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Optimization of significant insolation distribution parameters – A new approach towards BIPV system design

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ABSTRACT

System efficiency and payback time are yet to attain a commercially viable level for solar photovoltaic energy projects. Despite huge development in prediction of solar radiation data, there is a gap in extraction of pertinent information from such data. Hence the available data cannot be effectively utilized for engineering application. This is acting as a barrier for the emerging technology. For making accurate engineering and financial calculations regarding any solar energy project, it is crucial to identify and optimize the most significant statistic(s) representing insolation availability by the Photovoltaic setup at the installation site. Quality Function Deployment (QFD) technique has been applied for identifying the statistic(s), which are of high significance from a project designer's point of view. A MATLAB™ program has been used to build the annual frequency distribution of hourly insolation over any module plane at a given location. Descriptive statistical analysis of such distributions is done through MINITAB™. For Building Integrated Photo Voltaic (BIPV) installation, similar statistical analysis has been carried out for the composite frequency distribution, which is formed by weighted summation of insolation distributions for different module planes used in the installation. Vital most influential statistic(s) of the composite distribution have been optimized through Artificial Neural Network computation. This approach is expected to open up a new horizon in BIPV system design.

1. Introduction

The most significant ingress of renewable energy into the modern urban life has just been initiated through the installation of BIPV systems, which is essentially deployment and integration of large area PV panels with all possible facades of buildings [1]. Accordingly, PV Array configurations should be ‘space-intelligent’ [2] as well as ‘insolation-intelligent’ in nature in order to ensure true energy sustainable and economically viable [3] design. But like most other application areas of renewable energy technologies, some engineering gaps are still prevalent resulting in uncertainty of performance of BIPV energy systems. In fact this kind of techno-management shortcoming is primarily responsible for the inability of solar PV technology to attract adequate investment [4] and business intelligence required for its desired market penetration. This critical gap between laboratory and life for an emerging technology can be effectively bridged by Quality Engineering tools and techniques, which are in many cases based on proven statistical methods. Using such statistical methods, an extremely use friendly and economic yet accurate instrument for insolation measurement have been successfully developed [5]. In another application, an algorithm based on Quality Engineering tools like Designed Experiment (DOE), ANOVA, Regression modeling and Response Surface Methodology (RSM) was developed for accurate prediction of PV module behavior under any given environmental condition [6,7]. Further research showed that the term “*given environmental condition*” calls for objective quantification of the insolation availability for a site and to be more precise, for the solar photovoltaic installation at that site. It is to be noted that the ‘insolation availability at a site’ and ‘insolation availability by a Solar PV installation’ are not synonymous. Discussion in the subsequent sections will show why lack of clarity in understanding and estimating the most appropriate ‘Statistic(s)’ representing the insolation availability and its variation may lead to wrong selection of PV modules, over specification, cost escalation and error in performance prediction of the solar PV energy systems. In this paper, a new way of defining and maximizing the ‘insolation availability’ on a solar PV installation at a project site has been developed following three steps:

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1. Formation of composite frequency distribution of hourly total radiation round the year falling on the different module planes used in the installation.
2. Analyzing the descriptive statistics parameters of the composite frequency distribution towards identification of the 'statistic(s) of choice' representing insolation availability.
3. Optimizing these 'statistic(s) of choice' for ensuring better system efficiency and certainty of power delivery through intelligent combination of module planes using neural network computations.

2. Basic solar radiation modeling

Parameters pertaining to basic insolation modeling can be classified into three categories:

1. Insolation Parameters indicating values of the total incident solar radiation and its components.
2. Independent Parameters on which depends the insolation level with respect to time, location and orientation.
3. Intermediate parameters, which are calculated based on the independent parameters and required to get the values of the insolation parameters.

Table 1 lists the essential parameters involved in solar radiation modeling.

The set of equations [8,9] used for calculating the various components of insolation and intermediate parameters are given as follows:

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+n)\right] \tag{2.1}$$

$$\cos\theta = \sin\phi(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos\phi(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta \tag{2.2}$$

Table 1
Symbols and description of parameters pertaining to insolation modeling.

Independent parameters	
n	Day number ($n = 1$on Jan 1, $n = 365$ on Dec 31)
φ	Latitude of the place
K_t	Clearness index
ω	Hour angle (1 h ≡ 15°; $\omega = 0°$ at 12 noon)
β	Slope of the incident plane with horizontal (Horizontal surface $\beta = 0°$, Vertical surface $\beta = 90°$)
γ	Surface Azimuth Angle ($\gamma = 0°$ for module facing south)
Intermediate calculation parameters	
δ	Declination
ω_s	Sun rise or sun set hour angle (Sep 23–Mar 20)
ω_{st}	Sun rise or sun set hour angle (Mar 21–Sep 22)
θ	Angle between the incident beam and normal to the incident plane
θ_z	Value of theta, when $\beta = 0$, i.e. incident plane is horizontal surface
r_b	Tilt factor of beam radiation
r_d	Tilt factor of diffuse radiation
r_r	Tilt factor of reflected radiation
I_{sc}	Solar constant
I_{sc}'	Instantaneous value of extraterrestrial flux received on unit area perpendicular to the sun
Insolation parameters	
I_0	Hourly extra terrestrial radiation on a horizontal surface
I_g	Hourly radiation (flux) falling on a horizontal surface
I_d	Hourly diffuse radiation (flux) falling on a horizontal surface
I_b	Hourly beam radiation (flux) falling on a horizontal surface
I_T	Hourly radiation (flux) falling on a tilted surface

$$\cos\theta_Z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \tag{2.3}$$

$$\omega_{st} = \cos^{-1}[-\tan(\phi-\beta)\tan\delta] \tag{2.4}$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \tag{2.5}$$

$$r_b = \frac{\cos\theta}{\cos\theta_Z} \tag{2.6}$$

$$r_d = \frac{1+\cos\beta}{2} \tag{2.7}$$

$$r_r = \rho\left(\frac{1-\cos\beta}{2}\right) \tag{2.8}$$

$$a = 0.949 + 0.0118|\phi| \tag{2.9}$$

$$b = 1.185 + 0.0135|\phi| \tag{2.10}$$

$$I_{sc}' = I_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \tag{2.11}$$

$$I_0 = I_{sc}'\cos\theta \tag{2.12}$$

$$I_g = K_T I_0 \tag{2.13}$$

$$I_d = I_g\left[a - b\left(\frac{I_g}{I_0}\right)\right] = I_g[a - bK_T] \tag{2.14}$$

$$I_b = I_g - I_d \tag{2.15}$$

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r \tag{2.16}$$

Out of all the insolation parameters, I_T is the most meaningful for solar PV application as module voltage, current, power and conversion efficiency depend on this [10,11]. Equations (2.1)–(2.16) show that I_T (as well as other insolation parameters) depends on 6 independent parameters ($n, \varphi, \omega, K_T, \beta$ and γ). For a given site n, φ, ω, K_T are not in the hand of a designer. So essentially the designers are to work with just two variables – β and γ. A MATLAB™ program has been used to build the annual frequency distribution of hourly insolation over any module plane at a given site location. This software takes the input information with regard to $\varphi, \omega, K_T, \beta$ and γ. For the ease of discussion annual frequency distribution of I_T for a given module plane (β_i, γ_i) will be indicated as FD_I_T(β_i, γ_i). It could be mentioned here that values of clearness index K_T are easily available from the standard metrological data, published by local weather departments [12].

2.1. Significance of module planes in BIPV application

In the current global economic scenario space is becoming increasingly expensive in both urban and rural areas. It could be well imagined that even the cost of a rooftop in any city is a concern. As solar PV panels/arrays occupy a huge area for installation, the associated financial challenge could be best answered by space-saving technologies like building integrated photovoltaic installation. BIPV not only saves the cost of dedicated space allocated for the PV panels, but also it shares a certain portion of structural and civil construction cost. But at the same time BIPV restricts the absolute freedom of placing the modules in the so-called 'best possible' plane (inclination angle and azimuth angle)