Emulation Of Different Photovoltaic Materials And Technologies Using PV Array Emulator With Linear Quadratic Regulator

Mustapha ALAOUI, Hattab MAKER, Azeddine MOUHSEN, Hicham HIHI

Abstract: This paper proposes the emulation of different photovoltaic (PV) materials and technologies using an innovative PV array emulator based on Linear Quadratic Regulator (LQR), this electronic power device aims to reproduce faithfully the real PV module behavior independently on environmental conditions change, it allows scientists, industrialists and researchers to carry out their measurements and experiences on PV systems without depending on PV panels, which require the sun to perform tests and do not allow repetitive measurements at the desired temperature (T) and irradiance (G). Moreover, PV modules actually are very expensive and require a large area to reach some powers, all these limitations and others are handled using this designed PV emulator. Simulation results using Matlab Simulink software are given and analyzed in order to evaluate the performance of the developed equipment and to judge its efficiency and capacity to track rapidly and accurately the I-V characteristic of different PV modules.

Index Terms: PV array emulator, Linear Quadratic Regulator, PV technologies, I-V characteristic, power converter, optimization.

1. INTRODUCTION

With a large interest in renewable energy nowadays in order to combat climate change and contribute to the sustainable development, many researchers and manufacturers are interested in the study of photovoltaic (PV) systems and all related subjects which concern PV modeling and control, power optimization, solar connected inverters and many other fields. Those studies require photovoltaic array emulators which can reproduce the electrical behavior of the desired PV panel at any time without depending on the weather conditions [1], this will allow researchers to carry out efficiently their experiences and tests on photovoltaic energy without needing real PV panels which are generally expensive and require a large space [2]. This work consists of the development of new solar emulator based on Linear Quadratic Regulator (LQR) in order to track faithfully the I-V characteristic of the PV module and optimize the functioning of the full system. The proposed PV emulator is based on a DC-DC buck converter with closed-loop voltage control. The reason behind using LQR is its ability to deal with the non-linearity of both the power topology and the I-V characteristic [3], and its robustness against external disturbances, dynamic load change and variation of atmospheric parameters, unlike many existing PV emulators which suffer from inaccuracy in some zones of PV module I-V curve, besides their poor dynamic response [4]. Moreover, this controller ensures good performances in terms of speed, accuracy and overshoots limitation so that the designed circuit can meet the requirements and have a similar output response as a real PV module. Different PV material technologies are used so as to judge the ability of the proposed system to emulate accurately various types of PV module characteristics of power, material and manufacturers [5].

2 EMULATION SYSTEM COMPONENTS

The following figure illustrates the block diagram of the proposed system, it consists essentially of the power part which contains the DC-DC buck converter, and the control part which consists of the reference generator used to deliver the constant voltage reference, besides the controller to ensure the required performances of the PV emulator. The Matlab Simulink Model including the PV emulator with The PV model based on one diode two resistances model (1D-2R) [4], [6] is shown in figure 2.
Photovoltaic Source Emulator based on Linear Quadratic Regulator

Discrete,
Ts = 1e-006 s.

MATLAB Function
PV_Model_With_Newton_V=fR)

\[
\begin{align*}
V_{load} & \quad I_{load} \\
V_{pv} & \quad I_{pv}
\end{align*}
\]

Control system
Linear Quadratic Regulator

\[
\begin{align*}
P_{load} & \quad V_{ref} \\
V_{load} & \quad I_{load} \\
V_{pv} & \quad V_{load} \\
I_{load} & \quad I_{pv}
\end{align*}
\]

\[
\begin{align*}
\text{Photovoltaic Source Emulator} \\
\text{based on Linear Quadratic Regulator}
\end{align*}
\]

\[
\begin{align*}
\text{Fig. 1. PV array emulator components}
\end{align*}
\]

\[
\begin{align*}
\text{Fig. 2. PV array emulator components}
\end{align*}
\]

3 LQR DESIGN
The Linear Quadratic Regulator (LQR) has been chosen to control the DC-DC buck converter in order to provide the system with an optimal control taking into consideration the load variation and the environmental conditions change, it can ensure a good compromise between accuracy, speed and energy consumption optimization in the control law [7].

The cost function $J$ to be minimized is the following:

$$J(u) = \int_0^{\infty} (x^T(t)Qx(t) + u^T(t)Ru(t))dt$$  \hspace{1cm} (1)

Where:
- $Q$ and $R$ are positive definite matrix.
- $u(t)$ is the control input
- $x(t)$ is the state vector :

$$x(t) = \begin{pmatrix} V_{ref} - V_o \\ I_o \end{pmatrix}$$  \hspace{1cm} (2)

With $V_{ref}$ is the reference voltage, $V_o$ is the output voltage and $I_o$ is the output current.

We are penalizing both the state and the control effort, and the objective is to find the control input $u$ which minimizes the cost function $J$.

The power converter parameters are listed below:

**TABLE 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage $V_{dc}$</td>
<td>70 V</td>
</tr>
<tr>
<td>Capacitance $C$</td>
<td>3 μF</td>
</tr>
<tr>
<td>Inductor $L$</td>
<td>2 mH</td>
</tr>
<tr>
<td>Switching frequency $f$</td>
<td>100 KHz</td>
</tr>
</tbody>
</table>

The state model matrix of the DC-DC buck converter are expressed as:

$$A = \begin{pmatrix} -1/R & \frac{1}{C} & 0 \\ -1/L & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$  \hspace{1cm} (3)

$$B = \begin{pmatrix} 0 \\ \frac{V_{dc}}{L} \\ 0 \end{pmatrix}$$  \hspace{1cm} (4)

$$C = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix}$$  \hspace{1cm} (5)

The matrix $Q$ and $R$ are chosen as below

$$Q = \begin{pmatrix} 30 & 0 & 0 \\ L \times C & 400 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$R = 1$$  \hspace{1cm} (7)

The LQR gains have been computed using LQR command of Matlab.

4 steady state study

In this section, a comparison is done between the output $I$-$V$ curve of the proposed PV emulator with the expected $I$-$V$ characteristic of the real PV module, by this comparison, we can evaluate the performances of the designed PV emulator in terms of accuracy, speed, and overshoot limitation.

4.1 Emulation of Monocrystalline PV Module

The following table illustrates the electrical characteristic of the studied PV module.

**TABLE 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak rated power $P_{mpp}$</td>
<td>335 W</td>
</tr>
<tr>
<td>Open circuit voltage $V_{oc}$</td>
<td>46.1 V</td>
</tr>
<tr>
<td>Short circuit current $I_{sc}$</td>
<td>9.4 A</td>
</tr>
<tr>
<td>Maximum power point voltage $V_{mpp}$</td>
<td>37.8 V</td>
</tr>
<tr>
<td>Maximum power point current $I_{mpp}$</td>
<td>8.87 A</td>
</tr>
<tr>
<td>Temperature coefficient of $I_{sc}$ $k_i$</td>
<td>0.053%/K</td>
</tr>
<tr>
<td>Temperature coefficient of $V_{oc}$ $k_v$</td>
<td>-0.31%/K</td>
</tr>
<tr>
<td>Temperature coefficient of power $k_p$</td>
<td>-0.41%/K</td>
</tr>
</tbody>
</table>

The $I$-$V$ curve of the PV emulator with the PV module under STC conditions is presented in figure 4:

![Fig. 4. Comparison between $I$-$V$ curve characteristic of Harvest Polycrystalline PV model, real PV module and PV emulator under STC conditions.](image)

**Fig. 5. Comparison between $I$-$V$ curve characteristic of the system with LQ controller**
As shown in figure 4, the designed PV emulator can generate accurately the voltage and current outputs as a real monocrystalline PV module for any operating point in the I-V curve since the steady state error is negligible, so it can efficiently imitate the electrical behaviour of PV sources.

4.2 Emulation of Polycrystalline PV module

**TABLE 3**

**POLYCRYSTALLINE HARVEST PV MODULE CHARACTERISTICS UNDER STC CONDITIONS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak rated power Pmpp</td>
<td>285 W</td>
</tr>
<tr>
<td>Open circuit voltage Voc</td>
<td>38.3V</td>
</tr>
<tr>
<td>Short circuit current Isc</td>
<td>9.64 A</td>
</tr>
<tr>
<td>Maximum power point voltage Vmpp</td>
<td>31.4 V</td>
</tr>
<tr>
<td>Maximum power point Impp</td>
<td>9.06 A</td>
</tr>
<tr>
<td>Temperature coefficient of Isc : $k_i$</td>
<td>0.05% / K</td>
</tr>
<tr>
<td>Temperature coefficient of Voc : $k_v$</td>
<td>-0.29% / K</td>
</tr>
</tbody>
</table>

**Figure 5** emphasizes the previous results of monocrystalline PV modules since the performances are remaining the same even with the change of technology, power and manufacturers.

4.3 Emulation of Amorphous PV module

**TABLE 4**

**NEXPOWER AMORPHOUS PV MODULE CHARACTERISTIC UNDER STC CONDITIONS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak rated power Pmpp</td>
<td>160 W</td>
</tr>
<tr>
<td>Open circuit voltage Voc</td>
<td>85.5 V</td>
</tr>
<tr>
<td>Short circuit current Isc</td>
<td>2.57 A</td>
</tr>
<tr>
<td>Maximum power point voltage Vmpp</td>
<td>65.9 V</td>
</tr>
<tr>
<td>Maximum power point Impp</td>
<td>2.43 A</td>
</tr>
<tr>
<td>Temperature coefficient of Isc : $k_i$</td>
<td>-0.07% / C°</td>
</tr>
<tr>
<td>Temperature coefficient of Voc : $k_v$</td>
<td>-0.32% / C°</td>
</tr>
</tbody>
</table>

**Fig. 7. PV source Emulator under temperature and irradiance variation**

It is clearly shown according to figure 6 that the proposed PV emulator is able to deliver the same I-V curve as a PV module for amorphous PV technology. So we can conclude that the static performances of the PV emulator are maintained at the same level for different technologies, power and PV module characteristics.

5 DYNAMIC STUDY

In this part, the dynamic performances of the proposed PV emulator are evaluated in regards to the ability of tracking the PV module output current and voltage under weather parameters change of temperature and irradiance. Besides, the transient response is analyzed too so as to show the settling time of the PV emulator and the output ripples of the DC-DC buck converter.
Further work will be dedicated to the experimental validation of the developed PV source emulator with MPPT algorithms and connected solar inverters.

REFERENCES


