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Performance and life prediction model for photovoltaic modules: Effect of encapsulant constitutive behavior

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ABSTRACT

An encapsulant in a Photovoltiac (PV) module is a polymer used for binding all the components together. It also provides protection of cells and interconnects from moisture, foreign impurities and mechanical damage. In addition to this, the encapsulant must possess certain desirable characteristics such as low cost, high transmittance of light, good thermal conduction and long operating range. The provision of such properties makes it a vital component on which the performance of a PV module depends. Currently, the PV industry is dominated with Ethylene-Vinyl Acetate (EVA) as an encapsulant, mostly due to its low cost. Other polymers such as polydimethylsiloxane (PDMS), polyvinyl butyral (PVB), thermoplastic polyurethane (TPU) and Ionomer have gained interest and are being tested for better encapsulation of PV modules. The current work deals with the comparison of the mentioned encapsulants and selecting the optimum one based on its properties such as light transmittance, UV durability, electrical insulation, water vapor transmission rate and cost. The structural life of PV module is also compared by using these encapsulants. For this purpose, previously developed structural and thermal models are coupled with electrical and life-prediction models to determine efficiency and life of PV module for each encapsulant case. Life prediction of PV module encapsulant is based on a year's data of Jeddah, Saudi Arabia where the interconnect crack initiation defines failure. Under these assumptions, a detailed structural analysis has been carried out. Finally, the results of simulation combined with the other outcomes of literature are used in a decision matrix to give Ionomer to be an optimum encapsulant for PV module.

1. Introduction

The photovoltaic (PV) industry has shown rapid growth in the last few decades. Its expansion has led to the selection of such materials in its construction, which enables it to meet its requirements efficiently. Now-a-days, research on PV modules is mainly focused on the encapsulant material, due to significant involvement of its properties over PV module performance. The structural performance of PV modules is enhanced due to the protective covering it provides to isolate silicon cells from the influence of the environment. At the same time, it also has to be transparent to light so as not to hinder the electrical performance of PV modules. In fact, it could also provide a medium to extract heat from the cells to increase their efficiency. So, the fulfillment of these requirements and others (discussed later) are important for an optimal performance of PV modules.

During the 1960s and 1970s, polydimethylsiloxane (PDMS)/silicone was used as an encapsulant for PV modules [1]. But from the 1980s till today, the PV industry is dominated with ethylene vinyl acetate (EVA) [2]. EVA was chosen over PDMS mainly due to its low cost. In the late 1990s, it was found that EVA turned yellow/brown due to UV radiation from the sun thus decreased its transmittance. It has also been reported to lose adhesion under UV light [3]. Furthermore, EVA has the ability to concentrate water due to diffusion which makes it to react with moisture to form acetic acid. The acetic acid speeds up the corrosion process of the inner components of the PV module [4]. This raises a question of its operation under humid climates. The glass transition temperature (T_g) of EVA is $-15\,^{\circ}\mathrm{C}$ [5] and it comes in between the operating range of a PV module in cold regions. Thus, compliancy of EVA is an issue for modules operating in such regions. The mentioned concerns have recently revitalized the interest to study different polymers for PV module encapsulation. Such polymers include polyvinyl butyral (PVB), Ionomer, PDMS and thermoplastic polyurethane (TPU). The mentioned encapsulants have their merits and demerits over one another, but the best compromise amongst them needs to be chosen with respect to PV module performance and life.

Failure is defined as the change in properties of a structure, machine or machine part that makes it inept to perform its intended functions. The occurrence of such failure is through physical means which are known as failure modes [6]. In the case of PV modules,

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Nomenclature

$A(T(t))$	WLF shift function
A_i	anisotropy index
A_{panel}	front area of the PV module (m^2)
b	fatigue strength exponent
C	specific heat capacity (J/kg K)
C_1, C_2	calibration constants for WLF shift function (C_2 is in K)
C_p	specific heat capacity (J/kg K)
c	fatigue ductility exponent
c_{01}, c_{10}	material constants for deviatoric deformation (Pa)
$[D]$	stiffness matrix (Pa)
d	material incompressibility parameter (Pa^{-1})
E_o	instantaneous Young's modulus (Pa)
G	horizontal plane solar radiation (W/m^2)
G_i	shear modulus of ith spring-damper in Maxwell's model (Pa)
G_o	instantaneous shear modulus (Pa)
G_∞	long term shear modulus (Pa)
h	heat loss coefficient (W/m^2 K)
$\bar{I}_1$	first deviatoric strain invariant
$\bar{I}_2$	second deviatoric strain invariant
K	initial bulk modulus (Pa)
$K_{\tau\alpha}$	incidence angle modifier
k	thermal conductivity (W/m K)
L_{avg}	average life (years)
L_F	final length (m)
L_{day_i}	life of the ith representative day (years)
L_O	initial length (m)
M	air mass modifier
N_f	no. of cycles to crack initiation
Q	volumetric heat generation (W/m^3)
q	heat conduction (W)
R	relaxation modulus (Pa)
R_{beam}	ratio of beam radiation on tilted plane to that on horizontal plane
$[S]$	compliance matrix (1/Pa)
S	absorbed solar radiation (W/m^2)
t	current time (s)
T	current temperature (K)
T_{amb}	ambient temperature (K)
T_s	surface temperature (K)
T_{max_i}	maximum ambient temperature of day i (K)
T_{min_i}	minimum ambient temperature of day i (K)
T_o	initial temperature (K)
T_r	reference temperature of WLF shift function (K)
T_{ref}	stress-free temperature or initial temperature (K)
T_{total}	total of average ambient temperatures (K)
V_{pvcell}	volume of the cells in the PV module (m^3)
W	strain energy potential (J/m^3)
W_{day_i}	weight of the ith representative day
W_{total}	sum of the weights of four representative days

Greek symbols

α_x	thermal expansion coefficient in x-direction (K^{-1})
β	tilt angle
η_{pv}	electrical efficiency of PV module
μ_i	initial shear modulus (Pa)
$\Delta\varepsilon/2$	total strain amplitude
ε_{max}	maximum total principal strain
ε_{min}	minimum total principal strain
ε_x	total strain in x-direction
$\varepsilon_f^{'}$	fatigue ductility coefficient
$\Delta\varepsilon_p/2$	plastic strain amplitude
$\{\varepsilon\}$	total strain vector
$\{\varepsilon^{el}\}$	mechanical strain vector
$\{\varepsilon^{th}\}$	thermal strain vector
ϕ_i	relative modulus of ith spring-damper in Maxwell's model
γ_{xy}	shear strain in xy-plane
ν_{xy}	Poisson's ratio in xy-plane
ρ	density (kg/m^3)
ρ	reflectivity of the ground
$\{\sigma\}$	stress vector (Pa)
$\Delta\sigma/2$	stress amplitude (Pa)
$\sigma_f^{'}$	fatigue strength coefficient (Pa)
σ_{von}	von-Mises stress (Pa)
σ_1	first principal stress (Pa)
τ_i	ith term for pseudo time (s)

failure may be stated as when the module is not capable of producing power as per its specification due to degradation caused by failure modes. While operating at the field, a PV module is subjected to various loading conditions. A number of failures have been reported during the course of its operation. Wohlgemuth et al. have gathered commercial PV module returns under warranty of BP Solar/Solarex from 1994 to 2005 [7]. Chaturvedi et al. [8] use electroluminescence (EL) imaging to find the failure mode due to thermal cycling. Dark images in their EL results suggested failure in the metal fingers due to improper soldering. Each product was examined and the cause of failure was found which is summarized by Fig. 1. It is seen that corrosion and cell/interconnect breakage have the highest part in failure. Wohlgemuth and Cunningham [9] have concluded that cell breakage during operation is due to pre-damaged cells during soldering. Interconnect breakage has been attributed to fatigue as a result of thermo-cycling in the literature [10,11]. Such failures deteriorate PV module performance, ultimately affecting its life.

The lifetime of today's PV module is expected to be 25 years with 20% reduction in its power output over this period, and this is usually guarantee of the manufacturer. In accordance with such requirements, the module must withstand mechanical loads reliably. Its high reliability will help it to reach grid parity. Qualification standards, such as ASTM E-1171-08 [12], are good to identify the initial design flaws or infant mortality but cannot validate a 25 year life of a PV module [13]. Irrespective of the operating

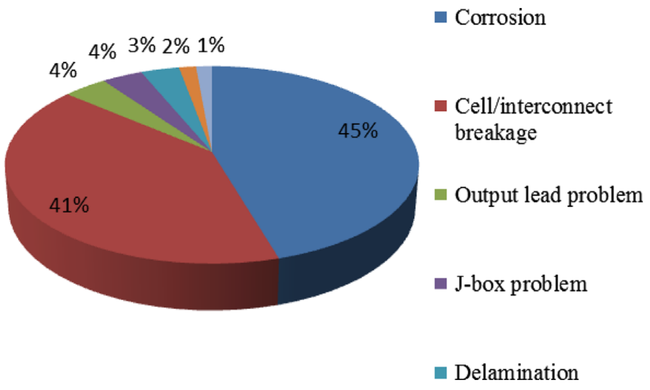

Fig. 1. Failure modes of PV modules [7].