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Energy rating estimation of PV module technologies for different climatic conditions

Birinchi Bora[a,b,*], Rajesh Kumar[a], O.S. Sastry[a], Basudev Prasad[b], Som Mondal[b], A.K. Tripathi[a]

[a] National Institute of Solar Energy, Gurgaon 122003, India
[b] TERI School of Advanced Studies, Delhi, India

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ABSTRACT

Energy rating of PV module as per the site-specific climatic condition is essential for customer's point of view to choose suitable PV technologies. For site and technology-specific energy rating of PV module, it is essential to design standard datasets for it. In this paper, energy ratings of three different technologies with the data sets based on the angle of incidence, spectrum, irradiance, wind and temperature using existing formulae has been reported. The performance surfaces of PV technologies are designed based on the IEC 61853-1 & 2, and IEC 60891. A procedure is reported to including the degradation rate in the energy rating method. Comparisons of energy rating of amorphous silicon, HIT and multi-crystalline silicon using the existing method considering the degradation rate are done with the measured data. It has been observed that all the three technologies at Cold & sunny zone shows the highest energy rating. A procedure, to find out the most frequent conditions in terms of occurrence probability for different PV technologies is also reported.

1. Introduction

Energy generation from the PV module depends on the environmental conditions of the surroundings. Usually, modules are tested as per the standard test condition (STC) only. However, the power output in field condition is mainly dependent on the irradiance, cell temperature, spectral content, and angle of incidence, which are function of the time of the day, season, location and climatic conditions. STC rating is a useful data to compare the performance of different technologies, but fail to give the accurate information how much energy it can generate for long-term operations (Kenny et al., 2006). The industry should design their cell and module to optimize the performance in real conditions rather than at STC. From a customer point of view, an energy rating of the PV module is more important than power rating. The energy rating of a module can be defined as the estimated DC energy generated in kWh per kWp per annum for a standard climate. The energy rating allows the customer to compare not only similar products from different manufacturers, but also completely different technologies. It should also provide a realistic estimated energy value for the region of installation and should be simple, accurate, repeatable, and acceptable for all (Whitaker and Newmiller, 1998). The performance of the PV module with respect to irradiance is not linear for all technologies. Under low light conditions, PV module with high shunt resistance shows higher power than a PV module with low shunt resistance (Bunea et al., 2006). The effect of irradiance on the performance of PV module depends on the angle of incidence (AOI) and spectral contents also. The main effect of angle of incidence can be defined in two ways: cosine effect and reflection of light from the top surface (Duffie and Beckman, 1991). With the increase in angle of incidence, the reflection of light is also increased (Adell, 1982). These types of angular losses can be quantified by different methodologies. Martin et al. have reported one analytical model to calculate the angular losses for PV module in field condition. They reported the behavior of angular losses for monocrystalline, polycrystalline and amorphous PV modules studding on ten different European sites, having diverse climates and latitudes, and with different tilt angles on the monthly and annual basis (Martin and Ruiz, 2001). The angle of incidence mainly affects the short-circuit current of the module because of the change in useful part of irradiance. Russell et al. reported that the angle of incidence affects the external quantum efficiency of PV module

* Corresponding author at: National Institute of Solar Energy, Gurgaon 122003, India.
E-mail address: birinchibora09@gmail.com (B. Bora).

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Nomenclature

E_{dni}	direct normal solar irradiance
E_{poa}	global solar irradiance on the plane-of-array (module)
E_o	reference global solar irradiance, typically 1000 W/m^2
AOI	angle between solar beam and module normal vector
T_c	measured module temperature
α_{Isc}	short circuit current temperature coefficient
Isc	measured short-circuit current
G_{eff}	effective solar irradiance
f_2(AOI)	relative optical response
Tm	module temperature
I	current
V	voltage
P	power
R_s	internal series resistance of the module
K	curve correction factor
α	current temperature coefficient
β	voltage temperature coefficient

Abbreviations

AOI	angle of incidence
ARC	antireflective coating
STC	standard test conditions
MFC	most frequent conditions
AM	air mass
a-Si	amorphous silicon
m-Si	multi crystalline silicon
HIT	heterojunction intrinsic thin film
APE	average photon energy
UF	utilization fraction
MMF	mismatch factor
PV	photovoltaic module
IEC	international electro technical commission
PR	performance ratio

technologies (Russell et al., 2014). They compute the changes in the spectrally resolved short-circuit current density as a function of the incidence angle, and provide cell level performance matrix that can be integrated into irradiance-to power model. Change in the spectrum and its effect on the PV module can be quantified by using average photon energy (APE), utilization fraction (UF) and mismatch factor (MMF). UF can be defined as the ratio of energy in the useful spectral range for the PV device under test to the total energy in the incident solar spectrum. UF can provide direct feedback of performance and quantifies spectral influence on PV devices. APE is the ratio of integrated solar irradiance to integrated photon flux density and indicates a spectral irradiance distribution of the solar spectrum measured. MMF is a correction factor applied to the short circuit current by taking into consideration the spectral mismatch between standard AM1.5 spectrum to the actual spectrum and it expresses the quantity of irradiance observed by the device under test as compared to reference device used for measuring irradiance. Bangar et al. have reported about the change in APE for different seasons of the composite climate of India. They found that most of the time the APE value of spectrum is above 1.88 eV (AM 1.5) for 350–1050 nm at the test site (Bangar et al., 2015). Cornaro et al. reported about the APE used to evaluate the spectral dependence of the performance of poly-Si and double junction a-Si modules. For a-Si, an increase in PR was observed with increase in APE and the poly-Si did not show a clear trend with APE evidencing stronger temperature dependence (Cornaro and Andreotti, 2013). They also reported that the PR dependence on module temperature for poly-Si is high as its temperature coefficients are more negative as compared to a-Si. Barua et al. have reported about the difference in the percentage of energy contribution for different seasons in two wavelength regions in terms of the blue and redshift. They have reported the spectral effect on the performance of CdTe technology and its quantification in terms of MMF for the test site (Barua et al., 2016). Gottschalg et al. reported the dependency of the short circuit current on the total spectral irradiance was explained with the experimental result by using UF. UF varies with the incident spectral irradiance and specific to the absorber material of the solar cell (Gottschalg et al., 2003). Magare et al. has reported about the effects of spectrum for HIT, m-Si and a-Si using UF in terms of the operating temperature and PR of the device (Magare et al., 2016). In this present study, the MMF is used to estimate the effect of the spectrum with respect to standard spectrum to estimate the effective irradiance for different PV module technologies. The energy generation of module technology also depends on the module temperature and module temperatures affect the voltage mainly. The temperature coefficients are depending upon the material properties of the solar cell. Makrides et al. reported about the simulated temperature coefficient of different types of PV technologies and compared with the measured and suggested that special attention need to give for temperature coefficient measurement of thin films (Makrides et al., 2009). The spectral effect is high in thin film module as compared to C-Si module because of the high band gap. For estimation of temperature coefficient, the spectral content of light in the outdoor condition should be maintained for different temperatures or it needs to be normalized to the standard spectrum. To include all these above-mentioned parameters and its effect on the energy generation from PV module, IEC has designed a standard IEC 61853 with four different parts. IEC 61853-1 is based on the effect of irradiance and temperature on the power rating with twenty two test conditions; IEC 61853-2 deals with test procedures for measuring the effect of spectral response, incidence angle, and module operating temperature measurements, as well as the estimation of module temperature from irradiance, ambient temperature, and wind speed; IEC 61853-3 deals with energy rating of PV modules; and IEC 61853-4 deals with the standard days, which describes the standard time periods and weather conditions that can be used for the energy rating calculations (TamizhMani and Mikonowicz, 2011). The IEC 61853-3 & 4 standards are going to be published very soon. This study is based on the energy rating estimation of three different technologies using the methodology provided in IEC 61853-1 to 3 for real-time measured data sets. There are very few literatures available in this particular area. In the