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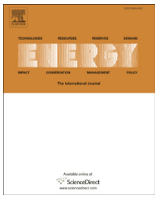

Performance evaluation of micromorph based thin film photovoltaic modules in real operating conditions of composite climate

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ABSTRACT

The micromorph thin-film photovoltaic (TFPV) technology uses tandem solar cell structure comprising of hydrogenated amorphous and microcrystalline p-i-n junction silicon cells which needs a long period of outdoor exposure for stabilization. In this paper, the performance analysis of grid interactive (GI) micromorph TFPV system has been assessed for a period of 166 days in real operating conditions on the basis of performance ratio (PR), thermal normalized PR (PR_{STC}), alternate reporting conditions (ARC), energetic and exergetic studies. A novel methodology for performance evaluation has been developed by utilizing per minute operating data collected from a micromorph based GI-TFPV system of 7.92 kW_P rated stabilized capacity. The system is found to be operating in the range of 5.1 kW_P to 5.6 kW_P as compared to the 5.94 kW_P stabilized rated capacity after removing the strings with mechanical damaged modules. The average PR and PR_{STC} of the system are found to be 0.83 and 0.89 respectively, with an average degradation rate of 1.53%/month and 1.22%/month respectively. The average exergetic, energetic and alternate current output efficiencies of the 7.92 kW_P GI-TFPV system are found to be 7.38%, 6.83% and 6.69% respectively. The performance of inverters and effect of module breakage has also been evaluated.

1. Introduction

The solar photovoltaic is coming out as one of the most promising alternatives to the conventional power generation technologies with considerable progress in installed capacity as well as industry oriented research in the field of modelling, design methodologies, size optimization techniques and reliability analyses [1]. The installation of PV systems has grown worldwide with compound annual growth rate of 40% from year 2000–2014. According to the photovoltaics' progress report by Fraunhofer Institute for Solar Energy Systems, the annual production of PV modules was about 47.5 GW_P in year 2014, out of which about 43.1 GW_P (90.73%) was well established and predominant silicon wafer based technology while the emerging TFPV technology accounts about 4.4 GW_P (9.26%) [2]. Although the world solar market is dominated by silicon wafer based module technology, efforts are still going to improve performance and stability of the TFPV technology such as CIGS, CdTe and micromorph due to their higher yields and PR in specific environmental conditions. The TFPV modules, which are fabricated by depositing a thin layer of PV material having a thickness in the range of μm, is competing the wafer based technology due to the high absorption coefficient of thin film material which reduces the material requirement and hence reduces the cost. The TFPV technologies are expected to have competitive efficiency, ease in producing large size modules, monolithic PV cell integration and low energy consumption in the manufacturing process which not only reduces the energy payback period but also decreases the manufacturing cost and greenhouse gas emissions [3].

Among TFPV technologies, the amorphous silicon (a-Si: H) is most popular and oldest, but it undergoes light induced degradation (LID) during stabilization because of Staebler-Wronski effect. Therefore, an alternative tandem cell structure of hydrogenated amorphous silicon (a-Si: H) based high band gap p-i-n junction semiconductor as top cell and hydrogenated microcrystalline silicon (μc-Si: H) based low band gap p-i-n junction semiconductor as bottom cell was suggested by Meier et al. (1994) in order to improve the stability which is named as micromorph technology [4]. The cells are deposited typically at 200°C-300 °C temperature using plasma enhanced chemical vapour deposition, which is relatively very low as compared to crystalline Si. The spectral

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Nomenclature

A	Area
B	Exergy
E	Electrical Energy
G	Irradiance
GI	Grid interactive
H	Radiation
I	Current
kW	kilo Watt
kWh	kilo Watt hour
P	Electrical Power
PR	Performance ratio
Q	Energy
sf	Spectral factor
T	Temperature
tf	Thermal factor
$TFPV$	Thin film photovoltaic
V	Voltage
y	Normalized energy yield
γ	Temperature coefficient
δB	Exergy destruction
ε	Emissivity
η	Energy efficiency
λ	Wavelength
ρ	Reflectivity
σ	Stefan-Boltzmann constant
ψ	Exergy efficiency

Subscripts

a	Ambient
AC	Alternate current
ARC	Alternate reporting conditions
C	Convective
d	Diurnal
f	Final
i	Instant
I	Current
INV	Inverter
M	Module
MP	Maximum power point
n	Number of individual array
p	Peak
P	Power
R	Reflective
RD	Radiative
ref	Reference
ROC	Real operating conditions
S	Sun
SKY	Sky
STC	Standard test conditions
T	Tilted
U	Recoverable
V	Voltage

response and electrical properties of the μc-Si:H p-i-n junction cell approaches the monocrystalline p-n junction cell [5]. The module has amorphous and microcrystalline silicon multi-junction cell coated with EVA foil and sandwiched between front and rear thermally strengthened glass. The a-Si:H and μc-Si:H p-i-n junction diodes of micromorph cell have 1.7 eV and 1.1 eV band gap respectively, which is nearly ideal to absorb more solar radiation spectrum with the thickness range of about 0.2–0.25 μm and 1.6–2.2 μm respectively. The efficiency of the technology has been improved by using highly reflective transparent conductive oxide (TCO), metal contacts and intermediate reflectors for light trapping, and depositing n-doped layer of silicon oxide for increasing current generation [6]. The highest stabilized power conversion efficiency of large area micromorph module (1.43 m^2) achieved so far is 12.34% by TEL Solar AG by using thicker intrinsic layer with optimized TCO layer, anti-reflective coating and doped layer [7]. Earlier in 2013, it was 10.7% for the same area module by the same manufacturer. The typical stabilization period of micromorph PV modules is 6–8 months with 8–20% LID of power [8].

Since, both the a-Si: H and μc-Si: H cells of the micromorph PV module have hydrogenated dangling bonds, which induces LID, therefore it is vital to carry out a detailed performance evaluation of the technology in real operating condition during stabilization in order to ensure the reliable lifetime operation. Tossa et al. (2016) have carried out performance analysis of monocrystalline, multicrystalline and micromorph based silicon PV modules in hot and harsh climate and found that micromorph is highest performing technology among the three with an average PR of 0.92 due to relatively low temperature coefficient and series resistance [9]. Torres-Ramírez et al. (2016) have studied the performance of micromorph TFPV technology on the basis of analytical modelling approaches in order to estimate the power and energy output of the technology [10]. Savvakis and Tsoutsos (2015) has presented a performance assessment of 2 years of operation of 2.18 kW_P micromorph based GI-TFPV technology having an average energy efficiency of 7.65% and a PR of 0.85 [11].

In this paper, performance studies are carried out using 7.92 kW_P micromorph based GI-TFPV system, having large area modules of 1.43 m^2, in order to understand their stabilization process so as to estimate the reliable outdoor spatial life of the technology.

2. Performance evaluation

Unlike wafer based PV technology, the micromorph thin film PV technology is neither proven nor established and moreover, it consists of a-Si: H which is prone to light induced degradation on the initial illumination of solar radiation. Hence, it is important to carry out performance evaluation and determine the degradation of emerging micromorph technology in real operating conditions. The outdoor experimental data have been filtered for improving the accuracy of the study and the required data have been analyzed in order assess the performance on the basis of energetic, exergetic, performance ratio, alternate reporting conditions and inverter performance. The detailed methodology used for the performance evaluation has been presented in flow chart as shown in Fig. 1 and discussed in the subsequent subsections.

2.1. Energetic and exergetic analysis

The energetic analysis is based on the first law of thermodynamics, which deals with energy efficiency and losses of individual PV array as well as PV systems. The first law of thermodynamics provides quantitative analysis based on the energy balance in which efficiency is defined as the ratio of energy or power output to the input. The micromorph TFPV module has glass to glass

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