State Feedback Control of a DC-DC Converter for MPPT of a Solar PV Module

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Abstract—The optimum solar PV module voltage is not constant. It varies with ambient conditions. Hence, it is advantageous to control the PV module voltage. The input voltage across a PV module is controlled using a DC-DC converter. The converter is controlled using state feedback where a reference signal is generated using a Perturb and Observe Maximum Power Point Tracking (MPPT) algorithm. The performance of the DC-DC converter is compared to the reference signal. The performance of the MPPT system is compared to a system held at a constant voltage.

I. INTRODUCTION

Climate change and greenhouse gases have been a huge environmental issue in the past decade. Consequently, alternative and renewable energy systems have experienced an increase in demand. In 2013, renewable energy made up 11% of the total energy production in the United States [1]. Of that percentage only 3% was from solar. However, solar PV power has been increasingly popular over the last few years. Solar PV power is especially appealing to many because it is a system that can be installed at individual homes or commercial estates. However, one of the obvious downsides to PV modules is that it only provides power when there is sunlight, therefore making the system somewhat unreliable. For this reason there has been a considerable amount of research in increasing the efficiency of the solar PV module.

The most basic solar PV energy system would be a PV module connected directly to the terminals of a storage battery. This PV module would essentially be fixed to a constant operating voltage with small variation due to battery charging and discharging. However, due to the nature of the solar cells, the optimum module voltage changes with temperature as seen in Figure 1. Colder cell temperatures have the capacity to produce more power than at warmer temperatures. Therefore, under the same solar irradiation levels, a PV module has the potential to produce more power during the cold months as opposed to the hot months. For this reason it is highly beneficial to adjust the module voltage according to ambient conditions. This type of control is known as maximum power point tracking, or MPPT. The voltage can be adjusted using a DC-DC converter.

There are many different types of DC-DC converters that are used, including buck, boost, buck-boost, and push-pull [2],[4]. There are several different MPPT control algorithms, such as perturb and observe, incremental conductance, and a method based on the power slope [3]. Perturb and observe is commonly used for its simplicity and will be implemented in this paper.

This paper proposes a scheme for controlling the module voltage using MPPT and a DC-DC converter similar to that used in [4].

Fig. 1. Plot of I-V curves for varying cell temperatures

II. PHOTOVOLTAIC MODULE MODEL

There are different equations used in literature to model the performance of a PV module [3]. The model chosen for this project is [5]

\[ I = I_{SC} \left( 1 - \exp \left( \frac{V - V_{OC}}{A_0 k T} \right) \right) \]  

where

\[ I_{SC}(G) = \frac{I_{SC}}{G} G_{eff} \]  

\[ V_{OC}(T_c) = V_{OC}^\ast + (T_c - T_c^\ast) \frac{dV_{OC}}{dT_c} \]  

\[ T_c = T_a + C_t G_{eff} \]  

\[ C_t = \frac{NOCT(\circ C) - 20}{800 W/m^2} \]

The variables with a superscript * denote standard conditions and can be found in the specification sheet of the PV module. \( I_{SC} \) is the short circuit current, \( V_{OC} \) is the open circuit voltage, \( G_{eff} \) is the incident solar irradiation, \( T_a \) is the ambient temperature, \( C_t \) is the temperature coefficient, \( T_c \) is the cell temperature, \( NOCT(\circ C) \) is the nominal operating cell temperature.
temperature, and \( k \) is the Stefan-Boltzmann constant (8.6e-5 eV/K). \( A_0 \) is an "ideality factor" which is usually between 1.0 and 1.2. \( R_s \) is the series resistance of the cell and is affected by the cell quality and the length of wires used. It is usually less than 10 milliohms. \( \frac{dV_{oc}}{dt} \) is the voltage thermal coefficient and is also sometimes denoted on specification sheets as \( \alpha_{V_{oc}} \).

III. MPPT

The method used for finding the maximum power point is perturb and observe. The algorithm is shown in Figure 2. The algorithm is performed at a predetermined frequency. It essentially perturbs the voltage by a predetermined step voltage and then compares the power output with the previous output. It then determines whether to increase or decrease the voltage. The voltage determined by the MPPT controller is the reference voltage the DC-DC converter tries to follow.

IV. DC-DC CONVERTER

The DC-DC converter is used to change the voltage across the PV module. The converter is the same converter used in [4]. The schematic of the system is shown in Figure 3. The module voltage will be the same as the voltage across the capacitor. The voltage across the capacitor can be controlled by varying the duty cycle of the two power switches. The state space equation of the DC-DC converter is found through circuit analysis. Figure 4 is a simplified version of the system and is used for the analysis. Applying Kirchhoff voltage Law around the left most loop yields

\[-V_{eq} + I_{pv} R + V_{pv} = 0\]  \(\text{(6)}\)

where \( V_{pv} \) is the voltage across the capacitor. This can be rewritten as

\[-V_{eq} + (C \frac{dV_{pv}}{dt} + I_L)R + V_{pv} = 0\]  \(\text{(7)}\)

since \( I_{pv} = I_C + I_L \) and \( I_C = \frac{C dV_{pv}}{dt} \). Solving for \( \frac{dV_{pv}}{dt} \) produces

\[\frac{dV_{pv}}{dt} = -\frac{V_{pv}}{R_{eq}C} + \frac{V_{eq} - I_L}{C} \]  \(\text{(8)}\)

Applying the same analysis around the second loop from the left yields

\[-V_{pv} + V_L + V_u = 0\]  \(\text{(9)}\)

The relationship between \( V_0 \) and \( V_{pv} \) is

\[V_0 = n \frac{V_{pv}}{d}\]  \(\text{(10)}\)

where \( d = 1 - D \). Assuming \( V_u \) can be replaced with \( V_{pv} \), Eq. 10 can be rearranged as

\[V_u = d \frac{V_0}{n}\]  \(\text{(11)}\)

Now, knowing \( V_u \) and that \( V_L = L \frac{dI_L}{dt} \), Eq 9 can be rewritten as

\[\frac{dI_L}{dt} = \frac{V_{pv}}{L} - \frac{V_0}{nL}d\]  \(\text{(12)}\)

Assuming \( V_{eq} \) will have minimal effect on the system, the state space equations can be written as

\[
\dot{x} = \begin{bmatrix} V_{pv} \\ I_L \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_{eq}C} & -\frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} V_{pv} \\ I_L \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{V_0}{nL} \end{bmatrix} d
\]

\[
y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} V_{pv} \\ I_L \end{bmatrix}
\]

\(\text{(13)}\)
V. STATE FEEDBACK CONTROL

The voltage into the PV module will be controlled via state feedback control. Figure 6 is the block diagram representation of the system. The reference input \( r \) is the voltage determined by the MPPT algorithm. The output \( y \) is the PV module voltage produced by the DC-DC converter. \( K \) is the state feedback gain matrix. The area in the dotted line box can be simplified to the transfer function \( \hat{g} \) where \( \hat{g} \) is defined as \[ \hat{g} := C(sI - A - BK)^{-1}B \] (14)

which is solved to be

\[ \hat{g} := \frac{V_0/LnC}{s^2 + \left(\frac{V_0k_2}{Ln} - \frac{1}{R_{eq}}\right)s + \left(-\frac{V_0k_2}{R_{eq}LnC} + \frac{1}{CL} - \frac{V_0k_1}{Ln}\right)} \] (15)

Figure 6 is then simplified to Figure 7. The gains of the system are determined by defining a desired characteristic equation. The characteristic equation of the the system in Figure 7 is \[ \Delta_f(s) = \det \left[ \begin{array}{cc} sI - A - BK & -Bk_a \\ C & s \end{array} \right] \] (16)

which is solved to be

\[ \Delta_f(s) = s^3 + \left(\frac{V_0k_2}{Ln} - \frac{1}{R_{eq}C}\right)s^2 + \left(-\frac{V_0k_2}{R_{eq}LnC} + \frac{1}{CL} - \frac{V_0k_a}{Ln}\right)s + \frac{V_0k_2}{LnC} \] (17)

Using (17) a desired characteristic equation is chosen such that each pole is on the left hand side of the \( s \)-plane in order to have a stable system. The equation is higher than second order, so percent overshoot and rise time cannot be predicted. Consequently, this is only a starting point for selecting the gains \( k_1, k_2, \) and \( k_a \). The guess and check method is then applied to tune the gains. The selected gains of the system are found in the Appendix.

VI. RESULTS

The system is modeled using Matlab and Simulink. The Simulink model is presented in Figure 5. It can be divided into three main sections: PV module, MPPT, and state feedback loop including the converter and voltage controller. The PV module is modeled using an Interpreted MATLAB Fcn block where its inputs are solar irradiation, ambient temperature, and voltage, and its output is current. The MPPT algorithm is contained within the function block using simulink memory blocks to capture the values at the previous time step. Finally, the state feedback loop shown in Figure 7 is directly implemented. The chosen parameters and constants of the PV module and converter are found in the Appendix.

The results are shown in Figures 8 through 10. Figure 8 shows the step reference voltages produced by the MPPT controller and the actual voltage response of the DC-DC converter. The controller tracks the reference voltage very closely. It has a rise time of about 25 ms. There is some “chatter,” but this is inherent in DC-DC converters due to
the switching. Even with the “chatter” the error stays within 0.005 volts of the reference voltage. It is also easily seen that the MPPT steps the voltage up or down by 0.1 volts every 0.1 seconds.

PV panels are inherently more efficient at colder temperatures. Figure 9 shows the PV module output power at varying temperature and constant irradiation. As expected, the power output increases with colder temperatures. Figure 10 compares a PV system with MPPT control with a system without MPPT control. This scenario undergoes the same ambient conditions (constant irradiation, varying temperature) as in Figure 9. The MPPT controlled system produces over twice as much power at cold temperatures. This verifies the MPPT controller works. There is a short time period where the constant voltage system produces more power. This is due to the ambient conditions changing faster than the MPPT controller can change.

Fig. 8. Actual voltage produced by the DC-DC converter based in step response.

Fig. 9. The PV module power output varies as temperature varies.

VII. FUTURE WORK

Future work would include upgrading the system to a multi-input converter in order to accommodate multiple PV modules. It is becoming increasingly popular for residences to install both solar and wind power. Therefore, it is also worth investigating into the integration of a wind energy conversion system with a PV module. In addition, it would be beneficial to add voltage control on the other side of the DC-DC converter to better track the optimum charging voltage of a battery.

APPENDIX

PV Module:

<table>
<thead>
<tr>
<th>Series</th>
<th>NOCT</th>
<th>$V_{oc}$</th>
<th>$I_{sc}$</th>
<th>$G^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>45 C</td>
<td>19.9 V</td>
<td>3.9 A</td>
<td>1000 W/m²</td>
</tr>
</tbody>
</table>

DC-DC Converter:

<table>
<thead>
<tr>
<th>$R_{eq}$</th>
<th>10 Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>300 μF</td>
</tr>
<tr>
<td>L</td>
<td>450 μH</td>
</tr>
<tr>
<td>n</td>
<td>12</td>
</tr>
<tr>
<td>$V_0$</td>
<td>50 V</td>
</tr>
</tbody>
</table>

Gains:

$$\begin{bmatrix} k_1 & k_2 & k_a \end{bmatrix} = \begin{bmatrix} 0.1 & 1.05 & 30 \end{bmatrix}$$

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REFERENCES


