

IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications

IEEE Power & Energy Society

Sponsored by the
Stationary Batteries Committee

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IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications

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IEEE Power & Energy Society

Approved 8 November 2010

IEEE-SA Standards Board

Abstract: Methods for defining the dc load and for sizing a lead-acid battery to supply that load for stationary battery applications in full-float operations are described in this recommended practice. Some factors relating to cell selection are provided for consideration. Installation, maintenance, qualification, testing procedures, and consideration of battery types other than lead-acid are beyond the scope of this recommended practice. Design of the dc system and sizing of the battery charger(s) are also beyond the scope of this recommended practice.

Keywords: battery duty cycle, cell selection, dc load, full-float operation, IEEE 485, lead-acid batteries, rated capacity, sizing, stationary applications, valve-regulated lead-acid (VRLA) cell, vented battery

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Introduction

This introduction is not part of IEEE Std 485-2010, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications.

The storage battery is of primary importance for the satisfactory operation of generating stations, substations, and other stationary applications. This recommended practice is based on commonly accepted methods used to define the load and to ensure adequate battery capacity. The method described is applicable to all installations and battery sizes.

The installations considered herein are designed for operation with a battery charger serving to maintain the battery in a charged condition as well as to supply the normal dc load. This recommended practice does not apply to “cycling” applications. (See IEEE P1660™/D9, June 2008 [B2]^a subject to approval before this revision is approved.)

This recommended practice was prepared by the Lead Acid Battery Sizing Working Group of the Stationary Battery Committee. It may be used separately, but when combined with IEEE Std 450™-2002^b and IEEE Std 484™-2002 (for vented lead acid batteries) or IEEE Std 1187™-2002 and IEEE Std 1188™-2005 (for valve-regulated lead-acid [VRLA] batteries), it will provide the user with a general guide to designing, placing in service, and maintaining the applicable lead-acid battery installation.

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^a The numbers in brackets correspond to those of the bibliography in Annex J.

^b Information on references can be found in Clause 2.

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Contents

1. Overview	1
1.1 Scope	1
2. Normative references.....	1
3. Definitions	2
4. Defining loads	2
4.1 General considerations.....	2
4.2 Load classification.....	3
4.3 Duty cycle diagram.....	4
5. Cell selection	5
6. Determining battery size.....	6
6.1 Number of cells	6
6.2 Additional considerations	7
6.3 Cell size	10
6.4 Cell sizing worksheet.....	12
7. Cell voltage/time profile calculation	13
Annex A (informative) Battery and cell sizing examples.....	15
Annex B (informative) Converting constant power and resistance loads to constant current	21
Annex C (informative) Calculating cell voltage during discharge	23
Annex D (informative) Consideration of cell types.....	31
Annex E (informative) Constant power sizing	32
Annex F (informative) Development and use of battery discharge curves.....	39
Annex G (informative) Random loads	50
Annex H (informative) Capacity variation during life	56
Annex I (informative) Full-size worksheet.....	57
Annex J (informative) Bibliography.....	59

IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications

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1. Overview

1.1 Scope

Methods for defining the dc load and for sizing a lead-acid battery to supply that load for stationary battery applications in full float operations are described. Some factors relating to cell selection are provided for consideration. Installation, maintenance, qualification, testing procedures, and consideration of battery types other than lead acid are beyond the scope of this recommended practice. The design of the dc system and sizing of the battery charger(s) are also beyond the scope of this recommended practice.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated referenced, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 450™-2002, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications.^{1,2}

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IEEE Std 484™-2002, IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications.

IEEE Std 1184™-2006, IEEE Guide for Batteries for Uninterruptible Power Supply Systems.

IEEE Std 1187™-2002 IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead-Acid Storage Batteries for Stationary Applications.

IEEE Std 1188™-2005, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications.

3. Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be consulted for terms not defined in this clause.³

battery duty cycle: The sequence of loads a battery is expected to supply for specified time periods.

cell size: The rated capacity of a cell or the number of positive plates in a cell.

equalizing charge: A charge, at a level higher than the normal float voltage, applied for a limited period of time, to correct inequalities of voltage, specific gravity, or state of charge that may have developed between the cells during service.

full-float operation (float service): Operation of a direct current (dc) system in which the battery spends the majority of the time on float charge with infrequent discharge. (The primary source of power is normally the battery charger or rectifier.)

period: An interval of time in the battery duty cycle during which the current (or power) is assumed to be constant for purposes of cell sizing calculations.

rated capacity (lead-acid): The capacity assigned to a cell by its manufacturer for a given discharge rate, at a specified electrolyte temperature and specific gravity, to a given end-of-discharge voltage.

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

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

4. Defining loads

4.1 General considerations

The duty cycle imposed on the battery by any of the conditions described herein will depend on the dc system design and the requirements of the installation. The battery must supply the dc power requirements when the following conditions occur:

³ The *IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

- a) Load on the dc system exceeds the maximum output of the battery charger
- b) Output of the battery charger is interrupted
- c) AC power is lost [may result in a greater dc power demand than item b)]

The most severe of these conditions, in terms of battery load and duration, should be used to determine the battery size for the installation.

4.2 Load classification

The individual dc loads supplied by the battery during the duty cycle may be classified as continuous or noncontinuous. Noncontinuous loads lasting 1 minute or less are designated “momentary loads” and should be given special consideration (see 4.2.3).

4.2.1 Continuous loads

Continuous loads are energized throughout the duty cycle. These loads are those normally carried by the battery charger and those initiated at the inception of the duty cycle. Typical continuous loads are as follows:

- a) Lighting
- b) Continuously operating motors
- c) Converters (e.g., inverters)
- d) Indicating lights
- e) Continuously energized coils
- f) Annunciator loads
- g) Communication systems

4.2.2 Noncontinuous loads

Noncontinuous loads are energized only during a portion of the duty cycle. These loads may come on at any time within the duty cycle and may be on for a set length of time, be removed automatically or by operator action, or continue to the end of the duty cycle. Typical noncontinuous loads are as follows:

- a) Emergency pump motors
- b) Critical ventilation system motors
- c) Fire protection systems actuations
- d) Motor-driven valve operations (stroke time >1 minute)

4.2.3 Momentary loads

Momentary loads can occur one or more times during the duty cycle but are of short duration, not exceeding 1 minute at any occurrence. Although momentary loads may exist for only a fraction of a second, it is common practice to consider each load will last for a full minute because the battery voltage drop after several seconds often determines the battery’s 1 minute rating. When several momentary loads occur within the same 1 minute period and a discrete sequence cannot be established, the load for the 1 minute period should be assumed to be the sum of all momentary loads occurring within that minute. If a discrete sequence can be established, the load for the period should be assumed to be the maximum load at any instant. Sizing for a load lasting only a fraction of a second, based on the battery’s 1 minute

performance rating, results in a conservatively sized battery. Consult the battery manufacturer for ratings of discharge durations less than 1 minute. Typical momentary loads are as follows:

- a) Switchgear operations
- b) Motor-driven valve operations (stroke time <1 minute)
- c) Isolating switch operations
- d) Field flashing of generators
- e) Motor starting currents
- f) Inrush currents

4.2.4 Other considerations

The preceding lists of typical loads are not a full catalog of the dc loads at any one installation. The loads applied to the battery are normally categorized as constant power, constant resistance, or constant current. However, for sizing purposes, the loads are treated as constant power or constant current. The designer should review each system carefully to be sure all possible loads and their variations are included (see Annex B). If the loads are solely constant power loads, sizing as described in Annex E is appropriate and may simplify the sizing process.

4.3 Duty cycle diagram

A duty cycle diagram showing the total load at any time during the cycle is an aid in the analysis of the duty cycle. To prepare such a diagram, all loads (expressed in either current or power) expected during the cycle are tabulated along with their anticipated inception and shutdown times. The total time span of the duty cycle is determined by the requirements of the installation.

4.3.1 Defined loads

Loads whose inception and shutdown times are known are plotted on the diagram as they would occur. If the inception time is known, but the shutdown time is indefinite, it should be assumed that the load will continue through the remainder of the duty cycle.

4.3.2 Random loads

Loads that occur at random should be shown at the most critical time of the duty cycle in order to simulate the worst-case load on the battery. These may be noncontinuous or momentary loads as described in 4.2.2 and 4.2.3. To determine the most critical time, it is necessary to size the battery without the random load(s) and to identify the section of the duty cycle that controls battery size. Then the random load(s) should be superimposed on the end of that controlling section as shown in Figure 1 (see 6.3.4).

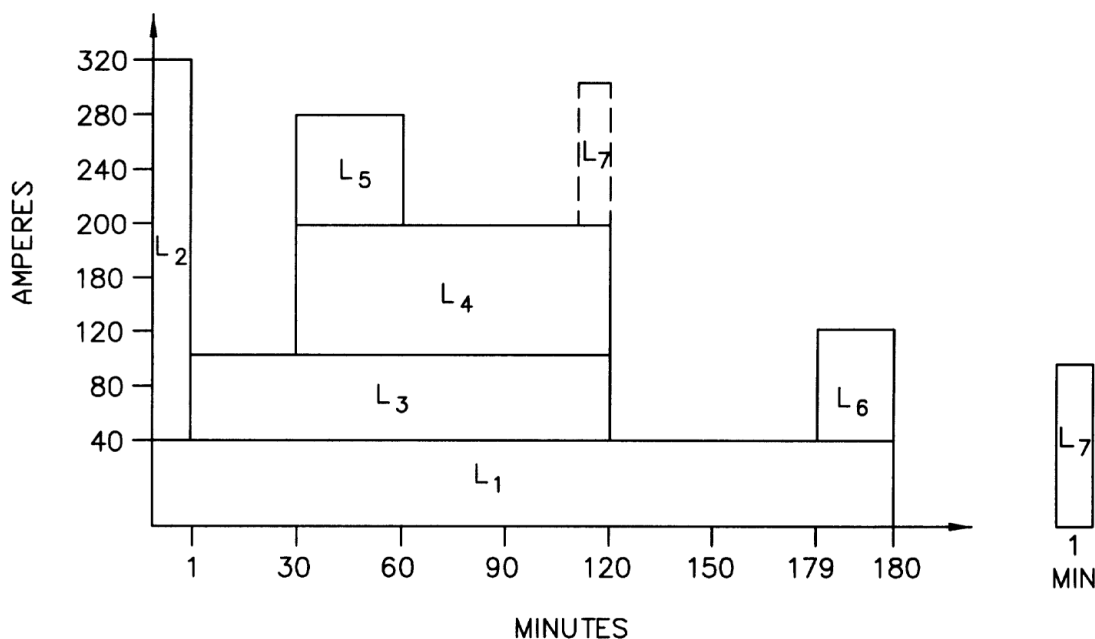


Figure 1—Diagram of a duty cycle

NOTE—This example is worked out in detail in Annex A. There it will be found that the first 120 min is the controlling portion of the duty cycle. Therefore, the random load is located on the duty cycle so that the random load ends at the end of the 120th min. This is indicated by the dashed lines. See Annex G for an additional discussion on treatment of random loads.⁴

4.3.3 Duty cycle example

Figure 1 is a diagram of a duty cycle made up of the following hypothetical loads expressed in amperes:

- L_2 40 A for 3 h, continuous load
- L_3 280 A for the 1st min, momentary load, actually 5 s starting current to load L_3
- L_4 60 A from the 1st min through the 120th min, noncontinuous load
- L_5 100 A from the 30th min through the 120th min, noncontinuous load
- L_6 80 A from the 30th min through the 60th min, noncontinuous load
- L_7 80 A for the last minute, momentary load, actually a known sequence of: 40 A for the first 5 s, 80 A for the next 10 s, 30 A for the next 20 s
- L_8 100 A for 1 min, random load (Actually this consists of four 25 A momentary loads that can occur at any time within the duty cycle. Therefore, the assumption is that they all occur simultaneously.)

When the duty cycle includes constant power and constant current loads, it is usually more convenient to convert the constant power load values to constant current values for sizing calculations (see Annex B).

5. Cell selection

This clause summarizes some factors that should be considered in selecting a cell design for a particular application. Various cell designs have different charge, discharge, and aging characteristics. Refer to

⁴ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

IEEE Std 1184™-2006, Annex D of this document, and vendor literature for a discussion of cell characteristics.

The following factors should be considered in the selection of the cell:

- a) Physical characteristics, such as dimensions and weight of the cells, container material, intercell connectors, and terminals
- b) Planned life of the installation and expected service life of the cell
- c) Frequency and depth of discharge
- d) Ambient temperature (Note that sustained high ambient temperatures result in reduced battery life. See IEEE Std 484™-2002 and IEEE Std 1187™-2002.)
- e) Charging characteristics
- f) Maintenance requirements
- g) Cell orientation requirements
- h) Ventilation requirements
- i) Seismic characteristics
- j) Spill management

6. Determining battery size

Several basic factors govern the size (number of cells and rated capacity) of the battery: the maximum system voltage, the minimum system voltage, correction factors, and the duty cycle. Because a battery is usually composed of a number of identical cells connected in series, the voltage of the battery is the voltage of a cell multiplied by the number of cells in series. The ampere-hour capacity of a battery is the same as the ampere-hour capacity of a single cell, which depends upon the dimensions and number of plates.

If cells of sufficiently large capacity are not available, then two or more strings (equal numbers of series-connected cells) may be connected in parallel to obtain the necessary capacity. The capacity of such a battery is the sum of the capacities of the strings. Consult the manufacturer for any limitation on paralleling.

Operating conditions can change the available capacity of the battery; for example:

- The available capacity of the battery decreases as its temperature decreases.
- The available capacity decreases as the discharge rate increases.
- The minimum specified cell voltage at any time during the battery discharge cycle limits the available capacity of the battery.

6.1 Number of cells

The maximum and minimum allowable system voltage determines the number of cells in the battery. It has been common practice to use 12 cells, 24 cells, 60 cells, or 120 cells for nominal system voltages of 24 V, 48 V, 125 V, or 250 V, respectively. In some cases, it may be desirable to vary from this practice to match the battery to system voltage limitations more closely. It should be noted that the use of the widest possible voltage window, within the confines of individual load requirements, will result in the most economical battery. Furthermore, the use of the largest number of cells allows the lowest minimum cell voltage and, therefore, the smallest size cell for the duty cycle. The application of the following principles is illustrated in A.1 of Annex A.

6.1.1 Calculation of number of cells and minimum cell voltage

When the battery voltage is not allowed to exceed a given maximum system voltage, the number of cells will be limited by the cell voltage required for satisfactory charging or equalizing. This is as follows:

$$\frac{\text{maximum system voltage}}{\text{cell voltage required for}} = \text{number of cells}$$

Example: Assume 2.33 V/cell is required for equalize charging and that the maximum allowable system voltage is 140 V or 135 V. Then

$$\frac{140 \text{ V}}{2.33} = 60.09 \text{ cells (use 60 cells)}$$

$$\frac{135 \text{ V}}{2.33} = 57.94 \text{ cells (use 58 cells)}$$

If the number of cells is rounded off, the charging voltage should then be recalculated and verified for adequacy of operation.

The minimum battery voltage equals the minimum system voltage plus the cable voltage drop. Ensure all voltage drops are considered: For example, the use of unusually long cable connections within the battery or inter-cell connections resistances greater than the values on which the ratings are based may require an adjustment to the calculated minimum battery voltage. The minimum battery voltage is then used to calculate the allowable minimum cell voltage.

$$\frac{\text{minimum battery voltage}}{\text{number of cells}} = \text{minimum cell voltage}$$

In an application with a wide voltage window, particularly when long discharge times are required, the minimum cell voltage recommended by the manufacturer for a given discharge time may be a factor. If so, reduce the number of cells in the preceding calculation so that the minimum cell voltage per cell does not fall below the recommended value.

Example: Assume that the minimum battery voltage for the examples above is 105 V. Then

$$\frac{105 \text{ V}}{60 \text{ cells}} = 1.75 \text{ V/cell}$$

$$\frac{105 \text{ V}}{58 \text{ cells}} = 1.81 \text{ V/cell}$$

This minimum cell voltage is then used in the sizing calculation.

6.2 Additional considerations

Before proceeding to calculate the cell capacity required for a particular installation, the designer should consider factors that will influence cell size but that are not included in the general equation.

6.2.1 Temperature correction factor

The available capacity of a cell is affected by its operating temperature. The standard U.S. temperature for rating cell capacity is 25 °C (77 °F). If the lowest expected electrolyte temperature is below this standard temperature, select a cell large enough to have the required capacity available at the lowest expected temperature. If the lowest expected electrolyte temperature is above 25 °C (77 °F), it is a conservative practice to select a cell size to match the required capacity at the standard temperature and to recognize the resulting increase in available capacity as part of the overall design margin. Table 1 lists cell size correction factors for various temperatures for lead-acid cells with nominal 1.215 specific gravity. For unlisted temperatures within the range of Table 1, interpolate between adjacent values and round off to two decimal places.

Table 1 shows typical temperature factors for lead-acid nominal 1.215 specific gravity cells. Consult the manufacturer to see whether specific temperature factors are available for the battery being evaluated.

6.2.2 Design margin

It is prudent to provide a capacity margin to allow for unforeseen additions to the dc system and less-than-optimum operating conditions of the battery due to improper maintenance, recent discharge, or ambient temperatures lower than anticipated, or a combination of these factors. A method of providing this design margin is to add 10% to 15% to the cell size determined by calculations. If the various loads are expected to grow at different rates, it may be more accurate to apply the expected growth rate to each load for a given time and to develop a duty cycle from the results.

The cell size calculated for a specific application will seldom match a commercially available cell exactly, and it is normal procedure to select the next higher capacity cell. The additional capacity obtained can be considered part of the design margin.

Note that the “margins” described by 6.3.1.5 and 6.3.3 of IEEE Std 323™-2003 [B3] are to be applied during “qualification” and are not related to “design margin.”

Table 1—Cell size correction factors for temperature for vented and VRLA cells

Electrolyte temperature (°C)	Electrolyte temperature (°F)	Temperature correction factor	Electrolyte temperature (°C)	Electrolyte temperature (°F)	Temperature correction factor
4.4	40	1.300	26.1	79	0.987
7.2	45	1.250	26.7	80	0.980
10.0	50	1.190	27.2	81	0.976
12.8	55	1.150	27.8	82	0.972
15.6	60	1.110	28.3	83	0.968
18.3	65	1.080	28.9	84	0.964
18.9	66	1.072	29.4	85	0.960
19.4	67	1.064	30.0	86	0.956
20.0	68	1.056	30.6	87	0.952
20.6	69	1.048	31.1	88	0.948
21.1	70	1.040	31.6	89	0.944
21.7	71	1.034	32.2	90	0.940
22.2	72	1.029	35.0	95	0.930
22.8	73	1.023	37.8	100	0.910
23.4	74	1.017	40.6	105	0.890
23.9	75	1.011	43.3	110	0.880
24.5	76	1.006	46.1	115	0.870
25.0	77	1.000	48.9	120	0.860
25.6	78	0.994			
NOTE—This table is based on lead-acid nominal 1.215 specific gravity cells. For cells with other specific gravities, refer to the manufacturer.					

6.2.3 Aging factor

IEEE Std 450™-2002 and IEEE Std 1188™-2005 recommend that a battery be replaced when its actual capacity drops to 80% of its rated capacity. Therefore, to ensure that the battery is capable of meeting its design loads throughout its service life, the battery's rated capacity should be at least 125% (1.25 aging factor) of the load expected at the end of its service life. See Annex H for additional discussions regarding the aging factor.

Exceptions to this rule exist. For example, some manufacturers recommend that vented batteries with Planté, modified Planté, and round plate designs be replaced when their measured capacity drops below 100% of their rated capacity (1.00 aging factor). These designs maintain a fairly constant capacity throughout their life.

6.2.4 Initial capacity

Batteries may have less than rated capacity when delivered. Unless 100% capacity upon delivery is specified, initial capacity may be as low as 90% of rated capacity. This will rise to rated capacity in normal service after several charge–discharge cycles or after several years of float operation.

If the designer has provided a 1.25 aging factor, there is no need for the battery to have full rated capacity upon delivery because the capacity normally available from a new battery will be above the duty cycle requirement. When a 1.00 aging factor is used, the designer should ensure that the initial capacity upon

delivery is at least 100% or that there is sufficient margin in the sizing calculation to accommodate a lower initial capacity. Annex H provides some additional information regarding the aging factor.

Example: If the cells have 90% initial capacity and the margin is greater than 11%, then no additional compensation for initial capacity is required.

6.3 Cell size

This subclause describes and explains a proven method of calculating the cell capacity necessary for satisfactory performance on a given duty cycle. The application of this method to a specific duty cycle, using an optional preprinted worksheet to simplify the calculations, is demonstrated in A.2 of Annex A. Instructions for the proper use of the worksheet are given in 6.4.

6.3.1 Initial calculation

Equation (1) (see 6.3.2) requires the use of a capacity rating factor C_t (see 6.3.3) that is based on the discharge characteristics of a particular plate type and size. Thus, the initial calculation must be based on a trial selection of positive plate type and capacity. Depending on the results of this initial calculation, it may be desirable to repeat the calculation for other types or sizes of plates to obtain the optimum cell type and size for the particular application. In addition, it may be desirable to repeat the calculation to take into account any differences in performance per plate within a given series of cells. Use the capacity from the first calculation as a guide for selecting additional types to size.

6.3.2 Sizing methodology

The cell selected for a specific duty cycle must have enough capacity to carry the combined loads during the duty cycle. To determine the required cell size, it is necessary to calculate, from an analysis of each section of the duty cycle (see Figure 2), the maximum capacity required by the combined load demands (current versus time) of the various sections. The first section analyzed is the first period of the duty cycle. Using the capacity rating factor (see 6.3.3) for the given cell type, a cell size is calculated that will supply the required current for the duration of the first period. For the second section, the capacity is calculated assuming that the current A_1 , required for the first period, continued through the second period; this capacity is then adjusted for the change in current ($A_2 - A_1$) during the second period. In the same manner, the capacity is calculated for each subsequent section of the duty cycle. This iterative process is continued until all sections of the duty cycle have been considered. The calculation of the capacity F_s required by each section S , where S can be any integer from 1 to N , is expressed mathematically in Equation (1). F_s will be expressed as watt-hours, ampere-hours, or number of positive plates, depending upon which C_t is used (see 6.3.3).

$$F_s = \sum_{P=1}^{P=S} \frac{A_P - A_{(P-1)}}{C_t} \quad (1)$$

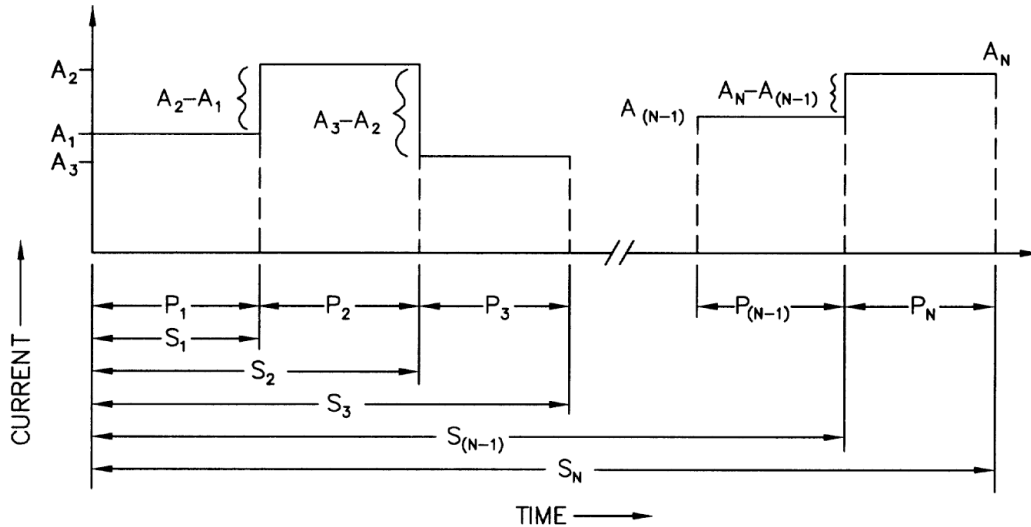


Figure 2—Generalized duty cycle

The maximum capacity (max F_S) calculated determines the uncorrected cell size that can be expressed by the general Equation (2):

$$F = \max_{S=1}^{S=N} F_S = \max_{S=1}^{S=N} \sum_{P=1}^{P=S} \frac{A_P - A_{(P-1)}}{C_t} \quad (2)$$

where

- F is the cell size (uncorrected for temperature, aging, and design margin)
- S is the section of the duty cycle being analyzed. [Section S contains the first S periods of the duty cycle (e.g., section S_5 contains periods S_1 through S_5). See Figure 2 for a graphical representation of “section.”]
- N is the number of periods in the duty cycle
- P is the period being analyzed
- A_P are the amperes required for period P
- t is the time in minutes from the beginning of period P through the end of Section S
- C_t is the capacity rating factor (see 6.3.3) for a given cell type, at the t minute discharge rate, at 25 °C (77 °F), to a definite minimum cell voltage
- F_S is the capacity required by each section

If the current for period $P + 1$ is greater than the current for period P , then section $S = P + 1$ will require a larger cell than section $S = P$. Consequently, the calculations for section $S = P$ can be omitted.

6.3.3 Capacity rating factor

There are two terms for expressing the capacity rating factor C_t of a given cell type in cell sizing calculations. One term R_t is the number of amperes that each positive plate can supply for t minutes, at 25 °C (77 °F), to a definite minimum cell voltage. Therefore $C_t = R_t$, and

$$F = \max_{S=1}^{S=N} F_S = \max_{S=1}^{S=N} \sum_{P=1}^{P=S} \frac{A_P - A_{P-1}}{R_t} \quad (3)$$