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AMPERE HOUR METHOD OF SIZING A STAND ALONE PHOTOVOLTAIC SYSTEM

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ABSTRACT

Stand-alone photovoltaic power systems are natural options for application in electrification of remote areas which are not served by the grid electricity supply system. An ampere-hour method of sizing a stand-alone PV system for application in any remote location has been presented. The design which is for both ac and dc operated appliances, has established an optimum relationship between the PV array and the balance-of-system so that the required unit of energy at a specified reliability can be supplied. Two approaches to the array sizing were considered. The first approach considered the seasonal derate negligible, in which case, the design current was calculated directly, while the second approach considered the seasonal derate non –negligible. In this case, the seasonal derate must be obtained before the design current is computed. Sizing of the balance-of-system were carefully handled to avoid undersizing or oversizing and subsequent variation in supply reliability. The temperature effects and the peak sun hours of the location in question were also considered in the design.

KEYWORDS: Ampere-hour; sizing; stand- alone; photovoltaics.

INTRODUCTION

One of the primary concerns in designing any photovoltaic system is the determination of the optimum relationship between the Photovoltaic array and the balance of system so as to supply a required unit of energy at a specified reliability. This paper is aimed at designing effective stand-alone system which can be utilized even in remote household locations. The most important consideration in this system design is to have the knowledge of the solar radiation data for the site, the consumption profile and the importance of uninterrupted power supply. Good system sizing was achieved in this work by optimizing the system and individual elements in the system to ensure that the life cycle cost is minimized. If less durable parts are specified, maintenance and replacement cost will increase and the life-cycle cost estimate can easily double.

Then the sizing procedure recommends the size of the Photonvoltaic generator and battery capacity that will be optimum for the application (Ugwuoke, 200). Even though it is ideal to avoid undersizing or oversizing, it is always difficult to predict accurately the weather pattern and load consumption profile. Moreover, since up to 97% system reliability is required in stand-alone Photovoltaic power system, the system can be oversized even though it will be expensive to install. In this case, the power system has to cover those few low-probability “no sun” days, unexpected peak loads and changes in consumption pattern within the year. So in sizing a stand-alone Photovoltaic system, it is always crucial to know how much power is going to be needed, the daily duty cycle and the weekly duty cycle. This will facilitate accurate determination of the load profile in the house. The basic parameters for determining the power needs of any appliance are the voltage (V), Current (Amp) and power (W). Many appliances have their current, voltage and power ratings listed on the unit. In some cases it may be necessary to measure the power required or to obtain it from manufacturer's literature. It is also normal to estimate the number of times the appliance will be needed per day, week or month and care should be taken not to over-estimate because the cumulative effect of over-estimation can cause the size and cost of a PV system to skyrocket.

Although if the losses at the wires and batteries are to be considered, it would be practicable to over-estimate so that after all these losses, an expected ampere-hour load may be achieved. The usual recommendation is that several large loads are not used simultaneously. For instance, an air-conditioner can only be more effectively used during the summer.

METHODOLOGY

The process of sizing a photovoltaic system consists in: Determining the number of PV modules that

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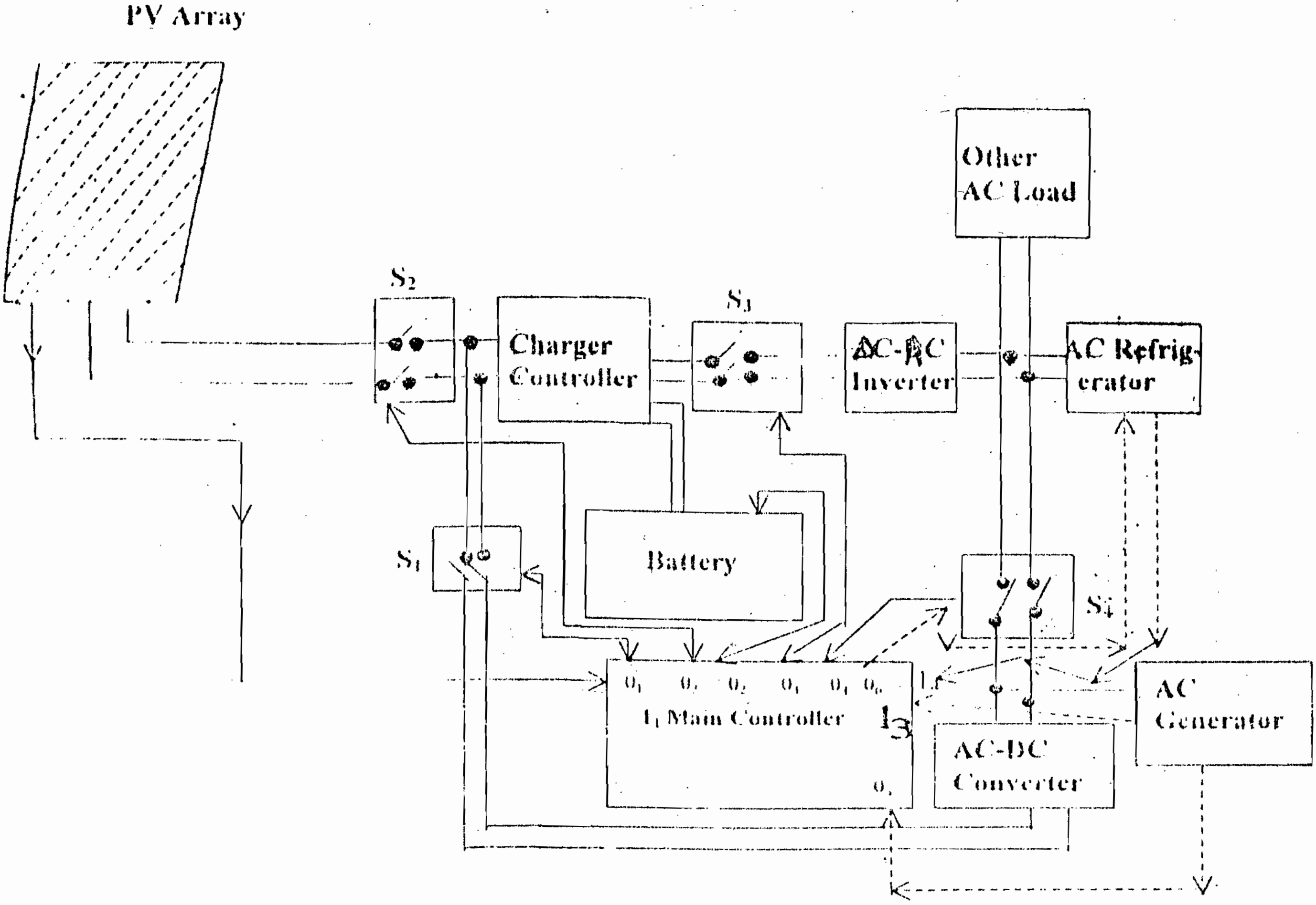

Fig. 3.1 Complete Schematic Block arrangement of a photovoltataic system, containing a power generator.

are required to reliably deliver the desired amount of electrical power; and appropriate determination of the number of components within the balance-of-system suitable to handle the electrical power.

Various methods have been employed in sizing photovoltaic systems. The ampere-hour method which was adopted in this paper, uses calculations in which electrical units are expressed in terms of ampere-hour. In this method of system sizing, the nominal output voltage of the array is selected to match the voltage requirements of the load. The ampere-hour method is preferably adopted in photovoltaic system sizing because it usually allows us to ignore the fluctuations in voltage that occur in the array output due to variations in temperature and load. Since almost all PV modules are designed for battery charging, it means that the module's nominal operating voltage must be approximately 25% higher than the battery's nominal rated voltage for charging to occur. Also since the battery storage bank is based on ampere-hours, it implies that an ampere-hour method of array sizing will relate well with the common method of sizing a battery bank (Strong and Scheller, 1991). Other methods of system sizing include: the watt-hour or kilowatt-hour method. This method expresses electrical unit in terms of watt-hours or kilowatt-hour and is usually employed when sizing utility-interactive PV system or stand-alone system that work without battery storage (such as direct – coupled water pumping system). Another method is the two event probability density approximation method by Bucciarelli (1984). In this approach, the load L on the system is assumed to be constant and the probability density for the daily surplus (or deficit) energy generated D, is obtained by shifting the probability density for the array power output to the left by an amount equal to L. From this probability density, σ_D and σ_D are obtained (Bagul et al, 1996).

The simulation method is yet another method of sizing a stand –alone system. This method uses the hourly meteorological data and hourly load data to simulate the energy flow in a PV system and predicts the system reliabilities under various array and battery sizes. The loss of load hours (LOLH) is adopted to express this reliability (Lasnier and Gan Ang, 1990).

LOAD EVALUATION IN TERMS OF AMPERE-HOURS

In PV system design, nominal system voltages of 12V, 24V, 48V or higher may be used depending on the total power requirement of the appliances. It is usually advisable that when the power demand of the appliances is large, a high system nominal voltage (usually 24V Or 48V) be used. It is not advisable to use a nominal voltage of 12 volts, except if the power demand is very small, because the high current required by loads much greater than 1000 watts will create problems with wire sizing and voltage drops.

The number of hours per day (called daily duty cycle) and the number of days per week (called weekly duty cycle) for which an appliance can be used are important parameters for determining the ampere-hour load (AH_L) for that appliance. The daily ampere-hour loads for an appliance is given by (PV Design Assistance Centre, 1998).

$$AH_L = \frac{\Pr XDDCXWDC}{V_{ns} X 7 X \eta_{cp}}$$

Another important factor for consideration in system sizing is the wire rating. Wire is usually rated according to gauges. There is usually a maximum current-carrying level for each gauge of wire, beyond which over heating and significant voltage drop will occur. Thus in designing for a heavy demand system, it is important to include the wire efficiency factor η_w. Therefore if 10% of the daily load can be allotted for internal system's loss, it follows that the battery could be 90% efficient. Consequently, a corrected ampere-hour load method is adopted and is calculated as

$$AH_c = \frac{AH_L}{\eta_W X \eta_B} \qquad 2$$

This corrected average daily ampere-hour load is the ampere-hour load per average day of charging current from the array to satisfy the typical rainy season load demand.

ARRAY SIZING

As previously mentioned, the ampere-hour method of array sizing has been adopted for this work because the battery losses of the storage batteries do not have to be figured separately since they are compensated for by the fact that the actual operating voltage of most photovoltaic modules is higher than the nominal voltage rating (usually 16 to 18 VDC for a 12 volt nominal module). In all, except during hottest climatic conditions, this extra margin of voltage is enough to satisfy the battery losses. Thus when ampere-hour method of array sizing is used, it becomes very unnecessary to calculate the effect of temperature on module output, although in very warm locations where average day time outdoor temperature will exceed 35^{0}C for significant periods, the effects of temperature must be considered. Since the system is to be designed for residential application, a weekly duty cycle of seven days will be ideal. Even though this encourages a considerable internal loss over a long period of use, we believe that careful system design and selection of good quality, high efficiency components could drastically minimize these losses. These losses usually occur in the voltage regulator, the wire runs, module mismatch, diodes etc. it is usually a good design consideration to allow 10% of the daily load for these internal system losses.

Another important parameter to be considered in the sizing process of this stand – alone system is the peak sun hour (S_P) of the location of the PV system. For any given latitude, the peculiarities of climate and weather at the specific site will determine the amount of solar energy that reaches the earth's surface at such location. Since energy is the product of power and the time the power is made available, we define the peak sun hour, S_P, as the number of hours of full sun intensity of 1kw per square metre [Strong & Scheller, 1991]. The peak sun hours are usually obtained from solar radiation data base. It is advisable to use the average rainy season peak sun hour rather than the annual average peak sun hours because rainy season is usually the time of both greatest load demand and lowest insolation. With all these in mind, we calculate the system design current C_D as

$$C_D = \frac{AH_C}{S_P} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

This shows the amount of current which the array is capable of generating at maximum power output.

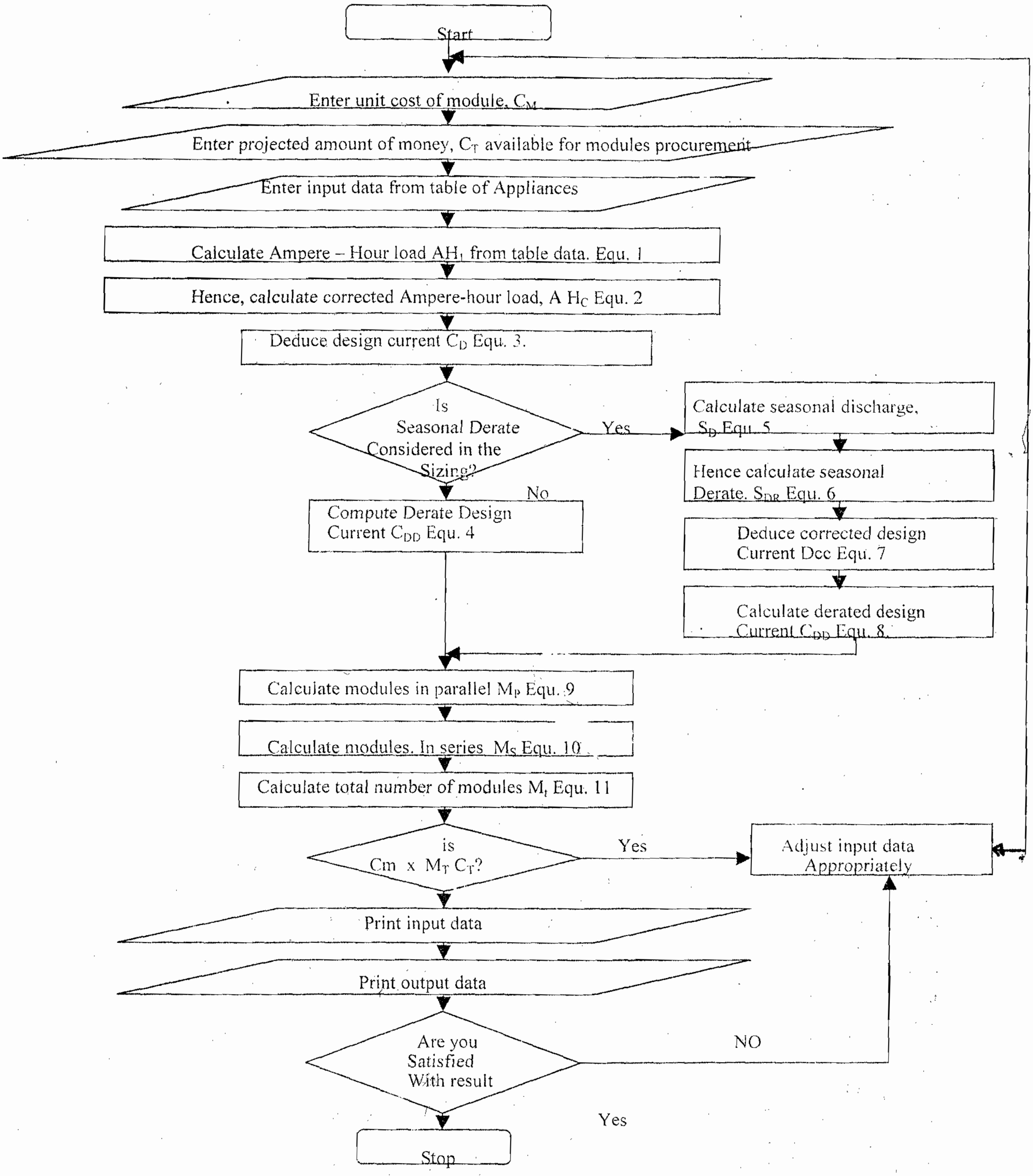

Fig. 1: Flow chart for Array sizing

If one is designing for a system in which the seasonal derate is considered neglible, the derated design current is calculated directly using the equation [PV Design Assistance Centre, 1998]

$$C_{DD} = \frac{C_D}{M_{DR}} \qquad \text{.......................4.}$$

If however, the seasonal derate is not to be neglected, we first compute the corrected design current D_{CC} before we can proceed to calculate the derated design current. We start from computing the seasonal discharge S_{DC} from

$$S_{DC} = B_{SC} \times D_S \qquad \text{.......................5.}$$

In this case, it is also important to know the consecutive number of days per annum when the sun will have its least intensity, called the seasonal consecutive least sun days S_L and hence we compute the seasonal derate S_{DR} as

$$S_{DR} = \frac{S_{DC}}{M_P x S_L} \qquad \text{.......................6.}$$

We now calculate the corrected design current D_{CC} from where we proceed to computer the derated design current C_{DD}

$$D_{CC} = C_D - S_{DR} \qquad \text{.......................7.}$$

Thus the derated design current of equation 4 becomes

$$C_{DD} = \frac{D_{CC}}{M_{DR}} \qquad \text{.......................8.}$$

Now the next step in this array sizing process is to select the PV module with correct specifications to meet up the current demand of the system. The current rating or current output of any module at full sun intensity is usually indicated in the manufacturer's literature. The number of modules in parallel M_P is calculated as

$$M_P = \frac{C_{DD}}{C_{RM}} \qquad \text{.................................9.}$$

The number of modules in series is calculated as follows:

$$M_S = \frac{V_{ns}}{V_{nm}} \qquad \text{.................................10.}$$

Finally the total number of modules, M_T needed for the PV system is given by

$$M_T = M_P \times M_S. \qquad \text{.................................11.}$$

BATTRY SIZING

A huge photovoltaic array field or a roof-mounted PV array, by itself, cannot constitute a viable home electricity source without other components. Battery is a vital component part of balance-of – system (BOS) and its selection and proper integration into the overall design is essential to the efficient functioning of PV systems. The size and type of batteries to be used are dependent on many factors. For instance, the systems Load or energy consumption pattern must certainly be considered when selecting the battery size. Also the deep-discharge batteries are usually used when fewer than five days of storage are required, while shallow-discharge batteries are used when more than five days of storage are required. For solar power systems, one of the basic requirements of good storage batteries is that the batteries must be capable of withstanding a large number of charge/discharge cycles. This is in addition to having a low self-discharge rate. However, deep-discharge batteries (which is designed especially for PV systems) may be used in both deep-discharge and shallow discharge applications. It is observed that when the deep-discharge batteries are used in a shallow discharge application, its encourage very long term service because the deeper a battery is repeatedly discharged, the shorter it's life time becomes. Thus it is advisable to use large number of batteries and to operate them at a slower charge/discharge cycle rate and a shallower depth of discharge (DOD). When sizing a photovoltaic system to meet a particular load, efficiencies of all components must be determined. The battery's internal losses are considered as another addition to the array's total load.

It is important to note that during the charge/discharge cycle, a battery is charged by receiving a certain number of amp-hours at an input voltage of about 15 volts for a 12 volts battery and discharged by delivering the same number of amp-hours out at a lower output of its output voltage to the input voltage. Since there are bound to be occasional prolonged days of cold weather which will severely reduce the insolation, the storage system should be capable of providing back-up power for several days [Strong & Scheller, 1991]. Usually a three to six days' storage without reliance on non-solar auxiliary generating equipments is recommended.

The following procedures are adopted in determining the battery capacity for any system. The daily ampere-hour load and hence the corrected ampere-hour load for the system is calculated as explained in the previous section on Load evaluation (see equ. 1 and 2 respectively of that section). Then the number of no-sun days for which to design battery storage is decided. The number will vary according to local weather condition and the required reliability of the system. Next is to study the manufacturer's recommendations on capacity adjustment for battery operating temperature as well as charge and discharge rates including maximum depth of discharge and then de-rate the batteries to fit the proposed system. Hence we calculate the corrected battery capacity B_C. It is important to not that battery performance decreases with temperature, hence the need for inclusion of the temperature correction factor T_F.

$$B_c = \frac{AH_C x S_D}{D_{\max} x T_F} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 12.$$

The numerator in equation 12 is referred to as the total usable battery capacity (TUC) required by a system.

We then proceed to determine the number of batteries required in parallel B_P, to satisfy the system's storage requirements.

$$B_P = \frac{B_C}{B_R} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 13.$$

The number of batteries required in series B_S, to satisfy the systems storage requirements is also determined.

$$B_S = \frac{V_{ns}}{V_{nB}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 14.$$

Finally we determine the total number of batteries B_t required to satisfy system storage requirements.

$$B_t = B_p \text{ x } B_s \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 15.$$

Car batteries should not be used in PV application because they are shallow- discharge batteries and are designed to produce a high current-cold cranking amps for a short period and are then quickly recharge [Bagul et al, 1996]. However, lead-acid batteries are used in most PV systems, but Nickel-cadmium batteries, though expensive, are ideally more suited to PV system. Advantages of Ni-Cd battery include

- problem of electrolyte depletion and stratification do not arise.
- The Ni-cd battery is less sensitive to temperature and rate of discharge
- it has no problem of electrolyte freezing.

CHARGE CONTROLLER SIZING

In a stand-alone Photovoltaic system that has provision for the storage of the electrical output of the PV array in batteries, it is necessary to include a charge regulator or controller (i.e. power conditioning) between the array and the batteries. The main purpose of integrating charge controllers into a stand-alone

Photovolaic system is to control the flow of current from the array to the storage batteries and to maintain the state of charge of the batteries, preventing them from over-charging or under-charging. For some basic reasons, it will be undesirable to overcharge the batteries. Over charging can cause corrosion and buckling of the lead plate, loss of battery electrolyte and a build up of hydrogen gas. All of these shorten battery life, ordinarily, it will be better not to allow the batteries to be charged at full current right up to the maximum level. Thus as they approach full charge capacity, the charge controller reduces and then terminates the flow of incoming power from the Photovoltaic array [Ken Olson & Weiss, 1987].

Most controllers sense battery voltage and take action based on voltage level. Some Controllers have temperature compensation circuits to account for the effect of temperature on battery voltage and state of charge. The controller must be sized to handle the maximum current produced by the PV array. Some important factors for charge controllers are: Temperature compensation, low voltage warning, Adjustable set points (i.e. high voltage disconnect and low voltage disconnect), reverse current protection, maximum power tracking and voltage meters. For system design purposes, manufacturer's guide should be consulted to select a charge controller unit that will meet the system's requirements and provide all or some of the desired features above.

Most controllers include a mechanism that prevents current flow from the battery to the array at night. This method by which the controller isolates the array at night is an important factor in determining parasitic loss, which may be a considerable portion of the total system's load. In order to avoid having to increase the array or battery size, it is best to select a controller that causes a neglible parasitic loss.

Low voltage disconnect (LVD) protection is recommended for all stand-alone PV system. Many charge controllers provide this to prevent excessive battery discharge.

In order to determine the size of a charge controller for a particular PV system, we need to measure the module short-circuit current and hence determine array short circuit current.

$$A_{SC} = M_{SC} \text{ X } M_P \qquad \ldots\ldots\ldots\ldots 16.$$

We then calculate the Design Controller Capacity C_{DC} as

$$C_{DC} = 1.25 \text{ x } A_{SC} \qquad \ldots\ldots\ldots\ldots 17.$$

1.25 = Constant [PV Design Assistance Centre, 1998]

$$\text{Then } C_N = \frac{C_{DC}}{C_{RM}} \qquad \ldots\ldots\ldots\ldots 18.$$

INVERTERS AND CONVERTERS

A photovoltaic array, regardless of its size or sophistication, can only generate direct current (DC) electricity. In any case, there are many application for which direct current is perfectly suitable. In this case, a dc to dc converter will be required if one is needed to supply dc loads operating at different voltages. Otherwise, dc electricity is usually converted to alternating current (AC) with relative ease through the use of power conditioning unit called inverter. It is the inverter that makes PV technology compatible with the type of equipment and appliances encountered in homes these days. The inverter is designed in such a way that it provides a stable voltage output, a steady ac frequency and a wave form that is as close as possible to the basic sinusoidal wave shape of the ac sine wave [Strong & Scheller, 1991]. Internal losses in a dc to ac inverter can consume between 5% and 40% of the system's dc output power. However, in inverter sizing, it is important to make the inverter large enough to be able to handle motor-starting surge currents and the resultant short-duration peak loads if two equipment happen to start up at the same time. But care must be taken to avoid over-sizing the unit because it will not deliver its peak efficiency when operated at only a portion of its rated capacity. On the other hand, over-sizing an inverter will increase its reliability and life time.

Basically there are two fundamental system parameters that should be considered before selecting a particular inverter. The first parameter is the system's dc operating voltage, which will determine the inverter's input voltage. The second is the size of the load both in terms of the total watt-hours or kilowatt hour per day and in terms of the size and type of individual peak loads which the inverter will be expected to operate. Even though some inverters can take any dc voltage and boost it to standard line current, the conversion efficiency of an inverter increases with increase in dc input voltage.

Information from manufacturers data are usually consulted before selecting the best inverter for any application. The manufacturer's data contain information concerning the performance and feature of their inverters such as total ac power demand, inverter output wave form, idle current, input voltage, output voltage, surge capacity, over-voltage protection, Duty rating, Efficiency, Power factor and modularity. Common stand –alone inverters operate at 12V, 24V, 48V or 120V DC input and 12V AC or 240V AC output voltage at 60 HZ. Inverter rating INV_R can be calculated as

$$INV_R = \frac{C_D X V_{ns}}{1.25} \qquad 19$$

Also recall that the design current is the dc input current to the inverter.

CONCLUSION

In most parts of the world, full sunlight is not available every day, and often the irradiance is reduced because of inclement weather and constant cloud cover in the sky. For this reason, several approaches to stand-alone PV system sizing have been suggested and used. However, on technical consideration, any system sized with the ampere-hour method, will perform reliably with few reports of failures or significant degradation if proper installation and monitoring principles are adopted.

In any case, load profile influence the size of a stand-alone PV power system significantly. Thus, load management is important for PV systems to save initial investment and to ensure the expected reliability (PV Design Assistance Centre, 1998).

NOMENCLATURE

AH_C = Corrected Ampere-hour load
AH_L = Ampere-hour load.
A_{SC} = Array short-circuit current
B_C = Corrected battery capacity (AH)
B_P = Batteries in parallel
B_R = Rated Battery capacity (AH)
B_S = Batteries in series
B_{SC} = System Battery capacity
B_t = Total number of Batteries

C_D = Design current
C_{DC} = Design controller capacity
C_{DD} = Derated ~~Design~~ current
C_N = Total number of controllers
C_{RC} = Controller rated capacity
C_{RM} = Rated module current
D_{CC} = Corrected design current
DDC = Daily duty cycle i.e. the number of hours per day for which the appliance is used
D_{max} = Maximum depth of discharge
INV_R = Inverter Power Rating
LOLH = Loss of load hours i.e. the number of hours in a year that the PV power system is unavailable to meet the load requirements owing to energy shortage.
M_{DR} = Module derate factor
M_P = Modules in parallel
M_S = Modules in series
M_{SC} = Modules short-circuit current
M_T = Total number of modules
η_B = Battery efficiency factor
η_{cp} = Power conversion efficiency (from dc to ac)
η_w = Wire efficiency factor
P_r = Power rating
S_D = Storage days

S_{DC} = Seasonal discharge
S_{DR} = Seasonal derate
S_L = Least sun days
S_P = Peak sun hours
T_F = Temperature correction factor
μ_D = Mean of the probability density for the surplus (deficit) energy.
σ_D = Standard deviation of the probability density
V_{nB} = Battery nominal voltage
V_{ns} = System nominal voltage
WDC = Weekly duty cycle i.e. the number of days per week for which the appliance can be used.

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