Simulation of stand-alone floating photovoltaic and battery systems

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Abstract. The implementation of photovoltaic (PV) system has been evolving all over the world as the alternative energy sources are getting more required. However, the construction of PV power plants on the ground would need a large space. In regions which are lack of sites for the ground PV installation, a floating PV system is one of the solutions. This study analyses the performance of floating PV in supplying power to loads with a battery as the energy storage in a stand-alone system. The system is simulated using small capacities of PV module, battery, and load, where all components are integrated using a solar charge controller to maintain a safe operation. The performance of floating PV is compared to the ground PV in terms of the capacity factor, conversion efficiency, and operating efficiency. The average of capacity factor and conversion efficiency of floating PV is 1.53% and 0.79% higher than the ground PV respectively. Meanwhile, in terms of operating efficiency, floating PV is 1.48% more effective compared to the ground PV. One can notice that the floating PV provides better power efficiency compared to ground PV as the cell temperature is maintained well in an optimal circumstance.

1. Introduction
According to the Paris Agreement, Indonesia has set an overall target to have modern renewable energy sources providing 23% of total primary energy supply (TPES) by 2025, and 31% by 2050 [1]. Solar PV plant is one of the most favourable renewable energy sources to support the program due to its feasibility for the implementation. Moreover, some solutions have been proposed and implemented to improve the power generation efficiency of PV systems, i.e. solar power tracking, concentrator, MPPT technology for PV inverter, and panel cooling [2-6].

The construction of solar PV plants on the ground, particularly for a large-scale capacity, would require a large space too. Floating PV could be the solution for the space availability issue, since the installation of this system is floating on the water surface [7]. Besides, this system offers other benefits such as the cooling effect from the water which naturally has low temperature [8]. This low temperature helps to maintain the cell temperature of PV plants to be more stable for a whole day compared to the installation of PV plant on the ground, which leads to improving the output power efficiency. Another impact of floating PV for environment is to reduce the evaporation of water and prevent algae due to shadows by the panels [9].

In this study, a simulation of floating PV plant is carried out to assess the output power efficiency and compared to the ground PV installation. The simulated system is consisted of a 50 Wp PV module which is installed floating on water, a battery which is connected to the PV and load by a solar charge controller (SCC), and a DC load. Another identical system is used for simulating ground PV installation.
The ambient circumstances which affect the PV output power such as solar irradiance, wind velocity, water temperature, cell temperature, and ambient temperature are measured for data validation [10].

2. Model of simulated system

The simulated system represents solar PV plants which are installed on the ground as well as floating on the water. As shown in figure 1, each system consisted of 50 Wp PV module, 7 Ah lead acid battery with 10 A SCC, and 5 W DC load. The specifications of PV modules and lead acid battery are shown in table 1-2.

![Figure 1. Configuration and power flow of simulated system, (a) floating PV and (b) ground PV.](image)

| Specification | Remarks            |
|---------------|--------------------|
| Maximum power | 50 Wp              |
| Voltage at maximum power | 18.1 V        |
| Current at maximum power | 2.76 A         |
| Open circuit voltage | 22.1 V         |
| Short circuit current | 2.64 A         |
| Panel efficiency | 13.8 %         |
| Power tolerance (positive) | +3 %       |
| Operating temperature range | -40~85 °C  |
| Temperature coefficient of Pmax | -0.4 %/°C |
| Temperature coefficient of Voc | -0.35 %/°C |
| Temperature coefficient of Isc | 0.06 %/°C |
| Cell type     | Monocrystalline   |

Both PV modules are 50 Wp with monocrystalline-type. The SCCs are PWM-typed, and the batteries are lead acid 7.2 Ah. The active power floating from the PV terminals are measured using four digital multi meters, where two multi meters are for current measurement, and other two multi meters are for voltage measurement. Besides, some parameters affecting the output power of PV is measured, such as ambient temperature, water temperature, PV cells temperature, solar irradiance, and wind velocity. Temperatures, solar irradiance, and wind velocity are measured using a thermometer, a solar power meter, and an anemometer respectively. Fig. 2 shows the measurement tools which is used in this study.
Table 2. Specification of 7.2Ah battery.

| Specifications          | Remarks                                      |
|-------------------------|----------------------------------------------|
| Type                    | Valve regulated lead acid                    |
| Nominal Voltage         | 12 V                                         |
| Nominal Capacity (20 hr)| 7 Ah                                         |
| Dimension (length x width x height) | 670x540x30 (mm)                 |
| Approx. weight          | 2.1 kg                                       |
|                         | 7.00 Ah/0.350 A (20h, 1.8V/cell, 25 °C)     |
|                         | 6.51 Ah/0.651 A (10h, 1.8V/cell, 25 °C)     |
| Rated capacity          | 5.95 Ah/1.190 A (5h, 1.75V/cell, 25 °C)     |
|                         | 5.37 Ah/1.790 A (3h, 1.75V/cell, 25 °C)     |
|                         | 4.40 Ah/4.400 A (1h, 1.6V/cell, 25 °C)      |
| Max discharge current   | 105 A (5s)                                   |
| Internal resistance     | Approx. 23 mΩ                                |

Figure 2. Measurement tools used in this study.

3. Performance analysis

As shown in Fig.1, one system is designed as a floating PV, and other system is the ground PV. Power is generated by both PV panels, and battery will charge or discharge the power difference between the generation and load consumption. SCC is used to manage the power flow in the system.

The output power flowing from both modules was measured and compared to PV module rating to assess the capacity factor of both systems. Solar irradiance and cell temperature were measured as well to assess the conversion and operating efficiencies. Besides, other parameters affecting PV output was measured, such as wind velocity, ambient temperature, and water temperature for validating the correlation of two assessed variables.

3.1. Capacity factor

The capacity factor $CF$ can be defined by

$$CF = \frac{P_m}{P_{PV}} \times 100\%$$

where $P_m$ and $P_{PV}$ are the measured PV output power and rating of PV module respectively.

3.2. Conversion efficiency

The conversion efficiency $\eta_c$ can be defined by

$$\eta_c = \frac{P_{m,i}}{G_A} \times 100\%$$
where $G$ and $A$ are solar irradiance and PV module area respectively.

### 3.3. Operating efficiency

The operating efficiency $\eta_o$ can be defined by

$$\eta_o = \frac{(T_m - T_{STC})TC_{Pmax}}{T_{Pmax}}$$

where $T_m$, $T_{STC}$, and $TC_{Pmax}$ are measured cell temperature, temperature of standard test condition, and temperature coefficient of $P_{max}$ respectively.

### 3.4. Correlation coefficient of two variables

The correlation coefficient of variable $X$ and $Y$ here is calculated using Pearson correlation $r_{XY}$

$$r_{XY} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\left(\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^{1/2}\left(\sum_{i=1}^{n}(y_i - \bar{y})^2\right)^{1/2}}$$

### 4. Measurement results and analysis

This experiment was done from 1.19-3.44 pm. The floating PV was installed on a pond, while the ground PV was installed beside the pond to obtain the same ambient circumstances. PV modules in both systems were arranged with 0° tilt. Some measurement results of ambient circumstances are presented, such as solar irradiance, wind velocity, ambient temperature, water temperature, and cell temperatures.

4.1. Solar irradiance

Solar irradiance was measured using a solar power meter. The highest irradiance was obtained at 02.08 pm, around 636.4 W/m². Meanwhile, the lowest one was at 03.42 pm, around 83 W/m². The measurement result is shown in Fig. 3.

4.2. Wind velocity

The wind velocity was measured using an anemometer. The highest wind velocity was derived at 1.20 pm, around 2.4 m/s. While 38% of measurement duration, the wind did not blow. The measurement result is shown in Fig. 4.

4.3. Temperature

Ambient temperature, water temperature, and cell temperature of both PV modules was measured using a thermometer with four thermal sensors. As shown in Fig. 5, the cell temperature trend of ground PV almost similar with ambient temperature. Using Equation (4), the correlation coefficient of ground PV cell temperature and ambient temperature is 0.897. According to [11], this coefficient value indicates a strong correlation between both variables.

Besides, the water temperature is relatively stable during the measurement, so does the cell temperature of floating PV. The coefficient correlation of both variables is 0.378 which does not indicate a strong correlation, this might be caused by other factors which make the data trend variations of floating PV cell temperature and water temperature are not similar, such as wind velocity and ambient temperature. However, the cell temperature variation of floating PV is more stable compared to the ground PV.

4.4. Power flow of the system

PV output power was measured using voltmeters and amperemeters at the terminal of both PV modules. The measured current and voltage in each system is multiplied to obtain PV output power value. The load is assumed always constant in 5 W. Thus, battery charging or discharging power is the power difference between PV modules and load. The system power flow is shown in Fig. 6.
4.5. Performance comparison between ground PV and floating PV

The performance of ground PV and floating PV is compared in terms of the capacity factor, the conversion efficiency, and the operating efficiency according to equation (1)-(3). The average of capacity factor of floating PV is 18.14%, while for ground PV is 16.61%. On the other hand, the average of conversion efficiency of floating PV is 10.14%, while for ground PV is 9.35%. With the same load consumption for both systems, floating PV is able to generate more power compared to the ground PV.

The average of operating efficiency of floating PV is -5.5% and for ground PV is -6.98%. The temperature coefficient of $P_{\text{max}}$ indicates the percentage of energy loses of a solar panel for every temperature unit due to the exceed measured cell temperature from its STC temperature, which is 25°C for PV modules used in this study. Thus, in this study, with average cell temperature of floating PV around 38.73°C, it is 5.5% less effective than it would be at a temperature of 25°C. Meanwhile, for ground PV with average cell temperature around 42.44°C, it is 6.98% less effective than it would be.
at its STC temperature. From the results above, one can notice that the floating PV has better performance compared to the ground PV.

5. Conclusion
In this study, the performance of floating PV is compared to the ground PV in terms of capacity factor, conversion efficiency, and operating efficiency. Besides, some factors which influence PV output power were measured, such as solar irradiance, wind velocity, ambient temperature, water temperature, and cell temperature. From the analysis above, the average of capacity factor of floating PV is 1.53% higher than the ground PV. On the other hand, the average of conversion efficiency of floating PV is 0.79% higher than the ground PV. Meanwhile, in terms of operating efficiency, floating PV is 1.48% more effective compared to the ground PV. According to the results, one can notice that floating PV has better efficiency in generating electric power compared to the ground PV.

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