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1. Introduction

Not applicable.

2. Supporting clauses

2.1 Scope

This standard identifies the various influencing factors and procedure that needs to be followed when sizing a DC system consisting of a battery and battery charger for substation applications.

2.1.1 Purpose

The purpose of the standard is to identify the various influencing factors and procedure that needs to be followed when sizing a DC system consisting of a battery and battery charger for substation applications.

2.1.2 Applicability

This document shall apply throughout Eskom Holdings Limited Divisions.

2.2 Normative/informative references

Parties using this document shall apply the most recent edition of the documents listed in the following paragraphs.

2.2.1 Normative

[1] ISO 9001 Quality Management Systems.

[2] IEEE Std 946™-2004: IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations

[3] 240-118870219, Standby power systems topology and autonomy for Eskom sites

2.2.2 Informative

[4] Alcad, Technical manuals for Nickel Cadmium Cells

[5] Cell Services CD, Ver 2.0, Oct. 2000: Eskom National Contract

[6] IEEE Std 485-2010: IEEE recommended practice for sizing lead-acid batteries for stationary applications.

[7] IEEE Std 1115-2014: IEEE recommended practice for sizing nickel-cadmium batteries for stationary applications.

2.3 Definitions

2.3.1 General

Definition	Description
Available capacity	The capacity for a given discharge time and end-of-discharge voltage that can be withdrawn from a cell under specified operating conditions.
Battery duty cycle	The different loads a battery is expected to supply for specified time periods. This is sometimes also referred to as the load profile.

Definition	Description
Float operation	Normal operation where the battery charger keeps the battery in a fully charged state by supplying a small trickle charge to overcome the self discharge of the battery due to its internal resistance.
Period	An interval of time in the battery duty cycle over which the load is assumed to be constant for cell sizing calculations.
Rated capacity (lead acid)	The capacity assigned to a lead acid cell by its manufacturer for a given discharge rate (constant discharge current over given discharge time), at a specified electrolyte temperature and specific gravity, to a given end-of-discharge voltage.
Rated capacity (nickel-cadmium)	The capacity assigned to a nickel-cadmium cell by its manufacturer for a given discharge rate (constant discharge current over given discharge time), at a specified electrolyte temperature, to a given end-of-discharge voltage.
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” batteries.

2.3.2 Disclosure classification

Controlled disclosure: controlled disclosure to external parties (either enforced by law, or discretionary).

2.4 Abbreviations

Abbreviation	Description
AC	Alternating current
Ah	Ampere hour
C10	Rated battery capacity at the 10 hour discharge rate
C5	Rated battery capacity at the 5 hour discharge rate.
DC	Direct Current
RTU	Remote terminal unit
UPS	Uninterruptible Power Supply
VRLA	Valve regulated lead acid

2.5 Roles and responsibilities

Not applicable.

2.6 Process for monitoring

Not applicable.

2.7 Related/supporting documents

Not applicable.

3. Requirements

3.1 General

The first starting point in determining battery size is to determine what loads are required to be powered from the battery when the following conditions occur:

a) The load on the DC system exceeds the maximum output of the battery charger;

b) The battery charger output is interrupted;

c) AC power or mains supply is lost.

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

3.2 Load classification

The different loads that are supplied from the battery can be classified depending on the period that they occupy within the duty cycle. Loads can be classified as been continuous, non-continuous and momentary.

3.2.1 Continuous loads

3.2.1.1 Continuous loads are energized throughout the duty cycle.

3.2.1.2 These loads are normally collectively referred to as the DC drain or standing load of the substation.

3.2.1.3 Typical continuous loads within the substation are protection schemes, RTU's, telecommunications equipment and the battery charger alarm cards.

3.2.2 Non-continuous loads

3.2.2.1 Non-continuous loads are energized only during a portion of the duty cycle.

3.2.2.2 These loads may come on at any time within the duty cycle and may be on for a set length of time. They may also be removed automatically or by operator action, or continue to the end of the duty cycle.

3.2.2.3 Typical non-continuous loads within the substation are emergency lights and spring rewind motors.

3.2.3 Momentary loads

3.2.3.1 Momentary loads can occur one or more times during the duty cycle, but their duration at any instance does not exceed 1 min.

3.2.3.2 Momentary loads may sometimes exist for only a fraction of a second, in which case it will be considered to last a full minute when including it on the duty cycle diagram.

3.2.3.3 When several momentary loads occur within the same 1 min period and a discrete sequence cannot be established, the load for the 1 min period shall then 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 shall be assumed to be the maximum load at any instant. The above approach will result in a conservatively sized battery.

3.2.4 Other considerations

3.2.4.1 In addition to the above, loads may also be classified as been constant power, constant resistance or constant current.

3.2.4.2 When the load is energized from the battery, the battery voltage decreases at a rate which is determined by the battery internal resistance and the load applied to the battery.

3.2.4.3 For constant power loads, the current increases as the voltage decrease. Inverters (DC-AC) and converters (DC-DC) are typical constant power devices, which are internally regulated to maintain a constant output voltage as the input voltage decrease, resulting in an increase in input current. For loads that are located far from the battery, the voltage drop along the connecting cable must also be taken into consideration.

3.2.4.4 A conservative method of converting watts to amperes is to assume a constant current for the entire load duration as being the maximum current that the load will draw at the minimum input voltage level (see equations 1 and 2).

$$I_{\max} = \frac{P}{V_{\min load}} \qquad (1)$$

$$V_{\min load} = V_{\min batt} - \Delta V_{cable} \qquad (2)$$

where

I_{max} is the discharge current at the end of the discharge period [A];

P is the discharge load [W];

$V_{min\ load}$ [V];

$V_{min\ batt}$ is the minimum battery voltage [V];

ΔV_{cable} is the cable voltage drop.

3.2.4.5 In the case of constant resistance loads, the current decreases with decreasing voltage. DC motor starting, DC lights and contactors are usually constant resistance loads. A constant resistance load may be conservatively estimated as a constant current load as follows:

$$I_{\max} = \frac{V_{OC}}{R_{AVG}} \qquad (3)$$

or

$$I_{\max} = \frac{W_R}{V_{OC}} \qquad (4)$$

where

V_{OC} is the battery open circuit voltage [V];

R_{AVG} is the average resistance [Ω];

W_R is the rated power value [W].

3.2.4.6 For constant current loads, the current is approximately constant as the voltage decreases. Running DC motors can be approximated as constant current loads.

3.3 Selecting a suitable cell type

This section summarizes some important factors that must be considered in selecting a cell type for a particular application. Various cell designs have different charge, discharge and aging characteristics. Vendor literature may be consulted for a discussion on offered cell characteristics.

The three commonly used standby applications are as follows:

a) Long duration: In these applications the standby loads are generally small and typical standby periods range from 3h to 8h+. Normally the discharge current is relatively low in comparison with the total stored energy, and the discharges are generally infrequent. Long duration batteries are characterized by thicker plates. Flat plate lead acid batteries are normally applied in these applications. In the case of nickel cadmium batteries, low performance or L-type nickel cadmium batteries are employed in these applications. The requirements of the substation environment can be classified as a long duration application.

b) Medium duration: In these applications the loads are generally of a “mixed” type (mixture of high and low discharge rates) with standby periods ranging from 1h to 3h. These applications can have frequent and infrequent discharges. Flat -, planté – or tubular plate lead acid batteries may be used in these applications. In the case of nickel cadmium batteries, medium performance or M-type nickel cadmium batteries are employed in these applications. Control and switchgear equipment are typical applications with medium standby duration requirements.

c) Short duration: These applications are recognized by relatively high discharge currents over a short period of time of 1h or less. Batteries used in these applications have thinner plates in order to expose a greater surface area for a high energy release rate. Planté – and tubular plate lead acid batteries are more suitable for these applications. In the case of nickel cadmium batteries, high performance or H-type nickel cadmium batteries are employed. Typical application examples are UPS and starting applications.

d) Below is a list of factors that should be considered when selecting a battery type:

   1) Physical characteristics, e.g. weight, dimensions, terminals, etc.
   2) Planned installation life and expected cell life;
   3) Frequency and depth of discharge;
   4) Environmental conditions like ambient temperature variations, corrosive atmosphere, pollution, etc.;
   5) Charging characteristics;
   6) Maintenance requirements;
   7) Ventilation requirements;
   8) Seismic requirements i.e. shock and vibration;
   9) Cell orientation requirements.

3.4 Determining the battery size

3.4.1 General

The size of the battery refers to the number of cells, connected in series or parallel, and the rated capacity of the cells which are determined by the maximum system voltage, the minimum system voltage, correction factors and the required battery duty cycle. A battery is a series connection of cells (sometimes also referred to as battery string) and therefore the battery voltage is the individual cell voltage multiplied by the number of cells. The total ampere-hour capacity of the battery consisting of one series connected string of cells is the same as the ampere-hour capacity of a single cell.

If cells of sufficiently large capacity are not available, then two or more battery strings are connected in parallel to obtain the required capacity. In such a case the total ampere-hour capacity of the resultant battery is the sum of the ampere-hour capacities of the individual battery strings. Paralleling battery strings is not recommended and the battery manufacturer should be consulted on limitations of maximum number of battery strings that may be paralleled.

In the following sections the application information required to size a battery successfully for a particular installation is discussed.

3.4.2 Load input voltage window

The load input voltage window determines the minimum and maximum voltage that may be applied to the load input terminals without damaging the load. This is the voltage range over which the battery must support the load for the entire duty cycle.

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 size. 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 maximum load input voltage normally determines the maximum no. of cells used for the battery. The number of cells is calculated as follows:

$$N_{cells} = \frac{V_{\max\ load}}{V_{cell}} \quad \text{(5)}$$

where

N_{cells} is the number of cells;

$V_{max\ load}$ is the maximum load input voltage [V];

V_{cell} is the maximum cell voltage to satisfactory charge the cell [V].

In order to charge the battery at a voltage that is higher than the maximum load input voltage, a load voltage regulator (dropping diodes) may be used. This regulator normally consists of diodes that are connected in such a way that will provide the most economical amount of voltage dropping stages to keep the load input voltage within the specified (safe operating) range.

The number of cells is used to determine the minimum cell voltage by using the following formula:

$$V_{\min} = \frac{V_{\min\ batt}}{N_{cells}} \quad \text{(6)}$$

where

V_{min} is the minimum cell voltage [V];

$V_{min\ batt}$ is the minimum battery voltage [V];

N_{cells} is the number of cells.

NOTE: The minimum battery voltage = Minimum load input voltage + cable voltage drop

The specified load input voltage window for equipment used in Distribution substations is $V_{nominal} \pm 20\%$. Table 1 shows the implications on voltages used and the resulting number of cells.

Table 1: Voltage ranges and typical no. of cells used in Distribution

V_{NOM}	V_{MIN}	V_{MAX}	Lead acid batteries			Nickel cadmium cells		
			No. of cells	V_{MIN} / cell	V_{MAX} / cell	No. of cells	V_{MIN} / cell	V_{MAX} / cell
12	9.6	14.4	6	1.60	2.40	10	0.96	1.44
24	19.2	28.8	12	1.60	2.40	20	0.96	1.44
36	28.8	43.2	18	1.60	2.40	30	0.96	1.44
50	38.4	57.6	24	1.60	2.40	38	1.01	1.52
110	88	132	52	1.69	2.54	85	1.04	1.55
220	176	264	104	1.69	2.54	170	1.04	1.55

3.4.3 Duty cycle diagram

The duty cycle diagram is a visual aid for analysing the battery duty cycle and is sometimes also referred to as the load profile. In order to prepare the duty cycle diagram, a list indicating all expected loads and their anticipated inception and shutdown times is required. Loads shown on the duty cycle diagram may be grouped into defined loads and random loads.

Defined loads are loads whose inception and shutdown times are known and they are plotted on the duty cycle diagram as they would occur. In the case where the inception time is known but the shutdown time is unknown or indefinite, it is assumed that the load will continue through the remainder of the duty cycle.

Random loads can occur at random and therefore they are shown at the most critical time of the duty cycle in order to cover for the worst case load on the battery. To determine the most critical time, the battery should be sized without the random load(s) and the control section of the duty cycle must be identified. Then the random load(s) should be superimposed on the end of the controlling section.

3.4.4 Cell performance data

Cell performance data indicates the amount of constant current that the cell can deliver over a predetermined period, at a specified temperature, to a specified final voltage. The final voltage is also referred to the end-of-discharge voltage. This data is normally in tabular form or in graphical format.

For lead acid cells, two terms are used to express the capacity rating factor of a given cell type. The one term, $\mathbf{R_t}$, is the number of amperes that each positive plate can supply for **t** minutes, at a specified temperature, to a specified minimum cell voltage. The other term, $\mathbf{K_t}$, is the ratio of rated ampere-hour capacity to the amperes that the cell can or must supply over a period to a given minimum cell voltage.

For nickel cadmium batteries, the $\mathbf{K_t}$ term is used in sizing calculations. For stationary applications, as used in substations, data based on prolonged float charging should be used in calculations. To calculate the $\mathbf{K_t}$ factor from discharge data for prolonged float charging, the rated capacity of the cell is divided by the discharge current for the specified time and end-of-discharge voltage.

$$K_t = \frac{C_{rated}}{I_{disc}} \qquad (7)$$

where

C_{rated} is the rated capacity [Ah];

I_{disc} is the discharge current [A].

The following formula is used for discharge data derived from constant current charging:

$$K_t = \frac{C_{rated}}{(I_{disc} \times F_{float})} \qquad (8)$$

where

C_{rated} is the rated capacity [Ah];

I_{disc} is the discharge current [A];

F_{float} is the float correction factor.

It is important to note that $\mathbf{K_t}$ factors differ for different cell types.

To calculate a $\mathbf{K_t}$ factor for a time not indicated in the discharge table, interpolation can be used. Interpolation must only be performed on the $\mathbf{K_t}$ factors, as interpolation of current values will yield incorrect results. The formula for interpolation is as follows:

$$K_t = K_{t2} - \frac{(K_{t2} - K_{t1}) \times (t_2 - t)}{(t_2 - t_1)} \qquad (9)$$

The latest $\mathbf{K_t}$ factors can be found on the DC & Auxiliary Supplies SharePoint site.

3.4.5 Temperature derating factors

The operating temperature of a cell affects its available capacity. The standard temperatures for stating cell capacity is 25°C and 20°C for lead acid – and nickel cadmium batteries respectively. If the lowest expected electrolyte temperature is below standard, it is necessary to select a cell large enough to have the required capacity available at the lowest expected temperature. For electrolyte temperatures higher than the standard temperature, there is a small increase in available capacity. Although the capacity of a cell slightly increases for electrolyte temperatures higher than the standard temperature, it is normal practice to select a cell size to match the required capacity at the standard temperature. The resulting increase in available capacity as a result of the higher electrolyte temperature is regarded as being part of the design margin. The temperature derating factor is also influenced by the discharge rate.

The formula for interpolation on the temperature factor graph is as follows:

$$T_F = T_{F2} - \frac{(T_{F2} - T_{F1}) \times (T_2 - T)}{(T_2 - T_1)} \qquad (10)$$

Table 2 shows the temperature derating factors for the Vantage and L-range nickel cadmium cells.

Table 2: Temperature derating factors for 5h discharge rate

Temperature [°C]	Vantage Cells	L-range Cells
0	1.08	1.1
5	1.05	1.05
10	1.03	1.03
15	1.01	1
≥ 20	1.00	1

3.4.6 Design margin

To allow for unforeseen circumstances, like growth in load, less-than-optimum operating conditions, etc. a design margin is included in the sizing calculations. A method to provide for the design margin is to add a certain percentage to the calculated cell size. The recharge efficiency of the battery may also be included in the design margin, because in order to ensure that a battery are recharged within a specified recharge time you need to ensure that the selected battery type complies, otherwise you need to make provision in the design margin.

The calculated cell size is seldom equal to commercially (of-the-shelf) available cell capacities. In such cases the next higher capacity cell is selected. The additional capacity obtained can be considered as part of the design margin.

3.4.7 Ageing factor

The capacities of both lead acid and nickel cadmium batteries decrease gradually over the life of the battery due to various factors, including operating temperature, electrolyte specific gravity, depth and frequency of discharge, amongst others.

An ageing factor of 1.25 is used, meaning that the battery is sized to carry the loads until its capacity has reached 80% of its rated capacity.

3.4.8 Calculated capacities

The uncorrected capacity (C_{UC}) can be calculated by using the following formula:

$$C_{UC} = (I_{SD} \times K_{ta}) + (I_{EL} \times K_{tb}) + (I_{SR} \times K_{tc}) \quad (11)$$

where

C_{UC} is the uncorrected capacity [Ah]

I_{SD} is the standing drain current [A]

I_{EL} is the emergency lights current [A]

I_{SR} is the spring rewind current [A]

K_{ta} is the K_t factor for the standing drain duration / total standby time [h]

K_{tb} is the K_t factor for the emergency lights standby time [h]

K_{tc} is the K_t factor for the spring rewind standby time [h]

The corrected capacity is calculated by taking the design margin, effects of temperature and aging into consideration. The following formula can be used to calculate the corrected capacity (C_C):

$$C_C = C_{UC} \times T_F \times D_F \times A_F \quad (12)$$

where

C_C is the corrected capacity [Ah]

C_{UC} is the uncorrected capacity [Ah]

T_F is the temperature factor

D_F is the design margin

A_F is the ageing factor

3.5 Battery sizing examples

In this section the battery sizing procedure will be applied to two applications. The first application will involve the use of nickel cadmium batteries and the other the use of lead acid batteries.

3.5.1 Nickel cadmium battery application design

In this example, the substation is equipped with a supervisory and a telecommunication system. The substation has four outgoing feeders with a breaker on each. Each 3 phase breaker has a single spring rewind motor. The substation is located within a radius of 200 km from the nearest DC TSS and accordance with the requirements of 240-118870219, Standby power systems topology and autonomy for Eskom sites, a standby time of 12 hrs is required. The block diagram is shown in Figure 1.

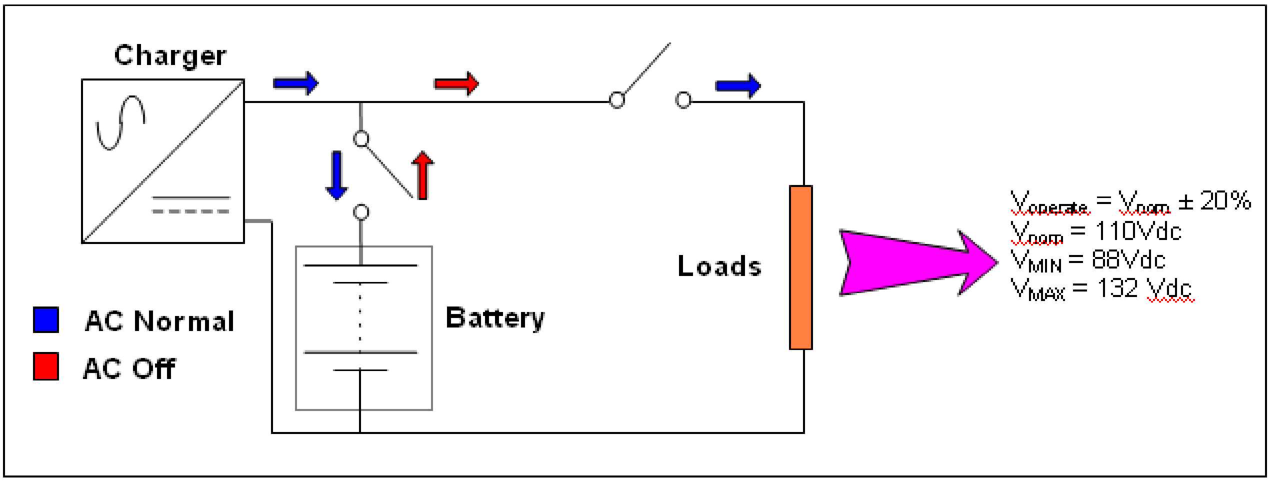

Figure 1: Diagram for the DC system

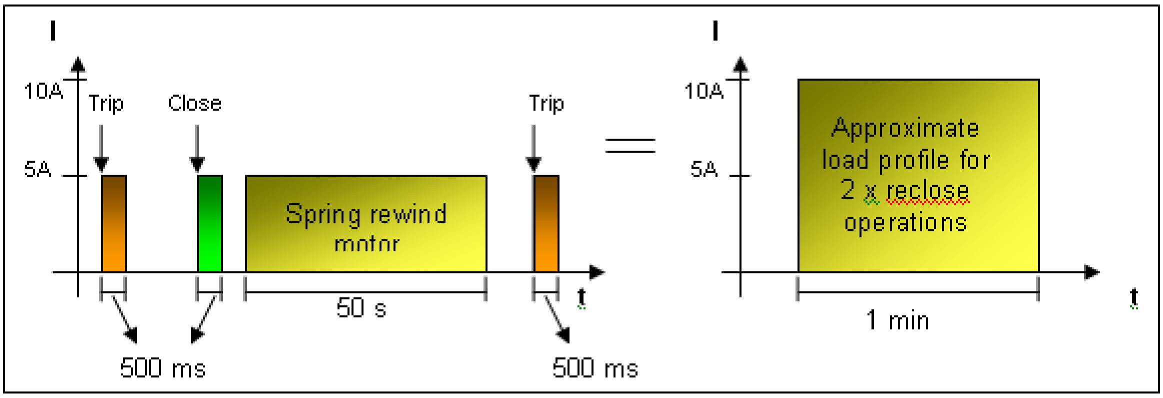

Figure 2: Load profile for a reclose operation

In order to approximate the load profile due to breaker operation, the auto-reclose protection philosophy and spring rewind motors ratings are required. The reclosing action load profile was approximated by using the requirements for 50% of the number of spring rewind motors.

It is assumed that both spring rewind motors are activated at the same time, hence the higher current of 10A (2 x 5A) as shown in Figure 2. The different load details are shown in Table 3 with the load profile indicated in Figure 3.

Table 3: Different loads at the substation

Load	Current [A]	Duration [min]	Load type
Protection schemes	1	720	Continuous
Supervisory equipment	0.6	720	Continuous
Telecomms equipment	0.2	720	Continuous
Spring rewind motors	10	1	Random
Emergency lights	0.5	240	Random
Other (Battery charger alarm card)	0.3	720	Continuous
I_{TOTAL}(Continuous) = 2.1 A for 720 min			

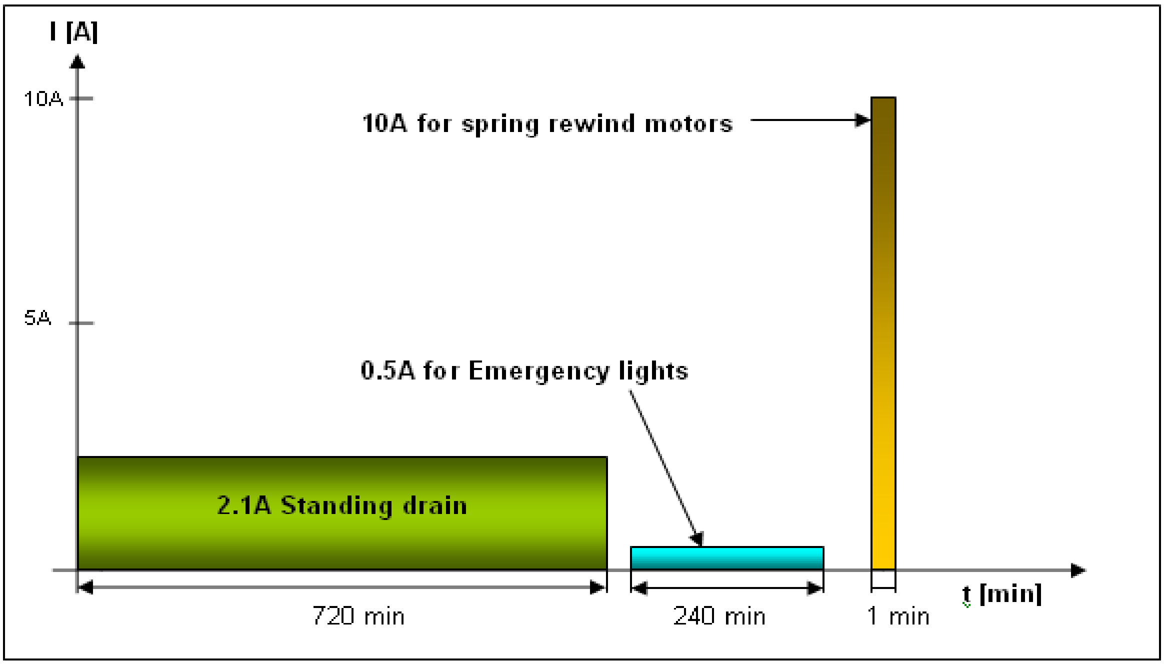

Figure 3: Load profile for the substation loads

3.5.1.1 The nominal DC voltage is 110V which means that the selected number of nickel cadmium cells is 85 as indicated in 1. Use the discharge data where the end-of-discharge voltage is 1.00V per cell.

3.5.1.2 The Kt factors are calculated using equations 6 and 8 and the discharge performance data to an end-of-discharge voltage is 1.00V per cell. This data is displayed in Table 4.

Table 4: Kt values for Vantage and L-range nickel cadmium cells to 1.00V/cell

Time		Time [min]	K_t (VN)	K_t (L range)
Seconds	1	0.02	0.31	0.54
	10	0.17	0.38	0.65
	30	0.50	0.45	0.71
	60	1	0.49	0.79
Minutes	5	5	0.66	0.95
	10	10	0.73	1.07
	30	30	1.00	1.33
	45	45	1.16	1.48
	60	60	1.31	1.64
	90	90	1.70	1.97

Time		Time [min]	K_t (VN)	K_t (L range)
Hours	2	120	2.11	2.32
	3	180	3.08	3.14
	4	240	4	4.07
	5	300	5	5.00
	8	480	8	7.86
	10	600	10	10
	11	660	11	11
	12	720	12	12
	24	1440	24	24
Days	2	2880	48	48
	4	5760	96	96
	6	8640	144	144
	8	11520	192	192
	10	14400	240	240
	12	17280	288	288

3.5.1.3 The uncorrected capacity is calculated per cycle by using equation (11):

The uncorrected capacities for the Vantage and L-range cells are respectively shown in Table 5 and Table 6.

Table 5: Uncorrected capacity when using Vantage cells

Load	Current [A] (1)	Duration [min]	K_t (2)	Uncorrected Capacity [Ah] (1) x (2)
I_{TOTAL}(Continuous)	2.1	720	12	25.2
Spring rewind motors	10	1	0.49	4.9
Emergency lights	0.5	240	4	2
TOTAL				32.1

Table 6: Uncorrected capacity when using L-range cells

Load	Current [A] (1)	Duration [min]	K_t (2)	Uncorrected Capacity [Ah] (1) x (2)
I_{TOTAL}(Continuous)	2.1	720	12	25.20
Spring rewind motors	10	1	0.79	7.87
Emergency lights	0.5	240	4.07	2.04
TOTAL				35.11

3.5.1.4 To calculate the corrected capacity, the design margin, temperature derating factor and aging factor need to be taken into account.

Let's assume for this example that the lowest expected temperature is 10°C. For substation applications, we will use the temperature derating factor applicable for the 5 hour discharge rate. Therefore the selected temperature derating factors (from 2) for Vantage and L-range cells are 3%.

By using equation (12), the corrected capacity can be calculated as follows:

Using Vantage cells:

$$\begin{aligned} C_C &= C_{UC} \times T_F \times D_F \times A_F \\ &= 32{,}1 \times 1{,}03 \times 1{,}20 \times 1{,}25 \\ &= 49{,}59\ Ah \end{aligned}$$

Therefore use **VN71** cells.

Using L-range cells:

$$\begin{aligned} C_C &= C_{UC} \times T_F \times D_F \times A_F \\ &= 35{,}11 \times 1{,}03 \times 1{,}20 \times 1{,}25 \\ &= 54{,}24\ Ah \end{aligned}$$

Therefore use **L60P** cells.

3.5.2 Lead acid battery application design

The same substation details as for the previous example in 3.5.1 has been used with the load profile details as shown in Table 7 and displayed in graphical format in Figure 4.

Table 7: Different loads at the substation

Load	Current [A]	Duration [min]	Load type
Protection schemes	5.0	720	Continuous
Supervisory equipment	1.0	720	Continuous
Telecomms equipment	2.0	720	Continuous
Spring rewind motors	10	5	Random
Emergency lights	0.5	240	Random
Other (Battery charger alarm card)	0.3	720	Continuous
I_{TOTAL}(Continuous) = 8.3A for 720 min			

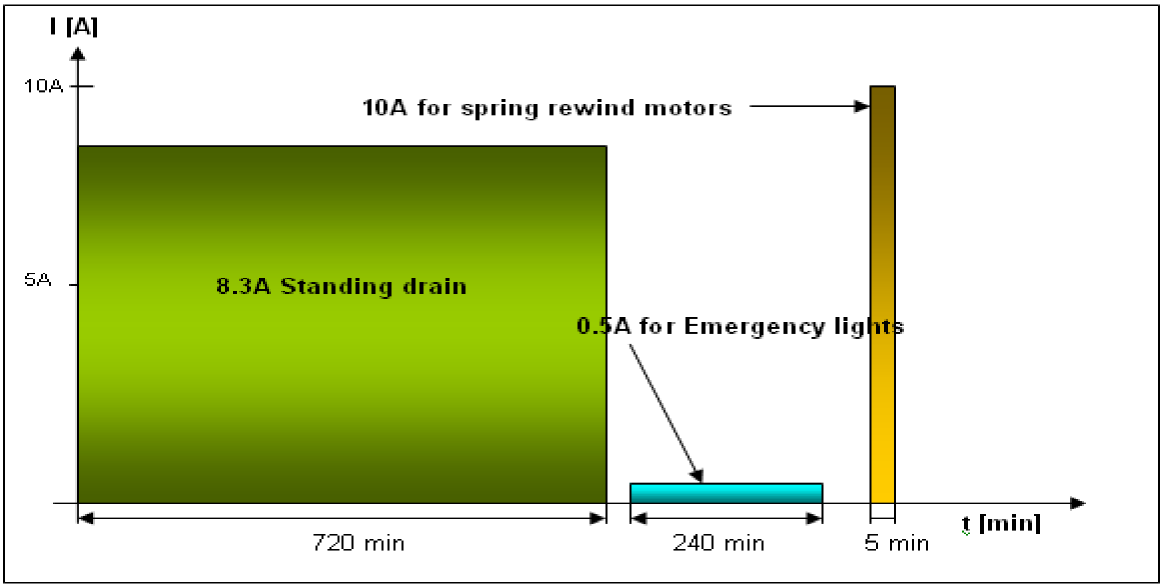

Figure 4: Load profile for the substation loads

3.5.2.1 The nominal DC voltage is 110V which means that the selected number of lead acid cells is 52 as indicated in **Table 1**. Use the discharge data where the end-of-discharge voltage is 1.75V per cell for the FCP range of cells.

3.5.2.2 The Kt and Rt factors are calculated from the discharge performance data for FCP lead acid cells to an end-of-discharge voltage of 1.75V per cell. This data is displayed in Table 8.

Table 8: Kt and Rt values for the FCP range of lead acid cells to 1.75V/cell

Time				Kt	Rt
Minutes	5	Minutes	5	0.91	35.30
	10		10	1.01	31.60
	15		15	1.16	27.50
	20		20	1.29	24.90
	30		30	1.47	21.75
	45		45	1.69	18.90
	60		60	2.00	16.00
Hours	2		120	3.17	10.10
	3		180	4.18	7.65
	5		300	5.98	5.35
	6		360	6.81	4.70
	8		480	8.53	3.75
	10		600	10.00	3.20
	12		720	12.00	2.67
	14		840	14.00	2.29
	18		1080	18.00	1.78
	24		1440	24.00	1.33
Days	2		2880	48.00	0.67
	5		7200	120.00	0.27
	10		14400	240.00	0.13

3.5.2.3 The uncorrected capacity is calculated per cycle by using equation (11):

Interpolation of $\mathbf{K_t}$ factors, given in Table 8, gives us the $\mathbf{K_t}$ factor for 240 min:

$$
\begin{aligned}
K_t &= K_{t2} - \frac{(K_{t2} - K_{t1}) \times (t_2 - t)}{(t_2 - t_1)} \\
&= 5{,}98 - \frac{(5{,}98 - 4.18) \times (300 - 240)}{(300 - 180)} \\
&= 5{,}08
\end{aligned}
$$

The uncorrected capacity for the FCP cells is respectively shown in Table 9.

Table 9: Uncorrected capacity for FCP cells when using Kt factors

Load	**Current [A] (1)**	**Duration [min]**	**K_t (2)**	**Uncorrected Capacity [Ah] (1) x (2)**
I_{TOTAL}(Continuous)	8.3	720	12	99.6
Spring rewind motors	10	5	0.91	9.1
Emergency lights	0.5	240	5.08	2.54
TOTAL				111.24

From the calculated $\mathbf{K_t}$, $\mathbf{R_t}$ can be calculated by using the following formula:

$$
\begin{aligned}
R_t &= \frac{C_t}{K_t} \\
&= \frac{32}{5{,}08} \\
&= 6{,}30
\end{aligned}
$$

where:

C_t is the rated capacity per positive plate = 32 Ah for FCP range of cells. The required number of positive plates is shown in Table 10.

Table 10: Number of positive plates required when using FCP cells

Load	**Current [A] (1)**	**Duration [min]**	**R_t [A/+plate] (2)**	**Uncorrected no. of + plates (1) / (2)**
I_{TOTAL}(Continuous)	8.3	720	2.67	3.11
Spring rewind motors	10	5	35.30	0.28
Emergency lights	0.5	240	6.30	0.08
TOTAL				3.47

3.5.2.4 To calculate the corrected capacity, the design margin, temperature derating factor and aging factor need to be taken into account.

Let's assume for this example that the lowest expected temperature is 10°C. For substation applications, we will use the temperature derating factors as per Annex E for the different discharge rates. The effect of temperature correction is indicated in Table 11 and Table 12.

Table 11: Temperature corrected capacity for FCP cells when using Kt factors

Load	Uncorrected Capacities from Table 6 (1)	Temp. Derating Factor (2)	Temp. Multiplying Factor T_F (3) = [1-(2)]+1	Temperature corrected Capacity [Ah] (1) x (3)
I_{TOTAL}(Continuous)	99.6	0.90	1.10	109.56
Spring rewind motors	9.10	0.88	1.12	10.19
Emergency lights	2.54	0.88	1.12	2.84
Temperature corrected total capacity				122.59

Table 12: Required no. of positive plates after temperature correction

Load	Uncorrected no. of + plates from Table 7 (1)	Temp. Derating Factor (2)	Temp. Multiplying Factor T_F (3) = [1-(2)]+1	No. of + plates (1) x (3)
I_{TOTAL}(Continuous)	3.11	0.90	1.10	3.42
Spring rewind motors	0.28	0.88	1.12	0.31
Emergency lights	0.08	0.88	1.12	0.10
TOTAL				3.83

By using equation 2), the corrected capacity can be calculated as follows:

Please note: T_F is unity in the equation as it has been already been compensated for above.

Using FCP cells:

$$\begin{aligned} C_C &= C_{UC} \times T_F \times D_F \times A_F \\ &= 122.59 \times 1{,}0 \times 1{,}20 \times 1{,}25 \\ &= 183{,}89\ Ah \end{aligned}$$

Therefore use **FCP13** cells with a capacity of 192Ah.

The required number of positive plates the following equation may be used:

Please note: T_F is unity in the equation as it has been already been compensated for above.

Using FCP cells:

$$\begin{aligned} P_n &= TP_n \times T_F \times D_F \times A_F \\ &= 3.83 \times 1{,}0 \times 1{,}20 \times 1{,}25 \\ &= 5{,}75 \end{aligned}$$

where:

P_n is the required number of positive plates after correction for design margin and ageing.

TP_n is the required number of positive plates after temperature correction.

Therefore 6 positive plates is required, which implies using a FCP cell with 13 ([6x2]+1) plates in total. This relates back to the **FCP13** cell as calculated previously.

3.6 Battery charger sizing

The current rating of the battery chargers shall be subject to the connected load and the standby capacity required for the site.

In the following sections two methods of battery charger sizing will be evaluated and the recommended method indicated.

3.6.1 Traditional method

The traditional method is relatively simple and easy to use. The method only takes the standing drain (continuous loading), battery rated capacity and the required recharge time into consideration as indicated in equation (13) below. Other important parameters like the non-continuous loads and the battery's recharge efficiency are not taken into consideration. Due to the fact that the corrected battery capacity is not exactly equal to the available battery capacities, the next highest available battery capacity is selected. One may thus argue that this extra capacity over and above the corrected capacity is making up for the recharge efficiency, but this cannot be bargained on since each substation will have a different amount of extra capacity. In some instances this extra capacity will be very small.

$$I_{ch} = I_{LC} + \left(\frac{0.8 \times C_{rt}}{T} \right) \qquad (13)$$

I_{ch} : Battery charger rated current.

I_{LC} : DC standing (continuous) load current, including future load growth.

0.8 : Fraction of rated capacity to which the batteries should be recharged within the period, T.

C_{rt} : Rated capacity of battery in Ah.

T : Time in which the battery must be recharged, to 80% of C_{rt}. This period is taken as 10h.

3.6.2 IEEE method

The method that is recommended to be used is the IEEE method in accordance with IEEE Std 946™-2004: *IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations*. In this method the non-continuous load and the battery's recharge efficiency (battery losses) are taken into consideration. The calculated corrected capacity required by the substation and not the selected rated capacity, as in the traditional method, is used as a determining factor in calculating the battery charger rating. This implies that the battery will be recharged to as close as possible to the calculated corrected capacity which is required to meet the substation load profile. The amount of charge delivered to the battery depends on the electrolyte temperature, battery state-of-charge as well as the battery charger voltage and the available current to recharge the battery. By including equation (15) as part of the decision making process, it is ensured that the battery charger will be able to provide current to non-continuous loads without discharging the battery under normal conditions.

$$I_1 = I_{LC} + \left(\frac{1.1 \times Q}{T} \right) \qquad (14)$$

$$I_2 = I_{LC} + I_{LN} \qquad (15)$$

I_1 : The minimum required battery charger output current

I_2 : The minimum battery charger output current that will supply the maximum operational load

I_{LC} : DC load current, including future load growth

I_{LC} : The largest combination of non-continuous load that is most likely to be connected to the bus at the same time.

A constant to compensate for battery losses, this is 1 divided by recharge efficiency. The different types of batteries have different recharge efficiencies which can be obtained from the manufacturer's data.

Q : The ampere-hours removed from the battery during the substation duty cycle. This means you use the capacity used during the discharge and not the rated capacity of the battery.

T : Time period in which the battery must be recharged. This time period is selected as 10h.

I_3 : The recommended battery charger output current, i.e. the larger one of I_1 and I_2.

4. Authorization

This document has been seen and accepted by:

Name and surname	Designation
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5. Revisions

Date	Rev	Compiler	Remarks
March 2020	2	P Saayman	Updated DSP_34-1299: Rev 0, Specification for the minimum reliability and capacity requirements of essential DC power supplies for various equipment at Distribution sites, with the latest reference document. Updated the IEEE standard references. 3.4.4 Added "The latest $\mathbf{K_t}$ factors can be found on the DC & Auxiliary Supplies SharePoint site."
March 2015	1	P Saayman	The contents of DST_34-478, Sizing of DC Systems for Substation Applications, were transferred to the latest template. No changes were made to the contents. Document number changed.

6. Development team

- Pikkie Saayman

7. Acknowledgements

Not applicable.

Annex A – Kt factors for nickel cadmium cells

End-of-discharge Voltage [V]			1.00V	1.05V	1.10V	1.14V	1.00V	1.02V	1.05V	1.10V	1.14V
Time		Time [min]	Kt Factors for Vantage Cells (Medium Perf)				Kt Factors for L-range Cells (Low Perf)				
Seconds	1	0.02	0.31	0.36	0.45	0.53	0.54	0.57	0.63	0.76	0.92
	10	0.17	0.38	0.46	0.57	0.69	0.65	0.69	0.76	0.92	1.09
	30	0.5	0.45	0.53	0.67	0.83	0.73	0.75	0.83	1.00	1.20
	60	1	0.49	0.60	0.76	0.96	0.79	0.84	0.93	1.13	1.37
Minutes	5	5	0.66	0.81	1.05	1.29	0.95	1.02	1.13	1.36	1.68
	10	10	0.73	0.94	1.23	1.51	1.07	1.14	1.25	1.43	1.91
	30	30	1	1.23	1.51	1.95	1.33	1.37	1.44	1.58	2.14
	45	45	1.16	1.36	1.67	2.16	1.49	1.53	1.59	1.71	2.31
	60	60	1.31	1.48	1.82	2.35	1.64	1.69	1.73	1.83	2.48
	90	90	1.7	1.86	2.29	2.96	1.97	2.04	2.11	2.18	2.84
Hours	2	120	2.11	2.29	2.67	3.33	2.32	2.36	2.41	2.52	3.13
	3	180	3.08	3.20	3.48	4.00	3.14	3.14	3.24	3.24	3.79
	4	240	4	4.10	4.24	4.67	4.07	4.07	4.12	4.24	4.65
	5	300	5	5	5	5.33	5.00	5.00	5.00	5.24	5.50
	8	480	8	8	8	8	7.86	7.86	7.86	8.46	8.46
	10	600	10	10	10	10	10	10	10	10	11
	11	660	11	11	11	11	11	11	11	11	11
	12	720	12	12	12	12	12	12	12	12	12
	24	1440	24	24	24	24	24	24	24	24	24
Days	2	2880	48	48	48	48	48	48	48	48	48
	4	5760	96	96	96	96	96	96	96	96	96
	6	8640	144	144	144	144	144	144	144	144	144
	8	11520	192	192	192	192	192	192	192	192	192
	10	14400	240	240	240	240	240	240	240	240	240
	12	17280	288	288	288	288	288	288	288	288	288

Annex B – Temperature derating factors for nickel cadmium cells

Temperature [°C]	Derating factors			
	L-range cells		Vantage cells	
	1h rate	5h rate	30min rate	5h rate
0	0.8	0.900	0.850	0.925
5	0.85	0.950	0.913	0.950
10	0.9	0.970	0.963	0.975
15	0.95	1.000	0.975	0.988
20	1	1.000	1.000	1.000

Annex C – Kt factors for FCP range lead acid cells at 25°C

(Informative)

End-of-discharge voltage [V]				1.60	1.65	1.70	1.75	1.80	1.85
Minutes	5	Minutes	5	0.60	0.65	0.71	0.91	1.01	1.32
	10		10	0.73	0.79	0.93	1.01	1.16	1.37
	15		15	0.80	0.91	1.01	1.16	1.29	1.42
	20		20	0.96	1.02	1.12	1.29	1.42	1.60
	30		30	1.29	1.29	1.29	1.47	1.72	1.90
	45		45	1.57	1.57	1.57	1.69	2.00	2.59
	60		60	2.00	2.00	2.00	2.00	2.34	2.87
Hours	2		120	3.17	3.17	3.17	3.17	3.40	3.68
	3		180	4.18	4.18	4.18	4.18	4.18	4.51
	5		300	5.98	5.98	5.98	5.98	5.98	6.15
	6		360	6.81	6.81	6.81	6.81	6.81	7.03
	8		480	8.53	8.53	8.53	8.53	8.53	8.53
	10		600	10.00	10.00	10.00	10.00	10.00	10.00
	12		720	12.00	12.00	12.00	12.00	12.00	12.00
	14		840	14.00	14.00	14.00	14.00	14.00	14.00
	18		1080	18.00	18.00	18.00	18.00	18.00	18.00
	24		1440	24.00	24.00	24.00	24.00	24.00	24.00
Days	2		2880	48.00	48.00	48.00	48.00	48.00	48.00
	5		7200	120.00	120.00	120.00	120.00	120.00	120.00
	10		14400	240.00	240.00	240.00	240.00	240.00	240.00

Annex D – Rt factors for FCP range lead acid cells at 25°C

End-of-discharge voltage [V]				1.60	1.65	1.70	1.75	1.80	1.85
Minutes	5	Minutes	5	53.50	49.50	45.10	35.30	31.80	24.20
Minutes	10	Minutes	10	44.00	40.50	34.50	31.60	27.60	23.30
Minutes	15	Minutes	15	40.00	35.00	31.60	27.50	24.80	22.50
Minutes	20	Minutes	20	33.50	31.50	28.50	24.90	22.50	20.00
Minutes	30	Minutes	30	24.80	24.80	24.80	21.75	18.65	16.85
Minutes	45	Minutes	45	20.40	20.40	20.40	18.90	16.00	12.35
Minutes	60	Minutes	60	16.00	16.00	16.00	16.00	13.65	11.15
Hours	2	Minutes	120	10.10	10.10	10.10	10.10	9.40	8.70
Hours	3	Minutes	180	7.65	7.65	7.65	7.65	7.65	7.10
Hours	5	Minutes	300	5.35	5.35	5.35	5.35	5.35	5.20
Hours	6	Minutes	360	4.70	4.70	4.70	4.70	4.70	4.55
Hours	8	Minutes	480	3.75	3.75	3.75	3.75	3.75	3.75
Hours	10	Minutes	600	3.20	3.20	3.20	3.20	3.20	3.20
Hours	12	Minutes	720	2.67	2.67	2.67	2.67	2.67	2.67
Hours	14	Minutes	840	2.29	2.29	2.29	2.29	2.29	2.29
Hours	18	Minutes	1080	1.78	1.78	1.78	1.78	1.78	1.78
Hours	24	Minutes	1440	1.33	1.33	1.33	1.33	1.33	1.33
Days	2	Minutes	2880	0.67	0.67	0.67	0.67	0.67	0.67
Days	5	Minutes	7200	0.27	0.27	0.27	0.27	0.27	0.27
Days	10	Minutes	14400	0.13	0.13	0.13	0.13	0.13	0.13

Annex E – Temperature correction factors for FCP range lead acid cells

(Informative)

Discharge Rate (Duration)	Temperature correction factor to be applied to 25°C at:								
	0°C	**5°C**	**10°C**	**15°C**	**20°C**	**25°C**	**30°C**	**35°C**	**40°C**
3 s to 4.9 m	0.73	0.80	0.86	0.91	0.96	1	1.03	1.05	1.07
5 m to 59 m	0.77	0.83	0.88	0.93	0.96	1	1.03	1.05	1.06
1 h to 24 h	0.84	0.88	0.90	0.94	0.97	1	1.02	1.03	1.04