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MODELING AND EVALUATION OF SOLAR PHOTOVOLTAIC EMULATOR BASED ON SIMULINK MODEL

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ABSTRACT

This paper presents the modeling and simulation of Solar Photovoltaic Emulator utilizing Buck Converter under MATLAB/Simulink software. The proposed model is designed using SimPower toolbox of Simulink block libraries. The characteristics of Photovoltaic Emulator model was tested by varying the value of load and considering the effect of irradiance and temperature variation. The output characteristics of Photovoltaic Emulator model is verified by comparing to the characteristics of the actual PV module. The Shell SP75 PV module is chosen as a reference for this simulation. The proposed Photovoltaic Emulator was found to be valid and accurate for any irradiance and temperature variations.

Keywords: PV emulator, buck converter, photovoltaic, matlab, simulink.

INTRODUCTION

Solar cells are solid state devices that convert the energy of sunlight directly into electrical energy. Solar cells have several advantages such as pollution-free, low maintenance costs and low operating costs. Their sources of energy, which is derived from solar energy, are also widely available and it is free.

Recently, the photovoltaic system is recognized to be at the forefront in renewable energy generation. It can produce direct current electricity directly when exposed to sunlight.

One of constraint that inhibits the growth of the photovoltaic system is the efficiency is relatively low. Therefore, further research towards the efforts to improve the efficiency of photovoltaic system is needed. Various attempts to optimize the work of photovoltaic system are necessary.

Many factors affect the performance of the photovoltaic system. Therefore, Solar PV Emulator is needed to find out how much these factors affect the performance of the solar photovoltaic system.

In this paper, a modeling and simulation of Solar Photovoltaic Emulator utilizing Buck Converter under MATLAB/Simulink software is carry out. The proposed model is designed using SimPower toolbox of Simulink block libraries. The characteristics of Photovoltaic Emulator model was tested by varying the value of load and considering the effect of irradiance and temperature variation. The output characteristics of Photovoltaic Emulator model is verified by comparing to the characteristics of the actual Shell SP75 PV module.

SOLAR CELL CHARACTERISTIC

Solar cell is a device that serves to transform solar radiation into DC current to generate electric power. The energy conversion occurs based on the principle of photovoltaic effect in semiconductor materials.

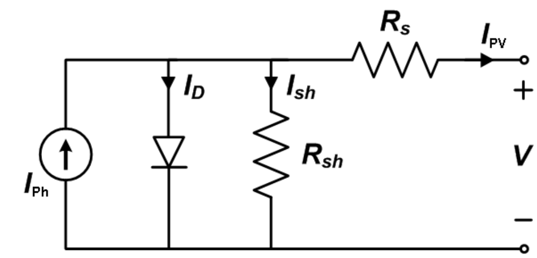

Figure-1. Solar cell equivalent circuit

The equivalent circuit of solar cell can be described consists of a photocurrent source, diode, series resistance (R_s) and the parallel resistance (R_{sh}), as shown in Figure-1.

Photocurrent (I_{ph}) varies linearly with the solar radiation and depends on the surrounding temperature. Resistor R_s and R_{sh} shows the intrinsic series and parallel resistance of solar cells [1]. From the circuit in Figure-1, the equation can be derived as follows:

$$I_{pv} = I_{ph} - I_D - I_{sh} \tag{1}$$

where
I_{pv} = output current (ampere)
I_{ph} = photocurrent (ampere)
I_D = diode current (ampere)
I_{sh} = shunt current (ampere).

The current through these elements is governed by the voltage across them:

$$V_D = V_{pv} + I_{pv} R_s \tag{2}$$

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where
V_D = voltage across diode and resistor R_{sh} (volt)
V_{pv} = voltage across the output terminals (volt)
I_{pv} = output current (ampere)
R_S = series resistance (Ω).

By the Shockley diode equation, the current diverted through the diode is:

$$I_D = I_O\left[e^{\left(\frac{qV_D}{nkT}\right)} - 1\right] \quad (3)$$

where
I_O = reverse saturation current (ampere)
n = diode ideality factor
q = elementary charge
k = Boltzmann's constant
T = absolute temperature

By Ohm's law, the current diverted through the shunt resistor is:

$$I_{sh} = \frac{V_D}{R_{sh}} \quad (4)$$

whereR_{sh} = shunt resistance (Ω).

Substituting equation (3) and (4) into the first equation and using equation (2) produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage [1-2]:

$$I_{pv} = I_{ph} - I_O\left[e^{\left(\frac{q(V_{pv}+I_{pv}R_s)}{nkT}\right)} - 1\right] - \frac{V_{pv}+I_{pv}R_s}{R_{sh}} \quad (5)$$

The nonlinear and explicit equation given by Equation (5) depends on the incident solar irradiance, the cell temperature, and their reference values which are generally provided by manufacturers of PV modules for specified operating condition such as Standard Test Conditions where the irradiance is 1000W/m^2 and the cell temperature is 25^{o}C[1-5].

MODELLING OF SOLAR PV EMULATOR

The model of the Solar PV Emulator was implemented using a MATLAB/Simulink model. The Shell SP75 PV module is chosen as a reference for this simulation, which provides 75W nominal maximum power and has 36 series connected cells [6]. Parameter specification of the Shell SP75 module is shown in Table-1.

The series resistance and ideal factor are calculated based on simplified explicit method [5], and the shunt resistance is adopted from [3].

$$R_s = \frac{\frac{N_s nkT}{q}\ln\left(1 - \frac{I_m}{I_{sc}}\right) + V_{OC} - V_m}{I_m} \quad (6)$$

$$n = \frac{q\left(2V_m - V_{OC}\right)}{N_s kT\left(\frac{I_{sc}}{I_{sc}-I_m} + \ln\left(1 - \frac{I_m}{I_{sc}}\right)\right)} \quad (7)$$

Model of solar cell is carried out by using mathematical characteristics of solar cells in equation (1) to (5). The developed solar cell model is shown in Figure-2. Figure-2 shows the model of the solar cells with input parameters irradiance, temperature and voltage. The contents of the block PV-Module in Figure-2 are shown in Appendix-1.

Table-1. Parameter specification of shell Sp75 module.

Parameters	Symbol	Value
Maximum power	P_m	75 W
Voltage at max power	V_m	17 V
Current at max power	I_m	4.4 A
Open circuit voltage	V_{oc}	21.7 V
Short circuit current	I_{sc}	4.8 A
Number of Series Cells	N_s	36
Number of Parallel Cells	N_p	1
Series Resistance	R_s	0.338 Ω
Shunt Resistance	R_{sh}	10850 Ω
Ideal factor	n	1.3971

The model of Buck Converter is carried out by using Power Electronic model of SimPower toolbox from Simulink Software. The Buck converter is one type of dc-dc converter that produces an output voltage lower than the input voltage. The Buck converter circuit consists of DC source, Power Mosfet, Diode, Inductor, Capacitor, and load Resistor [7-8]. Here, the buck converter is controlled by a PI controller and PWM generator. Both output current and output voltage are used as a feedback of the PI controller, which will be compared with a reference current.

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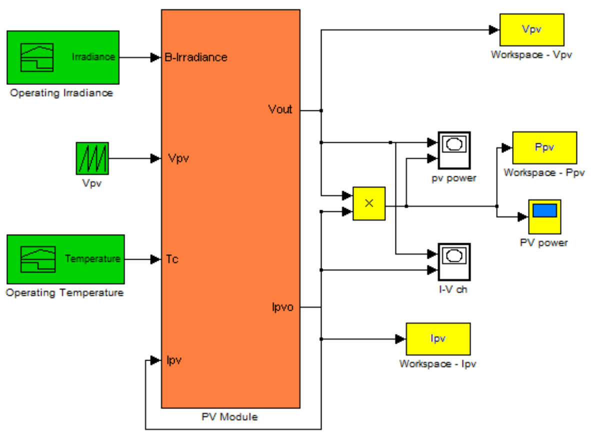

Figure-2. Model of the solar cell with input parameters irradiance, temperature and voltage.

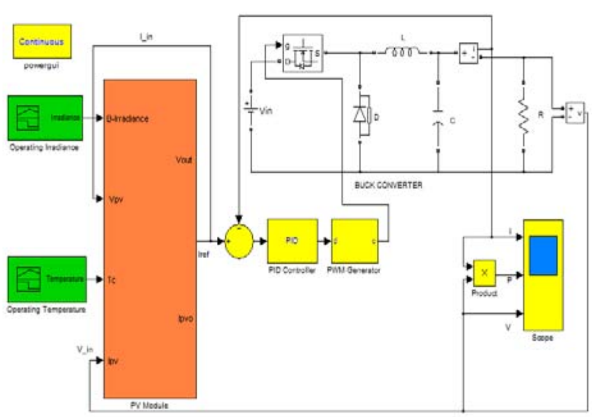

Figure-3. Model of solar PV emulator utilizing buck converter.

Finally, both of Buck Converter model and solar PV model are combined to produce a solar PV Emulator. The developed solar PV Emulator model is shown in Figure-3.

RESULT AND ANALYSIS

To verify the validity of the PV Emulator model that has been created, the testing is done through simulation. In this simulation the output of PV Emulator model was tested by varying the value of load under different value of specific irradiance and temperature.

The purpose of this test is to obtain the output characteristics of PV Emulator models. The obtained output characteristics of PV Emulator model will be compared with the characteristics of the actual solar cells. As a comparison reference used Shell SP75 solar cell modules.

PV Emulator output under irradiance variation

Data collection was performed for three different irradiance values, i.e. 1000W/m^2, 800W/m^2 and 400W/m^2. The data for each irradiance values are shown in Table-2 to 4.

From the simulation results obtained the curves that indicate the output characteristics of PV Emulator models during a variation of irradiance. Acquired characteristic curve is shown in Figures-4 and 5. Figure-4 shows the Current-Voltage (I-V) characteristics and Figure-5 shows the Power-Voltage (P-V) characteristics of the created PV Emulator models.

In the standard test conditions i.e. the irradiance of 1000 W/m^2 and the cell temperature of 25ºC, it was found that the obtained maximum power is 74.742 Watt with voltage at the maximum power of 16.962 V and current at the maximum power of 4,406 A at the value of 3.85 Ohm load. For comparison, according the datasheet, at standard test conditions the Shell SP75 solar module produces maximum power 75 Watt with voltage at the maximum power of 17 V and a current at the maximum power of 4.4 A [7]. It can be concluded that the developed model of PV Emulator is valid.

From Tables 2 to 4, the operating point of maximum power PV Emulator change depending on the radiation. For Irradiance 1000W/m^2, the maximum power of the PV Emulator occurs when the output voltage 16.962 V with a current of 4,406 A. For Irradiance 800W/m^2, the maximum power occurs in the output voltage 17.261 V with a current of 3,452 A. For Irradiance 400W/m^2, the maximum power occurs in the output voltage 16.690 V with a current of 1,757 A.

PV Emulator output under temperature variation

Data collection was performed for three different temperature values, i.e. 25ºC, 50ºC and 75ºC. The data for each temperature values are shown in table 5, 6 and 7.

From the simulation results obtained curves that indicate the output characteristics of PV Emulator models during a variation of temperature. Acquired characteristic curve is shown in Figure 6 and 7. Figure-6 shows the Current-Voltage (I-V) characteristics and Figure-7 shows the Power-Voltage (P-V) characteristics of the created PV Emulator models.

From the temperature variation curve in Figure 6, it appears that when the temperature increase from 25ºC to 50ºC, and 75ºC, the value of the output voltage will decrease, while the value of the output current relatively constant. This resulted in the power generated will be decrease.

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Table-2. Irradiance 1000 W/m^2.

No.	**R** (Ohm)	**V** (Volt)	**I** (Amp)	**P** (Watt)
1	0.01	0.048	4.798	0.229
2	0.2	0.959	4.798	4.600
3	0.6	2.878	4.798	13.820
4	2	9.590	4.795	46.000
5	2.25	10.785	4.793	51.690
6	2.5	11.969	4.787	57.300
7	2.75	13.128	4.774	62.650
8	3	14.232	4.744	67.520
9	3.35	15.585	4.652	72.500
10	3.6	16.355	4.543	74.300
11	3.85	16.962	4.406	74.742
12	4	17.262	4.315	74.490
13	4.25	17.678	4.160	73.530
14	4.5	18.015	4.003	72.190
15	5	18.528	3.705	68.650
16	5.5	18.903	3.437	64.970
17	6	19.193	3.199	61.394
18	7	19.615	2.802	54.960
19	8	19.909	2.488	49.545
20	9	20.128	2.236	45.020
21	9.5	20.219	2.128	43.030
22	10	20.299	2.029	41.208
23	11	20.435	1.857	37.963
24	12	20.546	1.712	35.180
25	15	20.787	1.386	28.808
26	20	21.021	1.051	22.095
27	160	21.612	0.135	2.918

Table-3. Irradiance 800 W/m^2.

No.	**R** (Ohm)	**V** (Volt)	**I** (Amp)	**P** (Watt)
1	0.01	0.039	3.833	0.146
2	0.2	0.766	3.838	2.935
3	0.6	2.303	3.838	8.840
4	2	7.675	3.838	29.450
5	2.25	8.634	3.837	33.130
6	2.5	9.590	3.836	36.790
7	2.75	10.545	3.835	40.450
8	3	11.495	3.833	44.050
9	3.35	12.810	3.823	48.950
10	3.6	13.705	3.808	52.230
11	3.85	14.568	3.784	55.100
12	4	15.041	3.760	56.554
13	4.25	15.755	3.707	58.420
14	4.5	16.360	3.635	59.455
15	5	17.261	3.452	59.580
16	5.5	17.876	3.251	58.106
17	6	18.316	3.053	55.930
18	7	18.918	2.703	51.130
19	8	19.308	2.414	46.600
20	9	19.588	2.176	42.635
21	9.5	19.701	2.074	40.855
22	10	19.799	1.980	39.200
23	11	19.965	1.815	36.240
24	12	20.100	1.675	33.665
25	15	20.382	1.358	27.695
26	20	20.654	1.033	21.325
27	160	21.315	0.133	2.839

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Table-4. Irradiance 400 W/m^2.

No.	**R** (Ohm)	**V** (Volt)	**I** (Amp)	**P** (Watt)
1	0.01	0.019	1.910	0.036
2	0.2	0.383	1.915	0.734
3	0.6	1.151	1.920	2.210
4	2	3.840	1.920	7.380
5	2.25	4.320	1.920	8.300
6	2.5	4.805	1.920	9.245
7	2.75	5.280	1.920	10.150
8	3	5.760	1.920	11.050
9	3.35	6.430	1.920	12.350
10	3.6	6.910	1.919	13.260
11	3.85	7.388	1.919	14.170
12	4	7.680	1.919	14.740
13	4.25	8.158	1.918	15.650
14	4.5	8.640	1.917	16.550
15	5	9.590	1.917	18.390
16	5.5	10.540	1.916	20.200
17	6	11.485	1.915	21.990
18	7	13.325	1.904	25.400
19	8	14.980	1.873	28.040
20	9	16.230	1.803	29.255
21	9.5	16.690	1.757	29.340
22	10	17.065	1.707	29.140
23	11	17.625	1.603	28.240
24	12	18.020	1.502	27.060
25	15	18.724	1.248	23.370
26	20	19.278	0.964	18.580
27	160	20.370	0.127	2.594

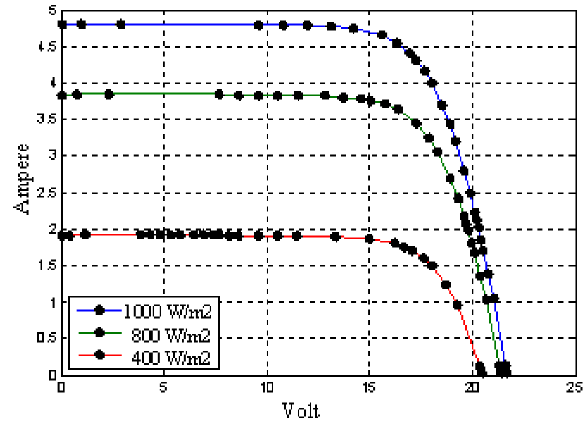

Figure-4. I-V characteristics at irradiance variation.

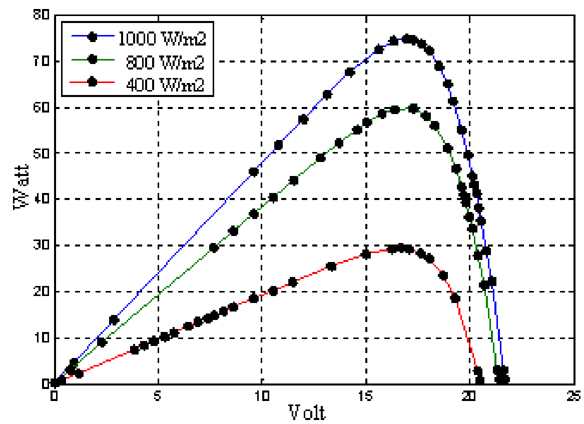

Figure-5. P-V characteristics at irradiance variation.

From the data characteristics of PV Emulator in Tables5, 6 and 7, shown the maximum power operating point of the PV Emulator will be change when the temperature changed. For temperature 25ºC, the maximum power operating point of the PV Emulator occurs in the output voltage 16.962 V with a current of 4,406 A. For temperature 50ºC, the maximum power operating point occurs in the output voltage 14,844V with a current of 4,431 A. For temperature75ºC, the maximum power operating point occurs in the output voltage 13,065 V with a current of 4,354 A.

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Table-5. Temperature 25 ºC.

No.	**R** (Ohm)	**V** (Volt)	**I** (Amp)	**P** (Watt)
1	0.01	0.048	0.229	4.798
2	0.2	0.959	4.600	4.798
3	0.6	2.878	13.820	4.798
4	2	9.590	46.000	4.795
5	2.25	10.785	51.690	4.793
6	2.5	11.969	57.300	4.787
7	2.75	13.128	62.650	4.774
8	3	14.232	67.520	4.744
9	3.35	15.585	72.500	4.652
10	3.6	16.355	74.300	4.543
11	3.85	16.962	74.742	4.406
12	4	17.262	74.490	4.315
13	4.25	17.678	73.530	4.160
14	4.5	18.015	72.190	4.003
15	5	18.528	68.650	3.705
16	5.5	18.903	64.970	3.437
17	6	19.193	61.394	3.199
18	7	19.615	54.960	2.802
19	8	19.909	49.545	2.488
20	9	20.128	45.020	2.236
21	9.5	20.219	43.030	2.128
22	10	20.299	41.208	2.029
23	11	20.435	37.963	1.857
24	12	20.546	35.180	1.712
25	15	20.787	28.808	1.386
26	20	21.021	22.095	1.051
27	160	21.612	2.918	0.135

Table-6. Temperature 50 ºC.

No.	**R** (Ohm)	**V** (Volt)	**I** (Amp)	**P** (Watt)
1	0.01	0.048	0.234	4.830
2	0.2	0.967	4.680	4.830
3	0.6	2.904	14.040	4.835
4	2	9.655	46.640	4.827
5	2.25	10.830	52.150	4.815
6	2.5	11.955	57.180	4.782
7	2.75	12.985	61.320	4.722
8	3	13.874	64.150	4.625
9	3.35	14.844	65.750	4.431
10	3.6	15.367	65.600	4.268
11	3.85	15.785	64.730	4.100
12	4	16.000	64.000	4.000
13	4.25	16.305	62.550	3.836
14	4.5	16.560	60.940	3.680
15	5	16.968	57.580	3.393
16	5.5	17.278	54.280	3.142
17	6	17.524	51.185	2.921
18	7	17.892	45.730	2.556
19	8	18.155	41.195	2.269
20	9	18.352	37.420	2.039
21	9.5	18.435	35.770	1.941
22	10	18.507	34.255	1.851
23	11	18.632	31.560	1.694
24	12	18.734	29.250	1.561
25	15	18.957	23.958	1.264
26	20	19.174	18.384	0.959
27	160	19.725	2.432	0.123

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Table-7. Temperature 75 ºC.

No.	**R** (Ohm)	**V** (Volt)	**I** (Amp)	**P** (Watt)
1	0.01	0.048	0.238	4.880
2	0.2	0.975	4.750	4.875
3	0.6	2.928	14.300	4.880
4	2	9.643	46.500	4.822
5	2.25	10.710	51.000	4.760
6	2.5	11.650	54.300	4.660
7	2.75	12.434	56.210	4.521
8	3	13.065	56.880	4.354
9	3.35	13.740	56.355	4.102
10	3.6	14.117	55.350	3.921
11	3.85	14.428	54.060	3.747
12	4	14.588	53.200	3.647
13	4.25	14.825	51.715	3.488
14	4.5	15.028	50.183	3.339
15	5	15.361	47.184	3.072
16	5.5	15.621	44.362	2.840
17	6	15.832	41.770	2.639
18	7	16.152	37.265	2.307
19	8	16.384	33.555	2.048
20	9	16.561	30.475	1.840
21	9.5	16.635	29.129	1.751
22	10	16.700	27.890	1.670
23	11	16.814	25.700	1.529
24	12	16.906	23.820	1.409
25	15	17.110	19.515	1.141
26	20	17.310	14.980	0.865
27	160	17.820	1.985	0.111

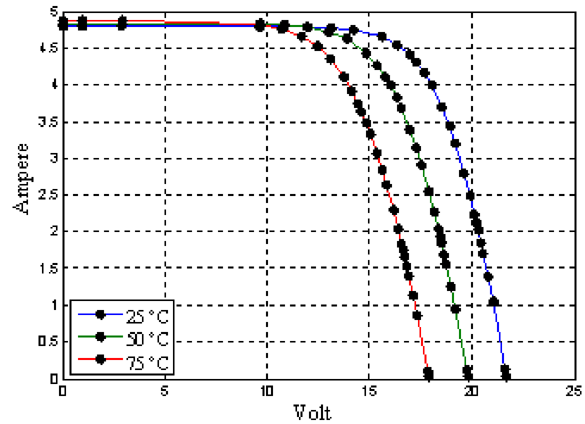

Figure-6. I-V characteristics at temperature variation.

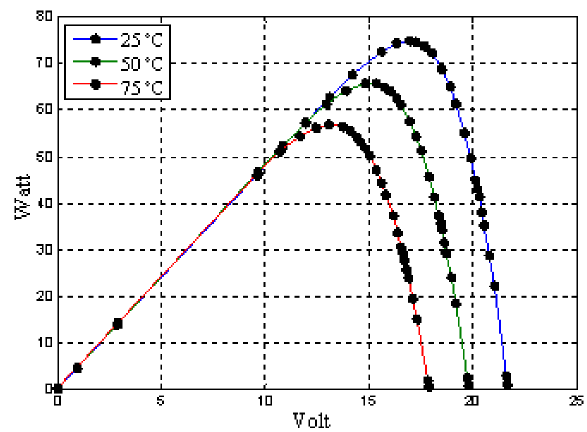

Figure-7. P-V characteristics at temperature variation.

CONCLUSIONS

A modeling and simulation of Solar Photovoltaic Emulator Utilizing Buck Converter is presented. The performance of the PV Emulator system has been investigated. The simulation results show the proposed Solar Photovoltaic Emulator model has similar characteristics to the actual characteristics of the solar cell. In the standard test conditions it was found that the proposed PV Emulator produces the maximum power 74.742 Watt with voltage and current of 16.962V and 4.406A. For comparison, according the datasheet, at standard test conditions the Shell SP75 solar module produces the maximum power 75 Watt with voltage at the maximum power of 17 V and current of 4.4 A.

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Appendix-1. The contents of the block PV-Module in Figure-2.