

IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Photovoltaic (PV) Systems

Sponsor

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Abstract: A method for sizing nickel-cadmium battery storage subsystems used in residential, commercial, and industrial photovoltaic (PV) systems is described.

Keywords: battery sizing, nickel-cadmium batteries, terrestrial photovoltaic (PV) systems

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Introduction

[This introduction is not part of IEEE Std 1144-1996, IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Photovoltaic (PV) Systems.]

This recommended practice applies to terrestrial photovoltaic power systems, regardless of size or application, that contain nickel-cadmium battery storage subsystems.

This recommended practice should assist a photovoltaic system designer in sizing nickel-cadmium batteries for a particular installation. A worksheet is included to facilitate the battery sizing process. Examples of its application are found in annex B.

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1. Overview

1.1 Scope

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

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 recommended practice.

1.2 Purpose

This recommended practice is meant to assist system designers in sizing nickel-cadmium 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 When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.¹

¹At the time this standard went to press, IEEE Std 100-1996 was approved but not yet published. Anticipated publication is April 1997. IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std 1115-1992, IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications (ANSI).

IEEE Std 1145-1990, IEEE Recommended Practice for the Installation and Maintenance of Nickel-Cadmium Batteries for Photovoltaic (PV) Systems (ANSI).

3. Definitions

In general, definitions of technical words and terms used in this document are found in IEEE Std 100-1996. The following definitions apply specifically to this recommended practice:

3.1 cell: The basic electrochemical unit, characterized by an anode, a cathode, and electrolyte, used to receive, store, and deliver electrical energy.

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 fully charged battery can satisfy the load with no contribution from the photovoltaic (PV) 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 watthours (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 discharged voltage.

3.8 overcharge: The forcing of current through a battery after it has been fully recharged.

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

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 occurring per unit of time in a battery as the result of self-discharge.

3.12 valve-regulated battery: A battery that is sealed with the exception of a valve that opens to the atmosphere when the internal gas pressure exceeds the atmospheric pressure by a preselected amount. Valve-regulated batteries provide a means for recombination of internally generated oxygen.

3.13 vented battery: A battery in which the products of electrolysis and evaporation are allowed to escape freely to the atmosphere. These batteries have commonly been 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 have to be considered to determine the necessary capacity and the number of cells comprising the battery. These factors, as follows, will be discussed in subsequent clauses:

- *Battery reserve considerations (clause 5).* The length of time that the load has to be supported solely by the battery is established by system design requirements.
- *Load determination (clause 6).* The requirements of the application determine the amount of current over a period of time that is to be supplied by the battery. The peak current and the operational voltage window are also 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's 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 have to be examined to ensure 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, a 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 worksheet (clause 10).* A worksheet that provides a systematic approach to the sizing of a battery for a PV system is presented. The application of this worksheet is explained in accompanying textual material.
- *Battery characteristics (Annex A).* System performance, life, maintenance, and cost are influenced by the type of battery selected for a PV application. Information regarding nickel-cadmium battery characteristics is presented.
- *Examples (Annex B).* Examples demonstrating various aspects of battery sizing are presented.

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 anticipated occurrence, such as unusually low insolation or failure of a system component. The number of days of battery is commonly specified as a system design requirement and is based on several considerations, including the following:

- *System availability.* System availability is the minimum percentage of the time that the PV system should satisfy the system loads.
- *System application.* Critical load application generally require more days of battery reserve than noncritical applications.
- *Solar irradiance variability.* Daily and seasonal variations in solar irradiance affect the required number of days of battery reserve.
- *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.
- *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.
- *Accessibility of site.* The worst-case time required for correction of any problem needs to be considered.
- *System cost.* Cost trade-offs associated with array and battery size relationships for the required system availability need to be considered.
- *Other costs.* Costs associated with maintenance and the interruption of service should also 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 array or auxiliary power source. For ac loads supplied through an inverter, these loads have to 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 the 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 ensure load satisfaction. A load profile diagram may be made as follows:

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

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 constitute 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 6.2.5.

6.2.1 Momentary current

Loads lasting 1 min or less are designated as momentary loads and are given special consideration. The ampere-hour requirement 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. As the battery voltage remains relatively constant until near the end of discharge, the running current for a constant-power device may be approximated as the current required at 95% of the system voltage.

NOTES:

- 1 — 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 to 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.
- 2 — Parasitic power losses, such as those resulting from tare losses of charge controllers and inverters and wiring, should be included as currents.
- 3 — Consideration of the battery self-discharge as a load is recommended as a check (see 9.5) after the battery is selected.

6.2.3 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.

6.2.4 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).

6.2.5 Maximum and minimum load voltage

The maximum and minimum voltage at which each load operates properly has to be determined and tabulated (see 8.2.). Voltage drops in 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 because, at times, the current and resulting voltage drops can be very low, 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 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 then 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.

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

6.3.2 Currents

The maximum momentary and running currents are determined and 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 load is known, the method described in IEEE Std 1115-1992² 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, 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 due to characteristics that are different for the various battery types, such as cycle life.

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

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

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 adjustment

The battery has to be capable of giving satisfactory cycle in life in the intended application. Nickel-cadmium batteries are characterized by both good deep-cycling capability and ability to be overdischarged. For this reason, maximum depth of discharge (DOD) figures are not published and it is generally necessary only to modify the unadjusted capacity to reflect end-of-life capacity. The aging process for nickel-cadmium batteries is a slow, even loss of capacity with no sharp falloff at the end of life. The user therefore defines the end-of-life for the battery using economic considerations (initial cost versus service life) alone.

Data can be obtained from the manufacturers regarding the number of charge/discharge cycles, relative to the DOD, available from a given battery type for a particular end-of-life capacity. This can be compared with the relationship

²Information on reference can be found in clause 2

between the length of duty cycle and the days of battery reserve. For example, for a daily duty cycle and a ten-day reserve, the average daily DOD is 10% (ignoring cloudy weather capacity deficits and occasional deep discharges). For a battery type capable of providing, for example, 3000 daily cycles of 10% DOD to 80% of rated capacity, this would equate to a service life of 8.2 years. However, the same battery type might provide 5000 cycles of 10% DOD to 60% of rated capacity, which is equal to 13.7 years.

The capacity adjusted for life is obtained by dividing the unadjusted capacity by the end-of-life capacity expressed as a percentage of the rated capacity.

It should be noted that a duty cycle that represents a 10% DOD compared with the unadjusted capacity would equate to only an 8% DOD for a battery adjusted for an 80% end-of-life capacity. This will allow additional margin for the battery to cope with cloudy weather deficits and occasional deep discharges.

7.3.2 Charge adjustment

Nickel-cadmium batteries exhibit high recharge efficiency up to reasonably high (>80%) state of charge (SOC). Beyond this point, the recharge efficiency begins to decline and it becomes progressively more difficult to reach higher states of charge. The point where this effect becomes important varies with the relative amount of overcurrent applied to the battery. For most PV system designs, the charging current will drop with increasing battery voltage, and the influence will not occur until an SOC of 90–95% is achieved. In some applications, for example, where a charge controller is installed to minimize water consumption, the system design may be such that the battery never reaches a 100% SOC. Although the battery is not damaged by being less than fully charged, the low SOC has to be taken into account in the sizing calculations. A common practice is to divide the capacity determined in 7.3.1 by 0.90–0.95.

7.3.3 Temperature adjustment

The available capacity of a battery is affected by its operating temperature. Cell capacity ratings are standardized at 25 °C (77 °F). Capacity increase at temperatures above 25 °C and decreases at temperatures below 25 °C. However, capacity increases above 25 °C are negligible. Therefore, 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 7.3.2 has to be corrected by this factor to yield capacity adjusted for temperature.

7.3.4 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, load growth, etc. A common practice to provide this design margin is to add 10–25% to the capacity as determined in 7.3.3.

7.4 Functional-hour rate

In order to correctly size the battery, the discharge rate and ampere-hour capacity have to 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 application, 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 may be greater than the period of battery reserve.

The functional-hour rate can be calculated as follows:

- a) Compare the sum of all coincident running currents with the highest noncoincident running current and select the larger.
- b) Divide the adjusted capacity as determined in 7.3.4 by the maximum running current selected in a).

Examples:

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 Ah divided by 25 A, or 6 h.

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 Ah divided by 1 A, or 150 h.

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

Although the nominal voltage of a nickel-cadmium cell is 1.2 V, dividing the nominal system voltage by 1.2 to arrive at the number of cells will frequently yield an incorrect answer. The number of cells has to be matched to the output characteristics (current-voltage curve) of the array used for its charging. It is common practice to use 9 cells for a 12-V system, 18 cells for a 24-V system, etc., but it is also common that the allowable voltage limits may require adjustment to this 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 6.2.5, 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. Since nickel-cadmium cells are not damaged by overcharging, a charge controller is not normally required unless water loss or damage from system overvoltage is consideration. In such cases, a charge controller is recommended. If a charge controller is used, its set points need to be within this voltage window (see clause 10, 4b).

8.3 Calculating the number of series-connected cells

The number of series-connected cells is function of both the voltage window of the loads and the manufacturer's charging recommendation for the selected cell. An optimum number of cells is determined as a result of iterative calculations.

8.3.1 Maximum number of cells allowed

The most important aspect of calculating the maximum number of series-connected cells is to ensure an optimal and safe cell recharge voltage. In determining the maximum number of cells allowed by the system, the following calculation is performed: