Solar Energy 157 (2017) 408–418

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Normalised efficiency of photovoltaic systems: Going beyond the performance ratio

Bert Herteleer[a,b,c,d,*], Bart Huyck[a], Francky Catthoor[b,c], Johan Driesen[b,d], Jan Cappelle[a]

[a] E & A Research Group, Faculty of Technology Engineering, KU Leuven, Gebroeders De Smetstraat 1, 9000 Gent, Belgium
[b] ESAT/ELECTA, KU Leuven, Kasteelpark Arenberg 10, B-3001 Leuven, Belgium
[c] IMEC vzw, Kapeldreef 75, B-3001 Heverlee, Belgium
[d] EnergyVille, Thor Park 8300, 3600 Genk, Belgium

ARTICLE INFO

Keywords:
Normalised efficiency
Performance ratio
Temperature correction
Shading detection

ABSTRACT

This article introduces the normalised efficiency of photovoltaic modules and systems as a performance monitoring metric, and its similarity to the Performance Ratio is shown. Detection of shading using the normalised efficiency is presented. From module temperature measurements and using the normalised efficiency, it is possible to calculate a system temperature coefficient, which then serves for temperature-corrected system analyses, and may serve to identify otherwise hidden temperature-dependent behaviour in the system studied. A simpler method to obtain coefficients for the modelled normalised efficiency is given which requires only irradiance, module temperature and power data as modelling inputs, and validated using three photovoltaic systems.

1. Introduction

The Performance Ratio (PR) has been the most widely used (Photovoltaic , 0000; Woyte et al., 2014) and reported measure to quantify and compare the performance of photovoltaic (PV) systems to date. Improvements to the original definition of PR by including (and correcting for) temperature effects were given, in Leloux et al. (2012) and Leloux et al. (2012) among others, with a report on the work in progress given by Gostein et al. (2014). King (2011) introduced the use of the regular (i.e. not normalised) AC (system) efficiency and Copper et al. extended this approach to the DC side of the photovoltaic array. Huld et al. (2010), Huld et al. (2011) used and defined a module-level model of the instantaneous relative efficiency η_{rel} and its hourly and yearly equivalent, by modifying the model of King et al..

The normalization aspect of the Performance Ratio, by which the performance systems of different power ratings and orientations can be compared to each other, is applied in this article to the time-dependent normalised efficiency of a PV system calculated from data of the measurement set-up described in Herteleer et al. (2014) with additional details given below. The applications of the normalised efficiency of a PV system will be explored, and a model of the short-term variation (time resolution of seconds) of the temperature-corrected normalised efficiency will be given and validated by measurements.

The main contributions of this article are in the introduction of the normalised efficiency of a photovoltaic module or system as an additional photovoltaic performance metric for monitoring and analysis purposes, which can be implemented on time scales ranging from seconds to days and longer. The normalised efficiency also permits an improved qualitative and quantitative comparison of systems with different power ratings in graphical displays and numerical calculations. A modification to the temperature-corrected form of the power rating model of Huld et al. (2010) and Huld et al. (2011) for photovoltaic modules is given, by applying it not only on individual PV modules, but also PV arrays and systems on the DC and AC side. A significant improvement in this work is that it is possible to obtain the polynomial coefficients for the model of temperature-corrected normalised power using a significantly reduced data set over a shorter measurement period with lower or similar errors than the reduced model of Huld et al., and allows these coefficients to be obtained from any source of MPP data (I-V curves, inverter MPP measurements). In particular, the approach of this work is more widely applicable for monitoring, as it can use lower-cost measurement equipment, and does not require I-V curve measurements, but uses widely monitored signals for PV systems: module or system DC or AC power, and irradiance and module temperatures.

This article is structured as follows: the theoretical background for

* Corresponding author at: Ekistica, Desert Knowledge Precinct, 0870, Alice Springs, Northern Territory, Australia.
E-mail addresses: bert.herteleer@gmail.com (B. Herteleer), bart.huyck@kuleuven.be (B. Huyck), catthoor@imec.be (F. Catthoor), johan.driesen@esat.kuleuven.be (J. Driesen), jan.cappelle@kuleuven.be (J. Cappelle).

http://dx.doi.org/10.1016/j.solener.2017.08.037
Received 22 September 2015; Received in revised form 2 August 2017; Accepted 12 August 2017

Nomenclature

G	irradiance [W/m^2]
G_{STC}	STC irradiance: 1000 [W/m^2]
PR_τ	Performance Ratio over period τ
P_N	normalized PV module or system power [kW$_p$]
$P^*_{N,mod}$	normalized temperature-corrected modelled power
P_{STC}	STC nameplate power of PV module or array [kW$_p$].
T_{STC}	STC module cell temperature: 25 [°C]
T_{cell}	cell temperature [°C]
$Y_{f,\tau}$	final yield over period τ [kWh/kW$_p$·τ]
$Y_{r,\tau}$	reference yield over period τ [kWh/m^2·τ]
ΔT_{STC}	module temperature difference to T_{STC} [°C]
$\eta_N(t)$	normalized instantaneous PV module or array efficiency [–]
$\eta^*_N(t)$	normalized temperature-corrected instantaneous PV module or array efficiency [–]
γ	efficiency temperature coefficient [%/°C]
$\langle\eta_N\rangle_\tau$	normalized average efficiency of PV module or system over period τ [–]
$\langle\eta^*_N\rangle_\tau$	normalized average temperature-corrected efficiency of PV module or system over period τ [–]
$\sigma_{\Delta G}$	standard deviation of the irradiance rate of change [W/m^2]
τ	time interval [second, hour, day, year]
MPP	Maximum Power Point
NVI	Natural Variability Index [–]
SSE	Square root of the Sum of Errors squared

the measured normalised efficiency (both regular and temperature-corrected) is given in Section 2. Using this framework, some measurement results and applications of the normalised efficiency are presented. Daily data analysis is shown for a few days, for which the Natural Variability Index (NVI) (Willy et al., 2014) is used and modified for the time scales employed. The improvements to the coefficient determination for the model of the temperature-corrected normalised efficiency are presented, and validated against the measured data. Finally, the conclusions for monitoring and modelling applications are given.

2. Theoretical background and definition of parameters

The definition of PR_τ is typically given as the ratio of the Final Yield $Y_{f,\tau}$ to the Reference Yield $Y_{r,\tau}$ over a time interval τ, which is generally taken in the range of days, and occasionally shorter periods (e.g. 5 min intervals Woyte et al., 2014). The Reference Yield is most often calculated in its discrete form:

$$Y_{r,\tau} = \frac{1}{G_{STC}}\cdot\int_0^\tau G(t)\cdot dt \equiv \frac{1}{G_{STC}}\cdot\sum_0^\tau G(t)\cdot\Delta t, \tag{1}$$

which is also the case for the Final Yield, which is normalised in order to allow a rapid comparison to $Y_{r,\tau}$:

$$Y_{f,\tau} = \frac{1}{P_{STC}}\cdot\int_0^\tau P(t)\cdot dt \equiv \frac{1}{P_{STC}}\cdot\sum_0^\tau P(t)\cdot\Delta t. \tag{2}$$

Eqs. (1) and (2) are then taken to calculate the Performance Ratio:

$$PR_\tau = \frac{Y_{f,\tau}}{Y_{r,\tau}}. \tag{3}$$

By fully writing out the equation of PR,

$$PR_\tau = \frac{\frac{1}{P_{STC}}\cdot\sum_0^\tau P(t)\cdot\Delta t}{\frac{1}{G_{STC}}\cdot\sum_0^\tau G(t)\cdot\Delta t} \equiv \frac{\langle\frac{1}{P_{STC}}\cdot P(t)\rangle_\tau}{\langle\frac{1}{G_{STC}}\cdot G(t)\rangle_\tau}, \tag{4}$$

it becomes clear that the Performance Ratio is also a mathematical expression for the arithmetic mean of the (scaled, or normalised) power divided by the mean of the irradiance, as in both cases the energy is calculated over the same time interval τ. Important to note here is that the time-dependent nature of photovoltaic power and energy generation is mostly removed by calculating PR, or any other summary metric.

Introducing the normalised efficiency $\eta_N(t)$ and its mean $\langle\eta_N\rangle_\tau$ over a period τ:

$$\langle\eta_N\rangle_\tau = \left\langle\frac{\frac{1}{P_{STC}}\cdot P(t)}{\frac{1}{G_{STC}}\cdot G(t)}\right\rangle_\tau = \langle\eta_N(t)\rangle_\tau, \tag{5}$$

the similarity to the calculation of PR_τ becomes apparent. The main difference is that for $\langle\eta_N\rangle_\tau$ the input (irradiance) is *first* linked to the output (power) on a moment-by-moment basis and *then* averaged. Conceptually, this is not a trivial distinction between PR and $\langle\eta_N\rangle_\tau$: for the (mathematical) calculation of PR, the sequence of PV power (and energy) is of no consequence, which does not represent reality. The normalised efficiency can be calculated using either a pyranometer or reference cell signal, which is discussed further in Section 5.3.

It is possible to obtain the temperature-corrected form of $\langle\eta_N\rangle_\tau$ and PR (Dierauf et al., 2013; Nordmann et al., 2014) ($\langle\eta^*_N\rangle_\tau$ respectively PR*), by using Eqs. (6) and (7), defined here as

$$T_{corr} = 1 + \gamma\cdot(T_{cell}-T_{STC}) = 1 + \gamma\cdot\Delta T_{STC}, \tag{6}$$

$$P^* = \frac{P(T_{cell})}{T_{corr}}, \tag{7}$$

and then replacing P by P^* in Eq. (5), with P the power (or efficiency) that shows a temperature dependence, as widely documented (Skoplaki and Palyvos, 2009). Important to note here, is that for mostly stable irradiance conditions (typically > 200 W/m^2), the graph of $\eta^*_N(t)$ should be as close as possible to a flat line. For a module or system performing at its STC rated temperature and near-STC spectrum, this should be a line equal to 1; deviations from this value may point to a variety of losses that can subsequently be investigated, such as spectral mismatch, optical losses, wiring or soiling losses. Fig. 1 illustrates the application of the temperature correction on the normalised efficiency, for both DC and AC values. The efficiency dip around 21 h is due to nearby shading caused by the sun's path being behind the measurement cabinets, casting shade on the modules. The value of the system temperature coefficient γ_{syst} may either be obtained from data sheets or experimentally determined using, e.g. $\eta_N(T)$, as explained in Section 4.

3. Description of measurement set-up and data treatment

The data presented in this article is obtained from the measurement set-up presented in Herteleer et al. (2014), which has been modified since. The software used to program and interface with the sensors and meters is LabVIEW, with power and weather data measured and stored per second. The system now measures DC voltage and current between PV module(s) and inverter or DC-DC converter using custom-built signal conditioning boards, which isolate the signal from the power side and scale the signals for acquisition by NI 9205/9206 analog voltage measurement cards. Three inverters are currently used and logged, with the AC parameters such as voltage, current, power and energy measured using a commercial 0.5% three-phase revenue meter and the energy additionally measured per phase using single-phase commercial 1.0% energy meters. Twelve PV modules (eight with standard mono-crystalline cells, four with Metal Wrap-Through (MWT) cells) are connected using individual DC-DC converters to a SolarEdge 3.0 kW inverter, with DC voltage and current centrally measured in temperature-controlled cabinets between PV module and DC-DC converter, and at two outputs of DC-DC converters and at the central DC input to the