The Resistance Comparison Method Using Integral Controller for Photovoltaic Emulator

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ABSTRACT

A Photovoltaic (PV) emulator is a device that produces a similar output as the PV module and it is useful for testing the PV generation system. This paper presents a new and simple control strategy for the PV emulator using the combination of the Resistance Comparison Method with the Integral Controller. The closed-loop buck converter system with the current-mode controlled and the single diode model are used for the PV emulator. The results obtained from the proposed PV emulator are compared with the conventional PV emulator using the Direct Referencing Method as the control strategy. The proposed PV emulator produces a more accurate output, 74 % faster transient response, and a lower output voltage ripple compared to the conventional PV emulator.

1. INTRODUCTION

The photovoltaic (PV) generation system has gained popularity in the energy sector. The world has gained interest in this system due to the government policies on the renewable energy, as well as the increases in the efficiency and the cost reduction of the PV panel. However, the energy produced by PV generation system is highly dependable on the ambient condition such as the irradiance and the temperature. While the output of the PV module is nonlinear, which further complicates the energy generation process. To ensure the maximum power is generated from the PV module, the Maximum Power Point Tracking (MPPT) is added into the PV generation system. In the MPPT research, the irradiance manipulation is essential to test the capability of the MPPT method. This leads to the use of controllable halogen lamp to control the irradiance for the PV panel. Nevertheless, this method is inefficient and requires a large area. Another way to test the MPPT is by using the PV emulator.

The PV emulator is a nonlinear Direct Current (DC) power supply that produces similar output as the PV module. The irradiance and the temperature are easier to control, is highly efficient, able to produce multiple different PV module characteristics, and requires a small testing area. There are three components in the PV emulator, which are the PV mathematical model, the power converter, and the control strategy [1]. The function of the PV mathematical model is to produce the Current-Voltage (I-V) characteristics curve of the PV module. The single diode model is commonly used in the PV emulator application as the PV mathematical model since this model is accurate and simple [2], [3]. The power converter emulates the I-V characteristics produced by the PV mathematical model. There are various topologies used in the PV emulator depending on the requirements of the system. However, the buck converter is widely used in the PV emulator application due to the simplicity, a low number of components, and easy to control [4], [5].
While the control strategy is the method used to integrate the PV mathematical model and the power converter into a PV emulator. The main function is to determine the operating point of the PV emulator. This means that the control strategy finds the voltage and the current on the I-V characteristics curve based on the load connected to the PV emulator.

The control strategy affects the steady state stability, the transient response, and the accuracy of the output for the PV emulator. The hardware platform used for the PV emulator is also affected by the control strategy. This is because different control strategies require different processing power and memory storage from the hardware platform. The Direct Referencing Method is commonly used control strategy for the PV emulator since it is simple to implement [6]-[8]. The operating point of the PV emulator is obtained from the external factors, which are the dynamic characteristic of the power converter and the PI controller. Due to the dependency of the control strategy on the external factors, the output of the PV emulator becomes oscillate at a certain load condition. The oscillating problem is overcome by using different control strategy such as the Hybrid-Mode Control Method [9] and the Resistance Comparison Method [10], [11]. The Hybrid-Mode Controlled Method combines two different Direct Referencing Methods (the current control and the voltage control) to prevent the oscillation problem. Nevertheless, the control is complex since there are two independent controllers are used to determine the one operating point for the PV emulator. The Resistance Comparison Method is simpler compared to the Hybrid-Mode Controlled Method. This control strategy tested multiple points on the I-V characteristics curve to determine the operating point. However, the tests are conducted at a fixed step size, which results in a slow computation of the operating point and a poor dynamic performance. There has been an improvement to solve the operating point for the Resistance Comparison Method by using the variable step sizes instead of a fixed step size. The Binary Search Method is implemented into the Resistance Comparison Method resulting a significantly faster computation of the operating point and produces a highly accurate output [12]. However, the Binary Search Method is complicated to implement.

A good control strategy needs to be simple likes the Direct Referencing Method while producing a non-oscillating and accurate operating point likes the Resistance Comparison Method with the variable step sizes. Nevertheless, the Direct Referencing Method produces oscillating operating points and the current Resistance Comparison Method with the variable step sizes is complex because of the Binary Search Method [12]. This shows the need for a simple and non-oscillating control strategy for the PV emulator. The Resistance Comparison Method with variable step sizes has a good potential as the control strategy for the PV emulator if this method is easy to implement. The function of the Binary Search Method in the Resistance Comparison Method with the variable step is to produce the output depending on the input error. This function is also similar to the easily implemented integral controller. Therefore, it is possible to simplify the design of the current Resistance Comparison Method with the variable step by replacing the Binary Search Method with the integral controller.

This paper discusses a new simple control strategy for the PV emulator using the Resistance Comparison Method. The operating point produced by the Resistance Comparison Method is computed using the integral controller, which produce variable step sizes. The buck converter is used for the PV emulator and it operates in the continuous current mode with the at most 1% output voltage ripple factor. The closed-loop power converter system is controlled using the PI controller and it operates in the current-mode controlled. The PV mathematical model used for the PV emulator is the single diode model. The simulation is conducted using MATLAB/Simulink® simulation package.

2. COMPONENTS OF PHOTOVOLTAIC EMULATOR
2.1. Photovoltaic Model

The PV mathematical model is used to generate the I-V characteristic of the PV module. The single diode model is a common PV mathematical model in the PV emulator application. The photovoltaic module current, $I_{pv}$, is calculated using (1) [13]:

$$I_{pv} = I_{ph} - I_s \left[ \exp \left( \frac{V_{pv} + I_{pv}R_s}{V_T A} \right) - 1 \right] - \frac{V_{pv} + I_{pv}R_s}{R_p}$$

where $I_{ph}$ is the photo-generated current (A), $I_s$ is the diode saturated current (A), $V_{pv}$ is the photovoltaic module voltage (V), $R_s$ is the series resistance (Ω), $V_T$ is the junction thermal voltage, where $V_T = kT/q$, $k$ is the Boltzmann constant (1.38×10^{-23} J/K), $T$ is the module temperature (K), $q$ is the electron charge (1.602×10^{-19} C), $A$ is the ideality factor, and $R_p$ is the parallel resistance (Ω).

The Newton-Raphson Method is used to solve (1) since it is an implicit equation. The irradiance and temperature affect $I_{ph}$, which is calculated using (2) [1]. $I_s$ only depends on the temperature which is
calculated using (3) [14]. The characteristic of the PV module is listed in Table 1. \( R_s \) and \( R_p \) is determined using the parameter extraction process [15].

\[
I_{ph} = \frac{G}{1000}[I_{sc} + \alpha (T - 25)] \tag{2}
\]

\[
I_s = \frac{I_{sc}}{\exp(V_{oc}/n)} - 1 \tag{3}
\]

where \( G \) is the irradiance (W/m\(^2\)), STC is the Standard Test Condition (1000 W/m\(^2\), 25 °C), \( I_{sc} \) is the short circuit current during STC (A), \( \alpha \) is the temperature coefficient of \( I_{sc} \), \( T \) is the temperature (°C), \( V_{oc} \) is the open circuit voltage during STC (V).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit Voltage, ( V_{oc} )</td>
<td>22.53 V</td>
</tr>
<tr>
<td>Short Circuit Current, ( I_{sc} )</td>
<td>2.97 A</td>
</tr>
<tr>
<td>Maximum Power Point Voltage, ( V_{mp} )</td>
<td>18.68 V</td>
</tr>
<tr>
<td>Maximum Power Point Current, ( I_{mp} )</td>
<td>2.77 A</td>
</tr>
<tr>
<td>Temperature Coefficient of ( V_{oc} ), ( \beta )</td>
<td>-0.35 %/°C</td>
</tr>
<tr>
<td>Temperature Coefficient of ( I_{sc} ), ( \alpha )</td>
<td>0.05 %/°C</td>
</tr>
</tbody>
</table>

### 2.2. Buck Converter

*The buck converter, shown in*

Figure 1(a), is commonly used in the PV emulator application due to the simplicity, a low number of components, and have a high efficiency. There are two considerations in designing the buck converter, which is the continuous current mode and the output voltage ripple factor. The continuous current mode operation is chosen since the design is simpler and the operation is more stable compared to the discontinuous current mode. The continuous current mode depends on the buck converter inductance, \( L \), which is calculated using (4) [17]. The output voltage ripple factor, \( \gamma_{Vo} \), needs to be lower than 1 % to ensure accurate emulation of the PV module. This is because the PV module does not contain output ripple and it is essential to keep the output voltage ripple of the PV emulator as low as possible. The output voltage ripple factor depends on the capacitance of the buck converter, \( C \), which is calculated using (5) [17].

\[
L = \frac{(1-D)R_o}{2f} \tag{4}
\]

\[
C = \frac{1-D}{8\gamma_{Vo}f^2} \tag{5}
\]

where \( D \) is the duty cycle, \( R_o \) is the output resistance, and \( f \) is the switching frequency.

The PI controller is important to obtain a good transient response and zero steady state error. The tuning of the PI controller requires the transfer function of the buck converter, \( G_b \), as shown in (6) [10]. While the transfer function of the PI controller, \( G_c \), is shown in (7) [10].

\[
G_p(s) = \frac{i_o}{d} = \frac{V_{in}}{R_o s^2 + \frac{1}{\frac{1}{L} + \frac{1}{C}}} \tag{6}
\]

\[
G_c(s) = K_p + \frac{K_i}{s} \tag{7}
\]

where \( K_p \) is the proportional gain and \( K_i \) is the integral gain.

The arrangement of the closed-loop buck converter system is shown in Figure 1(b). The tuning of the PI controller is focused on the lower limit of \( R_o \) since the transient response for the buck converter is the fastest during this load condition. The parameter for the buck converter and the PI controller is shown in Table 2.
The Resistance Comparison Method using Integral Controller for Photovoltaic Emulator (R. Ayop)

Figure 1. (a) The buck converter and (b) the closed-loop buck converter system.

Table 2. The parameter of the closed-loop buck converter system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage, $V_i$</td>
<td>30 V</td>
</tr>
<tr>
<td>Switching Frequency, $f$</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Output Resistance, $R_o$</td>
<td>3 Ω to 50 Ω</td>
</tr>
<tr>
<td>Inductance, $L$</td>
<td>1.8 mH</td>
</tr>
<tr>
<td>Inductor Internal Resistance, $r_L$</td>
<td>0.36 Ω</td>
</tr>
<tr>
<td>Capacitance, $C$</td>
<td>39 µF</td>
</tr>
<tr>
<td>Capacitor Internal Resistance, $r_C$</td>
<td>0.025 Ω</td>
</tr>
<tr>
<td>MOSFET Drain-Source Resistor, $R_{ds(on)}$</td>
<td>0.0106 Ω</td>
</tr>
<tr>
<td>Diode Forward Voltage, $V_f$</td>
<td>0.44 V</td>
</tr>
<tr>
<td>Proportional Gain, $K_p$</td>
<td>0.12392</td>
</tr>
<tr>
<td>Integral Gain, $K_i$</td>
<td>234.33644</td>
</tr>
</tbody>
</table>

3. PROPOSED CONTROL STRATEGY

The proposed PV emulator is shown in Figure 2. It is a closed-loop buck converter system using current-mode controlled. The reference input of the closed-loop buck converter system is connected with the proposed Resistance Comparison Method using the integral controller. By referring to Figure 2, the output voltage, $V_o$, and the output current, $I_o$, of the PV emulator is measured. $V_o$ is then divided with $I_o$ to digitally obtain $R_o$. $R_o$ is compared with the $R_{pv}$, which is obtained by dividing $V_{pv}$ over $I_{pv}$. The Resistance Comparison error, $E_r$, becomes the input of the integral controller, $G_i$. $G_i$ is calculated using (8):

$$G_i(s) = \frac{\gamma K_i}{s}$$

(8)

where $\gamma K_i$ the integral gain amplification factor.
Figure 2. The block diagram of the proposed Resistance Comparison Method using the integral controller.

In an ideal condition, $\gamma K_i$ is set to infinity for an instantaneous operating point computation. However, the discrete characteristic of the digital controller prevents $\gamma K_i$ to be set to infinity. $\gamma K_i$ is carefully selected to allow the hardware platform to cope with the processing burden. In this simulation, the sample time for the controller is set to 20 $\mu$s. This is done by using the discrete PI controller block and zero-order hold block in the MATLAB/Simulink$^\text{®}$'s library. Using Try and Error Method, $\gamma K_i$ is increased from 1 and stop when the reference input becomes oscillates. From the tuning process, the optimum $\gamma K_i$ is 2.5. Besides $\gamma K_i$, the initial output of the integral controller is increased. This is done to prevent spike during the start-up process of the PV emulator. The recommended initial output for the integral controller is the open circuit voltage during the lowest irradiance. For this simulation, the initial output of the integral controller is 15 V.

The output of the integral controller is $V_{pv}$ for the PV mathematical model. The PV mathematical model produces $I_{pv}$ corresponding to the $V_{pv}$. $R_{pv}$ is calculated again with $R_o$. This process is repeated until $E_r$ is very small.

4. RESULTS AND DISCUSSIONS

The results from the proposed PV emulator is compared with the conventional PV emulator using the Direct Referencing Method [6-8]. The optimum PI controller shown in Table 2 could not be used for the Direct Referencing Method due to the oscillation problem at a certain load condition [1]. To overcome this problem, the $K_p$ and $K_i$ is reduced to 80 % to become 0.0248 and 46.8673 respectively. The results obtained from the PV emulators are based on the temperature of 25 °C.

4.1. Accuracy

The accuracy of the PV emulator depends on the PV mathematical model and the control strategy. To test the accuracy of the PV mathematical model, the I-V characteristic produced by this model is compared with the I-V characteristic obtained from the PV panel. However, to test the accuracy of the control strategy, the I-V characteristic curve obtained from the output of the PV emulator is compared with the PV mathematical model. This step is taken to ensure that the error produced by the PV mathematical model is not taken into the results and only error produced by the control strategy is considered. Therefore, $V_o$ and $I_o$ obtained from the PV emulator are compared with the I-V characteristic curve produced by the PV mathematical model, as shown in Figure 3(a).

An accurate control strategy able to produce the output of the PV emulator similar to the I-V characteristic curve of the PV mathematical model. If the current-mode controlled is used for the closed-loop power converter system, the output of the PV emulator becomes oscillate in the constant voltage region. This is because a small change in $V_{pv}$ produces a large change $I_{pv}$ for the PV mathematical model. Therefore, analysis of the accuracy is focused in the constant voltage region, as shown in...
The simulations are conducted with nine different \( R_o \) ranging from 3 \( \Omega \) to 50 \( \Omega \). The irradiance is set at 200 W/m\(^2\) and 1000 W/m\(^2\). Each simulation is conducted for 0.3 s to ensure the PV emulator reaches the steady state condition. \( V_o \) and \( I_o \) obtained from the conventional PV emulator using the Direct Referencing Method and the proposed PV emulator are shown in Figure 3(a).

The \( V_o \) and \( I_o \) produced by the conventional and proposed PV emulator is accurate in the constant current region, as shown in Figure 3(a). The accurate results are observed when the output of the PV emulator is on the I-V characteristics curve produced by the PV mathematical model. Nevertheless, the output of the PV emulator becomes inaccurate when operates in the constant voltage region, as shown in Figure 3(b). During this condition, \( R_o \) connected to the conventional PV emulator is 31 \( \Omega \) and 50 \( \Omega \). The inaccurate output produced by the conventional PV emulator is caused by the unstable reference input and oscillation of \( V_o \) and \( I_o \). While 50 \( \Omega \) of \( R_o \) is connected to the proposed PV emulator when the inaccurate output is produced. The inaccurate output produced by the proposed PV emulator is caused by the limitation of the digital controller. This can be solved with a lower sampling time of the digital controller. To reduce the sampling time, a hardware platform with a higher processing power is needed.

Figure 3. a) The I-V characteristics curve of the PV mathematical model, conventional PV emulator, and the proposed PV emulator during 200 W/m\(^2\) and 1000 W/m\(^2\). b) The zoom-in view of Figure 3.

4.2. Transient Response

The transient response of the PV emulator is also an important factor that needs to be considered in the design. The slow transient response of the PV emulator can cause the MPPT converter connected to the PV emulator operates inaccurately. To prevent this, the PV emulator is designed to operate with a fast transient response.

There are two components that affect the transient response of the PV emulator, which are the power converter and the control strategy. Choosing a higher switching frequency can result in a faster transient response since the inductance and the capacitance used in the power converter becomes smaller. The different topologies of the power converter also affect the transient response of the PV emulator. Besides power converter, control strategy also affects the transient response of the PV emulator. Therefore, the analysis is conducted on the proposed control strategy to compare the transient response improvement against the conventional PV emulator.

In the simulations, two different \( R_o \) is tested on the conventional and proposed PV emulator, as shown in Figure 4(a) and Figure 4(b). The \( R_o \) chosen is the minimum and maximum \( R_o \) limits, which are 3 \( \Omega \) and 50 \( \Omega \) respectively. When 3 \( \Omega \) is connected to the PV emulator, the system operates in the constant current region. The settling time for the conventional and proposed PV emulator is 9.4 ms and 2.4 ms respectively. The proposed PV emulator is 74 \% faster compared to the conventional PV emulator. This slow response of the conventional PV emulator is due to the 80 \% gains reduction in the PI controller to compensate the oscillation problem. Even though the gains are reduced up to 80 \%, there is still an output current oscillation occur, as shown in Figure 4(b). The proposed PV emulator is not affected by the PI controller and the buck converter parameters. As a result, there no gains reduction needed on the PI controller and the optimum PI controller design can be used. This results in a fast transient response for the proposed PV emulator.

When 50 \( \Omega \) is connected to the PV emulator, the system operates in constant voltage region. The settling time for the conventional and proposed PV emulator is 5.4 ms and 28.2 ms respectively. The
The proposed PV emulator is 5.2 times slower than the conventional PV emulator. The proposed PV emulator with 50 Ω $R_o$ is 11.8 times lower than the proposed PV emulator with 3 Ω $R_o$. The transient response of the proposed PV emulator becomes slower as $R_o$ increases. This is due to the design of the PI controller. The PI controller is designed for the range of $R_o$, which is 3 Ω to 50 Ω. The transient response of the closed-loop buck converter system becomes more aggressive as $R_o$ decreases. Therefore, the tuning of the PI controller is conducted at the lower limit of $R_o$, which is 3 Ω. This results in a slower transient response as $R_o$ increases. The transient response of the conventional PV emulator also becomes slower as $R_o$ increases in the constant current region. However, the response becomes faster as $R_o$ increases in the constant voltage region. This is because the $I_{ref}$ produced by the Direct Referencing Signal is very high during the start-up of the PV emulator.

![Figure 4](image-url)

**Figure 4.** The output voltage and output current of the conventional and proposed PV emulator during 1000 W/m² with different output resistance. a) The minimum output resistance (3 Ω). b) The maximum output resistance (50 Ω).

### 4.3. Output Voltage Ripple

The buck converter is one of the Switched-Mode Power Supply (SMPS). The advantage of the buck converter is it has a higher efficiency compared to the linear voltage regulator [17]. Nevertheless, the output voltage produced by the buck converter contain ripple. The output voltage ripple is manipulated by calculating $C$ using (5). In the PV emulator application, the output voltage ripple is not only affected by the buck converter design but also the control strategy [1]. This is because the control strategy such as the Direct Referencing Method produced unwanted oscillation that results in a higher output voltage ripple factor, $\gamma_{Vo}$. As $R_o$ increases, $V_o$ increases. The increases in $V_o$ is caused by the increases in $D$. By referring to (5), if $L$ and $C$ are kept fixed, the increases in $D$ results in a lower $\gamma_{Vo}$. However, the conventional PV emulator does not follow this characteristic, as shown in Figure 5. The $\gamma_{Vo}$ decreases as $R_o$ increased up to 29 Ω. When $R_o$ is 30 Ω, $\gamma_{Vo}$ increases up to 44.6 times. The sudden increase in $\gamma_{Vo}$ is caused by the weakness of the Direct referencing Method. This unwanted oscillation is reduced by decreasing the gains of the PI controller. Since the gains in the PI controller is already reduced to 80 %, further decreases the gains results in a slower transient response. The proposed PV emulator eliminates the unwanted oscillation, as shown in Figure 5. The $\gamma_{Vo}$ decreases as $R_o$ decreases, which follow (5). This shows that the proposed PV emulator is a robust control strategy since it is not affected by the external factors such as PI controller and the parameters of the buck converters.
5. CONCLUSION

A new control strategy for the PV emulator has been designed using the Resistance Comparison Method with variable step sizes. The variable step sizes are computed using a simple integral controller. The proposed PV emulator shows higher output accuracy compared to the conventional PV emulator. The accuracy of proposed method depends on the sampling time of the digital hardware platform. As a result, the integral controller requires tuning based on the sampling time. The transient response of the proposed PV emulator is improved significantly in the constant current region. However, the transient response becomes slower as the output resistance increases. This is due to the weakness the PI controller. It is recommended to use a more robust controller as the replacement for the PI controller to overcome slow transient response. The proposed PV emulator is also more robust compared to the conventional PV emitter. This is because the control strategy used in the proposed PV emulator is not affected by the external factor such as the PI controller and the parameters of the buck converter. It is hoped that the simple adjustment made to the conventional PV emulator is easily implemented and allows significant improvement on the performance of the PV emulator.

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REFERENCES


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