A simple approach to the determination of the charging state, of photovoltaic-powered storage batteries

M. A. Hamdy
Faculty of Engineering and Technology, Helwan University, Cairo (Egypt)

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Abstract

Stand-alone photovoltaic (PV) applications, such as domestic and street lighting systems, usually include a storage battery which is subjected to a daily charge/discharge cycle. During such cycle the battery charges during the day and loses a percentage of its charge to the load at night. A knowledge of the battery state-of-charge (SOC) during charging is important since it leads to design information about the desired size of the PV array and battery capacity to satisfy a given load. A simple approach to the theoretical determination of the battery SOC in stand-alone PV systems is presented in this paper. The approach is based on the graphical determination of the system operating points found from the intersection between the *I–V* curves representing the power source (PV) under varying solar radiation and temperature conditions with the *I–V* curves representing the load (battery) under varying SOC conditions. The study is restricted to locally manufactured lead/acid batteries used to power TV sets in some of the rural areas of Egypt. It takes into consideration the different factors affecting battery performance. Conclusions are drawn from the analysis that permit a better design of the system for full utilization of the PV output power leading to the appropriate PV size that ensures proper system operation for the designed period.

Introduction

The most common application of terrestrial PV to date has been in stand-alone systems. Stand-alone PV systems, as the name implies, are completely on their own in that they are not connected to any nonsolar backup and are therefore the sole source of electric power for the load. Since a PV system can only produce electricity during the day, it is often necessary to store that energy for use during cloudy periods or night-time. The most reliable form of electrical energy storage available today is the battery. Anyone planning to use or design a stand-alone PV system should give the utmost care to the storage battery in that system.

There are two battery types that have been used in PV systems: lead/acid and nickel–cadmium. Due to higher cost, lower energy efficiency and limited upper operating temperature, nickel–cadmium batteries have been employed in relatively few systems. On the other hand, for virtually most stand-alone PV applications, the less expensive lead/acid battery has been the battery of choice [1].

Stand-alone PV systems usually include a storage battery with its charging and discharging control, an inverter and loads for night-time loads, such as domestic and street lighting, and a PV array charging the battery during the day. A regulator is

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used to control the flow of current from the array to the battery in order to prevent excessive overcharging during periods of high insolation. At night, the lighting load is operated either directly from the charged battery in case of d.c. loads or through the inverter in case of a.c. loads. A blocking diode or a special circuitry in the regulator is used to ensure that the battery will not discharge itself through the array. It is clear from the above that a charge/discharge daily cycle is imposed on the battery in which the battery charges during the day and loses a percentage of its charge at night. Since the battery is the only load imposed on the PV source during the day, the system state operation during the charging process can be determined graphically from the intersection between the *I–V* curve representing the power source (PV) and that representing the load (battery).

The main objective of this paper is to analyse the operation of a stand-alone PV system consisting of a storage battery as a daytime load to be charged from the PV array during the day in order to use its energy to operate a d.c. lighting load at night. The study includes system state determination with variations of solar radiation and ambient temperature as well as battery voltage. Possible trajectories of the charging state of the battery are presented and a simplified approach for determining such trajectories is suggested. The analysis takes into consideration the different factors affecting battery performance. Since most imported lead/acid batteries are considered hard currency consuming elements for a developing country like Egypt, this study is restricted to a locally manufactured lead/acid battery called Chloride TV used to power TV sets in some rural areas of Egypt.

Conclusions are drawn from the analysis that permit a better design of the system leading to an optimal design for the full utilization of the array output power and the appropriate PV size that ensures proper system operation for the designed period.

Lead/acid batteries background

In the last few years batteries have been made commercially available that are designed to meet the specific requirements of terrestrial stand-alone PV power systems. Lead/acid batteries, in particular, have received more attention because they are less expensive and are designed for a wide variety of applications. There are many factors which can affect battery performance that must be taken into consideration when using or designing a stand-alone PV system. Some of the most important factors are: the daily depth-of-discharge (DDOD), the maximum allowable depth-of-discharge (MDOD), the temperature of operation, the time spent discharged, the charge and discharge rates and the charging procedure.

Two conventional methods are usually used when charging a storage battery. The constant current method, in which a low charging rate called 'the finishing rate' is maintained, may require 16 h or longer to complete the charging process. The modified constant voltage method, on the other hand, is the most common and is used when circuit voltage limitations make it impractical to use the constant current method. It consists of a constant charging source (usually about 2.35 V/cell for lead–antimony grids) and a fixed resistor between source and battery [2]. In such charging method, as the battery is charged, the open-circuit voltage/cell increases and, the source voltage being constant, the charging current decreases until the battery is completely charged.

In a PV-powered system the situation is slightly different. The PV array is neither a constant current nor a constant voltage source. The output power of the array will vary with solar insolation and temperature conditions, as well as with the size of the load (the battery in this case) that can be powered from the array. This will be discussed in more detail in the following section.

Charging a battery at too high a rate or significantly past 100% state-of-charge (SOC) results in a sharp voltage rise within the cell (battery SOC is defined as the available capacity expressed as a percentage of the rated capacity C). This elevated voltage causes excessive production of hydrogen and oxygen (called gassing) which has several detrimental effects such as reducing charge efficiency, decreasing battery life and constituting explosive hazards. A typical maximum acceptable charging voltage for lead/acid batteries (lead–antimony grids) is 2.35 V/cell at 27 C [3]. When discharging a battery on the other hand, the average open-circuit voltage/cell decreases almost linearly with DOD until a point is reached where further discharge results in a greater drop in voltage. Manufacturers usually specify a discharge cutoff voltage, just past this point, beyond which the battery should not be operated because further discharge can result in permanent damage to the battery cells. A typical value for the open-circuit cutoff voltage of lead/acid batteries when discharged at a $C/500$ rate and 27 C is 1.9 V/cell [2]. It is to be noted that the DOD at which the cutoff voltage is reached, at a given temperature, decreases with increasing discharge rate. It is the role of the charge/discharge controls in the PV system to prevent the battery from excessive overcharging by disconnecting it from the PV array once it reaches the maximum allowable voltage, and from deep discharging by disconnecting it from the load once it reaches the minimum cutoff voltage. Thus, in a correct management of the battery in a PV system variation of the battery open-circuit voltage is confined to the region between a minimum cutoff voltage $E_{b\,min}$ and a maximum acceptable voltage $E_{b\,max}$.

Theoretical analysis

Design of PV systems can be based on an energy balance among the various subsystems that constitute the system under study. Such analysis may be adequate for a first-order evaluation of a system having large energy storage capabilities. If one wants to analyse a system with a small storage capacity or if it is desired to examine the power exchange between the various blocks, the energy method is no longer helpful and the analysis has to be done in terms of the current–voltage characteristics of the different subsystems.

Consider a simple stand-alone PV system configuration consisting of a storage battery as a daytime load to be charged from the PV array during the day. The equivalent circuit of such system is shown in Fig. 1, where the PV cell/module/array is represented by the single-exponential lumped-constant parameters model for which the solar cell I–V characteristic is described by ref. 4:

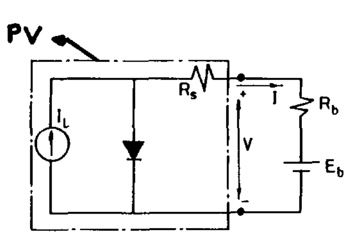

Fig. 1. Equivalent circuit for charging a battery from a PV array.

$$I = I_L - I_0(\exp^{B(V-IR_s)} - 1) \quad (1)$$

where I is the output current, I_L is the light-generated current, I_0 is the diode reverse saturation current, V is the terminal voltage, R_s is the lumped-effective series resistance, and $B = q/nKT$ where q is the electronic charge, n is the diode ideality factor, K is the Boltzmann constant, and T is the absolute temperature.

When charged, the storage battery, represented by its open-circuit voltage E_b in series with its internal resistance R_b, has a I–V characteristic described by:

$$V = E_b + IR_b \quad (2)$$

which can be written as:

$$I = -E_b/R_b + V/R_b \quad (3)$$

In order to obtain the system operating point, eqns. (1) and (3) have to be mathematically solved. Although eqn. (3) is mathematically simple, eqn. (1), on the other hand, is an implicit function and is nonlinear in its parameters. The determination of the solar cell equation parameters is important and must be done if eqn. (1) is to be used with eqn. (3) to determine the system operating point. However, such determination is mathematically difficult and recourse to numerical solutions is inevitable imposing more complexity to the problem. A much simpler approach would be to solve the problem graphically by determining the intersection of the I–V curve representing the PV array with the straight line representing the battery load (eqn. (3)). This is shown in Fig. 2 for a certain radiation level and battery SOC. The operating point defines the charging current I_K flowing into the battery and the charging voltage V_K at the instant k depicted. Under actual operating conditions, the I–V characteristic of the PV array changes in response to the variations in solar radiation and cell temperature resulting in a family of curves similar to curve B of Fig. 2. Also, as the battery is charged, its open-circuit voltage increases resulting in a family of load lines parallel to line A of Fig. 2. This situation is depicted in Fig. 3 where the shaded area represents the charging region in which the battery load line is allowed to exist, namely between the limits $E_{b\,min}$ and $E_{b\,max}$. The position of the load line depends on the charging rate which dictates the battery SOC and hence its open-circuit voltage as will be discussed later.

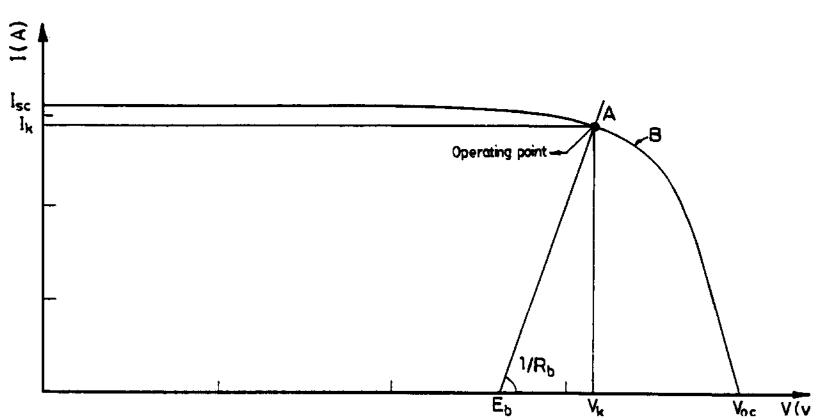

Fig. 2. Intersection point of the PV array curve (B) with the battery load line (A).

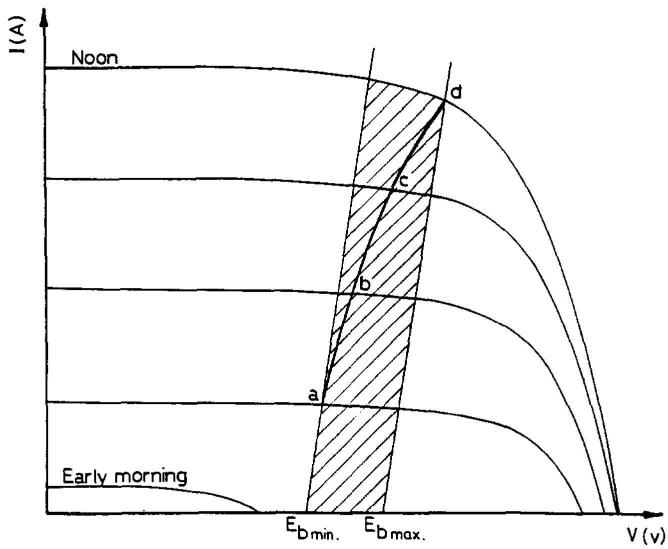

Fig. 3. System operation region during charging.

System operation

Consider a full cycle of battery operation which starts at night with the battery supplying a load for a specific period of time. As the battery is discharged, its open-circuit voltage will decrease and by the next morning E_b will reach a value somewhere between $E_{b\ min}$ and $E_{b\ max}$ depending on the depth and rate of discharge. In the worst case condition, the controller will prevent the battery from overdischarging by disconnecting it from the load once the battery voltage reaches the minimum cutoff voltage. Since the charging of the storage battery, when powered from the PV array, is for the condition of sufficient solar radiation, the battery load line will not intersect the PV *I–V* curves corresponding to low radiation levels occurring in the early morning as shown in Fig. 3. In such a case the battery will be sitting idle waiting to be charged. As the sun rises, the solar radiation level increases resulting in a PV *I–V* curve that intersects with the battery load line. An operating point will exist (point *a*) for which the charging current I_a flows into the battery causing its SOC and consequently its voltage to increase resulting in a new battery load line parallel to the first one. As the radiation level increases further a higher PV *I–V* curve results which intersects with the new load line in a new operating point *b* indicating a higher battery SOC and plate voltage. As the radiation level continues to increase further, the charging state of the battery may assume a trajectory *abcd* as shown in Fig. 3.

Trajectory *abcd* indicates that the battery reaches the maximum allowable voltage at maximum radiation level (noon). Other possible trajectories may exist. These are shown in Fig. 4, which is an enlargement of the charging region of Fig. 3. In Fig. 4, the trajectory *aef* shows that the battery also reaches $E_{b\ max}$ but at a lower radiation level. A similar trajectory is *agh* in which a different battery SOC as a function of time results. Another possibility still exists, such as *agi*, where the battery voltage does not reach $E_{b\ max}$ during the day. It is to be noted that reaching the maximum allowable voltage does not necessarily mean that the battery has reached full charge (100% SOC). Battery may reach full charge well before this point if the charging rate is low

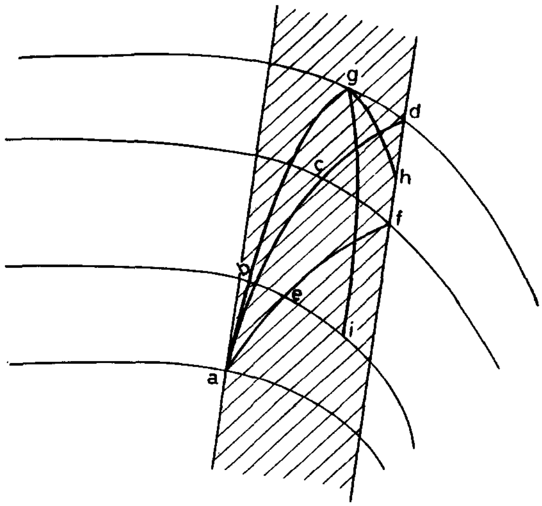

Fig. 4. Possible charging state trajectories.

($C/20$ or lower). On the other hand, a too high charging rate ($C/2$–$C/5$) causes the battery to reach the gassing voltage at a SOC less than 100% [1]. It seems that the last situation can seldom happen when charging lead/acid batteries from PV modules, unless we connect them in parallel to increase the charging current. This is because most available PV modules today give a maximum current that does not exceed 3.5 A, which occur around noon in a clear sunny day. This value corresponds to a charging rate in the vicinity of $C/20$ for a 65 A h battery capacity. For higher capacities the charging rate would be even lower leading to the possibility of attaining the gassing voltage. As it was mentioned earlier, it is the role of the controls in the PV system to disconnect the battery from the PV array once the battery reaches the maximum allowable threshold voltage (the gassing voltage).

The trajectories of Fig. 4, just described, are some possible operation cycles of the system and are dependent on many factors such as the battery type and capacity, date, site, size, and tilt angle of the PV array, etc. The optimum trajectory is the one in which the battery starts charging in the early morning and becomes fully charged (100% SOC) at the end of the day. In this case, no waste energy is encountered and all electric energy produced by the PV is used properly. Moreover, if the battery reaches 100% SOC on a daily basis, no fear of overdischarging is present, especially in the case of domestic and street lighting applications where the night load is kept constant. On the other hand, any battery state trajectory in which the battery reaches full charge before the end of the day results in a waste of PV energy indicating PV oversizing and hence higher costs. Similarly a state trajectory in which the battery voltage reaches the gassing voltage before reaching full charge results in an incomplete charging process indicating a higher charging rate than required. A smaller PV array size may not be sufficient to bring the battery to a full charge by the end of the day and a compromise between choices must take place in order to reach an optimum solution.

From the above discussion it is clear that the determination of the battery state trajectory can play an important role in the design of the system by leading to information about the desired size of the PV array needed to charge a battery with a given capacity or vice versa (the appropriate battery capacity to be charged from a given array size). Because the charge region is generally quite narrow, the dynamic operation behaviour of the system, as described by the state trajectory, can be determined with some approximations as described by the simplified approach that follows.

Charging state determination

Because of the complexity involved in determining the battery charging trajectory and in order to simplify the analysis, the following assumptions are adopted:

(i) The following equations are used to describe the battery open-circuit voltage/cell as a function of its SOC under both charging and discharging conditions [6].
Charging:

$$E_b = 1.95 + 0.43 \times \text{SOC} \tag{4}$$

discharging:

$$E_b = 2.22 - 0.32 \times \text{DOD} \tag{5}$$

where DOD is the battery depth-of-discharge (DOD = 1 − SOC). These equations were deduced using an analytical model in which the parameters were obtained by regression computations using monitored terminal voltage and specific gravity for a locally manufactured battery, the Chloride TV, rated at 65 A h (10 h rate) for charging (discharging) rates ranging from $C/100$ to $C/20$.

(i) The battery internal resistance R_b is considered constant.

(ii) Temperature influence on battery performance is neglected.

(iii) Self-discharging effects of battery are neglected.

(iv) The battery is characterized by an overall A h conversion efficiency $\eta_b = \eta_c \times \eta_d$ where η_c and η_d are the charging and discharging efficiencies respectively. For computation purposes, η_c and η_d are assumed to be equal and hence

$$\eta_c = \eta_d = \sqrt{\eta_b} \tag{6}$$

(v) The battery open-circuit voltage during charging is assumed to vary in the region confined between $E_{b\,min}$ and $E_{b\,max}$. These conditions are met by the charge/discharge controls.

(vi) The effect of the daily variation of the incident solar radiation on the PV I–V curves is considered on an hourly basis i.e., the day length in hours (N) is divided into N equal intervals spanning 1 h each. This results in a family of I–V curves for the PV module/array with each curve representing the PV characteristic for 1 h.

With the above assumptions, the method for determining the battery charging trajectory becomes simply a matter of determining the operating point of the system for each hour. This is found from the intersection of the PV I–V curve for that hour with the appropriate battery load line for the same hour. The starting point is usually a certain battery charge (capacity), a corresponding SOC, and open-circuit voltage. The initial battery capacity and the corresponding SOC are found from the discharging process which is assumed to take place in a prescribed constant lighting load for a certain period of time during the night, previous to the charging day. Knowing the discharge load current in A and the duration in h, the A h going to the load, $(\text{A h})_L$, is determined. Taking the discharging efficiency into consideration, the amount of charge actually taken from the battery is found $(\text{A h})_L/\eta_d$ and then subtracted from the nominal (rated) battery capacity — assuming the battery was fully charged before the start of the discharging process — to find the capacity at the end of the discharging period. Dividing this value by the rated capacity, the SOC at the end of the discharge period is obtained. It is to be noted, however, that the rated capacity is dependent on the discharge rate. A battery will deliver its maximum output when discharged at, or below, the manufacturer's recommended discharge rate. On the other hand, if battery is discharged quickly (at a higher rate) less capacity is available. This should be taken into consideration whenever the rated battery capacity is used in calculation. Manufacturer's data on A h capacity as a function of discharge rate may be helpfull, if available, in this case. Once the battery SOC at the end of the discharge period is obtained, eqn. (5) is used to calculate the battery open-circuit voltage/cell at the end of the discharge period. Neglecting the effect of self-discharge, the battery open-circuit voltage and SOC at the end of the discharge period are assumed to remain constant until the beginning of the charging process. These will be the initial values denoted by $E_b(0)$ and SOC(0) respectively. It is the value of $E_b(0)$ which dictates the starting point from which the battery load line is drawn. The charging current during the first morning hour of operation $I(1)$ is determined from the intersection of the I–V curve representing the PV module/array characteristic for that hour with the battery load line corresponding to $E_b(0)$. Assuming the charging current to remain constant during the entire hour, the amount of charge (in A h) actually stored in the battery during the first hour is calculated taking the charging efficiency into consideration ($I(1) \times 1$ h $\times \eta_c$). This stored charge represents the increment with which the capacity of the battery increases denoted by $\Delta C_b(1)$. The new battery capacity at the end of the first hour of operation $CC_b(1)$ is then found by adding this increment to the initial starting battery capacity $C_b(0)$. Once the new battery capacity is found, the new SOC is determined by simply dividing the above battery capacity by the rated value. The calculated SOC represents the battery state at the beginning of the next hour SOC(2). Using eqn. (4), the open-circuit voltage/cell at the beginning of that hour is found. A new load line, starting from $E_b(2)$, is then drawn intersecting a new PV I–V curve representing the same hour. This results in a new operating point from which the charging current during that hour $I(2)$ is obtained. The calculation procedure for updating the SOC and the open-circuit voltage/cell is repeated to find a new load line and operating point until we reach the full charge condition (100% SOC). In such case, the controller should disconnect the battery from the PV module/array to prevent it from excessive overcharging.

The above procedure is generalized mathematically by the following equations:

$$C_b(k) = CC_b(k-1) \tag{6}$$

$$SOC(k) = CSOC(k-1) \tag{7}$$

$$\Delta C_b(k) = I(k) \times \Delta t \times \eta_c \tag{8}$$

$$CC_b(k) = C_b(k) + \Delta C_b(k) \tag{9}$$

$$CSOC(k) = CC_b(k)/C_0 \tag{10}$$

with the initial conditions given by:

$$CC_b(0) = C_0 - (\mathrm{A\ h})_L/\eta_d) \tag{11}$$

and

$$CSOC(0) = CC_b(0)/C_0 \tag{12}$$

where $k = 1,2,\ldots N$ and N is the day length in h, $C_b(k)$ is the battery capacity at the beginning of the kth h, $CC_b(k)$ is the battery capacity at the end of the same hour,

$SOC(k)$ is the state-of-charge at the beginning of the kth h and $CSOC(k)$ is its value at the end of the same hour, $CC_b(k-1)$ and $CSOC(k-1)$ are the capacity and SOC at the end of the previous hour, $\Delta C_b(k)$ is the charge stored in the battery during the kth h, $I(k)$ is the charging current during the same hour, Δt is the time interval (taken as 1 h), C_0 is the rated battery capacity and $CC_b(0)$ is the battery capacity at the end of the discharge period. It should be noted that eqns. (11) and (12) are only true for fixed power loads where the rated battery capacity C_0 remains constant. If battery load changes, so the discharge rate does as well, and therefore the rated capacity and consequently the SOC. Hence for any operation condition, a corrective factor for the rated capacity, which depends on the discharging rate, must be included in eqns. (11) and (12). The same applies for eqn. (10) where in this case C_0 depends on the charging rate. If charging occurs at,or below, the recommended manufacturer's rate, C_0 would remain constant at its rated value. The results obtained from the application of the above approach could be used in determining the optimum module/array size required to charge a battery with a given capacity or vice versa the optimum battery capacity to be charged from a given PV module/array.

Best system operation is obtained, as discussed earlier, if the battery charging trajectory is such that the battery takes the entire day to reach full charge (100% SOC). In this case, all of the energy generated by the PV module/array is used in charging the battery with no waste energy indicating a good PV sizing judgement. If the PV module/array is oversized, the battery may reach its full charge or its maximum allowable gassing voltage well before the end of the solar day resulting in a waste of generated PV energy. An undersized PV array, on the other hand, may require more than one day for the battery to be fully charged. Both an oversized and an undersized PV array represent a poor design judgement. An optimum design criterion would be to minimize the PV waste energy/day under the condition that the battery is to reach full charge (or very close to it) in one day only. The following is a numerical example which illustrates the usefulness of the above-mentioned approach.

A numerical example

Assume that a commercial PV module, the MSX-56 from Solarex Corporation ($P_m = 56$ W, $I_{SC} = 3.46$ A, $V_{OC} = 21.2$ V) is used to charge a locally manufactured lead/acid battery, the Chloride TV, having a rated capacity $C_0 = 65$ A h (10 h rate), a rated voltage $V = 12$ V, and an internal resistance $R_b = 0.05\ \Omega$. The module is to be located in Cairo, Egypt, and is assumed to be tilted at an angle of 45° in winter and of 15° in summer to maximize the collected solar radiation. The hourly PV I–V curves for the module are computed using a detailed computer programme named Solsys [5]. The programme is capable of predicting the hourly I–V curves for a given module with any tilt anywhere in the northern hemisphere. Effect of module temperature are taken into consideration when computing these curves. Figure 5 shows the hourly I–V output curves for the MSX-56 in an average January day representing winter in Cairo as found by Solsys. The battery is assumed to operate two fluorescent lamps, 18 W each, for 3 h per night. It is recommended to be discharged by no more than 50% on an infrequent basis and has a recommended DDOD of 10–20%. The open-circuit voltage of the battery is assumed to vary between a minimum cutoff value $E_{b\,min} =$ 11.4 V (1.9 V/cell) and a maximum acceptable value $E_{b\,max} = 14.3$ V (2.38 V/cell). The average overall charge/discharge efficiency is assumed to be a conservative 75%. If the battery is discharged through the above-mentioned loading condition, it would

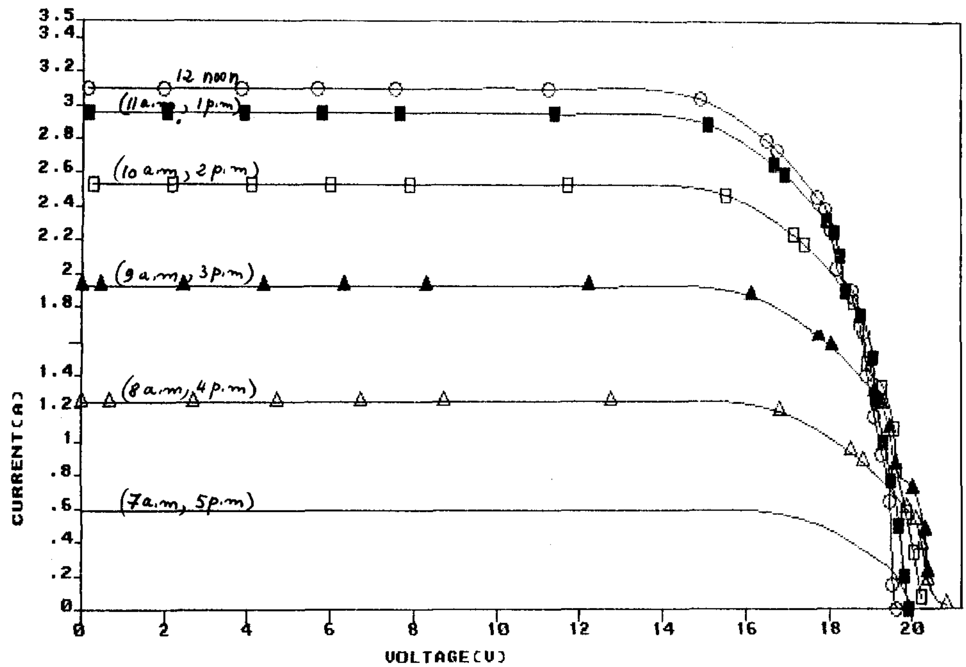

Fig. 5. Predicted *I–V* characteristics for the MSX-56 module for an average January day in Cairo, Egypt, using Solsys.

begin the charging process when its SOC is 84% (eqns. (11) and (12)). No corrective factor for the rated capacity is needed in these calculations since the discharge rate (3 A) is lower than the recommended 10 h rate. The battery open-circuit voltage/cell at the beginning of the charging process is found from eqn. (5) to be 2.17 V leading to $E_b(0)$ of 13 V. Following the method outlined earlier, the hourly-battery SOC is calculated for an average January day (representing winter) and an average June day (representing summer) in Cairo, Egypt. The result of the calculations is shown in Fig. 6 (solid lines). It is clear from Fig. 6 that the battery reaches full charge well before the end of the day resulting in 5 h (42%) and 7 h (52%) of wasted solar energy in winter and summer, respectively. Note that the day length is shorter in winter than in summer (the sun sets at 5 p.m in winter and at 7 p.m in summer). The above charging state trajectory is not, by any means, an optimum one. A smaller PV module may be used in charging the given battery in an attempt to decrease or, better yet, eliminate the wasted solar energy. Figure 6 (dotted lines) shows the result of using the SX-110 PV module from Solarex Corporation (P_m=36 W, I_{SC}=2.35 A, V_{OC}=22.25 V). It is seen from this Fig. that the performance of the system has improved. Only 1.5 h of late afternoon solar energy is now lost in winter. This represents only 8% of the day's solar energy available. The situation in summer has also improved, only 20% of the day's solar energy is not used. It is believed that any attempt to decrease the size of the PV module further may result in less-wasted solar energy in the summer on the account of a situation in which the battery fails to reach full charge in winter.

We could have a similar situation if we use the MSX-56 module in charging the battery provided we discharge it for a longer period. For example, it can be shown

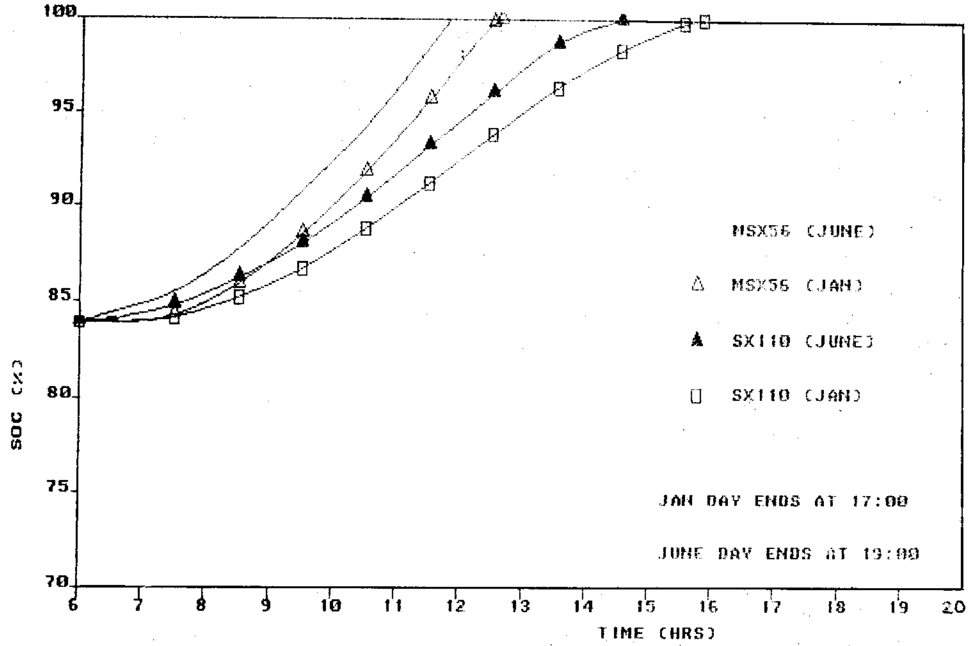

Fig. 6. Battery state-of-charge for average winter and summer days in Cairo, Egypt, using two types of PV modules.

that running the lamps for 5 h/night instead of 3 h would cause the battery to start the charging process at a lower SOC (73%) and consequently reaching full charge with 8% and 20% of unused solar energy in winter and summer, respectively. It is also believed that any attempt to extend the discharge period further will have detrimental effects on the battery. First, the daily DOD would surpass the recommended value (10–20%) by a bigger margin. Second, the battery, although may eventually reach full charge in summer without any lost solar energy, will fail to do so in winter. The reason is obvious, a prolonged discharge period will cause the battery to start charging at a lower SOC. Assuming the weather conditions to be constant on the average, the sunshine hours during winter would not be sufficient to bring the battery to a 100% SOC situation. Moreover, because the daily lighting load is constant, the daily discharge cycles will cause a continuous decrease in the battery SOC leading to a continuous increase in the daily DOD that can exceed the maximum allowable by the manufacturer causing serious damage to the battery. It can be seen from the above example that compromise is needed in order to select the best system to charge a given battery. Different optimization strategies can be adopted depending on the application and size of the battery used.

Conclusions

A simple approach to the determination of the battery SOC in stand-alone PV systems intended for small-scale lighting applications has been presented. The study is concerned with locally manufactured lead/acid batteries, the Chloride TV, used to power TV sets in some rural areas of Egypt. The approach is applicable for charge/

discharge rates in the vicinity of C_{20} (20 h rate) a value which is commonly encountered in small PV system applications. The method is suitable for domestic and street lighting applications in which the battery is the only load applied to the PV power source during the day. It predicts the battery state trajectory during charging using system operating points found from the intersection of the PV *I–V* characteristics with the battery load lines. The approach takes into consideration the different factors affecting battery performance with the exception of the influence of temperature and self-discharge which have been neglected.

It is to be noted that the suggested approach is theoretical and is recommended prior to the actual implementation of such systems i.e., in the design phase. It is believed that the results would lead to design information which permit better utilization of the PV output power and ensure proper system operation. Experimental behaviour of the above-mentioned battery type when charged from the MSX-56 module is currently underway in our laboratory in an attempt to validate the proposed approach and analyse any deviation that might exist between theoretical and experimental behaviour.

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