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Mathematical Models for the Design of PV Solar Power System as Alternative Energy Source in the Tropical Geoenvironmental Zone

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ABSTRACT

The move to sequestrate environmental pollutants occasioned by hydrocarbon related fuels has led to the search for alternative energy sources worldwide. The efficiency and reliability of most clean energy sources are functions of the design process and availability, which depend on the models and geographical location of a place, respectively. The geographical location of Nigeria in the tropical zone grossly favours the harvesting of solar energy as an alternative energy source. Unfortunately, despite the availability of solar energy flux in the area, the population still depends on hydrocarbon-related fuels, arising from the underperformance of PV solar power installed in homes and streets. Therefore, it is necessary to develop mathematical models that can aid in the installation of reliable PV solar power systems. These mathematical models can alleviate the level of population ignorance in the design of reliable PV solar systems. Mathematical models were used to design PV solar power system for hypothetical load systems. The results show that designing a PV solar power system using mathematical models with assumptions specific to local geoenvironmental conditions could aid the installation of reliable power systems.

Keywords: Alternative energy, Inverter, Photovoltaic, Models and geoenvironmental.

INTRODUCTION

Traditionally, the world's electrical needs have been fulfilled by fossil fuels like oil, natural gas, and coal. However, these energy sources have two main negative impacts: they play a bigger role in global warming and acid rain pollution, which negatively impacts many animals, plants, and humans in the environment. In addition, hydrocarbon has been discovered to be associated with global greenhouse gases responsible for depletion of the ozone layer [1,2]. Therefore, the quest for alternative energy supply becomes a global niche with the intentions of curbing environmental pollution. The dense pollution of the environment and its attendant effects have informed gradual shift from hydrocarbon energy source to renewable energy witness across the globe. Attempts to sequestrate greenhouse gases from the Troposphere have not been very successful [3-5]. Therefore, it is essential to explore clean energy sources which produce little to no global warming emissions.

Generating electricity from renewable energy rather than fossil fuels can offer significant public health benefits. Air and water pollution emitted by coal and hydrocarbon plants is linked to respiratory problems, neurological damage, cardiac attacks and cancer [1,6]. It has been discovered that of all renewable energy sources; wind, hydroelectric and solar power systems generate electricity with no associated air pollution emissions [1,3,7]. However, wind and solar energy require essentially no water to operate, therefore, do not pollute water resources or strain water supply by competing with agriculture, potable water systems, or other important water needs. In Nigeria, the erratic nature of wind energy and its associated complex technology to harvest and consume as electrical energy, has made solar energy system the best alternative energy option. In addition, the escalated price of hydrocarbon related fuels, which the country's economy relies on, has forced populace to explore alternative means of electrical power supply for private and public use. Today, a fraction of homes, banks and some public organisations obtained their electrical power needs from solar energy.

The Tropical Climatic Zone (TCZ) has advantage of receiving intense vertical sunlight that drives massive amount of solar flux of 1.08 GW x 108 GW to the Earth surface [8-10]. Interestingly, if just 0.1% of this energy is converted into electricity at as low as 10% efficiency, it would provide an equivalent of about 10,000GW of power generating capacity. This is large enough to be relied upon as to provide a significant share of future electricity needs. Despite that Nigeria is in the Tropical climatic zone, the imminent concern faced by the populace with PV solar power systems is poor performance and sometimes outright failure [9,11,12]. One is thereby faced to believe that there exit error in PV solar power components matching. Consequently, poor performance of PV solar power in the study area could result from the level of ignorance on the part of the populace on the design of PV solar energy system required to drive necessary appliances. It becomes imperative to outline mathematical models for PV solar power system design and installations. The rationale behind this research is to domesticate mathematical models for the design of PV solar power system with assumptions from local geoenvironmental conditions of the Tropical climatic zone.

MATERIALS AND METHODOLOGY

Major components of pv solar power system and their mathematical models

The energy from the sun is generated by nuclear reactions within the body of the sun. It reaches the earth surface in the form of electromagnetic radiation, which varies with locations. Therefore, solar energy is the transformation of solar radiation into needed power. This energy can be captured and utilized through passive and active methods [9,13]. The passive method such as Concentrated Solar Power (CSP) method does not use mechanical system [13-15]. The active method deploys mechanical equipment such as PV solar panel to capture solar radiation [13,16]. The PV solar power system is an ensemble of various components that trap solar radiation, regulates it transmission, stored electrical current, convert DC to AC and distribution to predetermined loads. Therefore, the primary components of a PV solar power system are: the solar panels, charge controller, storage batteries, inverter and loads (Figure 1). The current produced by cells depends upon the area of the panel, amount of light falling on the panel, angle of light falling on panel and current density [17-24].

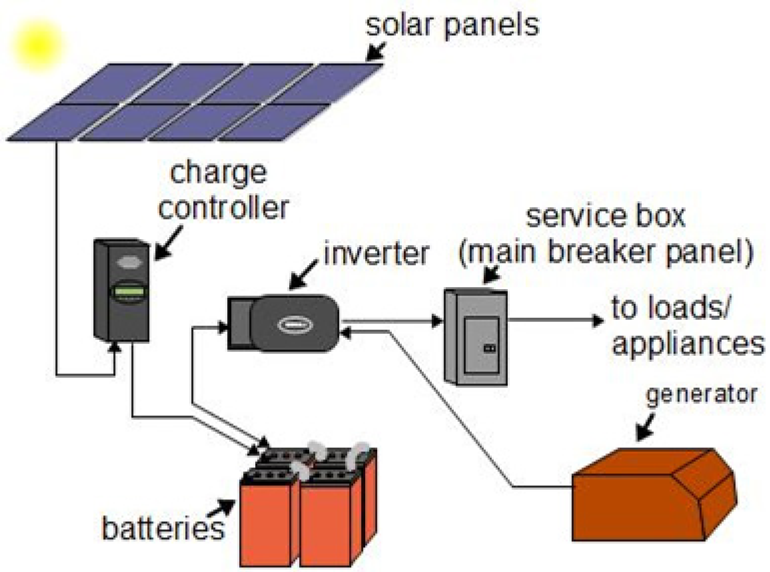

Figure 1. Typical configuration of solar power system

Operational design of solar panel model

The electrical power needed to drive loads cannot be provided by a single solar cell, therefore, an arrangement of solar cell called PV modules is required. The PV modules make it possible to supply large power demanded to derive loads in KW, MG or GW especially for industrial use [25-32]. The basic requirement of PV modules is to provide sufficient voltage to charge batteries use to power appliances. The cells of photovoltaic panel consist of positive and negative silicon that is placed underneath a slice of glass. When the photons from the Sunlight falls on the PV cells, they emit electrons present in the silicon atom, thereby setting up potential difference across it two terminals, the anode and cathode. Thin wires attached to the silicon cells in PV module transfer electrons to connecting PV circuit, which allow for direct current electricity [33]. According to [33-36]. in order to increase the Potential Difference (Pd) so as to achieve required Pd, N-number of cells are connected in series (Figure 2). For instance, suppose 40 cells of 0.6v are connected in series, 24v is achieved, while the current remains constant. Also, to build up current in the PV module, some cells are arranged in parallel (Figure 3), while the voltage remains constant. Solar PV modules are available in Watt, but many times, we need power in a range from KW to MW and sometimes GW. To achieve such a large power, we need to connect N-number of modules in series and parallel. The total N-number of PV modules are connected in series they form PV module string.

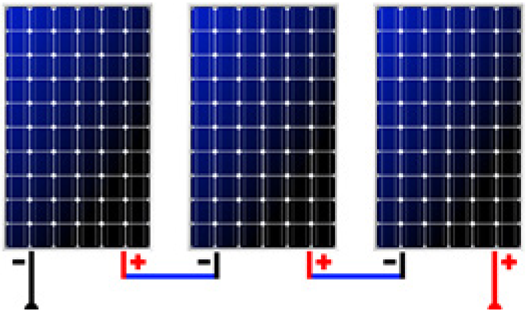

Figure 2. Series connection of cells in solar PV modules

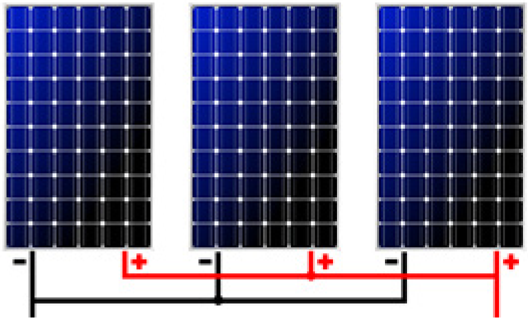

Figure 3. Parallel connection of cells in solar PV modules

For the safety of PV panel, the by-pass diode and the blocking diode are introduced. The by-pass diodes are connected in parallel to solar cells to act as an open circuit when a cell in a PV module is shade from solar radiation [37-40]. However, the blocking diode prevents current from leaving PV module when no solar radiation is reaching it. In general, PV module parameters are measured by the manufacturers under Standard Test Condition (STC), which is 25°C and solar flux of 1000W/m2 [36,41,42]. Unfortunately, PV module operation outside the STC, this could constitute uncertainty, which is often accomplished with drop in PV power output. Therefore, proper design is required to compensate for drop in power before components' installation phase. First in the design process is the determination of actual and realistic loads, as well as the module capacity to support the loads. These, the populace are ignorant of. Equation (1) determines the expected PV output power taking into consideration the compensation for PV power system drop:

$$P_{out} = \sum_{1}^{n} P_a + Z \quad (1)$$

where Pout is the desired output power to drive all Appliances Loads (Pa) and Z is compensation constant representing 40% of total appliances' wattage to compensate for power loss arising from PV system uncertainty. The Energy Require Per Day (Ee) can be computed by considering the summation of hours the PV system is supposed to drive each appliance. This is obtained by:

$$E_e = P_{out} * \sum H_r \quad (2)$$

where Hr is the running hours of appliance. By considering 4hours of Average Peak Sunshine (Shp) period in Tropical region, the solar PV module power capacity per peak hour can be determined using:

$$C_p = \frac{E_e}{SH_h} \quad (3)$$

Therefore, the required number of solar PV (Np) module to support the needed capacity could be obtained by:

$$N_p = \frac{C_p}{W_p} \quad (4)$$

where Wp is the wattage of available or choice solar PV module. It is a good estimation practice to add 25% to the Number Of Solar Modules (Np) to compensate for energy loss due to solar PV modules. Solar panels are mounted in open space that is not obstructed by trees, building, structure, facilities or any installation. Therefore the availability of space should be considered in the choice of solar panel options. The three main solar panel options available in the marketplace are: polycrystalline, monocrystalline and thin films. The disparity between the polycrystalline and monocrystalline lies in the constitution of the silicon crystal substrate utilized in the manufacturing of solar cells and ultimately, solar panels. The polycrystalline utilized numerous crystals, while monocrystalline panels are made from a single crystal, it the smallest in size, hence, are ideal for small spaces. However, the thin film is typically bigger in size and a lot more efficient during the day.

Model for estimating solar inverter size

The solar inverter is use to convert DC from the solar PV modules or from battery bank to AC, which can be used by various appliances just the way electronics powered with normal electricity. Some inverters are stand- alone while others are grid tie. The frequency of Grid Tie Inverter (GTI), by the usage of the local oscillator should get harmonized with the grid's frequency which is 50 Hz or 60 Hz. Also it regulates the voltage level of the inverter not to exceed the voltage level of the grid. In the small-scale grid, one have just two components which are the panels and inverter, while the off grid systems are complicated and consists of batteries which allows users to use appliances during the night when there is no Sunlight available. However, inverters are either rated in KVA or KWh.

In an elementary circuit of an inverter, DC power and a transformer are connected by the center tap of primary coil. Due to swift switching of the current between two distinct paths it reverses to DC source by one extreme of primary winding and the through other [14,41]. This gives rise to fluctuation of current of different route in the transformer's primary coils, thereby producing alternating current in the secondary coils. An inverter produces either square waves or a sine wave which is used for running appliances. A three-phase inverter is connected to one of the three load terminals. It consists of three single-phase inverter switches, as shown in Figure 4a. However, the connection of a single phase inverter is illustrated in Figure 4b. Basically, the capacity of inverters should be as large as the proposed loads so as to supply enough power to all the necessary appliances. The model to determine the right size of inverter is given by:

$$I_s = \sum I^n P_a + \ell \quad (5)$$

where ℓ is safety factor, which allowed for 40% of the Total Load Wattage (Pa). For inverter rated in KVA, the Is (KWh) divided by 0.8 to obtain the KVA equivalent size.

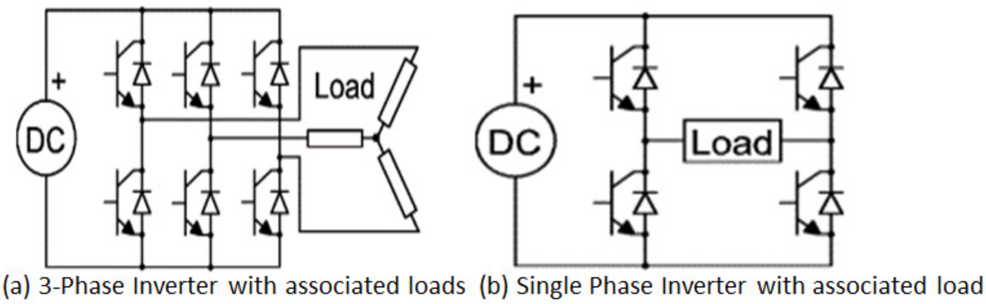

Figure 4. Circuit diagram showing phase connections of solar inverters with loads

Battery size

Battery is used for the storage of the output of solar PV and this is an essential component of the solar power system. The batteries capacity determine the current that is to run appliances when the solar panels no longer generate current. At the day time the battery stores the PV energy and after the sun has set this stored energy is provided to the appliances. The process of the charging and the discharging of the battery are also going on the same time which reduces the energy of the battery up to 15% [16,43]. thus the remaining efficiency of battery is 85%. This loss of the energy of the battery is the reason of the reduction in the efficiency of solar power system, it is also the reason for the use number of batteries in a system [15]. To determine the required number of battery, it was important to first determine the batteries size.

The Size Of Batteries (Bs) that could adequately support the needed loads, especially during the period of autonomy can be calculated as:

$$Bs = \frac{E_e * H_a}{(\varepsilon * d * V)} \quad (6)$$

where Pc is total loads in Watt hour per day (Wh/day), Ha is hours of batteries autonomy (1day) depending on geographical location, ε is 85% efficiency taking into consideration 15% allowed for batteries loss, d is 60% depth of discharge and V is the normal voltage of the battery bank, used to convert Watt hours/day to Amps Hours (Ah). The numbers of batteries required to drive appliances within specified periods can be determined from:

$$N_b = \frac{B_s}{B_{Ah}} \quad (7)$$

where BAh is the available solar battery rating in the market. Common ratings are 200Ah/12v and 240Ah/12v. For battery bank of 24v, it means that 2 numbers of 12v battery should be connected in series. For a battery bank of 36V, 3 numbers of 12v battery have to be connected in series.

Solar charge controller

The solar charge controller manages the power going into the battery bank from the solar module. This makes it to be one of the most critical components of a solar power system. It takes power produced by solar modules and feeds into the battery bank. It ensures that the deep cycle batteries are not overcharge during the day, and that the power does not run backwards to the panels during the night thereby draining the batteries. Some charge controllers have lighting and load control, but management of power are their primary function [36]. According to, two types of solar charge controller technology are available, the Pulse Width Modulation (PWM) and the Maximum Power Point Tracking (MPPT) [33]. Their operations in any system vary significantly from each other.

The PWM solar charge controller operates by making a connection directly from the solar array to the battery bank. During bulk charging there is a continuous connection from the solar array to the battery bank. The solar array output voltage is conveyed down through appropriate wire to the battery voltage [24,42]. asserted that as the battery charges, the voltage of the battery rises, so the voltage output of the solar array rises as well. Therefore, more of the solar radiation is been used during charging process. This underlines the need to match the normal voltage of the solar array to the battery voltage. Additionally, a battery would not charge when the solar panel voltage is lower than battery voltage [23,43]. This is because higher voltage source is require to charge the battery, thereby wasting 100% of the solar panel potential [9,12].

The Maximum Power Point Tracking (MPPT) charge controllers are the newest, most advanced and most efficient. They track voltage and amperage produced by the PV solar panels, use the tracked information to find the most effective charging voltage and converts it to the battery voltage. Based on the principle of conservation charge, the power that comes into the charge controller equals the power that leaves the charge controller. Therefore, voltage is dropped to match the battery bank, the current increases, hence more of the power available in solar panel is been used. It is always of advantage to design a PV solar system in such a way that the solar ar-ray voltage is higher than that of the battery. The MPPT can capture 10%-40% more power from solar panels than a comparable PWM [30,44]. Because charge controllers moderate the voltage difference between solar array batteries, it is necessary to determine the charge controller rating for effective PV solar power system design. This is given as:

$$I_c = \frac{C_p}{P_b} + \ell \quad (8)$$

where Ic is the charge controller rating in amperes, Cp panel capacity in watt, Pb is bank voltage when the circuit is open. Ƚis the safety factor, which allow for safe coordination of power between the PV module and the battery. Previous design authors [31,35] recommends 30%, but due to the recent fire outbreak resulting from breakdown of PV solar power system charge controller, we use 40% safety factor in designing charge controllers to contend PV solar system rise in temperature, which is common in the Tropical Zone.

TYPICAL DESIGN OF PV SOLAR SYSTEM

Consider an office room with 6 number 18 Watt electric bulbs to run from 0800 hours – 1400 hours; 3 number 80 Watt fans from 0800 hours to 1100 hours; 1number 75 Watt refrigerator to run from 0800 hours – 1400 hours; and 2 number 1.5 HP air conditioner from 1100 hours – 1400 hours (Table 1).

Table 1: Determination of anticipated Wattage for PV solar Power Design

S/N	Appliances	Qty	Unit Power (Watt)	Power (Watt)	Time (Hour)	Power (Wh/day)
1	Lighting Bulbs	6	18	108	8	864
2	Fans	3	80	240	3	720
3	Refrigerator	1	75	75	8	600
4	Air conditioner	2	1119(1.5HP)	2238	5	11190
Σ				**2661**		**13374**

The design considers major components of PV solar power system, which are PV modules size, the numbers of PV modules, the inverter size, the batteries size and the number of solar batteries.

Applying equ 1, the effective energy require to drive the loads per day is:

Ee=13374×1.4=18723.6 Wh/day

From eq (3), the require capacity of PV Solar Modules (Cp) is:

Cp=18723.6/4=4600.9w

The number of PV Solar Modules (Np) to provide this power is obtained from Equ. (4):

Np=4600.9W/300W=16panels. By adding 25% to account for power loss on the modules we have 20Panels. Therefore, the system should be powered by at least 20 number of 300w/24v panels.

The Inverter Capacity (Is) is obtained from the total load wattage and the safety factor as previously stated in Equ. (5). The total load wattage used in designing the present PV solar power system had been determined to be 2661w. By adding 30% safety factor to the total load wattage, we have that:

Inverter Capacity (Is)=2661×1.4=3725.4w, which is 3.7KW. But most inverters are rated in KVA. This implies that, the PV solar system would need 4.6 KVA. In practice, 4.6 KVA inerter is not available in the market, hence, 5 KVA inverter becomes the next option. 5KVA inverter can effectively converts the DC from the panels to AC used to power the appliances.

Battery Capacity (Bs) is designed to from Equation (6), and using one Day of Autonomy (Da) since the location is in the Tropical Zone. With the battery efficiency of 85%, depth of discharge of 60% and battery bank of 24v, the require battery capacity needed to drive the loads is calculated as:

$$B_s = \frac{13347*1}{0.85*0.6*24} = 1090.4Ah$$

Since solar batteries common in the market are rated 200 Ah/12v, 12 pieces of batteries should be used to optimally drive the appliances.

The quantities of PV solar power components achieved from using the mathematical models were compared to that obtained from a PV solar calculator showed significant disparity (Table 2). This was accruable to the geoenvironmental conditions for which the PV solar power system was designed for, and the PV solar calculator could not account for them.

(V) Charge controller (Ic) size was determined from equ (8) written as:

$$I_c = \frac{4600.9}{24} = 1917A$$

Table 2: Comparing PV solar design based on quantities of components obtained from mathematical model and solar Calculator

S/N	Component	Quantity/Size	
		Mathematics Model	PV Solar Calculator
1	PV Solar Module	20Sheets (300w/24v)	2 Sheets (300w/24v)
2	Inverter Size	3.5kw	2.3kw
3	System Bank	24v	24v
4	Battery	12Pcs (200 Ah/12v)	9 Pcs (108 Ah/12v)
5	Charge Controller		26 A

CONCLUSIONS

The Tropical geoenvironmental zone is endowed with adequate solar energy which can be efficiently harvested with the assembling of effectively designed and installed solar power harvesting components. By taking into consideration the increasing amount of aerosol in the atmosphere resulting from heavy pollution of the local atmosphere, mathematical models have been assembled for the design and installations of a functional solar power system. The selection of components for PV solar power installation require careful design methods using local geoenvironmental conditions. PV solar power system had been design and installed to drive office appliances and has been observed to be very reliable in the past two years. However, the design using mathematical models in this paper deviates significantly from that obtained from PV solar calculator in terms of the required number of major components.

CONFLICT OF INTEREST

We do not have conflict of interest to disclose.

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