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Holistic performance appraisal of a photovoltaic system

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ABSTRACT

During this research, performance of a 2.45 kWp PV system was evaluated over a period of 5 years. International electrotechnical committee (IEC) standard, IEC 61724: 1998 and a robust mathematical model were used as a guide for the purpose. Performance of the system was closely monitored during the dry winter season. Annual production decreased from 3463.8 kWh to 3370.9 kWh and the capacity utilisation factor decreased from 16.14% to 15.71% over the period. Monthly production was stochastic, but the average monthly production curve followed the same trend as incident global horizontal radiation with low production during dry winter months. Performance ratio was above 90% at the beginning of dry winter month, it then decreased to less than 70% after three months. A mathematical model based on five parameter model and one diode equation was then used to extract essential cell parameters and simulate performance of the system. Statistical indices were computed to assess performance of the model against measurement data. Hence the quality factor of the PV system was computed and was found to be between 60% and 100% with an average of 87% in the dry winter month.

1. Introduction

In order to advance sustainable growth many countries are bound to increase renewable energy production under the COP21 agreement and meet 2030 targets. To set the tone, the photovoltaic (PV) sector has seen a new record growth in year 2015 with more than 50 GW added to reach a total of 227 GW of installed capacity [1] and maintained the exponential growth in the sector. While most of the new installations were in Europe, Asia and USA, other countries are lagging far behind in terms of implementation of renewable energy systems. Africa must increase its energy production by 630% to reach 2030 target [2]. Mauritius, though a small island, has set a target to achieve renewable energy (RE) production of 35% by 2030 [3]. With the aid of energy policies and promotion mechanisms such as small scale distributed generator (SSDG) feed in tariff introduced in 2010 and SSDG and medium scale distributed generator (MSDG) net metering schemes in 2015 and 2016 respectively, the installed capacity of RE systems has increased to almost 30 MW in 2016, representing almost 4.5% of total installed capacity, with a major share of PV. The current share of RE production share is 0.9% for PV, 0.1% for Wind, 17% for Bagasse, 4.1% for Hydro and 0.7% for land fill gas out of 2995 GWh produced in 2015 [4].

While integration of RE systems, especially PV, will keep on increasing during the next decade, it is also important to assess performance of installed systems such that it can be optimised to decrease levelised cost of electricity production and make the PV plants more competitive against other sources. Researchers and scientists have studied the performance of PV systems for many years and developed and proposed various methods for the evaluation of performance of photovoltaic systems [5–9]. Kelly *et al.* [10] assessed the effect of tilt angle of solar arrays on the energy output using four identical solar arrays during eight months and showed how direct and diffuse components affect the yield. The effect of local environmental effects, humidity and temperature on grid connected thin film PV system has been performed by Hanai et al. [11]. Makrides *et al.* [12] have measured the performance of thirteen different PV technologies in European countries with high irradiation and showed that similar systems have different outputs in different locations and as well showed that thin film technologies retain more stable efficiency compared to crystalline Si technologies in the Mediterranean region. Virtuani *et al.* [13] compared the indoor and outdoor performance measurements of recent commercially available solar modules and observed that maximum power of outdoor measurements under natural light was lower than that under standard measuring conditions due to spectral mismatch and sweep time effects. Various studies have been

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Nomenclature

Abbreviations

BoS	Balance of System
CUF	Capacity Utilisation Factor
GHI	Global Horizontal Irradiance
IEC	International Electrotechnical Committee
MABE	Mean Absolute Bias Error
MAPE	Mean Absolute Percentage Error
MBE	Mean Bias Error
MPE	Mean Percentage Error
MSDG	Medium Scale Distributed Generator
NOCT	Nominal Operating Cell Temperature Condition
NSE	Nash-Sutcliffe Equation
POA	Plane of Array
PV	Photovoltaics
RE	Renewable Energy
RMSE	Root Mean Square Error
SSDG	Small Scale Distributed Generator
STC	Standard Test Condition
κ	Material and construction constant
η_{load}	Load's Efficiency
α_t	Temperature coefficient of short circuit current
$\tau\alpha$	Effective transmittance-absorbance product
E_a	Energy generated per day
E_g	Energy bandgap
G_i	In-plane radiation
I_m	Maximum power point current
I_{ph}	Photocurrent
$I_{ph,ref}$	Photocurrent at reference condition
I_s	Saturation current
I_{sc}	Short circuit current
K	Boltzmann constant
L_c	Array capture loss
M_i	Simulated results
n	Ideality factor
O_i	Observed values
P_0	Peak rating
q	Charge of electron
Q_f	Quality factor
R_p	Performance ratio
R_s	Series resistance
R_{sh}	Shunt resistance
S	Solar irradiance
SC	Solar cell
S_{NOCT}	Irradiance at NOCT condition
S_{STC}	1000 w/m^2
S_T	Irradiance at given temperature
T	Temperature
T_a	Ambient temperature
T_c	Cell temperature
T_{STC}	298 k
U_l	Loss coefficient
$U_{l,NOCT}$	Loss coefficient at NOCT
V_m	Maximum power point voltage
V_{oc}	Open circuit voltage point
V_T	Thermal voltage
Y_a	Array yield
Y_f	Final system yield

carried out to measure the effect of orientation and inclination on the PV system performance [14–16]. Vashist *et al.* [17] studied the performance of solar plants under different seasons and climatic conditions of Bangalore in India. During the study the authors computed the performance ratio (R_p) and capacity utilisation factor (CUF) to assess and compare performance of the system with other systems. Similar works were performed by Shivalkar *et al.* [18] in Mumbai, India and Mediavilla et al. [19] in Serbia. IEC 61724: 1998 - Photovoltaic System Performance Monitoring - Guidelines for Measurement, Data Exchange and Analysis is an international standard [20] which describes procedures and methods for monitoring of energy related PV system characteristics in stand-alone or grid tied PV systems. While many researches have used terms like quality factor and performance ratio interchangeably, IEC 61724:1998 defines performance ratio as the overall effect of losses on the arrays rated output while other reports define performance ratio as the ratio of actual yield over calculated yield. During this research the term quality factor will be used to represent the latter.

Measurement system's performance requires huge investment in equipment and purchase of modules, hence modelling of the power produced by a PV system is more appropriate for technical as well as financial decisions [5]. The PV system simulation results provide researchers with a valuable tool to improve performance of the systems. PV performance models are used to simulate the performance of PV systems and they include: one diode solar cell model [21], four parameter cell model [22], five parameter cell model [6] and the SANDIA PV array performance model [23]. The main electrical parameters of modules are generally provided by manufacturers in the datasheets of modules while the resistances and the ideality factor must be extracted using appropriate models. Cotfas *et al.* [24] outlined, discussed and compared the main issues of 34 methods, which were developed and validated over 35 years, in order to determine the essential parameters of solar cells. Ramgolam *et al.* [25] analysed the 4- and 5- parameter models and compared results of System Advisor Model and the one-diode model for assessing PV systems. In general, the one-diode model is widely used for modelling of wafer technology PV modules. Inputs to the model are weather parameters such as temperature, irradiance and wind speed, design configurations such as number of panels per string, number of strings in the array, tilt and orientation as well as essential cell parameters obtained from 5- or 4-parameter models. Various techniques and equations have been prosed for quantifying the cell temperature with respect to site specific weather conditions [26–29]. Generally statistical indices are used for appraisal of models and they include mean bias error (MBE), mean absolute bias error (MABE), mean percentage error (MPE), mean absolute percentage error (MAPE), root mean square error (RMSE) and Nash-Sutcliffe equation (NSE) [30–32].

As knowledge of performance of PV systems across the globe is highly important for higher level of penetration and holistic system design, the aim of this research was to appraise the performance of a 2.45 kWp PV system as per IEC 61724: 1998 since installation of the plant in 2011. The quality factor is computed using a robust technique whereby the calculated power is obtained by modelling the performance of the system using one-diode and 5-parameter model with input as design configurations, weather data and cell characteristics. Statistical indices are used to assess performance of the model to justify its use and such that conclusions could be made