Investigating the Shading Impact of Rail on the Energy Output of a PV System in Hong Kong

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Abstract

This paper investigates the shading impact of rail on the power performance of a PV system. In order to find out the reasons of energy loss, an on-site inspection and testing was conducted. The shading and aging problems were found in the process of visual inspection. The shading problem can be further subdivided into edge-shading, pillar-shading and nameplate shading. To further understand and quantify the impact of different types of shadings on the power output performance, the I-V curves of a PV module were tested under different solar radiation. The testing results showed that the impact of different types of shadings on the power performance varied with the Sun position, solar radiation as well as the time. In general, the edge-shading effect reduced the energy output of PV system by 11%-15%, the pillar-shading effect reduced the energy output by 15%-19%, and both effects of edge-shading and pillar-shading reduced the energy output of PV system by 18%-35%. Thus, the main reason that resulted in the energy loss of this PV system was attributed to the shading impact. If the edge-shading and pillar-shading problems are solved, the annual energy output of the PV system could increase about 20%-24%.

1. Introduction

The photovoltaic (PV) system diagnosed in this study is located in Pak Kong water treatment works (PKWTW) in Hong Kong. This PV system was built in 2007. It is facing southwest and with a tilted angle of about 20°. The total PV installation capacity is about 10.6 kWp, comprising by 60 pieces of mono-Si PV modules. Recently, the customers reflected that the PV system is always operating under a low energy conversion efficiency state, thus an on-site testing and diagnosing work has been done to find out the problems. It was found that the actual average annual energy output was 9396 kWh, which is lower than the theoretical annual energy output by 23%, and lower than the PV system with current PV technology (17% efficiency) by 57%. Thus the

purpose of this study is to find out the reasons causing the 23% energy loss. The PV arrays of this PV system are shown in Figure 1. These PV modules purchased from three different manufacturers, viz. Suntech, Shell and Solgro, and were divided into 6 PV arrays. The specification parameters of the PV modules are listed in Table 1. In each array, 10 pieces of the same modules were connected in series. Every two arrays, whose PV modules came from the same manufacturer, were connected in parallel before connected into an Inverter. Three SMC 6000A inverters manufactured by SMA were used in this system to invert the DC power to AC power. Figure 2 shows the picture of the SMC 6000A inverter. The specification parameters of the inverters are listed in Table 2. The schematic diagram of the PV system is presented in Figure 3. From the specifications of the PV modules and Inverters, there is no mismatching problem between the PV modules and inverters.

Figure 1. The PV arrays of the PV system (only half arrays were shown in this photo)

Figure 2. The photo of the SMC 6000A inverter (three this kind of inverters were used in this system)

Table 1. Specification parameters of the mono-Si PV modules

Parameters/manufacturers	Shell	Suntech	Solgro
Maximum Power at STC (P_{max})	175 W	175 W	180W
Optimum Operating Voltage (V_{mp})	35.4V	35.2V	35.2V
Optimum Operating Current (I_{mp})	4.95A	4.95A	5.11A
Open Circuit Voltage (V_{oc})	44.6V	44.2V	43.6V
Short Circuit Current (I_{sc})	5.43A	5.2A	5.5A
Module Efficiency	13.3%	13.7%	14%
No. of PV modules/PV arrays	20/2	20/2	20/2
Dimensions	1622 × 814 × 40mm	1580 × 808 × 35mm	1580 × 808 × 35mm

Table 2. Specification parameters of the SMC 6000A inverter

Parameters	values
Max. operating voltage (DC)	600V
Operating voltage range (DC)	213-600V
Nominal operating voltage (DC)	270V
Max. input current (DC)	26A
Nominal operating voltage (AC)	230V
Nominal operating frequency (AC)	50/60Hz
Nominal output power (AC)	6000W
Max. output power (AC)	6000W
Max. output current (AC)	26A

Figure 3. Schematic diagram of the PV system

2. Analyzing of energy loss

The theoretical annual energy output of this PV system can be calculated by (1):

$$E_{\text{theoretical}} = A_{\text{act.}} \times G \times \eta_{\text{stc}} \times \lambda \quad (1)$$

Where, $E_{\text{theoretical}}$ is the theoretical annual energy output, (kWh); $A_{\text{act.}}$ is the active area of the all PV modules, (m^2), the total active area is about 77.4 m^2 ; η_{stc} is the PV modules' energy conversion efficiency under standard test conditions (STC). According to the specifications of PV manufacturers, the energy conversion efficiency of the above mentioned three

kinds of PV modules are respectively 13.3% for Schell, 13.7% for Suntech and 14% for Solgro. λ is the performance ratio of PV system. This ratio considers all losses from converting solar energy into direct current electricity and then inverting the direct current into alternating current electricity. In this study, λ is assumed to be 0.75 [1]. G is the annual total solar radiation received by the PV modules, (kWh/yr.) The horizontal hourly solar radiation was recorded by a sun tracker with two pyranometers in the Hong Kong Polytechnic University. However, only horizontal total and diffuse solar radiations can be recorded by this equipment. Thus, it is necessary to transfer the total solar radiation on a horizontal surface into the incident solar radiation on the sloping surface of PV modules. The hourly total solar radiation incidence on a tilted surface, G_{tt} (W/m^2), can be expressed as follows:

$$G_{\text{tt}} = G_{\text{bt}} + G_{\text{dt}} + G_{\text{r}} \quad (2)$$

Where, G_{bt} is the hourly beam solar radiation incidence on a tilted surface, W/m^2 ; G_{dt} is the hourly diffuse solar radiation incidence on a tilted surface, W/m^2 ; and G_{r} is the hourly reflected solar radiation, W/m^2 .

The ratio of beam radiation on the tilted surface to that on a horizontal surface can be defined as geometric factor of R_b , which is given in the equation (3). Therefore if we get the beam radiation on the horizontal surface, the beam radiation on the tilted surface can be easily calculated by the equation (4) [2].

$$R_b = \frac{G_{\text{bt}}}{G_{\text{bh}}} = \frac{\cos \theta}{\cos \theta_z} \quad (3)$$

$$G_{\text{bt}} = G_{\text{bh}} \times R_b = G_{\text{bh}} \times \frac{\cos \theta}{\cos \theta_z} \quad (4)$$

Where G_{bh} is the beam radiation on the horizontal surface which can be extracted from the total radiation of G_{th} on the horizontal surface (provided by Hong Kong Observatory); θ is the angle of incidence, i.e. the angle between the beam radiation on a surface and the normal to that surface; θ_z is the zenith angle, i.e. the angle between the vertical and the line to the sun.

In order to calculate the reflected term, it is assumed that all the surrounding surfaces are condensed into one large horizontal diffusely reflecting ground. The radiation reflected from this composite “ground” contributes to the reflected component. The inclined surface with β degree to the horizontal has a view factor of $(1 - \cos \beta) / 2$ to the ground. If the ground has a reflectance of ρ_o for the total solar radiation, the reflected radiation from the ground, G_r , can be written as:

$$G_r = \frac{\rho_o}{2} \cdot G_{th} \cdot (1 - \cos \beta) \quad (5)$$

Where G_{th} is the total irradiance on a horizontal surface, which can directly obtain from the Hong Kong Observatory; ρ_o is the ground reflectance which is equal to 0.2 for normal ground and may range from 0.35 to 0.95 for ground covered by snow.

Although there are a lot of models, such as Liu & Jordan Model, Hay & Davies Model, Perez Model and Reindl Model [3], can be used to simulate the diffuse solar irradiance on tilted surface, it is also the most difficult part to be simulated and a relatively big error may be generated if the choosing model is not suitable for the local weather condition. Lu [4] compared various diffuse models in different tilted angles at five orientations (south, southeast, southwest, east and west) using a typical meteorological year (TMY) weather data in Hong Kong. Results showed that for PV modules with a lower tilted angle, Perez model provides results with high accuracy after validation using Hong Kong weather data. Thus, in this study, the Perez model [5-6] was chosen to simulate the diffuse radiation on tilted surface. This model considered the circumsolar and horizon brightening. In addition, it derived the reduced brightness coefficients which are functions of the sky clearness, ε and sky brightness, Δ to account for the isotropic diffuse radiation. The diffuse on the tilted surface is given by following equation [5-6]:

$$G_{dt} = G_{dh} \cdot \left[(1 - F_1) \cdot \left(\frac{1 + \cos \beta}{2} \right) + F_1 \cdot \frac{a}{b} + F_2 \cdot \sin \beta \right] \quad (6)$$

Where G_{dh} is the diffuse radiation on the horizontal surface which can be extracted from the total radiation on the horizontal, G_{th} ;

Where $a = \max[0, \cos \theta]$,

$b = \max[\cos 85, \cos \theta_z]$,

$F_1 = F_{11}(\varepsilon) + F_{12}(\varepsilon) \cdot \Delta + F_{13}(\varepsilon) \cdot \theta_z$

$F_2 = F_{21}(\varepsilon) + F_{22}(\varepsilon) \cdot \Delta + F_{23}(\varepsilon) \cdot \theta_z$

The values of F_{11} , F_{12} , F_{13} , F_{21} , F_{22} , and F_{23} can be found from the tables given by Perez et al [5]. The value of ε and Δ can be calculated as follows:

$$\varepsilon = \frac{[(G_{dh} + G_{bn}) / G_{dh} + 1.041\theta_z^3]}{[1 + 1.041\theta_z^3]} \quad (7)$$

$$\Delta = \frac{G_{dh} \cdot m}{G_{on}} = \frac{G_{dh} \cdot m}{G_o / \cos \theta_z} = \frac{G_{dh}}{G_o} \quad (8)$$

Where θ_z is in radian; m is the air mass.

In order to simulate the annual solar radiation received by the PV modules, a FORTRAN program was developed based on the above mathematic models. Figure 4 presents the simulated annual solar radiation incident on different tilted surface. It was found that the average annual solar radiation received by the PV modules installed with 20 degree tilted is about 1340kWh, which is a little less than the highest solar radiation received by the optimum orientation and tilted angle. In Hong Kong, the optimum orientation for PV installation is south facing with 22 degree tilted. In addition, it is also found that the average diffuse solar irradiance on tilted surface is higher than the average beam irradiance by 90 kWh/m²/yr., which means that the diffuse solar irradiance would contribute to more PV power output. Substituting the solar radiation G , energy conversion efficiency η_{stc} , performance ratio

λ , and active area A_{act} into equation (1), the theoretical energy output was calculated to be 11700 kWh/year. The actual energy output of this PV system was recorded from June 2007 to June 2013. Figure 5 presents the monthly energy output of this PV system. Figure 6 shows the annual energy output from 2008 to 2012. It is found that the actual average annual energy output was 9396 kWh, which is lower than the theoretical annual energy output by 24.5%. Thus the purpose of this study is to find out the reasons causing the 24.5% energy loss.

Figure 4. The simulated diffuse and beam irradiance incident on different tilted surfaces

Figure 5. Monthly energy output of the PV system

Figure 6. Annual energy output and the average energy loss of the PV system

3. Inspecting and Testing

3.1 Visual inspection

Three problems were found in the process of visual inspection. First of all, two kinds of permanent shading were found to affect the power output performance of PV system, viz. edge-shading caused by the U-bar and the pillar-shading caused by the pillars in front of the PV modules. Figure 7 shows the edge-shading caused by the U-bar. Almost all PV modules, except the PV modules manufactured by Shell, are affected by the edge-shading. Figure 8 shows the comparison of edge-shading effect on Shell's PV module and Suntech's PV module. It can be seen that there is almost no edge-shading for the Shell's PV module due to its longer length (1622 mm) than the other two types of PV modules. And this is the reason why the inverter connected to the PV modules made by Shell has higher average electricity production rate. The hourly average electricity production rate of the Shell's PV arrays is about 0.81 kWh, while they are 0.65 and 0.71 kWh for the PV arrays made by Solgro and Suntech, respectively. Thus, from the average electricity production rate, it is found that only the edge-shading could reduce the energy output of the PV modules by about 12%.

Figure 7. Edge-shading caused by the U-bar

Figure 8. Comparison of the edge-shading effect on the Shell's PV module (left one) and the Suntech's PV module (right one)

Figure 9. the pillar-shading caused by the pillars in front of the PV modules.

Figure 9 shows the pillar-shading caused by the pillars in front of the PV modules. It can be seen that almost all the PV modules in the first row were shaded by the pillars. Secondly, a temporary shading caused by a nameplate was found and showed in Figure 10. This kind of shading may cause the energy output performance of the PV array reducing significantly.

Figure 10. A temporary shading caused by a nameplate

Last but not least, it was found that there are some quality problems for the PV modules made by Solgro. Firstly, a few pieces of multi-Si solar cells exist in the mono-Si PV panels, as shown in Figure 11. Secondly, as shown in Figure 12, the aging problem is very serious and the EVA of the PV modules has become yellow. Thus it can be seen that the PV modules made by Solgro have quality problems on the solar cells and EVA. And this is the reason why the inverter connected to the PV modules made by Solgro has the lowest average electricity production rate of 0.65 kWh, even its rated power is higher than the PV modules made by the other two manufacturers.

Figure 11. A few pieces of multi-Si solar cells were found in the mono-Si PV panels

Figure 12. The aging problem is very serious and the EVA of the PV modules has become yellow

3.2 I-V measuring and power testing

In order to further understand and quantify the impact of different types of shadings on the power output performance, a PV module made by Suntech was disassembled for conducting I-V testing.

Figure 13 presents the I-V testing results under different shading conditions at 12:51-12:56. It can be seen that the maximum power is about 146W without shading, but it was reduced to 126W affected by edge-shading, to 118W affected by pillar-shading, and further reduced to 110W affected by both edge-shading and pillar-shading. The edge-shading resulted in the reduction of open circuit voltage and short circuit current, and reduced the power output by about 14%. The pillar-shading caused the reduction of the maximum power of PV module and reduced the power output by about 19%. Both the effects of edge-shading and pillar-shading reduced the power output by about 25%.

Figure 13. I-V testing results under different shading conditions at 12:51-12:56

Figure 14 presents the I-V testing results under different shading conditions at 14:11-14:23. It can be seen that the maximum power is about 122W without shading, but it was reduced to 103W affected by edge-shading, to 102W affected by pillar-shading, and further reduced to 93W affected by both edge-shading and pillar-shading. The edge-shading effect reduced the power output by about 15%. The pillar-shading effect caused the reduction of the maximum power of PV module and reduced the power output by about 16%. Both the effects of edge-shading and pillar-shading reduced the power output by about 24%.

Figure 14. I-V testing results under different shading conditions at 14:11-14:23

Figure 15 presents the I-V testing results under different shading conditions at 15:17-15:19. It can be seen that the maximum power is about 111W without shading, but it was reduced to 96W affected by edge-shading, to 94W affected by pillar-shading, and further reduced to 91W affected by both the effects of edge-shading and pillar-shading. The edge-shading effect reduced the power output by about 14%. The pillar-shading effect caused the reduction of the maximum power of PV module and reduced the power output by about 15%. Both the effects of edge-shading and pillar-shading reduced the power output by about 18%.

Figure 15. I-V testing results under different shading conditions at 15:17-15:19

Figure 16 presents the I-V testing results under different shading conditions at 16:11-16:13. It can be seen that the maximum power is about 90W without shading, but it was reduced to 80W affected by edge-shading, to 73W affected by pillar-shading, and further reduced to 59W affected by both edge-shading and pillar-shading. The edge-shading effect reduced the power output by about 11.1%. The pillar-shading effect caused the reduction of the maximum power of PV module and reduced the power output by about 19%. Both the effects of edge-shading and pillar-shading reduced the power output by about 35%.

Figure 16. I-V testing results under different shading conditions at 16:11-16:13

4. Suggestion

Based on the above analysis, some suggestions are proposed to solve these problems and improve the PV system's energy output.

- (1) As shown in Figure 17, removing or cutting down the pillars in front of the PV modules to completely avoid the pillar-shading. Actually, the pillar-shading has worse effect on the energy output of PV system than the edge-shading.
- (2) As shown in Figure 18, readjusting the position of the U-bar to reduce the edge-shading. This is the easiest way to reduce the effect of edge-shading on the energy output, but it may not completely avoid this shading effect. Thus other installation way should be developed to replace the existing installation

way to completely solve the edge-shading problem.

Figure 17. Removing or cutting down the pillars in front of the PV modules to completely avoid the pillar-shading

Figure 18 Readjusting the position of U-bar to reduce the edge-shading effect

5. Discussion and Conclusions

Based on the above testing results, it was found that the impact of different types of shadings varied with the Sun position, solar radiation as well as the time. In general, on 20th June 2013, the edge-shading effect reduced the energy output of PV system by 11%-15%, the pillar-shading effect reduced the energy output by 15%-19%, and both effects of edge-shading and pillar-shading reduced the energy output of PV system by 18%-35%. It is worth noting that the shading effect varies with the Sun position, it may cause much more energy loss in winter than in summer due to the increase of shading area.

In addition, the inverters' energy output data was recorded. The inverter, which was connected to the PV modules made by Solgro, generated about 10.5 kWh on June 20, but the inverter connected to the PV modules made by Shell generated about 12.6 kWh, which is higher than that of Solgro's PV modules by 20%. There are two reasons may explain why the energy output performance of Solgro's PV modules was lower than that of Shell's. On the one hand, the power performance of Solgro's PV modules was decayed due to the aging problem. On the other hand, the edge-shading also reduced the power output of Solgro's PV modules.

Ideally, the inverters connected to the PV modules made by Shell and Solgro should generate

about 14 kWh on June 20 based on the solar radiation and PV modules' temperature. Thus the energy loss caused by the shading effect was about 1.4 kWh for the Shell's PV modules, which is accounted for 10% of the ideal energy output. These results agree well with the I-V testing results which were mentioned above. The energy loss for the Solgro's PV modules was about 3.5 kWh, which is account for 25% of the ideal energy output. This energy loss was mainly caused by the both effects of edge-shading and pillar-shading, as well as the PV modules' performance degradation.

In a word, it can be concluded that the main reasons causing the energy loss of the PV system are the shading problems. If the edge-shading and pillar-shading problems are solved, the annual energy output of the PV system could increase about 20%-24%.

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7. References

- [1] J. Peng, L. Lu, "Investigation on the development potential of rooftop PV system in Hong Kong and its environmental benefits," *Renewable and Sustainable Energy Reviews*, vol. 27, pp. 149-162, November 2013.
- [2] J. A. Duffie, W.A. Beckman, *Solar engineering of thermal processes*, (Third Edition). John Wiley & Sons, INC., New York, 2006.
- [3] Li Danny HW, Cheung Gary HW. Study of models for predicting the diffuse irradiance on inclined surfaces. *Appl Energy* 2005;81(2):170-86.
- [4] Lu L. Investigation on characteristics and application of hybrid solar-wind power generation systems. Ph.D. dissertation, The Hong Kong Polytechnic University; 2004.
- [5] R. Perez, P. Ineichen, R. Seals, Modeling of daylight availability and irradiance components from direct and global irradiance, *Solar Energy*, vol. 44(5), pp. 271-289, 1990.
- [6] R. Perez, R. Seals, P. Ineichen, R. Stewart, D. Menicucci, A new simplified version of the Perez diffuse irradiance model for tilted surfaces, *Solar Energy*, vol. 39(3), pp. 221-231, 1987.