On the Storage Batteries Used in Solar Electric Power Systems and Development of an Algorithm for Determining their Ampere-Hour Capacity

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Abstract
Storage batteries are indispensable in all standalone solar electric systems (PV power systems). Their efficiency and life time affects significantly the overall PV system performance and economics. Even though, most PV research papers don't pay a proper attention for batteries. Batteries specified especially for use in PV systems have to be distinguished with standing of very deep discharge rate and high cycling stability.

Depending on long field experience in PV applications, the ordinary batteries being marketed world wide for use in automobile, are mostly not appropriate for PV power systems. The most important characteristics of lead acid batteries necessary for evaluation of their performance are presented and discussed in this paper. Moreover, the paper illustrates an experimental procedure for developing a mathematical algorithm for determining the ampere hour capacity of batteries operating in PV systems. This algorithm enables determining the state -of-charge of a battery by measuring it's voltage and electrolyte-specific gravity at definite temperature. This enables correct settings of the limits of the charge - discharge hysteresis of the battery charger to avoid extremely deep discharge and over charge of the battery. The derived algorithm, which has been verified by data acquisition capacity measurements, is applicable also for large battery storage systems.

Keywords:, Electrical energy storage, photovoltaic power systems, storage batteries.

1. Introduction
With respect to reliability and cost of stand alone PV power systems, storage batteries represent main and important components. Even a battery block represent only 8% of the initial cost of a new PV system, it represents 23% of the total system cost when considering the replacement of batteries during the total life time of the system (20 years) [1]. Storage batteries provide the PV system with advantages such as ability of providing energy during night time and sunless periods, ability

to meet momentary peak power demands and stabilizing the system voltage [2].
PV power systems place high demands on storage batteries represented mainly in low maintenance, capability of standing very deep discharge and overcharge, high cycling stability, high charging efficiency and long life time [2].
Research papers on PV power systems concentrate mostly on the PV generator, the system performance and cost without giving adequate attention to the batteries and their characteristics. Therefore, this paper is established to illustrate the most important characteristics of storage batteries used in PV systems and to present experience results in this field. Especially important functions represented in battery voltage with electrolyte temperature, specific gravity and with depth of discharge as well as the degradation of ampere-hour capacity in function of increasing the discharging current have been measured and illustrated. The paper presents also an experimental method for derivation of a mathematical algorithm for determining the ampere hours capacity of lead acid batteries. This algorithm allows the calculation of the stored energy by measuring the battery voltage and the specific gravity of its electrolyte.

2. Storage Battery in PV Power System

Except in PV powered water pumping systems [3] , storage batteries are indispensable in all PV power systems operating in standalone mode to act either as a power buffer or for energy storage as illustrated in Fig. (1).

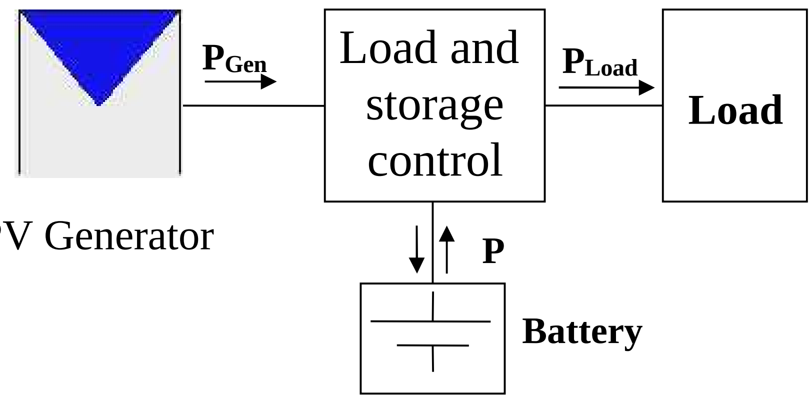

Fig.(1) Schematic diagram of a PV power system with battery storage

The PV generator is neither a constant current nor a constant voltage source. The maximum power output of the generator varies according the solar radiation and temperature conditions.

In the early morning or late afternoon, the PV generator may not be able to meet the load demands especially with short high current peaks such as during motor-startup. A battery which is a constant voltage source acting as a power buffer between the PV generator and the load, will compensate for the limitation of the generator. When solar radiation is higher than that needed to meet the load requirement, excess energy is stored in the battery to supply power to the load during night and cloudy days of low solar radiation [3] .

2.1 Battery types

The two battery types that have been used for PV systems are lead - acid and nickel - cadmium. Due to higher cost , lower cell voltage (1.2 V), lower energy efficiency and limited upper operating temperature (40 C°), nickel - cadmium batteries have been employed in relatively few system. Their use is based mainly on their long life with reduced maintenance and their capability of standing deep discharge without damage [2] . The lead acid battery will remain the most important storage device in the near future, especially in PV systems of medium and large size [5] . It is a lead / sulfuric acid / lead dioxide electrochemical system , whose overall reaction is given by the following equation [2,4] .

$$Pb + PbO_2 + 2H_2\,SO4 \underset{charge}{\overset{Discharge}{\rightleftarrows}} 2\,PbSO4 + 2H_2O$$

A battery is made up of two or more electrochemical cells interconnected in an appropriate series / parallel arrangement to provide the required operating voltage and current levels. The familiar 12V Lead - acid battery used in automobiles consists of six 2- volt cells connected in series and packaged in a rubber or plastic case [4] .

2.2 Lead - acid battery characteristics

2.2.1 Voltage, specific gravity and state of charge

The nominal voltage of a lead - acid cell is 2V, while the upper and lower limits of discharging and charging open circuit voltage at 25C° cell temperature are 1.75 and 2.4V , which corresponds to 10.5 and 14.4V for a 12 V battery (respectively) . The maximum acceptable battery cell voltage decreases linearly with increasing cell temperature as illustrated in Fig. (2). The specific gravity of the acid solution of the battery decreases slightly with increasing temperature . Cell voltage and specific gravity of the acid solution are mainly a measure for the state of charge of the battery cell as recognized in the following table.

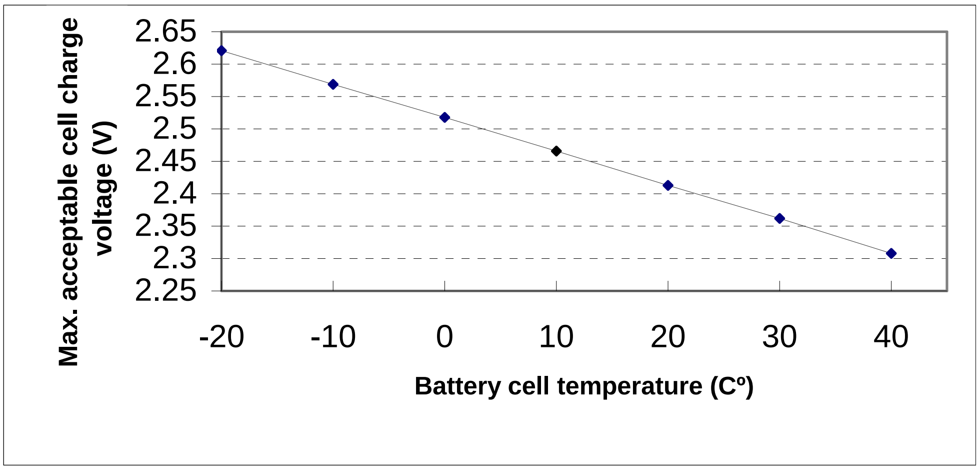

Fig.(2): Maximum acceptable battery cell charge voltage in function of internal cell temperature .

Table (1): Typical open circuit voltage and specific gravity for a lead - acid cell at 26.7 Cî [5] .

State of Charge (Charge Level) (%)	**Specific Gravity gr. / m³**	**Cell Voltage (V)**	**Battery Voltage (12V) (V)**
100	1.265	2.116	12.7
75	1.225	2.066	12.4
50	1.190	2.033	12.2
25	1.155	2	12
10	1.120	1.983	11.9

The depth of discharge (DOD) is the obverse of state of charge. As measurement results in section (3) will show, cell voltage decreases almost linearly with depth of discharge until a point called cut-off-voltage is reached.

Battery cells should not be operated beyond the cut off voltage, because further discharge will result in increasing the internal resistance of the battery and can result in permanent damage to it . On other hand, overcharging the batteries until gassing leads also to cell damage [6].

Therefore, batteries have to be connected to the output of the PV generators and the load via a charge controller as shown in Fig.(1). This controller, protects the battery against deep discharge and excessive overcharge.

Lead acid battery cells are available with either pure lead or lead - calcium grids to minimize the self- discharge rate. All lead - acid cells have some loss in capacity on standing due to internal chemical reactions. Fig. (3) presents typical self discharge rates for a cell containing antimony or calcium grids . Self- discharge rate , increases with increasing cell temperature and remain relatively low for cell with lead calcium grids [2].

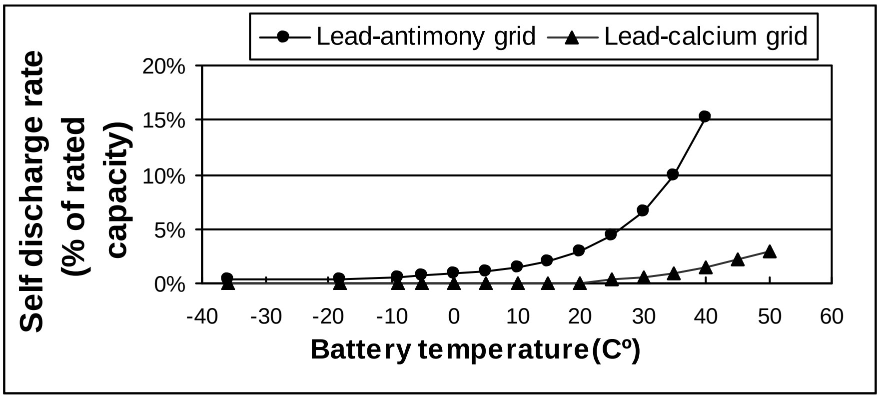

Fig. (3): Lead - acid battery self discharge rate in function of cell temperature .

2. 2.2 Storage capacity and efficiency.

Batteries are commonly rated in terms of their Ampere - hour (Ah) or Watt-hour (Wh) capacity. Ah - capacity is the quantity of discharge current available for a specified length of time valid only at a specific temperature and discharge rate. For example, a 12 V battery rated at 100 Ah over 20 hours can deliver 5A per hour for 20 hours (C_{20} - rate) is equivalent to 1.2 kWh of energy (12 V × 100 Ah) . At 5 - hour discharge rate, the same battery will deliver a maximum of 70 Ah equivalent to 0.8 kWh of energy (C_5-rate). The discharge curve in Fig. (4) illustrates the relationship between Ah - capacity and discharge current for a typical 100 Ah / 12 V - lead-acid battery. High discharge current would result in reduction of the battery capacity and will shorten its life [3,7].

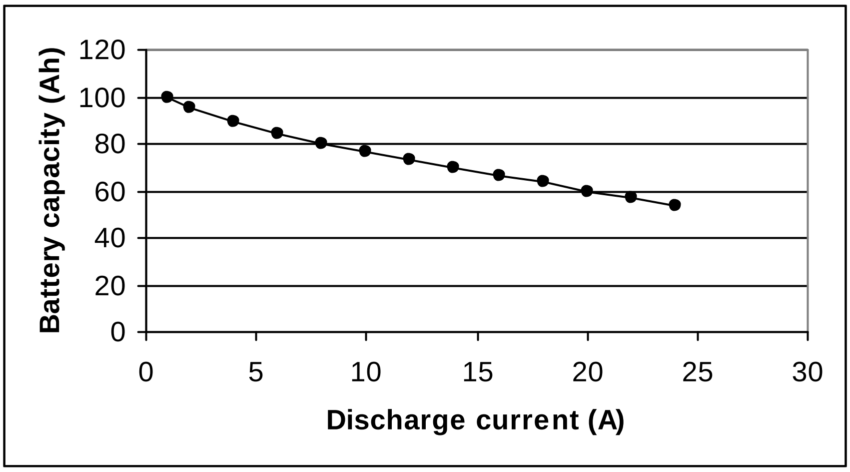

Fig. (4): The ampere - hour capacity of a lead - acid battery in function of the discharge current.

In addition, the Watt - hour capacity (Wh) or energy capacity is the time integral of the product of discharge current and voltage from full charge to cutoff voltage . Battery capacity increases almost linearly with temperature and achieves to 112% of its rated capacity when its temperature is raised from 26C° to 36C° .

The ampere hour efficiency of a battery cell (η_{Ah}) is the ratio of the number of ampere hours obtainable during discharge to that required to restore it to its original condition. The value for a lead - acid cell is about 90%. The Watt hour efficiency takes the voltage variation into account, and its value is about 75% [7].

3. Determining the Ah - Capacity of a Storage Battery

Developing an algorithm appropriate for determining the Ah - capacity of a storage battery through its voltage and electrolyte concentration requires the measurement of these parameters at constant temperature. For this purpose, a new lead - acid storage battery rated at 12 V/ 110 Ah type Anker - Sun Power (Norway) was selected to be exposed for measurements. This battery type had been world wide used in small size PV power systems (Solar Electric Home Systems).

Following the instructions of the producer (Anker Company), the battery was filled with sulfuric acid , whose concentration (ρ) is 1.24 kg / litre, then fully charged till its charging voltage (open circuit voltage) reached 12.76 V, which corresponds to a final voltage value of 2.13 V per cell and a storage capacity of 110 Ah.

3.1 Measurement of the battery parameters through discharging

The battery was loaded with a resistive load rated at 12 V / 120 W. Output current (I) , voltage (V) , acid concentration (ρ) and acid temperature (T) were measured with a scan rate of 10 seconds by a data acquisition system , where n average values on 1/2 hourly basis were built:

$$I_n = \frac{\sum_{m=1}^{180} I_m}{180} \quad (1)$$

$$V_n = \frac{\sum_{m=1}^{180} V_m}{180} \quad (2)$$

$$\rho_n = \frac{\sum_{m=1}^{180} \rho_m}{180} \quad (3)$$

$$T_n = \frac{\sum_{m=1}^{180} T_m}{180} \quad (4)$$

Considering the initial capacity (C_o) at which the battery was charged (110 Ah) , the n- ampere hour capacity (C_n) is obtainable as:

$$C_n = C_{n-1} - \frac{1}{2} I_n \quad (5)$$

The above mentioned measuring procedure has been repeated till a 66.18% depth of discharge (DOD) was achieved .

Table (2) : Measured and calculated parameters of a lead acid battery rated at 12 V / 110 Ah . (Type Anker- Sun Power , Norway)

n	**I_n (A)**	**V_n (V)**	**°$_n$ (kg/litre)**	**T_n (Cî)**	**DOD_n (%)**	**C_n (Ah) (measured)**	**C_n (Ah) (calculated)**
0	-	12.76	1.24	27	0	110	112.4
1	9.19	12.57	1.24	27.5	4.18	105.4	103.54
2	9.34	12.52	1.24	28	8.45	100.7	101.2
3	9.67	12.47	1.227	28.5	12.82	95.9	95.25
4	9.82	12.42	1.2075	28	17.27	91.0	87.465
5	9.79	12.38	1.2025	27.625	21.73	86.1	84.2
6	9.76	12.34	1.2013	27.75	26.18	81.2	82.002
7	9.69	12.29	1.1975	27.75	30.55	76.4	78.61
8	9.67	12.24	1.18125	27.75	35	71.5	71.736
9	9.67	12.19	1.175	27.575	39.36	66.7	67.66
10	9.70	12.15	1.169	27.30	43.73	61.90	64.116
11	9.61	12.10	1.151	27.35	48.18	57.0	56.75
12	9.69	12.06	1.1425	27.40	52.55	52.2	52.5
13	10.08	12.01	1.130	27.325	57.09	47.2	46.69
14	9.99	11.95	1.1175	27.2	61.64	42.2	40.395
15	9.91	11.90	1.1175	27.35	66.18	37.2	38.064

$$DOD_n = \frac{C_0 - C_n}{C_0} \qquad (6)$$

The obtained measuring results are illustrated in Table (2) while Fig.(5) and Fig (6) show the battery voltage in function of DOD and acid concentration respectively. It is worth mentioning that the measured voltage and concentration values satisfy to a large extent eq.(7) which was developed by G. Lehner [5] for one lead - acid battery cell.

$$V_n = 1.85\ V + 0.917\ V\ (\rho_n - 1) \qquad (7)$$

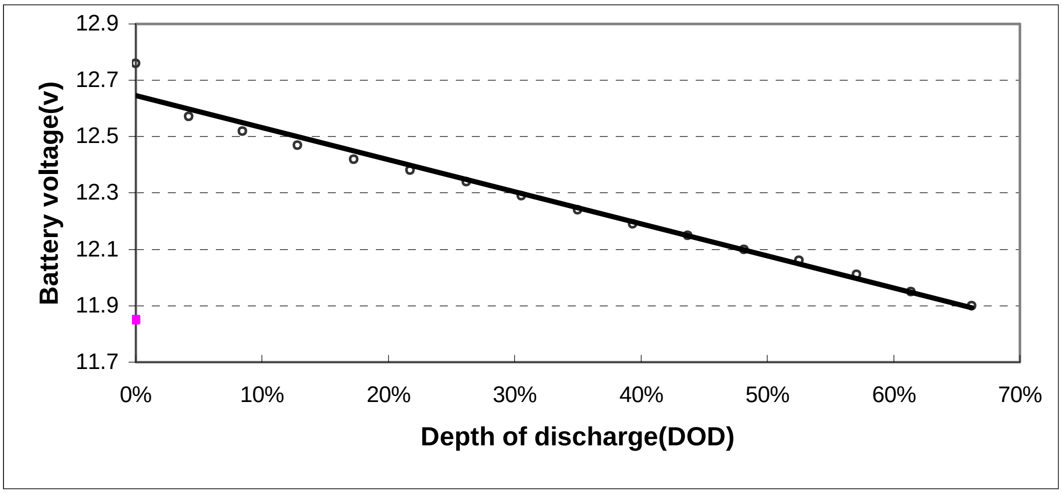

Fig.(5): The battery voltage in function of depth of discharge .

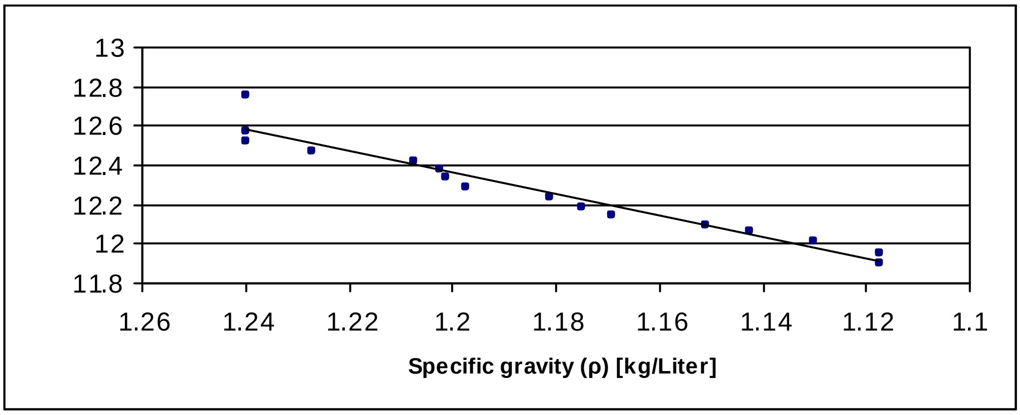

Fig.(6) : The battery voltage in function of electrolyte specific gravity .

3.2 Developing an algorithm for determining the battery - Ah capacity

At quasi constant acid temperature, the ampere - hour capacity of a battery (C), can be represented as a linear function of voltage and acid concentration according to equation (8) .

Applying the least square method on the measured V and ρ values illustrated in Table (2) we obtain eq. (9) :

$$C = aV + b\rho + c \qquad (8)$$

$$E = \sum \{C - (aV + b\rho + c)\}^2 \qquad (9)$$

Where a, b, c are constants and E is the error. For a minimum error, E will be differentiated according to a , b and c and set to zero:

$$\frac{dE}{da} = 0 \qquad (10)$$

$$= 2 \sum \{C - (aV + b\rho + c)\}\{-V\}$$

$$a \sum V^2 + b \sum V\rho + c \sum V = \sum CV \qquad (11)$$

$$\frac{dE}{db} = 0 \qquad (12)$$

$$= 2 \sum \{C - (aV + b\rho + c)\}\{-\rho\}$$

$$a \sum V\rho + b \sum \rho^2 + c \sum \rho = \sum C\rho \qquad (13)$$

$$\frac{dE}{dc} = 0 \qquad (14)$$

$$= 2 \sum \{C - (aV + b\rho + c)\}\{-1\}$$

$$a \sum V + b \sum \rho + c = \sum C \qquad (15)$$

Calculating V^2 , $V\rho$, VC , ρ^2 , ρC and their summations from Table (2) and substituting the corresponding values in equations (11) , (13) and (15) we obtain the following three equations with three unknown constants:

$$2410.457\ a + 232.575\ b + 196.35\ c = 14595.609 \qquad (16)$$
$$232.575\ a + 22.447\ b + 18.940\ c = 1414.590 \qquad (17)$$
$$196.35\ a + 18.940\ b + 16\ c = 1182.60 \qquad (18)$$

Solving these equations we obtain the values for a, b and c :

$a = 46.614$, $b = 279.573$, $c = -829.069$.

Substituting these values in eq. (8) we obtain eq. (19) which represents the ampere - hour capacity of the battery as a function of the voltage and acid concentration :

$$C = 46.614\ V + 279.573\ \rho - 829.069 \qquad (19)$$

Substituting V and ρ values from Table (2) in eq. (19) we obtain the calculated values for the ampere hour capacity (C_n) presented in column (8) of Table (2). Comparing these value with the measured capacity - values (C_n) in column (7), one finds that the corresponding values are very closed which verifies the correctness of the applied procedure.

4. Conclusions

Lead - acid storage batteries are usually used in small and large PV power systems operating in stand-alone mode. Selection of battery type and capacity are important factors to realize an efficient PV system. Battery types marketed for use in automobile are economically not appropriate for utilization in PV systems because their life time is relatively very short since they can not stand deep discharge and high cycling rate. Battery voltage in function of electrolyte temperature, depth of discharge and specific gravity as well as the battery capacity in function of discharge current illustrated in figures (2), (5), (6) and (4) resp., have to be given special consideration when evaluating or designing storage batteries for PV power systems.

Battery voltage and specific gravity together are the key for determining the ampere - hour capacity of a battery and the stored energy in it. Measuring them at the same time and substituting their values in the developed algorithm eq. (19) results the capacity of the battery in Ah. This algorithm enables knowing the energy storage within a PV power system and to perform accordingly in setting the battery charger control limits correctly, which consequently elongate the life time of the battery and enhance the over all PV system performance and economics.

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