Year-Long Profiling of Voltage Output And Maximum Power of PV Module Using Simulation-Based Model

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Abstract— Solar photovoltaic (PV) energy systems is one of clean energy technologies actively being used. It is also finding its wide usage in countries with abundance of sunlight. One of such places is Republic of Botswana where PV systems used in different applications such as street lighting, borehole water pumping, telecommunications repeater stations, household lighting. The usage prompted further research on improvement of power output and overall efficiency of the system. Dealing with power output means studying further PV module which is an important part of solar photovoltaic energy system. Important role played by solar photovoltaic module is to convert solar power into electrical power. To study the PV module output, a PV cell electrical characteristics can be studied because it will resemble the characteristic behavior of the module considering that the PV panel is an assembly of cells of photovoltaic material that are connected together mechanically and at the same time making a complete electrical circuit. The characteristics of interest are the outputs of voltage and power at its maximum value. The electrical characteristics of the module are affected by a different factors such as ambient temperature, amount of solar radiation, humidity, and wind velocity. To study the PV module electrical characteristics being yearly voltage output profile and profile of the maximum power, this paper presents Simulink-model to analyse a model of single diode used to represent a PV cell used in simulations. The results show generally constant value of voltage output obtained all year round whereas the profile of maximum power follows the solar insolation profile.

Keywords— Photovoltaic cell, temperature, solar insolation, single diode model.

1. Introduction

Solar photovoltaic (PV) energy systems is made up of mechanical and electrical interconnection components to produce electricity using solar energy as its energy source. One of such components is the PV module which plays a critical role in the operation of PV system. This is where the photon energy from the sun is converted into electrical energy. The PV module also consists of assembly of solar photovoltaic cells which are also electrically and mechanically connected together. Connecting them in series increases the voltage output of the module while parallel connection increase the current out of the PV module. The PV cells are manufactured from the semiconductor materials [1]. The semiconductor materials are themselves made from elements of group IV in periodic table or from group 14 of the modern periodic table [2]. The characteristic of these materials are in between conductors and insulators hence they are neither conductors nor insulators. Having PV module available in all solar PV energy systems and being used under different conditions such as wind velocity, rainfall/ relative humidity, ambient temperature, solar radiation, geographical locations, it is pertinent to study and understand its output while operating under normal operating conditions because the manufacturers provide PV module data tested under controlled conditions (standard test conditions). This paper, therefore, uses data obtained from Clean Energy Research Centre at the University of Botswana (CERC) to profile yearly outputs of the voltage out power at its maximum value. The remaining sections are presented as follows. Section II explains operation of PV cell and details the mathematical equations used in the modelling of voltage and power. Section III outlines the process of modelling the output voltage maximum power. Section IV give presentation and analysis and discussion the results. Lastly Section V concludes on the findings of the study.

2. Principle of Operation of Photovoltaic cell and Equivalent Equations for Modelling

The characteristics of group IV elements which make semiconductor are such that they are between conducting and non-conducting properties. To conduct the semiconductor materials need be supplied with thermal energy which makes the atoms to vibrate and in the process cause the covalent bonds of the atomic structure to break up hence enabling the electrons to disengage from the atom. The free moving electrons then migrate to conduction band leaving behind positively charged carriers called holes. The movement of electrons to the conduction band causes the apparent movement to holes to the opposite side as in Fig.1 The movement the these positively charged particles, electrons and holes, ultimately lead to the net flow of current referred to as photon current (Iph) [1]. Not all electrons result in Iph because some of them recombine with the positively charged holes, a process referred to as recombination process and it takes place in a junction called cell or diode pn-junction. The process results in a reduced net flow of current in the circuit because the recombining charged particles appear as leakage current.

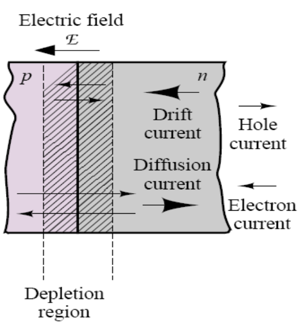

Fig.1. Pn junction with diffusion and drift currents [1]

To model PV cell, a model which normally uses single diode shown in Fig.2 is used to represent a PV cell [2, 3, 5, 6, 9]. The diode is connected parallel to the current sourced denoted with photon current (Iph). Also parallel to both the current source and the diode, a resistance is connected denoted shunt resistance (Rsh). Another resistance denoted series resistance (Rs) is connected between Rsh node and terminal of the model. The Rsh resistance represents those leakages (Ish) which are experienced by the PV cell. It is normally very much higher than the series resistance (Rs) which is the resistance between cell terminals and source resistance.

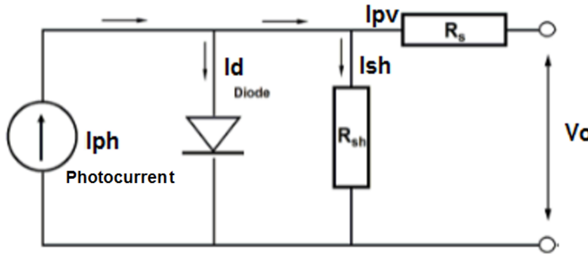

Fig.2. A model using single diode to represent solar photovoltaic cell

The current flow expressions of the model with a forward-biased pn-junction of a semiconductor diode shown in Fig.3 is expressed in (1) [1]. The current through the diode (I_D), is the difference between diffusion current (I_d) and reverse saturation current (I_s)

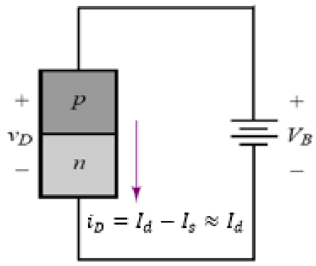

Fig.3. Diffusion and drift currents on a pn-junction with a forward biased mode [1]

$$I_D = I_d - I_s \quad (1)$$

The diffusion current itself is a function of reverse saturation current, diode voltage, and temperature as shown in (2). The expression of (2) shows that the environmental variable, temperature, has an effect on the current of a PV cell. The other contants in the expression are electron charge, q, with a value of (1.602×10-19 C) and the Boltzmann constant, k, with a value (1.381×10^{-23} J/K). Due to the forward biased mode of the pn-junction the potential difference across the pn junction decreases and as it does so the diffusion of majority carriers (I_d) increases because of the availability of applied voltage from external source.

$$I_d = I_s e^{\frac{qV_D}{kT}} \quad (2)$$

Substituting (2) in (1) gives an expression of diode current in terms of diode voltage, V_D and the temperature T with units kelvin (K), of the PV module expressed in Kelvin (K). When expressing the diode voltage by considering the voltage output, V_{PV} and output current , I_{PV} , of a PV module respectively, series resistance, R_S, the number of cells connected in seriese, N_S, and cell's ideality constant, n, then the current through the diode can be further stated as in (4). The output voltage, V_{PV}, can be expressed as open circuit voltage, V_{OC}, if there is no load connected to the terminals and are left open [4].

$$I_D = I_s e^{\frac{qV_D}{kT}} - I_s = I_s(e^{\frac{qV_D}{kT}} - 1) \quad (3)$$

$$I_D = I_S\left[e^{\frac{q(V_{PV}+I_{pv}R_S)}{N_S nTk}} - 1\right] \quad (4)$$

In calculating electrical characteristics, the photovoltaic current I_{pv}, of the model detailed in Figure1 can be expressed as in (5) and with other important components of the cell current being photon current, I_{ph}, and shunt current, I_{sh} being expressed in (6) to (8) respectively [4, 5, 9].

$$I_{pv} = I_{ph} - I_D - I_{sh} \quad (5)$$

Where

$$I_{ph} = \left[I_{SCr} + K_i(T - 298)\frac{G}{G_0}\right] \quad (6)$$

The expression (6) shows that photon current is depended on various variables being the temperature (T) and irradiance (G) recorded during normal operating conditions of the PV module. They are considered with the corresponding values measured under standard test conditions (STC) of Irradiance 1000 W/m^2, Temperature 25^oC, Air Mass (AM 1.5) , Other factors to consider include the short-circuit current (I_{SCr}) and the short circuit temperature coefficient (K_i) which are also measured at standard test conditions.

The mathematical model also defines the presence of another current, reverse saturation current, I_s, in (7). The expression shows that the instantaneous value of this current is influenced by different factors. The factors are gap energy of semiconductors (J), E_{go}, and the constant, B, with a value varying from 1.5 to 1.6, reference temperature, T_r, and reverse saturation current, I_{rs}, at reference temperature (25^oC)

$$I_s = I_{rs}\left(\frac{T}{T_r}\right)^3 e^{\left(\frac{qE_{go}}{Bk}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right)} \quad (7)$$

To calculate the shunt current, I_{sh}, the following terms in the model need to be known. PV module output voltageV_{PV}, series resistance, R_s, PV module output current, ,I_{PV} and shunt resistance,R_{sh}. Therefore, can be expressed as in expressed in (8).

$$I_{sh} = \frac{V_{PV}+R_s I_{PV}}{R_{sh}} \quad (8)$$

With voltage output and current output now known, PV module power output can be determined according to (9).

$$P_{out} = I_{pv} x V_{PV} \quad (9)$$

3. Modelling, Simulation and |Profiling Maximum output power

Single diode model was used to model and simulate the maximum output power. To get the maximum power output basing on single diode model, simulink models in Fig.4, Fig.5 and Fig.6 were designed. The models have temperature and irradiance as inputs and determine how the Pmax will change as different values and irradiance are entered in the model because both the temperature and irradiance have influence on the amount of maximum power output of the module as expressed by (5) and (6) respectively [7]. With the model it is possible to get the value of the current (Ipv), module output voltage, Vpv and the the maximum power out, Pmax [2, 8]. Fig.6 was designed such that Pmax can be read directly from the scope and imported into the excel spreadsheet. Using readings from scope an excel spreadsheet it is possible profile the Pmax, graphically and determine its relationship with associated current, Ipv and the voltage output, Vpv.

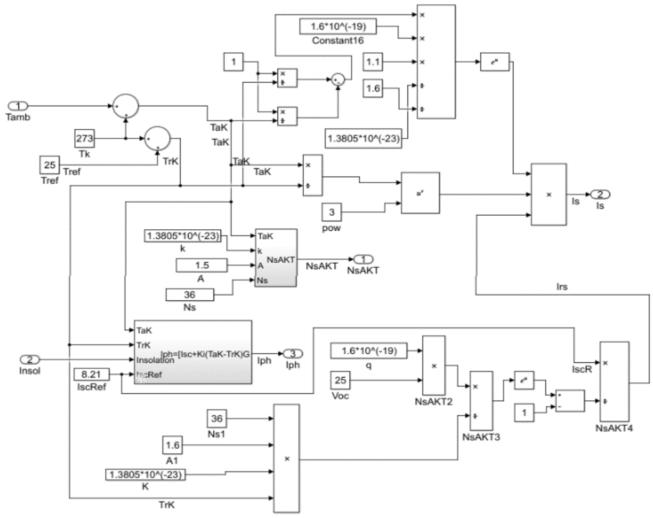

Fig.4. Modelled subsystem of reverse saturation current and product of NsAKT,

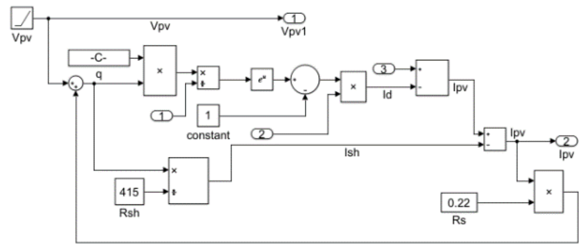

Fig.5. Modelled subsystem of output voltage and output current

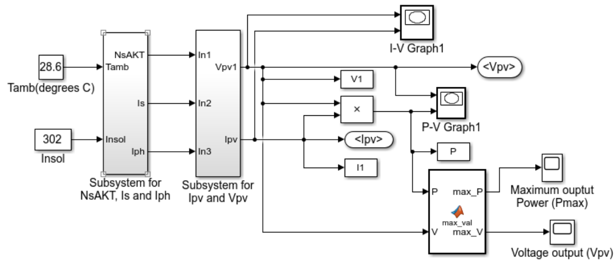

Fig.6. Comprehensive systems encompassing all subsystem models

Entries for the temperature and the irradiance are monthly averages of the daily recordings of the data collected at CERC in Gaborone. The geographical positioning system location coordinates of Gaborone are 24° 39' 11.7252" S and 25° 54' 24.4512" E [10]. The data is how in table 1 which details the specifications of the PV module at the same station. Table 2 shows the GHI and the average temperature of the year 2015 from January to December obtained at the same station.

Table 1. Specification of a photovoltaic module used in the simulation

Name	**Solaire Direct Technologies**
Model	**SD ECO PLUS 150 W**
Electrical Ratings at STC: 1000 W/m^2; AM 1.5 spectrum; Temperature 25 ^oC	
Peak Power	150 W_p
ΔP_{max}	$\pm$ 2.5 W_p with tolerance 1%
Warranted minimum P_{max}	147.5 (tolerance 1%)
Voltage (V_{mp})	18.0 V
Current (I_{mp})	8.05 A
Open Circuit Voltage (V_{OC})	22.6 V
Short Circuit Current (I_{SC})	8.72 A
Maximum System Voltage	1000 V

Table 2. Data recorded on daily basis from CERC station in 2015

UBG - USAid Gaborone	**Latitude: -24.6693; Longitude: 25.9340; Elevation: 1014 m**						
TmStamp	**RecNum**	**GHI_Avg**	**DIF_Avg**	**DNI_Avg**	**Temp_Avg**	**Temp_Max**	**Temp_Min**
		W/m^2	W/m^2	W/m^2	Deg C	Deg C	Deg C
01/01/201500:00:00	400	358.6819	59.80934	385.9271	30.29	38.17	23.05
02/01/2015 00:00:00	401	325.0141	81.7312	290.9827	32.59	41.18	24.89
03/01/2015 00:00:00	402	336.7805	100.4277	287.1254	30.16	40.26	20.98
04/01/2015 00:00:00	403	347.5162	75.07162	369.7458	29.75	38.12	23.43
05/01/2015 00:00:00	404	365.5566	53.58696	422.7337	31.37	39.27	24.75
06/01/2015 00:00:00	405	365.7897	50.4836	429.7393	31.63	41	23.67
07/01/2015 00:00:00	406	366.1081	46.37333	436.9836	33.45	43.7	24.93
08/01/2015 00:00:00	407	352.9264	51.33611	385.6259	36.3	46.54	26.04
09/01/2015 00:00:00	408	310.1507	75.98606	288.3435	32.9	40.37	25.38
10/01/2015 00:00:00	409	319.2531	50.90958	340.7473	27.85	38.13	21.73
11/01/2015 00:00:00	410	343.7817	45.91104	375.9787	27.09	34.61	20.38
12/01/2015 00:00:00	411	308.5322	111.9618	233.3843	28.26	34.16	23.45
13/01/2015 00:00:00	412	336.6043	71.8624	346.1673	24.94	33.18	17.87
14/01/2015 00:00:00	413	329.5555	57.13977	342.1989	27.08	37.4	17.77
15/01/2015 00:00:00	414	221.8333	171.1902	76.59804	25.5	31.67	19.53
16/01/2015 00:00:00	415	306.1345	122.9005	220.2596	27.69	35.46	20.26
17/01/2015 00:00:00	416	143.7723	121.1083	29.65572	23.83	28.58	20.95
18/01/2015 00:00:00	417	222.3347	178.1833	50.44952	24.16	29.22	21.29
19/01/2015 00:00:00	418	314.9669	114.2046	250.6209	25.07	31.59	20.23
20/01/2015 00:00:00	419	339.759	99.73664	298.0654	26.55	35	19.89
21/01/2015 00:00:00	420	296.0561	167.9796	155.5987	28.62	36.29	23.18
22/01/2015 00:00:00	421	258.7829	158.0251	115.8836	27.49	33.41	23.59
23/01/2015 00:00:00	422	317.9539	140.2989	210.9074	29.39	36.68	24.17
24/01/2015 00:00:00	423	211.6299	162.9697	55.26595	27.26	34.07	21.85
25/01/2015 00:00:00	424	128.7536	123.3726	16.14679	24.39	28.2	21.38
26/01/2015 00:00:00	425	286.2407	73.41884	305.2752	28.42	35.64	21.28
27/01/2015 00:00:00	426	288.9184	66.80491	325.9402	27.9	36.06	20.25
28/01/2015 00:00:00	427	335.1237	69.3605	342.4597	27.63	36.73	21.37
29/01/2015 00:00:00	428	319.0305	81.68188	282.2448	30.11	39.52	24.19
30/01/2015 00:00:00	429	274.8182	114.5626	229.7712	30	36.32	25.01
31/01/2015 00:00:00	430	342.3528	78.92997	363.2447	29.81	37.1	23.32
AVERAGE		302.4100774			28.628387		

4. Results and Analysis

Table 3 shows the average values of global horizontal irradiance and the average temperature of 2015 obtained from CERC station. The results obtained from simulation models is consistent with places in southern hemisphere where the GHI is lowest during the months of low temperatures which happens in winter. In Botswana this season comes in May, June and July, whilst the highest is recorded around summer season which occurs around November, December and January. Fig.7, Fig.8 and Fig.9 show the results from January to and including the month of December obtained from scopes of simulink models. Voltage output was general constant throughout the year while the Pmax was varying with month of the year.

Table 3. Temperature and irradiance recorded at CERC in 2015

Month	GHI(w/m2)	Average Temp (°C)
Jan	302	28.6
Feb	285	29.5
Mar	239	25.3
Apr	217	23.4
May	186	18.5
Jun	165	15.7
Jul	184	14.9
Aug	224	18.5
Sept	247	23.7
Oct	283	26.7
Nov	291	27.1
Dec	273	27.8

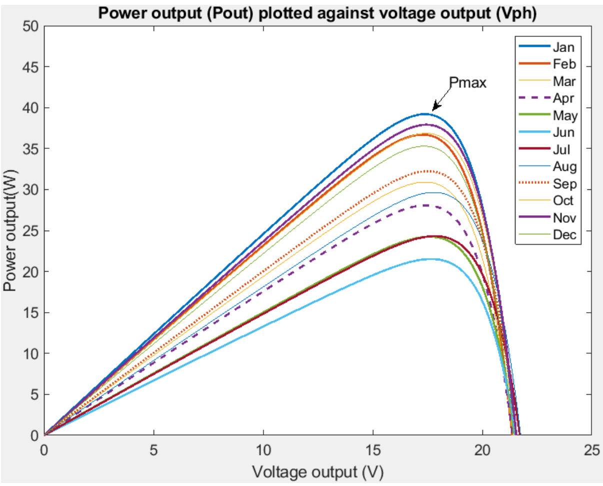

Fig. 7. The module power out for the months of January to December

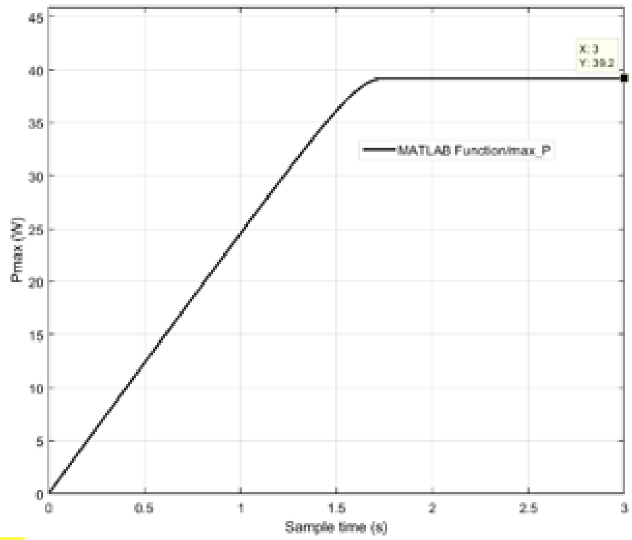

Fig.8. Graphical representation showing exact value of output power at its maximum vales for input temperature and irradiance of model in Fig.6

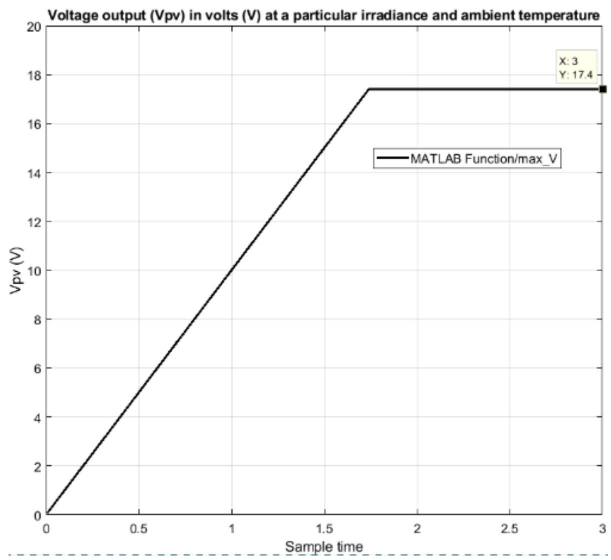

Fig.9. Graphical representation showing exact value of output for input temperature and irradiance of model in Fig.6

Using the data in Fig.7 and Fig.8 the PV module electrical parameters being P_{max} and V_{PV} for months of January to December were entered in table 4. From table 4, a Pmax profile of the year 2015 was developed as shown in Fig.10. The results show yearly constant voltage output and a maximum power whose value various throughout the year with the minimum recorded experienced in winter season..

$$y = 0.0008x^5 - 0.0469x^4 + 0.8196x^3 - 5.0664x^2 + 7.6369x + 36.912 \quad (6)$$

Table 4. Output values of maximum power, voltage and current recorded from simulation models

Month	GHI (w/m2)	Average Temp (°C)	P_{max}(W)	V_{pv}(V)	Sample Time(sec)
Jan	302	28.6	39.2	17.4	3
Feb	285	29.5	36.7	17.3	3
Mar	239	25.3	30.9	17.4	3
Apr	217	23.4	28.1	17.4	3
May	186	18.5	24.2	17.6	3
Jun	165	15.7	21.5	17.7	3
Jul	184	14.9	24.3	17.8	3
Aug	224	18.5	29.7	17.8	3
Sep	247	23.7	32.2	17.5	3
Oct	283	26.7	36.7	17.5	3
Nov	291	27.1	37.9	17.5	3
Dec	273	27.8	35.6	17.3	3

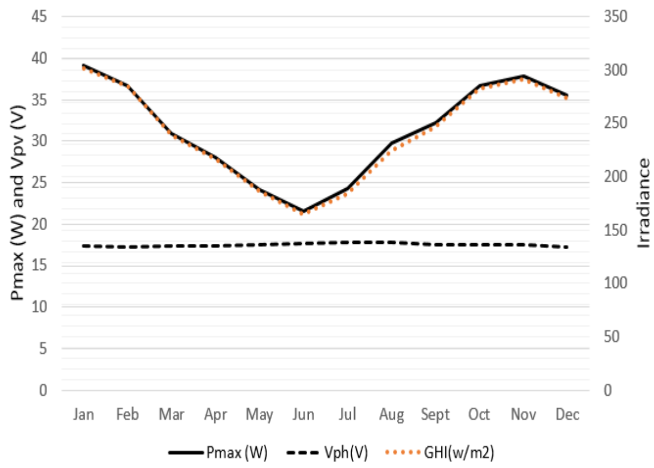

Fig.10. Profiling of output voltage and power output at its maximum values

5. Conclusion

The study's findings, as illustrated in figures 5, 6, and 7, indicate that the module's maximum power output and voltage output are dependent on, among other parameters, the ambient temperature and irradiance. This confirms other prior findings in the literature that revealed the same thing. From January to December, the voltage output was relatively steady around 17.6 V, whereas the maximum output varied each month. The Pmax was lowest in June/July and highest in December/January.

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