ENERGY MANAGEMENT OF PHOTOVOLTAIC SYSTEM UNDER PARTIALLY SHADED CONDITIONS

SYAFARUDDIN¹, Satriani LATIEF²

¹Universitas Hasanuddin, Department of Electrical Engineering, Makassar-Indonesia
²Universitas Bosowa, Department of Architecture, Makassar-Indonesia

¹syafaruddin@unhas.ac.id; ²satriani.latief@yahoo.com

Abstract: One of the recent concerns in the photovoltaic (PV) system practice is solving the mismatching losses due to the partially shaded conditions. Mismatching problems mean that the I-V and P-V curves between the shaded and non-shaded parts of PV module are totally different. Under mismatching condition, multiple local peaks can be observed in the PV module characteristics which put difficulties for controllers to track the maximum point. To overcome such problems, current injection method is used to compensate the output current of the shaded part. This paper presents current compensation method for improving the maximum power transfer of PV system under short-term period of shading by using Electric Double Layer Capacitors (EDLC). The amount of injected current and to which part of EDLC being injected are determined by utilizing the intelligent network by means of Artificial Neural Network (ANN). The proposed method is always end up with single local maximum point and prevents to occur multiple local maximum power point (MPP) that makes the optimum point can be easily identified using conventional controller algorithm.

Keywords: ANN, current sources, EDLC, PV module, partially shaded conditions

Introduction

Building integrated PV system is recently increasing in the market share of the PV application. A small size of PV modules can be easily found on the roof of the private residences. Since the PV module is statically installed on the top of the building, then the mismatching operation is being inevitable. The potential causes of mismatching losses can be the shading of other parts of the building, dirt on the top of the surface and the unpredictable cloudy condition. In this study, the mismatching problem is focused on the partially shaded condition on PV module. Mismatching problems is defined as the different I-V and P-V characteristics output between the shade parts and the non-shaded parts of the module. Normally, all cells inside the module produce the same output current under uniform irradiance condition. However, it is not the case if some parts of module receive less intensity of sunlight. The shaded parts will produce lower level output current and power as well compared with the output of non-shaded parts. Furthermore, multiple peaks can be observed in the output terminal and the operating voltage may also be shifting to the lower region that makes some difficulty for controllers to track the optimum point.

Partially shaded condition of PV system has great implication on the controller performance. It is due to the optimum operating point of PV system under this condition may change irregularly. Until now, no single control method can be claimed to be the best to solve this kind of problem. The novel techniques to minimize the mismatching losses of partial shading still require more additional sensors, auxiliary algorithms, and power electronics units. As the output current of the shaded part is noticeably decreasing, the current injection on the shaded parts can be a promising solution. Solving the mismatching problems with current compensation method has been studied so far. Mishima and Ohnishi (2003) have proposed the electric double layer capacitors as the power compensation and system control to solve the mismatching problem under partially shaded condition. However, this method is less flexible due to the necessary an auxiliary control of relay for charging and discharging the capacitor. Mutoh and Inoue (2007) have proposed a control method to charge series-connected ultra electric double-layer capacitors (ultra-EDLCs) for maximum power point tracking (MPPT) controller. In addition, Simjee and Chou (2008) have proposed the effective charging method of supercapacitor for wireless sensor network application. All the above efforts may solve the mismatching losses problems under certain conditions, but end up in the excessive complexity of the system configuration and create difficulty in practical system use.

The current compensation method is utilized for solving the mismatching losses due to partially shaded condition using the intelligent network by means the Artificial Neural Network (ANN). The proposed ANN acts as a switch to control the current source in terms of amount of injected current and to which terminal this current being injected. The method is simpler than other methods due to there are no complicated algorithms and required power electronic units. The necessary points in this method are only in the development of rule base for the amount and
Another advantage of this method is always end up with single peak point that makes the conventional controller algorithms such constant voltage control, perturbation and observation, incremental conductance, and current feedback algorithms are working perfectly in identifying the optimum point (Esram, T. & Chapman, P.L., 2007, Hohm, D.P. & Ropp, M.E., 2003)

Fast moving shadows cause problems to conventional maximum power point (MPP) trackers such as Perturb and Observe (P&O), Incremental Current Conductance and Hill Climbing methods because they are mainly designed for stationary applications. Mostly their algorithms approach the zero gradient of power after taking certain step-time, but they will end up in a local maximum power point (MPP). Fast shadows cause these trackers to lose the maximum power point momentarily, and the time lost in seeking it again, because the point has moved away quickly and then moved back to the original position, equates to energy lost while the array is off power point. On the other hand, if lighting conditions do change, the tracker needs to respond within a short period of time to the change to avoid energy loss. The solving of this problem is very important for moving devices due to the unpredictable conditions such as passing under the narrow shadows of tree branches or the quick-moving shadows of passing vehicles.

In this paper, the current compensation method by means the Extra Double Layer Capacitor (EDLC) is utilized to improve the maximum power transfer of PV system under short-term period of shading. We received inspiration from Mishima and Ohnishi method for this study. The important characteristics of EDLC are high charging and discharging capabilities according to conventional batteries, but it behaves as a capacitor. If the partially shaded condition is short, the EDLC is enough to compensate the current of partially shaded PV arrays for reducing the power losses. Of course, the time period depends on the capacity of EDLC. When the EDLC is fully charged, the EDLC current becomes zero. It means that the EDLC don't absorb energy from PV when there are no shading conditions. With this method, if the EDLC is used, the I-V responses of PV array will be slow with respect to the no EDLC. Therefore, under the fast changing irradiance conditions, the conventional MPPT controller algorithms like P&O method can follow the MPP easily due the slow changing of current and voltage of PV array. Moreover, it is a simple unit due to the EDLC does not need the charger controller unit as compared with batteries. Meanwhile, ANN is utilized to operate switches that connected to the EDLC unit based on the irradiance signals condition. The method is simpler than other methods due to there are no complicated algorithms and required power electronic units. Another advantage of this method is always end up with single peak point on power-voltage curve that makes the conventional controller algorithms are working perfectly in identifying the optimum point.

### Table

<table>
<thead>
<tr>
<th>ΔE</th>
<th>Current Injection (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>0.345</td>
</tr>
<tr>
<td>200</td>
<td>0.690</td>
</tr>
<tr>
<td>300</td>
<td>1.040</td>
</tr>
<tr>
<td>400</td>
<td>1.380</td>
</tr>
<tr>
<td>500</td>
<td>1.720</td>
</tr>
<tr>
<td>600</td>
<td>2.060</td>
</tr>
<tr>
<td>700</td>
<td>2.420</td>
</tr>
<tr>
<td>800</td>
<td>2.760</td>
</tr>
<tr>
<td>900</td>
<td>3.096</td>
</tr>
</tbody>
</table>

![Diagram](image.png)

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**Configuration of Proposed Systems**

The configurations proposed method is described in Fig 1. There are two main parts in this model i.e PV module and ANN network. The PV module is divided into two series-connected parts, called Part-I and Part II based on the bypass diode connection. The irradiance, denoted with $E_1$ and $E_2$ in W/m² and cell temperature in degree Celsius are the input signals for both parts of PV module. The second part is the ANN block which is working as controller for the current sources of $I_1$ and $I_2$ based on the input signals of $E_1$ and $E_2$. The outputs of this model are...
indicated with current ($I$) and voltage ($V$) of the load that can be measured in the output terminal.

The type of PV module is Siemens SM55 with 36 monocrystalline Si cells in series (Karatepe, E., Boztepe M., & Colak, M., 2007). Two bypass diodes are connected for each 18 cells with non-overlapped cells configuration. Under uniform irradiance condition of 1000W/m² and cell temperature of 25°C, both parts produce similar $I$-$V$ and $P$-$V$ curves with maximum power point voltage ($V_{mp}$) and power ($P_{mp}$) are 8.798V and 27.78W, respectively (Fig. 2a). However, when Part-I of module shades with 100W/m², then both curves are exactly different and two peaks occur in the output terminal (Fig. 2b). To solve this condition, current compensation method is the most logical option. Injection 3.096A in the terminal of Part-I will bring back the curves as the uniform irradiance condition (Fig. 2c). The amount of injection current is determined by the difference of short circuit current between both parts when receiving 100W/m² and 1000W/m². In this case, the module parts with higher irradiance are selected as the target operation.

To solve the overall shading condition, a rule base for the amount of current injection and its direction are developed following the irradiance condition in both parts. The rule base of this method is expressed as follows:

$$\Delta E = E_1 - E_2$$

$$\Delta E = \begin{cases} 
0 & ; \text{no current injection} \\
- & ; I_1 \text{ injects current} \\
+ & ; I_2 \text{ injects current}
\end{cases}$$

From this heuristic approach, About 100 training data set for the ANN can be generated. The ANN method is the three feed-forward neural networks with two input signals of $E$; and $E^2$ and two outputs $I_1$; and $I_2$. After the training process, the number of hidden nodes is determined at 10 with minimum errors at 0.00132846.

**Table 1:** Comparison between the target and the proposed method under partially shaded conditions under $T_c=25°C$

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>$E$(W/m²)</th>
<th>$V_{mp}$(V)</th>
<th>$P_{mp}$(W)</th>
<th>$V_{mp}$(V)</th>
<th>$P_{mp}$(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Part-I</td>
<td>Part-II</td>
<td>Target</td>
<td>Proposed Method</td>
<td></td>
</tr>
<tr>
<td>10.00</td>
<td>150</td>
<td>950</td>
<td>17.54</td>
<td>52.54</td>
<td>17.50</td>
</tr>
<tr>
<td>10.30</td>
<td>225</td>
<td>875</td>
<td>17.53</td>
<td>48.02</td>
<td>17.45</td>
</tr>
<tr>
<td>11.00</td>
<td>315</td>
<td>780</td>
<td>17.28</td>
<td>42.36</td>
<td>17.21</td>
</tr>
<tr>
<td>11.30</td>
<td>230</td>
<td>675</td>
<td>17.09</td>
<td>36.16</td>
<td>17.09</td>
</tr>
<tr>
<td>12.00</td>
<td>350</td>
<td>580</td>
<td>16.82</td>
<td>30.63</td>
<td>16.92</td>
</tr>
<tr>
<td>12.30</td>
<td>650</td>
<td>125</td>
<td>16.94</td>
<td>34.70</td>
<td>17.00</td>
</tr>
<tr>
<td>1.00</td>
<td>775</td>
<td>235</td>
<td>17.25</td>
<td>42.06</td>
<td>17.29</td>
</tr>
<tr>
<td>1.30</td>
<td>820</td>
<td>320</td>
<td>17.31</td>
<td>44.74</td>
<td>17.42</td>
</tr>
<tr>
<td>2.00</td>
<td>940</td>
<td>425</td>
<td>17.60</td>
<td>51.93</td>
<td>17.58</td>
</tr>
<tr>
<td>2.30</td>
<td>999</td>
<td>335</td>
<td>17.59</td>
<td>55.50</td>
<td>17.68</td>
</tr>
</tbody>
</table>

The output of the proposed method can be verified by varying the irradiance in both parts of module. In Table 1, the output target means the expectation of operating point based on the maximum irradiance on the module parts under uniform condition. If shading occurs in any parts, then the ANN should decide the amount injection current and its direction. The results of proposed method are very similar to the target points in terms of $V_{mp}$ and $P_{mp}$.

The configuration of proposed method with EDLC utilization is described as in Fig. 3. The irradiance, denoted with $E_1$ and $E_2$ in W/m² and constant cell temperature ($T_c=45°C$) are the input signals for both parts of PV module. The ANN network controls to operate the EDLC units through the turn-on and off of the switches S1 and S2 based on the input signals of $E_1$ and $E_2$. The proposed method is integrated by conventional perturbation and observation MPPT system. The Part-I is arbitrarily considered as the shaded parts with determined irradiance levels. Meanwhile, the irradiance in the second part ($E_2$) is kept constant at 850W/m².
a. Matching $I$-$V$ and $P$-$V$ curves under uniform irradiance condition

b. Mismatching $I$-$V$ and $P$-$V$ curves under partially shaded condition

c. $I$-$V$ and $P$-$V$ curves due to the injection current in the shaded part

Fig. 2 Comparison of $I$-$V$ and $P$-$V$ curves before and after injection current
The ANN is utilized to operate the EDLCs (60F) through the switches $S_1$ and $S_2$ based on the irradiance conditions. Initially, both $S_1$ and $S_2$ are in the normally closed condition ($S_1=S_2=1$), means both the EDLCs are in charging state. Then, the switches are regulated based on the difference $E_1$ and $E_2$ as follows:

$$
\Delta E = E_1 - E_2 \quad (3)
$$

$$
\Delta E = \begin{cases} 
0 & S_1 = 0, S_2 = 0 \\
- & S_1 = 1, S_2 = 0 \\
+ & S_1 = 0, S_2 = 1 
\end{cases} \quad (4)
$$

The ANN method is the three feed-forward neural networks with the number of hidden nodes is determined at 2 with minimum errors of $0.99\times 10^{-5}$ for 100 training data set. In this study, the shading is intentionally occurred in the first part of the module. The ANN will send input signal 1 to $S_1$ to be remained the EDLC-1 connected, while 0 to $S_2$ to let the EDLC-2 disconnected.

**Results and Discussion**

Most of the quick changes in MPP on a mobile PV array is due to the fast-moving shadows. Fast-moving irradiance condition is one of the problems that need to be solved in the non-stationary PV system applications. Under this condition, the conventional tracker starts searching the optimum point continuously which is one of the loss factors. This paper presents a novel current compensation method for improving the maximum power transfer of PV system under short-term period of shading by using Electric Double Layer Capacitors (EDLC). The Artificial Neural Network (ANN) is utilized to operate switches that connected to the EDLC unit based on the irradiance condition. This paper is directly purposed to reduce the power losses for moving objects powered by solar energy, such as solar car and solar boat systems. The proposed method can prevent to occur multiple local MPP that makes the optimum operating point can be easily identified by using a conventional controller algorithm.

Fig. 3. Configuration of proposed method with EDLC utilization

Fig. 4. PV array outputs between using EDLC and without EDLC

a. Effect of EDLC in the short period of shading  
b. Effect of EDLC on the variety period of shadings
The capacitor size is the important factor for this system. If the capacitor size increases, it needs to wait for more time to charge. The EDLC can provide energy according to its capacity rating. The EDLC is connected to each module parts. In this reason the number of series connected EDLC should be adapted according to optimum MPP voltage for each module type. Tap changer is a method to adjust the optimum voltage according to irradiation and temperature (Nagaoka, N., Miyamoto, A., & Ametani, H., 2004). ANN can be also used for controlling the tap changer unit in a future work.

Fig. 4 show the simulation results in different scenarios. If the period of partial shading is too long, the PV system power output with EDLC and no EDLC is the same after discharging. However, if the shading period is not too long as shown in Fig. 4a, the EDLC can reduce the power loss by compensating current of shaded module. Fig. 4b shows the results when suddenly shadow conditions occur with different time interval. The shading patterns are from 850 to 400, 350, 300, and 250W/m² during 200, 100, 75, and 50s, respectively.

**Conclusion**

New approach of current compensation method for solving mismatching losses due to partially shaded condition has been presented. This method is simple and able to maximize the performance of conventional controller in order to meet the optimum point. The utilization of EDLC to improve the maximum power tracking control of PV system has been presented. This method is effectively solving the mismatching losses under fast-moving shadow condition. The purpose of this study is intended to reduce the power losses for moving objects powered by solar energy, such as solar car and solar boat systems during short-term period of shading.

**References**


