

IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems

Sponsor

**IEEE Standards Coordinating Committee 21,
Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage**

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Abstract: A method for sizing both vented and valve-regulated lead-acid batteries used in terrestrial photovoltaic (PV) systems is described. Installation, maintenance, safety, testing procedures, and consideration of battery types other than lead-acid are beyond the scope of this document. Recommended practices for the remainder of the electrical systems associated with PV installations are also beyond the scope of this document.

Keywords: photovoltaic power systems, sizing lead-acid battery

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Introduction

[This introduction is not part of IEEE Std 1013-2000, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems.]

This recommended practice describes a method for sizing both vented and valve-regulated lead-acid batteries used in terrestrial photovoltaic (PV) systems. Installation, maintenance, safety, testing procedures, and consideration of battery types other than lead-acid are beyond the scope of this document. Recommended practices for the remainder of the electrical systems associated with PV installations are also beyond the scope of this document.

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IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems

1. Overview

1.1 Scope

This recommended practice describes a method for sizing both vented and valve-regulated lead-acid batteries in photovoltaic (PV) systems. Installation, maintenance, safety, testing procedures, and consideration of battery types other than lead-acid are beyond the scope of this document. Recommended practices for the remainder of the electrical systems associated with PV installations are also beyond the scope of this document.

Sizing examples are given for various representative system applications. Iterative techniques to optimize battery costs, which include consideration of the interrelationship between battery size, PV array size, and weather, are beyond the scope of this document.

1.2 Purpose

This recommended practice is meant to assist system designers in sizing lead-acid batteries for residential, commercial, and industrial PV systems.

2. References

This recommended practice shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision should be used.

IEEE Std 485-1997, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications.¹

¹IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

IEEE Std 937-2000, IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic (PV) Systems.

3. Definitions

The following definitions apply specifically to this recommended practice. For other definitions, see *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B1].²

3.1 array-to-load ratio: The array-to-load ratio is the average photovoltaic ampere hours available divided by the average daily load in ampere hours (Ah). The average daily PV ampere hours is calculated by taking the average daily solar resource for the month of interest in kilowatt hours per square meter (kWh/m^2) times the array current at its maximum power point under a solar irradiance of 1000 watts per square meter (W/m^2).

3.2 cycle life: The number of cycles (discharges and recharges), under specified conditions, that a battery can undergo before failing to meet its specified end-of-life capacity.

3.3 days of battery reserve: The number of days a fully charged battery can satisfy the load with no contribution from the photovoltaic array or auxiliary power source.

3.4 depth of discharge (DOD): The ampere hours removed from a fully charged battery, expressed as a percentage of its rated capacity at the applicable discharge rate.

3.5 discharge rate: The rate, in amperes, at which current is delivered by a battery. *See also:* **hour rate**.

3.6 energy capacity: The energy, usually expressed in watt hours (Wh), that a fully charged battery can deliver under specified conditions.

3.7 hour rate: The discharge rate of a battery expressed in terms of the length of time a fully charged battery can be discharged at a specific current before reaching a specified end-of-discharge voltage.

3.8 rated capacity (C): The capacity, in ampere hours (Ah), assigned to a cell by its manufacturer for a given constant-current discharge rate, with a given discharge time, at a specified electrolyte temperature and specific gravity, to a specific end-of-discharge voltage.

3.9 regulation voltage: The maximum voltage that a charge controller will allow the battery to reach under charging conditions. At this point the charge controller will either discontinue charging or begin to taper the charging current to the battery.

3.10 self discharge: The process by which the available capacity of a battery is reduced by internal chemical reactions (local action).

3.11 self-discharge rate: The amount of capacity reduction in a battery occurring per unit of time as the result of self-discharge.

3.12 valve-regulated lead-acid cell (VRLA): A lead-acid cell that is sealed except for a valve that opens to the atmosphere when the internal gas pressure in the cell exceeds the atmospheric pressure by a preselected amount. Valve-regulated cells provide a means for recombination of internally generated oxygen and the suppression of hydrogen gas evolution to limit water consumption.

²The numbers in brackets correspond to those of the bibliography in Annex C.

3.13 vented battery: A battery in which the products of electrolysis and evaporation are allowed to escape freely to the atmosphere. These batteries are commonly referred to as “flooded.”

4. Outline of sizing methodology

The function of a battery used in a PV system is to supply power when the system load exceeds the output of the PV array. For a satisfactory PV battery system, many factors should be considered to determine the necessary capacity and the number of cells composing the battery. These factors, as follows, will be discussed in subsequent clauses:

- Battery reserve considerations (Clause 5). The length of time that the load should be supported solely by the battery is established by system design requirements.
- Load determination (Clause 6). Requirements of the application determine the amount of current that is to be supplied by the battery over a period of time. The peak current and the operational voltage window are determined by the system's load devices.
- Battery capacity and functional-hour rate determination (Clause 7). The battery capacity and its discharge functional-hour rate are determined by the specific application load, days of battery reserve, and battery characteristics (see Annex A).
- Determining number of series-connected cells (Clause 8). The system's voltage limits (voltage window) determines the required number of cells in series. Several criteria should be examined to assure a workable system.
- Cell capacity and battery size determination (Clause 9). Once the overall battery capacity and number of cells in series have been determined, the final selection of a specific cell can be made and the final battery size can be calculated.

NOTE—Because of the interaction of these factors, an iterative process may be needed to determine the optimum battery for the application.

- Battery sizing worksheets (Clause 10). Worksheets that provides a systematic approach to the sizing of a battery for a PV system is presented. The application of the worksheets is explained in accompanying text.
- Battery characteristics (Annex A). System performance, life, maintenance, and cost are influenced by the type of battery selected for a PV application. Information regarding lead-acid battery characteristics is presented.
- Examples (Annex B). Presented are examples demonstrating various aspects of battery sizing.

5. Battery reserve considerations

Photovoltaic power systems may require some battery reserve, both for reliability of service and to provide time for intervention in the event of an unanticipated occurrence such as unusually poor weather or failure of a system component. The number of days of battery reserve is commonly specified as a system design requirement, and is based on several considerations including the following:

- a) System application. Critical load applications generally require more days of battery reserve than noncritical applications.
- a) System availability. System availability is the minimum percentage of the time that the PV system should be able to satisfy the system loads.

- b) Solar irradiance variability. Daily and seasonal variations in solar irradiance affect the required number of days of battery reserve.
- c) Predictability of load. The load may or may not be predictable; also, there may be the possibility of adjusting the loads, e.g., dropping nonessential loads.
- d) Backup power provisions. If the PV system includes provisions for backup power, the desired frequency and duration of operation of the backup power source needs to be considered.
- e) Accessibility of site. The worst-case time required for correction of any problem should be considered.

6. Load determination

6.1 General considerations

The overall duty cycle imposed on the battery is the description of the dc load current and its duration within the days of battery reserve, during which it is assumed that no power is provided by the PV array or auxiliary power source. For ac loads supplied through an inverter, these loads should be tabulated separately, totaled, and combined with the inverter losses to determine the actual dc load on the battery.

The system's load can be expressed in a tabular or graphical form. As both descriptions start with a tabulation of the individual loads and their durations, the tabular form is more general. The load-profile diagram, the graphical representation, is necessary to visualize the interrelationships of the individual loads. For both load descriptions, all loads expected during a 24 h period are tabulated along with their anticipated durations. Worksheet 1 in Clause 10 provides a convenient method of tabulating load data in accordance with the sizing method of this document.

It may be necessary to consider a longer period of time when a 24 h period does not accurately describe the load profile. For those cases where the load profile exceeds 24 h, an average and a maximum daily load should be determined for subsequent battery capacity determinations. Worksheets 2 and 3 in Clause 10 provide a convenient method for determining these loads. The average daily load is used in the initial determination of the battery size.

Once the battery has been sized, the maximum daily load is used to determine the ability of this battery to sustain it. If the maximum daily load sequence cannot be established, the days should be arranged in the worst possible order, generally with the maximum load day last. The battery's capacity may need to be increased to satisfy the maximum daily load in this partially discharged state.

A load-profile diagram is a necessary aid in determining those areas where the battery's performance needs to be checked to assure load satisfaction. To make a load profile diagram, do the following:

- a) Tabulate all the individual loads along with their starting and stopping times.
- b) Total the coincident loads for their respective periods of time.
- c) Plot the resulting total load versus time of day or elapsed time, as appropriate.

The resulting curve is the load-profile diagram. If the daily loads vary during the days of battery reserve, the individual daily load-profile diagrams, plotted in sequence, constitutes the system's load-profile diagram. See Annex B for examples.

6.2 Load data

The information that should be gathered for each load is discussed in 6.2.1 through 6.2.6.

6.2.1 Momentary current

Loads lasting one minute or less are designated “momentary” loads and are given special consideration. The ampere hour requirements of this type of load are usually very low, but their effect on battery terminal voltage may be considerable and should be taken into account. Momentary loads can occur repeatedly during the duty cycle. Typical momentary loads are as follows:

- a) Motor starting currents
- b) High inverter surge currents

6.2.2 Running current

Running current is the current required by a load after its starting current has subsided. Certain devices require a constant power, thus the current required will rise as the battery voltage falls. Since the battery voltage remains relatively constant until near the end of discharge, the running current may be approximated as the current required at 95% of the system voltage.

NOTE—For certain loads, it is necessary to consider both the momentary and running current components of the load. For example, if an electric motor starts during the duty cycle, both the starting (momentary) current and running current need to be considered. The starting current need not be considered if the load was operating at the beginning of the duty cycle, i.e., at the beginning of the days of battery reserve.

6.2.3 Parasitic current

Parasitic losses, such as those resulting from tare losses of charge controllers and inverters, should be included as currents. These currents should be included as part of the running-current loads. Consideration of the battery’s self-discharge is recommended as a check (see 9.5) after the battery is selected.

6.2.4 Load duration

The load duration is the time, in hours, of operation of each load. For PV systems, it is very common for load duration to be expressed in terms of a daily cycle that repeats over the days of battery reserve. If the inception time of a load is known, but the shutdown time is indefinite, it should be assumed that the load will continue through the remainder of the days of battery reserve.

6.2.5 Load coincidence

Each load current (momentary or running) is classified as to whether or not it is coincident with any other loads, and tabulated accordingly. Loads that occur at random are assumed to be coincident loads. This information, portrayed in the load-profile diagram, is later used in battery selection and to check discharge rate (see 6.3).

6.2.6 Maximum and minimum load voltage

The maximum and minimum voltage at which each load operates properly should be determined and tabulated (see 8.2). Voltage drops, such as those associated with cabling, overcurrent protection, and connectors, between the battery and the loads are not to be considered as an adjustment to a load’s maximum voltage. This is because the current and resulting voltage drops can be very low at times, thus exposing the device to battery terminal voltage. However, these voltage drops should be determined individually for each load

device and added to its minimum operating voltage to ensure that the required minimum voltage will be present at the load.

6.3 Data analysis

6.3.1 Ampere hours

It is usually possible to calculate an equivalent daily load by multiplying each load current by its daily duration, and summing the results. If the duration of the momentary load is known, calculate the ampere hour load by multiplying this duration by the momentary current. If the duration of the momentary load is not known, assume the time to be 1 min and calculate the load accordingly. For voltage-drop considerations, a full-minute duration is used in either case.

If the duty cycle does not repeat each day, it is necessary to describe the load over all the days of battery reserve. Worksheet 2 in Clause 10 is provided for this purpose. If the graphical form of the load description is used, the ampere hour load is the total area under the load-profile curve.

6.3.2 Currents

The maximum momentary and maximum running currents are determined and are used to calculate the battery's maximum discharge current. Since the system loads may operate in various combinations, the maximum current (momentary or running) is the largest summation of the individual loads that can occur simultaneously. If the battery's maximum discharge current is greater than the 20 h discharge rate and the sequence of loads is known, the method described in IEEE Std 485-1997³ may result in a less conservatively sized battery.

7. Battery capacity and functional-hour rate determination

The required battery capacity for a PV application is determined by the number of days of battery reserve and by the characteristics of the load, battery, and installation. A functional-hour rate for the application is determined by capacity and load calculations.

7.1 Unadjusted capacity

The unadjusted capacity, in ampere hours, is calculated by multiplying the days of battery reserve by the average daily load (in ampere hours/day as determined in Clause 6). This capacity will be adjusted in 7.3 for battery characteristics and operating conditions.

7.2 Battery type selection

A trial battery type should be selected before proceeding with the sizing process. This is necessary because performance characteristics, such as design depth of discharge and cycle life, are different for the various battery types.

If a vented battery is used, it should be selected for the intended application by considering watering intervals, the consequences of hydrogen and oxygen evolution, and wear-out mechanisms.

³Information on references can be found in Clause 2.

If a valve-regulated battery is used, it should be selected for the intended application by ensuring that recombination is effective and that dry-out, thermal runaway, and the consequences of hydrogen and oxygen evolution are considered (see A.4.3).

Annex A provides a more detailed catalog of battery characteristics that should be considered. Reevaluation of the applicability of the trial battery is recommended throughout the sizing process. Refer to manufacturer's literature for specific data on the type of battery selected.

7.3 Capacity adjustment

7.3.1 Discharge adjustments

The unadjusted capacity should be modified to assure satisfactory battery cycle life. Battery manufacturers rate lead-acid cells for maximum depth of discharge (MDOD), maximum daily depth of discharge (MDDOD) and end-of-life (EOL) capacity. The battery capacity should be adjusted in the following ways:

- a) The capacity adjusted for MDOD is obtained by dividing the unadjusted capacity by MDOD (in percent).
- b) The capacity adjusted for MDDOD is obtained by dividing the maximum daily ampere hours by MDDOD (in percent).
- c) The capacity adjusted for life is obtained by dividing the unadjusted capacity by the end-of-life capacity expressed in percent of the rated capacity, commonly 80%.

The largest of these three capacities will satisfy the depth-of-discharge and end-of-life adjustments.

7.3.2 Temperature adjustment

The available capacity of a battery is affected by its operating temperature. Cell capacity ratings are generally standardized at 25 °C. Capacity increases at temperatures above 25 °C and decreases at temperatures below 25 °C. Capacity is rarely adjusted for warm temperature operation, but adjustments are routinely made for cold weather applications. Refer to the battery manufacturer's literature for temperature correction factors. The adjusted capacity determined in 7.3.1 should be corrected by this factor to yield capacity adjusted for temperature.

7.3.3 Design margin adjustment

It is prudent design practice to provide a capacity margin to allow for uncertainties in the load determination, e.g., less-than-optimum conditions and load growth. A common practice to provide this design margin is to add 10–25% to the capacity as determined in 7.3.2.

7.4 Functional-hour rate

In order to correctly size the battery, the discharge rate and ampere hour capacity should be considered together. In continuous load applications, the battery should have sufficient capacity to supply the constant discharge rate over the number of days of battery reserve. However, in noncontinuous load applications, the discharge rate varies and could include high rates of discharge periodically throughout the days of battery reserve. Using an average rate to size the battery could result in insufficient capacity to supply high currents above the minimum voltage late in the battery discharge. The functional-hour rate conservatively approximates a single discharge rate that is equivalent to the varying discharge rates of a particular duty cycle. The functional-hour rate used in 9.1, for cell selection, may be greater than the period of battery reserve.

The functional-hour rate can be calculated as follows:

- a) Compare the sum of coincident running currents (I_{coin}) with the maximum noncoincident running current (I_{noncoin}) and select the larger.
- b) Divide the adjusted capacity as determined in 7.3.3 by the maximum running current selected in step a).

Examples:

1—The adjusted battery capacity in a system with 5 days of battery reserve is 150 Ah, with a maximum current drain of 25 A. The functional-hour rate is 150 divided by 25, or 6 hours.

2—The adjusted battery capacity in a system with 5 days of battery reserve is 150 Ah with a continuous current drain of 1 A. The functional-hour rate is 150 divided by 1, or 150 hours.

8. Determining number of series-connected cells

A battery is usually composed of a number of identical cells connected in series. The maximum and minimum system voltages determine the number of series-connected cells of the battery.

8.1 Nominal system voltage

The lead-acid cell has a nominal voltage of 2 V; therefore, the number of cells may be estimated by dividing the nominal system voltage by 2. It is common practice to use 6 cells for a 12 V system, 12 cells for a 24 V system, etc., but it is possible that the allowable voltage limits may require adjustment to this general rule.

8.2 Voltage window

The system equipment will always have a voltage range within which the equipment will operate at rated capacity and efficiency. If the equipment is exposed to higher- or lower-than-specified voltages, it may be damaged or operate improperly. This high (V_{max}) and low (V_{min}) limit of system voltage is called the voltage window. The magnitude of this window has a direct effect on the number and capacity of battery cells selected. The narrower the window, the larger the cell's capacity needs to be; the wider the window, the smaller the cell's capacity can be.

From the tabulated maximum and minimum voltages in 6.2.6, the lowest maximum voltage (V_{max}) and the highest minimum voltage (V_{min}) define the voltage window within which all loads in the system will operate properly (see item 4b of Clause 10). If a charge controller is used, its setpoints should be within this voltage window.

When a temperature-compensated charge controller is used, the setpoints vary with the temperature of the battery. (The temperature used for the voltage compensation should be sensed at the battery.) The voltages associated with the anticipated temperature extremes of the battery should be used for this voltage window check. Since the charging voltage of the battery increases with decreasing temperature, generally only the voltage associated with the lowest anticipated temperature will be of significance.

NOTE—The battery may be excessively overcharged by a voltage less than V_{max} . It is recommended that a charge controller be used to limit the charge voltage. The consequences of excessive overcharging are described in item a) of 9.5.