Teaching Maximum Power Point Tracking (MPPT) Algorithms of Photovoltaic (PV) Systems Using MATLAB

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Abstract

This paper presents the development of MATLAB Simulink models that will aid in teaching maximum power point and maximum power point tracking (MPPT) algorithms in photovoltaic systems. The aim of these models is to help students have a deeper understanding of MPPT by examining Simulink models and carrying out various simulations. Three Simulink models were created to study maximum power point in solar cells and modules. One Simulink model was developed to explore two MPPT algorithms: Perturb and Observe (P&O) and Fractional Open-Circuit Voltage (Fractional OCV). The response of PV output power to the changes in environmental factors like solar irradiance and temperature was also examined.

1. Introduction

Solar energy is clean, free, and abundant. It holds the potential to support a clean, reliable, and more sustainable energy future. From the years 2000 to 2019, global cumulative installed photovoltaic (PV) capacity has increased by 632.4 GW [1]. In 2019 alone, 116.9 GW of new PV was installed. It was estimated that global solar PV installation in 2020 would increase approximately 132 GW from 2019. Despite the impact of pandemic on the economy, the United States installed 11.1 GW of solar PV in the first 9 months of 2020 which is the largest first 9-month total ever [2]. With the increase in PV installation, employment in solar PV sector also increased significantly. The total jobs in PV globally were estimated at 3.76 million in 2019, increased from 3.1 million in 2016, a 21% increase [3]. To meet the workforce needs of the PV industry, the School of Engineering at Grand Valley State University has developed a solar energy curriculum [4]. The aim of this curriculum is to provide students with fundamental theory and practical hands-on experiences on solar PV.

1.1 Overview of the Solar Energy Curriculum

Three learning modules on solar energy have been developed to be incorporated in two courses in the electrical engineering undergraduate program. One is the sophomore-level course “Electronic Materials and Devices” and the other is the senior-level course “Embedded Systems Interface”. The curriculum also includes a graduate-level course titled “Photovoltaic Systems”. The three learning modules are [4]:

1. Solar Radiation Module
2. Solar Cell Module
3. Solar Energy Harvesting Module (for senior-level course only)
The Solar Energy Harvesting Module focuses on learning and building a solar energy harvester to power an embedded system. Topics include:

a. Requirements of a solar energy harvesting system  
b. DC/DC conversion circuit  
c. Maximum power point tracking (MPPT) algorithms  
d. Solar energy harvesting IC selection  
e. Design and build a solar energy conditioning circuit that is used to charge a rechargeable Li-ion battery and to power an embedded system.

In teaching the Solar Energy Harvesting Module, students often ask questions like “How would duty cycle change the voltage of the solar cell?” “How to implement different MPPT algorithms?” “Is one algorithm much better than the other?”. To help students understand these, we developed MATLAB Simulink models that can be used to study the conditions of maximum power point (MPP) and different MPPT algorithms.

2. MATLAB Simulink Models

Three Simulink models were developed to provide students with hands-on experiences in studying the MPP of solar cells/modules. These include (1) Solar Cell with Variable Load, (2) Solar Module with Variable Load Voltage, (3) PV Array with DC-DC Converter. The fourth Simulink model was developed to study different MPPT algorithms.

2.1 Maximum Power Point of Solar Cells/Modules

Most solar cells are diodes that operate in the fourth quadrant of its current – voltage curve. A typical solar cell can be modeled with the circuit shown in figure 1 which contains a constant current source, a diode, a series resistance, and a parallel resistance. The terminal current and voltage relationship can be expressed with equation 1, where $I_{ph}$ is light generated current; $I_s$ is the diode saturation current; $V_T$ is the thermal voltage, and $n$ is the diode ideality factor.

![Figure 1: One-diode solar cell equivalent circuit](image)

$$I = I_{ph} - I_s \left( e^{\frac{V + IR_s}{nV_T}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

Equation 1 shows that even though solar cells can be used as power sources, they operate differently as batteries or power supplies which supply either constant current or voltage. The operating current and voltage of the solar cell, hence the power, change as the load changes. A MATLAB Simulink model shown in figure 2 was developed to illustrate this point. The model
uses the solar cell from the Simscape Electrical library, the signal generator for light irradiance, the variable resistor as a load, and the scope to capture the current, voltage, and power. The first exercise for students to do is to manually change the resistance value and observe the current, voltage, and output power and get a feel that when adjusting the load resistance, the output power changes accordingly. To find the resistance value that produces the maximum power available from the solar cell, the load was swept from 0 to 10ohm and the current, voltage, and output power were captured as shown in figure 3.

![Figure 2 Simulink model: Solar cell with variable load](image)

Figure 2 Simulink model: Solar cell with variable load

![Figure 3 Scope capture of current, voltage, and output power as load changes from 0 to 10 ohm](image)

Figure 3 Scope capture of current, voltage, and output power as load changes from 0 to 10 ohm

Figure 3 clearly shows that when the load resistance is 0, the voltage is small (0V); the current is high (8A); and the power is low (0W). As the load resistance increases, the current stays the same and then decreases while the voltage increases, which results in a peak output power at a specific load.

The maximum power point voltage ($V_{mpp}$) of a silicon solar cell is between 0.5 and 0.6V. To obtain higher voltage, solar cells are connected in series to form solar modules which are also modeled in Simulink to study their behavior. In figure 4, the solar cell was replaced with the solar module which contains 60 solar cells connected in series [5]. Also, in figure 4, the variable
load resistor was replaced with a test voltage to simulate the load voltage. The load voltage was changed from 0V to 40V and the current and output power were studied.

![Simulink model: Solar module with variable load voltage](image)

Figure 4 Simulink model: Solar module with variable load voltage

![Scope capture of current, voltage, and output power as load voltage changes from 0 to 40V](image)

Figure 5 Scope capture of current, voltage, and output power as load voltage changes from 0 to 40V

It is seen in figure 5 that as voltage increases current stays constant and then decreases to zero. The output power increases to the maximum value at voltage of 30V ($V_{mpp} = 30V$) and then reduces to zero. Both figures 3 and 5 indicate that in order to extract the maximum power available from the solar cell or module, one needs to have a specific load or voltage connected to it. However, in many applications, the load is either varying or fixed at a value that does not correspond to the maximum power point. To solve this problem, a DC-DC converter can be inserted between the solar module and the load. By changing the duty cycle of the DC-DC converter, the solar module voltage can be adjusted while keeping the load intact. Figure 6 shows the Simulink model of a PV array (two solar modules each with 360 solar cells connected in parallel), a DC-DC buck converter, and a load. The duty cycle can be manually entered to see its effects on the current, voltage, and power of both the PV array and the load. The duty cycle can then be changed to sweep from 0 to 1. Figure 7 shows the resultant current, voltage, and power.
2.2 MPPT Algorithm

Figure 6 Simulink model: PV array connected to the load via DC-DC converter

Figure 7 Scope capture of current, voltage, and output power of the PV array and load as duty cycle changes from 0 to 1

Figure 7 shows the change of extracted PV power as the duty cycle changes. For this specific load, the maximum power is reached when the duty cycle is set at 0.55. The load resistance was then changed and it was seen that the maximum power was obtained at a different duty cycle which confirmed that maximum power can be supplied to different loads by properly selecting the duty cycle of the DC-DC buck converter.
Instead of manually locating the maximum power point, different algorithms were developed to automatically track it [6, 7]. MPPT algorithm controls the duty cycle to ensure that the system operates at or near the maximum power point under different conditions such as temperature, solar irradiance, and load. There are three most common MPPT algorithms which are Perturb and Observe (P&O), Fractional Open Circuit Voltage (FractionalOCV), and Incremental Conductance. The first two were examined and incorporated in the Simulink model.

2.2.1 Perturb and Observe (P&O)

P&O perturbs the duty cycle of the DC-DC converter and observes the power from the PV array. Perturbation changes the PV array current and voltage which are measured and used to calculate the power. Both the voltage and power are compared to those of previous values, respectively, to determine the new duty cycle. This process keeps going until the maximum power point is found. Based on the simulation results of figure 7, the relationship among the voltage change, power change, and the duty cycle change are summarized in table 1.

<table>
<thead>
<tr>
<th>If</th>
<th>Then</th>
<th>duty cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta P = 0; \Delta V = 0 )</td>
<td></td>
<td>no change</td>
</tr>
<tr>
<td>( \Delta P &gt; 0; \Delta V &gt; 0 )</td>
<td></td>
<td>decrease</td>
</tr>
<tr>
<td>( \Delta P &lt; 0; \Delta V &lt; 0 )</td>
<td></td>
<td>decrease</td>
</tr>
<tr>
<td>( \Delta P &gt; 0; \Delta V &lt; 0 )</td>
<td></td>
<td>increase</td>
</tr>
<tr>
<td>( \Delta P &lt; 0; \Delta V &gt; 0 )</td>
<td></td>
<td>increase</td>
</tr>
</tbody>
</table>

Table 1 Determination of duty cycle change from the power change (\( \Delta P \)) and voltage change (\( \Delta V \))

To implement the relationship in table 1, a MATLAB script was written which is shown in figure 8 and from which a Simulink model of P&O was created.

```matlab
% Increase or decrease duty cycle based on conditions
if (P/wp - Pwp) == 0
    if (P/wp - Pwp) > 0
        if (P/wp - Pwp) > 0
            D = Dprev - deltaD;
        else
            D = Dprev + deltaD;
        end
    else
        if (P/wp - Pwp) < 0
            D = Dprev - deltaD;
        else
            D = Dprev + deltaD;
        end
    end
else
    D = Dprev;
end
```

Figure 8 MATLAB script of P&O

2.2.2 Fractional Open-Circuit Voltage (FractionalOCV)

It was observed that \( V_{mpp} \) is linearly proportional to the open circuit voltage (\( V_{oc} \)). The proportionality constant is empirically obtained to be between 0.7 and 0.9. The open-circuit voltage can be measured from a reference solar cell or by temporarily disconnecting the PV array.
from the load which results in power loss. In this simulation, a reference solar cell is used to determine $V_{oc}$ and hence $V_{mpp}$. The PV voltage is compared with the $V_{mpp}$ to create the error voltage which is used to control the duty cycle. The Simulink model is shown in figure 9 where the proportionality constant is set to be 0.82.

![Simulink model: Fractional Open-Circuit Voltage](image)

Both algorithms are implemented in the PV array Simulink model. As seen in figure 6, the DC-DC Buck controller can use either P&O or Fractional OCV algorithm. The output of the controller is connected to the duty cycle of the DC-DC buck converter. The effects of changes in solar irradiance, temperature, and load on output power based on the two MPPT algorithms can be studied. Figure 10 shows the response of PV power to the step and gradual changes in solar irradiance. It can be seen that both algorithms provide good dynamic and static responses. Fractional OCV method provides more stable power but it relies on accurately selecting the proportionality constant. Due to the perturbation nature of P&O method, the instantaneous power fluctuates, which can be eliminated with filtering techniques.

![Figure 10 The response of PV array power to the gradual and step change in solar irradiance (a) using Fractional OC voltage (b) using P&O](image)
3. Assessment

The MATLAB Simulink models were first made available to the graduate student taking the independent study course. After going through the models and simulating at different environmental conditions, the student was able to get a deeper understanding of the maximum power point and most importantly different MPPT algorithms and how to implement them. The student is now expanding the models to study the partial shading effects on the PV systems. The models were then added as a supplemental module to the Solar Energy Harvesting module. Students learned the theory in class, examined and simulated the Simulink models as homework assignments, and built the solar energy harvester in the lab. In the first homework assignment, students studied the one-diode model of the solar cell and used the Simulink program to simulate the current vs. voltage and power vs. voltage behavior with different resistive loads. The average grade of this assignment is 8.41/10 and the standard deviation is 2.67. Figure 11 shows the grade distribution of this assignment.

In the second homework assignment, the DC-DC converter was inserted between the solar panel and the load to eliminate the effects of load on the solar panel performance. Students used the Simulink models to study the effects of duty cycle of the DC-DC converter and MPPT controller on the solar panel power and the reaction of the MPPT controller to the change in solar irradiance. The average grade of this assignment is 7.25/10 and the standard deviation is 4.36. Figure 12 shows the grade distribution of assignment 2. Four students were not able to get the Simulink model to work and received zero for this assignment.
Most students were able to successfully complete the homework assignments and the feedback on the Simulink models from the students were positive. Many stated that the models gave them clear view of solar cells and the MPPT and helped them in troubleshooting their solar energy harvesters.

4. Conclusions

A set of MATLAB Simulink models was developed to supplement the learning modules of our solar energy curriculum. Three models were used to study the maximum power point of solar cells and modules. One model was used to study the maximum power point tracking algorithms which include P&O and FractionalOCV. The performance of the PV array was examined at different environmental conditions like solar irradiance, temperature, and load. By working with these models and carrying out simulations, students were able to gain a deeper understanding of MPP and MPPT algorithms.

References