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Study on the electrical performance of underwater photovoltaic modules

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Abstract. Light intensity directly affects the output current of photovoltaic (PV) modules. The output characteristics of underwater photovoltaic modules are directly affected by light intensity. In this paper, utilizing the matrix simulation of light, and solar module analyzer (PROVA) test equipment, the electrical parameters of polycrystalline silicon PV modules are tested underwater. The relationship between the output characteristics of the PV module and water depth is analyzed. The results show that the output characteristics of PV modules is insensitive to increasing water depth. For the vertically irradiated photovoltaic module, the short-circuit current of the silicon photovoltaic module decreased by 2.39 A, the power decreased by 2.57 W, and the efficiency decreased by 5% when the water depth was increased by 1 cm. Similarly, the when the dip angle is 30 degrees, 45 degrees, 60 degrees, with an increase of water depth by 1cm, the PV module of short-circuit current, power and efficiency were decreased by 2.05 A, 2.1 W, 8%; 1.85 A, 2.07 W, 6.93%; 1.05 A, 0.74 W, 3.67%, respectively. Relative to the 0 degree angle, when the dip angle is 30 degrees, 45 degrees, 60 degrees angle, the percentage drop in PV module of short circuit current is14%, 23%, 56% and the power is 18.3%, 19.5%, 71.2% respectively.

1. Introduction

The development of solar energy photovoltaic power systems has made remarkable strides in recent years. At the same time, solar module development has changed rapidly. This development makes the test of solar module more standardized. From component IV feature testing to component mechanical damage testing, and from component thermal performance testing to temperature impact testing on component performance, the standards are very strict. But Photovoltaic modules often need to work outdoors for a long time, under a variety of climate conditions. In particular, the effect of rain on these devices is very critical. When a photovoltaic module is saturated in rain water, the incident light entering the water will refract and reflect, and at the same time, it will be absorbed and scattered during propagation. Compared with the photovoltaic module in the air, the power generation efficiency of the water photovoltaic module decreases with increasing water depth. Therefore, both for the photovoltaic modules test standard, and for photovoltaic engineering design, it is highly important to explore the influence of water depth on the output performance of PV modules.

Photovoltaic components in the water were patented in the United States in 2006 [1]. In 2008, Wang [2] investigated the performance of silicon solar cells operated in liquids. In 2014, Saurabh Mehrotra [3] studied the performance of a solar panel with water immersion cooling technique. In

2016, at the University of Shanghai for Science and Technology, Chen [4] studied the application characteristics of surface water cooling solar photovoltaic modules. Starting from the propagation law of light in water, this paper explores the relationship between water depth change and the power and output efficiency of photovoltaic modules. In water, the IV output characteristics of polysilicon photovoltaic modules under different dip angles were tested by the solar module analyzer (PROVA). The findings reveal that the law of water depth and solar cell output characteristics play a key role in evaluating the relationship between the output characteristics of underwater photovoltaic modules and water depth.

2. Theoretical model of underwater photovoltaic modules

The heat transfer model of an underwater PV module is shown in figure 1. The heat transfer energy of underwater photovoltaic module mainly includes the energy of incident solar radiation, the output power of the photovoltaic module, the heat transferred by the upper surface layer of the PV module, the heat stored in the lower surface layer of the PV module, and the PV module output power. According to the principle of conservation of energy, the unsteady energy equation of underwater PV component has the formula (1):

$$C_{pv}\frac{dT}{dt} = A(1-\rho)I_s\tau - \mathrm{Q}_1 - \mathrm{Q}_2 - \mathrm{P}_{\mathrm{out}} \tag{1}$$

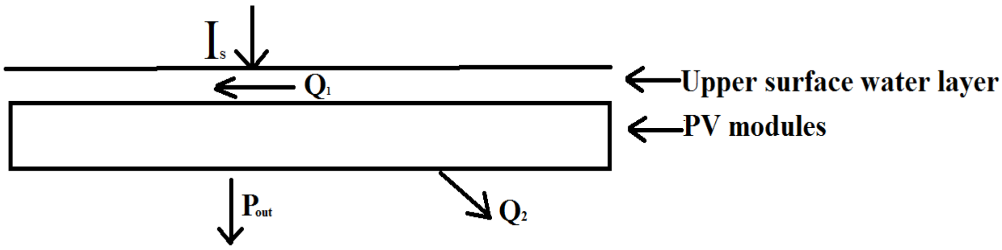

Figure 1. Heat transfer model of underwater photovoltaic module.

In formula (1), C_{pv} represents the total heat capacity of a single cell assembly, with C_{pv}=2918 J/K; T represents the operating temperature of the PV module, K; The T approximation is equal to the average temperature at the front and back of the PV module; A represents the area of PV modules, with A=0.53 m^2; ρrepresents water reflectance of solar radiation; with ρ=0.1; τ represents the transmissivity of solar radiation in the water, with τ=0.8; Is represents the intensity of solar radiation projected onto the surface of a module, W/m^2; Q1 represents the heat transferred by the surface water of a photovoltaic module; Q_2 represents the heat transmitted by the lower surface of the PV module, W; Pout represents the power output of photovoltaic modules, W.

2.1. Surface heat conduction of an underwater photovoltaic module

The upper surface heat transfer of an underwater photovoltaic module satisfies Fourier's law of heat conduction. One-dimensional flat wall heat conduction, i.e., Q_1, λ, and A, does not vary with temperature.

$$Q_1 = -\lambda A\frac{dT}{dx} \tag{2}$$

In formula (2), λ is thermal conductivity, w/ (m·k); A is the PV module area, m^2 boundary condition of temperature is that heat generated by the PV module and the water temperature at the top of the PV modules.

2.2. The lower surface heat conduction of an underwater photovoltaic module

Unlike the upper surface heat conduction, the lower surface heat conduction of the PV module can be considered as a process of the gradual change of the heat source from temperature T_2 to the water temperature, thus:

$$Q_2 = \lambda A \frac{dT_2}{dx} \tag{3}$$

In formula (3), dx is the distance between the temperature of the backplane of the PV module and the average temperature of the water temperature; T_2 is the temperature of the PV module backplane. boundary condition of temperature is that heat generated by the PV module and Mean water temperature.

2.3. Output power of PV modules

The output power of the PV module is determined by the fill factor model constant [5]; it can be expressed by formula (4):

$$P_{out} = C_{ff} \frac{I_s ln(CI_s)}{T} \tag{4}$$

In the formula, C_{ff} is the fill factor model constant, C_{ff}, =1.22 K·m^2, K; C is constant, C=10^6, m^2/W.

2.4. The conversion efficiency of a PV module

The conversion efficiency of a PV module is defined by its formula (5):

$$\eta_e = \frac{P_m}{AI_s} \tag{5}$$

In the formula, η_e represents the PV module conversion efficiency, %; P_m represents the maximum output power of PV module, W.

2.5. Absorption of light waves in water

At the same time, according to the Law of Lambert [6], when light incidents a transparent medium, the light and medium undergo a molecular interaction so that the intensity will be weakened. The weakened light intensity is related to the absorption coefficient and the passing path. The available expression (6) describes this phenomenon:

$$I_s = I_0(1 - \mathrm{R})e^{-\alpha_a d} \tag{6}$$

Where I_0 is the incident light intensity, I_0=800 W/m^2; α_a is the absorption coefficient, α_a= 5.6197 m^{-1} [7]; d is the length of the light through the path.

3. Experiment device and test process

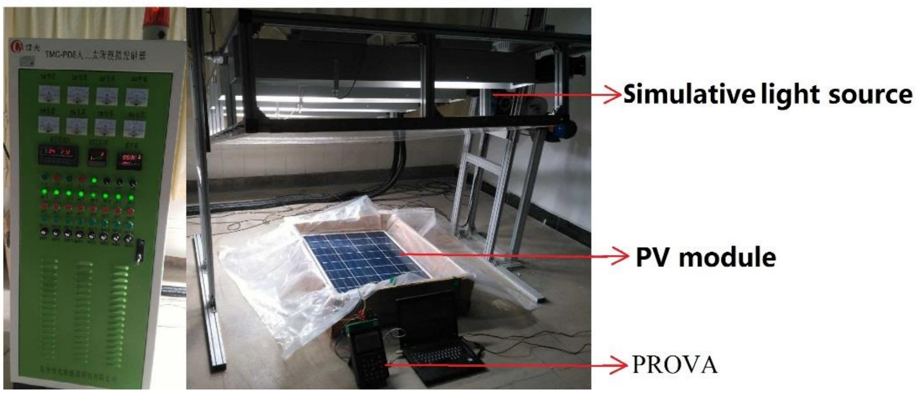

Figure 2. Experiment device.

Underwater photovoltaic module testing systems consists of a solar simulator, a photovoltaic module, a solar module analyzer, as well as other equipment. The test system is shown in figure 2. Among them are the solar simulator which consists of a matrix-type light emitting device, a host power control cabinet, a high voltage trigger controller, an optical radiation sensor, a temperature sensor, a solar analog transmitter monitor, and solar simulation management software. The technical parameters of the simulated light source are shown in table 1.

Table 1. The technical parameters of the simulated light source.

Model	TMC-PD8	Spectral rating	Class B
Light unevenness	≤5%	Irradiation adjustment range	600-1000 W/m^2
Light Instability	≤5%	Light source output mode	parallel light

According to the theoretical model of underwater photovoltaic modules, this experiment selects the polysilicon photovoltaic module tested by the Solar Energy Ltd. The component parameters are shown in table 2. In the process of experiment, the PV modules need to be intruded into the water-filled containers. The maximum distance between the upper surface of the water and the PV module is H, and the maximum value of the distance is 15 cm. Then, in turn, the capacity of the water in the container is reduced, and the water level in the container is reduced to 1 cm height until H equals 0 cm. The simulated light source used in the test is the TMC-PD15 artificial solar simulator produced by the Dongguan Green Light new energy technology company. The simulated light source is composed of 16 independent xenon light sources. The PV module is tested using the Taiwan solar module analyser (PROVA) to collect information about the work of PV modules.

Table 2. The parameters of polycrystalline silicon PV module of photovoltaic solar energy limited company.

Model	GHM80 W	operating current	4.55 A
Maximum power	80 W	open circuit voltage	21.6 V
Operating voltage	17.6 V	short circuit current	5.35 A

4. Experimental results analyses

4.1. The relationship between water depth and output current of the PV module

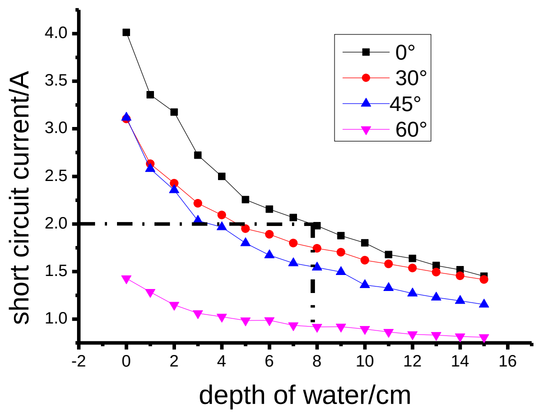

Figure 3. The relationship of depth and short current for a PV module.

In order to reveal the relationship between the water depth, the output current and the angle, it is necessary to draw water depth, current and angle diagrams. Figure 3 shows the relationship between water depth and the short circuit current of PV module. With increasing water depth, the short circuit current of the PV module decreases, and the deeper the water depth, the lesser the change of short-circuit current. On the other hand, with an increase of dip angle, the intensity of incident light decreases, and the decrease of short-circuit current is evidently weakened. For example: when the incident angle is 0 degrees, and water depth varies from 0cm to 15 cm, the average drop in unit water depth current is 2.39 A/cm. With the increase of incident angle, the change of current decreases. When the incident angle is 30 degrees, 45 degrees and 60 degrees, the current changes are 2.05 A/cm, 1.85 A/cm, 1.05 A/cm. On the whole, the current change of PV module exhibits an exponential distribution. When the incident angle is 0 degrees and the water depth is 8cm, the short circuit current of the PV module diminishes by half.

4.2. Influence of water depth on IV characteristics of photovoltaic modules

The change of short circuit current will directly lead to the change of output power of the PV module. At the same irradiation conditions, the water depth will affect the light intensity of the surface of the PV module. The deeper the water, the weaker the intensity of the surface of the PV module. Figure 4 shows the IV characteristics curve of polysilicon PV module with perpendicular irradiation at differing water depths. There is a direct relationship between the depth and the PV module short-circuit current. When the depth of the water is increased, the effect of current is gradually weakened. For perpendicular irradiation, when the water depth is 5 cm, the density of current is reduced by nearly half for the PV module. The greater the water depth, the less significant the current changes, and intuitively, the output power of PV modules decreases with the increase of water depth, among which the former 5 cm power decreases the fastest. Figure 5 shows the relationship between water depth and output power of a PV module with perpendicular irradiation. With an average water depth of 1 cm, there is a 4.78 W reduction in the output power of photovoltaic module, which is far greater than the average value 2.57 W. When the angle of incident light is 30 degrees, the output power of PV module is reduced by 2.1 W/cm. When the incident light angle is 45 degrees, the output power of the PV module changes to 2.07 W/cm, while when the incident light angle is 60 degrees, the output power of the PV module changes to 0.74 W/cm. As the light intensity directly affects the current change of the PV module, the output power of the PV module is mainly reduced by the decrease of incident light intensity, resulting in a smaller output current of PV module. For 30 and 45-degree angles, the incident light will produce a strong reflection, and the light entering the solar cell will be reflected and weaken, leading to a significant decrease in the current.

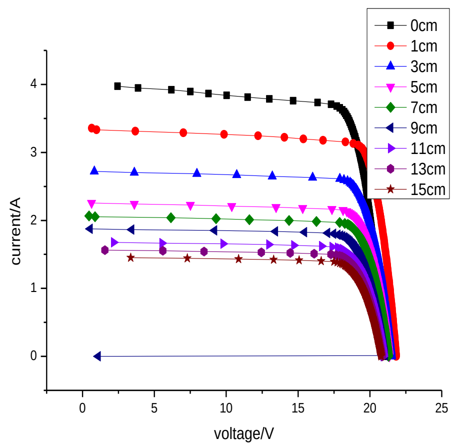

Figure 4. The IV characteristics curve of a polysilicon PV module for perpendicular irradiation at different water depths.

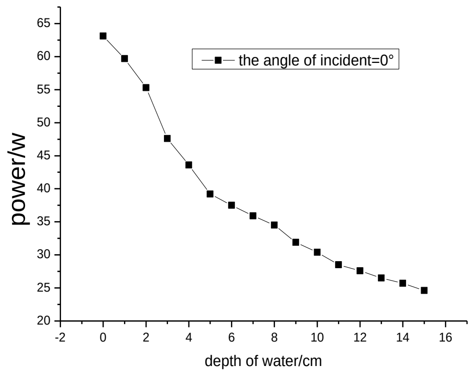

Figure 5. Relationship between water depth and output power of a PV module with perpendicular irradiation.

4.3. Relationship between water depth and output efficiency of PV module

When the PV module short-circuit current changes, the output efficiency and power will change accordingly. This rule is depicted in figure 6. This figure gives the relationship between the variation of water depth and the output efficiency of PV modules, and shows that there is an inherent correlation between the water depth and the conversion efficiency and output power.

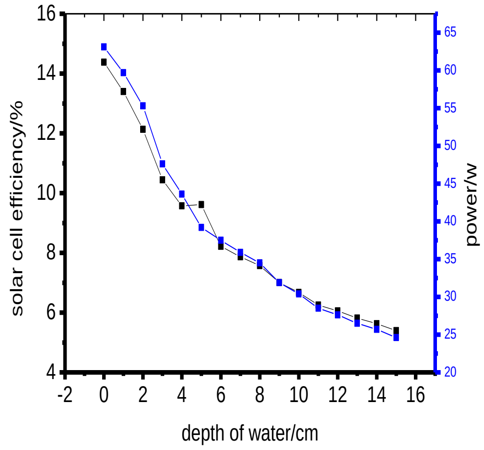

Figure 6. The relationship between the variation of water depth and the output efficiency of PV modules.

In fact, the photoelectric conversion efficiency of a solar cell refers to the ratio of the maximum output power of the PV module to the light incident upon the cell. This relationship can be expressed by formula (7) [8]:

$$\eta = \frac{I_m V_m}{AP_{in}} = \frac{P_m}{AP_{in}} \tag{7}$$

When the incident light intensity is constant, the photoelectric conversion efficiency of the solar cell is linearly related to the maximum power.

For incident angles of 0 degrees, 30 degrees, 45 degrees, and 60 degrees, when the water depth increases to 1 cm, the output efficiency and power change are reduced to 9.07%/cm, 40.8 W/cm; 8%/cm, 36.3 W/cm; 6.93%/cm, 31.7 W/cm; 3.67%/cm, 16.6 W/cm, respectively.

5. Simulation and measurement analysis

The short-circuit current of PV module is simulated and compared in this section. The relationship between water depth and short circuit current of photovoltaic module is also explored. When the water depth is 0 cm, the current test result of the PV module is 4.01 A, and the simulation current result is 3.79 A. The test results of PV modules match well with the simulation results. Figure 7 compares short-circuit current simulation and test results of PV modules.

According to equation (4), the output power of the PV module is calculated and can be compared with the measured results. Figure 8 is a comparison between simulated and measured output power of an underwater photovoltaic module. It can be seen from figure 8 that the output power of the PV module is well matched with the output curve of the PV module. The output power shows a downward trend with increasing water depth. At a measured water depth of 0 cm, PV module output power is 63.1 W, the analogy PV module output power is 61.2 W. At a measured water depth of 16 cm, PV module output power is 24.6 W, and the analogy PV module output power is 25.4 W.

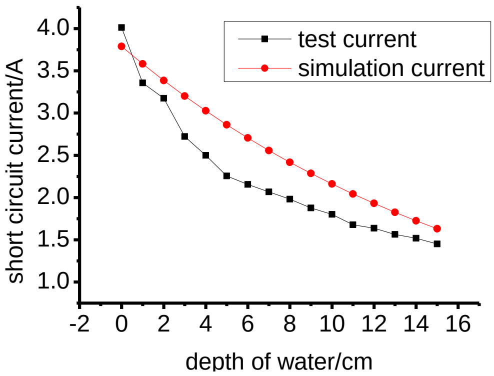

Figure 7. Comparison of simulated and measured short current of underwater photovoltaic module.

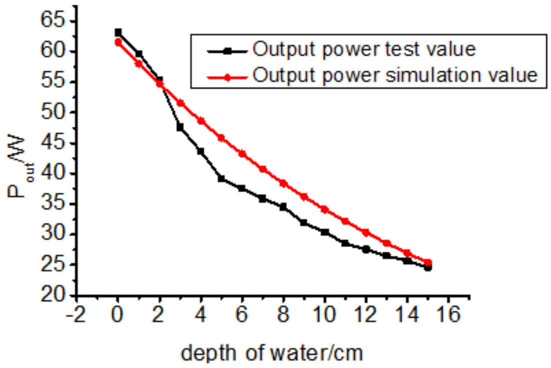

Figure 8. Comparison of simulated and measured output power of underwater photovoltaic module.

6. Conclusions

In order to analyze the output characteristics of polysilicon photovoltaic modules in water, this paper uses the Taiwan solar module analyzer (PROVA) to test the output characteristics at 0 to 15 cm depth of water under the simulated light source. The experimental results are analyzed and studied in detail, and the following conclusions are obtained:

- The water depth directly affects the output power of PV modules. When the incident light is direct, the output power of the PV module drops by half for a water depth of 5 cm. The PV output power of unit water depth is decreased by 2.57 W/cm.
- The output power of the PV module is affected by the short circuit current, and if the water depth of the PV module increases by 1cm each time, the short-circuit current will decrease by 2.39 A/cm and the output efficiency will decrease 9.07%/cm.
- Finally, in this study, the output power of underwater photovoltaic module was also simulated, and the simulation results were in good agreement with the test results.

Acknowledgments

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References

[1] Mook J R W J 2006 Solar panels with liquid super concentrators exhibiting wide fields of view (patent US 2006/0185713 A1)
[2] Wang Y P, Fang Z L, Zhu L, *et al* 2009 The performance of silicon solar cells operated in liquids *Appl Energ* **86** 1037-42
[3] Mehrotra S, Rawat P, Debbarma M, *et al* 2014 performance of a solar panel with water immersion cooling technique International *J Sci, Environ Technol* **3** 1161-72
[4] Chen J B, Yu H Z and Yao J S 2016 Research on application characteristics of surface water cooling solar photovoltaic modules *Acta Energiae Solaris Sinica* **37** 1768-72
[5] Liu J M 2010 *The Utilization of Solar Energy: Principle, Technology, Engineering* (Beijing: PublishingHouse of Electronics Industry)
[6] Yao Q J 2002 *Optics Course* (Beijing: Higher Education Press)
[7] Deng R R, He Y Q, Qin Y, *et al* 2012 Pure water absorption coefficient measurement after eliminating the impact of suspended substance in spectrum from 400 nm to 900 nm *J Remot Sens* **16** 176-84
[8] Zhao F X and Wei Y Z 1985 *Solar Cells and Applications* (Beijing: National Defense Industry Press)