Rear Side Solar Radiation Model of Bifacial Photovoltaic Module for Equatorial zone

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Abstract. Many models are available to simulate the solar radiation incident on monofacial photovoltaic panels but these models cannot be used to evaluate the radiation incident on a bifacial photovoltaic panel as it does not consider the bifacial gain due to ground reflection and diffuse sky radiation. In this paper an optical model was developed to measure the global solar irradiance on front and rear side of a bifacial photovoltaic module. The bifacial gain at the rear surface is modelled by considering the diffuse sky radiation and reflected component of light from ground and nearby surfaces. An optimised model is developed for Equatorial zone for maximum bifacial gain considering tilt and shading parameters. A comparative study on annual gain for the bifacial module compared to monofacial module also done for the topical latitude zone.

1. Introduction
Monofacial silicon solar panels comprises the bulk of solar photovoltaic installations in solar farms thought the world. However, these panels are made of a technology which collects solar energy on only one surface of the cell unlike the bifacial solar cells which are capable of producing energy from both the surfaces of the cell. The bifacial panels performs better than monofacial in cloudy or winter conditions better due to the large fraction of diffuse irradiation on the rear side. The higher output in bifacial photovoltaic modules is caused due to the additional radiation falling on the rear side of bifacial panels. However the amount of radiation depends on the light reflected from the rear side and the area of shadow formed.

The area of shadow formed determines the amount of radiation falling on the rear and is the most important parameter in determining the performance of a bifacial module. If the rear side irradiation is calculating the reflected light from both shaded and unshaded region of the ground then an optical model can be developed. This helps in calculating the bifaciality factor which is a performance parameter of bifacial solar panels compared to monofacial solar panels. The bifaciality factor (%) is defined as the ratio of the rear side efficiency to the front side efficiency, measured under standard test conditions. Since the Bifacial Photovoltaic Technology (BPVT) is new, many models were developed to study the performance of bifacial systems. However, these are either partial models which study only a particular phenomenon, are not accurate and are mostly location specific. J.R. Ledesma, et.al. [1] developed a simplified two-dimensional view factor model for bifacial Photovoltaic plants in an open simulation tool, SISIFO, for static and horizontal single-axis tracked structures for Madrid location shows a non-
homogeneous rear irradiance. Also the model predicts that the row to row spacing of module is a more important parameter that influences the bifacial gain compared to height of installation of panel.

A comprehensive optical-electrical-thermal model for the bifacial PV module was developed by Wenbo Gu, et al. [2] gives global irradiance gain in optical model, the cell temperature in thermal model and power output in electrical model. The validated model shows a good year round bifacial gain of 22% for Hong Kong and Shanghai locations. The model also predicts better bifacial gain in cloudy environmental conditions compared to clear sky due to diffuse radiation. The thermal performance of bifacial module was analysed by a thermal steady state model by considering the gain from ground reflectivity was developed by Zhen Zhang, et.al. [3]. The effect of radiation gain in three different ground types and module back cover material on bifacial module temperature was studied using the model. A. Abotalab, et.al [4] developed a thermal model in COMSOL Multiphysics to calculate the module temperature, energy yield and theoretical power output. The model predicts a gain in short circuit current with increase in the ratio of diffuse radiation.

A numerical model using irradiance values from a NASA meteorological database was developed for vertical bifacial panel farm by M. Ryyan Khan, et al. [5]. The numerical calculation is a non-trivial generalization of the view-factor method used for flat-ground solar farm energy-yield calculations. An electrical model combined with optical model calculates the energy output of a panel. The current work is a preliminary study to develop a reliable optical model for the bifacial system. The system is developed and simulated for Equator and the same can be modified and the optical model of any place on the Globe can be developed.

2. Radiation Model
To make the model simple, the bifacial photovoltaic panel was assumed to be located in the Equator. The panel is installed at East-West orientation in the model as in figure 1.

![Figure1. Bifacial photovoltaic module installed in East-West orientation](image)

2.1 View Factor / Shape factor
The radiation transfer between two or more surfaces depends on the orientation between the two surfaces. The view factor from a ‘surface i’ to ‘surface j’ can be defined as the fraction of radiation leaving the ‘surface i’ that strikes ‘surface j’ directly. It is denoted by Fi-j. The shape factor of a ‘surface i’ with respect to ‘surface j’ is given by equation (1).

\[
F_{ij} = \frac{Q_{Ai-Aj}}{Q_{Ai}} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j}{\pi r^2} dA_i dA_j
\] (1)

The view factor is independent of the surface properties, temperature, etc and is purely geometric quantity. The major assumption made is that all the surfaces are diffuse emitters and diffuse reflectors of radiation.
2.2 Length of the Shadow
The shadow formed by the panel at the rear side in the equator is a function of height of the panel and the altitude angle of the sun. The length of the shadow ($L$) is given by equation (2).

\[
L = \frac{H}{\tan \alpha} 
\]

Table 1 gives the altitude angle for various times of day. The length of shadow is obtained for every hour duration from 06:00 hours to 18:00 hours that is from Sunrise to Sunset is used and the view factor for every hour interval of a day is modelled.

| Time of day (hrs) | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Altitude angle   | 90  | 75  | 60  | 45  | 30  | 15  | 0   | -15 | -30 | -45 | -60 | -75 | -90 |

2.3 Bifacial Gain
The bifacial gain is calculated from the view factors from the ground to rear sides of the modules. This is measured as the sum of the irradiance on the rear side from the shaded and unshaded region of the ground surface [8]. The intensity of reflected light falling on the rear side of the bifacial module ($I_{refl,r}$) is given equation (3).

\[
I_{refl,r} = \alpha_1 GHI F_{Ansh-AM} + \alpha_1 DHI F_{Ash-AM} 
\]

where, $\alpha_1$ is the albedo of the ground surface, GHI is the Global Horizontal Irradiance, DHI is the Diffuse Horizontal Irradiance, $F_{Ansh-AM}$ is the view factor between unshaded ground surface element and a surface element on the module rear side and $F_{Ash-AM}$ is the view factor between a shaded ground surface element and a surface element on the module rear. Synthetic hourly data was generated for a day at Singapore location (1.3521°N Latitude) from Meteonorm database in PVsyst software. This data was approximated for Equatorial location to find the average hourly GHI and DHI at the Equator.

3. Design and Simulation in COMSOL Multiphysics
A bifacial photovoltaic view factor model to find rear side irradiation was designed in COMSOL Multiphysics software. Nicolas Huc [6] developed new operators in COMSOL Multiphysics version 5.0 and above to model view factor between two concentric spheres. The module computes the view factors using the operators provided by surface-to-surface radiation features. The geometric configuration consists of two concentric spheres, and the results include computed view factors, which are compared with analytical values. The view factor between the surfaces of the two spheres are evaluated by the syntax given in Figure 2.

Using the concentric sphere model as reference, a view factor model for flat plates representing the bifacial photovoltaic panels and ground shaded and unshaded regions were developed. The bifacial photovoltaic panel was assumed to be located in the Equator and the panel is installed at East-West orientation in the model. This helped in neglecting the effect of solar azimuth angle and latitude angle in determination of the shaded and unshaded region and making the preliminary model simple. The shadows formed in the Equator is perfect rectangles and are in alignment with the installed panels. Such a model was also specifically selected to validate the model with the standard view factor for rectangular surfaces available in data books. The specification considered for the model was Panel Dimension: $1 \times 0.5$ m; Reflection Area: $2 \times 2$ m; Location: Equator; Mounting: Ground Mounted; Altitude angle: $0^\circ$ -
90°; Slope: 0° - 90°; Orientation: East-West. The ground reflection area considered is 4 m² because it the average area available per panel in a field of solar photovoltaic panels in large commercial installations. The model determined the view factor for shade and unshaded ground region in the rear side of a bifacial photovoltaic panel. A view factor syntax was also developed for the flat plate model to find the view factor by simulation. The view factor for the model was validated by the standard results available in the Heat and Mass Transfer Data Book [7] for mutually perpendicular planes view factor. The validation was done for varying the size of the panel and shaded region. The view factor of unshaded region was validated mathematically by the reciprocity relation, \( A_i F_{ij} = A_j F_{ji} \).

4. Results and Discussion

For any Slope condition, the view factor from the unshaded region first decreases and the increases with increase in altitude angle as in Figure 3. The view factor gradually increases with 30° to 90° increase in altitude angle as the area of the shadow cast by the panel decreases. However the view factor from 0° to 30° altitude angle shows a decreasing trend against the actual expected increasing trend because of the restriction made in the unshaded region dimension. The total ground area was fixed at 2 × 2 m considering the spacing between panels in a row to be 0.5 m and column spacing as 2 m in a solar field installation. The peak view factor is at solar zenith as the shading is negligible.

The view factor of bifacial panels varying with the slope was also simulated. The bifacial panel with slope 15° gave the worst view factor. Vertically oriented panels showed an average view factor with the overall best performance at solar noon with value of 0.050013, which is the highest view factor in any orientation. Bifacial panels at slope 60° gave the best view factor for all altitude angles except solar zenith.

Figure 4 shows the view factor from the unshaded region to the rear side of the bifacial panel. For any Slope condition, the view factor from the shaded region increases with increase in altitude angle. This is because of the reduction in non-intercepted area between the shaded region and rear side of panel due to reduction in shade area at higher altitude angles. The shaded region to panel view factor has a decreasing trend with slope. The view factor from the unshaded region is maximum for slope 15° and minimum for slope 90°. For vertical panels (slope 90°), the view factor at zenith from shaded region becomes zero as the relevant shaded region is negligible or zero.

| Expression                  | Unit | Description                    |
|-----------------------------|------|---------------------------------|
| intop_int(comp1.rad.radopu(int, 0))/intop_int(1) | 1    | Interior to interior view factor |
| intop_ext(comp1.rad.radopd(int, 0))/intop_int(1) | 1    | Interior to exterior view factor |
| intop_ext(comp1.rad.radopd(0, ext))/intop_ext(1) | 1    | Exterior to exterior view factor |
| intop_int(comp1.rad.radopu(0, ext))/intop_ext(1) | 1    | Exterior to interior view factor |

Figure 2. View factor syntax for concentric sphere [6]
Figure 3. Rear side View Factor (Unshaded) vs Altitude Angle

Figure 4. Rear side View Factor (Shaded) vs Altitude Angle

Figure 5 gives the plot of Intensity of Reflected Light at the Rear Side vs Altitude Angle with the albedo of the ground surface as \( \alpha_1 = 0.5 \). The Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DHI) are obtained from synthetic hourly data generated in Meteonorm and intensity of reflected light at the rear side is calculated from equation (3). For any slope conditions, the highest intensity of rear reflected light (bifacial gain) is for the sun at zenith due to negligible shading.
The bifacial gain of the bifacial panels was also calculated by varying with the slope. The bifacial panel with slope 15° showed the worst bifacial gain. Vertically oriented panels showed an average bifacial gain with the overall best performance at solar noon with value of 90.4 W/m² corresponding to GHI = 820 W/m² and DHI = 350 W/m², which is the highest bifacial gain in any orientation. Bifacial panels at slope 60° gave the best bifacial gain for all altitude angles except solar zenith. The best slope for installation of fixed bifacial panels for maximum bifacial gain is found to be 60°.

5. Conclusion
For Bifacial Photovoltaic panels installed in Equator in East-West Orientation at Ground Level:

- For a bifacial panel installation at any fixed slope, the view factor from unshaded region, the view factor from shade region and bifacial gain is maximum at Solar Zenith.
- For an installation at any fixed slope, the view factor from unshaded region gradually increases with 30° to 90° with increase in altitude angle as the area of the shadow cast by the panel decreases. The shaded region view factor also increases with increase in altitude angle.
- Bifacial panels tilted at 60° gives the best view factor from unshaded region and the best bifacial gain. A tilt of 15° gives the highest view factor value from shaded region.
- Bifacial panels tilted at 15° gives the worst view factor from unshaded region and the worst bifacial gain. A slope of 90° gives the highest view factor value from shaded region.
- For fixed installations of bifacial panels, the performance of the panels increases 0° to 60° slope and then decreases from 60° to 90° slope, except at solar zenith.
- The Vertically installed panels gives moderate bifacial gain and gives the best overall bifacial gain at solar noon.

Future improvements in the model can be to model the system for the whole sky dome and for any other location on the globe.

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