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Integration of Solar Energy into an Existing Power Grid

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Abstract

As the global community strives to transition towards cleaner and more sustainable energy sources, the integration of solar energy into existing power grids has emerged as a crucial step in reducing greenhouse gas emissions and enhancing energy resilience. This study focuses on the integration of solar energy into an already established electrical grid, addressing the technical, economic, and environmental aspects of this transition. This study work entails a comprehensive literature review on the subject matter, and existing works were studied and analyzed. Data were collected from an existing work (75MW Katsina Solar Farm), which were used as a case study in modeling and simulating to analyze the feasibility of the study. This simulation was carried out using MATLAB SIMULINK. From the results gotten, the technical, economic and environmental feasibility of the solar grid integration were discussed and analyzed. This study has shown that with careful planning and appropriate technology selection, integration of solar energy into an already existing grid is not only feasible but also highly beneficial. It has also shown that the integration of solar energy into a grid has a substantial positive impact on the environment. By reducing reliance on fossil fuels, it lowers greenhouse gas emissions, and contributes to cleaner air and healthier planet. Also, while the initial cost of implementing solar integration is substantial, it has also been shown that it can yield long term cost savings. Solar energy can provide a hedge against volatile energy prices and generate revenue through excess energy production, feed-in tariffs, and other incentives.

1. Introduction

The World is having an energy shift from fossil fuels to renewable energy sources. This is mainly as a result of the health problems, greenhouse effect and global warming issues associated with fossil fuels, hence the need for renewable energy sources is continually increasing and the era of increased demand is achieved by Distributed Generation (DG) system based on Renewable Energy Sources (RES) [1].

Nigeria, as the most populous country in Africa, faces significant challenges in meeting its electricity demand. The power sector has been plagued by issues such as inadequate generation capacity, poor transmission and distribution infrastructure, and high transmission losses. As a result, a significant portion of the population lacks access to reliable electricity. Nigeria is blessed with abundant solar resources. The solar potential for three locations within Nigeria using simulated Typical Meteorological Year (TMY2) data was reported which were Kano, Onitsha, and Lagos as 6.08, 4.43, and 4.42kWhm-2 respectively. The solar radiation potential in the northern and southern region of Nigeria has been reported as 5.62 - 7.01kWhm-2 and 3.54 up to 5.43kWhm-2 respectively using artificial neural networks [2], which is a high level of solar radiation intensity. This makes solar power a viable and sustainable solution to address the energy deficit. Solar energy can be harnessed through various technologies such as photovoltaic (PV) panels and concentrated solar power (CSP) systems.

Over the years, electric grids involved large-scale, centralized energy generation located far from consumers. Modern electric grids are much more complex, involves variable renewable energy sources like solar, wind, etc., energy storage systems, power electronic devices like DC-DC converters, DC-AC inverters, etc. and micro grids. This type of grid is a solar integrated grid system [3]. Solar energy can be said to be radiation from the sun capable of generation heat, causing chemical reactions and generating electricity. The total amount of solar energy incited on the earth’s crust is sufficient for the energy requirement of the world, so if properly harnessed, this energy source has the capability of satisfying our energy demands [3]

Solar-grid integration is a system that allows penetration of Photovoltaic (PV) power into a utility grid while maintaining the reliability, security and efficiency of the grid. This is an important technology as the integration of solar energy into grids optimizes the energy balance, improves the economics of the solar PV system, reduces operational costs, and provides added value to the consumer and the utility [4-5]. Solar-grid integration is now a usual practice in many countries in the world, as there is a growing demand of use of clean energy as against fossil fuels [6].

According to International Renewable Energy Agency [7] statistics, 2022 has seen the largest increase in renewable energy capacity to date. The world added almost 295 gigawatts (GW) of renewables, increasing the stock of renewable power by 9.6% and contributing an unprecedented 83% of global power additions, largely due to the growth of solar and wind power [7-9], and the further decommissioning of fossil fuel power plants in several large economies. Solar power alone accounted for almost two-thirds of the renewable additions with a record 192 GW, while 75 GW of wind energy was added, slowing from the 111 GW added in 2020. As at end of 2022, the total production of solar energy in the world was about 1053GW with China being the leading producer of solar energy with about 393GW of solar power while the whole of Africa generates around 12GW which is less than 3.5% of what China alone produces and Nigeria producing a meagre 37MW, which is less than 0.4% of what Africa produces [7]. So it’s evident that the whole of Africa needs to step up its production of solar energy and utilize the abundance of sunlight generously available in Africa. Solar grid integration in Nigeria faces several challenges. These include the intermittency of solar power, lack of grid infrastructure in remote areas, limited technical expertise, and inadequate funding for large-scale study. Addressing these challenges requires investments in grid infrastructure, development of energy storage technologies, policy and regulatory frameworks, and capacity building programs [3].

Solar grid integration offers numerous benefits to Nigeria. It diversifies the energy mix, reduces dependence on fossil fuels, and contributes to the reduction of greenhouse gas emissions, thus mitigating climate change. It also enhances energy access, especially in rural and underserved areas, and stimulates economic growth by creating job opportunities in the renewable energy sector. The future of solar grid integration in Nigeria looks promising. With the government's commitment to renewable energy and ongoing efforts to attract private investments, the capacity for solar power generation is expected to increase significantly [4]. Continued advancements in solar technologies, coupled with supportive policies and adequate infrastructure development, will be crucial for achieving sustainable solar grid integration in Nigeria.
Nigeria’s major problems with regards energy sustainability is the unavailability of power supply and a major cause of this is the poor amount of electrical power generated, transmitted and

distributed from our national grid to the end consumer. According to 2018 data, Nigeria experiences a power outage for about 4600 hours in a year which is over 50% of electricity unavailability in a year [10]. Nigeria is endowed with large oil, gas, hydro and solar resources, and it has the potential to generate 12,522 MW of electric power from existing plants. On most days, however, it is only able to dispatch around 4,000 MW, which is insufficient for a country of over 195 million people [11]. So there is a great need for more power generation facilities and this can be done using distributed generation of solar energy integrated to the utility grid.

There are situations where the solar power system continues to generate electricity even though the utility grid is down. This is known as islanding. This can be dangerous when utility workers are working on fixing the grid, as they can get injured from the generated electricity that goes to the grid from the solar power system. Due to this, most modern inverters are built with anti-islanding features, this anti-islanding disconnects the solar system from the grid during a power outage from the grid. The grid-tied inverter is fitted with anti-islanding protection (which is based on voltage and frequency detection) that senses when the grid is down and stops feeding the grid with power from the solar system hence protecting the utility workers [14].

Integrating solar power requires a more flexible and resilient grid infrastructure. The grid should be able to handle bidirectional power flows, accommodate distributed solar generation, and adapt to changes in power generation patterns caused by factors such as cloud cover or sudden solar resource fluctuations.

Efficient management of solar power generation is crucial to ensure grid stability and balance electricity supply and demand. Grid operators need advanced energy management systems that incorporate forecasting techniques, energy storage technologies, and demand response mechanisms to optimize solar power integration.

Lots of previous research have been carried out on this topic, some of which are ; grid integration challenges and solution strategies for solar pv systems: a review [16] and an overview of solar power (pv systems) integration into electricity grids [5]. These researches did a great study in analyzing the challenges faced in solar grid integration and gave feasible solutions on how to overcome these challenges. but they failed to give a step by step approach on how solar system can be integrated into the grid which is the base of this research, this research gave a feasible step by step approach on how solar power can be integrated into an existing grid using matlab simulink for the simulation.

2. Methodology

This study developed a computerized model and performing simulations of a solar energy farm with a 5MW power generation capacity that is integrated to the electrical grid. The simulations was carried out using a computer program called MATLAB R2020a Simulink. A computer language called MATLAB and its extension Simulink are both used to create and test the dynamic systems using visual block diagrams. The program is used to investigate numerous parts of the solar energy farm and evaluate its performance under various circumstances which makes it possible to assess elements like power output, voltage control, and grid integration. The simulations aims to maximize the total efficacy and efficiency of the solar energy farm.

The PV panel used for this simulation is a SunPower SFR-315E-WHT-D panel with a STC power rating of 315W and a PTC power rating of 290W [15]. The numbers of panels used were 3200*5 panels, I.e 3200 in parallel, and 5 in series. The calculation on how the numbers of panels used was gotten was done as we go further. Also, a VSC inverter from MATLAB SIMULINK was used.

2.1 proposed solar-grid integration network system

In order to link a 5MW solar farm to the national grid, the study entails building a network infrastructure. This indicates that energy will be produced by the solar farm and fed into the existing power system for distribution. This system's performance is simulated using MATLAB Simulink The simulation makes it easier to comprehend and research how the solar farm will function inside the network. The schematic diagram of the solar grid integration system is shown in figure1 and a graphic illustration of this simulation is shown in Figure 2, which offers a clear grasp of how the suggested study would operate. The study evaluates many components of the solar farm's interaction with the grid using MATLAB Simulink, resulting in optimum performance and effective electricity production.

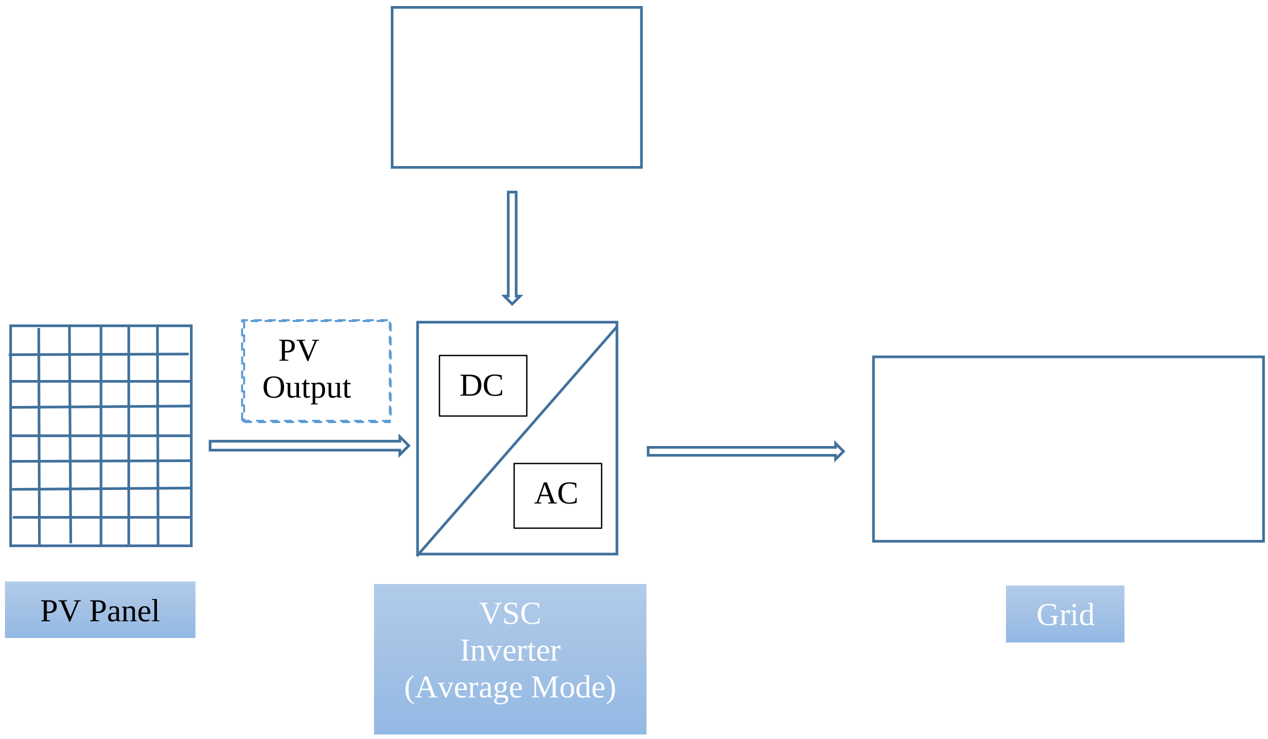


Fig 1: Schematic Diagram of the Solar Grid Integration System

PV Panel: The PV panel converts sunlight into DC electricity, so it basically generates the power for the system.
Inverter: The inverter converts the DC electricity generated to an AC electricity which can then be synchronized with the grid.
VSC Controller: Voltage Source Converter (VSC) Controller basically controls the voltage and frequency and ensures voltage and frequency of the VSC inverter is compatible with the grid. It also helps in the grid stability by providing voltage regulation.
Grid: The grid connects the inverter with the local utility grid, it also helps to ensure that there is power supply to the utility grid when the solar power is insufficient.

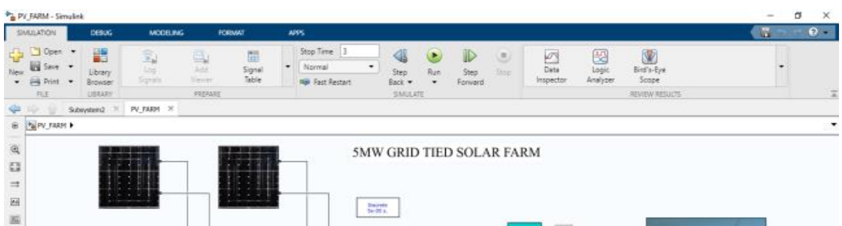


Figure 2: MATLAB Simulink Simulation Model

2.2 Simulation Approach and Calculations

To simulate the proposed circuit, we first have to design it in MATLAB Simulink. The design process is broken into key logical steps and the calculations pertain to the choice of value determined.

Step 1: PV array module design

The solar panels are represented by the solar PV array model from MATLAB Simulink's specialized power package. The PV Array block is a five-parameter model that represents the modules' irradiance- and temperature-dependent I-V characteristics utilizing a light-generated current source (IL), diode, series resistance (Rs), and shunt resistance (Rsh).

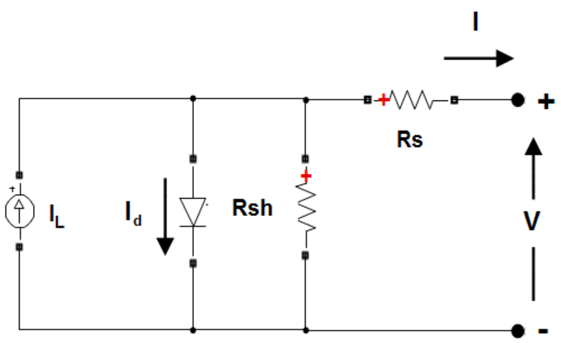


Figure 3: PV Block Array Model (MATLAB Simulink)

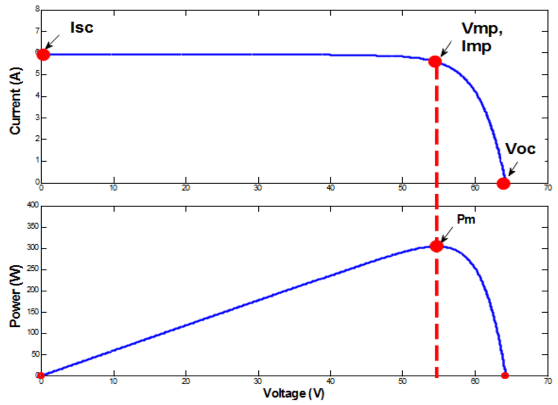


Figure 4: Solar Panel Diode Characteristics

The diode I-V characteristics for a single module are defined by the equations (1) and (2).

$$I_d = I_o[\exp^{\frac{v_d}{v_T}} - 1] \quad [14] \qquad (1)$$

$$V_T = \frac{KT}{q} * nI * N_{cell} \quad [14] \qquad (2)$$

Where:

I_d	Diode current (A)
V_d	Diode voltage (V)
I_0	Diode saturation current (A)
nI	Diode ideality factor, a number close to 1.0

K	Boltzmann constant = 1.3806e-23 J.K-1
Q	Electron charge = 1.6022e-19 C
T	Cell temperature (K)
N_{cell}	Number of cells connected in series in a module

This PV block is used to model a solar PV module with the following specification; this PV module was chosen because of its availability and cost effectiveness.

Rated maximum power	315W
Open circuit voltage	64.6V
Maximum power voltage	54.7V
Short circuit current	6.14A
Maximum power current	5.76A
Module efficiency	16.73%
Power tolerance	−0~+5W

To obtain a 5MW 323V system using the PV module, PV array was form. The number of series connected module is given in equation (3).

$$No.of\ series\ connected\ module = \frac{Output\ Voltage}{Open\ Circuit\ Voltage} \quad [14] \quad \text{--------}(3)$$

$$= \frac{323}{64.6} = 5$$

The number of parallel strings is given in equation (4).

$$No.of\ parallel\ String = \frac{Output\ power}{PV\ power * No.of\ series\ connected\ module} \quad [14] \quad \text{-------}\ (4)$$

$$= \frac{5000000}{315 * 5} = 3174$$

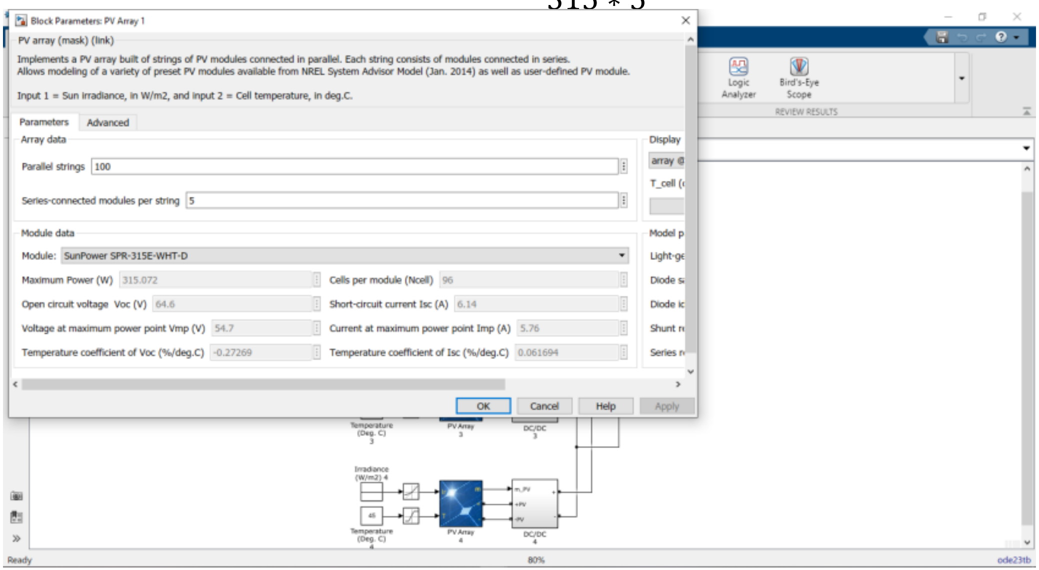


Figure 5: Setting the PV array block

The PV model was then connected in groups of four, and then in group of 8, making a total of 3200 parallel strings.

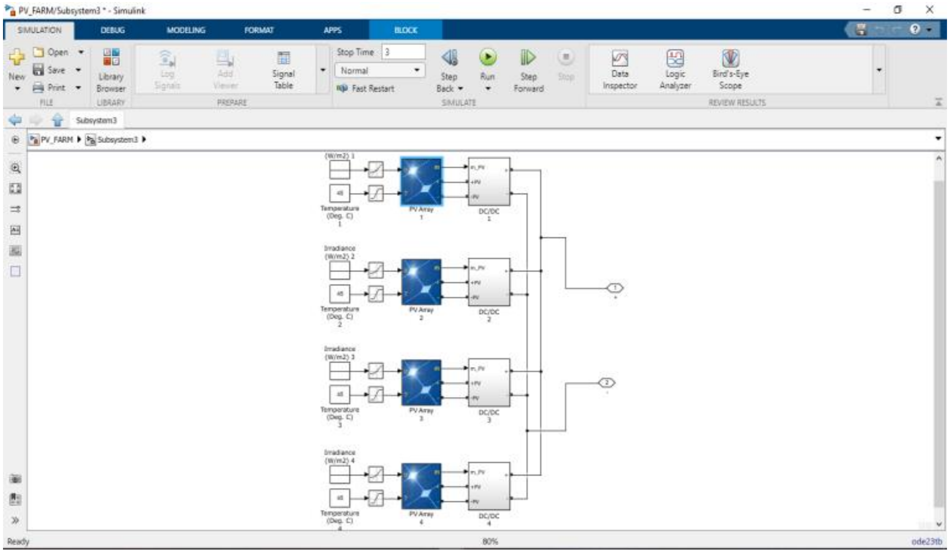


Figure 6: An array of PV arrays

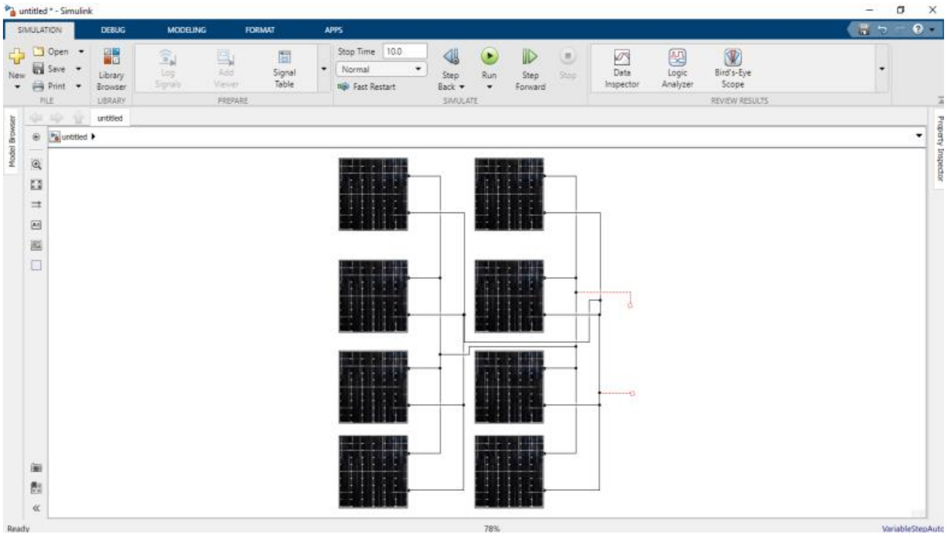


Figure 7: Design of the circuit with just the PV arrays

Step 2: MPPT Control Design

For the individual PV array model, the system employs a P&O algorithm for power optimization. P&O optimization is a well-known MPPT control approach that is based on PSO (particle swarm optimization).

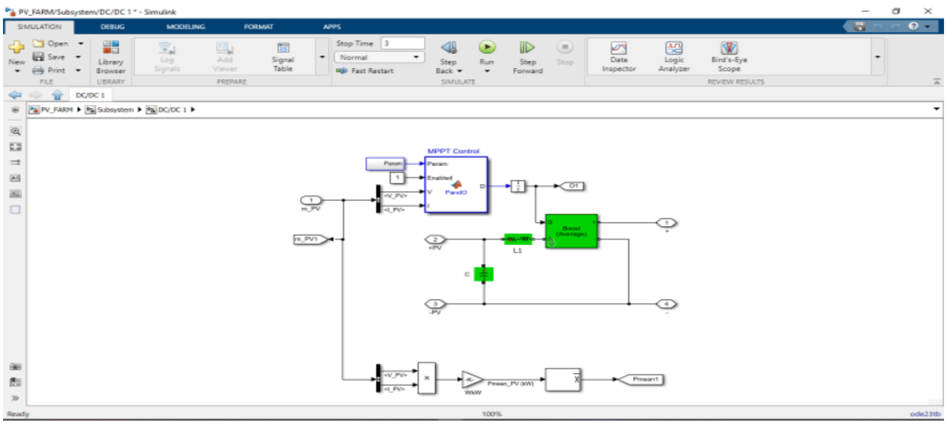


Figure 8: Control block

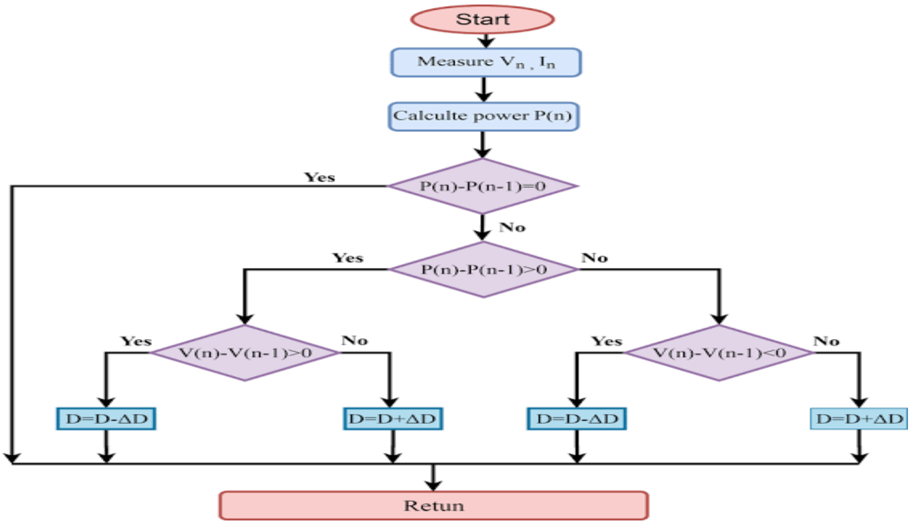


Figure 9: P&O control algorithm

The flow chart was coded into the P&O block model.

Step 3: Inverter Design

The output of a PV module is direct current (DC), whereas the national grid is alternating current (AC) with a frequency of 50 hertz. To connect our system to the grid, we must first convert DC to AC using an inverter. In this simulation, a VSC (voltage source converter) and a VSC controller were employed. In order to convert the DC to AC signal for synchronism, the VSC controller monitors the grid voltage, current, and frequency. The VSC controller is made up of a PLL & Measurement block that measures grid current and voltage, a VDC regulator that measures and monitors the voltage from the PV arrays to a reference voltage, a current regulator that measures and regulates currents, and finally a control block that controls the VSC block's inversion.

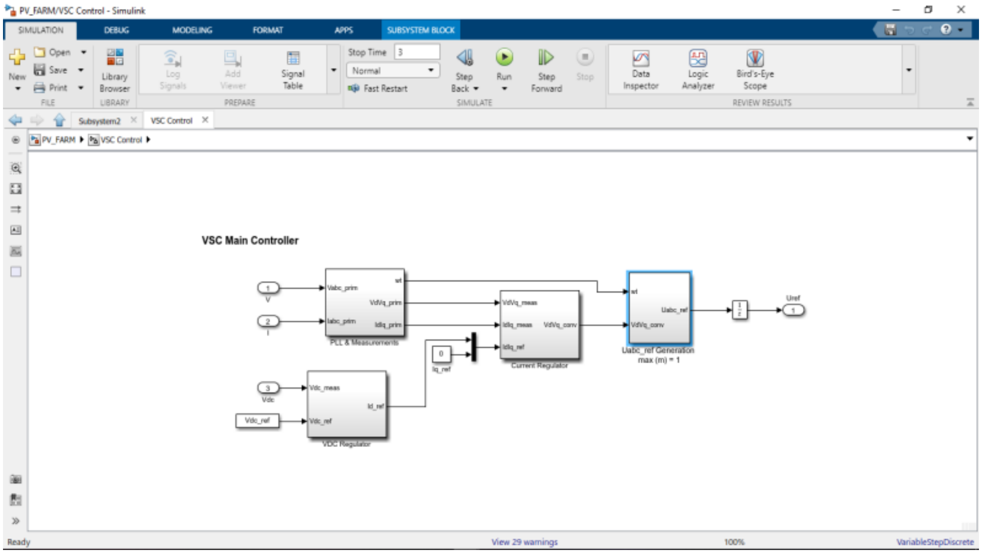


Figure 10: The VSC controller

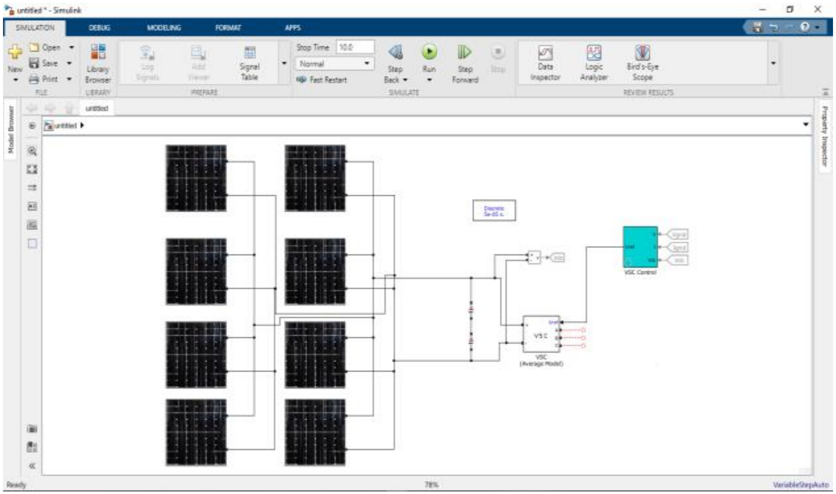


Figure 11: Design of the circuit after adding the inverter

Step 4: Filter Design

The inverter output is not a pristine sine wave, necessitating the use of a low pass filter. In the filter design, an LC filter is utilized with values chosen to filter out high frequency signals over 60Hz. The inductor was supposed to have a value of 15uH per phase. The capacitance was determined using the method in equation (5) and a maximum frequency of 60Hz.

$$C = \frac{1}{4\pi^2 f^2 L} \quad (5)$$

$$= \frac{1}{4\pi^2 * 60^2 * 15 * 10^{-6}}$$

$$= 0.5\ Farad/phase$$

This value was expressed in kvar using the voltage from the inverter and the total capacitance

$$= 0.5 * 1.5 * 323^2$$

$$= 78kvar$$

40kvar was used because a better result was obtained with this value.

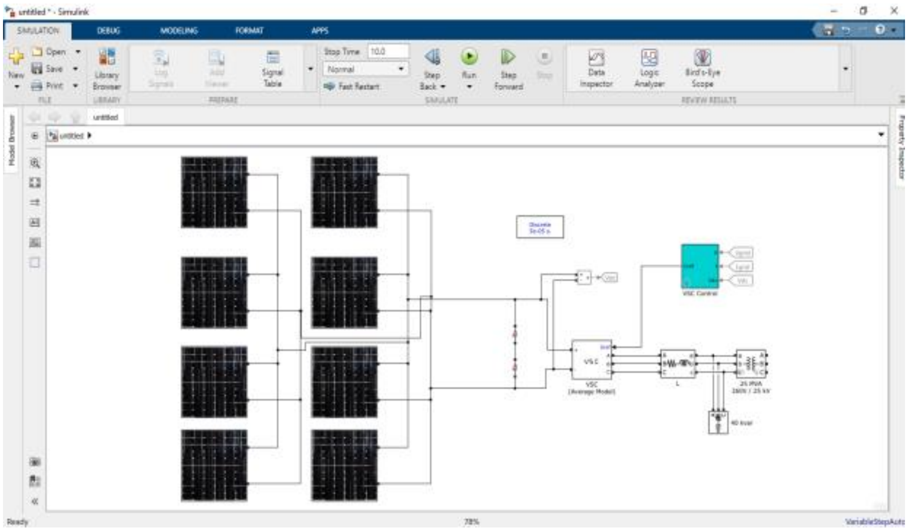


Figure 12: Design of the circuit with filter added

Step 5: Transformer Design

The ac voltage from the inverter is less that the grid supply voltage hence the need to setup the supply using step up transformer. The figure 13 shows the type and settings of the of the transformer used.

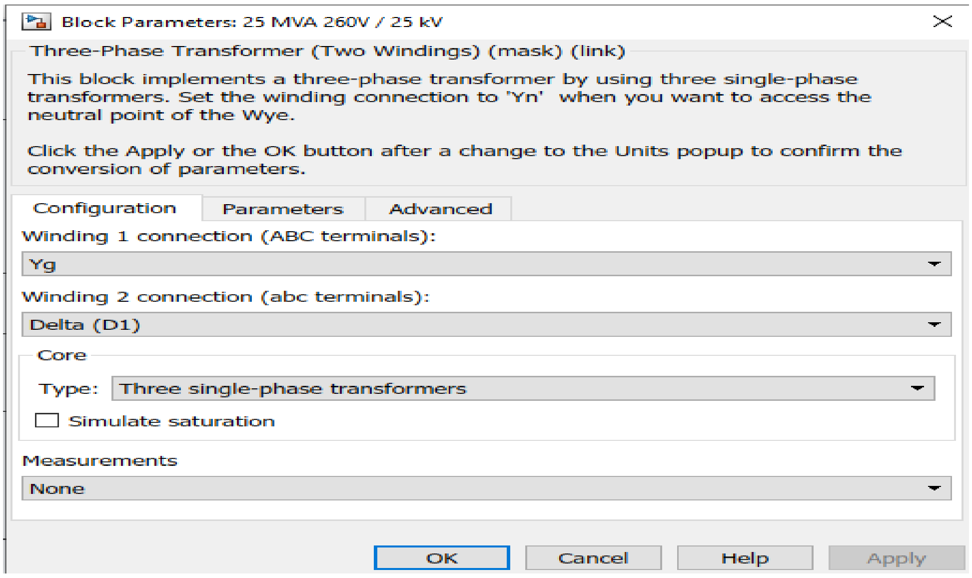


Figure 13: Step up transformer type

Step 6: Grid design
The grid was simulated using the feeder block model, transformers, and loads.

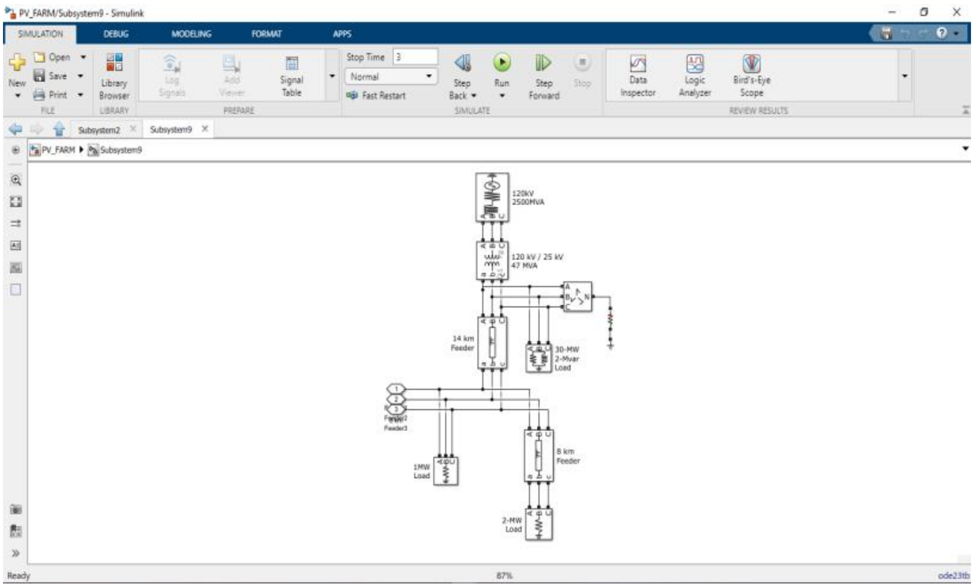


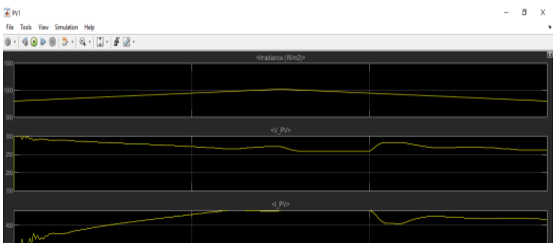
Figure 14: simulation of a typical grid system

After the grid design, the circuit is ready for simulation. The final image of the design is as given in figure 2. The simulation data obtained from this circuit is presented in table 1 of this study, the performance of the PV array module and P&O algorithm also presented in figure 15 to 17.

3. Results and Discussion

Table 1: Result from PV array

Solar Irradiation (W/m^2)	**PV_Voltage (V)**	**PV_Current (A)**	**Power (KW)**	**Duty_cycle**
814.52	294.89	225.35	62.53	0.49
829.18	288.91	310.99	83.80	0.50
843.85	288.75	319.49	90.99	0.51
858.52	285.71	359.67	101.34	0.52
873.18	283.21	390.88	109.54	0.53
887.85	280.98	417.33	116.25	0.54
902.52	278.84	441.33	122.13	0.55
917.18	276.66	463.98	127.50	0.56
931.85	274.32	485.96	132.50	0.57
946.52	271.72	507.63	137.18	0.58
961.18	268.75	529.01	141.50	0.59
975.85	265.33	549.78	145.33	0.60
990.52	267.54	550.15	147.18	0.60
1005.18	270.96	543.26	147.20	0.59
1019.85	271.48	548.54	147.90	0.59
1005.50	259.66	582.31	151.52	0.59
990.84	258.91	575.47	149.36	0.58
976.17	258.79	567.19	147.15	0.57
961.50	258.74	558.78	144.95	0.57
946.84	259.11	549.52	142.74	0.57
932.17	283.37	418.02	120.42	0.58
917.50	281.72	425.81	118.13	0.58
902.84	272.74	478.89	129.60	0.59
888.17	268.96	487.69	131.53	0.59
873.50	269.60	476.99	129.08	0.60
858.84	269.70	468.45	126.70	0.60
844.17	268.17	466.02	125.08	0.59
829.50	264.52	469.03	124.32	0.58
814.84	261.79	467.26	122.69	0.57
800.17	261.77	458.81	120.47	0.56



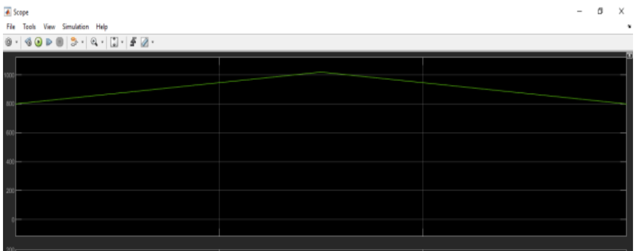


Figure 15: Graphical Presentation of Data

Figure 16: PV optimization due to P&O algorithm

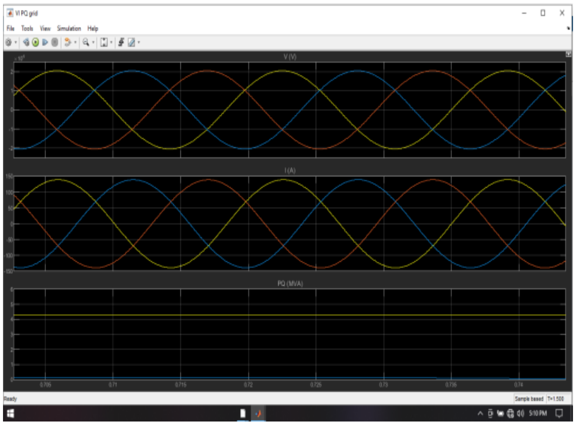


Figure 17: Output of the grid tied solar farm

Table 1 shows the performance result of PV array model used in the simulation at the given irradiation value. Although the simulation is for a single array block, other model will perform similarly.

Figure 15 is a graphical representation of the data of table 1. From the graphical data, it can be observed that the voltage and current from the PV array varies with the amount of solar irradiation reaching the surface of the panels, this variation is minimized by the P&O algorithm implemented in the design.

Figure 16 shows simulation data of the PV optimization algorithm, this data shows the importance of control algorithm in maintaining constant power by perturb and observe method.

Without the control algorithm, the output of the PV array is completely dependent on the environmental variable and maximum power is not obtained.

Figure 17 shows the output of the simulation; the DC voltage from the PV array is converted to AC voltage and then stepped up to the grid voltage. From the figure, we can see that the solar farm takes in DC voltage as input and Outputs AC quantities suitable to be tied to a grid.

Simulation data obtained shows that the design and implementation of a grid tied solar farm is possible and feasible. The PV arrays are at their optimal performance due to the control algorithm implemented in the design that ensure that maximum power is always obtained from the system and that the power is independent of environmental factors affecting the PV array models (solar irradiation).

4. Conclusion

This study has made significant strides in the integration of solar energy into an existing grid. These efforts have been driven by the urgent need to transition towards a more sustainable and environmentally friendly energy ecosystem. It is aimed at harnessing the power of the sun and making it an integral part of our energy mix while ensuring the stability and reliability of our grid.
During the course of the research, solar energy technologies had been successfully implemented, such as photovoltaic panels, advance grid management software, etc. These technologies have played a vital role in enhancing the efficiency of the solar energy integration system.
Grid operations have also been optimized to accommodate intermittent solar power generation. This has led to a more resilient and adaptive grid capable of accommodating a higher percentage of renewable energy sources.

We have also seen that with solar grid integration, the reliance on fossil fuel is reduced, hence lowering greenhouse gas emissions. With this, a great step has been taking into generating a more sustainable and environmentally responsible energy future. The integration of solar energy into the grid has directly contributed to mitigating climate change impacts.
Solar energy integration system is also reliable hence minimizing downtime and disruptions to energy supply. As energy demands continue to rise, this study has demonstrated that solar energy can be a dependable and scalable source of power, helping meet the growing energy need of our nation, Nigeria.

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