Maximum Power Point Tracking Techniques and Control Algorithm in a Hybrid Power System

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ABSTRACT

The Nigerian power problem resulted in an incessant and erratic supply of electricity. This has destroyed many industrial processes and increased the unemployment rate in the country to over 50 million (unfortunately, this figure is over 70% of Nigerian youths). This leads to an increase in crime rates and the death of many innocent citizens in the country. As of 2022, the electricity energy consumption in the world from the World Factbook revealed that the average power per capita (watts per person) in Norway is 2,740 Watts. In the United States, it is 1,377 Watts per person and in Germany, it is 753 Watts per person. In Trinidad and Tobago, average power per capita (watts per person) is 1,851 Watts and in North Korea, it is 1,109 watts per person. Whereas, the average electricity consumed in watts per person in Nigeria is just 14 Watts. This has put Nigeria in the rank of 189 out of 219 countries, estimated. Currently, power generating capacity in Nigeria is estimated to be 6,803 megawatts, with average working capacity between 2,400 to 3,500 megawatts for over 180 million people. There is an urgent need, therefore, to provide a solution to this problem. In this research work, efficient, reliable and low-cost electric power will be generated from the developed Hybrid Electric Power System (HEPS). The Hybrid Power System mathematical and Simulink models were developed using MATLAB/Simulink software. The developed Simulink models were interconnected and the final model was developed. The outputs of the developed Simulink model were optimized using maximum power point optimization techniques. Hence, it was possible to generate a reliable and continuous power supply at maximum efficiency and minimum cost.

INTRODUCTION

In Nigeria, it has been estimated that only *40* % of Nigerians are connected to the national grid and the few connected population are exposed to frequent power outages. (Abubakar Sadiq *et al*. 2015), (energypedia.info, 2020). Nigeria's electricity grid is mainly powered by large hydro-power and depleting hydrocarbon resources. (Aliyu *et al*, 2015). These problems therefore necessitated the need for the development, design and construction of a Hybrid Power Supply System using Renewable energy resources that renew themselves at a faster and sufficient rate for sustainable extraction after consumption. This is because they are reliable and freely available with sustainable economic benefits in all parts of the world. (Sawsan *et al*, 2016). Also, the per capita cost of production of electricity from non-renewable energy resources is very high. (Phebe *et al*, 2016). Therefore, returning to renewable energy to help mitigate climate change is an excellent approach, which needs to be sustainable to meet the energy demand of future generations.

Aim of the Research

To develop a Hybrid Power System Model for feasibility assessment of renewable energy and establish advanced control of renewable energy micro grids using Maximum Power Point Tracking Techniques.

Objectives of the Research Work

1. To evaluate the operating parameters and performance of the components of the Hybrid Power System Model (HPSM)
2. To develop Simulink models of the HPSM using MATLAB/Simulink 8.1.0604 (2022a) version software
3. To develop an effective Hybrid Power System model with Optimum Performance using Maximum Power Point Tracking (MPPT) Techniques and Genetic Algorithm (GA) optimization processes
4. To develop the design process and algorithms for the establishment of the HPSM using PVS-WTG at maximum efficiency and minimum cost

METHODS Components and Operating Parameters of the Hybrid Electric Power System (HEPS)

The Hybrid Electric Power System (HEPS) developed in this research work consists of Solar Photovoltaic System (SPVS) and Wind Turbine Generator (WTG) as shown in Figure 1

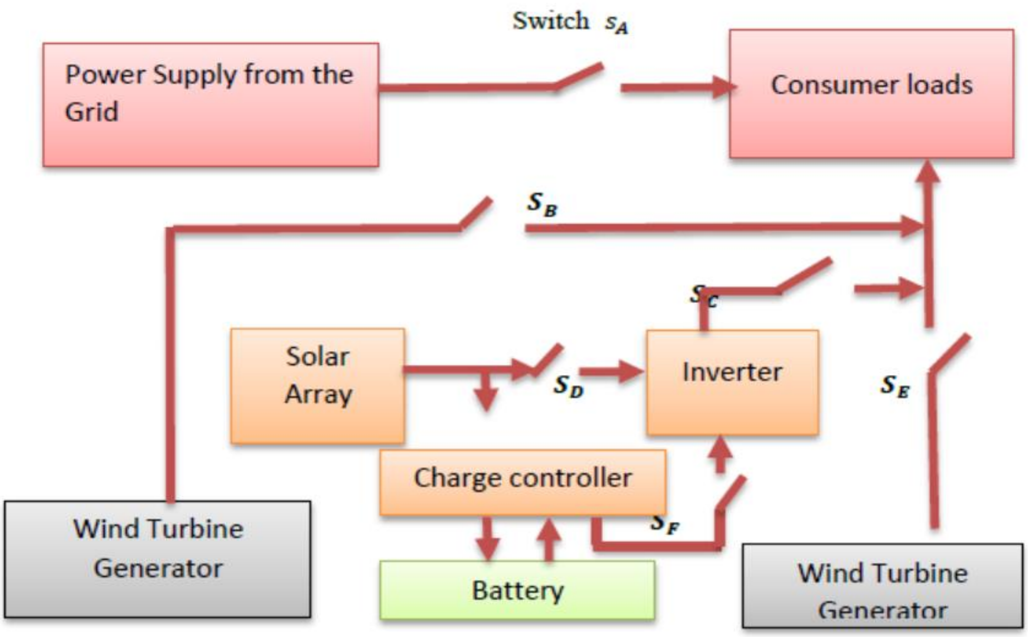

Figure 1: Hybrid Electric Power System (HEPS)

Equivalent Circuit of the General Solar PV Model

The equivalent circuit of the general solar PV model, shown in Figure 2, consists of a photo current, a diode, a parallel resistor expressing a leakage current and a series resistor which offers internal resistance to the flow of current.

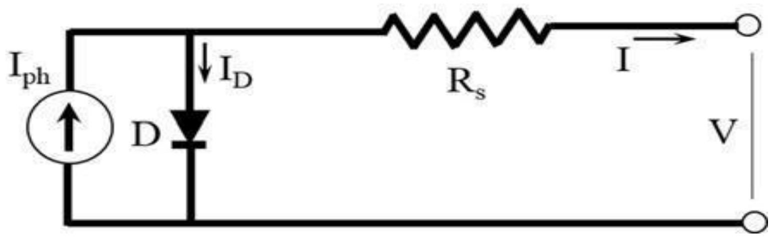

Figure 2: The equivalent circuit of the general solar PV model using a single diode.

The output current I or I_{PV}, *saturation currrent and photo current* equation of an ideal single diode PV cell module is given by:

$$I = I_{ph} - I_{rs}\left[.\exp\left(\frac{q\,(V + I\,R_s)}{AKT\,N_s} - 1\right)\right] \quad 1$$

$$I_s = I_{rr}\left[\frac{T}{T_r}\right]^3 \left[\exp\left(E_{g*}\,\frac{q\,(T - T_r)}{AK\;T{*}T_r}\right).\right] \quad 2$$

$$I_{ph} = [I_{SCR} + k_1\,[T - T_r]\;]\lambda \quad 3$$

Where,

I_{PV} = output current , I_{ph} = light generated photo current

I_{rs} = cell reverse saturation current at cell temperature T

I_{rr} = cell reverse saturation current at a cell reference temperature T_r (25º C)

I_{SCR} = Short circuit current at reference temperature 25ºC,

V = cell output voltage, K = Boltzmann's constant 1.38 * 10^{-23} J/K

A = Ideality factor, K_i = Short circuit current temperature coefficient at 25ºC

T_{nom}= $T_{ref} = T_r$= Reference temperature in Celsius = 25 degree celsius, T = Cell temperature in Celsius q = Charge of electron = 1.6 x 10^{-19} C, λ = Solar irradiation in Watts/m^2, E_g= Band gap energy for silicon Semiconductor material has a specific band gap. For instance, silicon (Si) has a band-gap value of 1.12 electron volt (eV) and germanium 0.66 eV at room temperature (RT)

I_S = Cell saturation current at T_{nom} , R_s = Series resistance in ohms

$$I \text{ or } I_{PV} = N_P I_{ph} - N_P I_S\left[.\exp\;\frac{\left(\frac{V}{N_S} + \frac{I\,R_S}{N_p}\right)}{AKT} - 1\right] - \left[\frac{\frac{V*N_P}{N_S} + IR_S}{R_{sh}}\right] \quad 4$$

Where, *i.* N_P = number of parallel cells and ii. N_s = number of series cells

The reference values will be taken from the PV module manufacturer's datasheet for specified operating conditions, such as STC (standard test conditions) in which the irradiance is 1000W/m^2

The reverse saturation current (Irs) is given by

$$I_{rs} = I_{SC}\;/\;\left[.\exp\;\frac{(q*V_{oc})}{N_S AKT} - 1\right] \quad 5$$

Where, I_{SC} = short circuit current

I_S = Cell saturation current, which is dependent on the temperature as shown in equation 6 below:

$$I_S = I_{rs}\left[\frac{T}{T_r}\right]^3 \left[\exp\left(E_{g*}\,\frac{q(T - T_r)}{A*\;K.T.T_r}\right).\right] \quad 6$$

(Binayak Bhandari1 *et al* 2014, Divine Alsu, Alok Dhaundiyal, 2019)

The output current flowing in the cells array = I

The output voltage = V, $I = I_{ph} - I_D$

I_{ph} = photo current. I_D = diode current,

The array of current can be related to the array of voltage as shown in equation 7:

$$I = N_P\left[I_{ph} - I_{rs}\;\left\langle\exp\left(\frac{q\,(V + I\,R_s)}{AKT\,N_s} - 1\right)\right\rangle\right] \quad 7$$

I_{ph} = photo current, I_D = diode current, I_{rs} = reverse saturationcurrent

N_P = number of parallel connected cells ,. I_s = cell saturation current ,

N_s = number of series connected cells

$$T = I_{rr}\left[\frac{T}{T_r}\right]^3 \exp\left[\frac{qE_g}{AK}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad 8$$

T_r = cell referred temperature, I_{rr} = reverse saturation current at T_r

E_g = Band gap energy of the semiconductor used in the cell

Observation revealed that the photocurrent I_{ph} varies with the cell short-circuit current I_{SCR}, cell temperature T, cell referred temperatureT_r, shirt circuit current temperature coefficient k_1 and solar radiation S (in mW/cm^2) as shown in equation 9:

$$I_{ph} = [\ I_{SCR} + k_1\ [T - T_r]]\ \frac{S}{100} \quad 9$$

Reverse saturation current is the current that is produced due to the small reverse voltage when a p-n junction diode is reverse-biased. In reverse characteristic of p-n junction, current increases in the range of nano-amp (silicon) or micro-amp (germanium) concerning reverse voltage. This reverse current is negligible on most occasions, but it should be taken into account to prevent undesired performance. The generation of current in a solar cell due to the exposure of solar cells to solar radiation is known as the "photo-generated current". It is the current generated due to the absorption of incident photons to create electron-hole pairs. These electron-hole pairs will be generated in the solar cell provided that the incident photon has energy greater than that of the band gap. The saturation current or scale current is that part of the reverse current in a semiconductor diode caused by diffusion of minority carriers from the neutral regions to the depletion region. This current is almost independent of the reverse voltage. (Steadman 1993).

WIND TURBINE GENERATOR

The mechanical power of an induction machine, like a wind turbine generator, is given as:

$P = \omega$ T 10 a. P = mechanical power

b. ω = angular speed of the machine in rev/sec c. T = Torque

The model equation for the wind power system is shown in equation 11:

$$P_{wind} = \frac{1}{2}\ C_p\ \lambda\rho\ A\ \ V^3 \quad 11$$

$$A = \pi\ R^2 \quad 12$$

Since the Tip Speed Ratio = $\lambda = \frac{R\omega}{V}$ Hence, $V = \frac{R\omega}{\lambda}$ 13

P = Power Output of the wind turbine in kilowatts, ρ = Air Density, measured in kilograms per cubic meter A = intercepting area of the rotor blade in square meters, V = Wind Speed, miles/seconds

λ = Tip Speed Ratio (TSR), Cp = Turbine power efficiency coefficient or Bertz coefficient, which is a maximum of 0.593

Then from equations 2.11 and 2.12

$P_{wind} = \frac{1}{2}\ C_p\ \lambda\ \rho\ A\ \ V^3$ will become $P_{wind} = \frac{1}{2}\ C_p\ \lambda\rho\ \pi\ R^2\ \ V^3$ 14

From 2.10 and 2.14, $\omega\ T = \frac{1}{2}\ C_p\ \lambda\rho\ \pi\ R^2\ \ V^3$

$$T = \frac{1}{2}\ C_p\ \lambda\rho\ \pi\ R^2\ \frac{R^3\ \ X\ \ \omega^2}{\lambda^3}$$

Optimum Torque Control System $T = \frac{1}{2}\ C_p\ \lambda\rho\ \pi\ \frac{R^5\ \ X\ \ \omega^2}{\lambda^3}$ 15

Power generated in a wind turbine generator can be controlled by the Tip Speed Ratio (TSR) control method. The method of optimization method aims to determine the optimum TSR. From the optimum TSR, the optimum angular rotor speed can be obtained. Irrespective of the wind speed, the optimum TSR for a given wind turbine generator is constant. Abdulateef *et al* (2016).

Therefore, maintaining optimum TSR will ensure optimum angular rotor speed and the operation of the wind turbine generator at maximum power point. To measure the turbine speed and wind speed, a tachometer and an anemometer will be required. The TSR obtained will then be compared with the optimum value of TSR, which is already stored in the power system. The difference in the two values of TSR is fed to the controller, which will adjust the angular speed of the generator to ensure maximum power output, as shown in Figure 3. Raza *et al* (2010), Kumar *et al*, (2017)

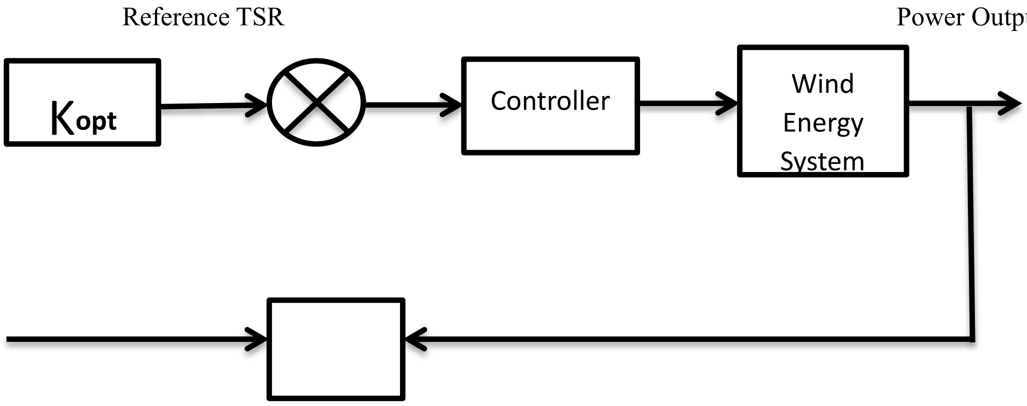

Figure 3: Working principle of TSR control

RESULTS AND DISCUSSIONS Electrical Parameters of the Solar Photovoltaic System

Standard Test Conditions were taken at a temperature of 25 °C, solar irradiance of 1000 W/m^2 and air mass 1.5 AM and the electrical Parameters of Photo-Voltaic cells were evaluated at specified Standard Test Conditions (STC) using the following procedures:

Nominal rated maximum power output (kW_p) of the solar array of n modules was obtained using Equation 16

$$kW_P = \frac{n \text{ X } W_p}{1000} \qquad 16$$

where n = number of solar modules, W_p =maximum power out of a solar cell

The proposed number of solar panels at the reference area is 80. The solar module is 325 W each and the area of each module is 1.63m^3.

Table 1: Electrical specifications of the poly-crystalline solar module STP 255-20/Wd

S/N	Specifications	Variable	Values
1	Optimum operating voltage	V_{mp}	30.79 V
2	Optimum operating current	I_{mp}	8.29 A
3	Maximum power at STC	P_{max}	255 W
4	Short circuit current	I_{sc}	13.136 A
5	Open circuit voltage	V_{oc}	32.1 V
6	Number of series cells	R_s	10
7	Number of parallel cells	R_{sh}	8
8	Module efficiency	η	83.6 %

The efficiency of the solar cell is 83.6 and the average annual solar radiation in Ikere Community, in Oyo State (the study area) is 1000 Wm^{-2} with a mean daily value of 5.25 kWh/m^2 / day.

Hence, from the data obtained, the nominal rated maximum power output of a solar array of 80 modules, kW_p was obtained using equation 17

$$kW_p = \frac{n \ X \ W_p}{1000} \quad k\,W_p = \frac{80 \ x \ 325}{1000} = 26\ kW \qquad 17$$

Where n = number of solar modules, W_p = maximum power out of a solar module

Daily energy produced in the community was also obtained as shown below:

Daily energy produced = kW_p *x average sunshine hour x* ŋ *=26* x *7 x 0.836 = 152,152 kWh/day*

$$\text{Daily energy produced/module} = \frac{kW_p \ x \ average \ sunshine \ hour \ x \ ŋ}{80} = \frac{26 \ x \ 7 \ x \ 0.836}{80} = \frac{152{,}152}{80} = 1{,}901.9 \ Wh/day$$

Then, the annual energy produced = kW_p *x average sunshine hour/day x 365 x* ŋ

=26 x *7 x 365 x 0.836 = 56,923.867 kWh*

The solar orientation and inclination correction factor is 1.1

Hence, annual energy output = *56,923.867 x 1. 1 = 62,616.2537kWh*

$$\text{Average power delivered by the solar system} = \frac{\text{annual energy output}}{hours \ of \ sunshine} = \frac{626{,}162.537Wh}{365 \ x \ 7} = 24.50734 \ kW$$

Energy Consumption and Meteorological Data

Energy audit data and Meteorological data were collected from the reference site. The community has an energy consumption of 182,000 Watt hour

This implies that the total energy to be supplied = 182,000 Wh

$$\text{Watt peak} = \frac{\text{Energy to be supplied}}{number \ of \ hours \ of \ sunlight} = \frac{182{,}000 \text{ Wh}}{7} = 26{,}000$$

$$\text{Number of 325 W panels} = \frac{\text{Watt peak}}{Wattage \ of \ a \ solar \ panel} = \frac{26{,}000}{325} = 80$$

System voltage = Voltage of a battery x number of batteries in series = 12 X 10 = 120 V

$$\text{Charge to be stored in the solar system} = \frac{Grand \ total \ energy \ x \ Day(s) \ of \ autonomy}{nomoinal \ \ Voltage} \qquad 18$$

$$\text{Charge to be stored in the solar system} = \frac{182{,}000 \ \ x \ 1}{12} = 15{,}166.667 \text{ Ampere hour (Ah)}$$

$$\text{System Current} = \frac{\text{Total power}}{system \ voltage} = \frac{24{,}507.34}{120} = 204.23 \text{ A}$$

Land Area = Area of one module x number of modules = 1.63 x 80 = 130.4 m^2

200 Ah batteries were used at the reference area

$$\text{Hence, the number of batteries required} = \frac{\text{Charge to be stored in the solar system}}{0.85 \ x \ rating \ of \ a \ battery \ in \ Ah \ x \ depth \ of \ discharge} \qquad 19$$

The depth of discharge is 70%, while 0.85 accounts for battery loss Hence, the number of batteries required = = 127.5, approximately $\frac{15{,}166.667}{85 \ x \ 200 \ x \ 0.7}$ equal to 128 .

Photo Current (I) of the Photovoltaic module

The subsystem module photo current model is presented in Figure 4. The results were obtained and presented in Table 2

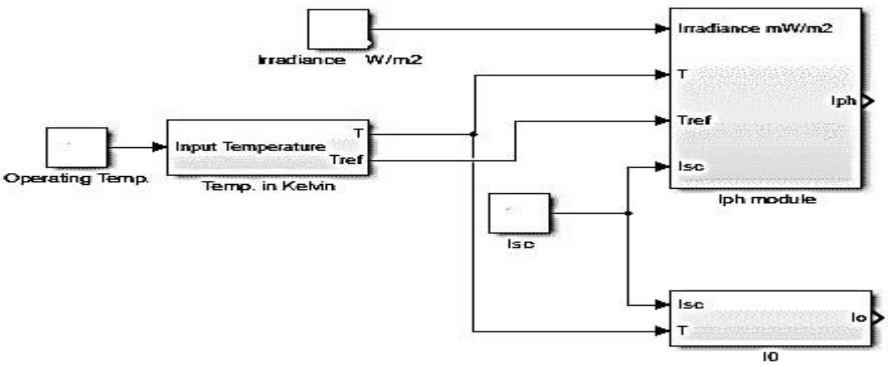

Figure 4: Simulink model of solar photovoltaic Photo Current

Table 2: Subsystem Photo Generated Current under varying temperature and irradiance

S/N	Temperature (ºC)	Irradiance kW/m^2	Photo current (A)
1	25	1	13.1362
2	30	1	12.986
3	40	1	12.6862
4	60	1	12.0862
5	80	1	11.4862
6	100	1	10.8865

The subsystem module reverse saturation current varies with the cell temperature

The Reverse Saturation Current (I_{rs}) for various temperature was obtained and presented in Figure 5 and Table 3

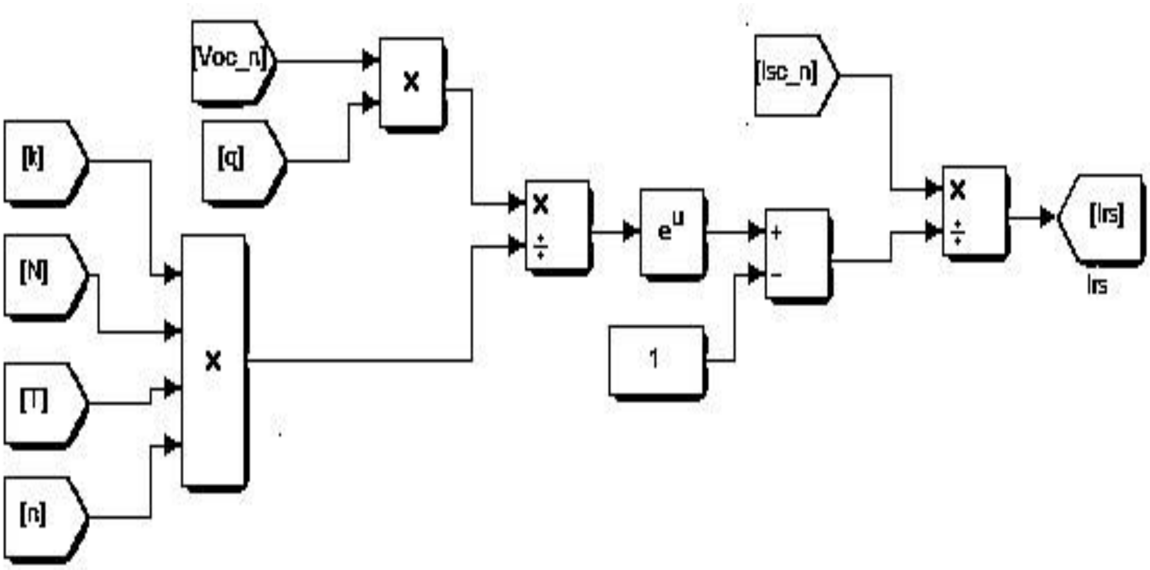

Figure 5: Reverse Saturation Current (I_{rs}) for various temperature

Table 3: Reverse Saturation Current (I_{rs}) for various temperature

S/N	Temperature (^{0}C)	Reverse Saturation Current (A)
1	25	2.3996 x 10^{-6}
2	30	3.1800 x 10^{-5}

3	40	8.0725×10^{-4}
4	60	2.0200×10^{-2}
5	80	1.0379×10^{-1}
6	100	2.7731×10^{-1}

The final output voltage, current and power under varying irradiance and temperature

The final model which produced the output voltage, current and power under varying irradiance and temperature is shown in Figure 6.

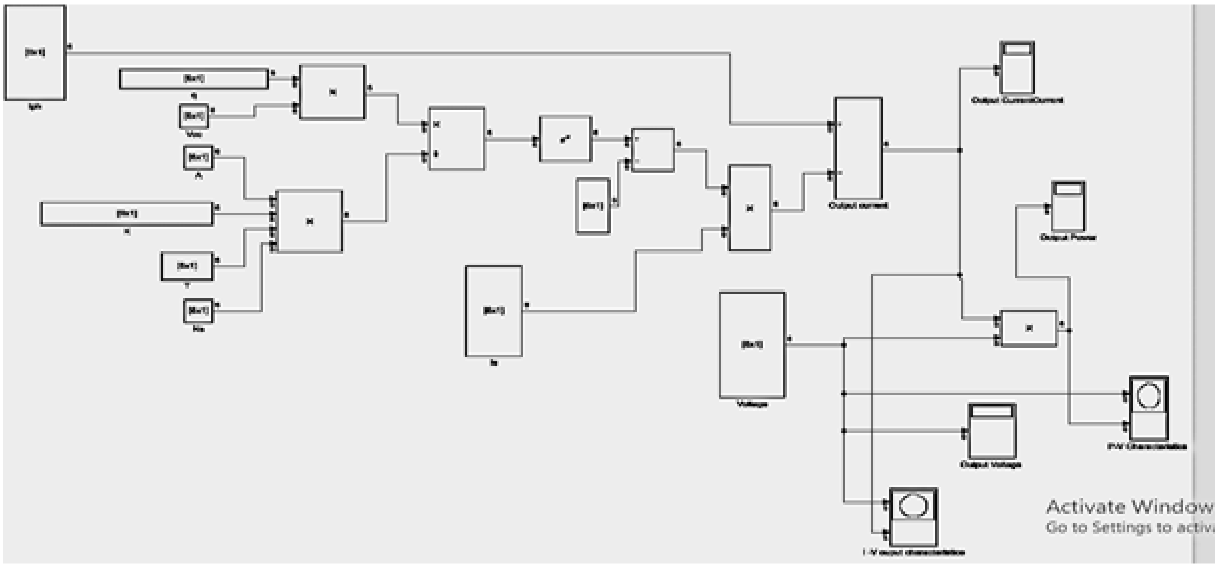

Figure 6: The final model produced the output voltage, current and power under varying irradiance and temperature

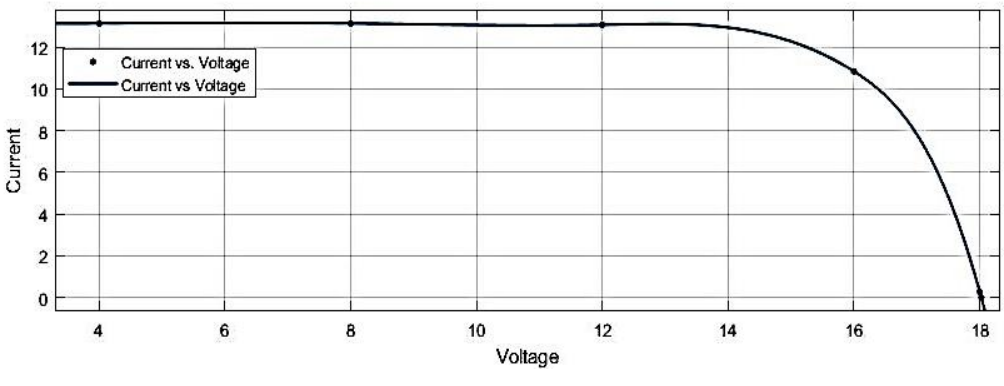

Figure 7: I-V characteristic of the developed Simulink model

The output current was obtained from the final model shown in Figure 6 and the result is presented in Table 4 and Figure 7.

Table 4: Subsystem Output Current under varying temperature and irradiance

S/N	Temperature (°C)	Irradiance kW/m^2	Output current (A)
1	25	1	13.1424
2	30	1	13.1316
3	40	1	13.0612
4	60	1	10.8402
5	80	1	0.2827
6	100	1	0.0031

The Current Voltage characteristic result is presented in Figure 7

The Power - Voltage Characteristics Curve was obtained using Matlab Simulation and the results is presented in Figure 8

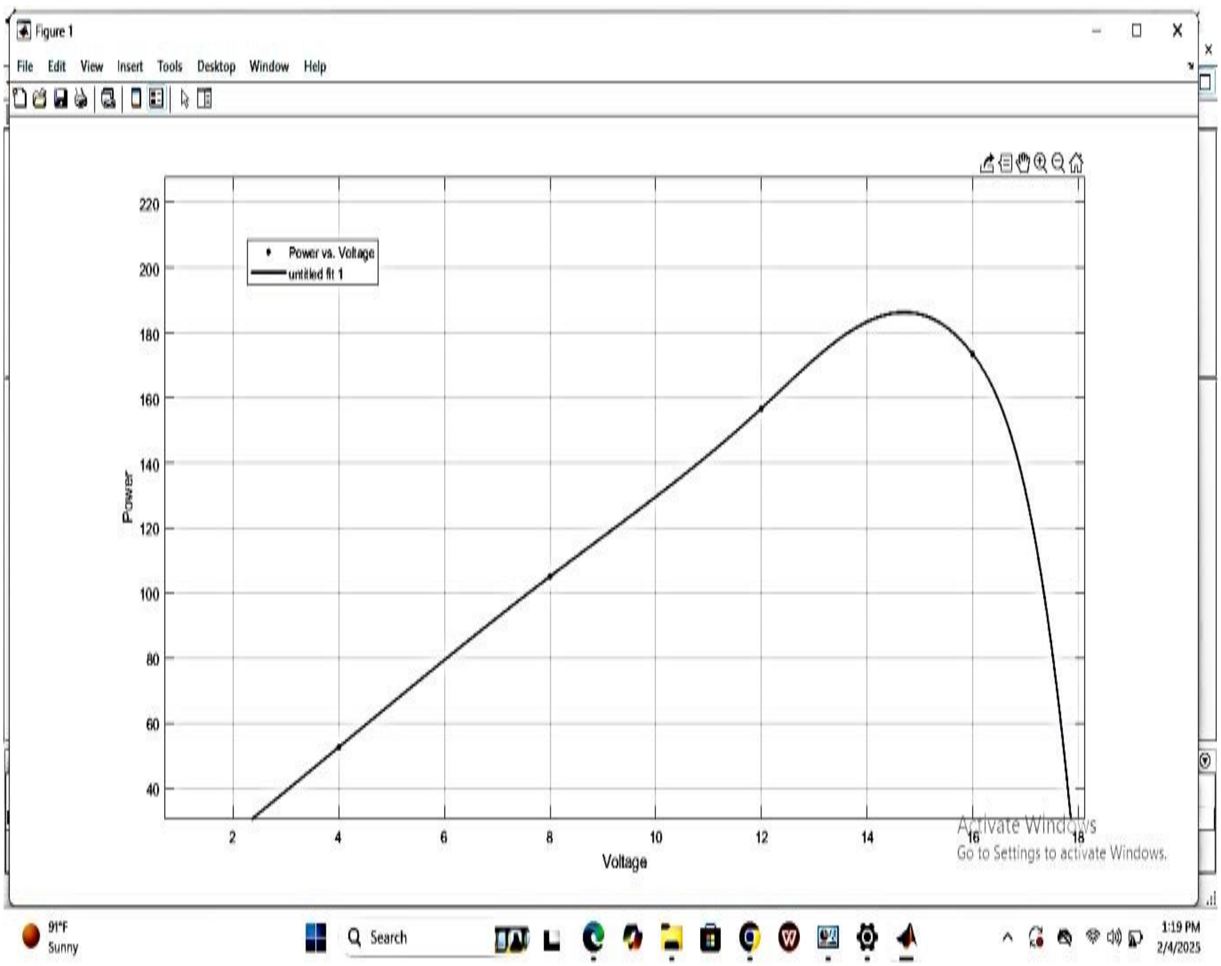

Figure 8: P-V characteristic of the developed Simulink model

The Wind turbine Simulation Model is presented in Figure 3.6. The Simulation results is presented in Table 5 and Figure 9

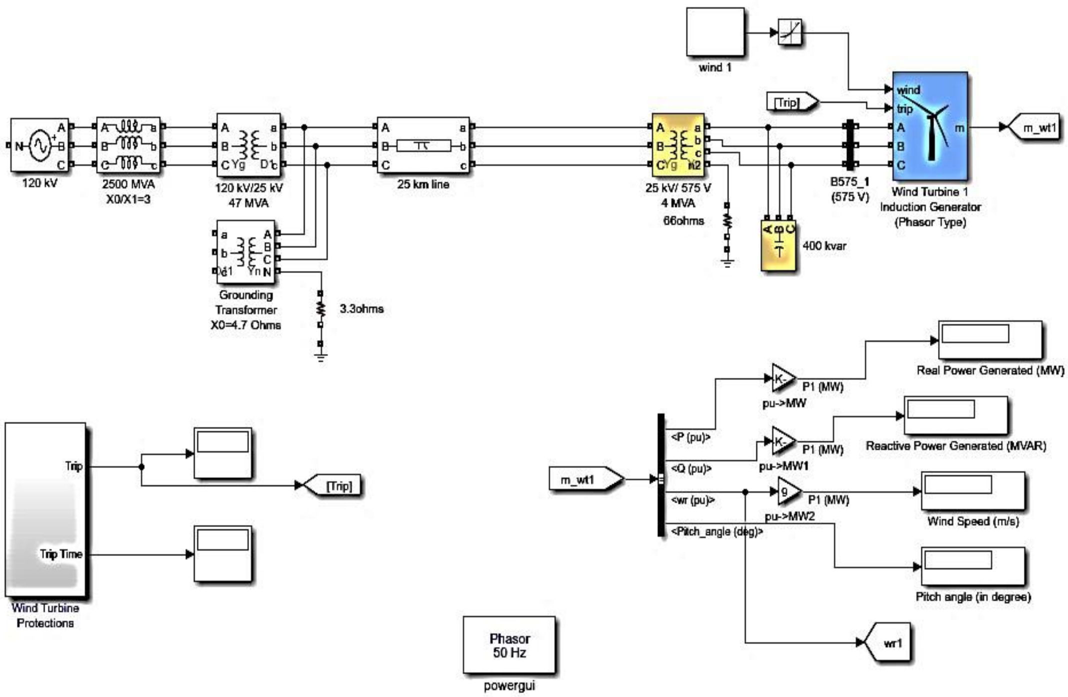

Figure 9: Wind Turbine Generator Simulink Diagram

Table 5: Wind Turbine Generator Optimum Output Power

S/N	Wind Speed	Root Angular Speed (rad/sec)	Power Generated (W)
1	1.9	1.5	0.000
2	2	1.6	0.706
3	2.1	1.7	1.654
4	2.2	1.8	2.883
5	2.4	1.9	4.435
6	2.5	2.0	6.354
7			8.688
8	2.6	2.2	11.480
9	2.7	2.3	14.800
10	2.8	2.4	18.680
11	2.9	2.5	23.190
12	3.0	2.6	18.910
13	3.1	2.7	15.910

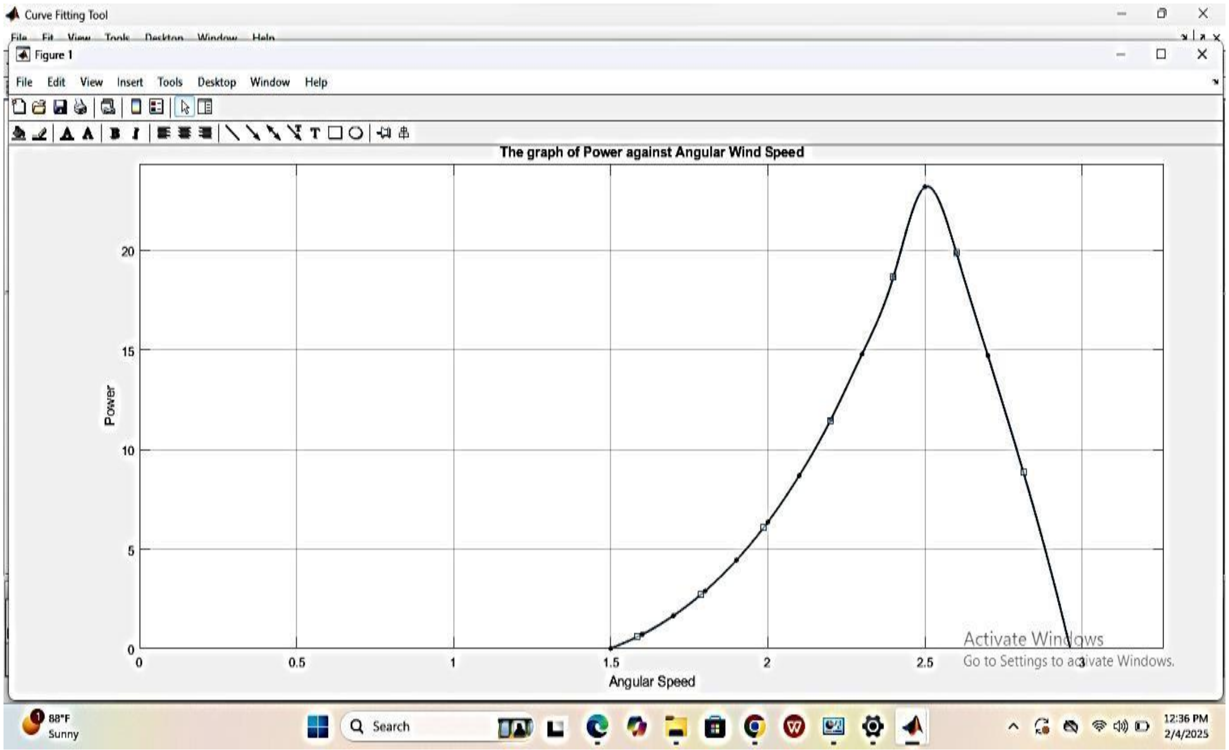

Figure 10: Wind Turbine Generator Simulink Results

From the results above, the speed cut is 1.5 m/s and the wind Turbine Generator reached optimum speed when the wind speed is 2.5 m/s. Finally, the cutout speed is 2.9 m/s. The developed Solar Photovoltaic Simulink models were used to obtain the output characteristics of the photovoltaic system. These include the Current-Voltage (I-V) and Power-Voltage (P-V) characteristics curves from which the optimum power points and the output current characteristics were obtained. From the Simulink model of the Wind Turbine Generator, the Power-Voltage (P-V) characteristic and the optimum wind speed for the Wind Generator were obtained.

CONCLUSION

The results of this study demonstrated the robustness of the hybrid GA-CCPSO method for optimal design of a hybrid power system considering renewable and non-renewable energy sources for rural electrification. The average hourly load demand, solar irradiance and wind speed for Kudedu, Mgbomo and Ikere communities located in Plateau, Enugu and Oyo states, respectively, were (17.29 kw/h; 247.01 $W/m^2/day$; 4.53 ms^{-1}), (17.58 kw/h; 225.81 $W/m^2/day$; 2.55 ms^{-1}) and (17.29 kw/h; 229.53 $W/m^2/day$;2.57 ms^{-1}), respectively. Therefore, it was established that Kudeku in Plateau State has high potential for the establishment of a wind turbine generating plant due to the high speed of wind in the location and solar irradiation is very high in the three locations. Hence, there is substantial availability of solar energy for the establishment and development of the hybrid power system in these locations. This will guarantee the supply of an adequate power supply for the end consumers.

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