Simulation of photovoltaic module configuration for different shaded patterns

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Abstract. This paper presents the simulation of photovoltaic (PV) module operation which is created from basic equation of photovoltaic module. The three standard configurations of PV module consisting of series-parallel (SP), bridge-linked (BL), and total cross-tied (TCT) are studied. Nine photovoltaic cells are arranged in a three by three array and the effect of different shaded patterns on electrical generation is predicted. In order to find the optimal configuration of PV module which can generate the highest power during shading and develop the automatic connecting system of each PV cell, the conditions of shading 1 in 9 PV, 2 in 9 PV, 4 in 9 PV, and 6 in 9 PV are simulated. The effectiveness comparison between the case of with and without the automatic array connecting system is tested. When the three standard configurations of PV module are tested during shading, the result found that BL is better than SP by 0.1 – 14 % and TCT is better than SP by 2 – 20 %. It can be concluded that TCT is the best configuration of PV module under shaded conditions.

1. Introduction  
Due to oil price increase and the emission problem by using fossil fuel such as oil, coal, and natural gas, renewable energy is one of alternative ways for reducing the oil price and emission problems. Consequently, solar energy which is clean and free is attractive from the past to the present. The statistical data from the Ministry of Energy, Thailand have been found that the potential of solar energy in Thailand is in the high level (4-5 kWh/m² per day) [1]. To generate electricity, the PV transforms solar energy into direct current of electricity. The PV material is composed of semiconductor which uses solar energy to stimulate electron transfer reaction in order to generate electricity. Therefore, there is no emission during electricity generation process which is different from using fossil fuel for generating electricity. Nevertheless, there are many factors that affect to the PV generation such as solar radiation, temperature, and solar incidence angle. Because the sun always moves, the fixed installation type of solar PV cannot always generate the power at its maximum capacity. Moreover, many PV modules are series and parallel connected for the large scale of PV array. Therefore, each PV module may obtain different solar radiation which can be occurred when some parts of the PV array are shaded by cloud, dust, construction or any objects. The shading causes voltage and current of PV decreases resulted in the reduction of power generation.

From the literature review of an increasing on efficiency for solar PV generation by using solar tracking system, the study in 2011 presented the image-guided control for central receiver system by...
using PID controller with digital camera to track the position of the sun. The result found that the proposed system can track the sun with ±5 Pixel error [2]. In 2012, the battery charging by using dual-axis solar tracker was studied. The solar radiation resistance sensor and microcontroller were used to measure the solar radiation. It was found that solar PV with dual-axis solar tracker could increase the power generation more than the generation from fixed installation type of solar PV by 17.72% [3]. In addition, the application of amorphous silicon solar PV using reflective mirrors for the purpose of increases the incidence of solar radiation was studied. This study found that solar PV with solar tracking system could generate power more than fixed installation type of solar PV by 15.33% [4]. In 2013, the dual-axis solar tracker system with water level balancing by using microcontroller was studied. The sunlight was tracked by light dependent resistor (LDR) and the obtained voltage was compared with reference voltage. This study found that solar PV with solar tracking system could generate more power than fixed installation type of solar PV by 37.63% [5]. In 2015, a low cost solar tracking system was developed by using the sun position calculation to control the solar PV movement and light intensity sensor to adjust the solar PV position. This study found that the incorrectness of the sun position was best achieved not more than 1 degree. [6] In 2015, the driven system of PV module for automatically tracking sunlight by using microcontroller was studied. This study found that solar PV with solar tracking system generated more power than fixed solar PV installation by 13% [7]. This agrees well with the data from electricity generating authority of Thailand (EGAT) [8]. However, solar tracking system generally uses mechanical or electrical devices to tune the movement of single or dual axis trackers. These device causes an increase of initial cost, therefore, there should be an alternative method to increase efficiency of solar PV with a lower cost. The alternative method is the PV array reconfiguration which can be classified into three standard configurations consisting of series-parallel (SP), bridge-linked (BL), and total cross-tied (TCT). Presently, the most popular configuration is SP, however, TCT is most suitable for reducing operation loss when PV module is shaded [9]. In 2011, the configuration of PV module was studied by using 52 PV cells which were arranged in a thirteen by four array. The three standard configurations were tested for their effectiveness. The result found that when some part of PV module were shaded, the generation power changed depending upon the number of shaded PV modules. If there is low number of shaded PV cells, SP can provide the highest power output. However, when there is high number of shaded PV cells, power output from TCT is 5% better than SP [10]. Moreover, the mathematical simulation of solar panels have been studied by using basic equations of solar PV in order to study the effect of solar radiation, temperature, diode variables, serial - parallel resistor on the power generation of solar PV. The simulation have been applied to the commercialized solar PV and the result between the simulation and the real commercial solar PV were compared. It was found that series and parallel resistance affected on fill factor and variable diodes, and temperature of PV cells also affected on the output voltage of the solar PV as well as the solar radiation affected on the output current of the solar PV. [11]. In 2012, the dynamic efficiency increase of solar PV generation was studied by using a four by four array TCT configuration. Particularly for shading conditions, the solar PV with and without automatic array connecting system were compared. The result found that the output of solar PV with automatic array connecting system was 10% higher than that of the case without automatic array connecting system [12]. Furthermore, mathematical simulation of PV module configuration was studied via PSIM for the purpose of calculation speed time. Eight PV cells arranged in four by two array were used in the test. The simulation result found that the calculation speed has been reduced for the arrays current calculation from the PV model that were connected by SP and TCT configuration [13]. In 2013, the generated power of solar PV was studied by considering the maximum power points (MPP) of each PV cell. The three groups of array for testing were classified by using MPP of each PV cell as the criteria. For the group 1, all of the arrays were configured by considering the real MPP values obtained from the test. For group 2, all of the arrays were configured without considering the MPP values. Lastly, in the group 3, all of the arrays were configured by considering the simulated MPP values specified in the nameplate. From the test, it was found that the generated power obtained from the group 1 was 15% higher than that of group 2 [14].
In 2014, the effect of PV module configuration was studied via Matlab/Simulink. The 36 PV cells arranged in six by six array were used in the test. The SP, BL and TCT configurations were compared under shading on some parts of PV module. The result found that TCT had the highest power output which was higher than the other configurations by approximately 5.84% [15].

Therefore, based on the literature review, this research proposes the method for increasing the power generation of solar PV by using PV array re-configuration. This first part of the work investigates the effect of different shaded patterns on the power output when the PV modules were connected in three different configurations. The three by three PV array configuration are used for this research. The shading conditions of 1 in 9 PV, 2 in 9 PV, 4 in 9 PV, and 6 in 9 PV are simulated in order to find the optimal configuration of PV modules which can generate the highest power.

2. Method

2.1. PV module

The operation of PV module is the process to convert the solar energy to electricity directly. When sunlight which is the electromagnetic wave incidents to the semiconductor in PV module, the solar energy will be transmitted to electrons and holes in semiconductor. The electrons and holes will move to n-type and p-type levels, respectively. Afterwards, electrons will move to front electrode and holes will move to back electrode. Electrical circuit is completed by connecting front electrode and to the back of electrode, the electric current will occur. The equation (1) shows the characteristics of current and voltage of PV.

\[ I = I_{ph} - I_{s} \left( \exp \left( \frac{q(V+I_{R_s})}{A.K.T} \right) - 1 \right) \frac{(V+I_{R_s})}{R_{sh}} \]  

(1)

When, \( I_{ph} \) is the current from sunlight (A), \( I_{s} \) is the reverse biased current (A), \( q \) is the electron charge = 1.602×10\(^{-19}\) (C), \( A \) is the constant value at P-N Junction, \( K \) is the Boltzmann constant = 1.3806504×10\(^{-23}\) J/K, \( T \) is the temperature during PV operation (K), \( V \) is the voltage drop at diode (V), \( R_s \) is the series resistance of PV (Ω) and \( R_{sh} \) is the parallel resistance of PV (Ω).

The important parameters representing characteristic of PV are consisted of open circuit voltage \( (V_{oc}) \), short circuit current \( (I_{sc}) \), maximum power point \( (P_{mp}) \), current at maximum power point \( (I_{mp}) \), and voltage at maximum power point \( (V_{mp}) \). Moreover, there are other parameters related to the quality of PV module as shown below.

Fill factor (FF) is the ratio of maximum power and the product of short circuit current and open circuit voltage as shown in equation (2).

\[ FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \]  

(2)

Efficiency of PV module (\( \eta \)) is the ratio of output power and solar input power (\( P_{in} \)).

\[ \eta = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}} \]  

(3)

Maximum power of PV module can be determined by equation (4).

\[ P_{max} = I_{mp} \times V_{mp} \]  

(4)

2.2. Design of PV module re-configuration

PV module re-configuration can be classified into three standard configurations consisting of series-parallel (SP), bridge-linked (BL), and total cross-tied (TCT). For SP, it is the integration of series and
parallel connections in one circuit. For BL, it is the circuit that includes the bridge connection into the circuit. Finally, TCT is the array connection similar as BL but each row of TCT are connected in order to distribute current when it is shaded. The example of each configuration type is shown in Figure 1. This PV module consists of nine PV cells with rated capacity of 180 W. The output power of the PV module for the SP type is used as a base line power for comparisons.

![Figure 1. Each type of PV module configuration](image)

2.3. Simulation of shading patterns
For the condition of solar PV in normal operation, the solar radiation and the temperature are constantly defined as 1,000 W/m² and 40°C, respectively. In the condition of partial shaded as 1 in 9 PV, 2 in 9 PV, 4 in 9 PV and 6 in 9 PV, the solar radiation and the temperature are constantly defined as 600 W/m² and 40°C. The shading patterns of solar PV on the SP configuration type are defined as shown in Figure 2. For the BL and TCT configuration types, the same shading patterns are applied. All three types of PV module configurations are tested according to the above shaded conditions in order to find the configuration that can provide the highest output power.

![Figure 2. Partial shading conditions of a PV module for SP configuration type](image)

2.4. Simulation model
Matlab/Simulink software is chosen for the calculation of power obtained from the aforementioned shaded conditions. The characteristics of PV used in this research are shown in the Table 1.
Table 1. Characteristic of PV cell poly-crystalline type at the size of 20 W

| Characteristics                          | Spec. |
|------------------------------------------|-------|
| Maximum power (P_{max})                  | 20W   |
| Maximum power voltage (V_{max})          | 17.6V |
| Maximum power current (I_{max})          | 1.14A |
| Open circuit voltage (V_{oc})            | 21.4V |
| Short circuit current (I_{sc})            | 1.57A |
| Output tolerance (%)                     | ±3%   |

Figure 3. Model of PV modules in SP configuration type

The model of PV modules in SP configuration shown in Figure 3, is used to simulate on Matlab/Simulink for different shaded patterns. The BL and TCT configuration types are similarly simulated. The effects of each PV module configuration under partial shading of 1 in 9 PV, 2 in 9 PV, 4 in 9 PV and 6 in 9 PV are studied.

3. Results and discussions

Firstly, the PV module using SP configuration type is tested for analyzing the effect of shading on characteristic of PV module. In the case of without shading, the I-V and P-V curve of PV module are plotted as shown in Figure 4. Shaded pattern 5 is shown as an example to illustrate the effect of shading situation. The I-V and P-V curve of PV module in this case are shown in Figure 5. As seen in Figure 4 and 5, when there is shading on PV module, the current, voltage and power of PV module decrease. For BL and TCT configuration types, the results are in the same trend and shown in Table 2 and 3.

Figure 4. I-V and P-V curves of SP configuration case 1 (without shading)
Figure 5. I-V and P-V curves of SP configuration case 5

Table 2. Currents and voltages of each PV module configuration type when various shadings occur

| Shaded Patterns | Series-Parallel (SP) | Bridge-Linked (BL) | Total Cross-Tied (TCT) |
|-----------------|---------------------|--------------------|------------------------|
| Voltage (V)     | Current (A)         | Voltage (V)        | Current (A)            |
| Case 1 (No shaded) | 51.65   | 3.44   | 51.78   | 3.44   | 52.13   | 3.47   |
| Case 2 (1 in 9) | 48.21   | 3.21   | 48.99   | 3.26   | 49.63   | 3.31   |
| Case 3 (2 in 9) | 47.52   | 3.16   | 47.53   | 3.17   | 49.11   | 3.27   |
| Case 4 (2 in 9) | 44.45   | 2.96   | 44.72   | 2.98   | 45.79   | 3.05   |
| Case 5 (4 in 9) | 42.44   | 2.83   | 43.02   | 2.87   | 43.87   | 2.92   |
| Case 6 (4 in 9) | 39.90   | 2.66   | 42.55   | 2.84   | 43.73   | 2.91   |
| Case 7 (6 in 9) | 41.65   | 2.77   | 42.19   | 2.81   | 42.72   | 2.85   |
| Case 8 (6 in 9) | 37.24   | 2.48   | 37.29   | 2.48   | 38.18   | 2.54   |

From Table 2, it can be seen that the current and voltage of PV module decrease when solar radiation decreases. From the simulation results on SP configuration, the output current of PV module decreases when shading is occurred compared with no shaded condition as it can be seen in the case 2.

For case 3 (2 in 9), there are two cells shaded in the same string. The results showed that the output current were reduced. However, when shaded pattern were changed to case 4 (2 in 9), the shaded cells occurred in different string and the output current is further reduced. For the case 5 and 6 (4 in 9), the shading covers four cells but in different string arrays as shown in the Figure 2. The results showed that the output current in case 6 is much less than that of case 5. In case 7 and 8 (6 in 9), the shading covers six cells but in different configuration. For case 7, there are six cells shaded under two whole strings which is different from case 8 that is partially shaded 6 cells under three strings. The results showed that, although the number of shaded cells are equal, the output current in case 8 is much less than that of case 7. Based on these results. It can be concluded that under shaded condition with same number of cells but different shaded patterns, the output power will be different. It was found that shading in the same string would result in a better output than that of shading cross from one to the other string.

Thus, for PV module using SP configuration type, the current in a string will decrease when shading has occurred. This causes the output power to decrease as well. Therefore, the configuration should be changed from SP to BL or TCT in order to pass the current from the shaded string to neighbour string. Consequently, the currents as well as power obtained from BL and TCT are increased after it has been reconfigured as shown in Table 2 and Table 3 respectively.
Table 3. Generation power of each PV module configuration type when there are different shadings

| Shading patterns | Generation power of each PV module configuration (W) |
|------------------|------------------------------------------------------|
|                  | SP         | BL         | TCT         |
| Case 1 (No shaded) | 177.68     | 178.12     | 180.89      |
| Case 2 (1 in 9)   | 154.75     | 159.71     | 164.28      |
| Case 3 (2 in 9)   | 150.16     | 150.67     | 160.59      |
| Case 4 (2 in 9)   | 131.58     | 133.27     | 139.66      |
| Case 5 (4 in 9)   | 120.11     | 123.47     | 128.1       |
| Case 6 (4 in 9)   | 106.13     | 120.84     | 127.25      |
| Case 7 (6 in 9)   | 115.37     | 118.55     | 121.75      |
| Case 8 (6 in 9)   | 92.36      | 92.48      | 96.98       |

As seen in Table 3, it can be concluded that when shading decrease the output power of PV module, re-configuration is needed in order to avoid a reduction in the output power. When SP configuration is re-configured to BL type power is higher generated by 0.1-14%. Similarly, if SP configuration is re-configured to TCT type, the increase of power is expected to be around 2-20%. These results conform well to the previous research works [10–15]. Therefore, the PV module TCT configuration type is by far the best configuration when there is partial shading on PV module.

4. Conclusion

The results of PV module operation are simulated by using Matlab/Simulink. Nine PV modules arranged in a three by three array are used for investigation of shading effect on the output power. The output power of three standard configurations of PV module called series-parallel (SP), bridge-linked (BL), and total cross-tied (TCT) are compared for different shaded patterns of 1 in 9 PV, 2 in 9 PV, 4 in 9 PV and 6 in 9 PV. The simulation results show that the output power of BL and TCT configuration types are higher than that of SP configuration type by 0.1-14% and 2-20%, respectively. It can be seen that, the most suitable configuration when PV modules are partially shaded, is the TCT configuration type giving the highest power. However, in the normal operation condition (without shading), the suitable configuration is of SP type because this configuration is the most simple connection which can reduced the risk of overloading when the connection point is increased. In conclusion, the configuration of PV module can affect to the output power of solar PV therefore, the configuration should be suitably selected according to each condition of shading. For the future work, the implementation of automatic array connecting system hardware will be designed and integrated into the interconnection arrays in order to provide the maximum output power depending upon the condition of shading.

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