Design Analysis of a Typical Off-Grid Solar Power System and The Need for Adequate Maintenance: A Case Study of a Two Bedroom Flat Apartment

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Abstract- Most engineering infrastructures require proper design and regular maintenance to keep them in an efficient operating condition. This maintenance work required can either be preventative or routine, corrective and emergency/breakdown maintenance. Preventative maintenance includes routine inspection and servicing of equipment to prevent breakdowns and production losses. Corrective or emergency addresses equipment breakdowns after the occurrence. This "break and fix" method has low upfront costs, but bears the risk of unplanned downtime and higher costs on the back end. Proper design of off-grid solar power system and regular maintenance could guarantee the effective and efficient operation of solar system. This work presents a step-by-step design approach of a solar power plant of a two-bedroom flat which considers environmental and safety factors. The need and the area which require regular maintenance has been highlighted.

Indexed Terms- Design Analysis, Solar Power, maintenance, efficiency, environmental pollution.

I. INTRODUCTION

In recent times, solar PV systems have received much attention globally [1]. One of the reasons is because of the potentials of renewable energy sources to reduce the emission of greenhouse gases and fossil fuel consumption in all sectors across the globe [8]. Photovoltaic (PV) systems have been effectively utilised in many developed and developing countries around the world and its development and utilisation is on the increase. In Nigeria for instance, more homeowners are investing in solar PV system energy alternative. Many homeowners also investing in renewable energy notably biomass and stand-alone solar PV systems. Among these two, solar PV is being more utilised. However, the continuous utilisation of solar PV system in Nigeria is being hampered by certain factors such as design defect due to the inadequate involvement of the professional and certified personnel which also results to poor maintenance of the system.

Climatic conditions such as temperature, wind speed, humidity, etc have been found to significantly influenced the performance of PV modules. In order to provide the amount of power required to operate the appliances, the operating temperature of the PV module must be considered in the design. Investigation of the impact of temperature and wind speed on the efficiency of PV installations have clearly shown that the difference between cell and ambient temperature decreases with increasing wind speed [2]. Environmental condition such as the partial and complete shadowing of module or a cell must be completely avoided in order to prevent the damage of the module [3]. This calls for the proper investigation of the solar potential of the building site. The installation site must be free from shading and obstructions from the nearby trees and building throughout the year.

proper sizing of the cables that connect various components of the solar photovoltaic system ensures the safety and reliability of the system. [4] had designed and determines the various cables sizes between the panels and the charge controller, battery bank and the inverter, inverter and the load.

This article takes a step by step design approach of a solar PV system of a two-bedroom flat apartment. Also, the need for proper maintenance of the system for greater efficiency has been highlighted.

II. METHODOLOGY

1.1 MATERIALS AND SPECIFICATIONS

1.2 SYSTEM COMPONENTS DESCRIPTION

1.2.1 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 module maximum power production occur at the same voltage.

1.2.2 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).

1.2.3 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. Thus, the charge controller charges the battery safely and maintains longer lifetime for them.

1.2.4 Inverter

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

1.2.5 Protection devices

In order to protect the PV system equipment from damage and prevent death or injury, over current protective devices and grounding must be properly utilised.

1.2.6 DC and AC disconnect

DC and AC disconnect switches isolate the panel from the system and the load from the inverter respectively.

1.2.7 Fuses

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

1.2.8 Miniature circuit breakers (MCB) and fuses

MCBs 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.

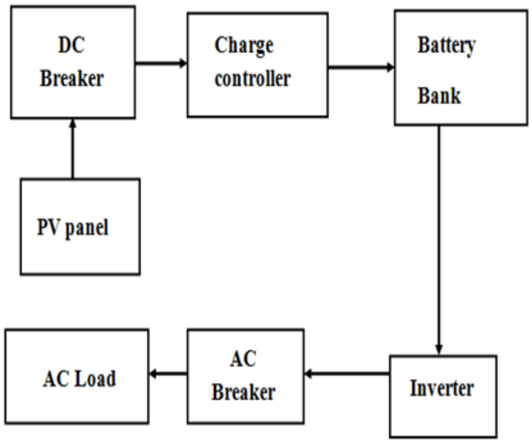

Fig. 1.0: Block diagram of a typical solar power plant with protective equipment

1.3 DESIGN OF 2.5KVA SOLAR PLANT

1.3.1 Determination of the Total Power consumption demand

Table 1.0: Total power consumption of non-motorised 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 Motorised load

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

1.3.2 Determination of the total daily energy demand

Table 3.0: Daily energy requirement of non-motorised 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 requirement of motorised loads

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

1.3.3 Determination of the Total PV Energy Needed

PV energy needed = F_c x Daily power consumption

$F_C = Efficiency\ factor$

Parameters required to calculate , F_C

Controller efficiency, $\eta_{ce} = 0.9$

Battery efficiency, $\eta_B = 0.85$

Electrical cable efficiency, $\eta_{CE} = 0.95$

Solution

$$Efficiency\ factor, F_C = \frac{1}{\eta ce \times \eta B \times \eta Ec}$$

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

$$\therefore PV\ energy\ needed = F_C \times Daily\ energy\ consumption$$

$$= 1.33 \times (3880 + 3760) = 10161.2\,Wh$$

1.3.4 Determination of total PV panel Peak watt Rating (Wh)

Parameters

$Average\ daily\ sunshine = 8h$

$PV\ energy\ needed = 10161.2\ Wh$

Solution

$$Peak\ watt\ rating = \frac{total\ PV\ energy\ needed}{average\ daily\ sunshine} = \frac{10161.2}{8h} = 1270.15\ w$$

1.3.5 Determination of the total number of PV panels

Parameters

$Total\ peak\ watt\ rating = 1270.15\ w$

$Panels\ rating = 100W, 150W, 200W$

Solution

$$Number\ of\ PV\ panels = \frac{\text{Total peak watt rating}}{\text{Total Panel rating}}$$

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

1.3.6 Determination of the Inverter Size

Parameters

$Wattage\ of\ motorized\ Equipment = 530$

$Wattage\ of\ non-motorized\ Load = 485$

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

$Inverter\ efficiency, \eta_I = 0.98$

$Power\ factor, cos\emptyset = 0.80$

Solution

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

$\therefore Total\ wattage\ of\ all\ appliances$

$= 485 + 2.55 \times 530$

$= 785 + 1351.5 = 1836.5$

$Inverter\ power\ (kW)$

$$= \frac{Total\ wattage\ of\ all\ appliances}{Inverter\ efficiency, \eta_I} = \frac{1836.5}{0.98} = 1873.97W$$

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

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

1.3.7 Determination of the Battery Size

Parameters

$Total\ daily\ Energy\ consumption =$

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

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

Solution

Total Battery capacity (Battery bank capacity) =

$$\frac{Total\ daily\ Energy\ consumption}{Norminal\ Battery\ voltage \times DoD} = \frac{7640}{12 \times 0.6} = 1061.11\ \text{Ah}$$

1.3.8 Number of Batteries required

Number of Batteries required

$$= \frac{Toatal\ Battery\ Capacity}{Battery\ rating} = \frac{1061.11}{220\text{Ah}} = 4\ batteries$$

1.3.9 Determination of Charge Controller Capacity

Parameters

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

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

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

Solution

$$Charge\ controller\ size = N_{MP} \times F_{SAFETY} \times I_{SC} = 6 \times 7.97 \times 1.25 \approx 60\ A$$

1.3.10 Cable Sizing and Selection

Cable sizing is an important part of solar PV system design. Having known the number of solar modules, the size and number of charge controllers, battery and inverter size, the next thing is the determination of the size and length of the cable required to connect the different components of the PV system [5]. The length of cable required depends on the location of installation. The cable length in this work is minimized to reduce voltage drop and the cost of cabling.

On the dc side, the maximum voltage drop should not exceed 3%. The voltage drop is determined by the following parameters: the leng and thickness of the conductor, the current flowing through the conductor and the material of the conductor. The absolute voltage drop is given by the formula:

$$\Delta V = \frac{2 \times l \times I_{rated}}{\rho \times A}$$

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 can also be calculated using the formula

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

$V_{system} = SYSTEM\ VOLTAGE$

$\gamma = maximum\ allowable\ voltage\ drop$

1.3.11 Determination of Cables Size from PV Modules to the Charge Controller

The maximum current produced by the solar panel is required in the determination of the cable size

$I_{RATED} = N_{MP} \times F_{SAFETY} \times I_{SC}$

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

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

$I_{SC} = short\ circuit\ current$

$$I_{RATED} = N_{MP} \times F_{SAFETY} \times I_{SC}$$
$$= 6 \times 7.97 \times 1.25 \approx 60\ A$$

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

$$A = \frac{2\times1.7\times10^{-8}\times 1 \times 60\ A}{12\times0.03} = 5.66 \times 10^{-6} m^2 \approx 6mm^2$$

resistivity of copper $= 1.7 \times 10^{-8}\Omega$-m

$cable\ length = 1\ m$

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 required.

- Determination of cables size for solar PV array through the batteries to the voltage regulator.

Maximum voltage drop $V_d = \frac{4}{100}$x24 = 0.96V

If the length of the cable is taken to be, L = 1m

For the cross-sectional area of the conductor, A= $\frac{2\times\rho\times l_{cable}\times I_{rated}}{V_{system}\times\gamma} = \frac{\rho LI}{V_d}$ x2

We can obtained A = $\frac{1.724 \times 10^{-8} x1x32}{0.96}$x2 = 1.15mm^2

This means, that a copper conductor of cross sectional area of 1.15mm^2, 32A and resistivity of 1.724 x $10^{-8}\Omega$m Could be used to interface PV array and the battery bank

It implies that any copper cable of cross sectional area of 17mm2, 48A and resistivity 1.724 x $10^{-8}\Omega$m can be

used for the wiring between the battery bank and the inverter.

- Determination of Cable Size between the Inverter and the Load

Let the maximum length of cable (L) =15m, the maximum current from the inverter at full load on the phase line

is given by:

$I_{Phase.} = \frac{Inverter\ Capacity}{V_{Out}\ x\ \sqrt{3}}$

$I_{Phase.} = \frac{2500}{220\ x\ \sqrt{3}}$ = 6.6A

Maximum voltage drop

$V_d = \frac{4}{100} \times 220 = 8.8V$

A = $\frac{1.724 \times 10^{-8} x1x2.6x10^{-5}}{8.8}$ x 2 = 1.5mm2

This means that, conductor of cross sectional area 1.5mm^2, 2.6x10^{-5}A

and resistivity $1.724 \times 10^{-8}\Omega$m is suitable for the wiring between the inverter and load.

III. 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 [6].

IV. FACTORS THAT AFFECT SOIL RESISTIVITY:

- Moisture content of soil

The resistivity of the soil varies with moisture content of the soil. The higher is 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 [6].

- 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 sink deep to the ground to the level where the temperature is above the freezing point. [6].

- 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 [6].

- 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 [6].

- 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.

V. SELECTION OF THE EARTH PIT LOCATION

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

VI. SYSTEM MAINTENANCE

Typical causes in power installations breakdown include causes before operation, forced outage, foreign influences, unknown causes, operation and maintenance, and others. Among these, operation and maintenance causes take the lion share. Thus, it is imperative that energy installations such as off-grid solar PV systems have maintenance management put in place to prolong their lifespan and maintain their reliability.

VII. RESULTS AND DISCUSSION

Table 5: Results of the different stages of design analysis

	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	220Ah x 4
		Number of batteries in parallel	4
4	**Charge controller**	Capacity of charge controller	30A
		Total number of charge controller	2
5	**Inveter**	Capacity of the inverter	2.5kVA
6	**Wire size**	Size of the wire between PV modules and the charge controller	$6mm^2$
		Between battery and inverter	$17mm^2$
		Between inverter and load	

2.0 Discussion of Result

The daily energy consumption of the 2 bedroom apartment is determined and presented in table 5. The energy that must be produced by a PV panel so as to be able to operate the load was calculated**.** The result shows that the 2 bedroom apartment requires 1.27kW of electricity which can be produced by the six 200 W, 12 V modules selected in this project.

CONCLUSION/RECOMMENDATIONS

Proper design approach and maintenance of the system for optimal performance of solar power system has been presented. The work also covers design procedure of a 2.5kVA solar power plant. Also core areas/components that need to be maintained have been highlighted. 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. If the system is regularly designed and maintained, there is assurance that it will deliver up to 98% of its installed capacity.

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