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Design of a Stand-Alone Roof-Top Photovoltaic System for a Residence in Zamfara State, Nigeria

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Abstract: This paper presents in detail the design analysis of a stand-alone photovoltaic power system for a typical residential building in Zamfara State, Nigeria. A photovoltaic power system can be used as a source of electrical power to our homes through the direct conversion of solar irradiance into electricity. The process of harnessing photovoltaic power generating system involves designing, and selection of the different components employed in the system. The success of this process depends on a variety of factors such as geographical location, weather condition, solar irradiance, and load profile. The paper outlines the procedures employed in specifying each component of the stand-alone photovoltaic power system and as a case study, of a medium range energy consumption residence in Zamfara State (Nigeria).

Keywords: Stand-Alone, Photovoltaic, Zamfara Residence.

1. INTRODUCTION

Today, as the world population increases, energy demand is increasing and therefore needs to be met. Other sources of energy are playing a role in meeting the demand power needs, which include natural gas, biomass energies, wind energy and so on. Environmental concerns and the search for lower cost energy have attracted a great deal of interest in these other sources of energy (Ramesh, Ganesh, Suganya, & Mahalakshmi , 2018)

Since it has been used as power source for space satellites since its inception, PV energy is becoming the largest and most rapid increasing renewables with a known history. As a result

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of increased efforts to develop silicon materials, commercial PV cells have emerged and thus make them an important alternative energy source (Bogdan, et al., 2012). The shortage of moving parts, which enables it to operate for much longer than 20 years, and less maintenance costs, is one of the major advantages of PV technology (Mohammad, 2010). The high manufacturing costs and low efficiency are the major drawbacks, which range from 15% to 20 %. The favourable government support for PV power generation has been a major boost to the development of one of the biggest promising Renewables and Clean Energy sources (Muyiwa, 2014).

A stand-alone PV power system is a complete set of interconnected components for converting solar irradiance directly into electricity and generally consists of the array, battery bank, charge controller, an inverter, protection devices and the system load. The average solar irradiance which passes through Earth's surface varies according to time of day, season, location and weather. Our location is an important factor in the design of PV systems; there are various microclimatic conditions all over the world and this makes a difference to our position. (Asad, 2010).

The constituent parts of a photovoltaic power system to be used in homes are set out in this paper. As a practical case study, a detailed procedural design process, including cost estimates, will then be presented for a housing model with an average energy requirement in Zamfara Nigeria.

Components of Photovoltaic Power System
Solar photovoltaic is a power generation process that uses sunlight to generate electricity. The majority of solar PV systems used in different applications are basically standing on their own. A photovoltaic system shall consist of six components, which must be interconnected to form an entirely functional unit able to generate and supply electricity. In Figure 2.1 you can see that common components of an integrated solar power system are interconnected and described below.

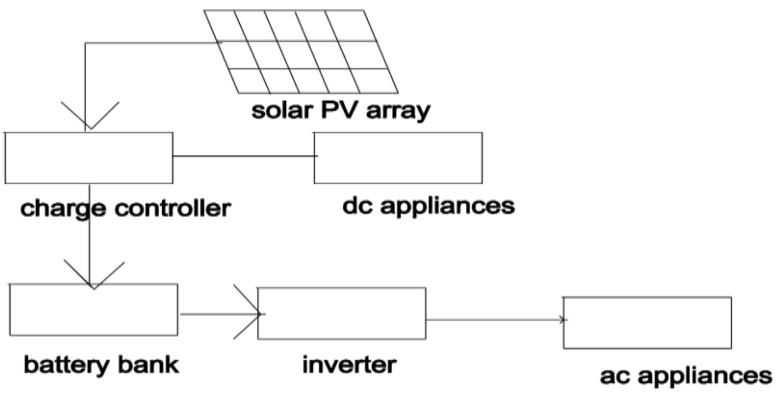

Fig: 2.1 Interconnection of Stand-Alone PV System Components

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Photovoltaic Array

The main driver of any single PV system is the photovoltaic array, which is therefore anessential component. It's charged with converting sunlight into electricity. Solar cells, which are generally only capable of generating a power output of about two watts, constitute the basic energy conversion units. In order to increase the amount of electricity produced, solar cells are usually connected in series and parallel to each other, so as to form the modules. In order to meet the intended output of power, modules shall also be interconnected in series and alongside parallel so as to form a range. (Miro, 2015)

Charge Controller

The charge controller also known as DC/DC converter regulates the flow of electrical energy between solar panels and batteries, thereby ensuring that system voltage is set according to its predetermined specification. (Energypedia, 2022). The primary responsibility of the charge controller is to protect the storage battery from being overcharged and also prevents it from excess discharged by disconnecting the load when the battery has discharged to a pre-set level, in order to prolong the battery life. (Johnson & Ogunseye, 2017)

Storage Batteries

The battery bank is responsible for supplying energy to the load during the night, when solar radiation is at zero level whilst being charged by the PV array during day time when solar radiation is high. Deep-cycle lead acid batteries are recommended for use in a portable solar power system because of their superior performance (Asad, 2010).

Inverter

In order to comply with the load requirements, an inverter also called a power conditioning system is necessary. A DC to AC converter is needed if a load requires an alternate source of electricity due to the power generated by PV arrays being in dc form (Guda & Aliyu, 2015).

Loads

The units of energy consumed by the PV system are the load units. Depending on the type of electrical power that they need to operate, there are two types of load ac and dc. Electrical load can, in general, be identified as either resistive or inductive for the purposes of this design. When energized, the resistance loads do not have an important inrush of electricity. Examples of load are resistive light bulbs and electric heaters. Inductive load on the other hand, draw large amount of current when first energized, examples include transformers, electric motors and coils. (Guda & Aliyu, 2015). The operating current and voltage of the photovoltaic panel will vary with regard to an identical environmental condition, according to how much electricity is consumed. (Selim, Ekrem, & Ali, 2015)

Case Study – A Typical Residence in Zamfara

Gusau the capital city of Zamfara State in Nigeria has an average daily solar radiation estimated to be 18.805 $MJm^{-2}day^{-1}$ (5.223$kWh/m^2/day$) while the average mean daily sunshine hour is 6.15 hours per day (Innocent, et al., 2015). Indeed, the level of Solar Radiation has been shown to give Zamfara a sufficient amount of viable energy resources that

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should be maximized in order to improve the quality of its community. The fact that, even when efforts to improve the energy sector continue to achieve results, there are still too many difficult communities in remote areas which could not readily be reached by a standard national network has led to this necessity.. Gusau (Zamfara Central) is located in the northern hemisphere part of the earth at latitude and longitude of 12.163° and 6.675° respectively and Talata Mafara (Zamfara West) is located on 12.561N, 6.075E while Kaura-Namoda (Zamfara North) is located on 12.583N,6.579E, which shows that the whole part of Zamfara State share similar weather. This geographical location of Zamfara State implies that the average solar irradiance are similar all over Zamfara (Innocent, et al., 2015).

Residence Load Profile

In order to achieve a total hourly average energy demand in watt hours Residence Load Profile as shown in Table 3.1, the residence load profile shall be defined by itemising all household appliances with their respective power rating and time of operation.

Table 3.1: Daily Load Profile of the Average Residence in Zamfara

S/N	Appliances	Quantity	Power Rating (Watt)	Hours of use per day	Energy per day
1	Refrigerator	1	150	12	1,800
2	Computer	1	65	3	195
3	42” Plasma TV	1	140	10	1,400
4	Washing Machine	1	335	1	335
5	LED Bulb	8	15	8	960
6	Cell Phone	3	10	3	90
7	Electric Fan	3	70	10	2100
8	Satellite Receiver	1	25	10	250
9	Submersible Pump	1	373	1	373
	Total				7,503

PV System Design

In order to meet the load profile of the house for which the design is made, PV system design is the process of determining the capacity of each component of a standalone photovoltaic power system in terms of voltage and current. We will also take into account the total cost impact of the whole system in order to ensure its completeness.

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Inverter Sizing

The power rating of the required inverter should be equal to 1.25 of the sum of the power of all non-inductive load and 3 times the sum of the power of all inductive load, that is "$1.25(P_{nin}+3P_{in})$", where P_{nin}=Power of non-inductive appliances and P_{in}=Power of inductive appliances. Thus the power of all non-inductive appliances (P_{nin}) is first determined, then the power of all inductive appliances multiplied by a factor of three ($3P_{in}$) is computed. The total inverter power is now simply the addition of the two previous powers ($P_{nin}+3P_{in}$) but however, scaled by a factor of 1.25 to take care of reasonable future expansion.

$P_{inv} = 1.25(P_{nin} + 3 \times P_{in})$

Where P_{inv} = Power of inverter

P_{nin} = Sum of non inductive load $= 65 + 140 + 120 + 30 + 210 + 25 = 590W$

$3P_{in}$ = Sum of inductive load $= 3(150 + 335 + 373) = 2574W$

The inductive loads are refrigerator, washing machine and submersible pump with power ratings of 2400W, 250W and 373W respectively, while the rest of the loads are non-inductive loads

P_{inv}=1.25(590+2574)=3955W. (Guda & Aliyu, 2015)

To get the actual inverter rating in VA, the wattage rating is divided by the power factor of the inverter

Inverter Rating (VA) = 3955/0.8 =4944VA = 4.944KVA.

The appropriate inverter for this job is Afripower 5KVA pure sine wave inverter with the following details: input dc voltage=48v, output ac voltage= 220v-240v, frequency 50Hz and power factor of 0.8 was selected for its ruggedness.

Battery Block Sizing

Required Information for battery block sizing:

Number of Days of Autonomy (D_{aut}) = 2 Days, Battery capacity (C_b) = 220 Ah, Battery terminal voltage (V_b) = 12 V, battery depth of discharge (D_{disch}) = 80%

To calculate battery block capacity, the following formulae will be applied:

$C_{tb} = \frac{E_d \times D_{aut}}{V_b \times D_{disch}}$

Where C_{tb} = Total capacity of battery bank

E_d = Expected demand = 5279Wh/day

$C_{tb} = \frac{7503 \times 2}{12 \times 0.8} = 1563.125Ah$

Total number of battery in bank (N_{tb}): $N_{tb} = \frac{C_{tb}}{C_b}$

Where C_b = Capacity of one battery

$N_{tb} = \frac{1563.125}{220} = 7.11 = 8$

Number of batteries in series (N_{sb}): $N_{sb} = \frac{V_{dc}}{V_b} = \frac{48}{12} = 4$

Number of battery in parallel (N_{pb}): $N_{pb} = \frac{N_{tb}}{N_{sb}} = \frac{8}{4} = 2$

Total number of batteries required $= N_{sb} \times N_{pb} = 4 \times 2 = 8$

Afripower Tubular battery (India made) with the following ratings: 220Ah, 12V was Selected for its durability

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Sizing of PV Modules

Required Information from the Solar Module: Sunpower SPR-E19-320, V_{mp} = 36V, I_{mp} = 8.34A, I_{sc} = 8.83A, dimension (LxB) = 1940mm x 992mm
System Voltage (**V_{dc}**) = 48V Average Sun-hours for Zamfara (**T_{sh}**) = 6.1 hour per day (Innocent, Jacob, Chibuzo, James, & Odeh, 2015), Daily Average Demand (**E_d**) from Table 1 = 7503Wh/day, Battery Efficiency (**η_b**) = 0.85 Inverter Efficiency (**η_i**) = 0.90 Charge Controller Efficiency (**η_c**) = 0.90
Sizing of PV will be carried out using the under listed formulae;

$$P_{av.peak} = \frac{E_d}{\eta_b \eta_i \eta_c T_{sh}} \text{ ……………………………. (3.1)}$$

$Where$:
$P_{av.peak}$ is the average peak power of the pannel
$\eta_b$is the battery efficiency
η_i is the inverter efficiency
η_c is the charge controller efficiency
T_{sh} is the average sun hour at the installation site
E_d is the average daily energy demand in KWh

$$P_{av.peak} = \frac{7503}{0.85 \times 0.9 \times 0.9 \times 6.1} = 1786.5W$$

$$I_{dc} = \frac{P_{av.peak}}{V_{dc}} \text{ ………………………………. (3.2)}$$

I_{dc} is the total dc current of the systm

$$I_{dc} = \frac{1786.5}{48} = 37.22A$$

No. of modules in series (N_{sm}) can be calculated as shown below;

$$N_{sm} = \frac{V_{dc}}{V_{mp}} \text{ … … … … … … … … … … … . . (3.3)}$$

$$N_{sm} = \frac{48}{36} = 1.2 = 2 \text{ modules}$$

No. of modules in parallel (N_{pm}) is given as shown below:

$$N_{pm} = \frac{I_{dc}}{I_{mp}} \text{ ……………………………….. (3.4)}$$

$$N_{pm} = \frac{37.22}{8.34} = 4.463 = 5\ modules$$

Therefore total number of modules = $N_{sm} \times N_{pm} = 2 \times 5 = 10\ module$… (3.6) Guda & Aliyu, (2015)
320W, 36V Felicity Panel is selected for the job

Sizing of Charge Controller

The following formulae will be required when sizing the charge controller

$$I_{cc} = I_{sc}^{M} \times N_{pm} \times F_{safe} \text{ ……………. (3.7)}$$

I_{cc} = Charge controller current
I_{sc}^{M} = Short circuit current of one module
N_{pm} = No. of modules in paralle
F_{safe} = Safe factor

$$I_{cc} = 8.83 \times 5 \times 1.25 = 55.2A$$

60A Felicity MPPT charge controller was selected for the job.

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Cable Sizing

Until the right size and type of cable is chosen to connect these parts, the PV Power System design has not yet been completed. Appropriate choice must be made with respect to these cable connections in the PV system:

- The dc cable from the solar array to the battery bank through the charge controller:

This cable can be selected using the following formulae

$I_{cab} = I_{rcc} = I_{sc} \times N_{pm} \times F_{safe} = 55.2A$

3x10 mm^2 Insulated Flexible Copper Cable is selected

- The ac cable from the inverter to the distribution board (DB) of the residence:

Cable link between the inverter and the distribution board is as calculated bellow

$$I_{oi} = \frac{P_i}{V_{oi}} = \frac{5000}{230} = 21.74A$$

3x4mm^2 insulated flexible copper cable is selected

Where I_{cab} = cable current between PV array and battery bank

I_{oi} = Inverter output current

P_i = power rating of inverter

V_{oi} = Inverter output voltage

Estimation of Roof Space Requirement for the PV Array

The space requirement is important in order to ascertain that the available rooftop will be enough for the solar panel installation. The dimension of the selected panel is 1940mm by 992mm, (1.94m by 0.992m).

Therefore, space requirement for one panel is 1.94 x 0.992 = 1.93m^2, the total space required for the sixteen panels is 1.93m^2 x 10 = 19.3m^2

Bill of Engineering Measurement an Evaluation (BEME)

The bill if engineering measurement and evaluation is a document representing the specific tasks to be carried out and material which needs to be procured in order to carry out the proposed project. Table: 4.1. below shows the various materials in use to install standalone solar power plants for an ordinary home in Zamfara state.

Table 4.1: Bill of Engineering Measurement and Evaluation (BEME)

Components Description	Quantity	Model	Component Rating			Unit Cost (Naira)	Total Cost (Naira)
			Power	Current (A)	Voltage (V)		
Inverter	1	Afripower	5KVA	-	48	420,000	420,000
Solar panel	10	Sunpower	320W	8.34	36	80,000	800,000
Charge Controller	1	Felicity (MPPT)		60A	-	120,000	120,000

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Battery	8	Afripower Tubular		220Ah	12	130,000	1,040,000
Cable panel-battery	25yards	3X10mm dc cable				1,200	30,000
Cable Inverter-DB	20	3X4mm ac cable				500	10,000
Panel mounting rail						10,000	10,000
Battery rack						20,000	20,000
Logistics						20,000	20,000
Installation cost						120,000	120,000
Miscellaneous						20,000	20,000
TOTAL							**2,610,000**

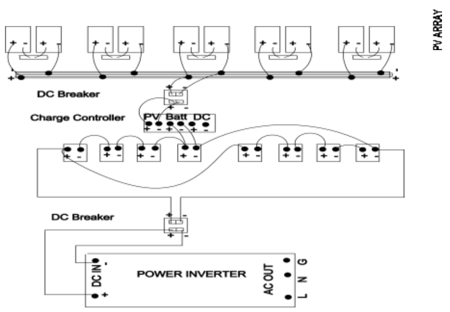

Figure: 4.1 Wiring Diagram of the Proposed Solar System

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2. CONCLUSION

The geographic location of Zamfara with an average daily solar radiation estimated to be 18.805 $MJm^{-2}day^{-1}$ (5.223kWh/m^2/day) and the average mean daily sunshine hour of 6.15 hours per day, if properly harness is capable of providing sufficient alternative and clean energy source, most especially to the remote rural area that are not covered by the national electricity grid. For example, the conflict areas of Nigeria and other parts of the world where electrical grid infrastructure is constantly being disrupted by conflicts are now more relevant to PV systems running solely on solar energy. A cost estimate of the entire network, including cables, construction elements, production and control equipment has also been submitted. Other locations and applications in which the consumption of energy is higher could also benefit from a similar design procedure. Given this alternative and renewable energy source's high capital requirement, it is strongly recommended that the Government should be involved in providing financial support for PV system equipment procurement and installation. In order to limit their cost in the long term, Government should also provide incentives for local production of these PV system components. Institutions should be set up to conduct research on the fabrication of Solar Cells from various technologies, in particular New Technologies such as Organic Solar Cells. It is certainly necessary that scientists, physicists and engineers collaborate to do so. To overcome a large energy supply shortfall that exists in Nigeria as well as other part of the world, rapid deployment of solar panels should be pursued. In particular, it could be done by very smart subsidies from the State and a cut in import duties on solar modules and other essential components of PV systems.

3. REFERENCES

1. Selim, B., Ekrem, K., & Ali, K. (2015). A SimplerSingle-Phase Single-StageGridConnectedPVSystemwith Maximum Power Point TrackingController. Elektronika IR Elekrotechnika, 21(4), 44-49.
2. Asad, A.-G. (2010). A Stand-Alone Photovoltaic System, Case Study: A Residence In Gaza. Journal of Applied Sciences in Environmental Sanitation., 5(1), 81-92.
3. Bogdan, C., Tamas, K., Dezso, S., & Remus, T. (2012). Control of Grid-Connected PV System with Grid Support Function. Aalborg, Denmark: Aalborg University.
4. Energypedia. (2022, May 18). Charge Controllers. Retrieved from https://energypedia.info/wiki/Charge_Controllers: https://energypedia.info/wiki/Charge_Controllers
5. Guda, H. A., & Aliyu, U. O. (2015, January). Design of a Stand-Alone Photovoltaic System for a Residence in Bauchi. International Journal of Engineering and Technology, 5(2), 1-11.
6. Guda, H. A., & Aliyu, U. O. (2015, January). Design of a Stand-Alone Photovoltaic System for a Residence in Bauchi. International Journal of Engineering and Technology, 5(1), 34-44.
7. Innocent, A. J., Jacob, E. O., Chibuzo, G. C., James, I., & Odeh, D. O. (2015, February). Estimation of Global Solar Radiation in Gusau, Nigeria. International Journal of Research in Engineering and Technology (IJRET), 3(2), 27-32.

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DOI: https://doi.org/10.55529/jeet.26.45.54

8. Johnson, D. O., & Ogunseye, A. A. (2017, April). Grid-Connected Photovoltaic System Design For Local Government Offices in Nigeria. Nigerian Journal of Technology (NIJOTECH), 36(2), 571 – 581.
9. Miro, S. (2015). Photovoltaic Systems. Delft, Nederland: Delft University of Technology. Retrieved April 06, 2022, from https://ocw.tudelft.nl/wp-content/uploads/Solar-Cells-R6-CH9_Photovoltaic_systems.pdf
10. Mohammad, H. R. (2010). Power Electronics Handbook: Devices,Circuits and Applications (Vol. 2). New York: Elsevier.
11. Muyiwa, S. D. (2014). Viability of Grid-Connected Solar PV Energy System in Jos, Nigeria. Nigeria Journal of Electrical Power and Energy System, 64-69.
12. Ramesh, K., Ganesh, G. R., Suganya, S., & Mahalakshmi , K. (2018, June). An Enhanced Incremental Conductance Algorithm for Photovoltaic System. ELECTRONICS, 22(1), 12-18.