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Simulative Design of an Indigenous PV Renewable Energy Farm System

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Abstract: *This paper proposes a greener environmental-friendly, renewable energy power generation solution deployable to indigenous farmlands in Nigeria when comparing them to the use of fossil fuels which produce high-level carbon dioxide (CO2) emissions. The PV solar panel farm system comprises of 4 PV arrays delivering a sum of 400kW at 100W/m2 sun irradiance in connection to the Grid. The Design and Simulation model (as shown in Figure 5) in this paper were carried out using MATLAB/SIMULINK version 2021a comprising of various physical and mathematical block models. The results (as seen in Figure 23) show the real power, reactive power and apparent power help to indicate the outstanding performance index of the model when compared to fossil fuel power generation. The economic relevance of this design is its ability to attenuate the cost of power generation and global warming.*

Keywords: *Photo Voltaic (PV); Maximum Power Point Trackers (MPPT); Voltage Source Converters; Perturb and observe algorithm; Phase Locked Loop (PLL); Maximum Power Point (MPP).*

1. INTRODUCTION

Energy happens to be a fundamental requirement for human survival and a pre-requisite in meeting up to various fundamental needs of man spanning from production of food to sustainable development of the economy [1]. In a bid to generate energy, the globe of today is been faced with a big challenge of fossil fuel as it is bedeviled with complications such as availability, environmental effect as global warming making it imperative that we explore alternate means of renewable energy for example solar, wind, geothermal and tidal [2]. However, Research indicates that the volume of greenhouse gases has tremendously increased from the last 250 years till date owing to more fossil fuel consumption, mechanized wide-scale agriculture, and land use alteration [3]. The Nigeria economy today thrives on agricultural products as investment are made into livestock farming, cash crops farming for e.g., cocoa and palm oil. Major mechanized farmlands in the nation like the Obasanjo farm Ota, Maizube farm Niger, Sebore farm Adamawa, Anadariya Farm Kano [4], require sustainable and renewable energy source for their optimal operation.

A PV solar powered renewable farm system proffers a reasonable solution to the above problem, thereby providing clean energy farming, sustainable distribution of that energy in an environmentally friendly, affordable, and socially acceptable manner. This farm energy system provides indigenous farmers with the following advantages viz: improved energy performance, cost effective power generation scheme, implementation of farming processes that help save both energy and preserve natural resources. For example, Bustos' solar-heated greenhouse in the US has proven to reduce cost of fossil fuel [5] and at the long run increasing the national GDP.

The work research work makes use of 4 PV cells to provide power to a farm. The work will help to provide greener, sustainable and renewable energy to local farmlands.

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2.REVIEW OF RELATED WORKS

The use of Photo Voltaic cells has proven to display high performance rating as an evaluation of the efficiency of installed 280 kW grid-connected photovoltaic solar farms in Lesotho were been compared with the basic parameters stated in the International Electrotechnical Commission (IEC) showed to perform optimally [6]. A photovoltaic cell generates more stable electricity when in comparison with conventional fuel and does not come with the demerit of by-product of greenhouse gases [7].

Photovoltaic cells produce electricity when sunlight excites electrons in the cells. Silicon photo voltaic cells are the most widely used and promising photovoltaic cells in terms of cost, mass production, and relatively high efficiency. Owing to the size compatibility, the unit is flexible and adaptable, photovoltaic cells can be installed in homes, industries, and utilities [8]. David in his article indicated that renewable energy technologies could if developed and implemented provide an estimate of 50% of a nation's energy needs.

The sun having been an ancient energy source for over 500 million years and is projected to remain so for at least the next 50 million years [9]. Furthermore, sun energy has an estimated worldwide average power potential of 24 W/m2 of earth's surface [10]. Nigeria happens to lie within a high sunshine belt of the globe, receiving between a range of 3.5 to 7 kW/m2/day from the coastal Latitude to the far North [11], thereby making her a viable region to explore the advantages of the energy of the sun as a major alternative energy source [12].

Chel [13] in his work highlighted the draw backs of conventional fuels in contrast to the use of renewable energy forms in farmlands. He highlighted drawbacks such as transportation of fuel, noise and fumes that can disturb live stocks, cost of fuels and spills which can contaminate farmlands, cost of maintenance of generators during break down of mechanical parts and etc. Exploring other forms of renewable energy aside solar energy Yu-Ting Wu [14] had carried out a work where he modeled turbine wakes and turbine losses within a wind farm. J. M. Torres [15] had carried out a work where he deployed a predictive model using deep learning technique to discover the power generation results in a wind farm.

The exploration into renewable energy proves to be the future of power generation as the top Oil and gas companies are sponsoring research in this area. Schlumberger's project on Geo-frame Energy which makes use of geothermal power generation has proven very viable [16]. Total Energies in collaboration with Siraj Energies is undergoing a project to construct one of the biggest solar power plants of 800MWP in Qatar [17]. The plant would be able to cater for about 55,000 Qatari household and contains an automated self-cleaning system.

3. METHODOLGY

3.1 Principle of Operation of a Photovoltaic Cell

Photo Voltaic cells makes use of transducers that convert light energy from the sun into electrical energy through a chemical action taking place in solar cells. These operate based on what is known as the photovoltaic effect, helps in developing an emf on absorption of ionizing radiation from Sun [18].

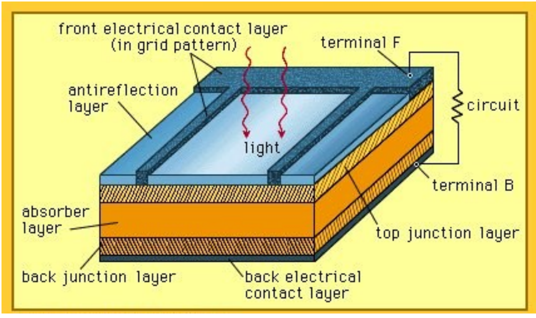

Figure 1: Photovoltaic Cell [19]

Light shining on the photo voltaic (solar) cell produces both a current and a voltage for generating electric power. This process requires mainly, a material in which the absorption of light causes the energy level of an electron to be raised, and secondly, the movement of this higher energy electron from the PV cell into an external circuit. The electron energy is then dissipated in the external circuit and returns to the PV cell. Different materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practicality virtually all photovoltaic energy conversion make use of the p-n junction found in semiconductor materials.

The basic steps listed below are responsible for the principle of operation of a photo voltaic cell:

I. the creation of light-generated carriers;
II. the gathering of the light-generated carriers to produce current;
III. the creation of a huge potential difference pd across the PV cell; and
IV. the dissipation of the power produced in the load and in parasitic resistances.

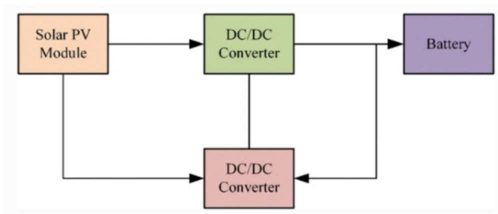

Figure 2: Diagram of a PV System [20]

ISSN: 2456 - 3935
International Journal of Advances in Computer and Electronics Engineering
Volume 7, Issue 4, April 2022, pp. 1 – 10

The solar cell equation is given as:

$$J = J_0\left(exp\left(\frac{qV}{nkT}\right) - 1\right) - J_{sc} \approx J_L \qquad (1)$$

$$V_{oc} = \frac{nkT}{q} ln\left(\frac{l_{sc}}{l_o} + 1\right) \qquad (2)$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}} = \frac{V_{mpp} I_{mpp}}{P_{in}} \qquad (3)$$

$$J_L = qG\left(L_n + L_p + W\right) \qquad (4)$$

$$J_L = q\int_0^W G(x)CP(x)dx \qquad (5)$$

From (5) J_L can be rewritten as

$$q\int_0^W [\alpha(\lambda)H_0\, exp(-\alpha(\lambda 0x]CP(x)dx \qquad (6)$$

The formula representing the I-V characteristics of PV cell is stated as follows:

$$I_L = I_L - I_0\left[exp\left(\frac{qV}{nkT}\right)\right] \qquad (7)$$

$$V = \frac{nkT}{q} In\left(\frac{I_L - I}{I_0}\right) \qquad (8)$$

The power curve has a maximum point that is denoted as PMP i.e., the point where the PV cell would give the maximum output when operated.

The maximum power voltage is said to occur when the differential of the power generated by the cell is zero.

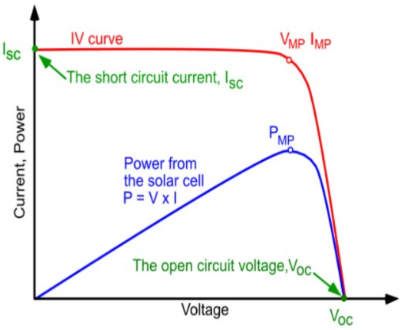

Figure 3: IV Characteristics of a PV Cell [21]

3.2 Simulation of a 400kW Grid Connected Solar Cell Farm using MATLAB/SIMULINK

The simulation shows a design model of a small Photovoltaic farm (400kW) that is been connected via a 25kV grid using a 2-stage converter.
The PV comprises of four PV cells arrays delivering a maximum of 100kW at 100W/m2 sun irradiance each.

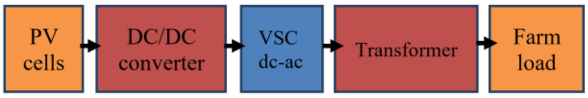

Figure 4: Block Diagram of PV Farm Energy System

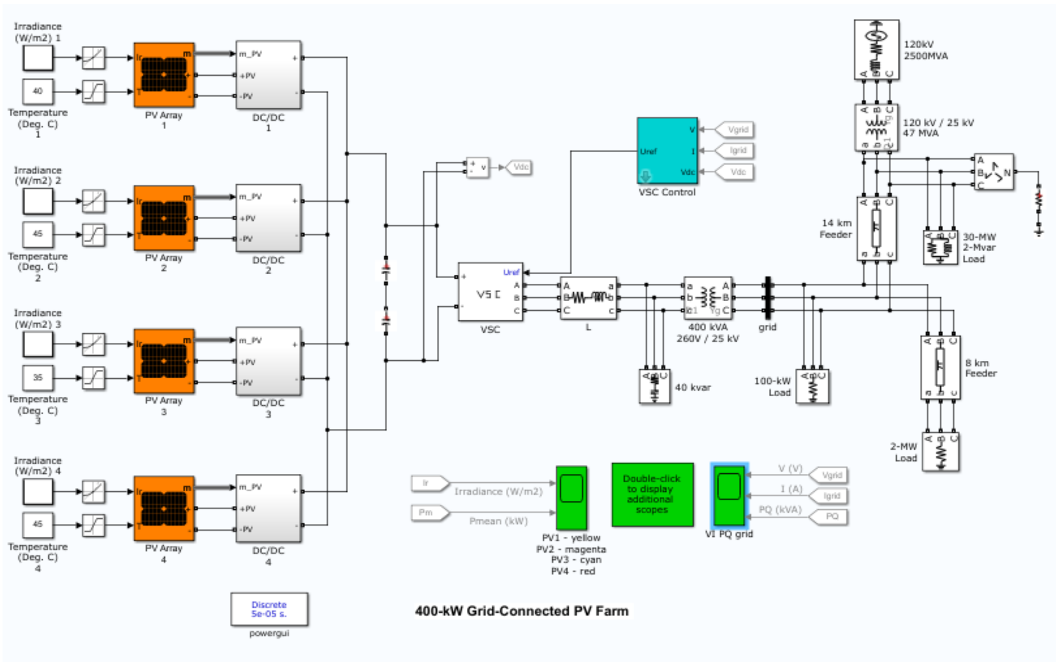

Figure 5: Simulation Diagram of a 400kW Grid Connected Solar Farm

3.3 Dc/Dc Converter

Each of the PV cell array is connected individually to a DC/DC Converter, thereby comprising of 4 DC/DC converters. The output from these boost converters is then connected together via a common DC bus of 500V. Each of the boost is individually controlled by the Maximum Power Point Track (MPPT). The MPPTs in this simulation make use of the "Perturb and observe" technique which varies the potential difference between the terminals of the PV array so as to obtain the maximum possible power. The equation masked in the boost in figure 5 is as follows:

$$P = V_a x I_a = V_{dc} x I_{dc} \tag{8}$$

$$from\ (9)\ \ PI_{dc} = \frac{V_a x I_a}{V_{dc}} \tag{9}$$

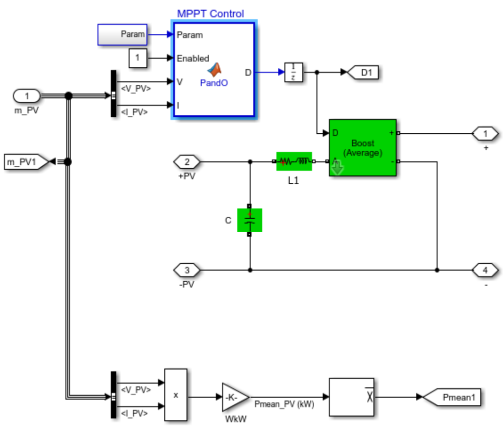

Figure 6: A DC/DC Converter Block in SIMULINK

$$\frac{di_L}{dt} = \frac{v_L}{L} = \frac{v_{in} - v_0}{L}, t \in [0, Dt] \tag{11}$$

At t =t_1

$$\frac{di_L}{dt} = \frac{v_L}{L} = \frac{-v_0}{L}, t \in [Dt, T] \tag{12}$$

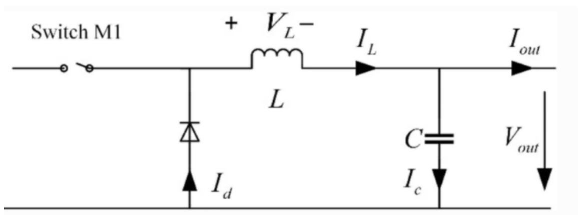

Figure 7: Electrical Model of a DC/DC Converter [20]

$$v_0 = \frac{1}{T}\int_0^T v_0\,(t)dt \tag{13}$$

therefore

$$v_0 = Dv_{in} \tag{14}$$

Where duty cycle is given as:

$$D = \frac{t_{on}}{t_{on} + t_{off}} \tag{16}$$

3.4 The Perturb and Observe Algorithm

The Perturb and observe technique is used for keeping track with the MPPT. In this algorithm, a minor perturbation is generated in order to cause a power disturbance/variation of the PV module. The output power of the PV is intermittently measured and is compared with the previous power. If the power of the output of the cell increases, the same process is repeated else the perturbation is reversed. In this, step wise process perturbation is produced in the PV module or the array voltage. The PV module voltage is either increased or reduced to evaluate if the power is increasing or attenuating. When an increase in voltage produces a corresponding increase in power, this implies that the operating point of the photo voltaic module is on the left-hand side of the MPP.

Henceforth it is imperative for further perturbation to the right to attain the MPP. On the other hand, if an increase in voltage produces a reduction in power, this definitely implies that the operating point of the PV module is located on the right side of the MPP and hence an increased perturbation towards the left is necessary to ascertain MPP. Immediately the MPPT charge controller is connected across the PV module and battery, it takes an instantaneous measurement of the PV and battery potential difference. After taking this measurement, it ascertains if the battery is fully charged or not. If the battery is charged to its maximum, it discontinues charging to prevent over charging of battery, else it engages charging by turning on the DC/DC converter.

The work of the microcontroller is meant to calculate the current output power P_{new} by measuring the present voltage and current, and then comparing this measured power to the previously measured power P_{old}. If $P_{new} > P_{old}$, the pulse width (TON) modulation duty cycle is raised to ascertain the maximum power from the PV cell. Conversely, if $P_{new} < P_{old}$, the duty cycle is reduced to ascertain the system returns to the previous maximum power.

ISSN: 2456 - 3935
International Journal of Advances in Computer and Electronics Engineering
Volume 7, Issue 4, April 2022, pp. 1 – 10

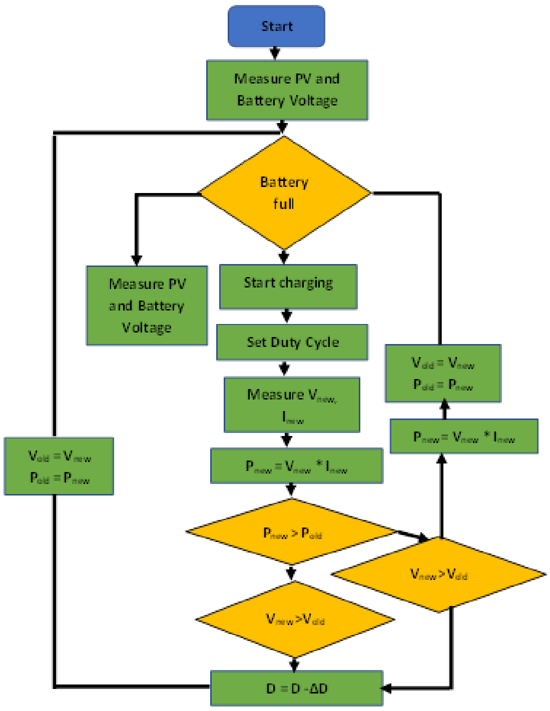

Figure 8: Perturb and Observe Algorithm for DC/DC Converter [20]

3.5 Voltage Source Converter

A voltage-sourced converter helps in generating an ac voltage from a dc voltage [22]. As illustrated in Fig 5, the 3 φ voltage source converter (VSC) converts 500V DC to 260V AC and keeps the power factor at unity. This voltage is meant to be distributed to the various compartments of the farm via a 3 φ coupling transformer which connects the converter to the grid. As shown in Fig 4, the grid model comprises of typical 25-kV distribution feeder and 120kV equivalent transmission system.

The boost and VSC converters are represented by their respective equivalent voltage sources by generating the average AC voltage over one cycle of the switching frequency. This model does not require harmonics, but the mechanism resulting from control system and power system interaction been preserved. The model makes use of larger step size for faster simulation (50μs), resulting in a much quicker simulation time frame. The VSC controller consist mainly of active devices as seen in Figure 10:

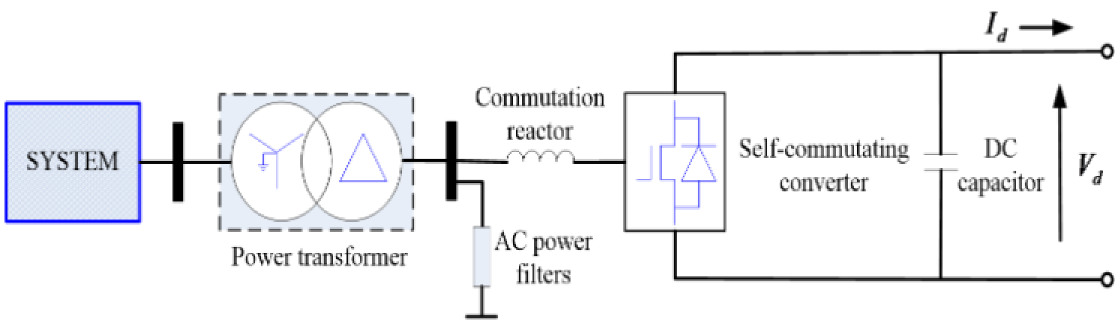

Figure 9: Electrical Model of a Voltage Source Converter [23]

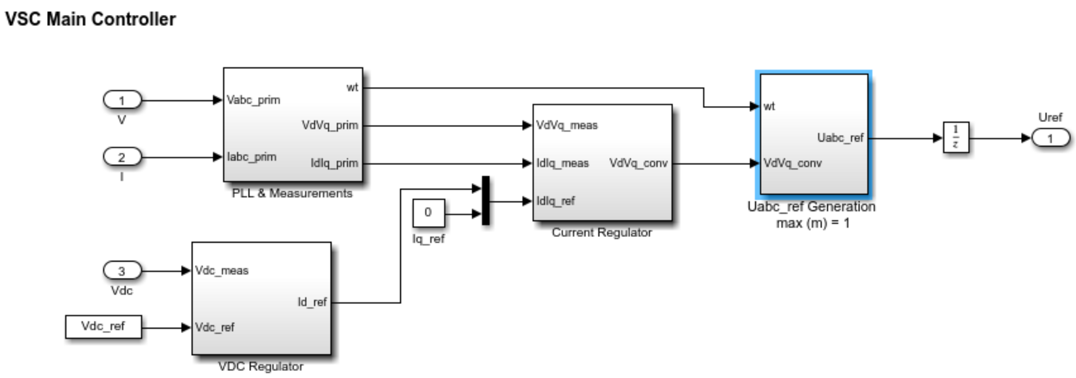

Figure 10: Block Diagram of Voltage Source Converter in SIMULINK

ISSN: 2456 - 3935
International Journal of Advances in Computer and Electronics Engineering
Volume 7, Issue 4, April 2022, pp. 1 – 10

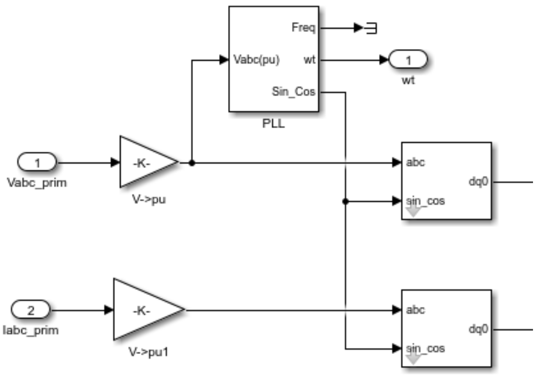

Figure 11: PLL Diagram

I. Phase Locked Loop (PLL) model

II. Vdc Regulator & Current Regulator.

1. A voltage reference generator (Uabc)

The mathematical model for the PLL block is stated as follows:

$$V_d = \frac{2}{3}(V_a \sin \omega wt + V_b \sin\left(wt = \frac{2\pi}{3}\right) +$$

$$V_c \sin + \ (\mathrm{V_c} \sin\left(\omega t + \frac{2\pi}{3}\right) \quad (17)$$

$$V_q = \frac{2}{3}(V_a \cos \omega wt + V_b \cos\left(wt = \frac{2\pi}{3}\right) +$$

$$V_c \cos + \ (\mathrm{V_c} \cos\left(\omega t + \frac{2\pi}{3}\right) \quad (18)$$

$$V_o = \frac{(V_a + V_b + V_c}{3} \quad (19)$$

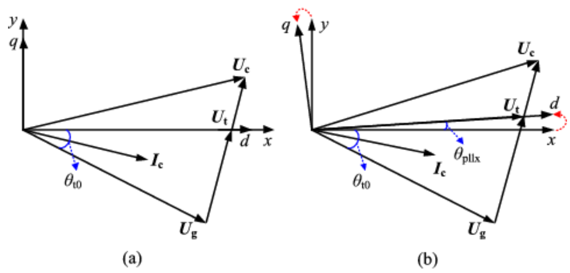

Figure 12: Phasor diagram for (a) VSC control in steady state (b) VSC control in transient state [24]

The purpose of the current regulator and voltage regulator is to provide a constant current and constant voltage regardless of changes in the input voltage or load current.

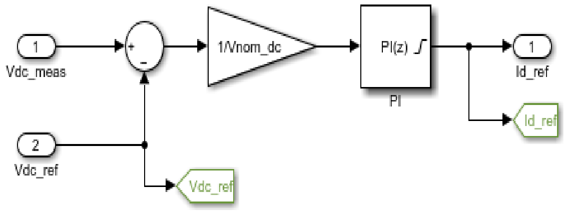

Figure 13: Block Diagram of Vdc Regulator in VSC

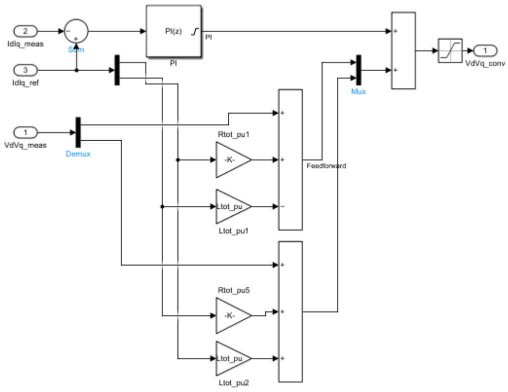

Figure 14: Block Diagram of Current Regulator in VSC

3.6 Transformers and Grid Connection for Solar Farm.

A 400kVA 260V/25kV step up transformer is deployed in the simulation to connect the converter to the farm load. A step-up transformer possesses more turns on the secondary windings than the turns on the primary windings. The voltage induced across the secondary windings is therefore larger than the applied voltage across the primary windings therefore one can say the voltage has been “stepped-up”.

As seen in figure 5 the grid model consists of the following:

1. A 120 kV transmission line.
2. A 25kV distribution feeder.

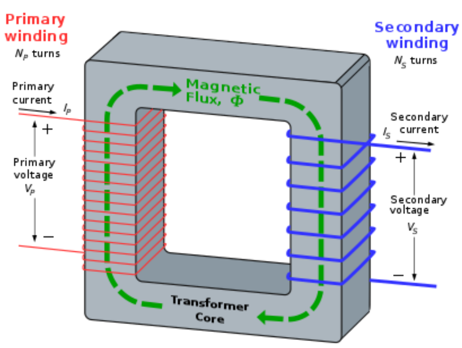

Figure 15: A Typical Transformer [25]

The basic mathematical formula for the step-up transformer is defined as follows:

$$\frac{Voltage\ in\ sec\,o\,ndary\ Coil}{Voltage\ in\ Pr\,i\,mary\ Coil} = \frac{Turns\ on\ Secondary\ Coil}{Turns\ on\ primary\ Coil} \qquad (20a)$$

Or

$$\frac{V_S}{V_P} = \frac{N_S}{P_S}$$

4. Results and Discussion

A three seconds SIMULINK simulation of the PV farm system is carried out allowing us to inspect the distinct operation of an individual PV array system under varying sun irradiance. A mathematical function is used to generate random irradiance of sunlight during the period of simulation.

The below graph (figure 16-19) shows the irradiance, the voltage, current, mean power and duty cycle respectively for the PV1, PV2, PV3 and PV4 cells made up of 5 sun power SPR-315E module.

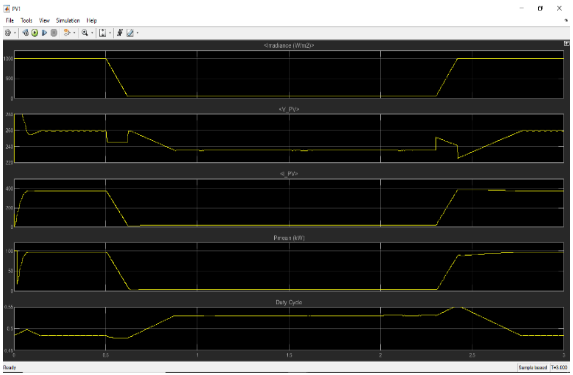

Figure 16: Graph showing irradiance, voltage, current, duty cycle and mean power for PV1

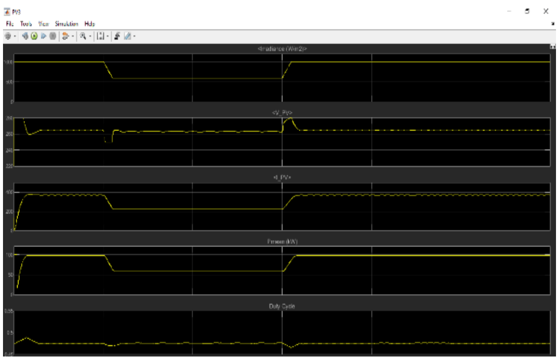

Figure 17: Graph showing irradiance, voltage, current, duty cycle and mean power for PV2 cell

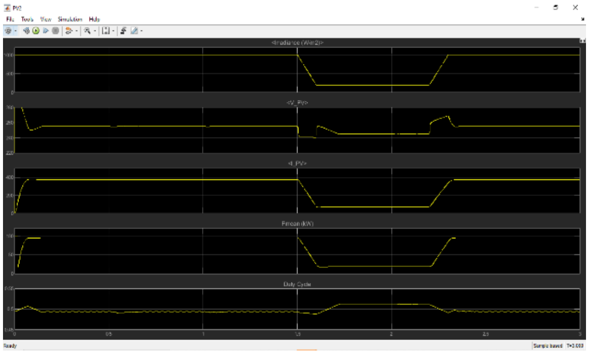

Figure 18: Graph showing irradiance, voltage, current, duty cycle and mean power for PV3 cell

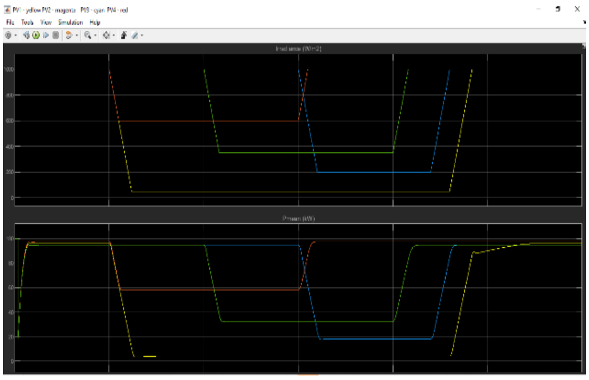

Figure 19: Graph showing irradiance, voltage, current, duty cycle and mean power for PV4 cell

The combined values of the irradiance of the PV cells and their equivalent average power is depicted by Figure 20:.

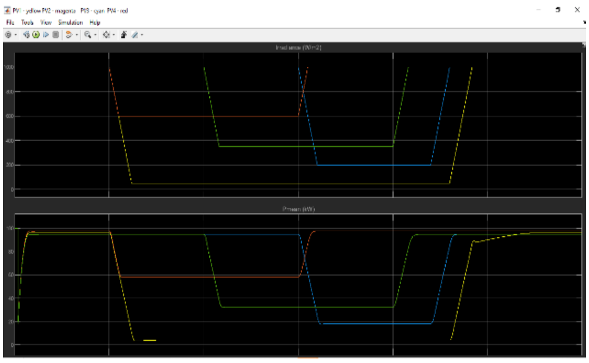

Figure 20: Graph comparing the instantaneous irradiance of the distinct cell and the average power

V1 – yellow
PV2 – magenta
PV3 – cyan
PV4 - red

The mean power increases as the sun irradiance increases for each PV cell as seen in Figure 20.

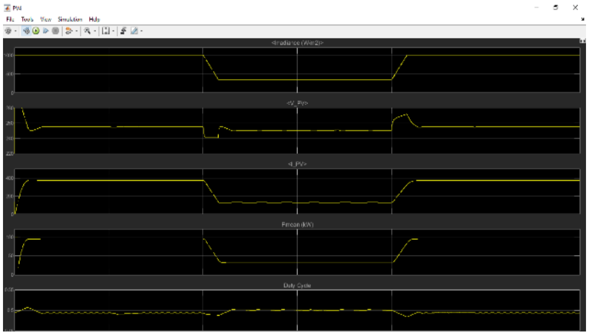

Figure 21: Graph showing the resultant DC voltage of the four PV cells at about 500Vdc

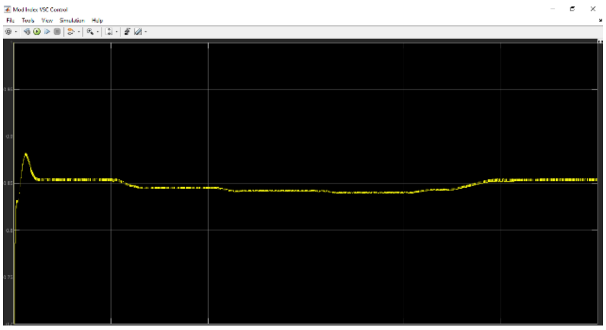

Figure 22: Modulation index of VSC.

The modulation index of the voltage source converter is observed to range from a value of 0.7-0.9 as seen in the figure above.

The real power (kW) finally generated to the farmland is observed to range between 400kW-500kW. A power factor of unity is achieved in the experimental design as the reactive power (Q) is observed to attenuate to zero as seen in Figure 23.

Real power P (kW) – yellow line
Reactive power Q (kVAR) – blue line.

The simualtion design of the PV farm system operates with negligible loss of power as the real power is approximately the same as the apparent power . The key result parameters of the power analysis is outlined below:

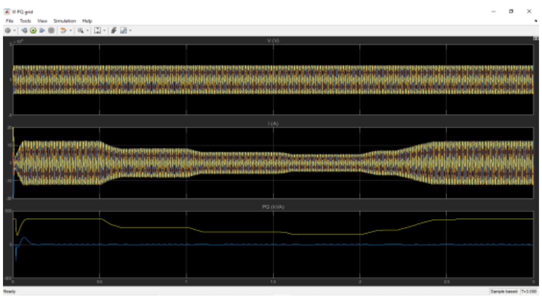

Figure 23: A graph showing voltage (V), current (I), real power(P) and reactive power (Q) at the grid.

Real power = 400kW-500kW
Apparent power = 400k
VA-500kVA
Reactive Power = 0kVAR
Power factor = Unity.

The mathematical expression relating the real power (P), reactive power (Q), apparent power (S) and power factor (θ) is illustrated by the figure and formula below.

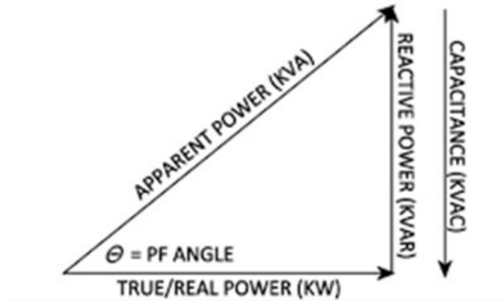

Figure 24: Electrical Power Triangle [26]

If :
S = Apparent power (kVA)
P = True/Real Power(kW)
Q = Reactive Power (kVAR).
θ = power factor angle

$$S = \sqrt{P^2} + Q^2 \qquad (21)$$

$$Power\ \ factor = \frac{P}{Q} = cos\,\theta \qquad (22)$$

The output power of the PV farm system is observed as to be very stable and reliable as seen in Figure 23. The simulation design can therefore be deployed as alternate power supply means to mechanized farms like the Obasanjo farm Ota, Maizube farm Niger, Sebore farm Adamawa, Anadariya Farm Kano in Nigeria.

Improvenment can be carried out on the research work to incerase the p efficiency of the power supplu using more optimized algorithm such as deep learning technique to minimize power consumption during idle time of farm land operation.

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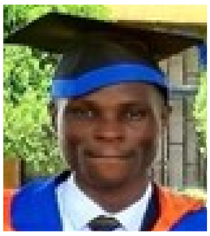

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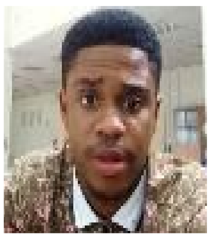

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