Water surface reflection characteristics and power generation of bifacial PV modules

Wei Lu* and Jiehua Tian

1Jiangsu Linyang Renewable Energy Technology Co., Ltd, Nanjing, Jiangsu, 210000, China
*Corresponding author’s e-mail: luwei@linyang.com.cn

Abstract. The power generation characteristics of bifacial PV module on water surface are complicated. This paper proposed a water surface reflectivity model, which takes the light reflection characteristics on the calm water surface and the fluctuating water surface into consideration. The experimental data shows that the average absolute difference between actual water surface reflectivity and simulation data is 0.88%. A power generation model of the bifacial PV module was proposed on the basis of considering of the background reflectivity and the feature of bifacial PV module. The experimental data shows that the average absolute difference between actual PV power generation and simulation data is 2.1%. An approximate power generation enhancement ratio was proposed to estimate the power generation of bifacial PV module. Experimental results show that the average absolute difference between the approximate data and the actual data is 0.7%.

1. Introduction
The back side of bifacial PV module, can convert the reflected light and scattered light of the surrounding environment into electric energy, which greatly improves the comprehensive conversion efficiency of photovoltaic panel. The power generation on the back side of the bifacial PV module is mainly determined by the reflected light received on the back side of the PV module. Water is a liquid, and water surface reflection characteristics are very different from that of the ground. The water surface reflectivity is not constant, and it changes with the solar altitude angle and the wind speed. So it is so complicated to analyse power generation of bifacial PV modules on the water surface. There are less relevant researches on the power generation characteristics of bifacial PV modules on the water surface. This paper will firstly study the reflection characteristics of the water surface, then make a research on the reflectivity of the water surface under different conditions, and finally get a water surface reflectivity model. According to the power generation characteristics of the bifacial module’s background reflectivity and feature of bifacial PV module, this paper will propose a power generation model of bifacial PV module on water surface.

2. Power generation characteristics of bifacial PV modules
The bifacial PV module can generate electricity on both the front and back sides. The front side of the bifacial PV module absorbs the direct sunlight to generate electricity, and the back side absorbs the reflected light of the background and scattered light in the surrounding areas to generate electricity. The reflectivity of the background directly affects the power generation on the back side of the bifacial PV module. The higher the background reflectivity, and the higher the power generation on the back
side of bifacial PV module. When the background reflectivity is 40%~90%, the bifacial PV module can generate 20% ~ 30% more electricity than the normal PV module. Researches have been made on the application of bifacial PV modules in scenes such as the land, the cement, the snow, the grass, the white paint, and the white stone [1]. The reflection characteristics of the water surface is very different from the ground’s reflection characteristics. The following chapters will study the power generation characteristics of the bifacial PV module on the water surface.

3. Water surface reflection characteristics

3.1. Light transmission in the water

The water and the atmosphere are two different matter. When the light passes through the water surface, the transmission path of light will change due to the refraction and the reflection. The water surface can be classified into the calm water surface and the undulating water surface. The light transmission model will be discussed as below according to the different conditions of the water surface.

3.2. Light transfer model of calm water

When the water surface is in a calm state, the radiant energy of light transmits on the water surface according to Snell's law [2] [3]. The equation represents as follows:

\[ n_s \sin \theta_s = n_d \sin \theta_d \]  

\( n_s \): the refractive index of air is 1; \( n_d \): the refractive index of the water body. After neglecting the influential factors such as the wavelength of the incident light and the temperature of the water body, \( n_s \) is usually 4/3. According to equation (1), when the incident angle is greater than 48.8°, the light will be totally reflected on the water surface. If the polarization effect is neglected, the direct reflection equation of the water surface can be worked out from Fresnel’s law [2] [3].

\[ R(\theta_s) = \frac{1}{2} \left[ \frac{\sin^2(\theta_s - \theta_d)}{\sin^2(\theta_s + \theta_d)} + \frac{\tan^2(\theta_s - \theta_d)}{\tan^2(\theta_s + \theta_d)} \right] \]  

\( R(\theta_s) \): the reflectivity of water surface; \( \theta_s \): the incident angle of the water surface.

The Figure 1. shows the water surface reflectivity when the incident angle \( \theta_s \) is from 0° to 90°. The figure shows that when \( \theta_s \) is less than 30°, the reflectivity of water surface \( R(\theta_s) \) is about 2%. For completely diffuse sky light, its reflectivity is about 6.6% [4]

3.3. Light transmission model of undulating water surface

The water surface will fluctuate influenced by wind, and the radiation transmission mode of light on the water surface no longer conforms to Snell's law (1) and Fresnel’s law (2). In this case, the amount of light radiation on the water surface is a function of the wind speed.

If the wind speed on the water surface is low, there are only ordinary waves on the water surface. As the wind speed increases, most of the water surface will produce the foam. The foam has high reflectivity. Its reflection coefficient \( R^* \) [5][6] can be represented as follows:
\[ R^* = \frac{\rho_f}{\pi} \]  

(3)

\( \rho_f \): foam albedo, which has nothing to do with the incident angle and the wavelength of solar radiation. Its value is between 0.45 and 0.9. In calculating the influence of the foam on water surface reflectivity, the foam coverage ratio \([5][6]\) should also be considered.

\[ C_f = \frac{\text{Foam coverage area}}{\text{Total water area}} \]  

(4)

The relationship between the value of  and the wind speed obtained through experiments represents as follows:

\[ C_f = \begin{cases} 
1.2 \times 10^{-5} \times V^{3.3} & V \leq 9m/s \\
1.2 \times 10^{-5} \times V^{3.3} (0.225V - 0.99) & V > 9m/s 
\end{cases} \]  

(5)

The total water surface reflectivity \([6][7]\) is:

\[ \gamma_f(\theta_a, \Phi_a, \theta_v, \Phi_v) = (1 - C_f) \cdot \gamma_v(\theta_a, \Phi_a, \theta_v, \Phi_v) + C_f \cdot \frac{\rho_f}{\pi} \]  

(6)

\( \gamma_v(\theta_a, \Phi_a, \theta_v, \Phi_v) \) is the bidirectional reflectivity of the foam-free water considering the wind speed \( V \). Using optical method \([7]\), the following calculation equation can be obtained:

\[ \gamma_v(\theta_a, \Phi_a, \theta_v, \Phi_v) = \frac{\pi R(\omega)}{2 \mu_v \mu_a^5} \cdot \frac{1}{4\pi \alpha^2} \cdot \exp(-\tan \beta \tan \beta/\alpha^2) \]  

(7)

\[ \alpha^2 = 0.003 + 0.00512V \]

\[ \beta = \arccos\left(\frac{\cos \theta_v + \cos \theta_a}{2 \cos \omega}\right) \]

\[ \omega \approx \frac{1}{2\arccos[\cos \theta_v \cos \theta_a + \sin \theta_v \sin \theta_a \cos(\Phi_v - \Phi_a)]} \]

The reflected radiation of the undulating water usually manifests as the solar flicker \( L_{sun} \) and the sky flicker \( L_{sky} \). The direct reflected radiance \( L_G \) \([3]\) of the water body includes the solar flicker \( L_{sun} \) and the sky flicker \( L_{sky} \).

\[ L_G = L_{sun} + L_{sky} \]  

(8)

In general, the sky flicker value is very small, and the water surface reflectivity is about 6.6\% \([4]\).
4. Water surface reflectivity

4.1. Relationship between the water surface reflectivity and the solar altitude angle

Due to the characteristics of water, the reflection of sunlight on the water surface changes with the solar altitude angle. The solar altitude angle refers to the angle between the incident direction of sunlight and the horizontal plane. According to the equation (2) derived from Fresnel's law, the relationship between the solar altitude angle and the reflectivity shows in figure 2.

Figure 2 shows that the lower the solar altitude angle, the higher the reflectivity, and the higher the solar altitude angle, the lower the reflectivity. That is to say, the reflectivity is high in the morning and the evening, and it is low at noon. As shown in figure 2, when the solar altitude angle is 10°, the reflectivity is 35%; when the solar altitude angle is greater than 40°, the water surface reflectivity is only about 2 to 3%.

According to the measured data on April 19 in Sihong, Jiangsu, China, figure 3 shows the relationship between the solar altitude angle and the water surface reflectivity. The solid line in the figure is the value of the solar altitude angle of each hour from 7 am to 12 pm. As shown in the figure, the solar altitude angle at 7 o'clock is 19°, and the reflectivity is 14.6%; the solar altitude angle at 9 o'clock is 44°, and the reflectivity is 2.6%. After that, the reflectivity is low and around 2.6%. The dotted line in the figure is the calculated reflectivity according to Fresnel's law. As shown in figure 3, the calculated values is so close to the actual values.

4.2. Diurnal and annual changes of water surface reflectivity

In addition to the diurnal change rule, the water surface reflectivity also has the annual change rule. The equation for calculating the solar altitude angle according to the time in different latitudes [8] represents as follows:

\[
\sin h_s = \sin \phi \cdot \sin \delta + \cos \phi \cdot \cos \delta \cdot \cos \Omega
\]

\[
\cos A_s = \frac{\sin \delta \cdot \cos \phi - \cos \delta \cdot \cos \phi \cdot \cos \Omega}{\sin h_s}
\]

\(\phi\) is the local latitude; \(\delta\) is the solar declination angle; \(\Omega\) is the solar time angle, \(\Omega=(TT-12)\times15^\circ\), TT is the true solar time, TT=C_T+L_C+E_Q, C_T is Beijing time, L_C is the correction of longitude (4min/degree); E_Q is the time difference.

According to the above equation, the solar altitude angle of each hour of 12 months in Sihong, Jiangsu, China shows in figure 4.

![Figure 4. Monthly solar altitude angle](image1)

![Figure 5. Solar altitude angle and average water surface reflectivity](image2)

The article [9] used the arithmetic average method to obtain the water surface reflectivity in the northwestern area of Shandong province each month of the year based on the observation data of the representative sunny day from January to December (Figure 5).
As shown on Figure 5, the average solar altitude angle in winter (November to February) is low, so the water surface reflectivity is high. At other times, due to the high average solar altitude angle, the water surface reflectivity is low. Then the water surface reflectivity is between 6% and 7% for most of the year.

5. Approximate water surface reflectivity model

Through the theoretical analysis in the above chapters, an approximate water surface reflectivity model is proposed as the equation (10). These equations represent the water surface reflectivity on both the calm water surface and the fluctuating water surface. The fluctuating water surface also considers the foaming and non-foaming conditions.

\[
R(\theta) = \frac{1}{2} \frac{\sin^2(90° - h_s - \theta_d)}{\sin^2(90° - h_s + \theta_d)} + \frac{\tan^2(90° - h_s - \theta_d)}{\tan^2(90° - h_s + \theta_d)} V < 1.5\text{m/s}
\]

\[
R(\theta_a, \theta_v, \theta_v, \theta_0) = (1 - C_f) \cdot \gamma(\theta_a, \theta_v, \theta_v, \theta_0) + C_f \cdot \rho_f / \pi
\]

\[
C_f = 0; 1.5\text{m/s} < V < 5.4\text{m/s};
\]

\[
C_f > 0; V > 5.4\text{m/s}
\]

(10)

According to the Chinese national standard GBT 28591-2012 Wind Rating, when the wind speed is less than 1.5m/s, the microwave starts to appear on the water surface, and when the wind speed is greater than 5.5m/s, and foam starts to form in the waves.

Figure 6. Measured and simulated reflectivity

Figure 7. Measured and simulated power generation of bifacial PV module

Figure 6. shows the actual water surface reflectivity and the simulated water surface reflectivity on a sunny day, in Sihong, Jiangsu, China, as well as simulated data are higher than the actual data in the morning and evening, and lower than the actual data in the rest of the time. The average absolute difference between the actual data and simulated data is about 0.88%.

6. Power generation of bifacial PV modules on water surface

According to the characteristics of the bifacial module, the output power of the bifacial module represents as follow:

\[
P = \eta (1 + R \times BiFi) P_{STC} (1 + r(T_r - T_0)) / (G/G_0)
\]

\eta is the system efficiency, \( R \) is the background reflectivity, \( BiFi \) is the bifaciality of the bifacial PV module, \( P_{STC} \) is the nominal power of the front side of the bifacial PV module, \( r \) is the temperature coefficient of the PV module, \( T_r \) is the backplane temperature of the PV module, and \( T_0 \) is the standard temperature 25°C, \( G \) is the irradiance on the PV module, \( G_0 \) is the standard irradiance of 1000W/m²;

The water surface reflectivity \( R \) is a variable that changes with the solar altitude angle and wind speed. When calculating the output power of the bifacial module on the water surface, it is necessary to determine the water surface reflectivity through using the equation (10).
The figure 7. shows the measured data and the simulated data of a 50kW inverter in a bifacial PV power plant on the lakes in Sihong, Jiangsu, China. The figure 7. shows that values of measured data and simulated data are approach and the average absolute difference is about 2.1%. The power generation on the back side of the bifacial PV module is proportional to the reflectivity of the background. In order to study the power generation enhancement ratio (PGER) of the bifacial PV module, the PGER equation represents as follows:

$$\alpha = \frac{W_r}{W_f} = \frac{(W_B-W_S)}{W_s}$$  \hspace{1cm} (12)

In the equation, $\alpha$ is the ratio of the power generation on the back side of bifacial PV module to the power on the front side; $W_r$ is the power generation on the back side of the bifacial PV module (kWh/kW); $W_f$ is the power generation on the front side of the bifacial PV module (kWh/kW); $W_B$ is the total power generation of the bifacial PV module (kWh /kW); $W_s$ is the power generation of normal PV modules with the same panel tilt (kWh/kW). Since the power generation of the front side and back side of the bifacial PV module is difficult to measure separately. An equivalent method is adopted here to use use unit power generation of normal PV modules with the same panel tilt is equivalent to the unit power generation of the front side of the bifacial PV modules. Substituting equation (11) into equation (12) can obtain an approximate equation of PGER of the bifacial module.

$$\alpha' = R \times BiFi$$ \hspace{1cm} (13)

In the equation, $\alpha'$ is the approximate PGER of the bifacial PV module; $BiFi$ is set as 0.8 due to use N type bifacial PV module.

In order to certificate the relationship between the reflectivity and the PGER of the bifacial PV module, the experiment was carried out at the bifacial PV power plant on the lakes in Sihong, Jiangsu, China. The bifacial PV module with a panel tilt of 26° is 2m away from the water surface. Both the front side and back side of the PV module were equipped with a pyranometer. The normal PV module with 26° panel tilt in the same PV power plant served as a control group.

The figure 8. shows the daily average reflectivity and PGER of the bifacial PV module from April 28th to May 12th. From top to bottom in the figure, the first curve is the measured daily average reflectivity, the second curve is the approximate PGER obtained by equation (13), and the third curve is the actual PGER of bifacial PV module. The average absolute difference is 0.7%. Considering that the DC and AC losses of the photovoltaic system are generally above 1%, the approximate $\alpha'$ still accurately reflects the power generation enhancement on the back side of the bifacial PV module.

**Figure 8.** Reflectivity and PGER of bifacial PV module

7. Conclusion

To analyse power generation characteristics of bifacial PV module on the water surface, this paper analyses the reflection of light on the water surface, and the light receiving situation of bifacial PV modules. Through the model and actual measurement, the water surface reflection law is as follows: the higher the solar altitude angle, the lower the reflectivity; the high reflectivity of water surface in the morning and evening, the low reflectivity of water surface at noon. The water surface reflectivity...
changes according to the solar altitude angle and is influenced by the wind speed. This paper proposed
the water surface reflectivity model on the basis of considering of the solar altitude angle and the wind
speed. The experimental result from the bifacial PV plant shows the average absolute difference
between the measured data and the simulated data is about 0.88%. The power generation model of the
bifacial PV module is also proposed in this paper. The power generation model, using the water
surface reflectivity model, can simulate the power generation of the bifacial PV module on the water
surface. According to the experimental data, the result of the power generation model proposed is
lower 2.1% than the actual power generation of bifacial PV module. This paper proposed the
approximate power generation enhancement ratio of bifacial PV module. Using the approximate
PEGR and the power generation of normal PV module could estimate the power generation of bifacial
PV module. Experimental results show that the average absolute difference between the approximate
PEGR and the actual PEGR is 0.7%.

References
[1] Chuigu, W., Xuebing, L., Lei, Z., Yin, L. (2017) N-type bifacial module and its application.
   Semiconductor technology, 42 (3): 200-204.
[2] Griffiths, David J. (1998) Introduction to Electrodynamics (3rd ed.), Prentice Hall.
[3] John, D.J., Johnson, S.G., Winn, J.N., Meade, R.D. (2008) Photonic Crystals Modelling the
   Flow of Light 2nd. Princeton University Press, Princeton NJ.
[4] Junsheng, Z., Shuchu, W. (2002) Ocean Optics, Beijing Science Press.
[5] Quenzel, H., Kaestner, M. (1980) Optical properties of the atmosphere: calculated variability
   and application to satellite remote sensing of phytoplankton. Applied optics, 19, 8:1338-1344.
[6] Gordon, H.R. (1976) Radiative transfer: A technique for simulating the ocean in satellite
   remote sensing calculations. Applied Optical, 15:1974-1979.
[7] Cox, C.S., Munk, W.H. (1954) Statistics of the Sea Surface Derived from Sun Glitter.
   Journal of Marine Research, 13:198-227.
[8] (2003) China Meteorological Administration. Ground Meteorological Observation
   Specifications. Meteorological Press, 133, Beijing.
[9] Zhifang, S. (1996) Reflectivity of fish ponds in northwestern Shandong. Lake Science, 8, 3:
   223-228.