Modification of circuit module of dye-sensitized solar cells (DSSC) for solar windows applications

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Abstract This research has been conducted to obtain a modification of circuit producing the best efficiency of solar window modules as an alternative energy for daily usage. Solar window module was constructed by DSSC cells. In the previous research, solar window was created by a single cell of DSSC. Because it had small size, it could not be applied in the manufacture of solar window. Fabrication of solar window required a larger size of DSSC cell. Therefore, in the next research, a module of solar window was fabricated by connecting few cells of DSSC. It was done by using external electrical circuit method which was modified in the formation of series circuit and parallel circuit. Its fabrication used six cells of DSSC with the size of each cell was 1 cm x 9 cm. DSSC cells were sandwich structures constructed by an active layer of TiO$_2$ as the working electrode, electrolyte solution, dye, and carbon layer. Characterization of module was started one by one, from one cell, two cells, three cells, until six cells of a module. It was conducted to recognize the increasing efficiency value as the larger surface area given. The efficiency of solar window module with series circuit was 0.06%, while using parallel circuit was 0.006%. Module with series circuit generated the higher voltage as the larger surface area. Meanwhile, module through parallel circuit tended to produce the constant voltage as the larger surface area. It was caused by the influence of resistance within the cable in each module. Module with circuit parallel used a longer cable than module with series circuit, so that its resistance increased. Therefore, module with parallel circuit generated voltage that tended to be constant and resulted small efficiency compared to the module with series circuit. It could be concluded that series external circuit was the best modification which could produce the higher efficiency.

1. Introduction
Dye-sensitized Solar Cell (DSSCs) was a solar cell device for converting solar energy into electrical energy. DSSC has advantages in the fabrication process, it fabrication process was easy and was not use high technology. DSSC cells were sandwich structures constructed by an active layer of TiO$_2$ as the working electrode, electrolyte solution, dye, and carbon layer [1,6]. The working principle of DSSC was when the light absorbed by dye on the working electrode, there will be excitation of electrons in the dye. The excited electrons be injected into the TiO$_2$ layer and then flowed through the outer circuit of DSSC towards the counter electrode. The functions of the counter electrode as a catalyst that will help hasten the reaction process between electrons with an electrolyte solution [2]. The results of reaction will charge a hole in the dye process and it will continue to be repeated.
In the previous research, solar window was created by a single cell of DSSC with a small size. Because it had small size, it could not be applied in the manufacture of solar window. Fabrication of solar window required a larger size of DSSC cell. It can be as an alternative energy for daily usage. The problem right now was the process of making a module of DSSC were difficult. It must has a large size module which then can be applied to solar window. Research of Pranoto (2013) has produced solar module interconnect design type Z series has three pieces of single cells the size of 1 cm x 9.8 cm with a conversion efficiency of 0.77% [3]. Therefore, in the next research, a module of solar window was fabricated by connecting few cells of DSSC. It used external electrical circuit method which was modified in the formation of series circuit and parallel circuit. It’s fabrication using six cells of DSSC with the size of each cell was 1 cm x 9 cm. Current-voltages Characteristics of data generated are in the form of voltage, current, and efficiency. This aims for the research is to determine the efficiency and the current-voltages characteristics resulted from modifications of Dye-sensitized Solar Cell (DSSCs). Modification of the circuit in DSSC that good produces current-voltages characteristics can expect to be applied became solar windows DSSC.

2. Methods
Materials are used in this research is FTO glass substrates 7 Ω Dye Sol, TiO$_2$ nanopowder Aldrich as the working electrode with a size of 21 nm, carbon as the counter electrode, electrolyte solution Dyesol, Dye Ruthenium N719 Dyesol, and silver paste. A module of solar window was fabricated by connecting few cells of DSSC. It using by external electrical circuit method which was modified in the formation of series circuit and parallel circuit. It was fabrication used six cells of DSSC with the size of each cell was 1 cm x 9 cm. FTO substrate was washed using soap water and then rinsed twice using aquades into ultrasonic cleaner, finally is rinsed with 96% alcohol by ultrasonic cleaner. Deposition of TiO$_2$ paste by screen printing technique [3,7]. TiO$_2$ paste will be coated on FTO substrate and then be annealed at temperature of 500 ° C in a holding time of 10 minutes. The working electrode is then soaked with dye for 24 hours. Coating the counter electrode used carbon pencil and be annealed with a temperature of 500 ° C. Finally process on the fabrication of DSSC is assembling to arrange the working electrode and the counter electrode with a sandwich structure, then assembled by series circuit and parallel circuit. Silver paste was used to connect between cells in series external circuit and parallel external circuit. DSSC has been formed and then injected with a solution of electrolytes (HSE) and then tested characteristics by using the I-V meter keithley 2602A with intensity of radiation 1000 W / m$^2$. DSSC modules were connected to the set of tools to probe positive to counter electrode and the negative probe to the working electrode.

3. Result and Discussion
This research resulted DSSC prototype were presented in Figure 1 and the scheme of the series connection and parallel connection were presented in Figure 2a and 2b.

![Figure 1](image-url) This single cell will be connected in series circuit and parallel circuit
In the series external circuit and parallel external circuit were tested from a single cell, two cells, three cells, four cells, five cells, and six cells. The characteristics produced was voltage, current, and efficiency. The results characteristics of voltage and current were plotted in I-V curve were presented in Figure 3 and Figure 4.

**Figure 2.** a) Schematics of series external circuit schematic, b) Schematics of parallel external circuit

**Figure 3.** Current-voltage curves for series external circuit
Figure 4. current-voltages curves for parallel external circuit

Figure 3 can be seen that voltages were resulted from series circuit showed shift to the right side which that indicated an increase in voltages, meanwhile the current changes too. Figure 4 showed the changes fluctuated current occur in parallel circuit and it was show resulted voltages were not changed significantly. The current-voltage curve were used to determine of efficiency from each circuit. The efficiency of solar cells depends on multiplication between the maximum voltage and the maximum current it called a maximum power (Pmax) toward the input power (Pin) was resulted from the intensity of radiation and active area of DSSC. The equation was used to find efficiency of a DSSC is presented in equation 1[2].

\[
\eta = \frac{P_{\text{max}}}{P_{\text{in}}}
\]  

(1)

| Characteristic | Single cell | Two series | Three series | Four series | Five series | Six series |
|----------------|-------------|------------|--------------|-------------|-------------|------------|
| V_{oc} (volt)  | 0.5103      | 0.9903     | 1.5605       | 2.1606      | 2.8908      | 3.2307     |
| I_{sc} (A)     | 0.0026      | 0.0024     | 0.0036       | 0.0038      | 0.0026      | 0.0033     |
| V_{max} (Volt) | 0.3002      | 0.5302     | 0.7901       | 0.9801      | 1.4304      | 1.9704     |
| I_{max} (A)    | 0.0015      | 0.0011     | 0.0019       | 0.0020      | 0.0025      | 0.0017     |
| P_{max} (watt) | 0.0004      | 0.0006     | 0.0015       | 0.0020      | 0.0035      | 0.0033     |
| P_{in} (watt)  | 0.9000      | 1.8000     | 2.7000       | 3.6000      | 4.5000      | 5.4000     |
| eff            | **0.0494**  | **0.0335** | **0.0549**   | **0.0555**  | **0.0784**  | **0.0610** |
| FF             | 0.3380      | 0.2560     | 0.2609       | 0.2438      | 0.4760      | 0.3072     |
Table 2. Current-voltages characteristics of parallel external circuit

| Characteristics | Single cell | Two parallel | Three parallel | Four parallel | Five parallel | Six parallel |
|----------------|-------------|--------------|----------------|--------------|--------------|-------------|
| $V_{oc}$ (volt) | 0.5103      | 0.5614       | 0.5791         | 0.5505       | 0.4405       | 0.4899      |
| $I_{sc}$ (A)   | 0.0026      | 0.0029       | 0.0037         | 0.0026       | 0.0028       | 0.0026      |
| $V_{max}$ (Volt)| 0.3002      | 0.2412       | 0.3090         | 0.2604       | 0.2299       | 0.2601      |
| $I_{max}$ (A)  | 0.0015      | 0.0016       | 0.0019         | 0.0016       | 0.0016       | 0.0014      |
| $P_{max}$ (watt)| 0.0004      | 0.0004       | 0.0006         | 0.0004       | 0.0004       | 0.0004      |
| $P_{in}$ (watt)| 0.9000      | 1.8000       | 2.7000         | 3.6000       | 4.5000       | 5.4000      |
| $\text{eff}$  | 0.0494      | 0.0214       | 0.0217         | 0.0112       | 0.0081       | 0.0065      |
| $FF$           | 0.3380      | 0.2407       | 0.2723         | 0.2810       | 0.3016       | 0.2809      |

Characteristics of series external circuit were presented in Table 1. Characteristics of series circuit generates an increase continuous voltage with an increase in the active area of the DSSC. This is appropriate, if the circuit is arranged in series so it will increase the voltages and it has constant current \([4,8,10]\). Meanwhile in this research, the current generated in series circuit were not constant. It’s also changed with the change of the active cell area. The resulting stream increase to the fourth series and then fell in the five series and start to rise in the six series. Increase and decrease the resulting of current change were not significantly and the range of change was not far, so it can be said that the current relatively constant. It can occur because of the additional resistance of the cable and the silver paste were used in constructed electrical circuits in series so it can affect the value of current. The current flowed in the circuit depends on the amount of load or resistance in the circuit.

Characteristics data on parallel external circuit were presented in Table 2 resulted the relative same voltages. It was a range (0.44 to 0.57) volt which can be said constant value because of the difference was not far too. The current of this circuit generated increased and decrease with an added active area from the cells. The increase occurred in single parallel into three parallel, and began to fall on the four parallel up to six parallel. In the parallel circuit has produced more large current from single cell to addition of the cells \([5,8]\), but this research has not resulted that. This can occurred because of a connection cable that has a longer size and increase the resistance of the silver paste so influence at circuit between cells in parallel DSSC modules.

Efficiency was resulted from series external circuit are presented in Table 1. It was generated increase value in single cell up to five cells, but at six cells the value of efficiency was declined. It can occur because the current was generated from six series down drastically compared with the current of the five series. The amount of the maximum current will affect the maximum power, then it will impact on the resulted efficiency. The addition of the active area caused efficiency of DSSC was changed. Equation 1 showed the efficiency of DSSC was opposite to the active area. It was obtained from the output power, so the larger active area, then was efficiency was resulted will be decreased.

Efficiency at each cell on a parallel external circuit declined in six solar cells. The efficiency of series circuit was a higher than the efficiency of parallel circuits. That situation may occur due to at the series circuit, voltage increases will affect the output power so if voltage were large, output power will be large and then the efficiency were generated also great. Parallel external circuit produced constant voltage at each of the cells, so that the power were not changed significantly the efficiency generated. Power was not increased, then by increased active area of the parallel circuit so it will produce a small efficiency according to equation \(1\)\([9]\).

A module was applied to the solar window has important consider is output current and voltage as well as the best circuit that could make DSSC be durable and can be daily usage. Series circuit has a large voltage and has a greater efficiency but the series circuit has the disadvantage. It when one of the cells in the module damaged or dies so all of the cells in the module will stop, which means...
not current was flowing and was not reusable. Parallel circuit has a constant voltage and small efficiency, but a parallel circuit becomes durable because it was based on the principle of the parallel circuit, if a single cell was not active then the other cells will remain active so that the module DSSC can still work and produced a current [5] but can not produce a large output power.

4. Conclusion
The efficiency of solar window module with series circuit was 0.06%, while using parallel circuit was 0.006%. Module with series circuit generated the higher voltage as the larger surface area. Meanwhile, module through a parallel circuit tended to produce the constant voltage as the larger surface area. It was caused by the influence of resistance within the cable in each module. Module with circuit parallel used a longer cable than a module with series circuit, so that its resistance increased. Therefore, module with parallel circuit generated voltage that tended to be constant and resulted small efficiency compared to the module with series circuit. It could be concluded that series external circuit was the best modification which could produce the higher efficiency.

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