IMPLEMENTATION OF OFF-GRID SOLAR PHOTOVOLTAIC SYSTEM FOR A TWO-BEDROOM APARTMENT

Bitrus, I.[1] & Abdulhamid, I.G.[2]
[1,2]Department of Electrical/Electronic Engineering,
The Federal Polytechnic Ilaro, Ogun State, Nigeria
07063065557

Abstract

A bill which proposes a ban on the importation and use of gasoline as well as diesel generators and generating set is being considered in the Nigerian national assembly in order to mitigate the menace of environmental pollution and facilitate the development of power sector. This attempt to restrict the use of fossil fuels for environmental reason should not be allowed to have a negative impact on economic development. It is therefore important that the attention should be shifted toward utilizing the abundant solar energy available in Nigeria to argument the existing hydro power plants, especially for domestic purposes. This paper provides a succinct procedural approach to the implementation of a typical domestic solar PV project. A load audit of a standard two-bedroom apartment and detailed design of the various components of the solar PV system are included in this work. The result obtained shows that the two bedroom apartment considered requires six 200 w solar modules, four 200 Ah battery bank, 60 A charge controller and 2.5kVA inverter to provide electric power for eight hours. It is therefore recommended that professionals should be involved in the design and implementation of solar power system so as to derive the maximum efficiency and reliability of the system.

Keywords: Implementation, Off-Grid, Solar Photovoltaic, efficiency, environmental pollution, reliability

Introduction

A nation's per capita energy consumption is an index of the standard of living or prosperity of the country's citizens(Khan, 2013). In order to improve their living standard and meet energy demand, household owners in Nigeria resolve to using generators to complement the supply from the National grid. Pollutants release in the process of energy generation lead to global warming with a serious negative impact on the environment e.g., flooding. This calls for the bill to ban the importation and use of generators and generating set by the National assembly.

Due to ample sunlight, photovoltaic electricity, which is recognized as free and non-polluting, has been found to be available in Nigeria(Benjamin & Dickson, 2017). Harnessing this abundant energy to solve power shortage problem and keep a clean environment is therefore necessary.

Solar photovoltaic (PV) systems convert solar energy directly into electrical energy (Iftikhar, 2012). The basic conversion device used is known as solar photovoltaic cell or solar cell. Solar cells are connected in series to form solar modules. Climatic conditions such as temperature, wind speed, humidity, dust etc. have been found to significantly influence the performance of PV modules(Kaldellis et al., 2020).

In order to generate the required amount of power to operate the connected appliances, environmental condition such as the partial and complete shadowing of modules or a cell must be completely avoided (Khan, 2013). The installation site must therefore be free from shading and obstructions from nearby trees and building throughout the year.

Another factor that significantly improve reliability and efficiency of the system is proper sizing of the cables that connect various components of the solar photovoltaic system (Unwaha et al., 2016).

This paper takes a step by step design approach of a solar PV system of a two bedroom flat apartment. The important aspect of the system such as PV system components, cable sizing, and system grounding have been discussed before going into the design aspect of the project.

It is believed that a PV system implemented by a professional will consider different environmental factors for improved reliability and safety of the equipment and users.

System Components

Solar modules

Solar photovoltaic (PV) systems convert solar energy directly into electrical energy. The basic conversion device used is known as solar photovoltaic cell or solar cell. Solar cells are connected in series to form solar modules. The most common commercial modules have a series connection of 32 to 36 silicon cells to make it capable of charging a 12-V battery. Several solar modules are connected in serial/parallel combination in a frame to form solar panel. This is to increase the voltage/current ratings of the modules. When modules are connected in parallel, it is desirable to have each modules maximum power production occur at the same voltage.

Battery bank

Batteries store the dc electricity produced by solar modules during the sun hours for later use. Lead acid batteries are commonly used in solar PV system for residential application because of their low cost. There are two types of lead acid batteries: the sealed lead acid battery and the flooded lead acid batteries. Flooded lead acid batteries are the least expensive but require adding distilled water monthly to replenish water lost during the normal charging process. A battery bank is formed when several battery packs are assembled in series or parallel to supply the required current for running the appliances in specific time period (hour).

Charge controller

The basic function of charge controller is to prevent over charging and deep discharging of battery bank. The actual life cycle of a battery is the number of discharge-charge cycles the battery would experience before it fails. The operating life of a battery is affected by the rate and depth of cycles and other condition such as temperature, humidity. The higher the depth of discharge (DOD), the lower the cycle life of the battery becomes. Thus, the charge controller charges the battery safely and maintains longer lifetime for them.

Inverter

Inverter converts the dc power generated by the PV modules and the dc energy stored in the battery for use with conventional appliances.

Protection devices

PV system is protected from damage caused by overcurrent using fuses, disconnect switches and grounding conductor. DC and AC disconnect switches isolate the panel from the system and the load from the inverter respectively.

DC Fuses are commonly used to protect wires connected to the battery and the PV modules from fault currents

Miniature circuit breakers (MCB) are like fuses but they have the ability to be switched back on after they tripped. The DC part of the PV system should be protected by a DC circuit breaker and the AC part is also protected by the AC circuit breaker.

The metal parts of the solar panel frame, charge controller and inverter must be connected ground electrode, this is required to protect the PV system from damage caused by lightning strikes and also to mitigate injury caused by electrocution.

Cable Sizing and Selection

Cables are required to connect the various components of the PV system. Cable sizing is therefore an important part of solar PV system. The cable length required depends on the location of installation from solar panels. The cable length should be minimized to reduce voltage drop and the cost of cabling(Unwaha et al., 2016).

On the dc side, the maximum voltage drop should not exceed 3%. Voltage drop is determined by the length and thickness of the conductor, the current flowing through the conductor and the material of the conductor. The absolute voltage drop is given by equation (1)

$$\Delta V = \frac{2 \times l \times I_{rated}}{\rho \times A} \quad (1)$$

Where $l = cable\ length$ $I_{rated} = maximum\ current\ produced\ by\ modules$

$A = cross\ sectional\ area\ of\ cable\ (mm^2)$ $\rho = resistivity\ of\ conductor$

The required minimum cross sectional area of the cable is determined by equation (2)

$$A = \frac{2 \times \rho \times l_{cable} \times I_{rated}}{V_{system} \times \gamma} \quad (2)$$

$V_{system} = System\ voltage$ $\gamma = maximum\ allowable\ voltage\ drop$

Earthing System of the Solar Power Plant

Grounding or earthing is defined particularly in Electrical/Electronic Engineering, as a common return path for electric current. It serves as a reference point in an electrical circuit. In power system engineering, earthing is defined as the process of connecting a non-current carrying part of an electrical system or some electrical part to earth. Connection to the earth is made through copper electrode to provide easy conduction of current to the earth. Earthing electrical equipment is usually done to guarantee the safety of operating personnel and equipment from electric shock or thunderstorm (N.A.Sundaravaradan & Reddy, 2018).

For maximum efficiency of the earthing system, Physical and geological survey should be carried out so as to avoid the locations prone to high resistivity. Locations with gravel chalk, dry sand, limestone, granite etc. should be completely avoided. Let us discuss factors that affect soil resistivity.

Factors Affecting Soil Resistivity

a) Moisture content of soil

The resistivity of the soil varies with moisture content of the soil. The higher the moisture content of the soil the lesser is the resistivity of the soil. Moisture is required by the soil to form a conducting electrolyte (sodium chloride, NaCl), sodium carbonate, Na2CO3, calcium chloride, CaCl2 and copper sulphate, CuSO4 salt (N.A.Sundaravaradan & Reddy, 2018).

b) Temperature of the Soil

The effect of soil temperature in determining resistivity of the soil is something that should not be overlooked by the installers of electrical earthing system. It becomes significant only at or near freezing point ($\leq 0^0$C). In this situation, earth rod should be buried to the level where the temperature is above the freezing point. (N.A.Sundaravaradan & Reddy, 2018).

c) Effect of current magnitude

The size of the electrode to be used should be such that it is able to conduct large fault/transient current to the ground as fast as possible. Therefore, proper sizing of the earth rod and it conductivity should be determined through design procedure to ascertain the right specification to be used. The number of earth rods to be used for a particular installation is determined by the optimum value of the earth resistance required for that system as prescribed in the equipment operational/installation manual (N.A.Sundaravaradan & Reddy, 2018).

d) Type of soil

Soil exhibits many physical and chemical properties such as grain size, texture and structure. These factors determine the way and manner in which moisture is conserved by the soil (N.A.Sundaravaradan & Reddy, 2018).

e) The Depth of the Pit

The depth of the earth pit to a greater extent determines the resistivity of the soil. The deeper it is the lesser the resistivity of the soil. Hence, extra effort should be made to have a deep earth pit so as to reduce the number of earth rod to be used to have the less possible resistivity.

Methodology

Load Audit

Successful implementation of solar PV system begins with the load audit of the connected facility. Table 1 and 2 give the load audit of the non-motorised and motorised loads of the two bed-rooms apartment considered in this paper. This is performed to enable power supply to the peak load for the required period of time.

Table 1.0: Total power consumption of non-motorized loads

S/N	APPLIANCES	RATING (W)	QUANTITY	TOTAL WATTAGE
1	CFL	11	8	88
2	Television set	118	1	118
3	Laptop	64	1	64
4	DSTV decoder	25	1	25
5	DVD Player	190	1	190
Total				485

Table 2 total power consumption of motorized load

S/N	APPLIANCES	RATING (W)	QUANTITY	TOTAL WATTAGE
4	Ceiling Fan	60	2	120
5	Blender	350	1	350
Total				530

Determination of the Total Daily Energy Demand

An 8 hrs daily operating hours is considered in the calculation of the total daily energy demand of the non-motorized and motorised appliances in the two bedroom apartment. The total power consumptions of the various appliances as presented in tables 1 and 2 had been utilized in the computations. The results are shown in table 3 and 4.

Table 3.0: Daily energy demand of non-motorized loads

S/N	APPLIANCES	TOTAL WATTAGE	OPERATING HOURS	WATT-HOUR
1	CFL	88	8	704
2	Television set	118	8	944
3	Laptop	64	8	512
4	DVD Player	190	8	1520
5	DSTV decoder	25	8	200
			TOTAL	3880

Table 4 Daily energy demand of motorized loads

S/N	APPLIANCES	TOTAL WATTAGE	OPERATING HOURS	WATT-HOUR
4	Ceiling Fan	120	8	960
5	Blender	350	8	2800
			TOTAL	3760

The total daily energy demand of the apartment

$$= daily\ energy\ demand\ of\ motorised\ loads + daily\ energy\ demand\ of\ motorised\ loads$$

$$= 3760 + 3880 = 7640\ \text{wh}$$

Determination of the Total PV Energy Needed

The total energy needed is the energy that should be generated by the solar panels so as to be able to operate the loads for the period of 8 hrs. This is obtained using equation (3)

$$PV\ energy\ needed\ = F_c \times Daily\ \ energy\ consumption \qquad (3)$$

Where, $F_c = efficiency\ factor$

The efficiency factor presented in equation (3) considers the efficiencies of the controller, batteries and electric cable in the implementation of the PV system. F_c is given by (4)

$$efficiency\ factor, F_c = \frac{1}{\eta ce \times \eta B \times \eta Ec} \qquad (4)$$

Where Controller efficiency, $\eta_{ce} = 0.9$ Battery efficiency, $\eta_B = 0.85$ Electrical cable efficiency, $\eta_{CE} = 0.95$

Hence, $Fc = \frac{1}{0.9 \times 0.85 \times 0.95} = 1.33$

$$\therefore\ PV\ energy\ needed\ = 1.33 \times (3880 + 3760) = 10161.2\ Wh$$

Determination of the Total Number of PV modules

To accurately determine the number of solar modules required, the total PV energy needed, the average daily sunshine hours of the installation location and the rating of the solar module selected are the key requirement.

$$Average\ daily\ sunshine\ = 8h$$

$$PV\ energy\ needed\ = 10161.2\ Wh$$

$$Peak\ watt\ rating\ = \frac{total\ PV\ energy\ needed}{average\ daily\ sunshine} \qquad (5)$$

$$= \frac{10161.2}{8h} = 1270.15\ w$$

Peak watt rating is the power that must be produced by the solar panel in order to operate the load.

$$\therefore Number\ of\ PV\ panels = \frac{\text{Total peak watt rating}}{\text{Module Rating}} \quad \ldots\ldots\ldots\ldots\ldots (6)$$

The rating of the solar module selected for this design is 200 W

$$= \frac{1270.15\ w}{200\ \text{w}} = 6.3 \approx 6 \text{ modules}$$

Determination of the Inverter Size

Inverter consumes power as it converts DC to AC. This leads to the increase of current that flows from the battery so as to run the inverter and support the load. As such inverters should be bigger than the total wattage of all appliances. Again, Motorised loads draw more current during starting than the normal rated current as such

$$Starting\ current\ factor\ for\ motorized\ appliances = 2.55$$

$$Total\ wattage\ of\ all\ appliances = Wattage\ of\ non-motorize\ Load + 2.5 \times Wattage\ of\ motorized\ Equipment$$

$$\therefore Total\ wattage\ of\ all\ appliances = 485 + 2.55 \times 530$$

$$= 785 + 1351.5 = 1836.5\, w$$

$$Inverter\ power\ (kW) = \frac{Total\ wattage\ of\ all\ appliances}{Inverter\ efficiency, \eta_I} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$= \frac{1836.5}{0.98} = 1873.97\text{W}$$

But inverters are rated in KVA, thus the KW is converted to KVA by dividing KVA by 0.8 (power factor)

$$Inverters\ size\ (KVA) = \frac{Inverter\ power}{Power\ factor} = \frac{1873.97}{0.8} = 2342.47\ VA \approx 2.5KVA$$

Determination of the Battery Bank Size

The life span of a battery is seriously affected by depth of discharge (DOD) of the battery; as such the battery must not be discharge below 60%

$$\text{Total Battery capacity (Battery bank capacity)} = \frac{\text{Total daily Energy consumption}}{\text{Norminal Battery voltage} \times \text{DoD}} \ldots\ldots\ldots\ldots\ldots (8)$$

$$Total\ daily\ Energy\ consumption = 7640\ \text{wh}$$

$$Depth\ of\ Discharge, DoD = 60\% = 0.6$$

$$Norminal\ Battery\ voltage, V = 12\ \text{v}$$

$$\text{Total Battery capacity (Battery bank capacity)} = \frac{7640}{12 \times 0.6} = 1061.11\ \text{Ah}$$

Number of Batteries required

$$\text{Number of Batteries required} = \frac{Total\ Battery\ Bank\ Capacity}{Battery\ rating} \ldots\ldots\ldots\ldots\ldots (9)$$

The rating of the Battery selected is 220 Ah

$$\text{Number of Batteries required} = \frac{1061.11}{220\text{Ah}} = 4\ batteries$$

Determination of Charge Controller Capacity

Number of solar modules required and the short circuit current of the module selected determine the size of the charge controller

$Charge\ controller\ size\ = N_{MP} \times F_{SAFETY} \times I_{SC}$.......................... (10)

Where,

$N_{MP} = Number\ of\ PV\ modules\ = 6$

$Short\ circuit\ current, I_{SC}\ = 7.97\ A$

$F_{SAFETY} = factor\ of\ safety\ = 1.25$

$\therefore Charge\ controller\ size\ according\ to\ equation\ (9)\ = 6 \times 7.97\ \times 1.25\ \approx 60\ A$ .... (11)

Determination of Cables Size from PV Modules to the Charge Controller

To determine the cable size, equation (2) is going to be utilized. The current produced by the PV module is required and has been found to be $60\ A$ as presented under the determination of charge controller size.

Cable length is taken as 1 m. the cable size is therefore determined as

$$A = \frac{2 \times 1.7 \times 10^{-8} \times 1 \times 60\ A}{12 \times 0.03} = 5.66 \times 10^{-6} m^2 \approx 6mm^2$$

A cable size with minimum cross section of $6mm^2$ which is capable of carrying 60 A with the maximum voltage drop of 3% is going to be selected.

System Installation

Eight major steps taken to ensure a successful installation of solar power plant viz:

1. Site surveying
2. Permits or contract award letter
3. Equipment procurement
4. Installation of PV array
5. Installation of indoor equipment
6. Installation of firefighting equipment
7. Installation of earthing system
8. Testing/commissioning

System block diagram

Fig 1.0 shows the interconnection of the various components of the solar power plant under consideration. Protective devices such as miniature circuit breakers and isolator were used to protect the system from over-voltage and or over-current.

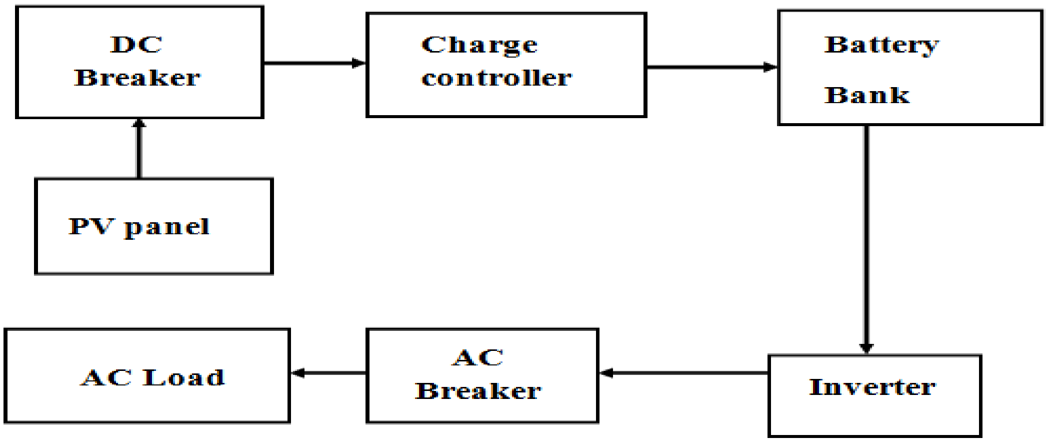

Fig. 1.0: Block diagram showing the interconnection between different components of a typical solar power plant with protective devices.

Results and Discussion

Result

The results obtained from the step by step design approach of the solar PV system are presented in table 5.

Table 5: Results Obtained from the propose sizing of Off-grid PV system

S/N	Components	Description of component	Results
1	Load estimation	Total estimated daily energy demand	10.16 kWh
2	PV array	Capacity of PV array	1.27 kW
		Total Number of modules in parallel	6
3	Battery Bank	Battery bank capacity	220 Ah
		Number of batteries in parallel	4
4	Charge controller	Capacity of charge controller	30A
		Total number of charge controller	2
5	Inverter size	Capacity of the inverter	2.5kVA
6	Wire size	Size of the wire between PV modules and the charge controller	$6mm^2$

Discussion of Result

The daily electrical energy demand of the 2 bedroom apartment is determined and presented in table 3 and 4. The results presented in table 5 show that six 200 W, 12 V PV modules must generate 1.27 kW of electricity from the sunlight so as to be able to operate the loads in the connected facility for the period of 8 hrs. The size of the charge controller and inverter are determined to be 60 A and 2.5 KVA respectively.

Conclusion

Design approach and cogent factors that must be considered for improvement of the reliability of the solar power system has been presented in this paper. It is therefore recommended that professionals should be involved in the design and implementation of solar power system in order that the system produces near installed capacity.

References

Benjamin, E. A., & Dickson, E. (2017). *Estimating the Solar Home System Sizing for Rural Residential Apartments Using a Panel Tilt Angle of 82 Degrees : Ilorin , Kwara State as Case Study*. *1*(3), 90–96.

https://doi.org/10.11648/j.ece.20170103.13

Iftikhar, H. (2012). Solar PV System Design By. *Transnational Journal of Science and Technology*, *8000*(4), 13.

Kaldellis, J. K., Kapsali, M., & Kavadias, K. A. (2020). Temperature and wind speed impact on the efficiency of PV installations . Experience obtained from outdoor measurements in Greece Temperature and wind speed impact on the ef fi ciency of PV installations . Experience obtained from outdoor measurements in Greece. *Renewable Energy*, *66*(June 2014), 612–624. https://doi.org/10.1016/j.renene.2013.12.041

Khan, B. H. (2013). *Non-Conventional Energy Resources* (second Edi). McGraw Hill Education (India) Private Limited.

N.A.Sundaravaradan, & Reddy, M. B. (2018). How is Earthing done? IEEE Potentials , 37 (2), 42-46.

Unwaha, J. I., Jones, N. D., & Musa, A. J. (2016). Design of Off-Grid Solar Photovoltaic (PV) System for Cottage Hospital. *Journal of Energy Technologies and Policy*, *6*(5), 25–30. www.iiste.org