American Academic Scientific Research Journal for Engineering, Technology, and Sciences
ISSN (Print) 2313-4410, ISSN (Online) 2313-4402
http://asrjetsjournal.org/

Modelling and Simulation of a Renewable Energy System for Remote Isolated Health Facilities in Uganda using Simulink

Kelechi John Ukagwu[a], David Kibirige[b], Afam Uzorka[c*], Mundu Muhamad Mustafa[d]

[a,b,c,d]*Kampala International University, Kampala, 256, Uganda*
[c]*Email: afamuzorka@gmail.com*

Abstract

Solar PV systems are now widespread across the globe. These systems generate electricity to fulfill the energy demands together with the existing resources as well as power including medical facilities situated in remote areas of Uganda where the main national electricity infrastructure has not been reached. In this paper, an off-grid PV system for rural medical facilities and the emergency situation has been simulated and modelled using the MATLAB Simulink toolbox. Because of the difference in temperature, solar irradiance, PV temperature, shading conditions, ambient temperature, wind speed, and dust, the electrical power generated by a photovoltaic (PV) module and hence the power sent to the load fluctuates, which rises the need to carry out analysis of the entire PV system to obtain peak and maximum power under these variable situations. In this paper, a complete off-grid PV module renewable energy generating system has been designed and simulated using MATLAB/Simulink and performance has been analyzed by subjecting the PV panels to various irradiances starting from 1 KW/m-2 for the Ugandan case. The simulation model consists of a solar PV array, and the battery system, the converter power stage with PWM control, and charge controlling functions and the performance of each block has been studied continuously. Finally, it has been found that this model is quite capable to simulate both the P-V and I-V characteristics of a PV module, and based on the result it has been forecast that the performance of several modules or even PV arrays connected in series and/or in parallel with the delivery of maximum power can be tested under diverse temperature and solar irradiances.

Keywords: Modelling; renewable energy; SIMLINK; health facilities; Uganda.

----

* Corresponding author.

1. Introduction

A Solar off-grid PV system is called so because there is no grid connection available and the PV system work independently [1, 2, 3]. For a rural, remote health facility load an off-grid PV system has components like PV arrays (for generating electrical dc power), battery (if battery backup), Charge control unit (For controlling the input and output charge during systems operations), inverter (for changing DC to AC power) and converter (changing from one dc level to another) [4, 5, 6]. For the entire system design, it is important to do load estimation and then followed individual component selection as per ratings and evaluations.

The problem of the energy predicament is becoming more and more impairing, resulting in increased exploitation, corruption, energy wars, and therefore increase in research and search for new energy resources such as tidal, wind, geothermal, water, solar energy, and biogas around the world today [7, 8, 9]. PV energy is Renewable and consistently replenished energy, which is environmentally friendly and inexhaustible. Due to this natural advantage, photovoltaic solar cells have been massively used to generate electric energy from sunshine irradiance [10, 11, 12].

A solar device, cell, or module and array convert sun energy directly into electrical energy. Energy gotten from a solar PV cell is not constant and consistent at all times. The amount of mined power from a PV system is a function of the PV module current and voltage at a given point in time [13, 14, 15]. Additionally, the energy is affected by external conditions like solar irradiance, wind speed, ambient temperature, and dust. During uniform solar irradiance levels with no partial shading, the nonlinear current-voltage (I-V) characteristics of a, PV solar module will have a single ideal operating point matching a unique maximum power point (MPP) on its power-voltage (P-V) curve. In practice, since a solar module is comprised of various solar cells which are connected with each other in parallel and in series, if some cells are on the irradiance or temperature variation the P-V characteristics of solar modules becomes very complex as many maximum power points occur on the P-V characteristic curves [16, 17, 18]. Due to the complicated behavior of a PV solar module under various illumination conditions, it is important to construct a simulation model to systematically investigate the voltage, current, and power relationship of a PV module under fluctuating surrounding circumstances.

2. Modeling of a PV Module-Based Power System

A PV cell is a simple PN junction that is fabricated in a layer of semiconductor material. When it is illuminated by the sunlight of photons with an energy equal to or slightly greater than the band gap energy of semiconductor material, it is absorbed and the valence electrons are knocked out from the atoms in the material and create electron-hole pairs [19, 20]. These photo-generated carriers are swept apart by the internal electric fields of this cell and if the cell is connected by an external circuit, they contribute to current.

2.1. Load Estimation

In a health facility, the following appliances are common and table 1 shows appliances with their rating and load estimations.

Table 1: Load estimations.

LOAD	WATTS	QUANTITY	HOUR /DAY	TOTAL WATTS	TOTAL WATTS-HOUR/DAY
PORTABLE REFRIGERATED CENTRIFUGE	150	1	6	150	900
Portable STERILIZER	20	4	10	80	800
PORTABLE ULTRASOUND SCAN/PORTABLE X-RAY MACHINE	500	1	12	500	6000
THEATRE LIGHTS	40	3	8	120	720
COMPUTER	150	1	2	150	300
TOTAL				960≅ 1000	8720≅ 8800

So a health facility load is = 1 kW or 8800 Wh/day.

For a 1 kW load following PV components are required as shown in table 2.

Table 2: PV Components and their ratings.

COMPONENT	DESCRIPTION	RESULT
Load	Estimated	0.8 kW
PV array	Size	1 kW
	Total panels	2
	In series	2
	In parallel	1
	Panel power	295 Wp
Charge controller	Capacity	52
	Number of controllers	3
Inverter	Size	2 kVA

The PV panel or module has the following specifications as shown in table 3.

Table 3: PV module specifications.

Parameter	Value
Peak power	295 watts
Module Efficiency	14.7%
Peak power voltage	36.51 volts
Peak power current	8.08 amps
Open circuit voltage	44.78 volts
Short circuit current	8.30 amps
Number of cells	72 cells
Max. System voltage	1000 volts DC

The block diagram of the system is shown in figure 1.

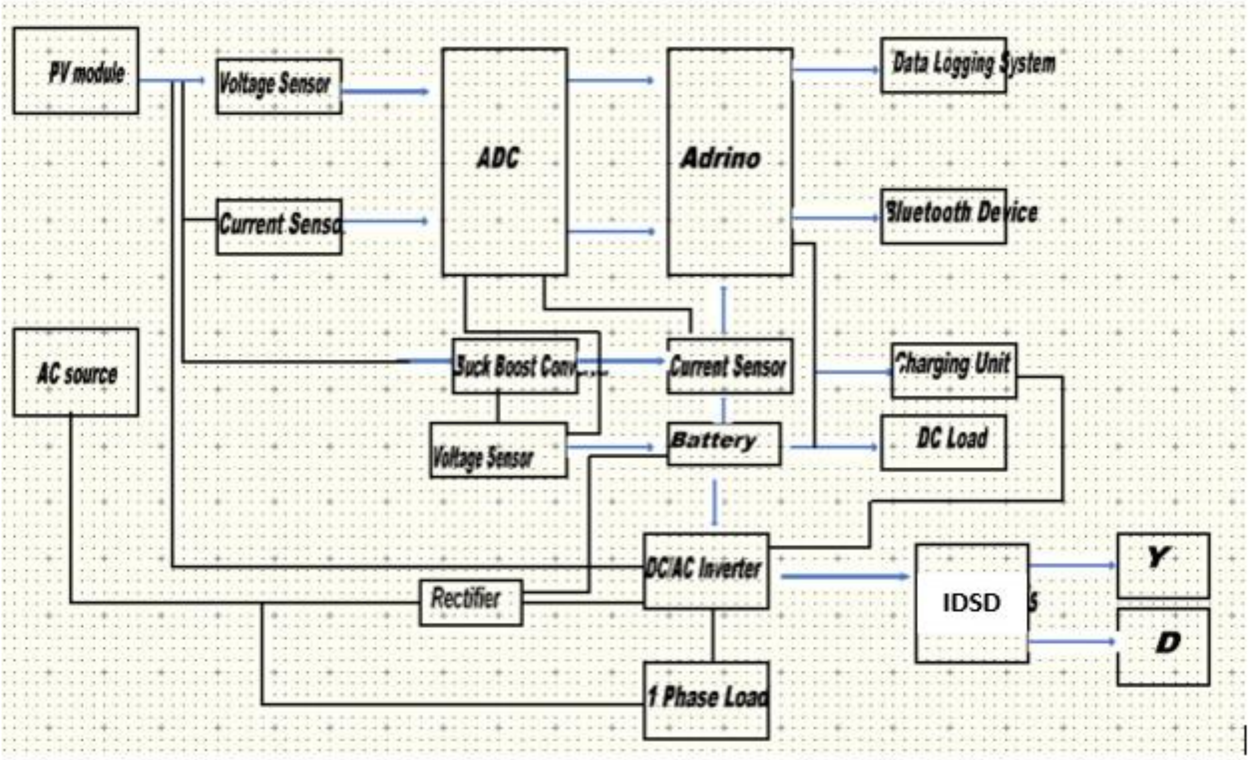

Figure 1: Block Diagram of the system.

NOTE: The entire systems design has four main components namely.

1. PV module. This is responsible for the generation of energy using radiation and solar irradiances. The system has 2 solar panels of a monocrystalline type.
2. Buck-boost converter. The main role of this component is to change power from one level to another by specifically increasing it.
3. Battery. this is responsible for storing the charge and presenting it for use if the sun cannot give enough irradiancies, the system has two batteries each has 50ampere Hours and 12volts
4. Inverter. This is capable of changing dc power to ac power to use by the ac loads, the inverter is of a bridge connection single phase. This is capable of giving 1000 w or 1 kw at the output. The single-phase inverter is connected to (IDSD) which is Inverter Driver System with a Display whose main role is to convert single face to three phase power.

2.2. PV Array Modeling

PV array in MATLAB Simulink is a mathematical model which uses the equations of the equivalent circuit model of the solar cells. This PV array configures according to the requirements of the model. Figure 2 shows a PV array:

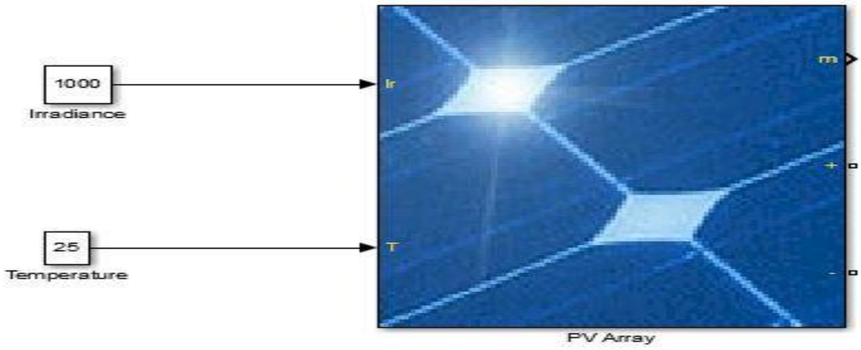

Figure 2: PV array subsystem.

2.3. Buck-Boost Converter Modeling

A buck converter with a fixed duty cycle is modeled to give constant output DC of 48 V. The circuit and Simulink model of the buck converter is shown in figures 3 and 4.

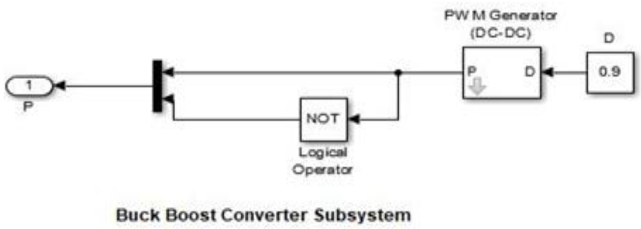

Figure 3: Buck converter subsystem.

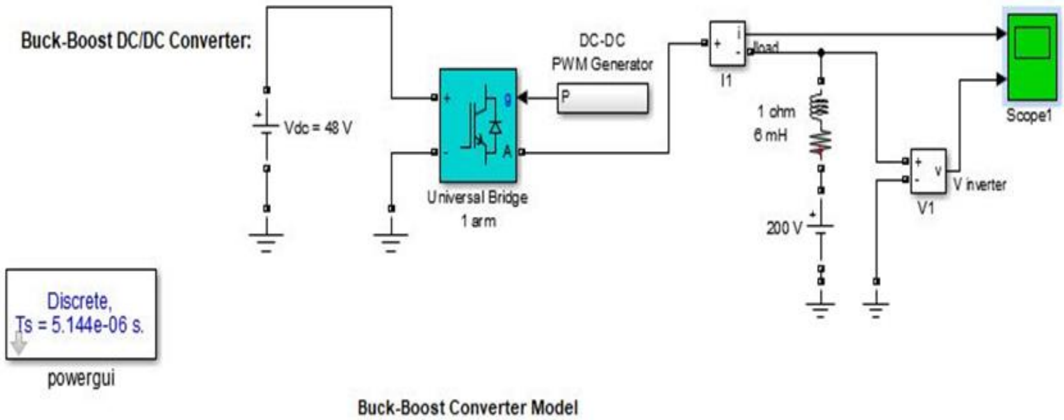

Figure 4: Buck converter model.

NOTE: Here values of inductor (L), capacitor (c), duty cycle (D) and PWM switching frequency (F_s) are:

$L > 0.0056\,H$ $C = 1.56e^{-7}f$

D = 0.42 and $F_s = 10000\,H_z$

2.4. Inverter Modeling

Here all the appliances need AC power for their working so the inverter is necessary for the system which gives AC output with desired level (120 V/230 V). The Inverter in this model is built by using the PWM technique. Sine wave and a triangular wave is compared to generate PWM which is used to switch on/off semiconductor switches and DC input is converted into AC [21, 22, 23]. A transformer for the step-up of converted AC is used to get desired AC voltage level (230 V here). Figures 5, 6, and 7 show the inverter model in MATLAB.

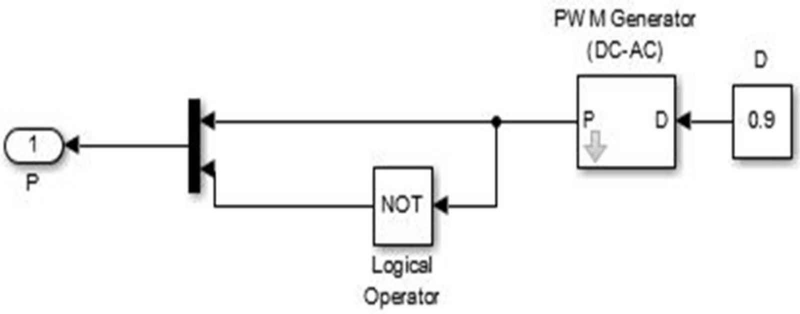

Figure 5: Inverter subsystem.

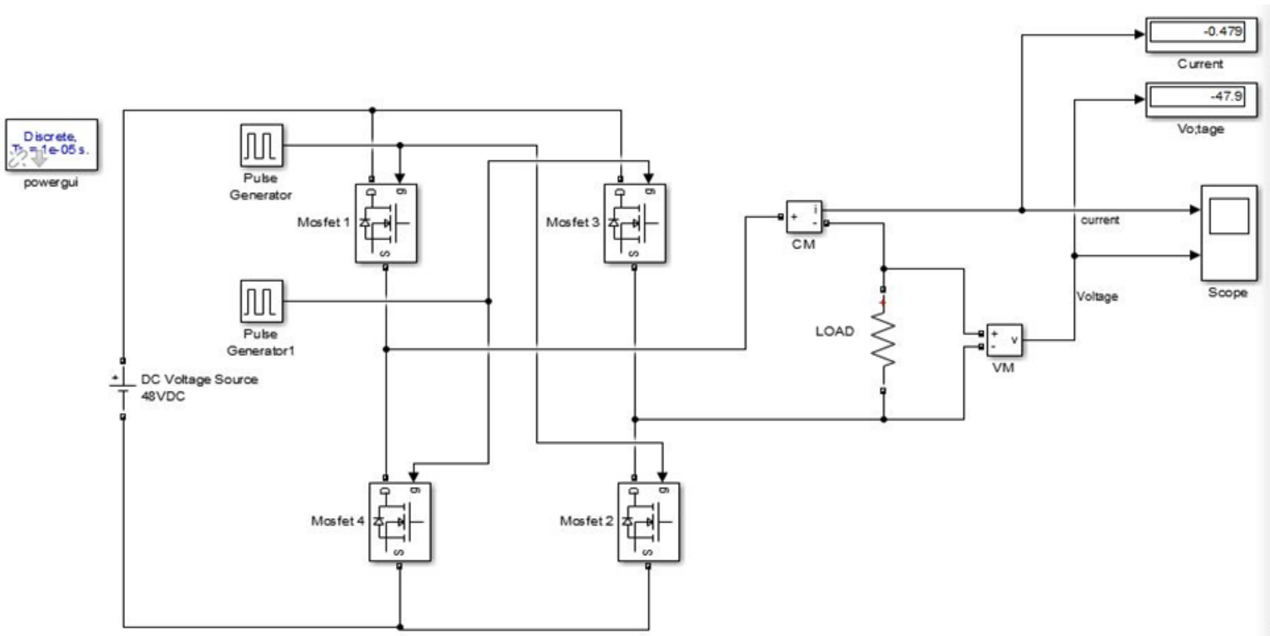

Figure 6: Inverter model.

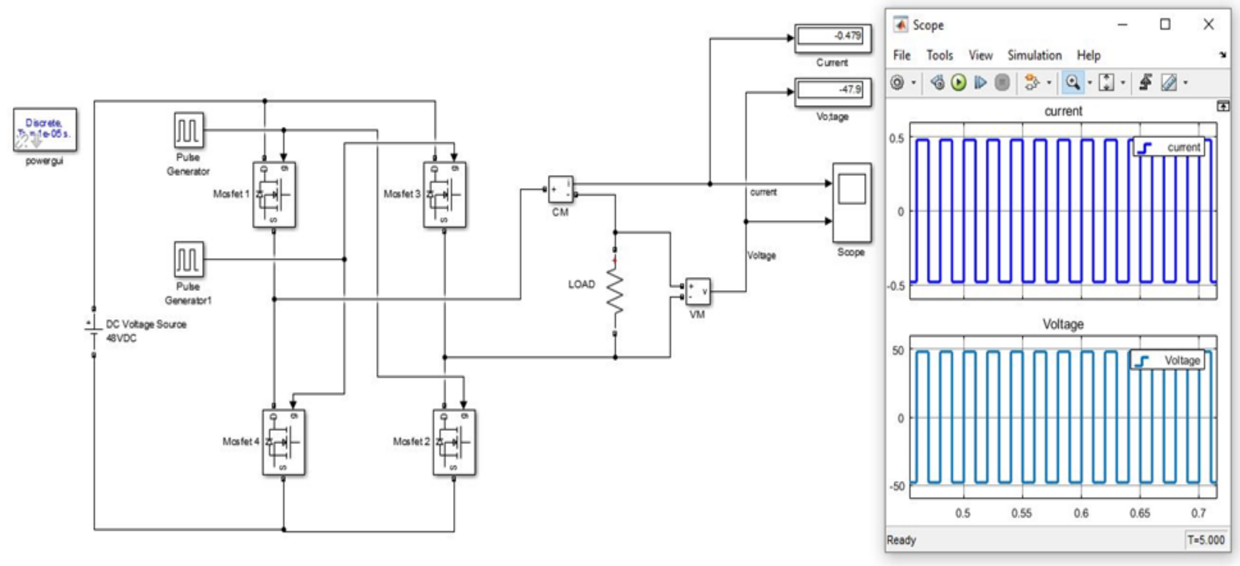

Figure 7: Inverter simulation.

NOTE: The circuit above shows the single-phase bridge inverter powered by two pulse PWM generators, one for current and the for voltage after powering in the discrete mode they produced the discrete waveforms for current and voltatge respectively.The graphs were obtained before connecting the inverter circuit in the main circuit.

2.5. Battery Modeling

Battery specifications are shown in figure 8 below.

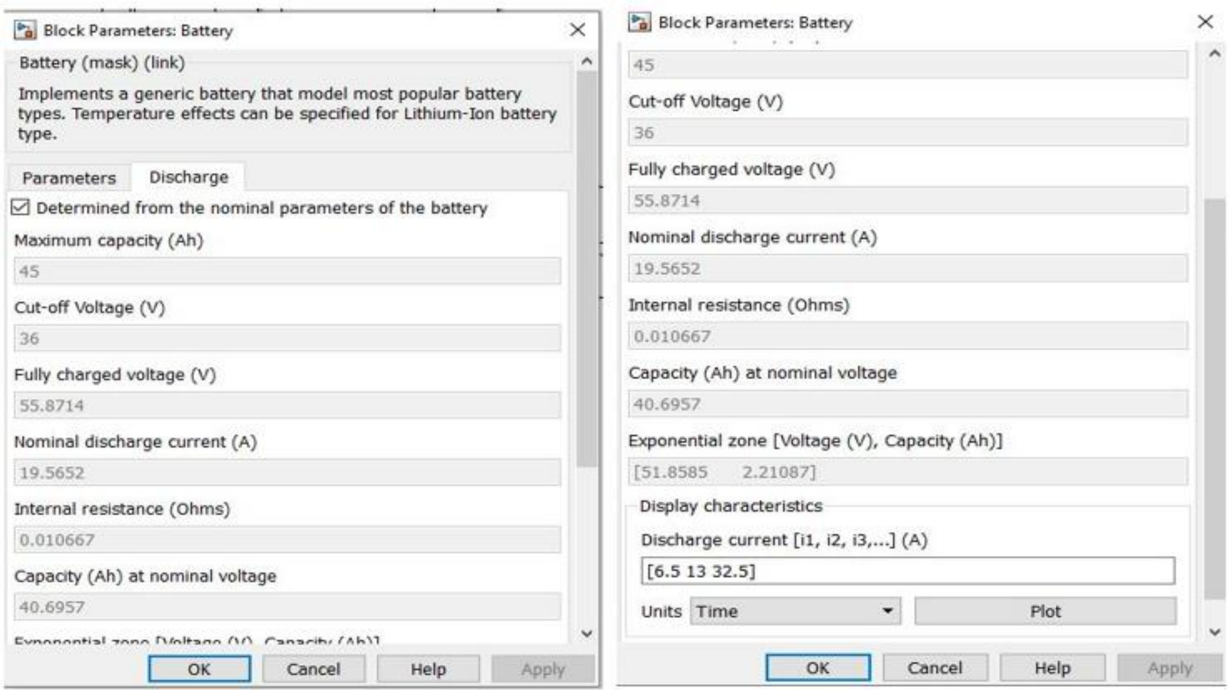

Figure 8: Battery modeling dialogue box.

This clearly shows the parameters and specifications of the system's design. The battery model is shown in figure 9.

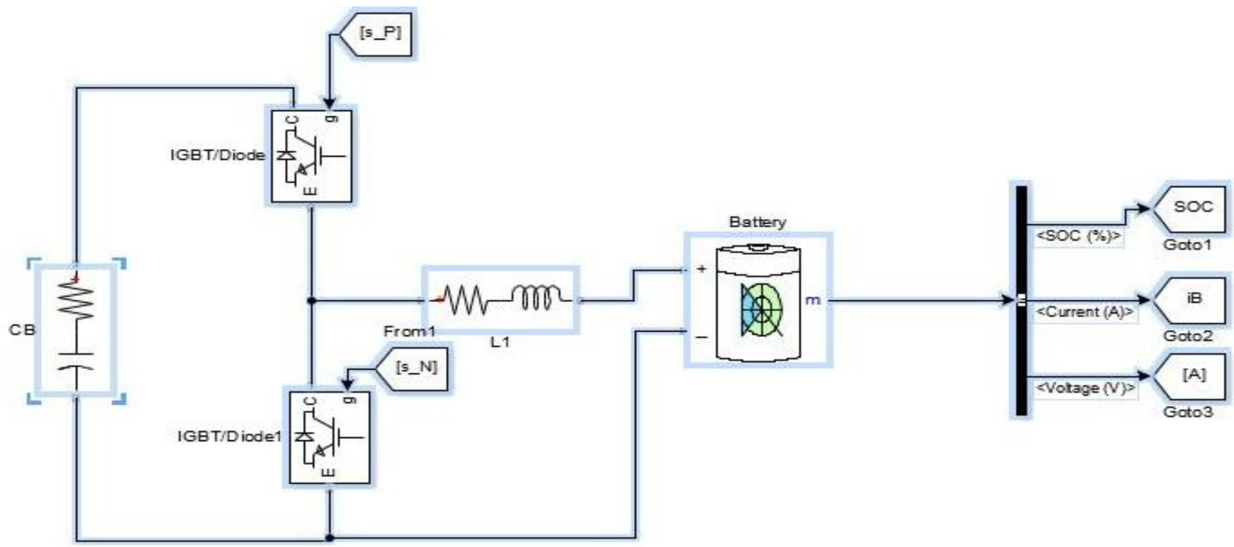

Figure 9: Battery Model.

The battery is used to store charge but the charge must be controlled that's why it has diodes, capacitors, inductors, and resistors, these will also help to filter out ac signals and further boost the charge for storage.

2.6. PID controller selection and scoping

PID controller selection and scoping are shown in figures 10 and 11 respectively.

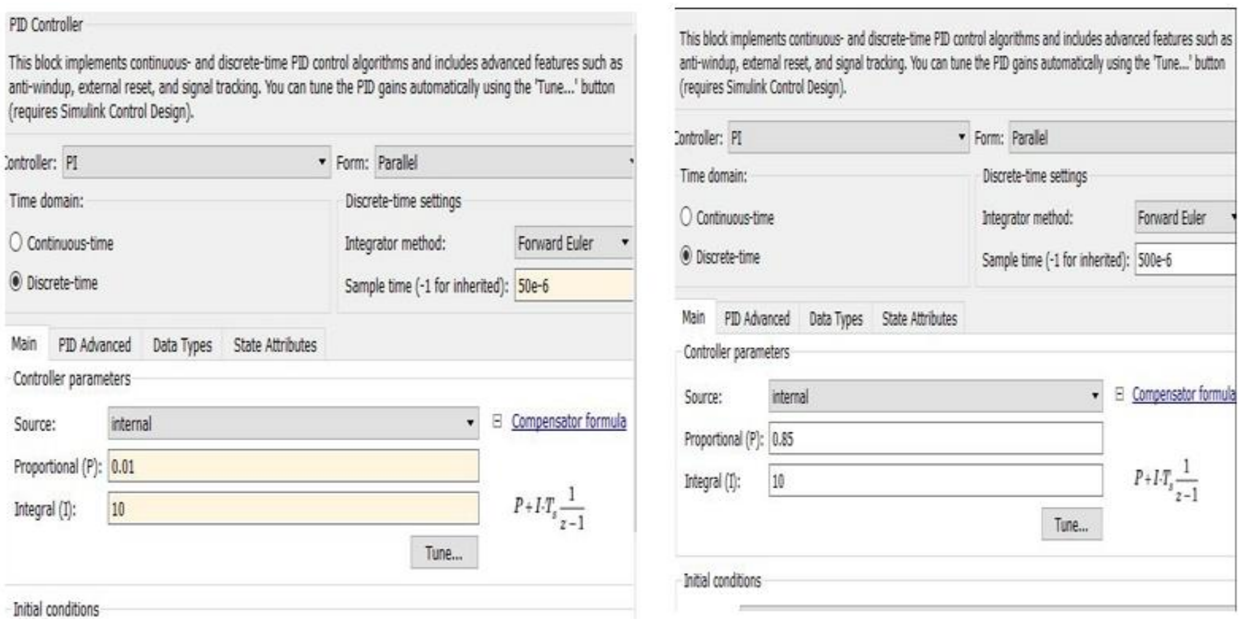

Figure 10: PID controller selection using MATLAB.

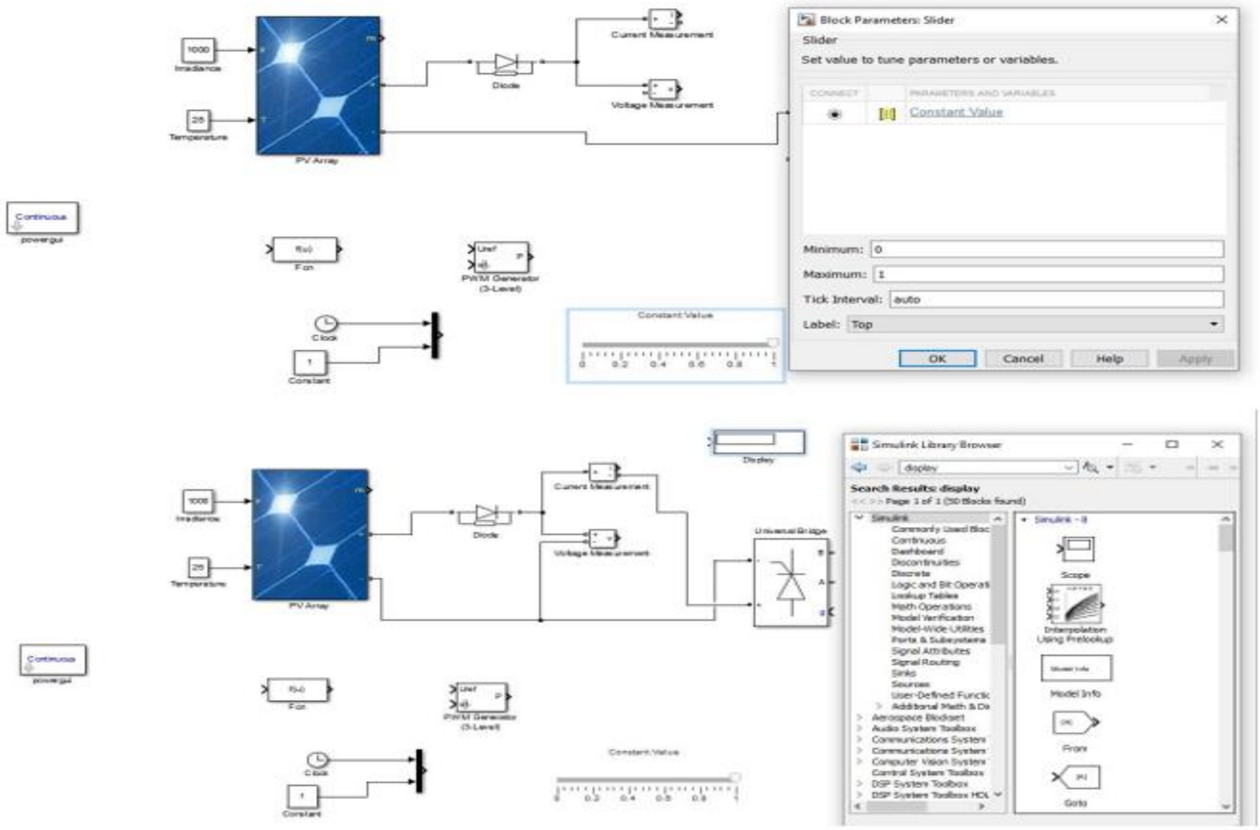

Figure 11: System's scoping and scaling.

3. off-Grid PV System Model with No Load

The models of the PV array, Buck converter, and Inverter is connected to make an off-grid PV system model. Figures 12, 13, and 14 show the PV system in MATLAB Simulink without load.

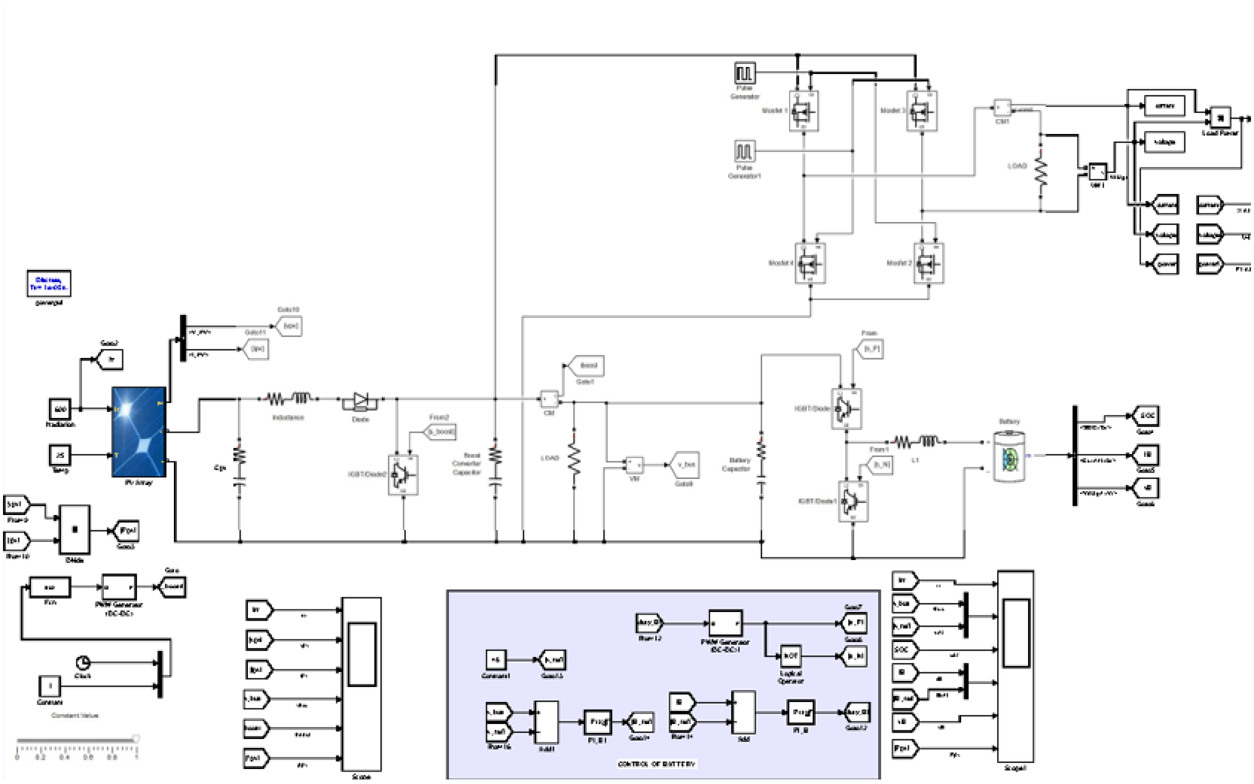

Figure 12: PV system Simulink model without load.

At no load and standard operating conditions (1 kW/m^2 irradiance and 25^o C operating temperature), the following results are obtained as shown in figure 13.

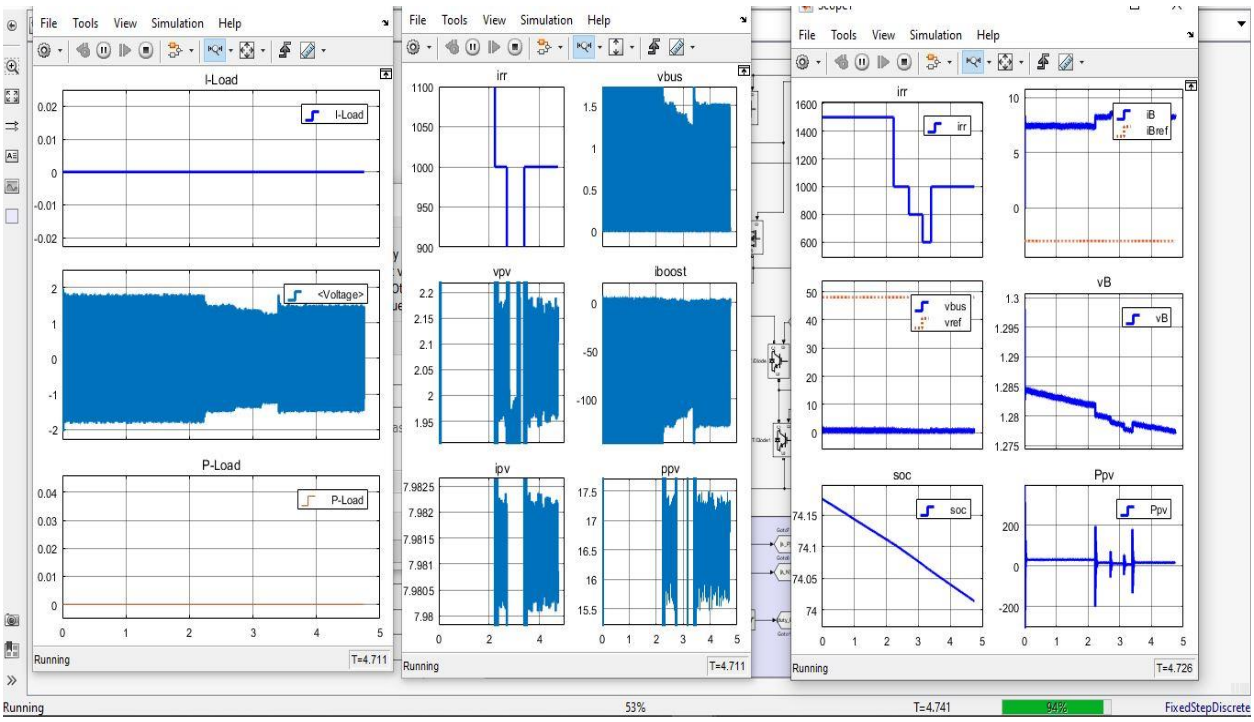

Figure 13: System Simulation on No Load.

On no load the graphs show the following the load current curve is zero, the load voltage curve shows increased voltage and low power, the battery voltage is low, and the state of battery charge is in a decreasing mode together with the boost voltage as the irradiance varies within the limits.

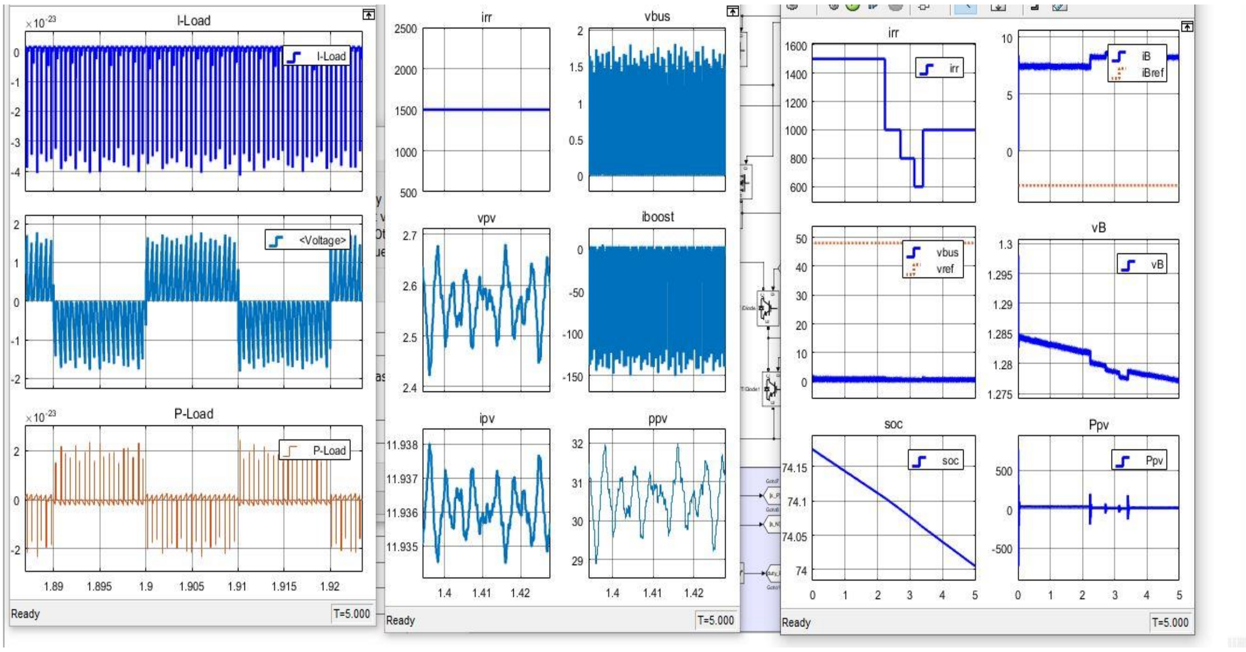

Figure 14: System Simulation on No Load Zoomed in.

After zooming this is how the various curves look like from the MATLAB tool of Simulink

4. off-Grid PV System with Load

Now the model is connected to a 1 kW load which is estimated. Figures 15 to 20 show the model with load and results obtained from the simulation. These results are taken at standard operating conditions (1 kW/m^2 Irradiance and $25^o\,C$ operating temperature of array).

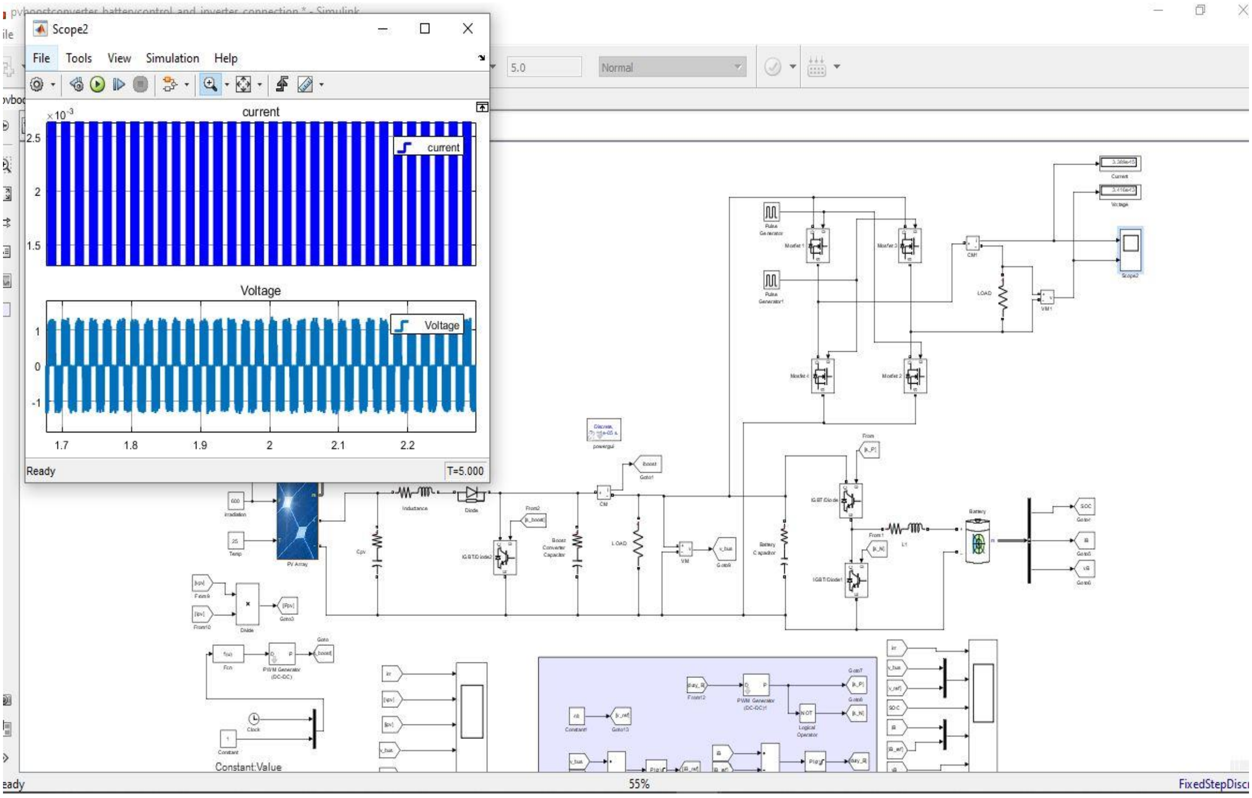

Figure 15: Inverter integration in the Circuit simulation.

Integrating the inverter into the entire system design means powering it with the PV array, battery, and converter. This produced a compressed waveform of voltage and current sinusoidal in nature.

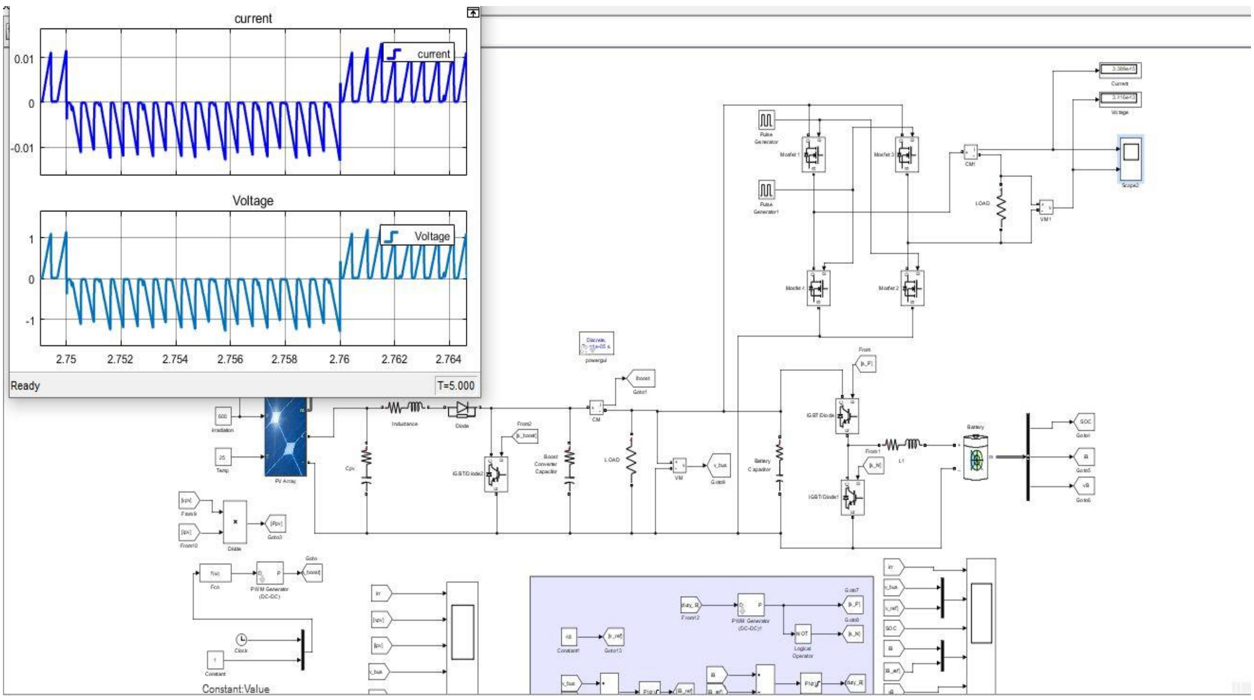

Figure 16: Inverter Simulation after zooming in.

After zooming in the waveforms for current and voltage became more visible and clearer which further makes it clear to determine the various characteristics of these waveforms.

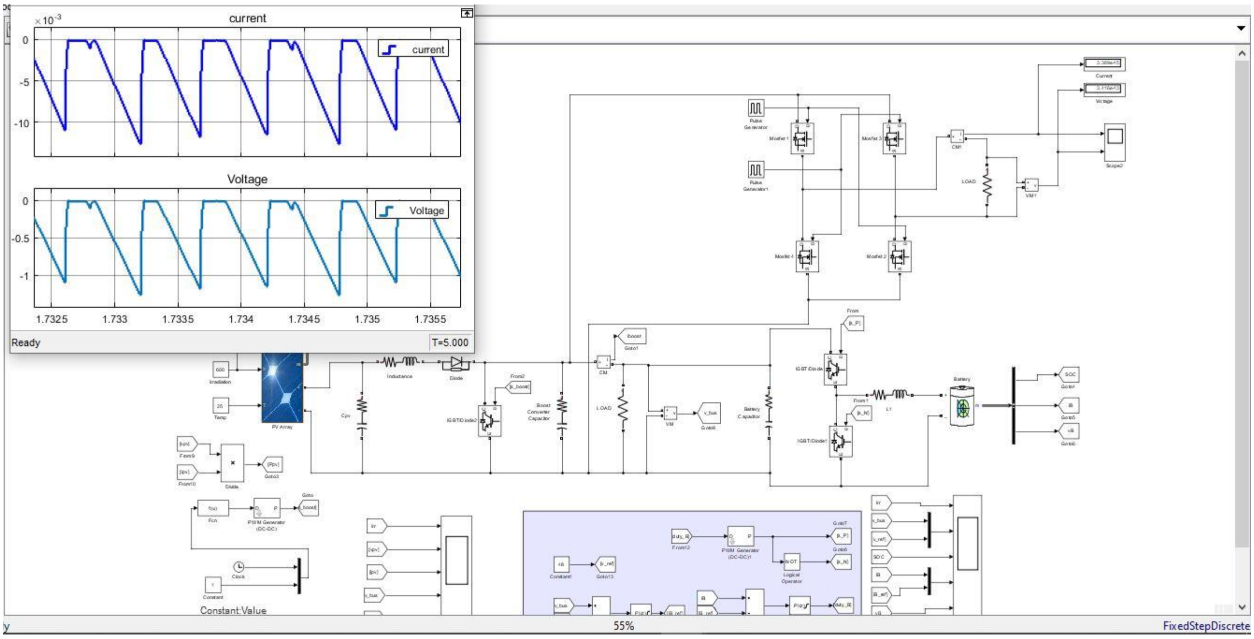

Figure 17: Inverter simulation after the change of inputs.

After changing the inputs, the MATLAB tool gave sawtooth waveforms for both currents and voltage.

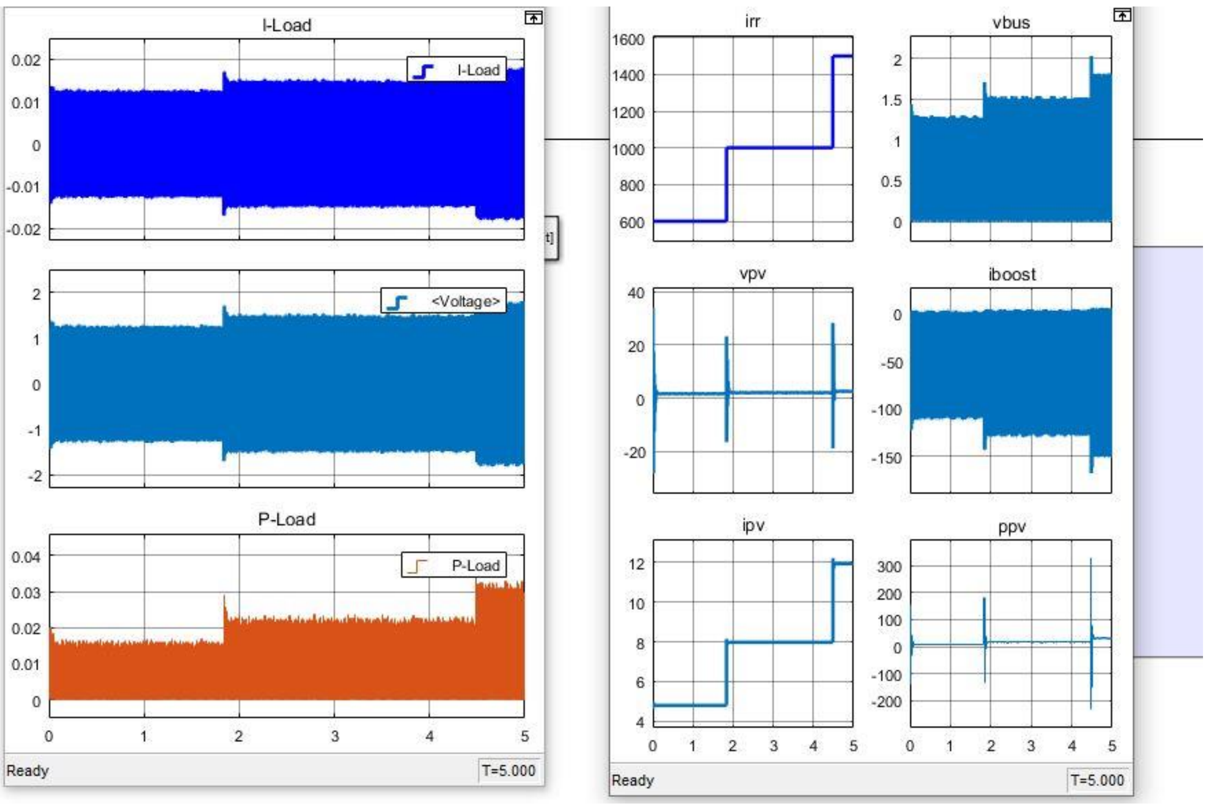

Figure 18: Increased Irradiation and Checked Inverter.

Simulating the system on load it showed a steady and constant current, voltage, and power, this resulted from a steady change in the irradiance at a fixed time constant.

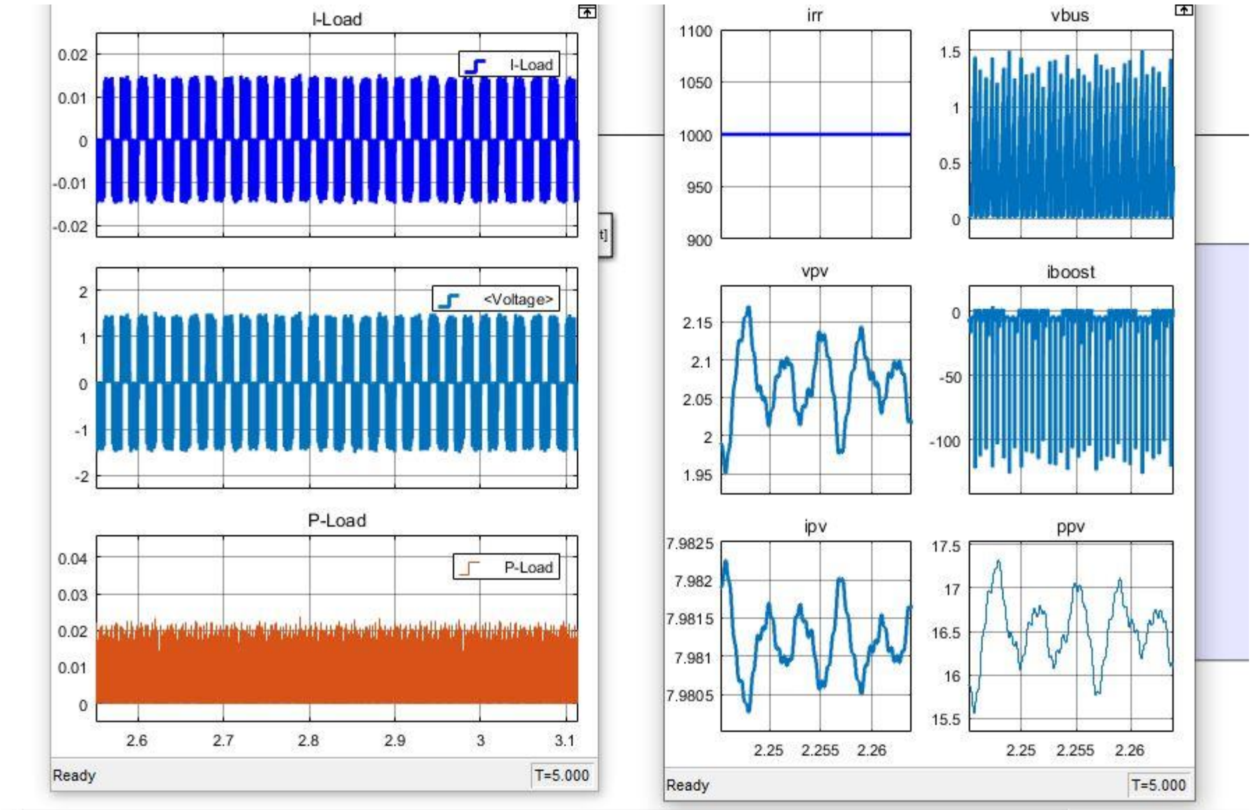

Figure 19: Increased Irradiation and Checked Inverter then zoomed in.

After zooming in the waveforms of current, voltage and power became distinguishable as they clearly showed the amplitudes or speakers and troughs as some of the features are exhibited by sinusoidal waves.

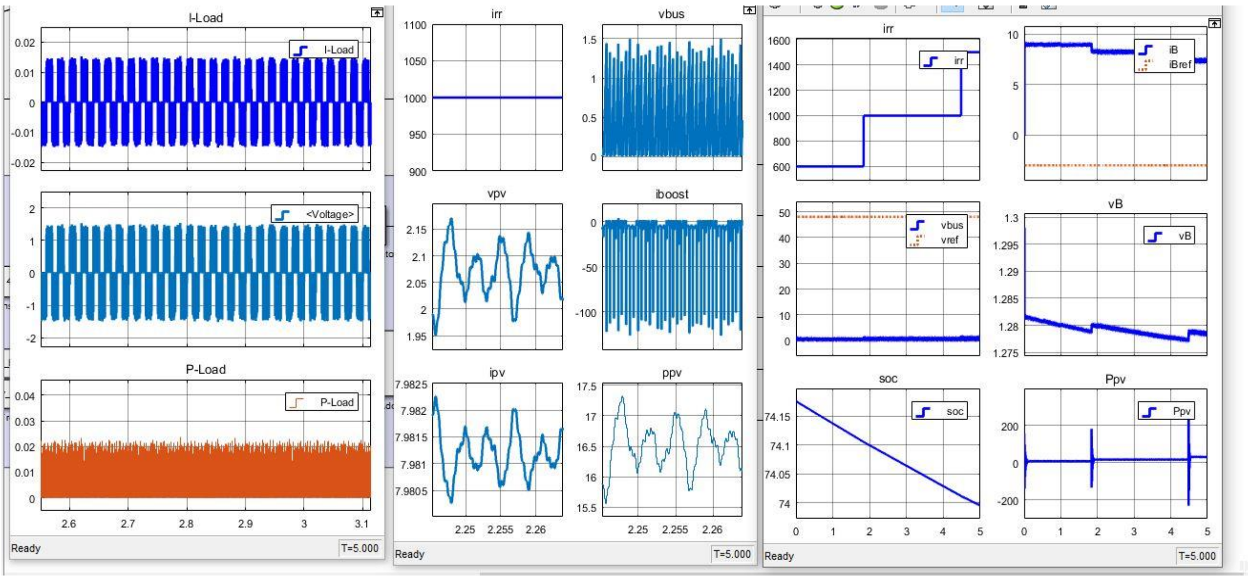

Figure 20: 3 Scope together the inverter PV battery.

5. System Function Inputs

This shows how all the input functions or equations are generated and fed into the software MATLAB/Simulink using continuous or discrete modes. This is illustrated in figure 21.

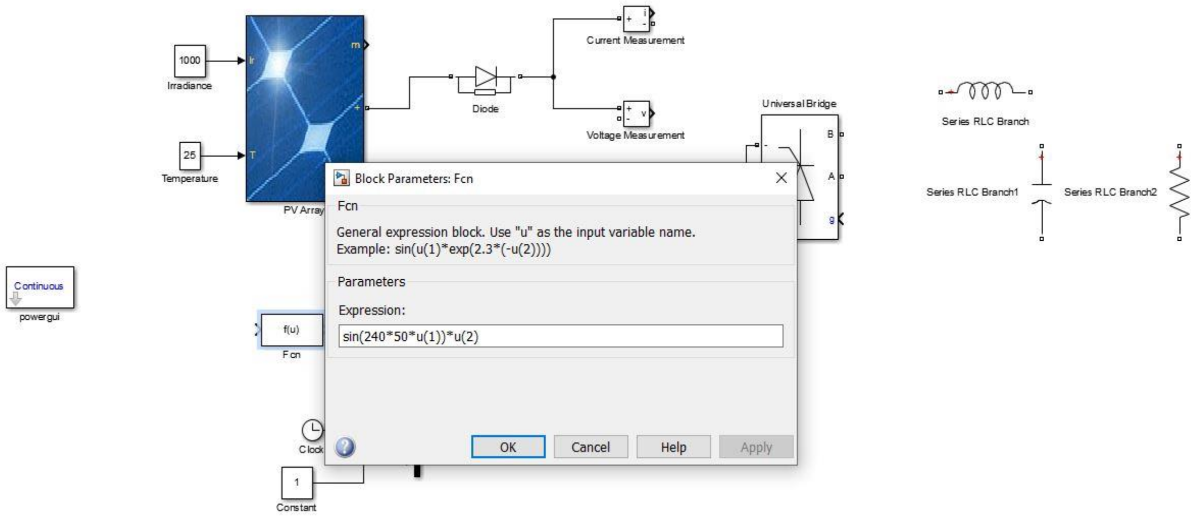

Figure 21: System's block parameters.

6. System Integration

Here the proposed renewable energy systems are modelled according to various part and components that make up this system, for example, the system comprises of the inputs with parameters such as temperature, irradiancies, and the outputs consists of power, voltage and current. Other key components include the PV array, converter, inverter, battery, and their controls plus monitors together forming the charge control unit of the system as shown in figure 22.

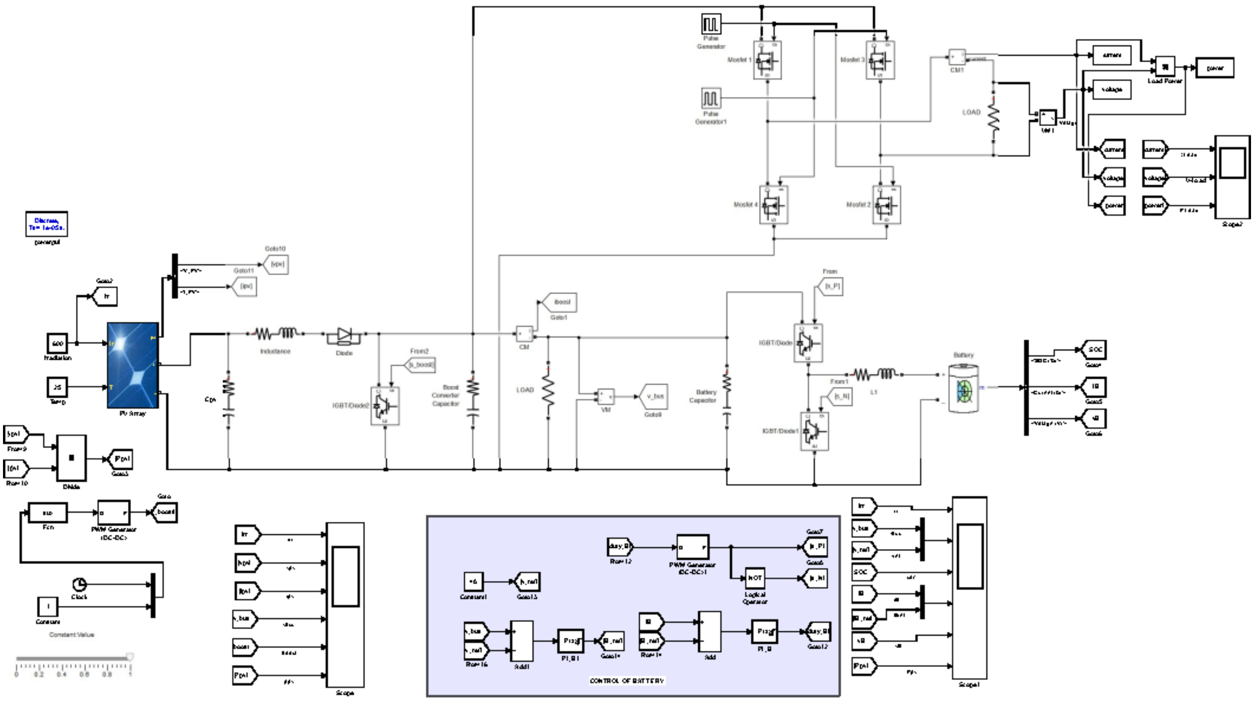

Figure 22: Entire system's integration on Load.

Figure 22 shows how the individual components were assembled and simulated to come up with this whole design. The PV, Converter, and Battery Integration are shown in figure 23.

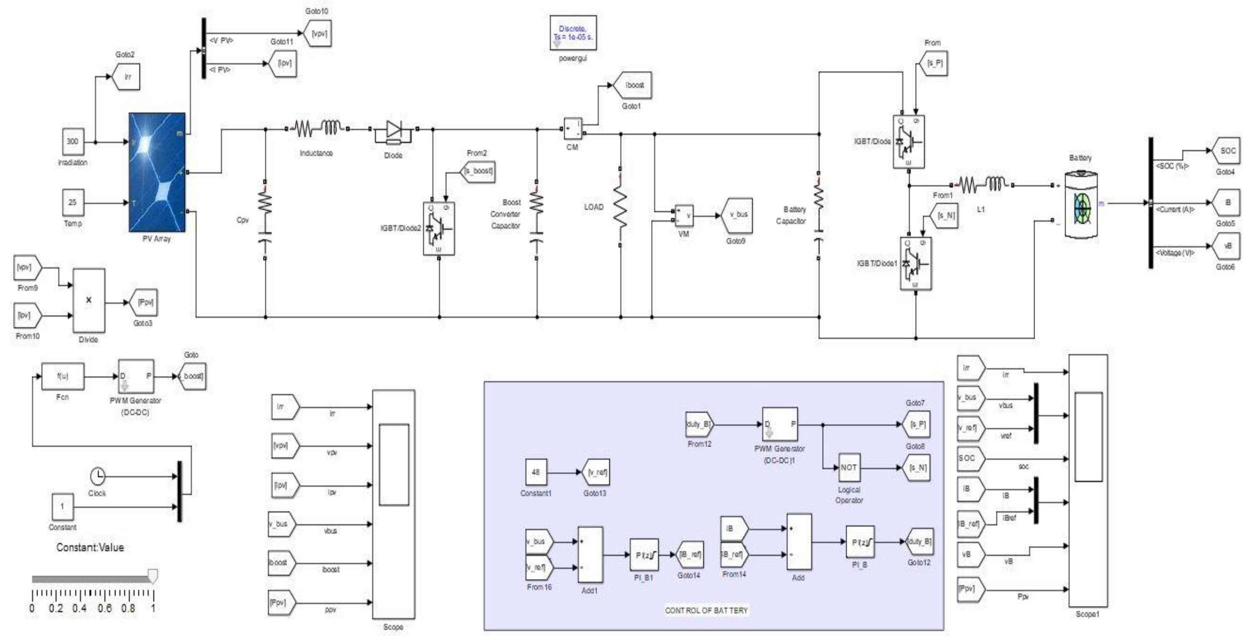

Figure 23: The PV, Converter, and Battery Integration.

7. Input Characteristic Curves of the System

I-V and P-V curves after simulation at different irradiancies input characteristics are shown in figure 24.

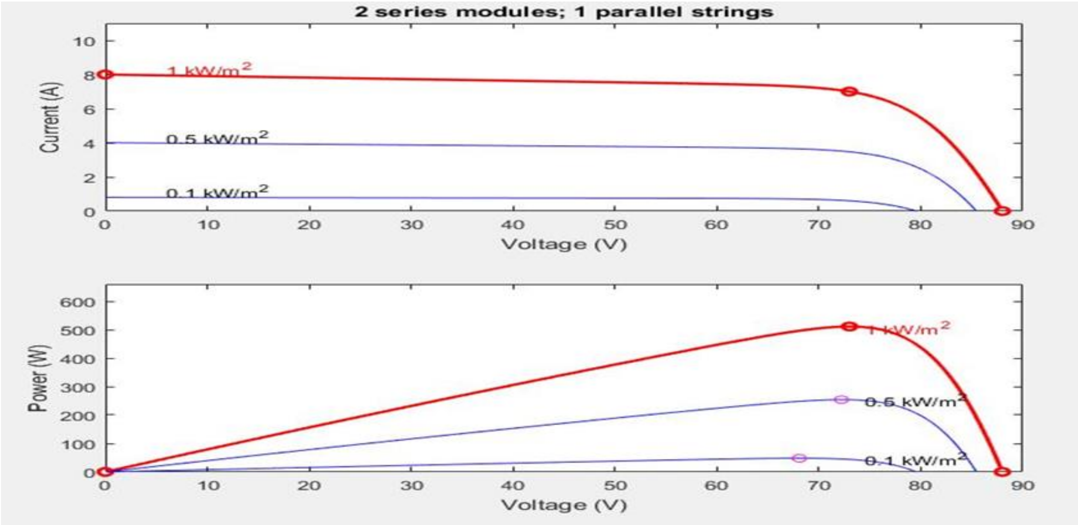

Figure 24: I-V and P-V curves after simulation at different irradiancies input Characteristics.

The graphs above shows that increase in irradiance increase short-circuit current as well as open-circuit voltage. Again this further shows that increase in irradiance increases the overall power output. Furthermore irradiance affects the power output in such a way that when the sunlight reduced this resulted in a reduction in current hence a reduction in the power output as well.

The graphs show increasing the irradiance increase the voltage together with current and power.

I-V and P-V curves at different temperatures are shown in figure 25.

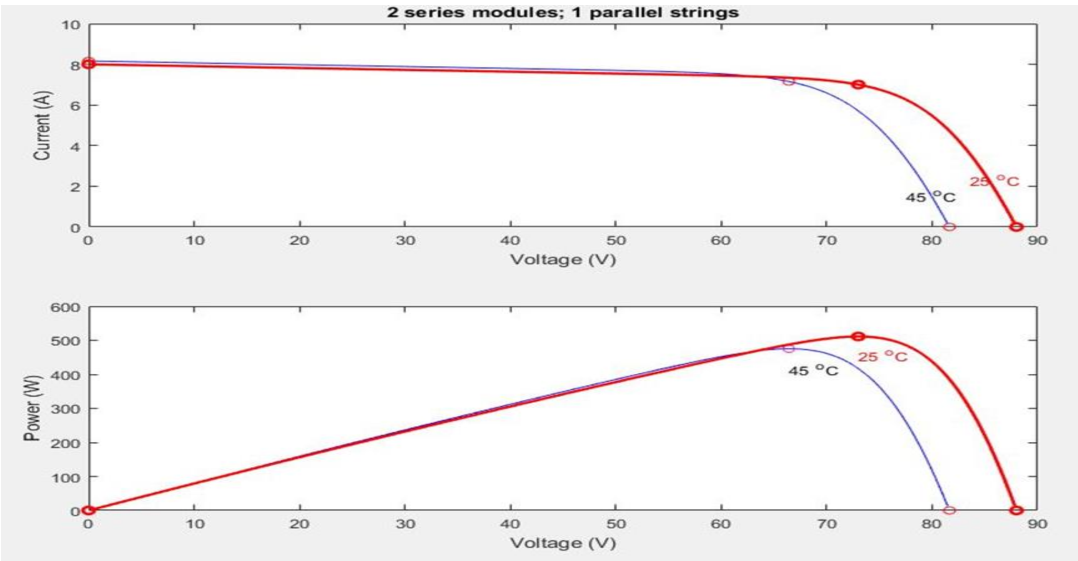

Figure 25: I-V and P-V curves at different temperatures.

The current-voltage characteristic curve shows that the higher the temperature the lower the open circuit voltage and the higher the short circuit current. The graph, further shows that the increase in temperature will reduce the power and the power will increase as temperatures decrease this is so because temperature generates heat that in general leads to the reduction of the overall efficiency of the system. It should be noted that as the temperature of the solar cells increases the output voltage is reduced linearly and the output current increases exponentially.

8. Input and Output Waveform

The input and output waveforms are shown in figures 26, 27, and 28.

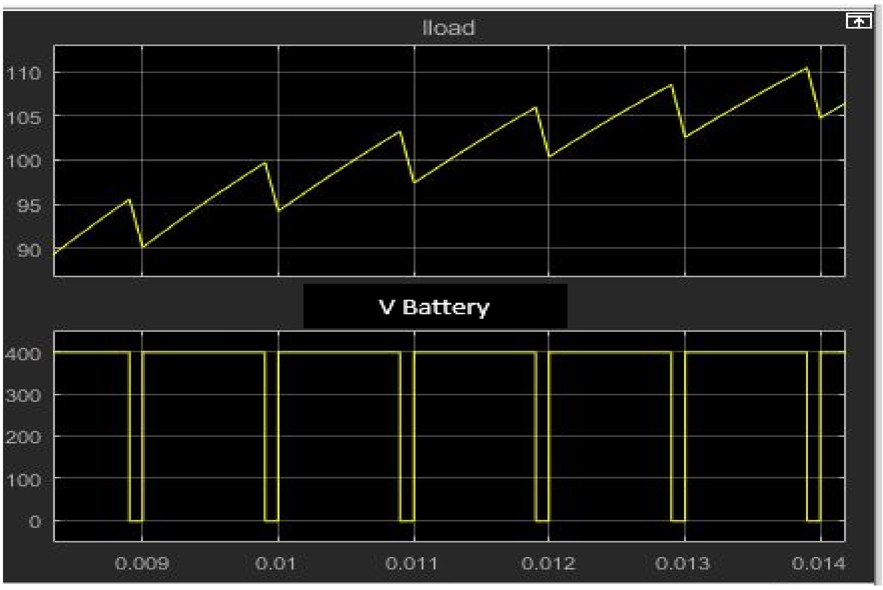

Figure 26: Battery Input and Output.

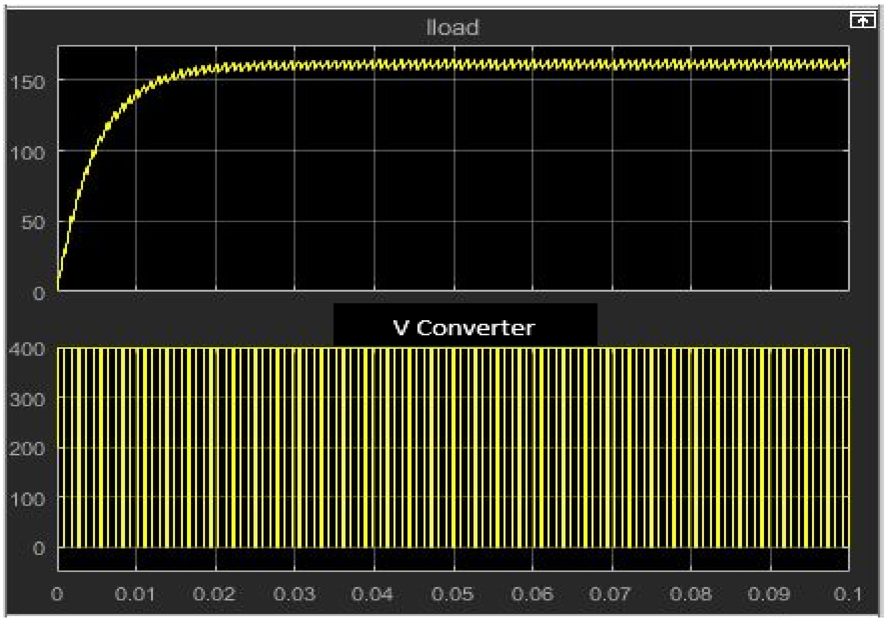

Figure 27: Converter Input and Output.

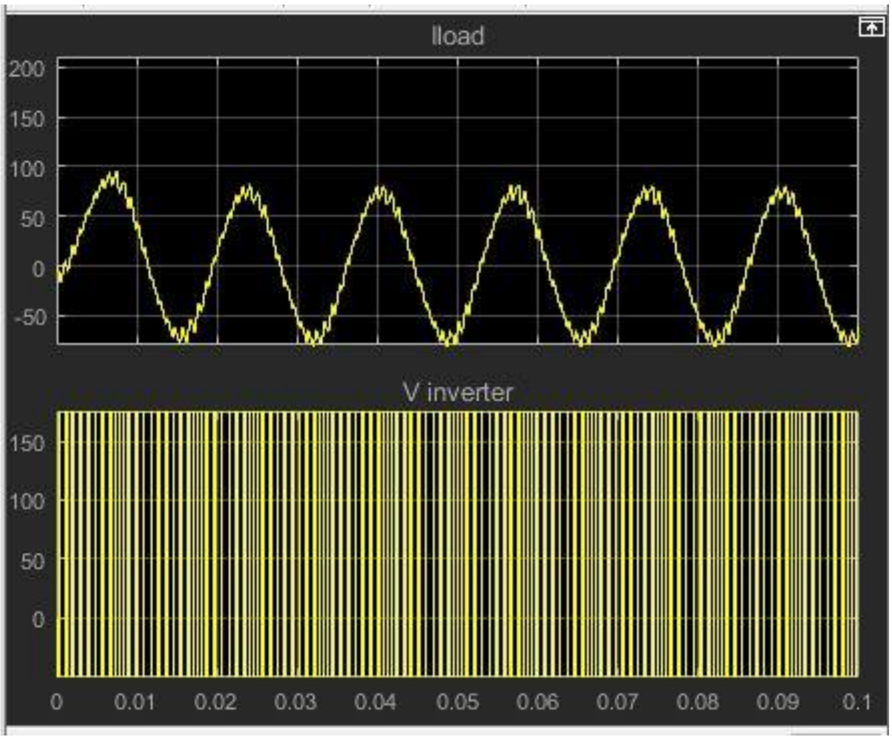

Figure 28: Inverter Input and Output

9. Output Analysis of the System

The output analysis of the system is shown in figures 29 - 31.

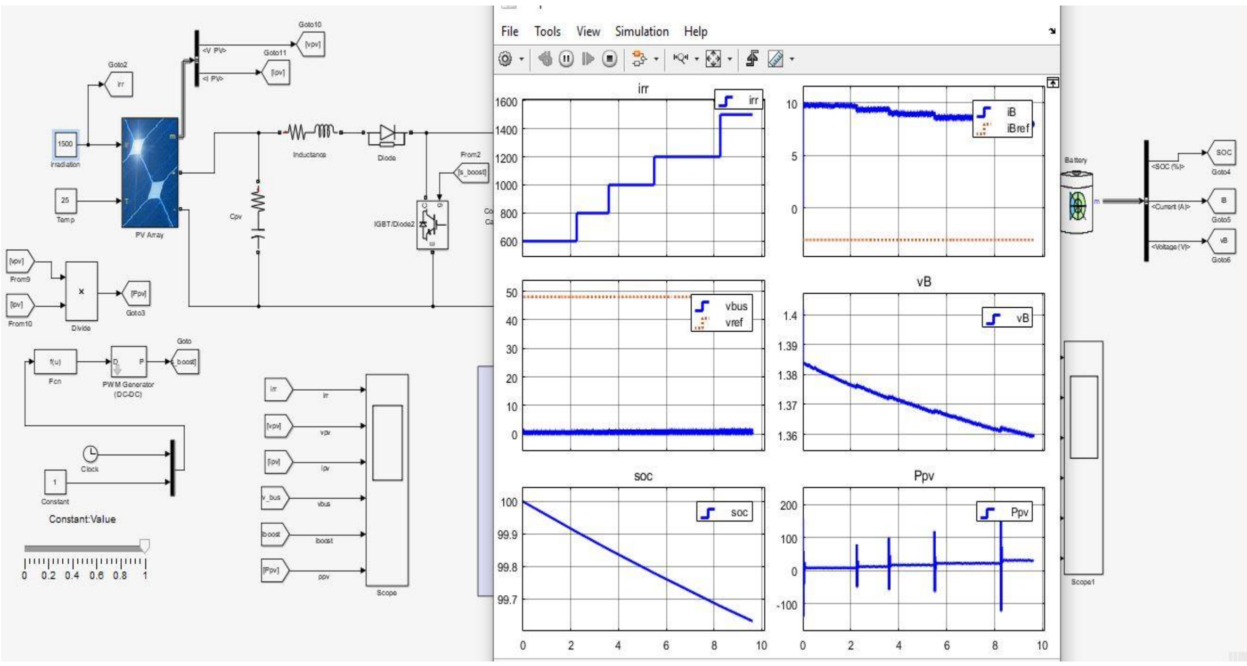

Figure 29: Results at 1500 W/m^2 Irradiance.

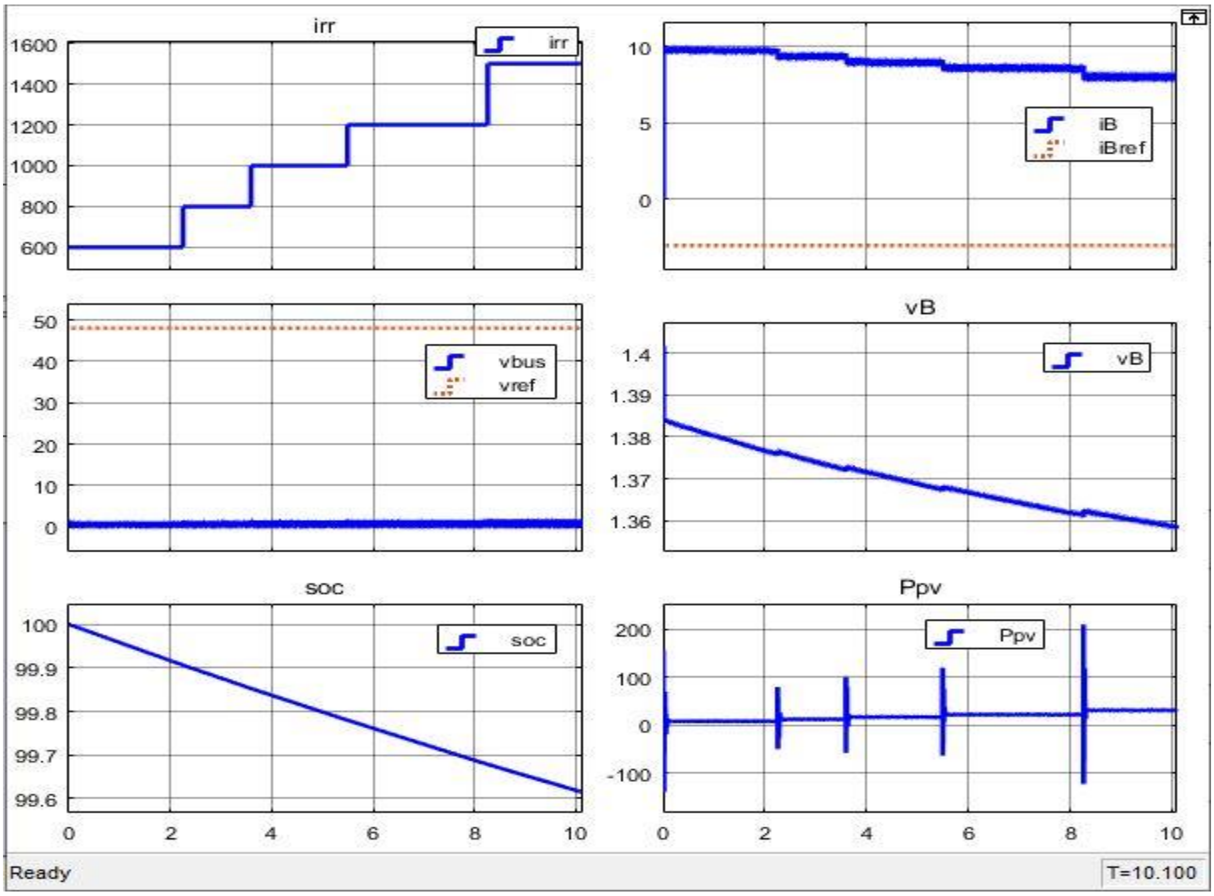

Figure 30: Graphs showing outputs at 1500 W/m^2 Irradiance.

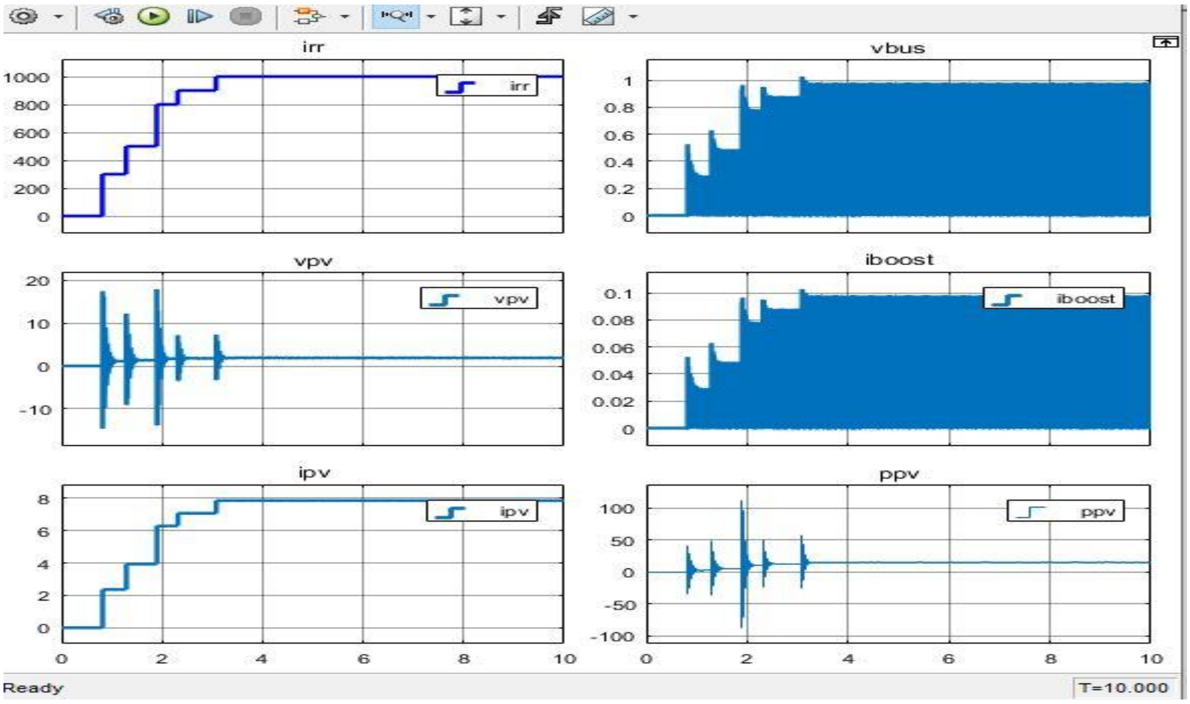

Figure 31: PV boast converter Final results at T=9.597.

10. Battery Operation

The battery in this system serves the role of storing the charge when there is no sun irradiance and deliver power to the load as required. Battery charge is controlled by a battery control system to prevent overcharges and undercharges that would actually damage the battery, this control system is extra sensitive to avoid necessary delays in switching from the array when the load is less and excess power is generated by the array and the battery discharge through the load when there is no power from the array. To avoid the under-discharging of battery state of charge is monitored and when it is less than 25% battery disengages form the load by the breaker.

11. Conclusion

This study presents a simple, efficient, and reliable renewable energy system (off-grid photovoltaic system) for medical facility loads located in rural isolated communities of Uganda, this system will meet the daily load demands during normal and emergency conditions. These results show that the average daily load requirement of such a medical facility is 8800 Wh/day. In order to meet this load demand, an array of solar panels is required. Modeling and simulation of the system show how the input results and the output results are analogous to each other, hence giving output load at standard operating conditions and at any instant.

A renewable energy system has been designed, analyzed, and simulated by MATLAB/Simulink using standard solar radiances data for Uganda. In order to achieve the performance, first each component and subsystem have been validated and analyzed. From the output characteristics of the PV module, it has been shown that the module is capable to deliver 130 W maximum power to the load under the effects of certain irradiance G=1 KW/m-2 and temperature T=45℃, which is very close to the desired data sheet value. PWM is able to get the operating point of the photovoltaic module at the maximum power point level and the charge controller controls the charge of the battery as has been shown in the simulation. It can be therefore concluded that a significant amount of additional energy can be extracted from a photovoltaic module by using simple maximum power point trackers and charge controllers and efficiency can be improved for the operation of renewable energy generation systems. The improved efficiency should prime to significant power savings and investments in the long run and at the same time provide information about the types of devices that should be chosen. In conclusion, it can be said that this simulation model will serve as a good tool to test the performance of any PV module/array under the variation of irradiance and temperature condition.

References

[1] Kempener, R., Lavagne, O., Saygin, D., Skeer, J., Vinci, S., & Gielen, D. (2015). Off-grid renewable energy systems: status and methodological issues. The International Renewable Energy Agency (IRENA).

[2] Mane, P., Madiwal, S., & Patil, P. (2022, August). OFF Grid PV System with PWM Inverter for Islanded Micro-Grid feeding critical loads. In 2022 IEEE 2nd International Conference on Sustainable Energy and Future Electric Transportation (SeFeT) (pp. 1-7). IEEE.

[3] Yates, J., Daiyan, R., Patterson, R., Egan, R., Amal, R., Ho-Baille, A., & Chang, N. L. (2020). Techno-economic analysis of hydrogen electrolysis from off-grid stand-alone photovoltaics incorporating uncertainty analysis. Cell Reports Physical Science, 1(10), 100209.

[4] Ogudo, K. A., & Umenne, P. (2019, August). Design of a PV Based Power Supply with a NonInverting Buck-Boost Converter. In 2019 IEEE PES/IAS PowerAfrica (pp. 545-549). IEEE.

[5] Chtita, S., Derouich, A., El Ghzizal, A., & Motahhir, S. (2021). An improved control strategy for charging solar batteries in off-grid photovoltaic systems. Solar Energy, 220, 927-941.

[6] E. I. Come Zebra, H. J. van der Windt, G. Nhumaio, and A. P. C. Faaij, “A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries,” Renewable and Sustainable Energy Reviews, vol. 144. 2021. doi: 10.1016/j.rser.2021.111036.

[7] Babatunde, O. M., Adedoja, O. S., Babatunde, D. E., & Denwigwe, I. H. (2019). Off-grid hybrid renewable energy system for rural healthcare centers: A case study in Nigeria. Energy Science & Engineering, 7(3), 676-693.

[8] Karatop, B., Taşkan, B., Adar, E., & Kubat, C. (2021). Decision analysis related to the renewable energy investments in Turkey based on a Fuzzy AHP-EDAS-Fuzzy FMEA approach. Computers & Industrial Engineering, 151, 106958.

[9] Akram, W., Arefin, A., & Nusrat, A. (2021). Prospect of green power generation as a solution to energy crisis in Bangladesh. Energy Systems, 1-39.

[10] Hioki, A. T., Silva, V. R. G. R. D., Vilela, J. A., & Loures, E. D. F. R. (2019). Performance analysis of small grid connected photovoltaic systems. Brazilian Archives of Biology and Technology, 62.

[11] Gilles, A. R., Audace, D., Aristide, H., Arouna, O., & Christophe, E. (2020, December). Evaluation of the photovoltaic power prediction performance of a neural network based on input data. In 2020 IEEE 2nd International Conference on Smart Cities and Communities (SCCIC) (pp. 1-6). IEEE.

[12] Rumokoy, S. N., Atmaja, I. G. P., Langie, M., & Sundah, J. Development of the Concept Design of Rooftop Solar Power Plant Practice Tool.

[13] Martynyuk, V. V., Voynarenko, M. P., Boiko, J. M., & Svistunov, O. (2021). Simulation of photovoltaic system as a tool of a state’s energy security. International Journal of Engineering, 34(2), 487-492.

[14] Hassan, Q. (2022). Evaluate the adequacy of self-consumption for sizing photovoltaic system. Energy Reports, 8, 239-254.

[15] Ma, M., Zhang, Z., Yun, P., Xie, Z., Wang, H., & Ma, W. (2021). Photovoltaic module current

mismatch fault diagnosis based on IV data. IEEE Journal of Photovoltaics, 11(3), 779-788.

[16] Bhukya, R., & Shanmugasundaram, N. (2021). Performance investigation on novel MPPT controller in solar photovoltaic system. Materials Today: Proceedings.

[17] Muni, T. V., Lalitha, S. V. N. L., Suma, B. K., & Venkateswaramma, B. (2018). A new approach to achieve a fast acting MPPT technique for solar photovoltaic system under fast varying solar radiation. Int. J. Eng. Technol, 7, 131-135.

[18] Gosumbonggot, J., & Fujita, G. (2019). Global maximum power point tracking under shading condition and hotspot detection algorithms for photovoltaic systems. Energies, 12(5), 882.

[19] Teh, C. J. Q., Drieberg, M., Soeung, S., & Ahmad, R. (2021). Simple PV Modeling under Variable Operating Conditions. IEEE Access, 9, 96546-96558.

[20] Chen, Z., Yu, H., Luo, L., Wu, L., Zheng, Q., Wu, Z., ... & Lin, P. (2021). Rapid and accurate modeling of PV modules based on extreme learning machine and large datasets of IV curves. Applied Energy, 292, 116929.

[21] Akpolat, A. N., Dursun, E., & Siano, P. (2021). Inverter-based modeling and energy efficiency analysis of off-grid hybrid power system in distributed generation. Computers & Electrical Engineering, 96, 107476.

[22] Rathnayake, D. B., Akrami, M., Phurailatpam, C., Me, S. P., Hadavi, S., Jayasinghe, G., ... & Bahrani, B. (2021). Grid forming inverter modeling, control, and applications. IEEE Access.

[23] Ku, H. K., Jung, J. H., Park, J. W., Kim, J. M., & Son, Y. D. (2020). Fault-tolerant control strategy for open-circuit fault of two-parallel-connected three-phase AC–DC two-level PWM converter. Journal of Power Electronics, 20(3), 731-742.