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Dynamic Simulation of Solar Energy System for A Shop in Nigeria Providing Community Cellphone Charging Service.

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***Abstract*— The dynamic simulation of a hybrid power system that combines solar energy and the traditional power supply system to ensure reliable and sustainable power supply for a shop in Nigeria that provides community cellphone charging services is presented in this paper. The name of the supermarket is Better Mart, and it is located at Remlek Bus stop Badore, Ajah Lagos State, Nigeria which is known for consistent power outages. The designed hybrid power system at Better Mart consists of 240 pieces of Trina Duomax PEG14 PV panels with a rated capacity of 320 Watts each and a total of 76.8 kW which is connected to a 360 VDC bus, 50 kVA Caterpillar generator that runs on diesel, Grid system, 24 kW Fronious Symo Inverter and 30 pieces of each 12 V/220 Ahr EnerSys PowerSafe SBS 1800 battery storage. The sizing of the designed system was carried out with Homer Pro software while the dynamic simulation was done in MATLAB Simulink environment. The dynamic model of the system is fast and accurate as can be seen from the MATLAB simulation results.**

***Index Terms*— Sustainable power, Hybrid power system, Dynamic simulation, Power outage Grid System, Dynamic Model**

1. INTRODUCTION

Electricity has been of immense importance to man, the contributions of early scientists brought to light the understanding and concept of power generation. This concept involves the conversion of finite natural resources to electricity which has been used for decades. The over reliance on these finite natural resources has caused depletion of these resources, disruption of natural environment and conflicts among nations and groups to have access and control over these resources. The over dependence on these natural resources like fossil fuels has negative effects on the atmosphere which has resulted to long term increase in average temperature due to pile up of greenhouse gases in the atmosphere. The primary greenhouse gases include carbon dioxide CO_2, Nitrous Oxide N_2O, methane CH_4, and other fluorinated gases[1]. Climate change is expected to cause approximately 250,000 additional death per year between 2030 to 2050 according to World Health Organization W.H.O. To avoid or mitigate the forecasted effects of climate change, individuals, communities, businesses and the government need to come up with a multifaceted approach that involves promoting clean and sustainable practices.

Transitioning to the use of renewable energy is one the key areas that need to be exploited to achieve zero emission. These sources of energy have no negative environmental impact and produce little or no greenhouse gases, it is also worth noting that these sources are abundant and replenishes naturally and will help to reduce the over reliance on the non-renewable sources such as coal, oil and natural gas. The addition of PV system to the traditional power supply will help to reduce electricity cost and diesel cost, it will also help to reduce vulnerability to grid outages thereby increasing system energy resilience. The hybrid power system consists of PV, Battery energy storage system, grid system and a diesel generator. The sizing of the hybrid system can be done with Homer Pro to determine the most cost-effective undersized energy resources which helps to reduce the capital, operational and maintenance cost, it will also ensure that resources are not over or under sized. The modelled system in the MATLAB environment is important to know how the system will behave over a period when subjected under various conditions, it also helps to provide real time control and analysis. Solar system has gained popularity in recent years because of its advantages especially in carbon reduction footprint, energy independence and long-term return on investment.

Nigeria has a great potential of photovoltaic energy because of its geographic location that is near the equator which makes it to receive an average sun irradiation of 5.4 kWh/ m^2/day with an average incident solar energy of 1831.06 kWh annually and a landmass of 924 km^2[2][3]. This statistic shows that Nigeria has a great potential of solar energy that can be utilized in solving the epileptic power supply in the country if only the right policies, reforms, investments and infrastructure improvement that will drive the massive utilization of the solar potential and other renewable sources of energy is put in place. In 2005, Nigerian government created Renewable Energy Master Plan (REMP) program in other to promote the diversification of renewable energy. The REMP program aims to achieve 23% of electricity generation from renewable energy sources in 2025 and further increase it to 36% in 2030. This paper will talk about the Dynamic simulation of solar energy system for a shop in Nigeria that provides community cellphone charging services, it has two outputs, one is for the cellphone charging service while the other one is for powering the electrical appliances in the supermarket. Many similar designs and projects related to this topic have been carried out by other scholars which will be discussed in this paper to get ideas and insights of their work.

In [4], a hybrid power system (HBS) was sized with homer pro and modeled with MATLAB, the project is designed for a remote town called Paradise river located in the north of Labrador, Canada. The renewable energy system (HBS) is made up of PV system, Battery storage system, Diesel generator, DC to AC inverter and the load model. The aim of the project is to provide affordable and sustainable energy while reducing greenhouse gas emissions. The electrical load data for a year of the site was collected and used for the homer pro sizing. The optimization results of the design shows that the following is needed: 186 kW capacity PV array, 780 number of batteries which means 13 strings with size of 60, one diesel generator Cat 45, and one IM 66kVA TR UL inverter. In the Simulink modeling, Perturb and Observation (P&O) method is used for controlling the MPPT.

In [5], the recent development of renewable energy in China was highlighted, Qinghai province was the selected site for this study. The sizing of the system was done with homer pro, Beopl software was used to generate the load data of the selected site while the system dynamic simulation was done with MATLAB. In this design, the charge controller of the battery sends signal to the MPPT and the PID of the diesel generator to avoid overcharging the battery.

In [6], the modeling and simulation of a stand-alone PV system was carried out in MATLAB environment under different load variation in other to analyze the system under these conditions. In this paper, a DC-DC converter with MPPT is connected to the solar array to extract maximum power from the PV while a second DC-DC converter is connected to the output of the first DC-DC converter with MPPT to increase the voltage received from the PV generator to match with the voltage level required by the voltage source inverter (VSI) through a LC filter. The simulation results of the design are as well presented in the paper.

2. DYNAMIC SIMULATION AND MODELING OF THE DESIGNED SYSTEM.

System dynamic simulation and modeling help to understand and visualize a complex system over time when subjected to various changes. Simulation is important in identifying potential issues in the system, allowing for testing and optimization of design thereby making sure that the design matches the energy needs and performance requirement. The system is designed and simulated in MATLAB/Simulink environment, and it consists of the PV system, Diesel generator, the grid and the battery system. The result of the simulation will be presented in this paper. The block diagram of the overall system can be seen in figure 1.

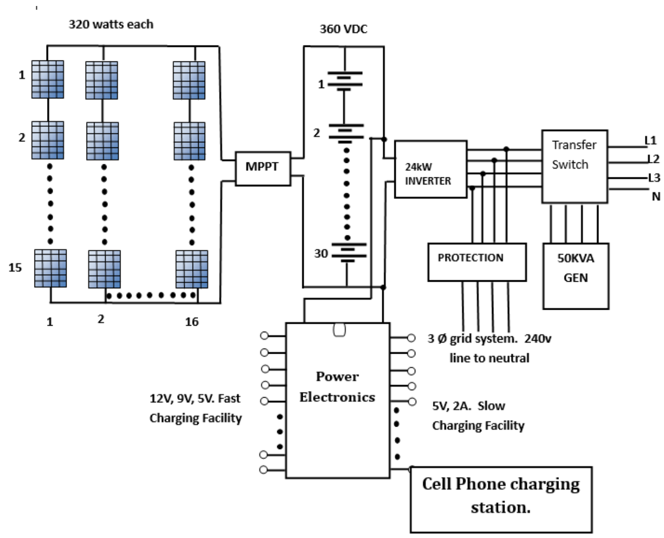

Fig 1: Complete block diagram of the system.

2.1. MODELING OF THE PV ARRAY.

PV array works with the principle of photovoltaic effect where sunlight arrays is converted to electricity. The sunlight is composed of packets of photons and when they hit the PV cells, it excites electrons which creates electron-hole pairs that is responsible for creating electricity[7]. A solar module or solar panel is made up of solar cells that are connected, they are the building blocks of solar system while solar array is made up of solar modules that are connected either in series or in parallel to form a larger solar power system. In this design, the PV array consists of 240 Trina Duomax PEG14 PV panels with a rated capacity of 320 Watts each and a total of 76.8 kW which is connected to a 360 voltage DC bus. The diode I-V characteristics for one module can be written as:

$$I_d = I_o\left[\exp\left(\frac{V_d}{V_T}\right) - 1\right] \quad (1)$$

$$V_T = \frac{KT}{q} \times nI \times N_{cell} \quad (2)$$

The current output of a PV cell can be written as:

$$I_d = I_{ph} - I_o\left(e^{\frac{V_d + IR_S}{nV_t}} - 1\right) - \frac{V_d + IR_S}{R_{sh}} \quad (3)$$

Where:
I_d = Diode Current (A)
I_{ph} = Photocurrent (A)
V_d = Diode Voltage (V)
I_o = Diode saturation current (A)
R_{sh} = Shunt Resistance (Ω)
R_s = Series Resistance (Ω)
nI = Diode ideality factor
K = Boltzmann constant = 1.3806e-23 J.K-1
q = Electron charge = 1.6022e-19C
T = Cell temperature (K)
N_{cell} = Modules connected in series.

2.2 MAXIMUM POWER POINT TRACKING (MPPT).

Maximum Power Point Tracking (MPPT) is important in PV design because of its ability to optimize the efficiency of the PV system, MPPT technology works by continuously monitoring or tracking the voltage and current output of the PV array in other to find the Maximum Power Point (MPP) which is a point on the PV array where the product of the solar panel's current and voltage V-I is at its maximum, it is at this point that the solar panel will operate in other to yield the maximum or optimal output[8]. In this design, the conventional Hill Climbing method MPPT was used. It works by continuously perturbing (changing) the duty cycle of the DC-to-DC converter that is connected to the output of the PV system, it then observes the power output of the change[9]. If the power output increases, the perturbation will continue in the same direction, if it reduces, the perturbation will reverse. The process will continue until the system reaches the maximum power point of the power-voltage curve, P-V.Hill Climb method was used because it is simple, and it efficiently tracks the maximum power point without requiring much computational resources[10]. Perturb and Observation method of hill climbing algorithm was adopted in the design and the output of the MPPT is 120 V which is further reduced to 12 V, 9 V, and 5 V by controlled voltage source. The output 5 V high and 5 V low are used for cellphone charging purposes[11]. The duty-based P&O works with the mathematical expression below:

$$D(K) = D(K-1) \pm Step. \quad (4)$$

Where:
$D(K)$ = Duty at K^{th} iteration.
$D(K-1)$ = Duty at $D(K-1)^{th}$ iteration and the step is the duty perturbation step - size.

2.2.Battery Storage Model.

Battery storage systems play a crucial role in hybrid power systems. They store excess energy from the PV array thereby ensuring that energy efficiency and electrical power reliability is maintained. Batteries reduce fuel consumption and maintenance cost of the generator when they are used as backup. The use of battery storage system in hybrid power system not only reduces the cost of electricity and fuel consumption but also has great environmental benefits by reducing the carbon dioxide CO_2 emissions and the noise from the diesel generator. In the design, 30 pieces of 12 V/220 Ahr is used, it has an initial state of charge of 100% and a minimum state of charge of 30%, the charge controller of the battery is embedded into the MPPT of the system, this is done to prevent the batteries from overcharging.
The following equation below is related to the charging and the discharging of batteries.

$$E_{charge} = E_o - \frac{KQi^*}{i_t + 0.1Q} - \frac{KQi_t}{Q - i_t} + Laplace^{-1}\left(\frac{A}{\frac{s}{Bi_t}+1} \cdot \frac{1}{s}\right) \quad (5)$$

$$E_{discharge} = E_o - \frac{KQi^*}{Q - i_t} - \frac{KQi_t}{Q - i_t} + Laplace^{-1}\left(\frac{A}{\frac{s}{Bi_t}+1} \cdot 0\right) \quad (6)$$

Where:
E_o = Constant voltage (V)
Q = Maximum battery capacity (Ah)
K = Polarization constant
i_t = Extracted capacity (Ah)
B = Exponential capacity $(\text{Ah})^{-1}$
i^*= Low frequency current dynamics (A)

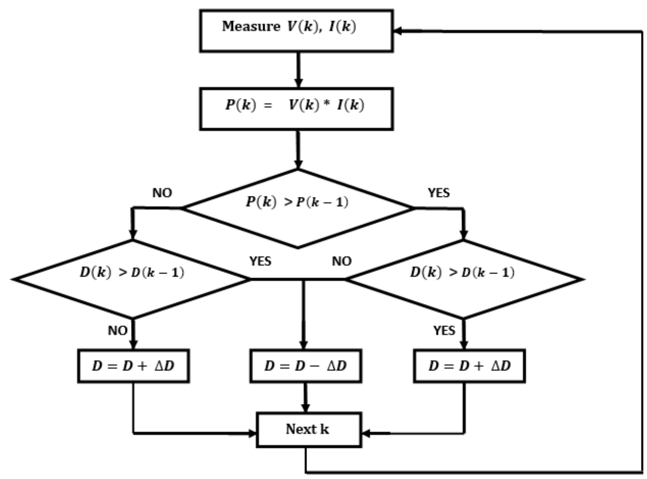

Fig 2: Flowchart of MPPT Algorithm.

2.3. Diesel Generator Model.

Diesel generator is an important component of the hybrid power system. It provides reliable power backup when there is no electrical power coming from other power sources of the hybrid power system. Diesel generators also come into play when balancing the load by supplying enough power that can serve the peak load. Over-discharge of battery storage unit can be prevented when the diesel generator is in operation. The combination of diesel generator and the other power source of the hybrid power system improves the reliability of the power system. AC generator was used because it is easier to maintain and does not have a commutator that is replaced regularly. The model of the diesel generator used in this project is CAT-50 kVA-50 Hz-PP. This model uses an internal combustion engine therefore, frequent on and off cycle that reduces the efficiency of the generator is avoided. To overcome this frequent on and off cycle, a charge control signal is assigned on, if the power generated by PV array is lower than the load power, the generator will be started; otherwise, the generator will be switched off. When the charge control signal is in an off state, the generator will be switched off regardless of the comparison result.
The transfer function of the generator that I used is:

$$Hc = \frac{K.(1 + T_3.S)}{(1 + T_1.S + T_1.T_2.S^2)} \quad (7)$$

Where:
Hc = Transfer function of generator controller.
K = The system gain.
$T_{1,}T_{2,}T_3$ = Time constant.
S = Frequency variable in Laplace transform.

2.4.Inverter.

An inverter is an electrical device that converts DC voltage to AC voltage, this technology is important in Renewable energy applications especially in PV application where the DC

voltage generated by the PV panel is converted to AC voltage that will be used in homes, offices, supermarkets etc. Inverters help to integrate the power generated by the solar panels with the conventional power systems therefore making the power system to be versatile and reliable. In this design, a universal bridge inverter is used because of its rapid switching in the direction of current flow through the electrical load. The configuration is made of four MOSFETS that are arranged to allow current to flow in both directions through the electrical load. An oscillator that produces square waves is used to control the switching of the MOSFETS which makes the direction of the current alternate thereby creating an AC waveform from the DC input. The output from the inverter is 120 V which enters the three-phase step-up transformer that raises the voltage to 400 V and then connects to 400 voltage bus. The 3-phase voltage coming from the grid is connected to 400 V AC bus voltage from which it is connected to a three-phase circuit breaker that connects the electrical load.
Fig 3 below shows the overall Simulink block diagram.

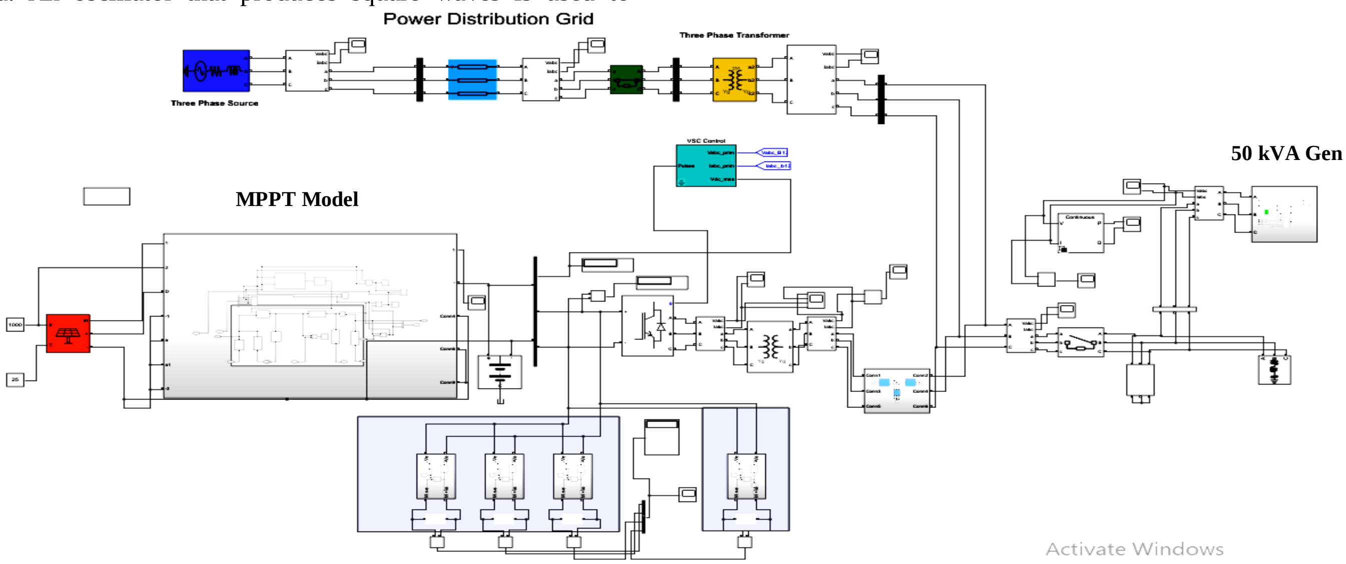

Fig 3: Simulink block diagram of the system.

3.0 SIMULATION RESULTS.

Simulation results are presented in this section, the results help to verify the validity of the hybrid power system of the supermarket. The result of the simulation was obtained with MATLAB/Simulink tool*[12]*.

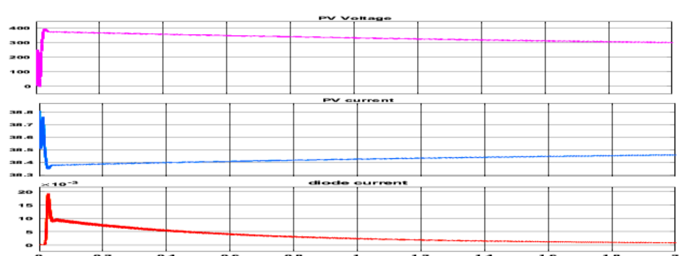

Fig 5: Current-Voltage characteristics of PV panel with diode current.

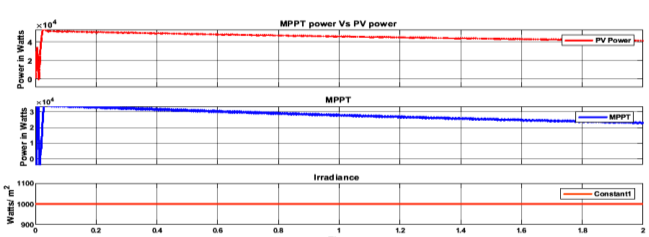

Fig 6: MPPT power when compared with PV power at 1000 W/m^2.

From the figures above, P & O MPPT algorithm was applied to 54 kW PV array that is made up of 240 modules, 16 parallel strings and 15 series connected modules per string at a constant irradiation level of 1000 W/m^2. With a constant irradiation of 1000 W/m^2, Perturb and Observation method was able to maintain stable PV output that is near the maximum power point. The output of the MPPT is connected to the 360 VDC bus which is a common direct current electrical pathway where power is distributed to various components of the hybrid system. In this design, the power for charging the battery storage system is tapped from the 360 VDC bus. The voltage for the cellphone charging facility is also tapped from the 360 VDC bus, the tapped voltage is reduced to 12 V, 9 V, and 5 V, the 5 V is for cellphone charging purpose as shown in figure 5 below.

Fig 7:12 V, 9 V, 5 V and 4.8 V output voltages.

The electrical load connected to the hybrid system is an RLC load (resistive, capacitive and inductive load). When the three phase circuit breaker is closed, the following result is obtained from the hybrid system and the backup 50 kVA diesel generator. Figure 6 below shows the simulation results.

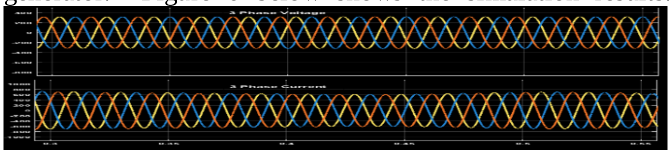

Fig 8: Voltage and current from the hybrid power system when the circuit breaker is closed.

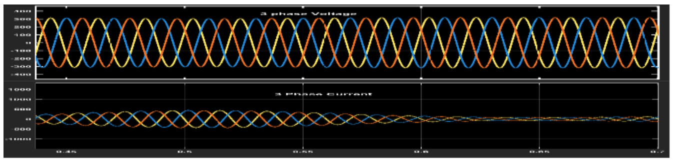

Fig 9: Voltage and current from the diesel generator when the circuit breaker is closed.

When the three phase circuit breaker is open, the following results are obtained in figures 8 and 9 below.

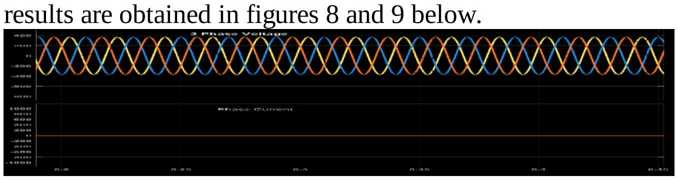

Fig 10:3 phase voltage and current from the hybrid system.

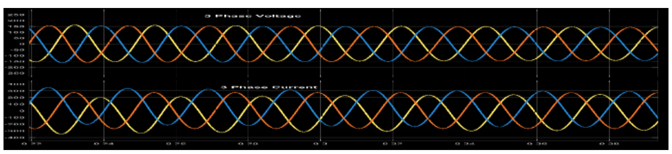

Fig 11: 3 Phase voltage and current from the diesel generator.

3.1. CONCLUSION

In this paper, the dynamic simulation of a hybrid power system that combines solar energy and the traditional power supply system to ensure reliable and sustainable power supply for a shop in Nigeria that provides community cellphone charging services is presented. The designed hybrid power system at Better Mart consists of 235 pieces of Trina Duomax PEG14 PV panels with a rated capacity of 320 Watts each and a total of 75.4 kW which is connected to a 360 VDC bus, 50 kVA Caterpillar generator that runs on diesel, Grid system, 24 kW Fronious Symo Inverter and 30 pieces of each 12V/220 Ahr EnerSys PowerSafe SBS 1800 battery storage. The simulation is carried out in a MATLAB/SIMULINK environment. The output of the simulation includes a stepped down voltages (12 V, 9 V, 5 V) the 5 V is used for cellphone charging purpose while 12 V and 9 V is used for charging other electronics that need to be charged with 12 V and 9 V. The three phase output from the grid, diesel generator and inverted voltage from the solar panel and battery storage is utilized in the supermarket for the efficient running of the electrical appliances in the supermarket. The transient of the simulation is presented in form of graphs as can be seen in the results presented.

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