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Statistical estimates of short duration power generated by a photovoltaic unit in environment of scattered cloud cover

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ABSTRACT

The statistics of low level scattered cloud cover (cumulus or strato-cumulus types), is evolved to formulate analytical expressions for *short duration mean output power* and its *variability*, as well as *power change distribution*, at the output of photovoltaic generating stations. The proposed expressions are used to obtain *statistical estimates* of the three, which are substantiated by comparison to empirical *ensemble estimates* reported in available literature.

The strength of concepts and formulations presented in the paper is their dependence on a single aggregated meteorological parameter, namely the *optical air mass*. Their applicability therefore spans over a range of PV generation plants regardless of geographical and weather conditions.

1. Introduction

Both spatial and temporal variability pose critical challenges to large scale integration of PV (photovoltaic) generating units within a conventional utility network [1,2]. However, while the IEC61853-1 Standard provides inferences and guidelines on geographical distribution of PV units for effective reduction of spatial variability [2], *temporal variability* (particularly over *short duration spans* of seconds or minutes) is a somewhat nebulous issue in the context of PV generation (which is in contrast to say, wind based generation [1]). There are several factors specific to PV power generation that contribute to complexity of temporal variation in the short duration:

i. Though solar irradiation is the fundamental source of PV energy, short duration variations are largely dependent on *cloud transients* – the intermittent light-and-shade effect caused by movement of clouds over PV receivers [3]. This is in contrast to variability of wind power, which is caused by *turbulence* within the source wind [1]. Therefore, while the source available to a turbine directly influences short duration variability of wind generation; the same can hardly be claimed about the effect of source irradiance on PV power output.
ii. Irradiation has its own diurnal variation from dawn to dusk under "clear sky" condition, and the short duration impact of cloud transients differs according to time of the day. Further, conversion of irradiation to output power depends on slow variation of the NOCT (*normal operating cell temperature)* as well as ambient wind [4–7]; thereby making power variations dependent on these exogenous factors.
iii. MPPT (*Maximum-power-point-tracking)* controllers, typically installed on PV power generation units today [8,9] have little filtering effect on power variations arising due to cloud transients. This aspect has been examined through simulation and experiments in Refs. [10–12]. Further in the same context, useful experimental comparison between different MPPT implementations has been presented in Refs. [13,14]. It can be concluded from the latter that regardless of the effect of cloud motion on irradiance, MPPT by different realisations of *incremental-conductance method* and *perturb-and-observe algorithm* [13] may convert over ninety nine percent of effective irradiance to PV output power.

Most reported studies on short duration variation of PV generation involve compiled *ensemble data* sets; elements of which are obtained by averaging data stream across a pre-decided recording interval (the so called *averaging time*). Power variations are typically assessed in terms of one or more of the following measures, all computed across recorded data ensembles [1,3,15,16]:

- The *short duration mean output power* evaluated usually across time span of minutes or less.
- The *short duration output power variability* is the normalised standard deviation of power output by a PV unit, evaluated under

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Nomenclature (with typical MKS units, where relevant)

A_1, A_2, A_i	scale coefficient for modified Boltzmann distribution
ε_t	per-unit instantaneous irradiance at the collector of a PV converter
$E_{GH}(.)$	global horizontal irradiance at the collector of a PV converter (kW/m^2)
E_t	instantaneous irradiance at the collector of a PV converter (kW/m^2)
E_{rat}	rated PV plant or converter capacity per unit collector area (kW/m^2)
$\overline{E_t}(.)$	short duration statistical mean of irradiance at PV unit (kW/m^2)
f	maximum fraction of rated PV plant or converter capacity, reached under "clear sky" condition
$\mathscr{F}_s(\eta)$	complete Fermi–Dirac integral of index s for argument η
ϕ	upper limit of per unit output power parameter for "less than" cumulative probability
$\Phi(.)$	"less than" cumulative probability of occurrence
$\Gamma(.)$	complete gamma function
h	elevation (m)
$K_t(.)$, K_t	instantaneous clearness index
$\overline{K_t}(.)$	short duration statistical mean of clearness index at PV unit
K_{to1}, K_{to2}, K_{toi}	modal value of clearness index for a modified Boltzmann distribution
κ	upper limit of clearness index parameter for "less than" cumulative probability
$\mathrm{Li}_s(z)$	polylogarithm function of order s for argument z
λ_1, λ_2, λ_i	width parameter for a modified Boltzmann distribution
m_a	relative optical air mass
N	whole number of days over which f and m_a are approximately constant
$p(.)$	probability density function
$P(.)$	probability
θ	phase angle variable to represent variation of daylight hours
s_1, s_2	short duration variance of clearness index for individual modal values K_{to1} and K_{to2} [35]
υ	short duration output power variability at PV unit
$\bar{\upsilon}$	time average of short duration output power variability at PV unit
T_L	Linke turbidity
z	zenith angle (rads)

(The symbols s, t, z, and η have been used as dummy variables for the basic expressions of polylogarithm functions and Fermi–Dirac integral.)

similar conditions as the mean output power. A measure of the randomness of instantaneous output *around* the short duration mean, this assumes zero value under "clear-sky" conditions. Together with the short duration variability of demand, the *output power variability* can be used to estimate reserve regulation requirements for large scale integration of PV resources [16].

- The *power change distribution* describes the probability distribution (or more commonly, the cumulative probability distribution) of incremental output power changes (sometimes referred to as *power ramps*) that occur in response to cloud transients. When evaluated against short duration demand changes, these can be used to (*a*) organise fleet topology of PV units for *temporal smoothing* of PV generation, (*b*) assess *load following capability* of the fleet, as well as (*c*) *ramp rate response* of connected conventional units. In practice, it is customary to present empirical distributions of *probability of occurrence* or *cumulative probability of occurrence* with *averaging time* as a parameter. Thus references to "*5-min ramp distributions*" or "*distribution at 15-s timescale*" are common in available literature [17–19].

While empirical evaluation of *ensemble estimates* is significantly dependent on data recording infrastructure and resources, closed-form analytical expressions for the same would be very useful support to the process of PV resource assessment and planning. First, estimates by analytical expressions are modest in computational requirement, and consequently less susceptible to measurement and recording errors. Second, expressions of suitable accuracy may be used for prior assessment of prospective PV installations against demand variations, so as to be followed by meaningful capital investments and restrict them only to operationally viable plants. Further in the context of networks with already commissioned PV resources, analytical estimates of short duration variation can be used to evaluate ramp-following capability of connected conventional units, together with reserve regulation.

Unlike the references cited above, this paper does not present primary *ensemble data* recorded through field studies. Based on a background of cloud transient statistics, the paper proposes suitable closed-form analytical expressions for *statistical estimates* of *short duration mean output power*, *variability,* and *power change distributions* applicable to existing or proposed PV installations sites. (Throughout this paper, estimates obtained using analytical expressions are referred to as *statistical estimates*, so as to distinguish them from empirically evaluated *ensemble estimates*.) Section 2 provides meteorological background for the analytical treatment to follow in Section 3. Through appropriate derivations, Section 3 proposes conclusive analytical expressions for all three measures, using *clearness index* as the basic temporal variable. Section 4 justifies the proposed expressions by comparison to empirical *ensemble estimates* reported in currently available literature [18,27,35].

An exposure to the concept of *optical air mass* is appropriate at this juncture, since this emerges as the single most important independent meteorological parameter in the treatment to follow. Fundamentally the optical air mass for an incident beam is the *integral of air density along the entire beam path*, or alternately the *mass of air along the path* per *unit cross section area of the beam* [20]. When used as a meteorological parameter to characterise a weather scenario, it is *aggregated over all possible beam paths* (direct as well as reflected) and normalised by the *air-density integral over the direct beam path from the zenith* [21,22]. The aggregated, normalised dimensionless parameter is commonly referred to as the "relative optical air mass", or simply the *optical air mass* m_a. Thus defined, m_a covers all reflective effects attributable to cloud cover, and therefore serves as a comprehensive independent parametric measure for the same. For further detail on this well established meteorological concept, the interested reader may please refer to [20–22].

2. Cloud transients and statistics of effective irradiation

Conventionally, the variable *irradiance* E_t at any PV converter is viewed as a product of the *global horizontal irradiance* E_{GH} and the *clearness index* K_t [23] as