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Modeling of Photovoltaic Energy Utilizations in Systems - Machines and Devices

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Abstract -- Solar energy is very relevant in applications in Industries, Agro- machines and homes. This has necessitated the development of some sort of scientific and engineering techniques to effectively harness Photovoltaic and solar heat energy generations and utilizations. As a result, there are three theoretical models instituted to effectively utilize the photovoltaic energy in different spheres of applications in technology. To this, considerations were made on the capacity requirements and reliability of the systems components and behavior as can be seen in: Solar Panel, Load Requirement, Battery Sizing, Discharge time of the stored energy, Time to fully charge the battery, charge controller sizing, and wires sizing for: Solar panel, Battery connection and Connections to the charge Controller. The scope of this study is the design of models for utilization of solar heat energy in different spheres of life. The main reason for this work is to ensure for effective development of models and applications of solar photovoltaic energy to machines and other devices or systems. It is also served as a guide to young and inquisitive technicians to design substantially in systems and machines applications.

Index Terms- Modeling, Photovoltaic energy, Devices, Machines, Systems

I. INTRODUCTION

A. Photovoltaic System and Solar Energy Need Assessment Globally

It is recorded that about 1.7–2.0 billion people in the world, mostly in rural areas of developing countries, have no access to electricity and further 2 billion are severely under supplied, according to UNEP (Shafiqur et al,2006). This imbalance in energy distribution is one of the most important causes of social evil in the society. The other factors of concern to environmentalist, scientists, meteorologists, engineers and to certain extent to governments as well include the increasing global population, exponentially growing need of energy, global climatic changes and fast depleting reserves of traditional sources of energy. According the UN-sponsored intergovernmental panel on climate change projects, the global temperature will rise by up to 5.8 1C over the next century. In the present scenario, many countries have realized the need for the reduction of greenhouse gases emission to combat the adverse global climatic change. Hence to meet the power requirements of our future generations, new clean, renewable and sustainable sources of energy should be utilized, whenever and wherever possible. Photovoltaic (PV) technology is proven and easy to use solar of energy to generate electricity. It is being used globally to supply power to remote communities, utility peak load shaving, cathodic protection in pipelines, remotely located oil fields and gas oil separation plants (GOSPs), telecommunication towers, highway telephones and billboard, off-grid cottage/s, resorts in desert areas, water pumping for community and irrigation, municipal park lighting, exterior home lighting and many other usage.

For proper utilization of PV technology for energy generation, thorough and accurate knowledge of global solar radiation variation is required. Several studies have been undertaken to understand the availability and variability of these radiation.

Rehman and Halawani (1998) reviewed around 100 published papers and reports and presented a summary on the work done on solar energy. The study revealed that a good effort has been made in all directions right from measurement to theoretical modeling and prototype model development of solar devices. The study suggested that more efficient, organized and concentrated effort should be made in the direction of solar energy devices development and utilization and some of the recent theoretical studies related to solar radiation prediction and understanding the behavior of the same.

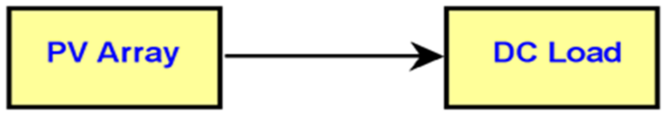
Advances in the measurements and applications of solar radiation energy on devices relative to geophysics, Rehman and Ghori (2000) used geostatistics along with available solar radiation to estimate the radiation at locations where it is not available with fairly good accuracy. Ali et al. (2001) used PV modules to supply electricity to demonstrate the working of an automated irrigation system. In order to predict the global solar radiation in time domain, (Mohandes et al, 2002), used artificial neural networks and showed that radiation data can be predicted in future time domain with the knowledge of available data with acceptable accuracy Moreover, solar radiation data is also measured by the Research Institute that presented an empirical formula obtained using the daily total solar radiation, sunshine duration, relative humidity, maximum temperature, latitude, altitude and the location of the place relative to the water surface. A good amount of funds has invested on the development of solar energy both on experimental and theoretical investigations. Solar energy-based appliances are being used at the Royal Commission of Yanbu and Jubail, Saudi Arabia. The world's first and the largest grid-connected PV facility was developed and tested at Solar Village situated on the outskirt of Riyadh, the capital city of Saudi Arabia (Alawaji SH., 2001).

PV technology is being used for cathodic protection in oil pipe lines, communication towers, water pumping for irrigation El Hori stated. The total PV-installed capacity in Libya, as of May 2003, is 633.88kWp. Furthermore, according to El Hori, Libya is planning to build a grid connected PV power plant with 1MW installed capacity in the near future. PV is also being used in Jordan to pump water and in lighting the streets, schools and other governmental institutions located in remote areas. According to Hrayshat and Al-Soud (2004), the total PV installed capacity in Jordan is 82kWp generating a total of 182.5MWh of electricity each year.

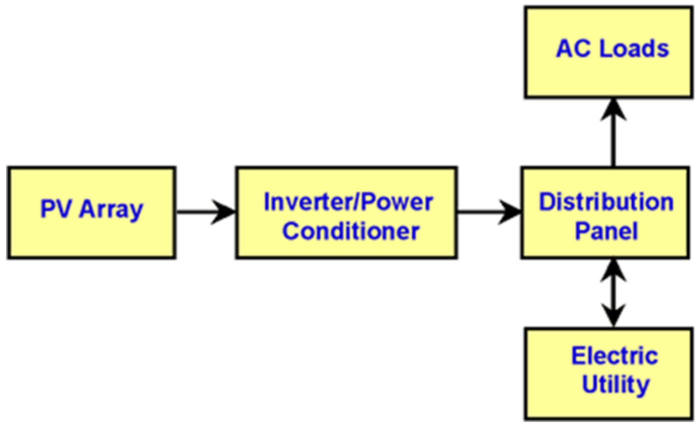
In order to study the energy production, a PV system of Wp installed capacity was considered. Monthly mean values of temperature and global solar radiation on horizontal surface along with latitude of the site were used as input in Ret Screen software to get the specific yield, renewable energy produced and green house gases avoided entering into the atmosphere as a result of clean energy utilization. The software also performs the economic analysis of the grid connected PV power plant in terms of internal rate of return (IRR), simple payback period (SPP), years to positive cash flow (YPCF), net present value (NPV), annual life cycle savings (ALCS) and profitability index (PI).

B. PV SYSTEM DESCRIPTION

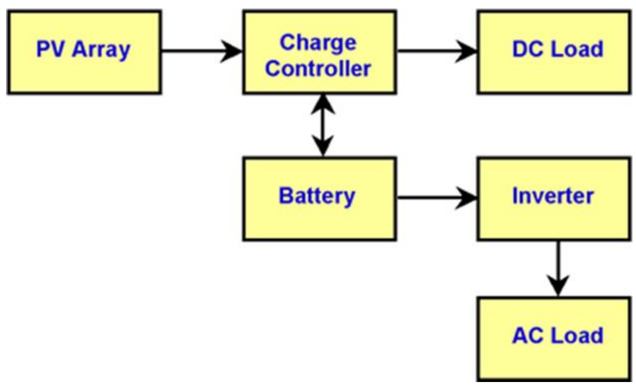
Types of PV- Systems



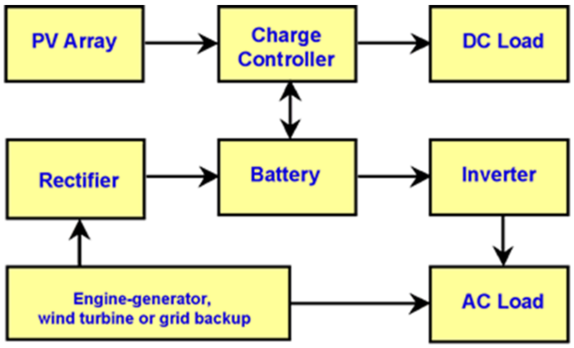
a. Direct-coupled PV system



b. Diagram of grid-connected photovoltaic system



c. Diagram of stand-alone PV system with battery storage powering DC and AC loads



d. Diagram of photovoltaic hybrid system

The solar module or the PV part is the heart of the whole PV system. The solar module is composed of several individual PV cells connected in series or parallel as shown (a – d) above. Primarily, the number of individual cells within a module and the arrangement of these cells in the module influence the energy produced by a PV module. The cells can be arranged in a module to produce a specific voltage and current to meet the particular electrical requirements. Similarly, the PV modules can be arranged to form a solar array to produce a specific voltage and the current. In the present study we have used the PV Module of 90W peak capacity comprised of mono-Si solar cells from BP Solar/Solarex. The specifications of the module are summarized in Table 1.

Table 1: Photovoltaic Module Specifications

Item Description	Item Specificatic
Voltage [@ peak power] (V)	18.5
Current [@ peak power] (A)	4.86
Voltage [open circuit] (V)	22.3
Current [short circuit] (A)	5.2
Frame area (m2)	0.63
Mounting dimensions thickness (mm)	43.5
Width (mm)	1188
Weight (kg)	7.5
Certification	CSA, CEC

Inverters with a certain total rated capacity and with 95% efficiency considered to convert DC into AC to directly feed the grid. The PV modules were assumed to be fixed, i.e. no solar tracking, and inclined at an angle equal to the site latitude and South facing. The azimuth angle was taken as zero for all the systems

C. Global Solar Radiation and Sunshine Duration Behavior

The long-term seasonal variation of global solar radiation must be known. From this, it is evident that higher values of radiation were observed during summer months and lower in the winter months. The seasonal pattern of solar radiation matches with electrical load pattern prevalent in Saudi Arabia. Hence, it will prove to be advantageous to use PV technology to generate electricity for grid connected applications to meet the peak load requirements. The long-term monthly mean values of sunshine duration for individual solar radiation stations can be shown. It is evident from the result that the sunshine duration is longer in summer months and shorter in winter months at all the locations. Longer durations of bright sunshine are observed in summertime compared to that in wintertime. The overall mean value of sunshine duration is obtained by using all the values from all the locations within a given space of study. Higher values of sunshine duration are noticed in the northern region while relatively smaller in the southern region.

D. Relevance of Solar Energy to Industries

It is basic to remember that solar energy is sent down to the earth freely from the sun energy produced through fusion reaction at the heart of the sun. This energy comes down in the form of light and heat energy through wave and radiation respectively. The energy from the sun is used in drying of agricultural crops directly, but now solar technology has made it possible for the development of different types of solar energy systems – those that convert solar energy to electrical energy (Photovoltaic, PV) and those that convert solar energy to heat energy (solar collectors). Solar energy is one of the energy sources available for use in industries and homes. Other forms of energy sources harnessed and utilized are hydro-, fuel, wood, wind, biomass, nuclear, geothermal, and oil and gas. But solar energy is among the renewable energy sources which are currently being developed for effective use because of its availability and sustainability.

Solar energy has a substantial growth potential for meeting energy needs in Nigeria especially in the rural areas where a large percentage of the population have denied access to energy supply. Presently, the natural

solar energy unconverted to any form is used for drying most especially for agricultural products. One may expect a wide use of this solar energy for at least partial supply of domestic; for small scattered consumers basically in small house areas.
Studies have proven that typically the overall efficiency of conversion of solar energy to useful high-grade heat or electricity is low, about 5%. But this notwithstanding solar energy can still be conveniently used in Industries and homes for water heating, distillation of water from salt or pond water (solar stills), plant growing stimulation (greenhouse), cereal grain crop drying, driving heat engines for water pumping or power generation, driving thermal refrigeration machines for air conditioning, food and drug preservation (solar cooling).

Solar energy availability and sustainability development is in advanced stage that the industries should have brighter future to operate extensively. It is very important to know that many industries environments utilize heavy driving electrical machines which require enormous power whose energy is tapped from electricity, as a result in solar electrical energy dimension designers of solar energy utilizations in industries will be taking into cognizance the power requirements in industrial machines to develop solar electrical energy supply system that is robust in use – the design of heavy capacity converters or inverters.

The effective design and development of reliable solar electric energy supply system can make industries to hope in the use of the renewable energy source that is economical to use and sustainability possible.
Solar energy is relevant in industries as earlier identified and elaborately used in many applications as can be further identified below.

Solar energy is found applicable in the Agro and allied industries, where drying, frying and heating are carried out to condition the agricultural produce to permit for storage and other preparatory models for agricultural production and distribution to the consumers.

Drying of grains to preserve their genetic potency can be possible with assurances through solar energy drying. Drying of herbs and roots are possible through solar energy harnessed, it offers a hygienic dried materials that are ideal for pharmaceutical uses. To this end, a lot of researches and designs have been put into motion to develop system that can increase the efficiency of solar drying. In the years 2012 and 2013 at the Faculty of Engineering, in the Department of Industrial and Production Engineering solar drying devices or systems were developed and being researched on, for the drying efficiency improvements. Several models of the designs were developed in this essence. Many other advanced researches have been carried out by other researchers like Nwokoye and Igboekwe, et al (1980) on optimization of solar modules for enhancing solar electricity generation.

Solar frying of cassava mash has been in use in agro-cottage industries for the production of gari and other agro-processed products like soya-bean cake, ground nuts, yams, plantain chips and potatoes chips for consumption.

It is now obvious, that in the supply of hot water by Water Corporation, solar energy is economical for use in heating and pumping water supplies to cities where hot water and water distributions by this corporation is needed in continuous quantity.

Solar electric energy is currently used in banking industry and other industries for lightening and in carrying out other operations because of the assurance in the steady supply of power which the system supply is within the office yard or room.

Solar energy can be used in the Green-House industry production. However, some institutions still operate the green house (despite none statistical), places like Natural Root Crop Research Institute, Umudike, Umuahia; University of Nigeria, Nsukka and Michael Okpara University of Agriculture, Umudike, etc.

Water irrigation machines/harvesting of crops, solar water pumping systems –machines that carry out the above work can be powered by solar energy.

Solar energy in fishing industry – Aquatic life is sustained, when photosynthetic activities releases a lot of oxygen both terrestrially and made water body as tidal wave, a form of energy carries across sea and down inside sea beds to reach the aquatic lives as

oxygen releases in water. All fishes, Zoo planktons, water animals and organisms receive oxygen dissolved in water for living and development.
Solar energy is used to drive all kinds of electronic, electrical and computerized system devices. Most industrial machines like hand drills, powered hack-saw, cutters, powered screw-drivers and other workshop machines are currently being made of solar base powered.

Almost all electronic and computing gargets are currently using solar energy power source in their operations.

Therefore, it can be categorically stated that the solar energy is so relevant in every industry, and so industries are encouraged to opt for it, because of its economic, availability, reliability and sustainability, despite its high initial cost. Solar energy therefore, you are highly welcomed.

Modeling of Photovoltaic Energy in Physical Systems

There are three theoretical models instituted to effectively utilize the photovoltaic energy in different spheres of applications in technology: the Solar energy source – charge controller – load model; Solar energy source - charge controller – Battery – load model; and Solar energy source - charge controller – Battery – Inverter – load model. The applications of these models to physical systems of devices and machines have certain concepts in common, which are the machine power (load) requirement, Solar Panel sizing, Battery Sizing, Discharge time of the stored energy, Time to fully charge the battery, charge controller sizing, and Wires sizing for: Solar panel connection, Battery connection and Connection to the charge Controller. These will help young inquisitors not to fall into errors in developing or powering devices and machines that use PV electricity.

Inverters with a certain total rated capacity and with 95% efficiency considered to convert DC into AC to directly feed the grid. The PV modules were assumed to be fixed, i.e. no solar tracking, and inclined at an angle equal to the site latitude and South facing. The azimuth angle was taken as zero for all the systems

II. INSTALLATION REQUIREMENTS

Any PV system will fall under the relevant regulations and standards governing electrical installations. Within the IEC framework this would be IEC 60364 “Electrical installation of buildings.” While any installation needs to fully comply with the standard, part 7-712 deals with particular requirements related to PV systems.

Local regulation will often be in force, for example in the UK, BS7671 (the IEE Wiring Regulations) is used. If in the US, then NFPA 70 (National Electric Code) would be used.

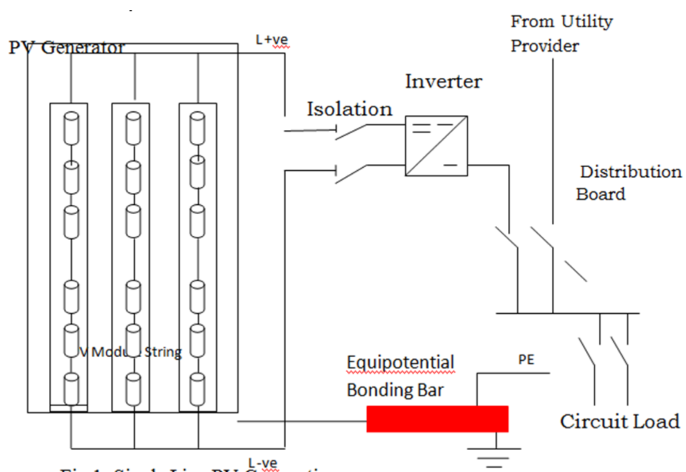


Fig 1: Single Line PV Connection.

In designing the PV system and its grid connection, the designer would typically need to consider the following:

i) D.C. protective devices on the array output
ii) A.C. protective devices on the inverter output
iii) Connection of the inverter into the installations main electrical systems
iv) PV array over voltage protection
v) Junction boxes for connecting multiple arrays
vi) Devices for isolation of PV array from the inverter
vii) Devices for isolation of inverter
viii) Earthen and Equipotential bonding of the equipment

III. DETERMINATIONS OF THE PARAMETERS IN PHOTOVOLTAIC ENERGY APPLICATIONS IN APPLIANCES AND MACHINES

A. Machines Power Requirements

Devices and machines are powered by solar photovoltaic energy. Solar photovoltaic system is a renewable energy system which uses PV modules to convert sunlight into electricity. The electricity generated can be either stored or used directly. Solar PV system is a very reliable and clean source of electricity that can suit a wide range of applications such as in residence, industry, agriculture, livestock, etc. The major components for a solar PV system are: a solar charge controller, a solar panel, and a rechargeable battery. Their respective functions are:

a. PV module (solar panel) – converts sunlight into D.C electricity.
b. Solar charge controller – regulates the voltage and current coming from the PV panels going to the battery and prevents battery overcharging so as to prolong the battery life.
c. Battery – stores energy for supplying to electrical appliances when there is a demand.

B. Solar Photovoltaic Modular in Machine System

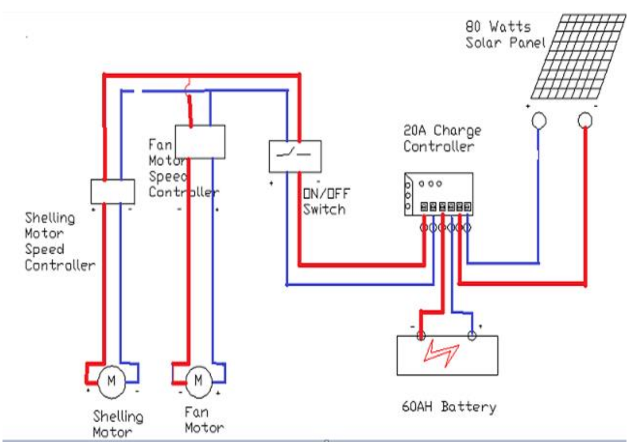
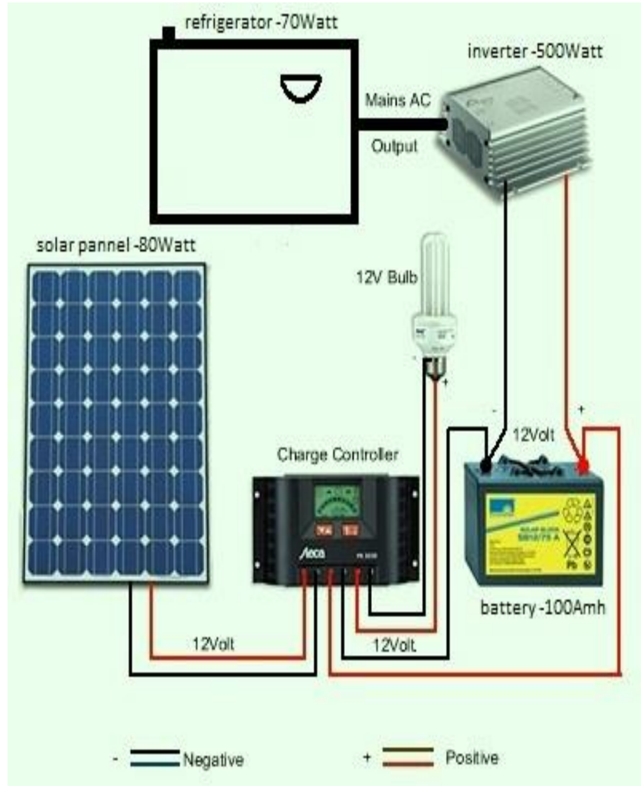


Figure 2: Electrical Photovoltaic – Appliances Interface

Figure 2, shows a system that carries d. c. loads – shelling motor and separator fan of melon (Egusi seeds) shelling machine.



Source: Tianshan Industrial Park, Songqiao

Figure 3: Electrical Photovoltaic – Appliances Interface

Figure 3, shows a system that carries a d. c. load (bulb) and an a. c. load (70watts) Refrigerator.

NB: During technical connection of the components with wires, ensure that RED wires are Connected to the positive sides (+) and BLACK wires are connected the negative sides (-) to avoid Biasing Semi Conductors, and discharging of Battery.

IV. SOLAR POWER SYSTEM COMPONENTS SIZING

A. Solar Panel Sizing

A. Determine the Power Consumption

The first step in designing a solar PV system is to find the total power or energy consumption of all loads that need to be supplied by the solar PV system. This is done as follows:

I) Calculate Total Watt-Hours per Day Needed for the Machine

Add the Watt-hours needed for all loads together to get the total Watt-hours per day

which must be delivered to the machine in fig. 2.

Total power required by the machine, P_{total} = Power of the impeller motor (P_{im}) +

power of the fan motor (P_{fm})

Power Requirements $P_{total} = (P_{im} + P_{fm})$ Watts.

Assuming the machine will run for 2hrs daily.

Power consumption = $P_{total} \times 2hrs = 2P_{total}$ (Wh), or

Assuming that the machine will run for 8hrs daily.

Power consumption = P_{total} x 8hrs = $8P_{total}$ (Wh)

II). Calculate Total Watt-Hours per Day Needed From The PV Modules.

Multiply the total Watt-hours per day by 1.3 (the energy lost in the system) to get the total Watt-hours per day which must be provided by the panel(s). The coefficient factor of 1.3 on multiplication gives a safety margin on to the power generated by the system.

Total watt-hours per day provided by the panel =

$2\ P_{total} \times 1.3 = 2.6\ P_{total}$ (Wh) or $8\ P_{total}$ x $1.3 = 10.4\ P_{total}$ (Wh)

B. Sizing the PV Modules

The peak watt (W_p) produced depends on size of the PV module and climate of site location. We have to consider "panel generation factor" which is different in each site location. For Nigeria, the panel generation factor is 5.25kwh/m² per day. To determine the sizing of PV modules, calculate as follows:

Calculate the total Watt-peak rating needed for PV modules by dividing the total Watt-hours per day needed from the PV modules by 5.25 to get the total Watt-peak rating for the PV panels needed to operate the machine.

$W_p = \frac{2.6\ P(total)}{5.25} = 0.495\ P(total)$ Watts or

$W_p = 1.98\ P_{total}$ Watts

Select the next available panel size of power requirement in Watts.

C. Battery Sizing

The battery type recommended for use in a solar PV system is the deep cycle battery. A deep cycle battery is specifically designed to be discharged to a low energy level and rapidly recharged or cycle charged and discharged day after day for years. The battery should be large enough to store sufficient energy to operate the machine at night and on cloudy days. To find out the size of the battery to use, calculate as follows:

1. Calculate the total Watt-hours per day used by machine.
2. Divide the total Watt-hours per day used by 0.85 (charge loss factor).
3. Divide the answer obtained in item II by 0.6 for depth of discharge.
4. Divide the answer obtained in item III by the nominal battery voltage (12V).

Multiply the answer obtained in item IV with the days of autonomy (i.e. the number of days that you need the system to operate when there is no power produced by the PV panels) to get the required ampere-hour capacity of the deep-cycle battery.

Battery Capacity (Ah) = $\frac{2.6\ P(total) \times 1}{0.85 \times 0.6 \times 12} = 0.425\ P(total)$ Ah

Select the next available battery size of 60Ah

D. Time of Discharge of the Battery

Since a D.C battery is to be used, it is pertinent to determine how long the battery can last during service, especially when it is not being charged.

Using Coulomb's Law,

$$Q = IT \quad (1)$$

Where

Q = Quantity of charge in the battery = 60 Ah

I = Total current consumed by the machine, in amps

T = Discharge time, in hours

From Ampere's Law,

$$I = \frac{P}{V} \quad (2)$$

Power consumed by the machine, $P = P_{total}$ Watts

Nominal Battery Voltage, V = 12V

Therefore,

$$I = \frac{\text{Power consumed by the machine}}{\text{Nominal Battery Voltage}} = \frac{P(total)}{12} = 0.0833\ P(total)\ \text{Amps}$$

$$\text{Discharge Time, } T = \frac{\text{Quantity of charge in the battery}}{\text{nominal battery voltage}} = \frac{Q}{12} = 0.0833Q\ \ (\text{hours})$$

E. Time to Fully Charge

Recall that Q = I.T (3)

Where, Q = Quantity of charge when full = 60 Ah

$I = I_r$ = Current rating of the panel = 5.17A

T = Time to fully charge, in seconds.

Charge loss factor ranges from 0.85-1.25, assume it is 1.25

$$\text{Therefore, time to fully charge, } T = \frac{Q}{I} \times \text{Loss factor} \quad (4)$$

$$T = \frac{\text{Quantity of charge when full}}{\text{Current rating of the panel}} \times \text{Charge loss factor}$$

$$= \frac{Q}{I} \times 1.25 = 1.25\ (Q/I_r)\ \ (\text{hrs.})$$

So, it will take $1.25Q/I_r$ hrs for the panel to fully charge the battery when it runs down.

F. Solar Charge Controller Sizing

The solar charge controller is typically rated against Amperage and Voltage capacities. Select the solar charge controller to match the voltage of PV array and batteries and then identify which type of solar charge controller is right for your application. Make sure that the solar charge controller has enough capacity to handle the current from the PV array.

For the series charge controller type, the sizing of controller depends on the total PV input current which is delivered to the controller and also depends on the PV panel configuration (series or parallel configuration).

According to standard practice, the sizing of a solar charge controller is to take the short circuit current (I_{sc}) of the PV array, and multiply it by 1.3 (energy lost n the system).

Solar charge controller rating = Total short circuit current of PV array x 1.3

Charge controller rating = $I_r \times 1.3 = 1.3I_r$ (Amps.)

Select the available charge controller whose value is as calculated or above Amperes.

G. Wire Sizing

1. The electrical components of the machine and solar photovoltaic system are connected with wires. In order to prevent current losses due to discharge from the battery and power losses during the machine operation, proper sizing of the wires to be used is necessary.

   Step 1: Determine the voltage drop index (VDI);

$$VDI = \frac{\text{Amps} \times \text{feet}}{\%\text{volage drop} \times \text{voltage}} \quad (5)$$

   Step 2: Determine the appropriate wire size from wire sizing charts

   Compare the calculated VDI with VDI in the chart to determine the closest wire size.

a. Wire Sizing for the Solar Panel

   Determine the voltage produced by the panel

   Power, $P_{total} = IV$ Where

   $P = P_{total}$, Watts

   I = short circuit current on the panel = 5.17 A

$$V = \frac{P}{I} = \frac{P(total)}{5.17} = 0.1934\ P(total)\ \text{Volts} \quad (6)$$

   If the length of the wire is 6ft,

$$VDI = \frac{5.17 \times 6}{2 \times 15.47} = 1.003$$

To determine the wire size in mm²,

VDI × Power factor (7)

Power factor for copper wires = 1.1

Therefore, 1.003×1.1 = 1.10 mm²

From Wire sizing chart in the appendix, 1.5mm² wire sizes is selected.

b. Wire Sizing for the Battery Connection

Maximum voltage transmitted by the battery = 13.5 - 14.5 V

Total power consumed, P_{total}. = power of the impeller motor + power of the fan motor

Maximum current in amps, $I = \frac{P}{V}$ (8)

$I = \frac{P(total)}{14.5} = 0.069P(total)$ Amperes

If the length of the wire, L is 5ft, then Voltage drop index, $VDI = \frac{10\times5}{2\times14.5} = 2.07$

Wire size in mm², will be 2.07×1.1 = 2.3mm²

From the chart, the nearest wire size is 2.5mm² and this nominal size is then selected.

c. Wire Sizing for the Connection to the Charge Controller

Maximum voltage transmitted to the machine = 12V,

Total current required, $I_{total} = \frac{\text{Power consumed by the machine,P(total)}}{\text{Voltage demand,V}}$ (9)

$I_{total} = \frac{P(total)}{12} = 0.0833P(total)$ Amps

If the length of wire needed is 6ft, then,

$VDI = \frac{I(totai)\times6}{3\times12} = 0.1667\ I(total)$

Wire size in mm², will be $0.1667\ I(total)\times 1.1 = 0.1834\ I(total)$ mm²

From the chart, select the nearest wire size as calculated for charge controller.

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