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Real-time Photovoltaic Simulator using Current Feedback Control

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Abstract

In this proposal article, mathematical model of Photovoltaic model is investigated the relationship of the Photo Voltaic's irradiance, temperature and parameters comparing to its output power. It leads in to an analyzing and developing of the Photovoltaic Simulator. By which, Photovoltaic simulator is utilized by the DC converter circuit with a current feedback control. This may be useful if is possible to implementing into a real world Photovoltaic simulator. In this paper, Photovoltaic simulator is modeled using MATLAB/Simulink program, which is composed of DC converter and a proper control scheme. It can be observed from the simulation results that I-V relationship of the Photovoltaic simulator is quite the same as of such Photovoltaic mathematical model. This means that, it is possible to build a real Photovoltaic simulator in commercial in a further work.

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Keywords: Photovoltaic model; Photovoltaic simulator; DC Converter; Feedback control

1. Introduction

Generally, Photovoltaic cell converts photons into electric potential from its PN junction [1]. Nowadays, it is worldwide renewable energy source because of their energy-friendly environment [2]. However, its high costs may cause the difficulties in development and experiments for laboratory. Mean by that, practical Photovoltaic simulator

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which emulates output characteristics of Photovoltaic module through a real converter circuit can be used in replacement of an actual Photovoltaic module in laboratory scale.

2. Photovoltaic Model

2.1. Mathematical model

The equivalent circuit of Photovoltaic is shown in Figure 1. When Photovoltaic cell is exposed to sunlight, an electrical current will flows proportional to the solar irradiance [3].

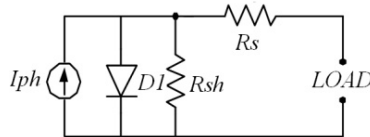


Fig. 1. Photovoltaic Single Diode model

In Figure 1, the circuit of Photovoltaic model is described using equations of schottky diode incorporated with quality factor in account of the recombination effects in space-charge region [3], which are given by equations (1) to (3).

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

$$I_{ph} = \left(I_{sc} + K_I \cdot (T - T_{ref}) \right) \lambda \quad (2)$$

$$I_s(t) = I_s \cdot \left(\frac{T}{T_{ref}} \right)^3 \cdot e^{\left\{ \left(\frac{T}{T_{ref}} - 1 \right) \cdot \frac{E_g}{NV_t} \right\}} \quad (3)$$

Where I_{ph} is photon current, R_s , R_{sh} are series and shunt resistance, N is ideal diode factor, K is Boltzman constant, q is electron charge and I_s is saturation current of diode, K_I is short-circuit current temperature coefficient of Photovoltaic cell, I_{sc} is short circuit (SC) current of cell, λ is solar irradiance, E_g is energy in band gap of semiconductor and V_t is ambient temperature voltage. By consideration, The behavior of Photovoltaic cell is the relation of N , I_{ph} , I_s , R_s and R_{sh} . In which, these parameter depend on solar irradiance (λ) and temperature (T) [1].

However, Photovoltaic module is a congregation of Photovoltaic cells. So, V-I relationship of Photovoltaic module (neglecting R_s , R_{sh}) is given in (4) [1], where n_s and n_p are number of series and shunt cells in Photovoltaic module.

$$I = n_p \cdot I_{ph} - n_p \cdot I_s \left(e^{\left(\frac{qV}{N \cdot K \cdot T \cdot n_s} \right)} - 1 \right) \quad (4)$$

- *Fill factor (FF)*: SC current and OC (open circuit) voltage, which are maximum current and voltage of Photovoltaic cell. By theory, the product of these values is the maximum power of Photovoltaic cell [3]. *FF* is defined as the ratio of actual maximum obtainable power, ($V_m \cdot I_m$) to the theoretical power, ($I_{sc} \cdot V_{oc}$). It is given as [3].

$$FF = \frac{V_m \cdot I_m}{V_{oc} \cdot I_{sc}} \quad (5)$$

- *Maximum efficiency (η)*: is the ratio of maximum output power to the input power [4].

$$\eta = \frac{V_{oc} \cdot I_{sc} \cdot FF}{P_{in}} \quad (6)$$

3. Simulation Model of Photovoltaic Module

3.1. Mathematical model

The Solarex MSX60 Photovoltaic module was chosen to do a Photovoltaic model. It provides 60 W. of nominal max. power, and it has 36 polycrystalline silicon cells in series connecting. The specifications are shown in Table 1 [5].

Table 1. Typical Electrical Characteristics of MSX-60.

Specification of Solarex MSX60 (1kW/m ² , 25°C)	
Characteristics	Specifications
Typical peak power (P_m)	60 W
Peak power voltage (V_m)	17.1 V
Peak power current (I_m)	3.5 A
Current at short-circuit (I_{sc})	3.8 A
Voltage at open-circuit (V_{oc})	21.1 V
Coefficient temp. of OC voltage (β)	-73mV/°C
Coefficient temp. of SC current (α)	3mA/°C
Approx. power by temp.	-0.38W/°C

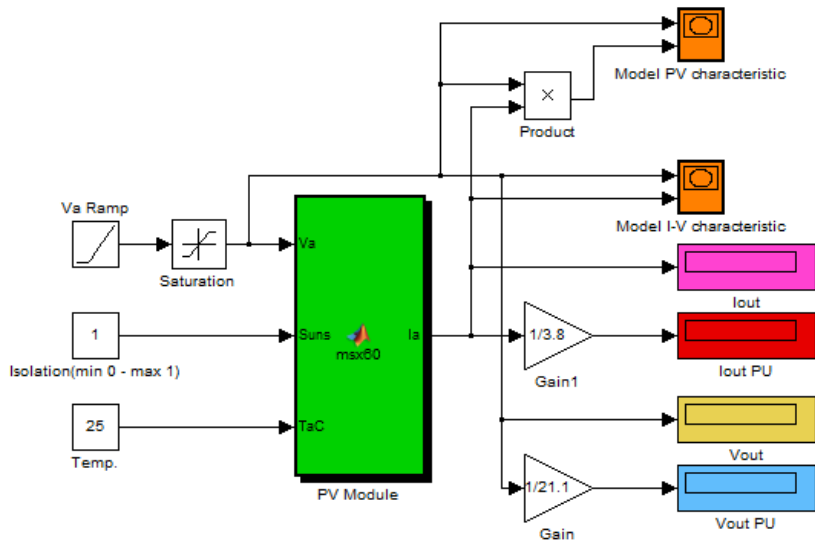


Fig. 2. Simulink model of Photovoltaic model

The model of the Photovoltaic module was implemented using MATLAB/Simulink program. Parameters of model are evaluated using equations on the previous section. The current and voltage were calculated from typical parameters of the module: $I_{sc}=3.8A$, $V_{oc}=21.1V$, $\beta=3mA/^{\circ}C$, $\alpha=-73mV/^{\circ}C$, $N=1.2$, $I_s=100nA$ and the variations of irradiation (λ) and temperature (T). The Photovoltaic model is shown in Figure 2.

3.2. Simulation results of Photovoltaic Cell and Module

3.2.1 Photovoltaic Cell

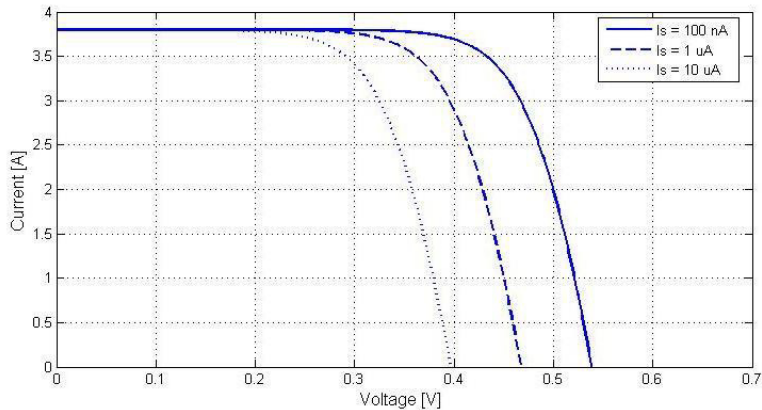


Fig. 3 (a). I-V Characteristic of Photovoltaic cell correspond on I_s .

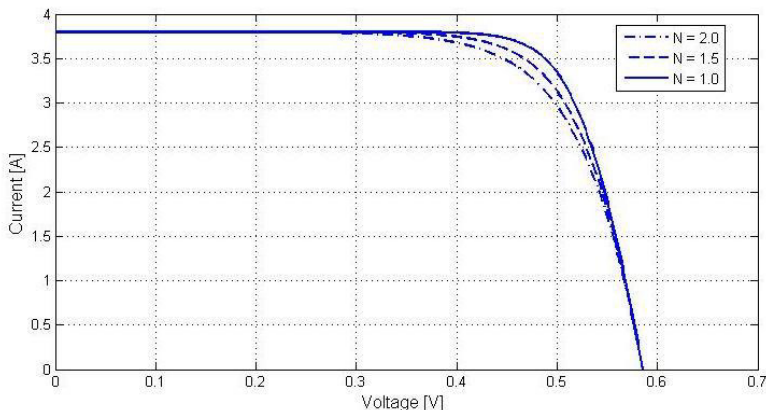


Fig. 3 (b). I-V Characteristic of Photovoltaic cell correspond on N

Figure 3(a) shows I-V curve of Photo-voltaic cell for the reverse saturation current of diode (I_s) at 100nA, 1 μ A, and 10 μ A. It is seen that the increasing of I_s is affected on the decreasing of V_{OC} (open circuit voltage). Figure 3(b) shows I-V curve of Photovoltaic cell for the ideal factor (N) at 1.0, 1.5 and 2.0. It can be observed that the increasing of N is affected on the increasing of V_{OC} .

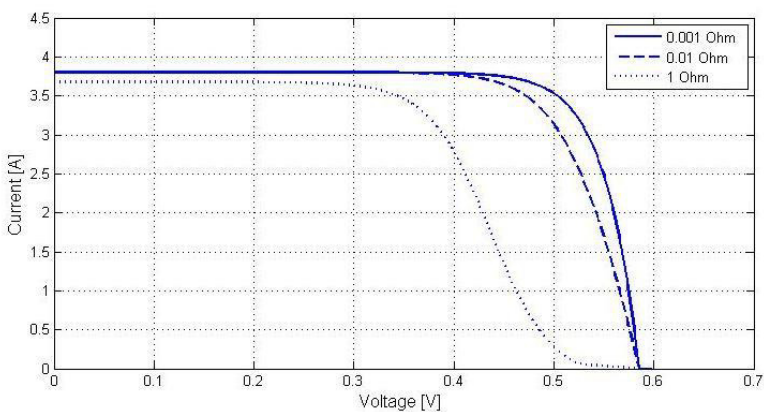
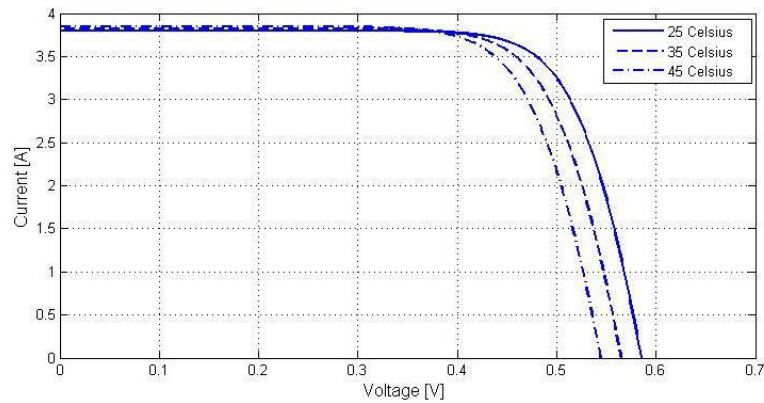
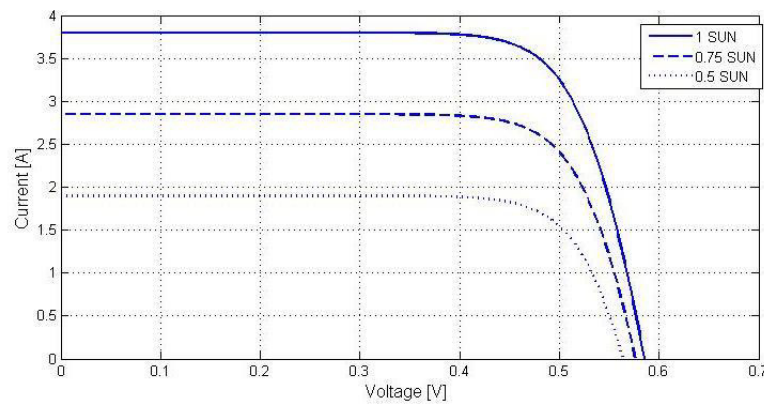


Fig. 4. I-V Characteristic of Photovoltaic cell correspond on R_S .

Figure 4(a) shows I-V curve of Photovoltaic cell for the values of R_s at 1m Ω , 0.01 Ω and 1 Ω . It is seen that increasing of R_s is affected on decreasing of Fill factor (FF). Shunt resistance R_{sh} relates with shunt leakage current inversely. In general, the efficiency of Photovoltaic is insensitive to the R_{sh} . That can be assumed that it will approach to infinity without leakage current [7].

Fig. 5 (a) I-V Characteristic of Photovoltaic cell on varying $T(^{\circ}C)$ Fig. 5 (b) I-V Characteristic of Photovoltaic cell on varying λ

From figure. 5(a) and 5(b), it found that increasing of working temperature, I_{SC} will increases. In another ways, increasing output current will leads to decreasing of Photovoltaic output voltage, which Photovoltaic output power always decreases at higher temperature. On the other hand, from Fig.5, the increasing of solar irradiance, I_{SC} of Photovoltaic will be increased, and the maximum output power may increase. This means that open-circuit voltage depends on solar irradiance, and short-circuit current is proportional to radiant intensity directly.

3.2.2 Photovoltaic Module

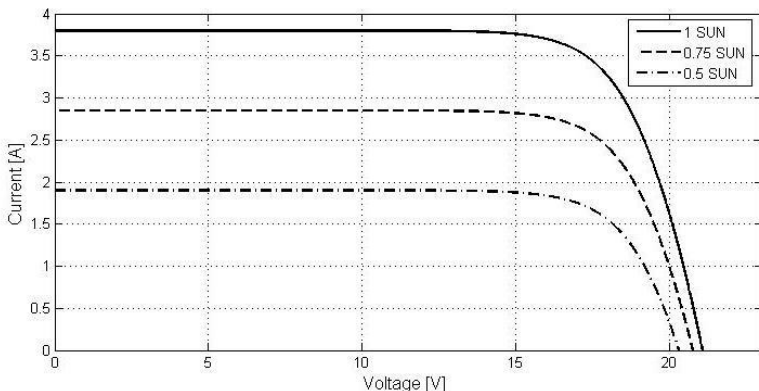


Fig.6 (a). I-V output characteristics of Photovoltaic module

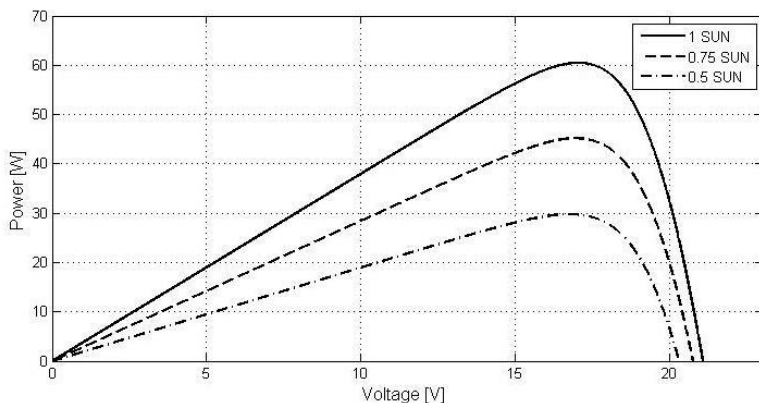


Fig.6 (b). P-V output characteristics of Photovoltaic module

In Photovoltaic module, only one path for conduction current due to Photovoltaic cells that connected in series is available, therefore $n_p = 1$. The Photovoltaic cell's member that connected in series is 36, hence n_s is 36. Therefore, the simulation result of I-V and P-V curve of Photovoltaic module are shown in Figure 6(a) and 6(b) respectively.

Table 3 shows the comparison between the simulation result of Photovoltaic module model and its electrical characteristics (Solarex MSX60). It found that the error is acceptable and the simulation result of I-V and P-V curve of a Photovoltaic module are shown in Figure. 7.

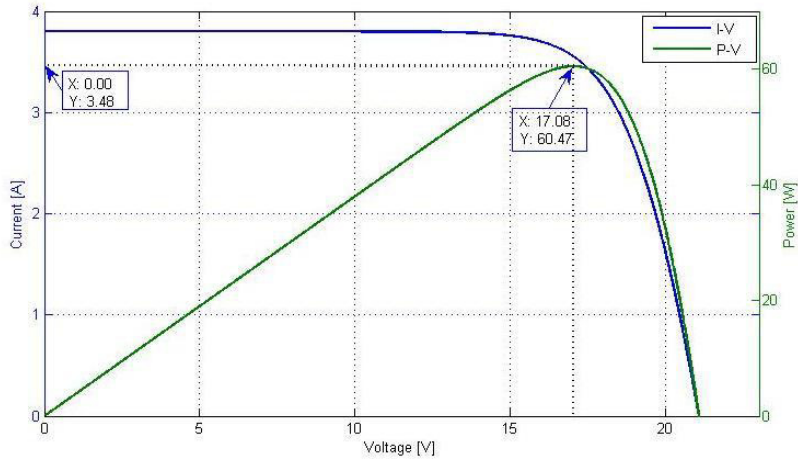


Fig.7 Simulation result of the I-V and P-V Characteristic of Photovoltaic Module

Table 2. Error of the Photovoltaic Module modeling.

Variables	Real MSX-60	MSX-60 Model	Error
P_m (W)	60.0	60.47	0.78%
V_m (V)	17.1	17.08	0.12%
I_m (A)	3.5	3.48	0.57%

4. Simulation of the Photovoltaic Simulator

4.1. Simulation Model

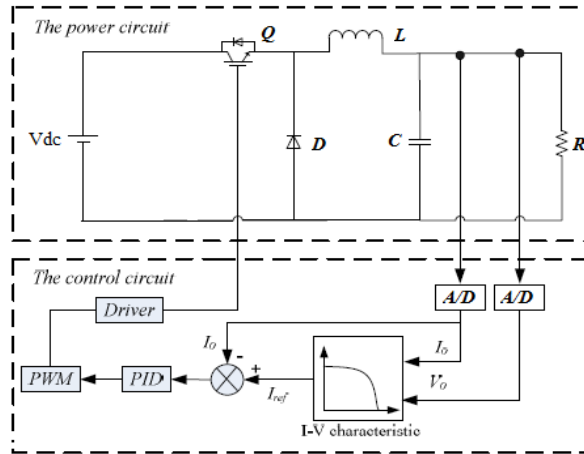


Fig.8 Block diagram of the proposed Photovoltaic Simulator

In this paper, a PV simulator which emulates the output characteristics of the photo-voltaic modules can be used in order to the replacement of a real Solarex MSX60 [6]. The PV simulator is consists of a DC buck converter and a

controller which is using a DSP board implementation. A current transducer (CT) was used to detect the output Photovoltaic module's current and then sent back to the DSP controller board in order to calculate PWM triggering signal for IGBT of the DC converter.

In the further works, real time hardware has to be accomplished in order to produce external output aspect following the I-V characteristics of such Photovoltaic modules. However, in this paper, Photovoltaic simulator is modeled using MATLAB/Simulink program. By which, Photovoltaic simulator that consisted of DC buck converter and a proper feedback control scheme as shown in Figure. 9.

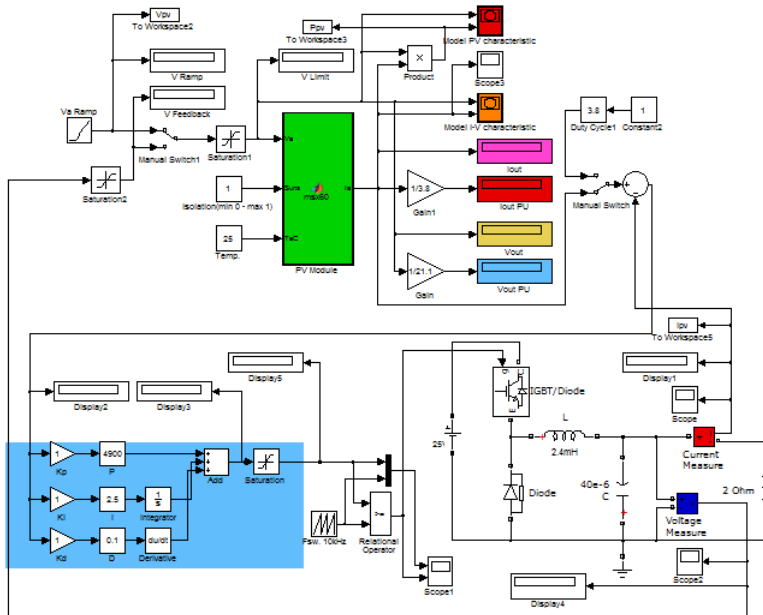


Fig. 9. DC Buck Converter and a PID feedback control scheme

4.2. Simulation Results

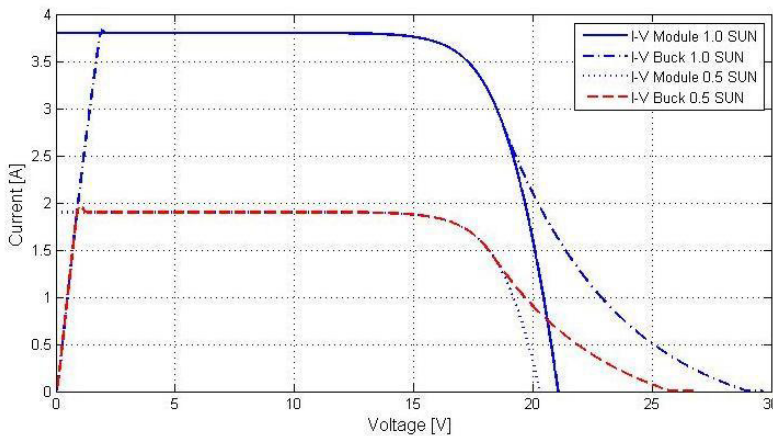


Fig. 9. I-V Characteristic of the Photovoltaic Module under different solar irradiance (T=25°C) compared with the Photovoltaic Simulator (DC Converter Based)

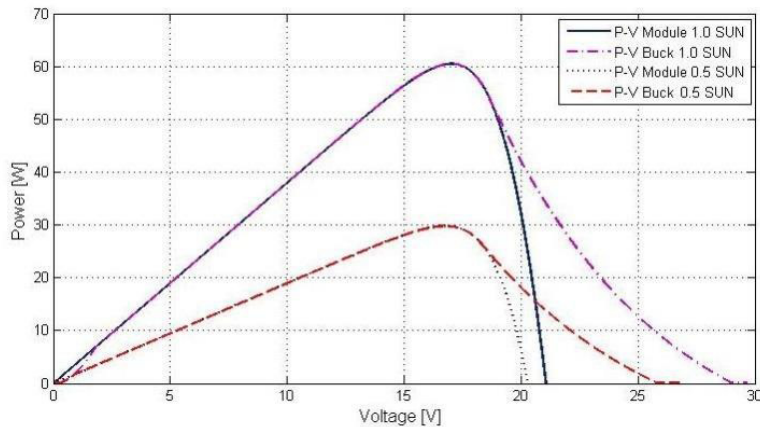


Fig. 10. P-V Characteristic of the Photovoltaic Module under different solar irradiance ($T=25^{\circ}\text{C}$) compared with the Photovoltaic Simulator (DC Converter Based)

The output voltage of the Photovoltaic simulator (DC converter based) in this article is designed to be adjusted from 7V to 22V. The experiment test of PV simulator is done by an adjusting the load resistor (R_{load}), in which, it may change the value of resistor from 2Ω to 49Ω . Figure 9 shows I-V curve of the Photovoltaic module under different solar irradiance 25°C compared to the Photovoltaic based DC-DC Converter. The comparison of P-V curve from the mathematical model of the Photovoltaic Simulator and the Photovoltaic model is also depicted in Figure 10. It show that I-V curve of the Photovoltaic simulator (DC converter based) is well matching with the Photovoltaic module except the small part of voltage control zone of Photovoltaic experimental curve need to be adjustment to the I-V curve with particularly in both different solar irradiance and the temperature are same.

5. Conclusions

At first part, the computer simulation is done using a Solarex MSX60 parameters in order to depict the output characteristics of such Photovoltaic cell in any operating circumstances such as a vary of sunshine intensity or working temperature etc. The results of the simulation confirmed that it is suited to the real Solarex MSX60. On the second part, the computer simulation is also done, but, in form of the Photovoltaic simulator. The Photovoltaic simulator in this article consists of a buck converter and a digital controller. From the simulation results, it shows that the output characteristic of Photovoltaic simulator has a well matching with a real Solarex MSX60. However, in practice, it needs to be adjusted at some part of the voltage control in the digital controller.

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