relationship between electrical resistance and electric current, an increase in resistance leads to a corresponding decrease in current and hence power output. Eqs. (3) and (4) represent these relations.

$$\rho = \rho_0[1 + \alpha(dT)] \tag{1}$$

$$R = R_0[1 + \alpha(dT)] \tag{2}$$

$$I = \frac{V}{R} \tag{3}$$

$$P = I^2R \tag{4}$$

where ρ_0 is initial resistivity (Ωm), $\rho$is final resistivity (Ωm), $R_0$is initial resistance (Ω), $R$is final resistivity (Ω), α is temperature coefficient of resistivity (K^{-1}) anddT is temperature change (K). I is electric current (amp.), V is voltage (volts) and P is electrical power (watts).

Although there are literature on the electrical power degradation of PV module which include (Bastidas-Rodriguez et al., 2017; Jordan et al., 2017; Sander et al., 2010), the present study focuses on the thermo-mechanical degradation of the PV solder interconnections in high temperature climates. The effect of non-STC operating temperatures on the PV module performance and reliability is critical and drives the module high failure rate in hot climate. There is therefore the need to critically investigate the effect of operations of PV modules in hot climate on its performance with focus on solder interconnection reliability. The rationale to investigate the degradation for every 1 °C rise from STC is borne out of the realisation that Dubey et al. (2013) and Kato (2012) reported that the temperature coefficient pMax of crystalline silicon PV modules is −0.5%. Implying that for every 1 °C rise from the STC, the power conversion efficiency (PCE) of the PV module decreases by 0.5%. This observation necessitates urgent research to ascertain the relationship between operating temperature and thermo-mechanical degradation of PV solder joints, hence provide information to improve the performance and reliability of PV module in hot climate. The claim is strengthened by the reports of (Huld et al., 2010; Hussein et al., 2004; King et al., 2002; Obinata et al., 2010; Pacca et al., 2007; Woyte et al., 2013) that the deviation of modules cell and ambient temperatures in the hot climate from the STC calls for research aimed at providing more information to predict the performance and fatigue life of modules in the climatic zone accurately.

This study aims to investigate the effect of high-temperature on degradation of solder joints in photovoltaic module for improved reliability in hot climate. In addition, the research seeks to identify the numerical relationship between cell temperature rise from STC and the solder joint degradation.

2. Thermal load

Studies report that operations of crystalline silicon PV (c-Si PV) module in hot climate is characterised with high failure rates that results in short fatigue lives and lifespan of the module. These high failure rates are attributed to deviant operating conditions in hot climates from