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DEVELOPMENT OF SOLAR POWERED GENERATING SET FOR URBAN AND RURAL COMMUNITIES IN NIGERIA

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Abstract: *Generators with solar back-up have opened up an era of regulated steady power supply in Nigeria especially in regions with hot climate. A steady power supply ensures productivity to improve the socio-economic well-being of the people. A 2.5 KVA solar generator is presented as a case study. This is a generator in which the solar energy harnessed with the solar panel is employed to charge a battery bank (in series) and the direct current from the bank is used to power a d.c. motor (1hp) which then kicks an alternator to give a regulated alternating current at the output. This can be called a photovoltaic process because it consists of solar modules and a solar charge controller which help to charge the back-up batteries while the alternator converts the direct current to alternating current for use at the output. Analysis and performance evaluation conducted had shown in figure 5.1 that the efficiency of the generator decreases with the increase in input load of the generator. Again, the output result is as good as the conventional fuel/ internal combustion engine generators but is better because it is cost-effective, cheaper to run and maintain than the conventional types which consume fuel and lubricants, and is again pollution free.*

1.0 INTRODUCTION

Solar energy and biomass (e.g. fuel wood) had been the exclusive energy resources for all socio-economic activities in the traditional society but later petroleum products and electricity grew to play the dominant role in the economy as both the energy sources and engine of the economic development. This state of affair continued until solar and fuel wood became reduced to energy forms consumed only in the rural areas with conversion technologies that are inefficient, small-scale and adequate only for the support of subsistent economic activities. Such technologies include the open-to-sun drying and 3-stone stove methods. On the other hand, petroleum products and electricity, with capacity to support larger scale and varied economic activities with improved standard of living, became exclusive reserve only for the urban dwellers.

Beyond these state of affairs, the supply chain of petroleum products and electricity are inadequate and epileptic both in quantity and quality nationwide and rural areas are even worse-off. This is as a result of far distance between the supply point and the rural population centres in the grid system.

Solar radiation, as with other renewable energy resources, are available in very reasonable intensities and are well distributed all over the country[1]. For instance, the annual averages of daily global solar radiation varies from 3.5 kwh/m^2 - day in the south to 7.0 kwh/m^2 - day in the north, while the average of daily sunshine duration similarly varies from 5 to 9 hours[1]. These have provoked researchers to come up with the new innovations of solar technologies which gave birth to solar generators, solar inverters, solar refrigerators, solar dryers, etc. Again, it was observed that beyond the far distances of transmission constraints to the rural population centres, the solar PV is more economical to use than the grid electricity and diesel generators.

2.0 PHOTOVOLTAIC POWER SYSTEMS

A photovoltaic power system is a collection of electronic/electrical devices able to produce electricity from sunlight clearly and silently for more than twenty-five (25) years with very little maintenance as no moving parts are involved[2]. Its capacity can be from few watts to megawatts and can take the form of an autonomous or stand-alone system to a grid connected or utility interactive system.

Innovations in science and technology has moved the use of solar voltaic from mere applications in electronic calculators and watches to giant breakthroughs and emergence of solar cars and even solar powered helicopters. The use of solar voltaic in Nigeria is all encompassing and cut across every sphere of life including rural electrification scheme, communication industry, water pumping for drinking and irrigations, cathodic protection of oil and pipelines and desalination of sea water. Photovoltaic power system comprises of photovoltaic solar cells, bank of storage batteries, charge controller and converts[2]. The following subsections are the highlights:

2.1 Photovoltaic Cells and Solar Array

Solar energy is the radiant light and heat from the sun and is harnessed using a range of ever evolving technologies such as solar heating, photovoltaic, solar thermal energy, solar architecture and artificial photosynthesis[2]. Photocells generate an electromotive force in proportion to the radiant light energy received and are similar in effect to photoconductivity. The most common photovoltaic material is the selenium used in solar cells. They are made from single crystal PN junctions, same as diodes, but with a very large sensitivity region and are used without reverse bias. When illuminated, the light energy causes electrons to flow through the PN junctions so that individual solar cell can generate an open circuit voltage of about 0.58V.

The solar array is the collection of photovoltaic panels or modules connected in series and parallel combinations to give the desired power according to the system design. A typical solar cell can give about 0.5V and 1.0 ampere under standard temperature of 25°C and solar radiation intensity of 1000W/m^2 [2]. The output from a solar cell is direct-current mode suitable for most communication equipment and battery charging. Various types of solar cells exist, ranging from crystalline to amorphous types with different current voltage values and hence, different power levels. Solar cells like electrical generating devices may be connected in series to produce higher voltages and this can be achieved by connecting positive terminal of one solar cell to the negative of the next cell. They can also be connected in parallel to increase the current delivery if the positive of one cell is connected to the positive of the next cell and the negative terminal of the first cell to the negative of the second cell. Photovoltaic module is the connection of solar cells in series to give the desired voltage. These modules are connected in series and parallel combination to give strings of different voltages and currents according to the desire of a particular system. Figure 2.1 shows typical photovoltaic cells while figure 2.2 shows different cell connections in strings.

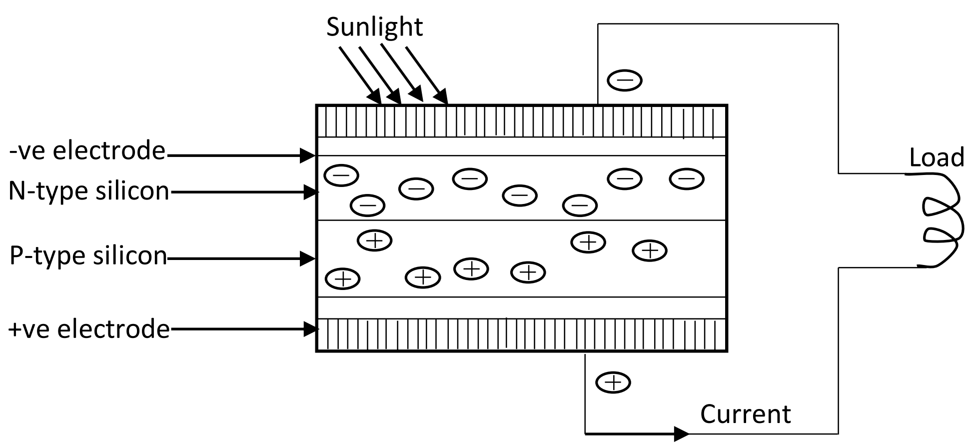

Fig. 2.1: Photovoltaic cells

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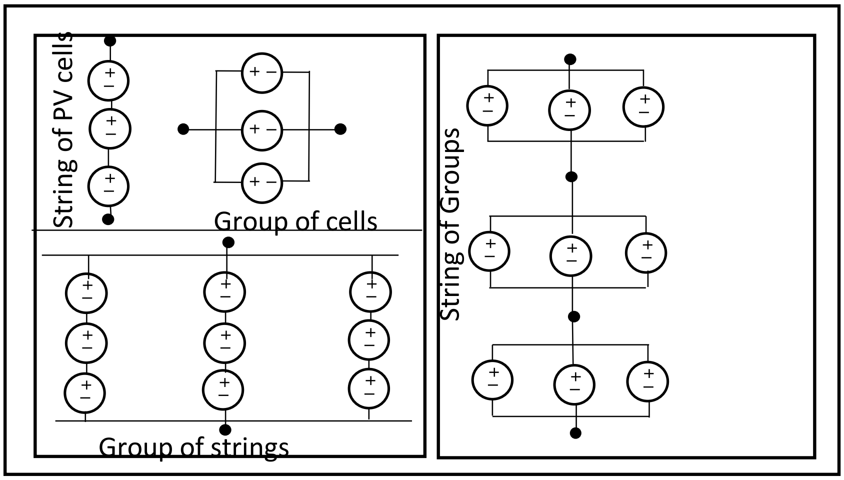

Fig. 2.2: Different solar cell connections

The solar array is a collection of photovoltaic panels and can be usually fixed to support structures. This can be permanently installed at a specific angle facing the sun (fixed arrays) or on mechanical devices to continually orient the modules to be perpendicular to the sun's rays (tracking array). In most cases, arrays are mounted to face the direction more exposed to the sun and tilted to the latitude of the site; in Nigeria, they are made to face the south[2]. From a given experimental data, the power delivered by photovoltaic solar cells can be displayed in table 2.1.

Table 2.1: Showing the size of photovoltaic solar cells in metre and the corresponding power output (MW)

Size of Solar Cell X (m)	Power Output (MW)
3	115
6	147
9	239
12	356
15	579
18	864

2.1.1 Bank of Storage Batteries

This is one of the sourcing units of the solar generators and consists of direct current batteries charged by the 'mains' supply and solar panel. Four of the d.c batteries each 12V 120Ah were connected in series to give 48V direct current (d.c) supply to the generator should the alternating current from the supply mains fail.

A battery is a power generating device capable of converting stored chemical energy into electrical energy[7]. There are different types of batteries but the two most popular types are the primary cells and secondary cells. While the primary or dry cells cannot be charged, the secondary or wet cells are rechargeable. Again, the primary or dry cells are inexpensive, light in weight and cannot be used for photovoltaic applications while the later are suitable for photovoltaic (PV) applications and should therefore be of high specific energy, low resistance, perform fine over wide temperature range and can withstand long cycle of charging and discharging[7].

Batteries are very important tools in photovoltaic process; and while the photovoltaic array is designed to provide both the needed powers to run the equipment and charge the batteries during the day time, the batteries when charged in turn act as backup to the PV array during the period of low solar radiation and at night time. The most suitable batteries for photovoltaic application are the lead-acid and lead-antimony batteries. They are available both as liquid electrolyte (flooded cell) and captive electrolyte (gel cells). The former is suitable for photovoltaic applications if made with lead-antimony or lead-cadmium plates. Note that periodic topping of distilled water is required to keep the lead plates fully immersed in the acid. The later (gelled/sealed) type is more maintenance-free but has shorter life cycle[2].

Batteries can be connected in series and parallel combination similar to PV modules to give the desired battery bank capacity. Batteries to be connected must match each other in voltage and storage capacity characteristics. Figure 2.3 shows the different battery combinations to give different voltage/capacities.

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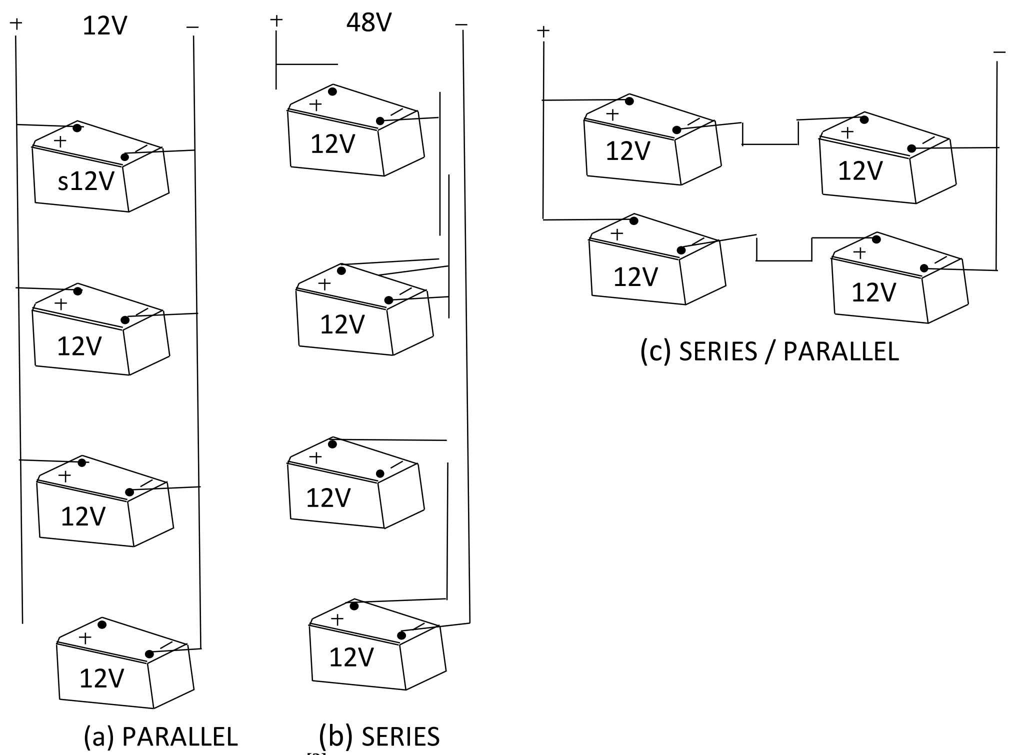

Figure 2.3: Different battery combinations[2]

2.1.2 Charge Controllers

This device serves as a current or voltage regulator to prevent the batteries from overcharge or discharge. Charge controller also protect against overvoltage by regulating the voltage and current coming from the solar panels and to the batteries. This important function of the controller is to disconnect the photovoltaic array when the batteries are fully charged and to disconnect the load when the batteries are discharged below safe level. This is a very important function because of the seasonal variation of the solar intensity which may result at times into excess or low powers. If the controller is not properly designed or checked, it may lead to the controller failure and hence, damage to the batteries or load. There are two main types of solar controllers, viz: (i) series controllers and (ii) parallel or shunt controllers[2].

Series controllers allow the charging current to be fully turned on or off as the need may be, when the battery depletes or fully charged respectively. This type can be called a single stage controller. When the battery voltage rises to near full state of charge, the regulator simply shuts the solar modules off. When the voltage drops to some predetermined point, full charging current is allowed to flow into the battery again. The multistage series controller also exists and allows different charging currents according to the battery state of charge and this increases the battery life.

Parallel or shunt controllers can utilize the energy produced by solar array or pass it away to some other loads when battery state of charge is reached without disconnecting the array from the battery. This type of controller can be used in a small PV power system but can combine with series regulators in or large PV power systems.

2.1.3 Alternator

This is a mechanical generator of alternating current type. In its principle, a coil or wire is allowed to rotate in a magnetic field; and if the connections to the end of the coil are made through sliprings, to ensure continuous contact, the wave form so generated will be alternating current whose voltage at time t is given by the expression $V = \omega B a \cos(\omega t)$. Where a is the side length of a square coil rotating with angular velocity ω. For a

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three-phase generator, three single phase coils (or windings) are combined on a single shaft and rotated in the same magnetic field while the end of each coil is brought out through a ship ring to an external circuit[4]. If the load is an alternating current type, the d.c motor will then operate the alternator to convert the d.c output of the solar array into alternating current (a.c). If the load is a direct current type d.c/d.c converter can be employed to match the output of the solar array with the load requirement.

3.0 PHOTOVOLTAIC SYSTEM DESIGN

Prior to any implementation, specific designs involving the basic calculations of every circuit should be carried out to determine the values of each component to be used and where and how it will be applied in the circuit to achieve a standard workable system. The aim of the system design is to determine the most reliable, safe and cost effective system that will meet a particular load demand. Here, several factors are considered such as the load analysis/ calculations to determine their power needs; estimation of the required solar array sizing and battery capacity are also inclusive. More importantly is to determine whether the load is a.c or d.c powered. Again, selection of the motor-alternator system is an important part of the design if the load is to be a.c powered; but if the load is d.c powered, d.c/d.c converter can be employed to match the output of the solar array with the load requirement[1].

3.1 Load Analysis and Battery Selection

Here, the power consumption of the electronic equipment used in houses and offices were calculated for the design of the 2.5KVA solar generating set; this is in order to know the battery size and solar panel suitable for charging the batteries. Here is the table of the load analysis for the design.

Table 3.1: Load Analysis for the 2.5KVA Solar Generator Design

Type of Appliance	Wattage	Number of Appliance	A_4 Rated Wattage	A_5 Adjustment Factor	$A_6 = A_4/A_5$ Adjusted Wattage	A_7 Hours Used	$A_8 = A_6 x A_7$ Energy/ Day
Point light	60	5	150	0.85	176	8	1408
Fan	75	2	100	0.85	118	3	354
TV set	200	3	200	0.85	235	8	1880
Laptop	50	3	100	0.85	118	3	354
Total			**550**		**647**		**3996**

From design specification and table 3.1,

- Let the alternator efficiency be A_1 = 85%
- Battery bus voltage A_2 = 48 volts
- Alternator AC output A_3 = 220 volts
- Total energy per day A_9(sum of A_8) = 3996 watt hr
- Total amp hr demand per day $A_{10}(A_9/A_2)$ = 3996/24 = 167Ah
- Maximum AC power required A_{11}(sum of A_4) = 550 watts
- Maximum DC power required A_{12}(sum of A_6) = 647 watts

Battery Sizing

- Days of storage required B_1 = 2 days
- Allowable depth or discharge limit B_2 = 42V
  If 48V = 100% for the battery bus voltage
  V = B_2

Therefore, B_2 = 4200/48 = 87.5% = 0.875

- Required battery capacity B3 (A_{10} x B_1/B_2) = 167 x 2/0.87
  = 384 Ah
- Number of batteries in series B_4 (A_2/selected battery voltage)
  B_4 = 48/12 = 4 batteries

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3.1.1 Design Specifications

Assumed capacity of the generating set = 2.5KVA
Battery capacity = 48V DC 100Ah

d.c motor

* Input voltage = 48V d.c (From battery)
* Input current = 15.54A
* Output power = 1hp or 746 watts

Alternator

* KVA rating = 2.5KVA
* Proposed KVA output rating when fully spun with the d.c motor = 2.5KVA
* Power factor (pf) = 0.85
* Output voltage of the alternator = 220V

To determine the proposed output power of the set
Generator: KVA rating = 2.5KVA (assumed)
Output power = $2.5 \times 10^3 \times 0.85$
= 2125 watts
Where 0.85 is the p.f.
Capacity of the d.c motor = 1hp or 746 watts
2125W – 746W = 1379W remaining power after d.c. motor has expended 746W to spin the alternator fully.
Remaining generator output power = 1379W or 1.379kw

$$\therefore \frac{1.379}{0.85} = 1.62\text{KVA} < 2.5\text{KVA}, \ \text{OK}$$

Solar Panel

Type	Monocrystalline
Max power	130 watts
Max voltage	19.5V
Max current	5.40A
Open circuit voltage	23.8V

Charge Controller

P/No	SC 330
Type	Automatic
Input	24V or 48V solar panel
Max input	50V, 30A
Max load	30A
Load switching	Negative
Battery	24V or 48V
Charge control	3-stage charging

4.0 IMPLEMENTATION USING THE DESIGNED OUTPUTS

In this section, the various designed outputs were integrated to form a perfect whole for the solar generator. In the construction, the designed apparatus were setup as shown in figure 4.1. A monocrystalline, 130 watt solar panel was connected to a charge controller (SC 330) and then connected to a battery bank of 48 volts. The battery energized the d.c motor which in turn

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started the alternator to give an a.c output of about 220 volts. In the development of the 2.5 KVA solar generator, the sourcing unit has two direct current (d.c) inputs, regulated by the charge controller, into the d.c motor-alternator system. These inputs are:

i. Single solar panel, 130W, 24V monocrystalline type.
ii. 48V d.c batteries each 12V d.c connected in series and charged by the solar panel during the day.

The charge controller not only charge the batteries but help to control the solar intensity to avoid excess or low powers. This important function disconnect the photovoltaic array when the battery is fully charged and disconnect the load when the batteries are discharged below safe level. Figure 4.2 shows the major components of a 2.5KVA solar generating unit.

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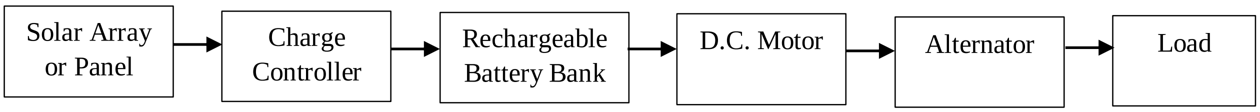

Fig. 4.1: Block diagram of the solar generator

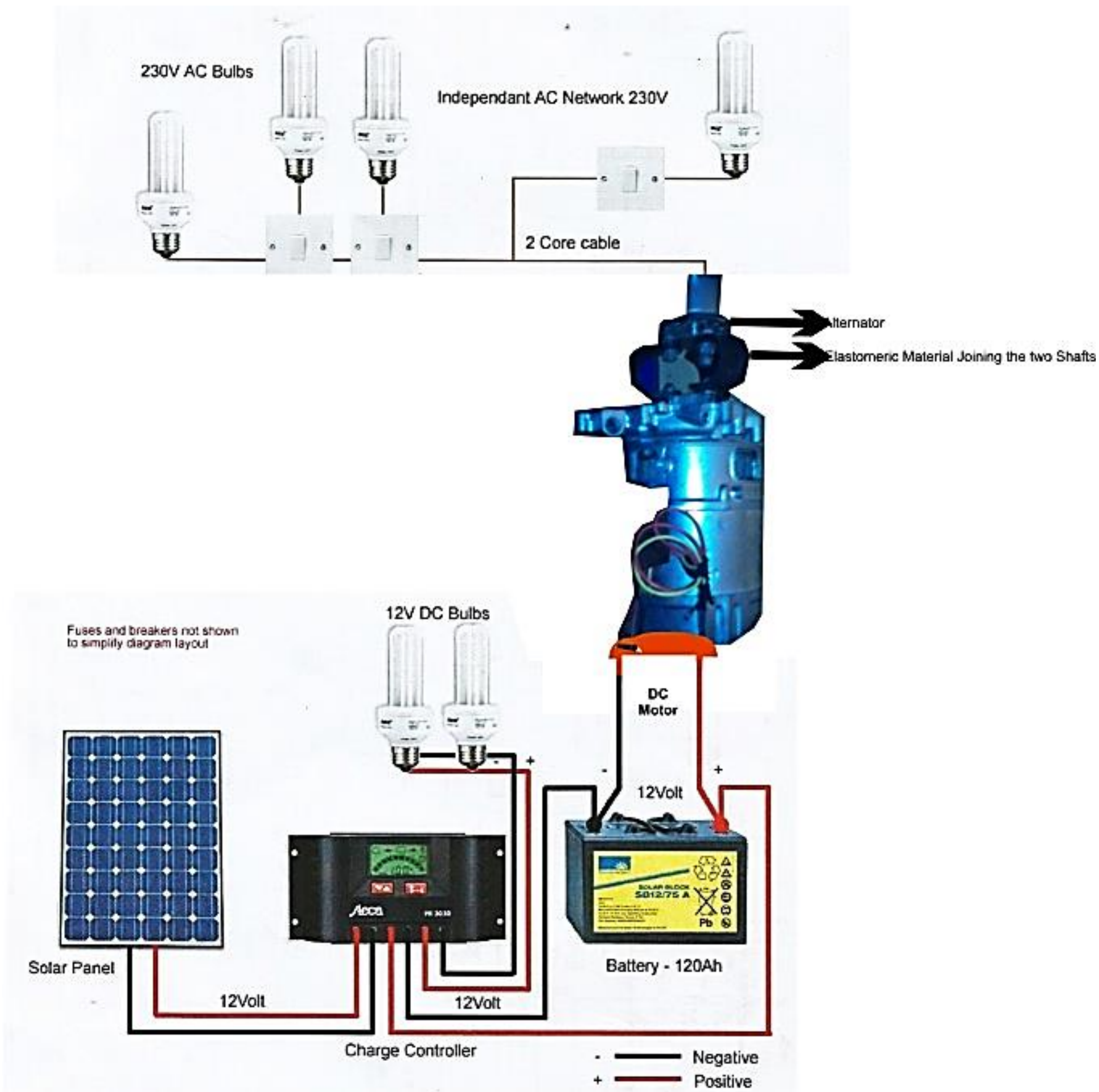

Fig. 4.2: Diagram showing the major components of a 2.5KVA solar generator

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5.0 ANALYSIS AND PERFORMANCE EVALUATION OF A SOLAR GENERATING SET

It is important to carry out analysis and performance evaluation after the design to determine whether the system meet some of the required specifications. Table 5.1 and figure 5.1 showed the results obtained from the solar generating set. The table and the plots simply showed the relationships between voltage and current at both input and output levels. The efficiency of the generator decreases with increase in input load of the generating set. The input power of the device is usually higher than the output power. Therefore, to operate the generator more efficiently, the maximum load of the device must be below 500 watts (see table 5.1).

Table 5.1: Efficiency of the 2.5KVA Solar Generator at various Loads

Trials	Load (W)	Input Voltage (V)	Output Voltage (V)	Input Current (A)	Output Current (A)	Input Power (W)	Output Power (W)	Efficiency (%)
1	0	31.66	562.50	0	0	0	0	0
2	250	31.50	545.00	18.35	0.95	231.20	206.03	89.11
3	300	31.63	502.00	19.49	1.05	246.48	210.75	85.50
4	350	32.01	470.00	19.68	0.99	226.29	185.60	82.02
5	400	31.87	384.00	20.40	1.21	260.07	185.77	71.43
6	450	31.79	361.50	19.50	1.09	24.96	157.34	63.45
7	500	21.19	327.00	16.87	0.91	210.44	118.74	56.42
8	550	31.50	232.37	13.21	0.74	166.40	68.64	41.25
9	600	30.94	107.30	11.38	0.60	140.92	25.49	18.09
10	650	30.86	68.16	8.83	0.53	109.18	14.42	13.20
11	700	29.20	70.60	5.75	0.33	67.31	9.10	13.51

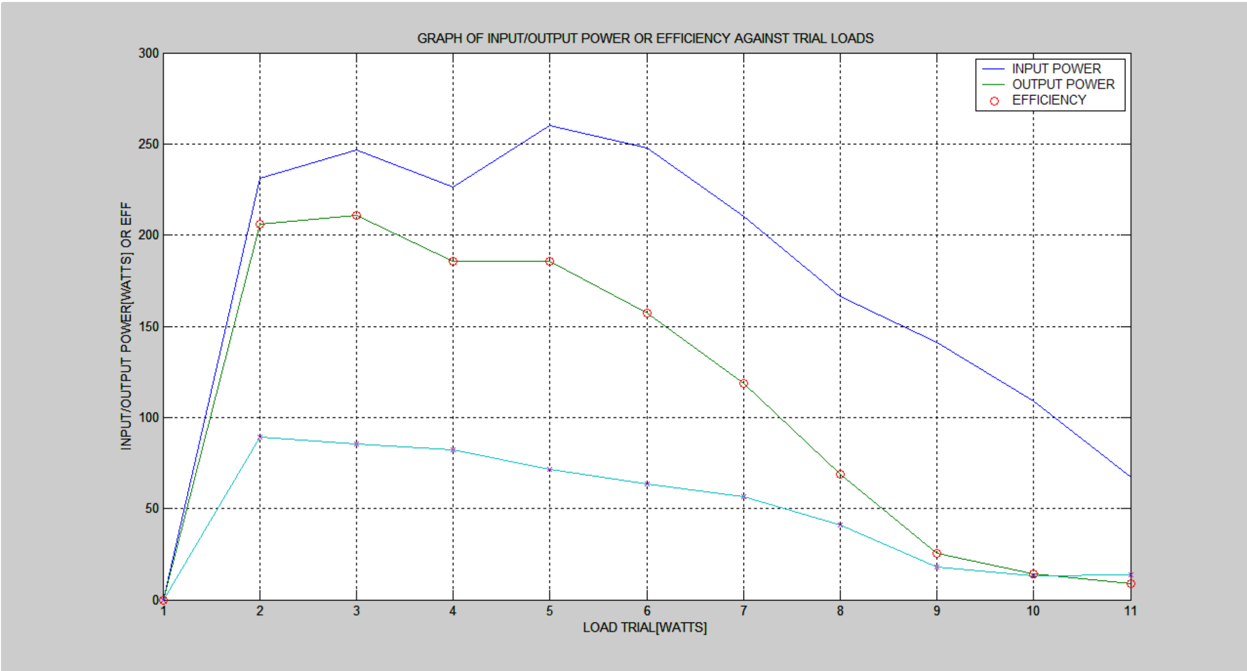

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Fig. 5.1: Showing the plots of input power, output power and efficiency of the solar generator against the trial loads.

6.0 CONCLUSION

Solar generating set is an improvement over self-sustaining type that use only battery as the source of power. It is more robust and can offer better sustainable power for rural and urban communities in Nigeria than the former because it taps directly from the rich natural solar endowments.

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