The use of supercapacitors in conjunction with batteries in industrial auxiliary DC power systems

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Abstract

Control and monitoring networks often operate on AC/DC power systems. DC batteries and chargers are commonly used on industrial plants as auxiliary DC power systems for these control and monitoring networks. The energy demand and load profiles for these control networks differ from application to application. Proper design, sizing, and maintenance of the components that forms part of the DC control power system are therefore required.

Throughout the load profile of a control and monitoring system there are various peak currents. The peak currents are classified as inrush and momentary loads. These inrush and momentary loads play a large role when calculating the required battery size for an application. This study investigates the feasibility of using supercapacitors in conjunction with batteries, in order to reduce the size of the required battery capacity. A reduction in the size of the required battery capacity not only influences the cost of the battery itself, but also influences the hydrogen emissions, the physical space requirements, and the required rectifiers and chargers.

When calculating the required size batteries for an auxiliary power system, a defined load profile is required. Control and monitoring systems are used to control dynamic processes, which entails a continuous starting and stopping of equipment as the process demands. This starting and stopping of devices will cause fluctuations in the load profile. Ideally, data should be obtained from a live plant for the purpose of defining load profiles. Unfortunately, due to the economic risks involved, installing data logging equipment on a live industrial plant for the purpose of research, is not allowed. There are also no historical data available from which load profiles could be generated.

In order to evaluate the influence of supercapacitors, complex load profiles are required. In this study, an alternative method of defining the load profile for a dynamic process is investigated. Load profiles for various applications are approximated using a probabilistic approach.

The approximation methodology make use of plant operating philosophies as input to the Markov Chain Monte Carlo simulation theory. The required battery sizes for

the approximated profiles are calculated using the IEEE recommended practice for sizing batteries. The approximated load profile, as well the calculated battery size are used for simulating the auxiliary power system.

A supercapacitor is introduced into the circuit and the simulations are repeated. The introduction of the supercapacitor relieves the battery of the inrush and momentary loads of the load profile. The battery sizing calculations are repeated so as to test the influence of the supercapacitor on the required battery capacity.

In order to investigate the full influence of adding a supercapacitor to the design, the impact on various factors are considered. In this study, these factors include the battery size, charger size, H_2 extraction system, as well as maintenance requirements and the life of the battery.

No major cost savings where evident from the results obtained. Primary reasons for this low cost saving are the fixed ranges in which battery sizes are available, as well as conservative battery data obtained from battery suppliers. It is believed that applications other than control and monitoring systems will show larger savings.

Keywords: Supercapacitor, Markov Chain Monte Carlo, load profiles found in industy, DC auxiliary power, battery sizing, H_2 extraction, cost comparison

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List of Abbreviations

Abbreviation	Description
AC	Alternating current
AC/DC	AC to DC
Cdl	Double layer capacitance
DC	Direct current
DCS	Distributed Control Systems
EIS	Electrochemical impedance spectroscopy
EMC	Electromagnetic compatibility
EPR	Equivalent parallel resistor
ESR	Equivalent series resistor
FCS	Field control station
HIS	Human interface station
HMI	Human machine interface
I/O	Input/output
IEEE	Institute of electrical and electronic engineers
IPR	Interposing run
IPS	Interposing stop
Kt	Capacity rating factor
LA	Lead-Acid
LOP	Local operator panel
MCMC	Markov Chain Monte Carlo
NiCd	Nickel-cadmium
NLEIS	Nonlinear electrochemical impedance spectroscopy
PLC	Programmable logic controllers
PV	Photovoltaic
RC	Resistor-capacitor
RFI	Radio-frequency interference
SCADA	Supervisory Control and Data Acquisition
SOC	State of charge
Tt	Temperature rating factor
UPS	Uninterrupted power supply

List of Symbols

Symbol	Description
°C	Degrees Celsius
Ah	Ampere-hour
C	Capacitance
cm^3	Cubic centimeters
dt or Δt	Change in time
dV or ΔV	Change in voltage
H_2	Hydrogen
i	Current
kW	Kilowatt
m^3/A^{-1}	Cubic meters per ampere
m^3/h	Cubic meters per hour
R	Resistance
V	Voltage
VAC	Voltage alternating current
VDC	Voltage direct current
V_{max}	Maximum allowable voltage
V_{min}	Minimum allowable voltage (V)
V_w	Working / operating voltage

CHAPTER 1: **INTRODUCTION**

1.1 BACKGROUND

Industrial plants are controlled by a network of control and monitoring systems. The networks consist of systems of interconnected equipment used to control and monitor dynamic processes on industrial plants. Industrial networks are employed in a wide spread of industrial domains including chemical refinement, oil and gas, food and beverage processes and electricity generation [1].

Industrial control networks are composed of specialized components such as Programmable Logic Controllers (PLCs), Supervisory Control and Data Acquisition (SCADA), and Distributed Control Systems (DCS) [1]. A typical control network consists of a Field Control Station (FCS), Input/output (I/O) cards, communication modules and network switches. Also included in the network will be at least one Human Machine Interface (HMI). HMIs can consist of Human Interface Stations (HIS) and/or Local Operator Panels (LOPs). The instruments in the field are controlled and operated by these networks. Figure 1 shows an example of a typical control network.

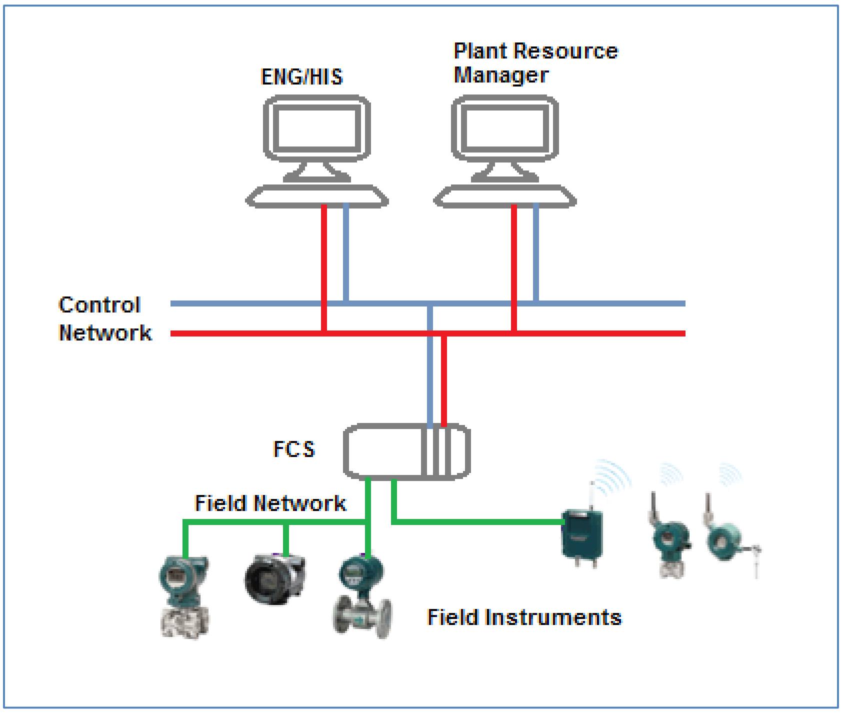

Figure 1: Typical control network [2]

The control and monitoring system controls the basic operation and general safety of the machines and equipment on an industrial plant. Since these networks are connected to physical equipment, failure of these systems can have a severe impact [1].

The energy demand and load profiles for these control networks differ from application to application. Most digital I/O cards are current limited for protection. Instruments with high current requirements are therefore operated via relays. The load requirements will rise and fall when instruments are switched as the process demands.

Control and monitoring networks often operate on AC/DC power systems. DC batteries and chargers are commonly used on industrial plants as auxiliary DC power systems for these control and monitoring networks. This makes availability and reliability of auxiliary DC systems an extremely important consideration in the overall design [3].

Failure of the DC control power can cause important detection, measurement and safety devices to fail, which can cause injury or production downtime. Auxiliary DC systems are designed to accommodate such failures. Upon failure or loss of the AC supply, the battery supports the continuous load until the AC supply can be restored. The battery also supports any intermittent and momentary loads that may occur during this time of AC loss [3]. The various types of loads mentioned above are clearly defined in the IEEE recommended practice for sizing batteries [4], [5].

Auxiliary DC systems are designed for a specific back-up time period as is required for the relevant application. In cases where the AC supply is not restored within this designed time, the design should also cater for any loads required while performing a last minute safety shutdown. Proper design, sizing, and maintenance of the components that forms part of the DC control power system are therefore required [3].

Part of the design process is selecting the type of battery technology that will best suit the design. The battery technologies allowed for auxiliary DC systems on electricity generating plants in South Africa are Lead-Acid and Nickel Cadmium type batteries. These batteries typically have an expected life of 20+ years [6], [7].When this lifetime is nearing its end, or when upgrades are due, the batteries need to be replaced. During the replacement of the batteries, the required size is recalculated to ensure that the new design will meet all the requirements for the next 20 years.

The replacement of auxiliary systems are quite costly, and the size of the system is proportional to the cost. As the required system load increases, the required battery size also increases. Auxiliary power systems used in industry can demand hundreds of amperes, and therefore, the costs of the batteries for these systems are high. Factors that may play a role in the increase of load requirements during the replacement of a system are, amongst others, different operating voltage levels of old and new equipment (220 VAC versus 24 VDC control system), additional devices and equipment, and expanding networks.

Control and monitoring systems are designed to control dynamic plants. Inrush currents and intermittent loads are common in these systems as they consist of multiples of different devices, each demanding energy as it is controlled. These loads can have a large effect on the required battery size.

Batteries have good energy densities but poor power densities. This makes batteries suitable to provide constant power for long durations. Supercapacitors, on the other hand, have good power densities but lower energy densities [8]. This attribute makes supercapacitors suitable to provide energy during short power peaks. Supercapacitors also do not have the drawbacks of batteries like poor temperature coefficient, limited charging and discharging cycle, and critical charging current [9]. Inrush currents and intermittent loads can, therefore, be managed by making use of supercapacitors. This could decrease the size of the required battery and therefore save costs.

In order to test the feasibility of using supercapacitors in conjunction with batteries, load profiles are required. For thorough testing, these profiles should detail the momentary loads, as well as intermittent loads that may occur during a dynamic process.

This study is based on an auxiliary DC power upgrade project that is currently being implemented for one of the electricity generating plants in South Africa. Ideally, data from these actual applications should be used as load profiles. Through discussions with the power utility, installations of temporary measurement devices on existing systems will not be allowed. The reasons supplied are as follows: firstly, the system is of a delicate and important nature and the plant is not prepared to install these devices for purpose of a study. Secondly, in order to obtain accurate data, an AC supply failure condition will have to be induced and the power utility is not prepared to take this risk. It is therefore not possible to collect practical load profiles for the purpose of this study.

In light of the above, this study compares data used during a new design. Battery sizing calculations in industries are based on assumptions of a worst-case load profile during the loss of AC supply [3]. Worst-case load profiles are created by calculating the combined load of all the equipment that may be present at any given moment. Power-generating plants in South Africa also share this approach. To measure the full influence that supercapacitors may have on an auxiliary power system, however, more complex load profiles are required.

During this study, load profiles for various applications are approximated. These approximated load profiles are created with a probabilistic approach, based on the operating philosophies of the relevant application. These profiles are used to test the influence of the supercapacitor when used in conjunction with the batteries of the auxiliary power system.

<u>Related Work</u>

Supercapacitors are used in a variety of different applications. In the renewable energy sector, energy requirements tend to have high charge-discharge cycle frequencies. They also demand high efficiency and depth-of-discharge capabilities. This draws a lot of attention to the use of supercapacitors [10], [11].

Supercapacitors are also very popular in the design of the power systems in hybrid electric vehicles. Supercapacitors are specifically used to allow higher accelerations and decelerations with minimal loss of energy [12]. Supercapacitor banks are also used as a power buffer to smooth power fluctuations during the operation of these electric vehicles.

Supercapacitors play a fundamental role in regenerative braking equipment [12]. The battery is sized to provide power surges as the electric vehicle accelerate or decelerate. The battery generates extensive heat due to this fluctuating load requirement. Supercapacitors have an advantage over batteries in terms of their power densities. Supercapacitors therefore assist the battery to capture energy during regenerative braking, and assist the battery during acceleration [13].

1.2 PROBLEM STATEMENT

The purpose of this study is to investigate the feasibility of using supercapacitors in conjunction with batteries in order to reduce the size in the required battery capacity. This could potentially have cost saving implications as the reduction in the required battery size directly influences the cost of the system. A decrease in the size of the required battery capacity not only influences the cost of the battery itself, it also entails less hydrogen emissions and therefore less expensive hydrogen management systems, less physical space requirements and thus smaller battery rooms, and also a decrease in the required rectifiers and chargers.

In order to evaluate the full effectiveness of supercapacitors, complex load profiles are required. Measuring data from actual plants for the purpose of obtaining load profiles are not permitted. In order to test the full influence of the supercapacitor, complex load profiles are required. Load profiles for dynamic system are approximated for the purpose of this study.

The primary aim of this study is to investigate a possible reduction in the required battery size for an auxiliary power system due to the addition of a supercapacitor. The cost impact of this reduction in battery size is also investigated.

1.3 ISSUES TO BE ADDRESSED

1.3.1 Literature study

A thorough literature study is required to gather information on all the technical and commercial aspects relating to this study. The following aspects are reviewed comprehensively:

- Load profiles found in industry
- Markov chain Monte Carlo theory for approximating probabilistic loads.
- Battery and supercapacitor sizing methodologies
- Modelling batteries and supercapacitors.

1.3.2 Defining load profiles

Using the worst case methodology of sizing batteries results in a flat load profile. Complex load profiles are required in order to test the full effectiveness of supercapacitors. Obtaining actual data to generate these profiles is not possible. Probabilistic approximations are created in this section for the purpose of testing the supercapacitors.

1.3.3 Validation of approximated load profiles

The approximated profile methodology followed during the previous section is validated by means of qualitative research. The opinions of industry experts are gained by means of interviews and completing a questionnaire.

1.3.4 Simulation model

A software model is used to test the influence a supercapacitor has on the required battery capacity. The model makes use of the load profiles approximated in the previous section, as well as existing validated battery and supercapacitor models. Graphical illustrations of the results from the software model are created.

1.3.5 **Cost impact**

The financial viability of combining supercapacitors and batteries is investigated. The cost of the system with the supercapacitor included is compared to the cost of the same system without the supercapacitor.

1.4 RESEARCH METHODOLOGY

1.4.1 **Literature study**

A thorough scan of the literature is conducted in order to obtain as much information on the topics listed in 1.3.1 as possible. The information found on these topics, that are relative relevant to this study, are summarized to form the literature study.

1.4.2 **Defining load profiles**

As stated in section 1.1, battery sizing calculations in industries are based upon assumptions of a worst case load profile during the loss of AC supply. Supercapacitors, however, store energy that can be instantly released during inrush currents, and intermittent or momentary loads. Therefore, to evaluate the full effectiveness of the supercapacitors, more complex load profiles are required.

During this section, probabilistic load profiles, based on plant operating philosophies, are approximated for various application in order to obtain more complex profiles. These approximated profiles are generated by using the Markov Chain Monte Carlo simulation method. The simulations are built using Microsoft Excel and the results are displayed on graphs.

1.4.3 **Validation of approximated load profiles**

The approximation methodology from the previous section is validated by following a qualitative research approach. The opinions of industry experts are gained by means of interviews. The interviews are formalized by completing a questionnaire. The questionnaire is aimed at determining to what extent the approximation methodology is accurate and realistic.

1.4.4 Simulation model

The approximated load profiles generated are simulated using Matlab ®. Preliminary supercapacitor sizes are calculated prior to the simulation. The simulation model uses existing validated battery and supercapacitor models.

The effect of the supercapacitor used in conjunction with a battery is investigated. The model is first simulated without the supercapacitor. The simulation is repeated with the calculated supercapacitor introduced in the system. The simulation is then iteratively repeated, each time using a smaller supercapacitor to determine the optimum battery-supercapacitor relationship for the application.

The required battery size, due the inclusion of the supercapacitor, is then calculated. The results from all the simulations are compared and tabulated.

1.4.5 Cost impact

The cost impact when adding supercapacitors to the system is investigated. The results are determined in terms of capital costs. The potential decrease in battery size due to the use of the supercapacitor, as well as the cost of the supercapacitor itself, is considered.

1.5 LIMITATIONS OF RESEARCH

Due to the delicate and important nature of power generation plants in South Africa, as well as the economic risk involved, permission to obtain live measurements of load profiles from the industrial plants relevant to this study was not granted. This data would be ideal to model the load profiles required for this study. Due to the unavailability of actual data, simulations that are based on the operating philosophies of the plant are used, in a probabilistic approach, to generate realistic load profiles.

Furthermore, a typical auxiliary back up supply system is designed to run for 15 – 20 years. The systems examined in this study are already reaching its end of life cycle. Due to their age, the design data for the existing systems is not readily available and could therefore not be obtained and used as comparison data for this study. In order to compare the data used in this study, the results are compared to typical worst case load profiles found in the industry.

1.6 DISSERTATION LAYOUT

In Chapter 2, a thorough literature survey is conducted. The survey is used to gather information on all the technical and commercial aspects relating to this study. This includes technical and commercial data for batteries and supercapacitors, modeling of components, typical load profiles found in industry, and approximating realistic load profiles.

In Chapter 3, approximations of battery load profiles are generated and compared to worst-case scenario load profiles. The approximated load profiles are created from simulations based on the plant operating philosophies. These approximated profiles are displayed using graphs.

In Chapter 4, the simulation methodology from the previous section is validated by means of qualitative research approach. The opinions of industry experts are gained through interviews and are formalized by completing a questionnaire.

In Chapter 5, software simulation models of the models are built using simulation tools. The effect that a supercapacitor has on the required battery size is examined.

In Chapter 6, the cost impact that the supercapacitor has on the each system is determined. The capital cost in savings due to potential battery size reduction, as well as the cost of adding the supercapacitors are considered.

In Chapter 7, the findings of this study is concluded. Recommendations are made relative to the findings of the study.

CHAPTER 2: **LITERATURE STUDY**

In this chapter a thorough literature survey is conducted. The topics covered in this section grants insight on techniques and methods used, and information available in the literature, relevant to this study.

Overview

This study investigates the feasibility of the use of supercapacitors in conjunction with batteries in industrial auxiliary DC power systems. The main focus is to test whether the addition of a supercapacitor to the design can potentially decrease the size of the required components, and in doing so, save costs.

The influencing factors considered during this study are the size battery, the size charger, the H_2 extraction system, battery end-of-life time, and the required maintenance practices.

When designing an auxiliary system, the first step is to calculate the required battery size. In order to complete these calculations, the load profile for the specific application is required. Once the battery size is calculated, the correct size charger and H_2 extraction system can be calculated.

Should the addition of the supercapacitor relieve the battery of some of its fluctuating or momentary loads, the battery load profile will be altered. This altered battery load profile may decrease the required size battery, which in turn may decrease the required size charger as well as the required H_2 extraction system.

Profiles found in industry

In section 2.1, the status quo regarding load profiles that are used in the industry is investigated. The section discusses industry standards for defining load profiles. The shape of a typical load profile is also discussed. The section is researched to ensure that the profiles created during this study conforms to what is typically observed in the industry.

Simulation theory

A typical load profile used in the industry is defined using a worst case methodology. This methodology has a constant current as a result. Supercapacitors can provide its biggest advantage during fluctuating loads.

A dynamic process will continuously start and stop equipment as the process demands. This will cause a fluctuation in the load profile. Unfortunately, obtaining live data from a plant for the purpose of defining load profiles is not allowed. Therefore, during section 2.2, an alternative method of defining the load profile for the dynamic process is investigated. The load profiles are created to fully test the advantages of the supercapacitor.

The Markov Chain Monte Carlo (MCMC) simulation theory is selected as it is deemed fitting for this application. The probability of a dynamic process changing its state is only dependent on its current state, and not any previous states. Using this MCMC theory introduces a more accurate approximation for the load profiles of the dynamic systems.

Sizing system components

Once the load profiles for an application have been defined, the correct equipment for that application can be calculated. Section 2.3 investigates the industry standards for sizing the various equipment. The section investigates the methodologies of sizing batteries, chargers, H_2 extraction systems, as well as the sizing of supercapacitors.

The standards developed by the IEEE and SANS are investigated when calculating the required battery size, charger size, and H_2 extraction system. These standards are also followed in industry. The supercapacitor sizing methodology investigated in this section is as per the manufacturer’s application notes.

Modelling batteries and supercapacitors

The effect of the supercapacitor on the auxiliary system has to be tested and quantified. This is achieved by simulating the system using software models. Section 2.4 investigates existing validated models for both the batteries and supercapacitors.

The validated battery model includes parameters for various types of battery technologies. As one of the main focus points of this study is cost, section 2.4 also investigates which battery technology has the lowest lifecycle cost. The parameters of this battery technology is used during simulations.

2.1 LOAD PROFILES FOUND IN THE INDUSTRY

As mentioned in the previous chapter, it is common practice to describe the load profile of a system in terms of the worst case load the battery is expected to supply. The load profile in Figure 2 indicates the load for an existing system used in the industry [14]. From this load profile it is clear that a continuous load was assumed throughout the entire discharge period.

This section explores typical DC load profiles used in industry.

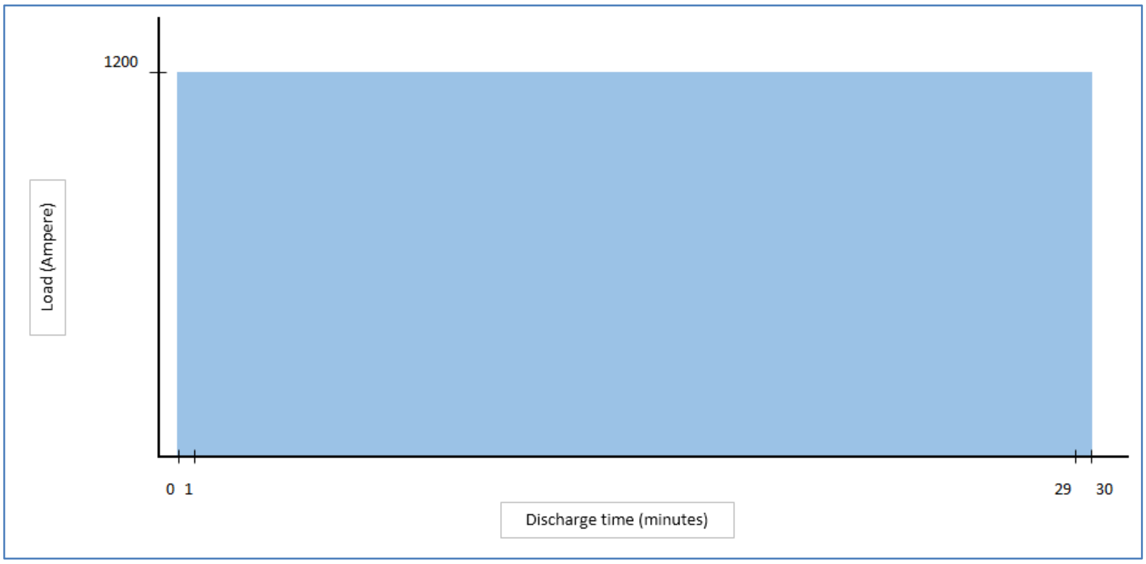

Figure 2: Load profile from an existing design

2.1.1 Defining the load profile

Defining load profiles that are imposed on a battery depend on the DC system design and system requirements. The battery load profile of a system is defined by all, or part of the load that it has to supply for a specified period of time. The battery has to supply this load when the system load exceeds the battery charger capability, the battery charger output is lost, or all AC power is lost. The required battery size should be determined by whichever of the last mentioned conditions are the most severe [4], [5], [15].

A typical load profile can consist of continuous, non-continuous, as well as momentary and random loads. Continuous loads are energized throughout the entire discharge time of the load profile. Non-continuous loads are only energized during part of the load profile. Non-continuous loads typically entail the switching on and off of valves, ventilation systems that turn on and off, etc. Momentary loads occur during the first and last minutes of the load profile, and random loads can occur during any unspecified time during the load profile [4], [5], [15]. Random loads are generally the result of a combination of circumstances throughout the normal course of the process. Table 1 indicate some typical examples of the above mentioned loads.

Table 1: Classifications of a load [4], [5], [15]

Classification	Typical load
Continuous / Static	Lighting, communications systems, inverters, continuously energized coils, etc.
Non-continuous / variable; Momentary	Motors, pumps, fire protection systems, switchgear operations, isolating switch operations, inrush currents, motors starting currents, etc.
Random	Momentary loads that occur at random

The battery load profile usually experiences its largest increase in load when the AC power is lost. This is due to additional equipment and components that have to be energized to render the process and area safe in the event of an AC failure. These equipment and components can include emergency lighting, trip coils, starting of diesel generators, etc. [15].

The middle part of the load profile has a fairly constant load. During this period, it is mostly continuous loads that are present [15].

The typical load profile also experiences an increase in load during the last minute of supply. This increase is only a fraction of the increase observed during the first minute. This last minute increase in load may be caused by either the collective loads of equipment that are energized when taking the system to a safe shutdown condition, or by the momentary loads that are energized as the AC power is assumed to be restored [15]. Typical last minute operations include switching valves, shutting off of drives, and other switchgear operations.

Momentary loads may occur once, or multiple times during a discharge period. These loads are generally short of duration and do not typically exceed one minute at any occurrence. Despite the fact that momentary loads only exist for a fraction of a second, it is common practice to consider that each load will last for a full minute. This is because the battery voltage drop after several seconds determines the battery's one minute rating and capability [4].

Non-continuous loads may switch on at any time during the discharge period. In the case that a discrete sequence cannot be defined, and several loads are simultaneously energized, the load should be assumed to be the maximum load at any instance. If loads are energized for less than a second, it is common practice to consider that load for a full second [5].

Figure 3 illustrates a typical DC battery load profile used in industry, capturing the events explained in the paragraphs above.

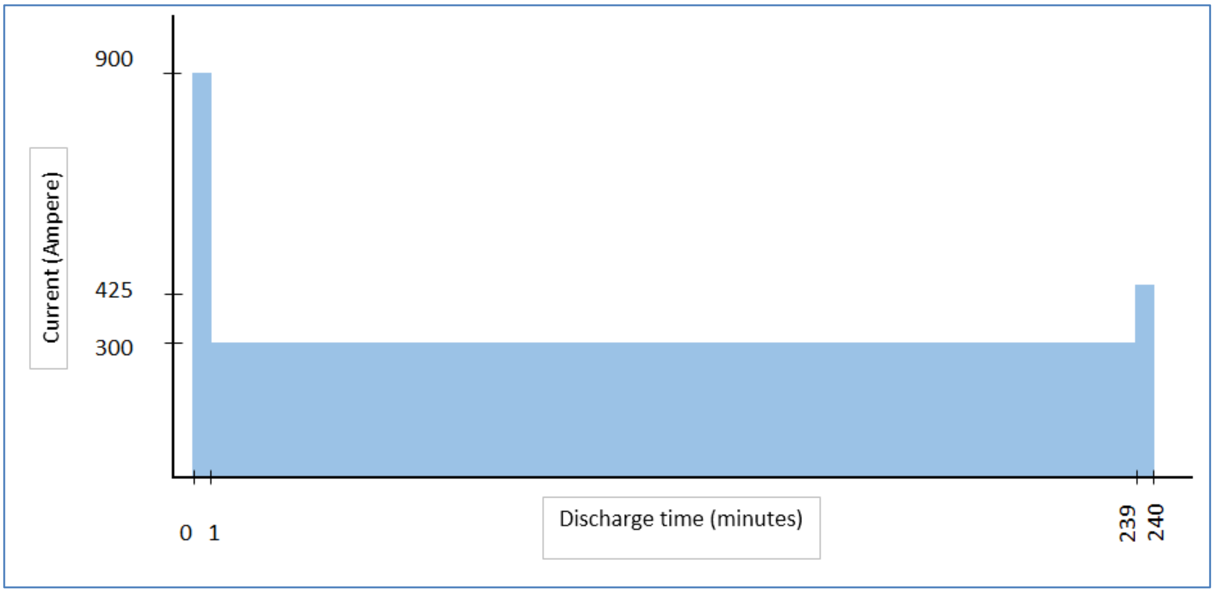

Figure 3: Typical battery load profile [15]

Although the load profile varies extensively with the industry and application, the shape of the profile in Figure 3 is most commonly found and used in DC systems [16].

Figure 3 is divided into three different periods. During the first period, the load is very high due to simultaneous energizing of components, as explained above. The second period is represented by the constant current which is observed for the center 238 minutes of discharge time. The third period illustrates the switching of the system into a safe state.

For the purpose of this study, the load profile will be examined in two stages. Firstly, the static or continuous part of the profile will be examined to determine the potential influence of the supercapacitor during this period. Secondly, the periods where the momentary loads are present in the profile will be examined to determine the influence that the supercapacitor may have in these periods.

2.2 SIMULATION THEORY

As mentioned in Section 1.1, it is practically impossible to obtain live load data from an actual running application for the purpose of this study. To obtain complex data of a dynamic system, the Markov Chain Monte Carlo simulation method is used to simulate probabilistic load profiles. This section provides background of what Monte Carlo, as well as Markov Chain Monte Carlo simulation entails, and how it is used for the purpose of this study.

2.2.1 Monte Carlo simulation overview

The Monte Carlo method introduces a solution to model uncertain scenarios through direct simulation of the essential dynamics of a system. Through random sampling of the relationships, or interactions of the input variables involved, a solution or result can be approximated [17].

In order to explain the fundamentals of the Monte Carlo method, the example of seating patterns for the audience members in an auditorium can be used. Figure 4 shows an example of the random pattern when an audience fills an auditorium [17]. In this example, occupied seats are represented by solid circles and empty seats by open circles.

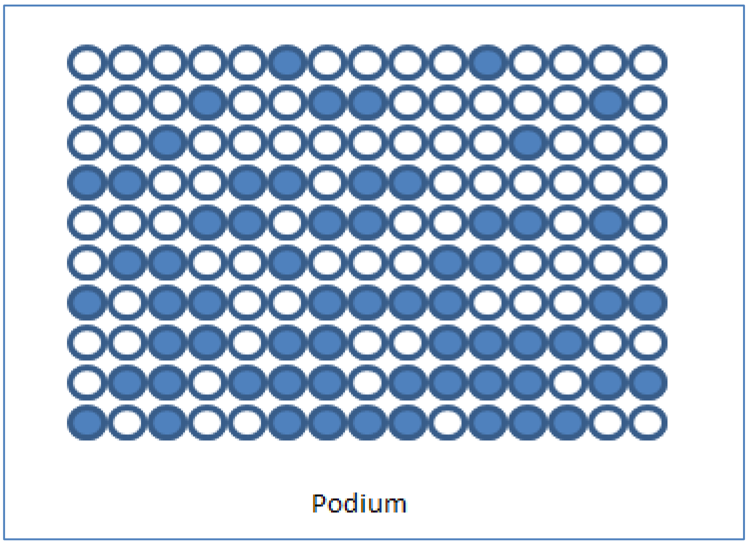

Figure 4: Random pattern of an audience filling an auditorium [17]

To calculate a pattern, certain assumptions have to be made. These assumptions include factors such as audience members arriving in pairs for certain types of shows, preference of an unobstructed view of the stage and seating locations [17]. The probability of each assumption is then determined. These probabilities are used together with a random number generator to simulate the different, yet most probable behavior of the audience. Mathematically the solution is difficult but by making use of Monte Carlo methods it becomes much easier.

Similar to the example above, the Monte Carlo method can be used to assist in determining suitable battery capacities. Certain relevant input assumptions are made regarding any unpredictable variables of the system. These variables may include the weather information, outage statistics, or certain load profiles. The probabilities of these variables influencing the system are then determined. A random number generator is then used to simulate the most probable battery load profile.

Figure 5 illustrates the method used in [18] to determine a suitable battery capacity for an uninterrupted power supply (UPS) system. The input assumptions affecting the Monte Carlo simulation for this scenario included seasonal outage occurrences and the frequency thereof, outage durations, daily building load profiles and temperature for photovoltaic (PV) generation. These conditions are all unpredictable of character, and therefore each condition is randomly considered, taking into account its probability of occurrence.

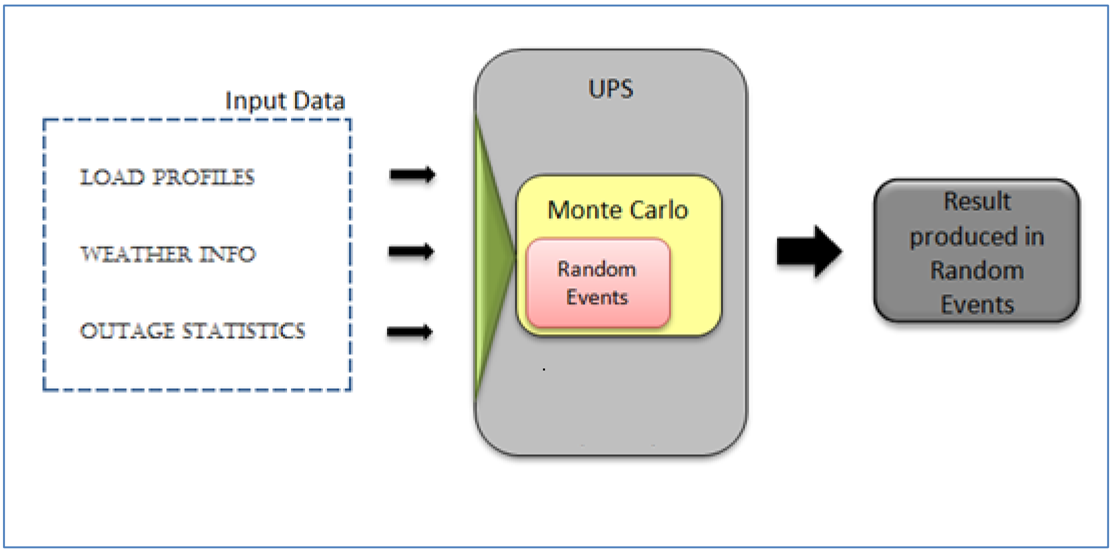

Figure 5: Monte Carlo method for assisting in battery capacity determination [18]

It is important to keep in mind that the simulation only represents probabilities and not certainty [19]. When simulating non-deterministic, or dynamic, scenarios, this becomes an advantage as the actual system will also differ every time it is measured. Thus, the uncertainty of a system can be simulated more appropriately through the Monte Carlo simulation method [20].

2.2.2 **Monte Carlo simulation for battery load profiles**

In cases where input data is non-deterministic, Monte Carlo simulations would perform the evaluation of the system more effectively than using analytical models. Weather conditions, outage events and demand peaks are non-deterministic in nature. To consider these uncertain, non-deterministic changes, the simulation for the required battery capacity should be based on a probabilistic approach [18], [20], [21].

The Monte Carlo simulation method is appropriate for analysis of short simulation periods, such as a simulation period of 24 hours. The method becomes rather impractical for real-time simulations [21].

2.2.3 **Monte Carlo simulation for control and monitoring system load profiles**

The load of an industrial control system is dependent on a number of different instruments and equipment. These instruments and equipment include relays, solenoids, computers, screens, DCS, network switches and other devices. Due to the switching of instruments as the process requires, the load constantly changes. The simulation therefore has to calculate the sum of all the probable loads that influence the system for a specific interval of time. Figure 6 shows a section of the control network for a paper factory.

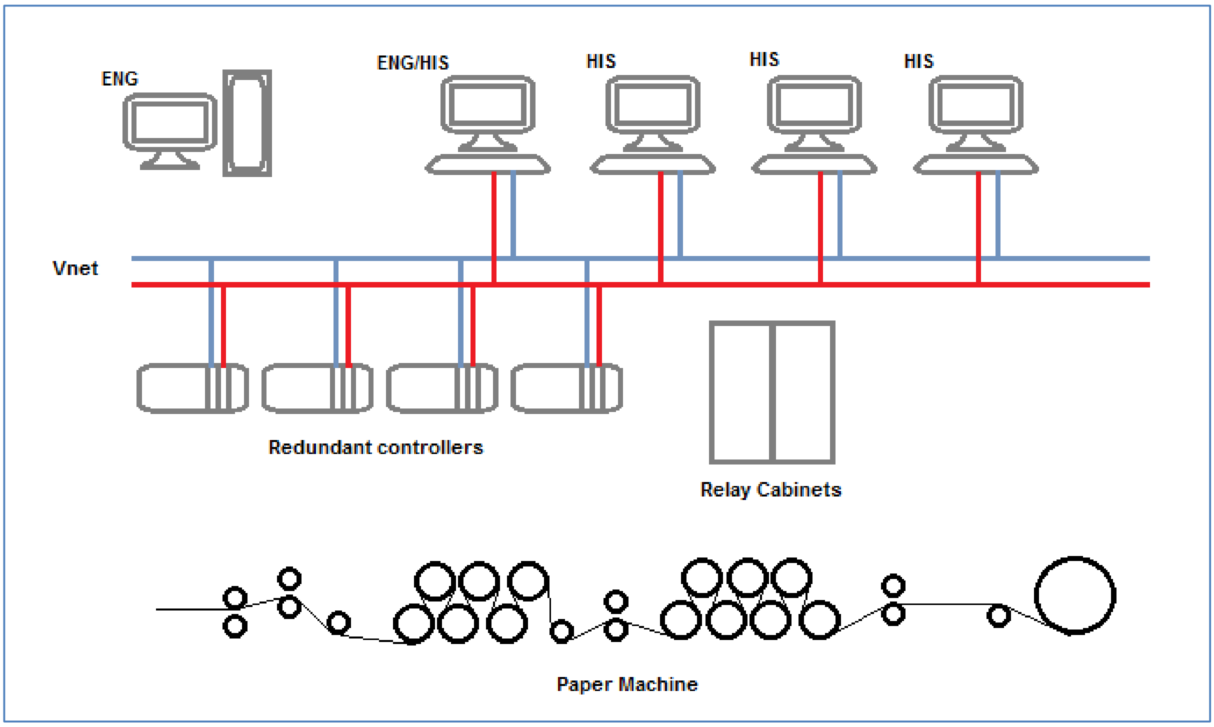

Figure 6: Control network for a section of a paper factory [2]

From the previous sections, it is clear that in order to create a successful Monte Carlo simulation, the first step is to identify the non-deterministic factors that will influence the relevant system. For each factor, the probability of it influencing the system is then determined. Making use of random number generators, the influence of all the non-deterministic factors can be simulated and a load profile can be created. The flow diagram in Figure 7 shows a summary of the Monte Carlo simulation method for control and monitoring systems, adopted from the above sections.

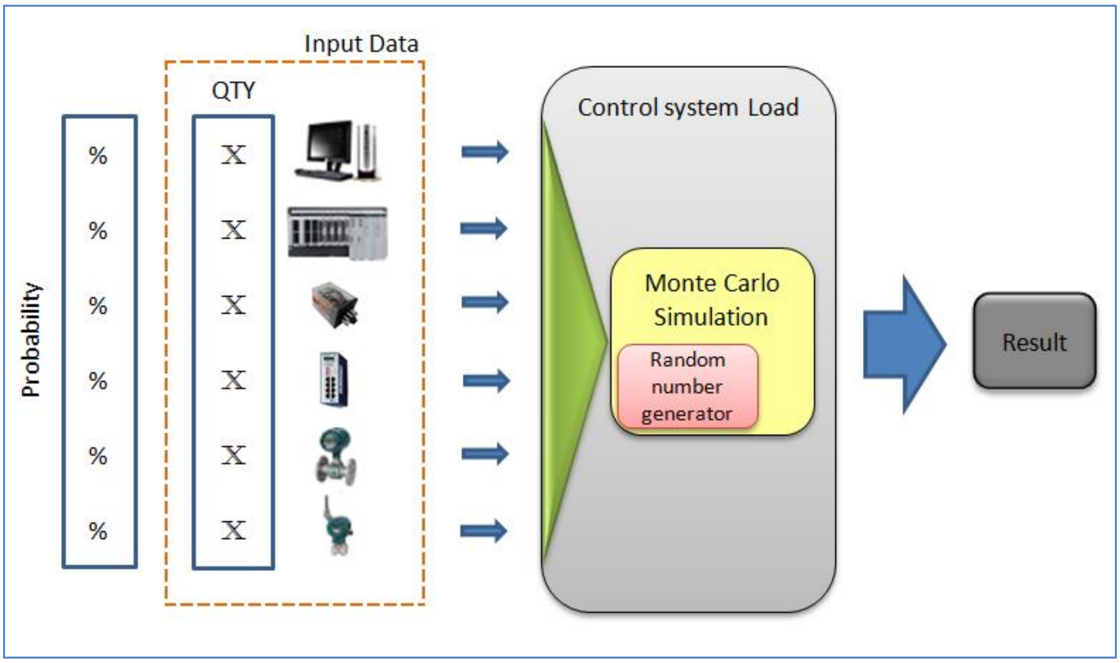

Figure 7: Monte Carlo simulation for control and monitoring system loads

2.2.1 Advantages and disadvantages of Monte Carlo simulation

Table 2 shows the advantages and disadvantages of Monte Carlo simulation compared to analytical models.

Table 2: Advantages and disadvantages of Analytical and Monte Carlo simulation methods [22]

	Simulation Method	
	Analytical	Monte Carlo
Advantages	a) Results are exact (given the assumption of the model)	a) Very flexible. There is virtually no limit to the analysis.
	b) Once the model is developed, output will generally be rapidly obtained.	b) Easily extended and developed as required.
	c) Does not always require a computer – paper analysis may suffice.	c) Easily understood by non-mathematicians.
Disadvantages	a) Requires restrictive assumptions to make the problem tractable.	a) Usually requires a computer.
	b) The scope for extending or developing a model may be limited.	b) Calculations can take much longer than analytical models.
	c) The model might only be understood by mathematicians.	c) All outputs are estimates.

2.2.1 **Markov Chain Monte Carlo simulation theory**

The Monte Carlo simulation theory, as explained in the previous sections, disregards the state which the process is in during simulation. When simulating a dynamic process, the current state has to be considered. This is achieved by integrating Markov chains into the Monte Carlo simulation theory.

Markov chains can be described as a process of moving from one step to a next through a chain of steps. The transition of moving from one step to the next, depend on a specific probability. If it is improbable for the process to move to the next step, the process may remain in its current step. The probability of transitioning to a next step only depends on the current state of the process, and does not depend on the state of the step before its current step.

Markov Chain Monte Carlo (MCMC) is used for generating samples $x^{(i)}$ in the state space X using a Markov chain mechanism. The stochastic process is called a Markov chain when

$$p(x^{(i)} \mid x^{(i-1)}, ..., x^{(1)}) = T(x^{(i)} \mid x^{(i-1)}) \tag{2.1}$$

where the samples $x^{(i)}$ only contain s discrete values, $x^{(i)} \epsilon X = \{x_1, x_2, \dots, x_s\}$.

By using this mechanism, the chain is influenced by the most important regions of sampling. It must specifically be constructed in such a way that $x^{(i)}$ mimics samples drawn from a target distribution $p(x)$. It is important to note that MCMC is used when samples cannot be directly drawn from $p(x)$ [23]. The example below illustrates the Markov Chain Monte Carlo method.

Consider a Markov chain with three states, namely X = {X1, X2, X3}.

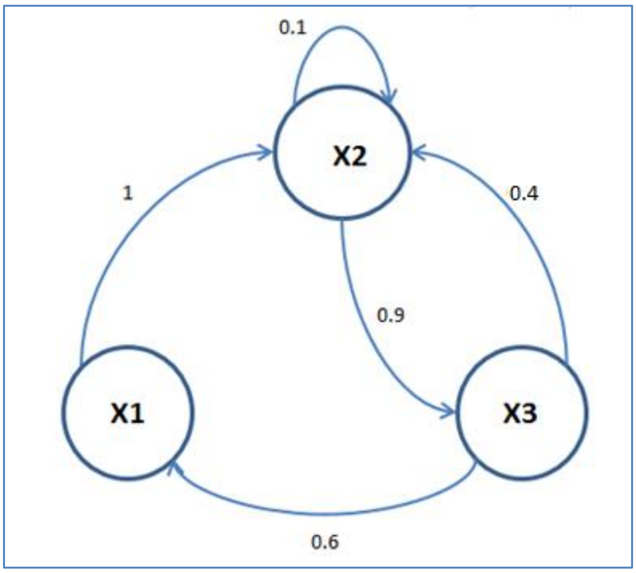

Figure 8: Transition graph for a Markov Chain

Figure 8, illustrates the three states, as well as the probability of changing from one state to another. If the system is in state X_1, for example, the probability of changing to state X_2 is one (1), or 100%. The combined probabilities of possible transitions flowing from a specific state, including any conditions that cause a return to that specific state, always add up to 100%. Figure 8 can also be written as the transition matrix T:

$$\mathbf{T} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0.1 & 0.9 \\ 0.6 & 0.4 & 0 \end{bmatrix} \tag{2.2}$$

For the purpose of the example, assume that the probability vector for the initial state is given by $\mu(x^{(1)}) = (0.5, 0.2, 0.3)$, it follows that $\mu(x^{(1)})T = (0.18, 0.64, 0.18)$. After several iterations, the product converges to $p(x) = (0.2, 0.4, 0.4)$.

Therefore, for any initial state, the chain will converge to the invariant distribution $p(x)$, as long as T is a stochastic transition matrix that is both irreducible[1] and aperiodic [23]. Figure 9 indicates a typical approximated result when using Markov chain Monte Carlo.

1 A Markov chain is irreducible if there is a non-zero probability of transitioning from any state to any other state.

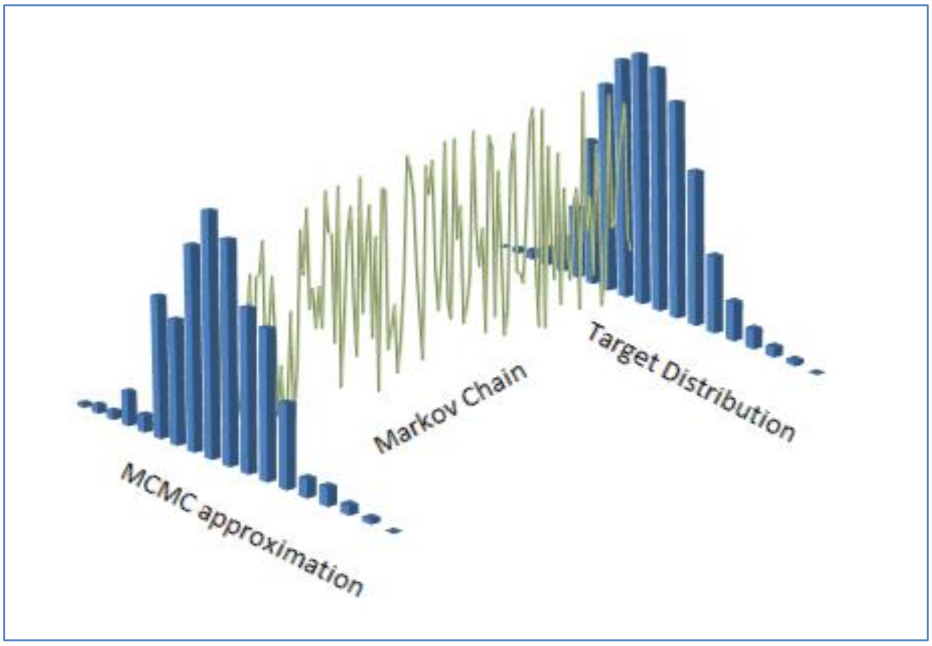

Figure 9: Approximation obtained using the MCMC simulation theory [23]

The probability of a dynamic process changing its state is only dependent on its current state, and not any previous states. Thus, the Markov Chain Monte Carlo simulation theory introduces a more accurate result when approximating the load profiles of a dynamic system. For this reason, the MCMC simulation theory is selected when approximating the load profiles of the dynamic systems investigated during this study.

2.3 SIZING SYSTEM COMPONENTS

The previous section explains the method to simulate probabilistic load profiles. Once a specific load profile can be determined or simulated, the correct size battery and supercapacitor to accommodate the load can be calculated. Battery and supercapacitor sizing calculations used in this study are based on existing sizing methodologies. In this section, these methodologies are discussed.

This section also discusses the methods of calculating the required charger size, and adequate ventilation systems for the purpose of H_2 extraction.

2.3.1 **IEEE standard practice for sizing batteries**

The Institute of Electrical and Electronic Engineers (IEEE) has developed standards for the sizing of Lead Acid and NiCd batteries. The methodology in both standards is the same, with the only difference being the type of battery and therefore the voltages each cell can provide. The other parameters that differ are battery specific and the data is obtainable from the relevant battery manufacturers [4], [5].

In order to explain the cell sizing methodology, the battery load profile in Figure 10 is considered. The figure indicate loads L1 through L7. These loads combined, results in the total load profile of the system. Load L7 represents a random load, which may occur at any given moment during the load profile.

The load profile in Figure 10 is broken down into sections and periods. Each change in load size constitutes a new period. The combined loads observed during each period are summarized in Table 3. The table also indicates the approximate capacity removed from the battery due to the various loads. The various sections are used during when completing the cell sizing table, as illustrated by Table 4.

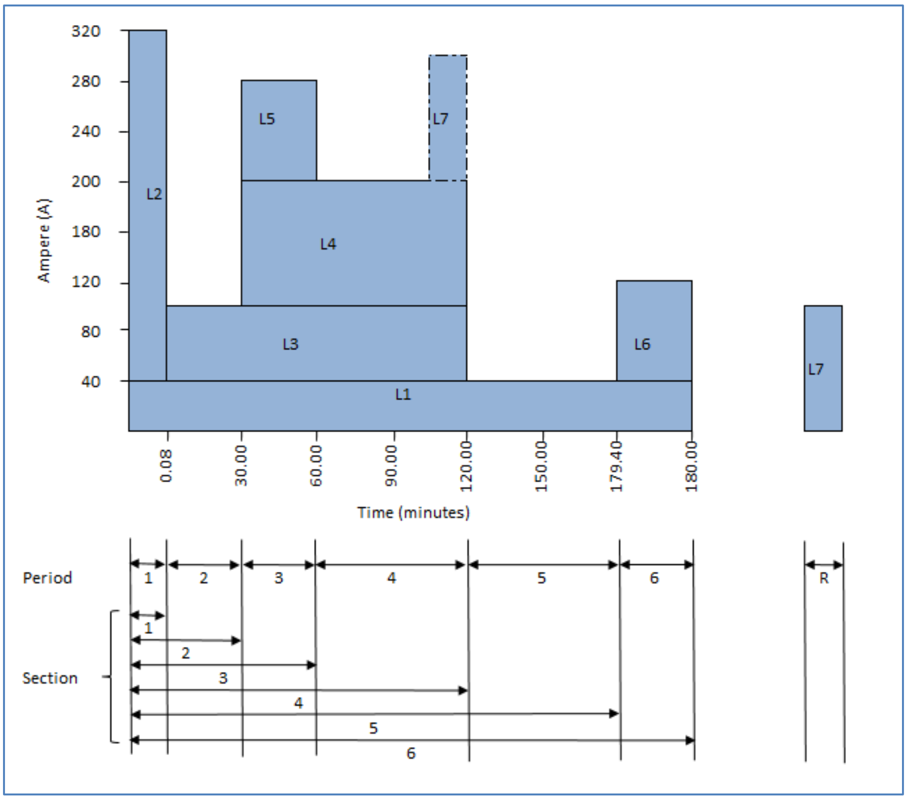

Figure 10: Battery load profile diagram [4]

Table 3: Sample cell sizing [4]

Period	Loads	Total Amperes	Duration (min)	Capacity removed (Ah)
1	L_1+L_2	320.00	0.08 (5s)	0.43
2	L_1+L_3	100.00	29.92	49.87
3	$L_1+L_3+L_4+L_5$	280.00	30.00	140.00
4	$L_1+L_3+L_4$	200.00	60.00	200.00
5	L_1	40.00	59.42	39.61
6	L_1+L_6	120.00	0.58 (35s)	1.16
7	L_7	100.00	1.00	1.67
			Total	432.74

Determining the battery size

The required battery size for any system is governed by several basic factors. These factors include the maximum system voltage, minimum system voltage, the load profile, correction factors, and design margins.

The available battery capacity can also be changed by the operating conditions of a system. A decrease in temperature, for example, causes a decrease in the available battery capacity. The available capacity also decreases as the discharge rate increases. The minimum specified cell voltage also limits the available capacity [4], [5].

The following factors should be considered before proceeding to calculate the required cell size for a specific application:

Temperature derating factor (Tt)

The operating temperature of a system affects the available capacity of a cell. The standard temperature for stating a cell capacity is 25°C. If the operating temperature of a system is different to the standard temperature, the battery manufacturer should be consulted for capacity derating factors [4], [5].

Design margin

Prudent design principles dictate that a capacity margin is provided to allow for unforeseen additions to the system. This margin also ensures that adequate capacity is available during less-than-optimum operating conditions, or improper maintenance conditions. The design margin is provided by adding a percentage factor to the cell size [4], [5].

Aging factor

The capacity of a battery decreases gradually throughout the life of the battery. The rate of capacity loss is independent of factors such as operating temperature, electrolyte specific-gravity, and the depth and frequency of discharge. A battery's aging factor is chosen based on the required service life. Therefore, the choice of aging factor is in essence an economic consideration [4], [5]. Generally, an aging factor of 1.00 is used for Lead Acid batteries and an aging factor of 1.20 is used for Nickel Cadmium batteries.

Capacity rating factor (*Kt*)

The ratio of the rated Ampere-hour capacity of a cell, to the current that can be supplied by that cell for *t* minutes, is known as the capacity rating factor (*Kt*) of that cell. The *Kt* factor of the cell is measured at 25°C, and at a given end-of-discharge voltage. *Kt* factor are available from the relevant battery manufactures [4], [5].
Table 3 indicate an approximate removed capacity for the described system. In order to calculate a more accurate value of the removed capacity, the factors explained above are considered.

Using the values in Table 3, together with each battery's relevant factors, Table 4 can be completed. The battery Kt factors are determined by making use of the battery's hypothetical discharge current tables, obtainable from the manufacturers. Should these tables not have a column indicating the *Kt* factor for the exact discharge time required, the Kt factor can be calculated by using interpolation.

$$Kt = Kt_2 - \frac{(Kt_2 - Kt_1)(t_2 - t)}{(t_2 - t_1)} \tag{2.3}$$

The interpolation must, however, only be performed on the Kt factors. Interpolation of the current values will yield incorrect results [4], [5].

If the calculation results indicate that a larger cell size is required than what was used during the calculation, the calculations should be repeated using the larger cell's Kt factors. This iterative process is continued until the cell size and its Kt yield the required result.

In Table 4, the Kt factor is dependent on column (5) of the cell sizing worksheet. The relevant Kt for each period is calculated when completing the table.

Table 4: Cell sizing worksheet [4], [5]

(1) Period	(2) Load (amp)	(3) Change in Load (amp)	(4) Duration (minutes)	(5) Time to end of section (minutes)	(6) Capacity rating Factor (Kt)	(7) Temp derating factor (Tt)	(8) Required size (3)x(6)x(7) (Rated Ah)	
							Pos	Neg
Section 1 –First period only – If A2 is greater than A1, go to section 2								
1	A1=	A1-0=	M1=	t=M1=				***
Total								***
Section 2 –First two periods only – If A3 is greater than A2, go to section 3								
1	A1=	A1-0=	M1=	t=M1+M2=				
2	A2=	A2-A1=	M2=	t=M2=				
						Sub Total		
Total								***
Section 3 –First three periods only – If A4 is greater than A3, go to section 4								
1	A1=	A1-0=	M1=	t=M1+…M3=				
2	A2=	A2-A1=	M2=	t=M2+M3=				
3	A3=	A3-A2=	M3=	t=M3=				
						Sub Total		
Total								***
Section 4 –First four periods only – If A5 is greater than A4, go to section 5								
1	A1=	A1-0=	M1=	t=M1+…M4=				
2	A2=	A2-A1=	M2=	t=M2+…M4=				
3	A3=	A3-A2=	M3=	t=M3+M4=				
4	A4=	A4-A3=	M4=	t=M4=				
						Sub Total		
Total								***
Section 5 –First five periods only – If A6 is greater than A5, go to section 6								
1	A1=	A1-0=	M1=	t=M1+…M5=				
2	A2=	A2-A1=	M2=	t=M2+…M5=				
3	A3=	A3-A2=	M3=	t=M3+…M5=				
4	A4=	A4-A3=	M4=	t=M4+M5=				
5	A5=	A5-A4=	M5=	t=M5=				
						Sub Total		
Total								***
Section 6 –First six periods only – If A7 is greater than A6, go to section 7								
1	A1=	A1-0=	M1=	t=M1+…M6=				
2	A2=	A2-A1=	M2=	t=M2+…M6=				
3	A3=	A3-A2=	M3=	t=M3+…M6=				
4	A4=	A4-A3=	M4=	t=M4+…M6=				
5	A5=	A5-A4=	M5=	t=M5+M6=				
6	A6=	A6-A5=	M6=	t=M6=				
						Sub Total		

Total								***
Section 7 –First seven periods only – If A8 is greater than A7, go to section 8								
1	A1=	A1-0=	M1=	t=M1+…M7=				
2	A2=	A2-A1=	M2=	t=M2+…M7=				
3	A3=	A3-A2=	M3=	t=M3+…M7=				
4	A4=	A4-A3=	M4=	t=M4+…M7=				
5	A5=	A5-A4=	M5=	t=M5+…M7=				
6	A6=	A6-A5=	M6=	t=M6+M7=				
7	A7=	A7-A6=	M7=	t=M7=				
						Sub Total		
Total								***
Random Equipment Load Only (if needed)								
R	AR=	AR-0=	MR=	t=MR=				***

The Total values calculated in column (8) of Table 4 are used to determine the required battery cell size. The following formulas are used:

$$\boldsymbol{Max\ Section\ Size} + \boldsymbol{Random\ Section\ size} = \boldsymbol{Uncorrected\ Size\ (US)} \tag{2.4}$$

$$\textbf{Uncorrected Size (US)} \times \textbf{Design Margin} \times \textbf{Aging factor} = \textbf{Corrected Capacity} \tag{2.5}$$

The **Maximum Section size** refers to which ever section has the greatest calculated value. **Random Section size** refers to any random additional loads that are expected to form part of the load profile. No such loads are indicated in the example above.

2.3.2 Preliminary sizing of supercapacitors

The section explains a method to calculate the initial sizing for a supercapacitor. The method is useful to make a good first estimate for an appropriate size supercapacitor for a specific application [24].

The method requires that the basic system parameters are determined. These parameters are the following:

Variable	Description
V_{max}	Maximum allowable voltage (V)
V_w	Working / operating voltage (V)
V_{min}	Minimum allowable voltage (V)
Power	Required power (kW)
Δt	Duration of discharge (s)

Figure 11 indicates a constant current discharge profile of a supercapacitor. The supercapacitor's voltage profile has a capacitive and a resistive component. The capacitive component represents the voltage change in energy within the supercapacitor, whereas the resistive component represents the voltage change due to the equivalent series resistor (ESR) of the supercapacitor [24].

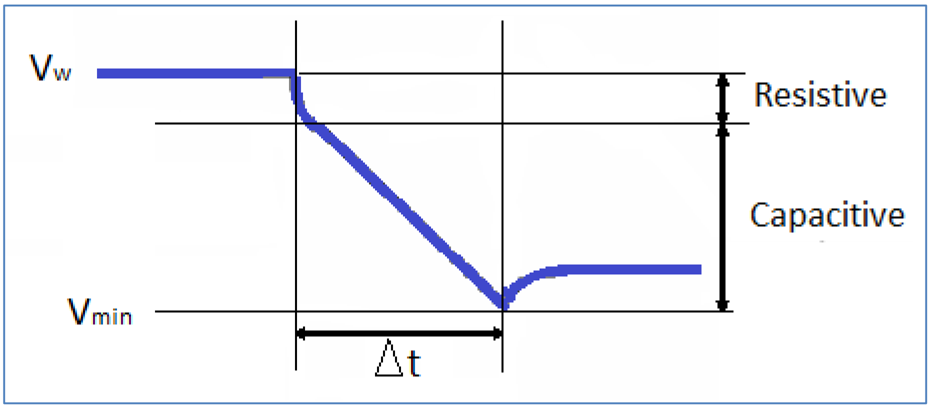

Figure 11: Constant current discharge profile of a supercapacitor [24]

The parameters as defined above are then used to calculate the variables required to solve the equation:

$$\Delta V = i_{avg} \cdot \frac{\Delta t}{C} + i_{avg} \cdot R \tag{2.6}$$

where:

- $\boldsymbol{\Delta V}$ is the change in voltage during the discharge of the capacitor,
- $\boldsymbol{C}$ is the capacitance of the complete supercapacitor system,
- $\boldsymbol{R}$ is the resitance of the complete supercapacitor system,
- $\boldsymbol{i_{avg}}$ is the average current of the capacitor during discharge, and
- $\boldsymbol{\Delta t}$ is the discharge duration in terms of seconds.

This value for $\boldsymbol{\Delta V}$ is calculated by the following:

$$\boldsymbol{\Delta V = V_w - V_{min}} \, . \tag{2.7}$$

The average current value is calculated by:

$$\boldsymbol{i_{avg} = \frac{i_{max} + i_{min}}{2}}, \tag{2.8}$$

where:

$i_{max} = \frac{Power}{V_{min}}$ and $i_{min} = \frac{Power}{V_{max}}$.

The stack capacitance, C, is the value of the complete supercapacitor system. The value is based on the number of capacitors in series or parallel.

The product of the capacitance and resistance values of a supercapacitor has the RC time constant of the supercapacitor as result [24]. Through manipulating the equation, the resistance value of the supercapacitor can be calculated.

$$\tau = R \cdot C_0$$
$$\therefore R = \tau / C_0 \qquad (2.9)$$

If the time constant for an application is known, the resistance and capacitance values for the supercapacitor can be calculated. If the time constant for an application is unknown, a value of 1 second is used and the calculation is repeated until it meets the cell requirements [24].

Solving for *C*, equation (2.6) becomes

$$C = \frac{i}{\Delta V} \cdot (\Delta t + \tau)\ . \qquad (2.10)$$

Using the calculated stack capacitance, the required cell capacitance can be calculated by manipulating the following equation:

$$C_{Total} = C_{Cell} \cdot \frac{nCells_p}{nCells_s}$$

$$\therefore\ C_{Cell} = C_{Total} \cdot \frac{nCells_s}{nCells_p} \qquad (2.11)$$

where $nCells_s$ is the number of series cells and $nCells_p$ is the number of parallel cells.

The number of parallel cells is calculated by the required current, whereas the number of series cells is calculated by the required voltage. If a single cell supercapacitor can deliver sufficient current, the number of parallel cells is 1. The number of series cells is calculated using the rated cell voltage.

$$nCells_s = \frac{V_{Req}}{V_{Rated}} \quad (2.12)$$

The result of the cell calculation is compared with actual product offerings to determine the appropriate size supercapacitor [24].

2.3.3 Sizing battery chargers

The required charger size of an application is a function of the capacity removed from the battery during discharge, the load of the system, and the required recharge time. Although this study only investigates the discharge characteristics of the batteries and supercapacitors, the influence on the required charger size is also taken into consideration. This will allow a deeper impact study on the total cost saving due to the addition of a supercapacitor. The section explains the method to calculate the required size battery charger for each application.

Designing a charger requires consideration of many aspects including the maximum system voltage, minimum system voltages, cable losses, and the number of blocking and dropping diodes required. For this study, however, these details are not relevant as they do not influence the cost of the charger. The determining factor for this study is the actual size of the required charger, i.e. the ampere rating of the device.
The calculations in this section, therefore, only indicate the method of calculating the size charger required for an application.

<u>Constant and momentary loads</u>

Stationary battery chargers are designed to accommodate constant loads while recharging batteries. It is recommended that momentary loads are accommodated by the battery, and not the charger. Battery chargers also offer the best efficiencies when they operate close to their full load rating. It is therefore imperative to calculate the required size charger as accurately as possible [25].

Properly calculating the required charger for an application is done with the following equation [25]:

$$\frac{(Ah_{\mathrm{Re}m}) \bullet R}{T} + L = C_{Size} \tag{2.13}$$

where:

- $Ah_{\mathrm{Re}m}$ is the number Ah removed calculated by using the load profile and IEEE recommended practice for sizing batteries, as explained in section 2.3.1,
- R is the recharge factor, determined by the additional energy required to recharge a given battery. Valve regulated NiCd batteries typically require a recharge factor of 1.4,
- T is desired recharge time value in whole hours. Typically this value ranges between eight and twelve hours. For this study, ten hours is used as the desired recharge time,
- L is the value of constant load that the charger has to supply while charging the battery, and
- C_{Size} is the charger output current as the result of the calculation, given in ampere.

Charger manufacturers typically build chargers in a specific range of sizes. This is because of the high cost to perform type testing on different size of chargers [26]. Type testing is a process whereby a specific design of charger undergo a wide range of tests. Tests conducted for a type test range from paint thickness tests, to electromagnetic compatibility (EMC) and radio-frequency interference (RFI) tests.

Once the required charger size is calculated, the next charger size available from the manufacturer is selected as the required battery charger. The available range of charger sizes from the manufacturer, studied in this dissertation is 30 A, 60 A, 100 A, 150 A, 400 A, and 750 A.

2.3.4 **H_2 extraction system**

During the final stages of charging, hydrogen and oxygen are emitted from battery cells [27]. These gasses require extraction in order to maintain a safe working environment. Larger batteries emit more gasses than smaller batteries. As with the chargers, the influence on the size and complexity of the extraction system is taken into consideration in order to conduct a full impact study of the potential cost saving due to the addition of the supercapacitor.

When a gas mixture has a hydrogen concentration of a volume fraction between 4 % and 75 %, it is considered explosive. Oxygen enrichment will further enhance burning [28]. Safety standards dictate that a mixture of flammable gas with air is considered safe only if the gas concentration is less than volume fraction of 20 % of the lower explosive limit [28].

Due to the difficulty of controlling ignition sources in equipment rooms, the best strategy to prevent explosions in rooms where batteries are charged is to provide sufficient ventilation. Ventilating the room will dilute the explosive atmosphere to below the explosive limit [28].

The hydrogen evolution[2] of a system can be calculated as follows [28]:

$$V = N \times I \times c \tag{2.14}$$

where:

- ***V*** is the volume of hydrogen liberated per hour (m^3/h, at standard atmospheric pressure),
- ***N*** is the number of cells in the battery,
- ***I*** is the overcharge current, given in amperes (A),
- ***c*** is a constant, ***0.00045*** (m^3A^{-1}).

The gas evolution of a battery is a function of the amount of water electrolyzed into hydrogen and oxygen. The equation above disregards technical data from specific battery technologies. The battery technology used for this study is the ALCAD Vantex battery. This battery technology has a recombination level of 90 %. The amount of water that is electrolyzed into gas is, therefore, very little. The typical value of hydrogen emissions liberated for this battery technology is three cubic centimeters of hydrogen per ampere-hour of the cell per day [7].

2 A hydrogen evolution reaction is the production of hydrogen through the process of water electrolysis.

When converting the hydrogen emissions liberated by the Vantex cell to cubic meters per hour, the volume of hydrogen liberated by the cell can be calculated as follows:

$$V_{H_2} = \frac{3 \times 10^{-6}}{24} \cdot Ah \ \cdot number\ of\ cells \tag{2.15}$$

Calculating the amount of hydrogen emitted in a specific room is dependent on the size of the room or battery cabinet. The volume of the room is calculated by deducting the volume of all equipment in the room from the volume of the room itself. This will result in the volume of air in the room [28].

For this study, it is assumed that all batteries are installed in an isolated battery cabinet with its own extraction and ducting system. In doing so, the size of the battery room, as well as all additional equipment in that room, can be disregarded. This is a good practice when the required details about the room are unknown. If there are any other hydrogen producing equipment in the room, for example, it will not influence the calculation for this specific design.

The dimensions of the battery cubicle selected for this study are 800 mm x 650 mm x 1950 mm. The volume of the cubicle is therefore 1.014 m^3. The volume of air in the cubicle is given by the following equation:

$$V_{air} = V_{cubicle} - (V_{cell} \times number\ of\ cells) \tag{2.16}$$

$$\therefore V_{air} = 1.014 - (V_{cell} \times number\ of\ cells)$$

The percentage concentration of hydrogen in the cubicle after one hour of charging would then become [28]:

$$\%H_2 = \frac{V_{H_2}}{V_{air}} \cdot 10 \tag{2.17}$$

To ensure the concentration of hydrogen gas remains below a volume fraction of 20% of the lower explosive limit, the air should be changed at a calculated rate. The rate of required air changes is calculated as follows [28]:

$$R_{air\ changes} = \frac{\%H_2}{20\% \times 4} \tag{2.18}$$

Extraction fans are typically rated according to the air flow they can provide. The air flow required to maintain the required air changes is calculated with the following equation:

$$F = R_{air\ changes} \times V_{air} \tag{2.19}$$

Once the required extraction fan size is calculated, the next fan size available from manufacturers is selected as the required fan.

The general arrangement of the relevant equipment room is unknown. The routing and lengths of ducts can therefore not be calculated. The routing and lengths of these ducts are not influenced by the size of the battery, nor the amount of H_2 that needs extracting. Therefore, for the purpose of this study, the ducting is deemed irrelevant and is disregarded.

Due to the potential explosive characteristics of the vented gas, the fans used for the extraction system should explosion proof (Ex rated). The range of explosion proof duct fans, as per the Systemair catalogue, is used during this study.

2.4 MODELLING BATTERIES AND SUPERCAPACITORS

This section describes the details of the proposed supercapacitor and battery model to be used during simulations. Both the models discussed in this section have been validated in existing studies.

2.4.1 **Supercapacitor**

This section discusses the proposed model for the supercapacitor. The model represents most types of supercapacitors. This is achieved by implementing a generic model with a specific set of parameters. Figure 12 illustrates the equivalent circuit for the supercapacitor model [29].

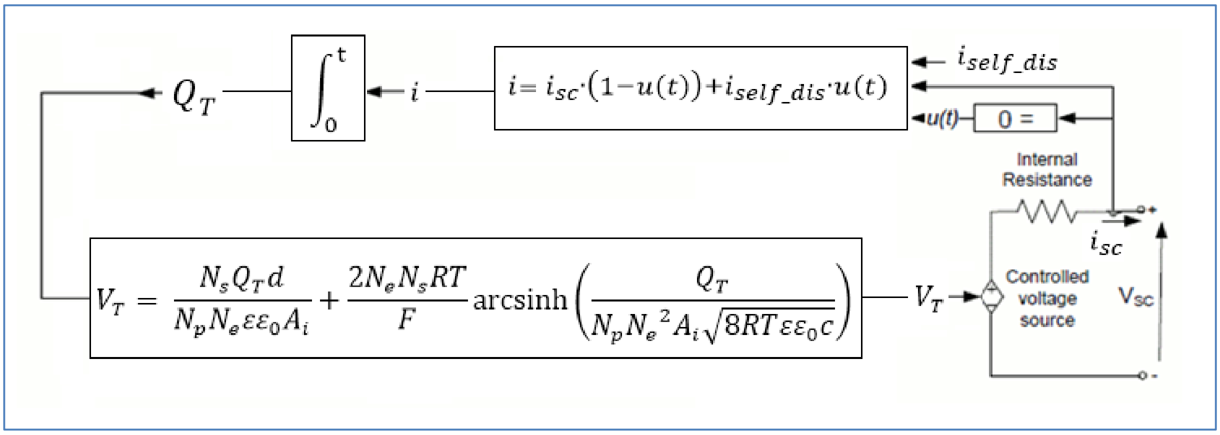

Figure 12: Proposed supercapacitor model [29]

A Stern equation is used to express the output voltage of the supercapacitor:

$$V_{SC} = \frac{N_s Q_T d}{N_p N_e \varepsilon \varepsilon_0 A_i} + \frac{2 N_e N_s RT}{F} \sinh^{-1}\left(\frac{Q_T}{N_p {N_e}^2 A_i \sqrt{8RT \varepsilon \varepsilon_0 c}}\right) - R_{SC} \cdot i_{SC} \qquad (2.20)$$

with

$$Q_T = \int_0^t i_{SC} \, dt \qquad (2.21)$$

Table 5 lists all the Stern equation variables and their descriptions.

Table 5: Stern equation variables and descriptions

Variable	Description
A_i	Interfacial area between electrodes and electrolyte (m2)
C	Molar concentration (mol m −3) equal to c = 1/(8NAr3)
F	Faraday constant
i_{SC}	Supercapacitor current (A)
V_{SC}	Supercapacitor voltage (V)
C_T	Total capacitance (F)
R_{SC}	Total resistance (ohms)
N_e	Number of layers of electrodes
NA	Avogadro constant
N_p	Number of parallel supercapacitors
N_s	Number of series supercapacitors
Q_T	Electric charge (C)

R	Ideal gas constant
D	Molecular radius
T	Operating temperature (K)
ε	Permittivity of material
ε_0	Permittivity of free space

The supercapacitor electric charge is modified, when $i_{SC} = 0$, in order to represent the self-discharge phenomenon of the supercapacitor. The electric charge then becomes as follows:

$$Q_T = \int i_{self\_dis} dt \tag{2.22}$$

where

$$i_{self\_dis} = \begin{cases} \frac{C_T \alpha_1}{1+sR_{SC}C_T} & if\ t - t_{oc} \leq t_3 \\ \frac{C_T \alpha_2}{1+sR_{SC}C_T} & if\ t_3 < t - t_{oc} \leq t_4 \\ \frac{C_T \alpha_3}{1+sR_{SC}C_T} & if\ t - t_{oc} > t_4 \end{cases} \tag{2.23}$$

Figure 13 indicates the supercapacitor model voltage curve. The rates of change of the supercapacitor voltage during time intervals (t_{oc}, t_3), (t_3, t_4), and (t_4, t_5), determine the constants α_1, α_2 and α_3 respectively.

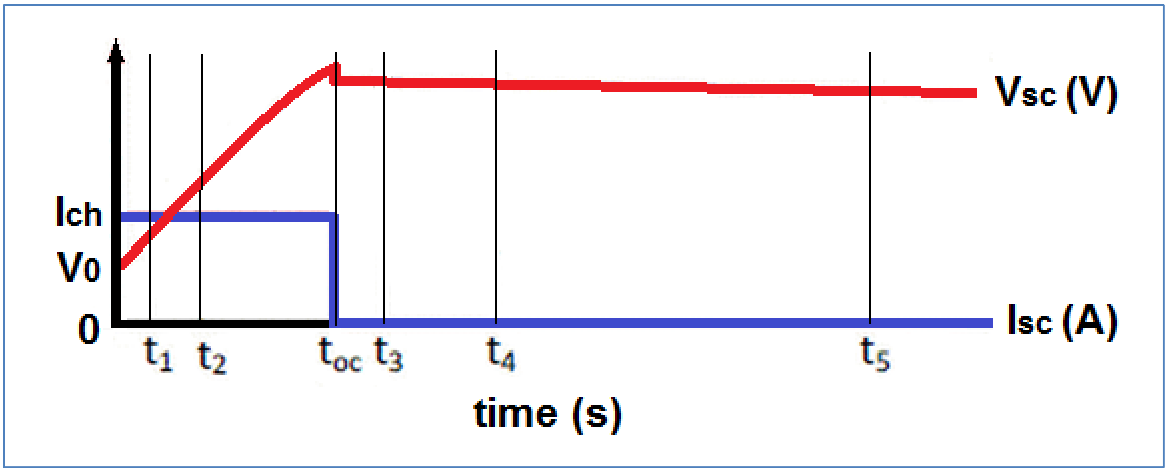

Figure 13: Supercapacitor model voltage curve model [29]

2.4.1.1 Model assumptions

The following list indicates the assumptions made regarding the proposed model [29]:

- Internal resistance and capacitance are assumed constant during the charge and the discharge cycles.
- The model does not take the temperature effect into account.
- No aging effect is taken into account.
- Charge redistribution is the same for all values of voltage.
- The model does not take into account any cell balancing.
- Current through the supercapacitor is assumed to be continuous.

2.4.1.2 Model validation

The model is built based on the Stern model as explained and validated in [30] and [31]. The data from the study conducted in [31], also show significant nonlinear responses at high frequency. This is contrary to the understanding that a double layer capacitor is more linear than the Faradaic processes. The study proves that the assumption of a linear capacitor is not valid when using large excitations and it is necessary to take the capacitance nonlinearity into account when investigating the Faradaic kinetics of a heterogeneous interface.

The proposed supercapacitor model uses predetermined parameters of the Stern model. These values can be used as default values to represent a common supercapacitor. When using the predetermined parameters, experimental tests indicated that the model has a maximum error of 2% for both charge and discharge cycles [29].

2.4.2 **Batteries**

2.4.2.1 Lifecycle comparison of battery types

For this study, two battery technologies where considered, namely Lead-acid batteries, and Nickel Cadmium (NiCd) batteries. One of the key focuses of the study is the cost impact the results will present. The technology with the lowest life-cycle cost is therefore used for this study, as it supports the above mentioned key focus.

In order to compare battery life cycle costs, there are a number of factors that need to be considered. These factors include the following:

- initial costs,
- administrative costs,
- transportation costs,
- storage costs,
- installation costs,
- commissioning costs,
- routine surveillance costs,
- end of life testing costs,
- decommissioning costs,
- disposal costs,
- replacement costs.

According to studies, NiCd batteries are a more cost effective option compared to lead-Acid batteries [32], [33]. It has high performance, good cycling capability, and resistance to abuse, particularly in the form of high temperatures. NiCd batteries have a higher initial cost than lead acid batteries, but demonstrates a lower life cycle cost [33].

The following section briefly discusses some of the life-cycle cost components.

2.4.2.1.1 High performance

NiCd batteries have superior performance characteristics when compared to lead acid batteries [32]. In NiCd batteries, there is no corrosion or deterioration of the underlying plate structure. This enables the use of thinner plates, without any shortening of life. A battery with these thinner plates will cost more per ampere hour than a thick-plate battery, but it will have much better capacity utilization in high-rate discharges and is therefore more cost effective [33].

While the same utilization issues apply to lead-acid batteries, the positive grid corrosion that is inherent to all lead-acid batteries attacks thin plates at a much greater rate that thick plates. A thin plate lead-acid battery is more cost-effective for high-rate discharge, but it also has a shorter life. [33]

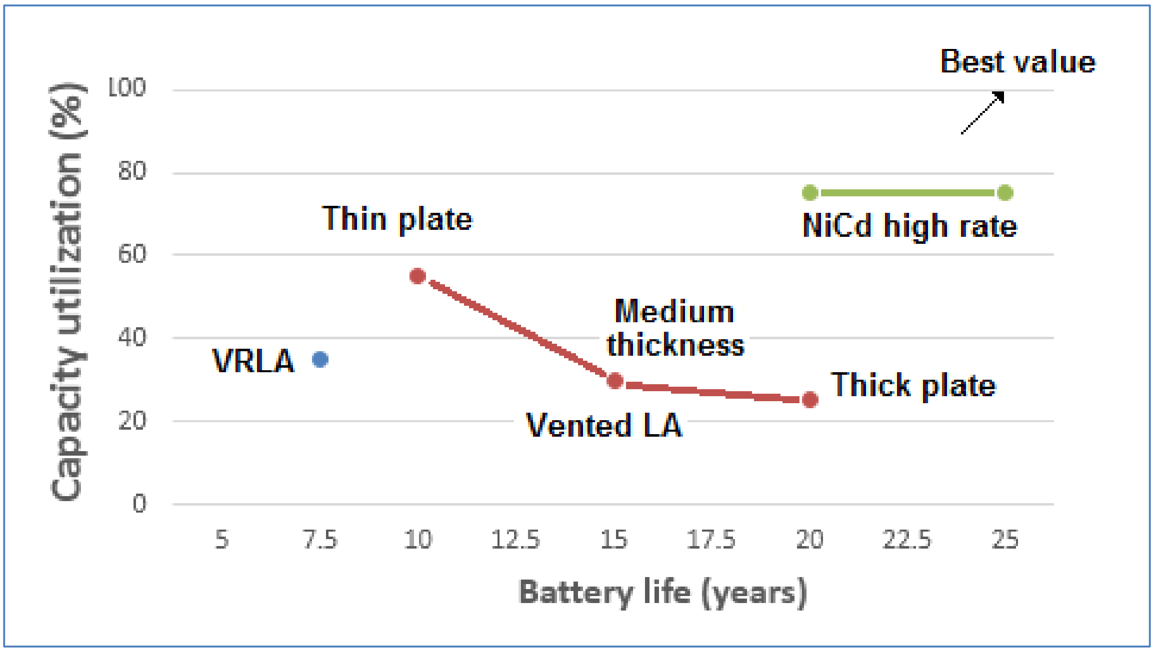

Figure 14: 20 minute capacity utilization vs. battery life [33]

Figure 14 indicates that 20-25 year NiCd batteries provide a significantly better performance-to-life ratio than lead-acid batteries.

2.4.2.1.2 Low maintenance

Battery maintenance involves various tasks. These tasks include water additions, voltage readings, specific gravity checks, internal resistance measurements, and connection maintenance. Maintenance programs for NiCd batteries mainly consist of float voltage readings and water additions. Figure 15 compares the required watering intervals of different technologies [33].

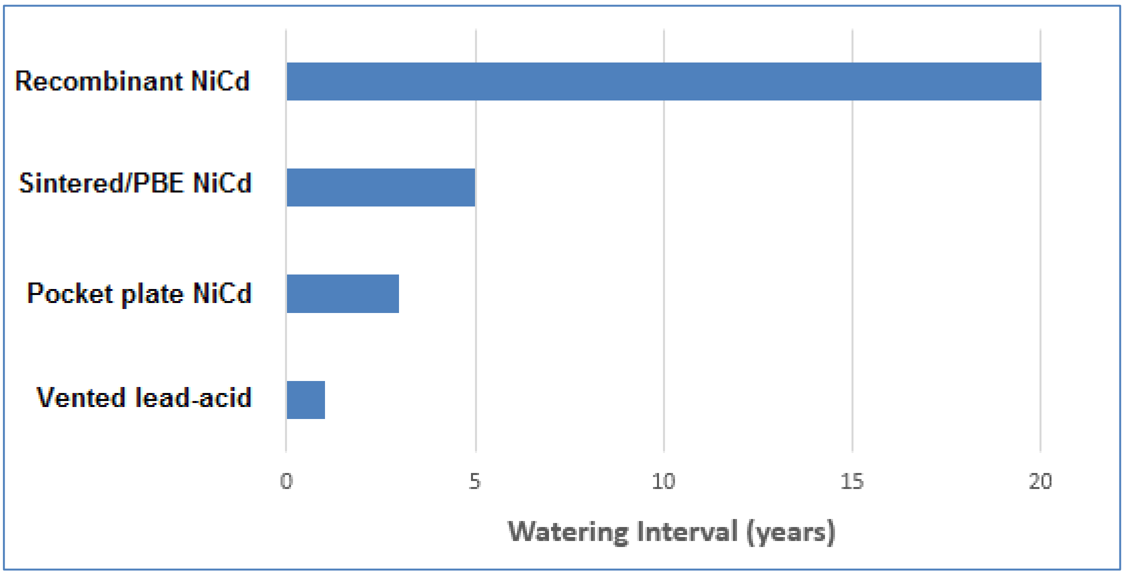

Figure 15: Watering interval for battery types [33]

2.4.2.1.3 High operating temperatures

NiCd batteries are much more resistant to high temperatures. Lead-Acid battery life is reduced by approximately 50 % for every 8 °C above 25 °C. The same increase in temperature will decrease the NiCd battery life with only 20% [33]. Figure 16 indicates the effect of temperature on the calendar battery life [32].

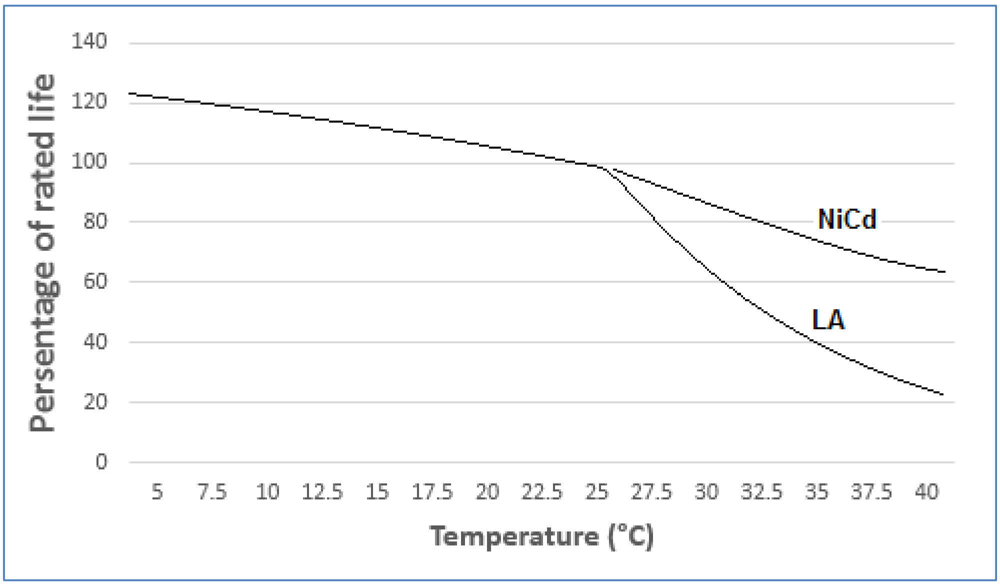

Figure 16: Effect of temperature on calendar life of battery [32]

Due to the lower life-cycle cost of NiCd batteries, this study will use the NiCd battery technology.

2.4.2.2 NiCd battery model

This section discusses the proposed model for the NiCd battery. As the focus falls on the discharge characteristic of the battery during this study, this section does not discuss the charge characteristics of the proposed battery model.

The battery's hydrogen and oxygen gas evolution, however, occurs under high charge currents. This high charge current is typically referred to as the auto boost current. Battery hydrogen emission calculations are only dependent on the capacity of the cell, the charge current, and the relevant battery technology. Hence, the charge characteristics of the battery itself, does not influence the calculation of the H_2 extraction system.

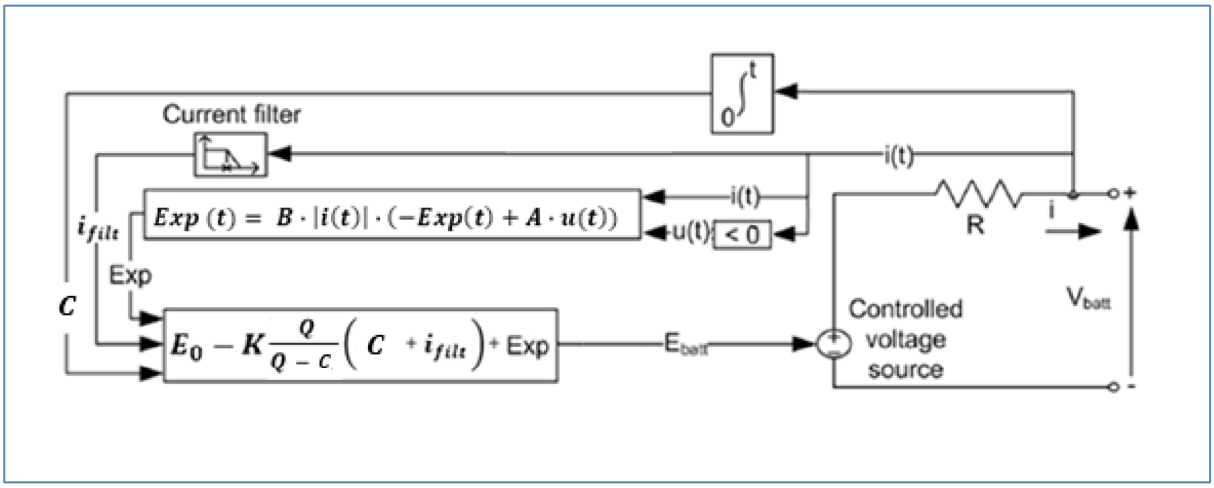

Figure 17: Proposed battery discharge model [34]

The battery voltage obtained is given by the following [34]:

$$V_{batt} = E_0 - K\left(\frac{Q}{Q-C}\right)C - R(i) + Aexp(-B \cdot C) - K\left(\frac{Q}{Q-C}\right) \cdot i_{filt} \qquad (2.24)$$

where the various symbols are as explained in Table 6.

Table 6: Battery model voltage equation variables and descriptions

Variable	Description
V_{batt}	Battery voltage (V)
E_0	Battery constant voltage (V)

K	Polarization constant (V/(Ah))
Q	Battery capacity (Ah)
C	$\int idt$ = actual battery charge (Ah)
A	Exponential zone time amplitude (V)
B	Exponential zone time constant inverse $(Ah)^{-1}$
R	Internal resistance (Ω)
i	Battery current (A)
i_{filt}	Filtered current (A)

Figure 18 indicates the typical nominal current discharge characteristics of the NiCd cell.

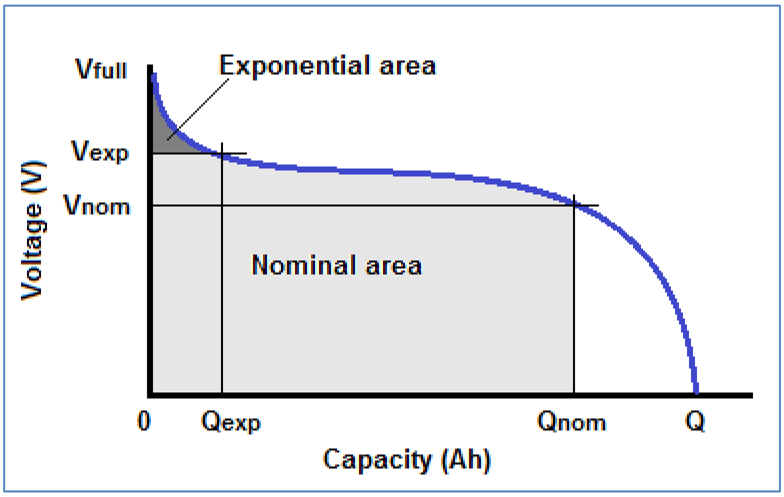

Figure 18: Typical nominal current discharge curve of battery [34]

The proposed model can accurately represent the voltage dynamics when the current varies [34]. This is a key aspect of the model as the system to be simulated in this study has a voltage controlled, current varying load.

The dynamic model parameters for the proposed model can be extracted from the manufacturer's discharge curve. Battery manufacturers typically provide discharge characteristics from where it is possible to extract the following [34]:

- Fully charged voltage (V_{full})
- End of the exponential zone (Q_{exp}, V_{exp})
- End of nominal zone (Q_{nom}, V_{nom}),

- Maximum capacity (Q)
- Internal resistance (R).

Using the equation above, together with the values extracted from the manufacturer's datasheets, the following set of equations can be solved [34]:

$$V_{full} = E_0 - R \cdot i + A \tag{2.25}$$

$$V_{exp} = E_0 - K\left(\frac{Q}{Q - Qexp}\right)\left(Q_{exp} + i\right) - R \cdot i + A_{exp}\left(\frac{-3}{Q_{exp}} \cdot Q_{exp}\right) \tag{2.26}$$

$$V_{nom} = E_0 - K\left(\frac{Q}{Q - Q_{nom}}\right)\left(Q_{nom} + i\right) - R \cdot i + A_{exp}\left(\frac{-3}{Q_{exp}} \cdot Q_{nom}\right) \tag{2.27}$$

2.4.2.2.1 Model assumptions

The following list indicates the assumptions made regarding the proposed model [34]:

- The internal resistance is assumed constant during the charge and discharge cycles and does not vary with the amplitude of the current.
- The capacity of the battery does not change with the amplitude of the current (The Peukert effect is disregarded).
- The temperature does not affect the model behaviour.
- Battery self discharge is not represented in the model.
- The battery has no memory effect.

2.4.2.2.2 Model limitations

The following list indicates the proposed model limitations [34]:

- The maximum No-Load battery voltage is 0 V and the maximum battery voltage is $2 \cdot E_0$.
- The minimum capacity of the battery is 0 Ah and the maximum capacity is Q. Therefore, the maximum state of charge cannot be greater than 100 %, even if the battery is overcharged.

It is also important to note that the manufacturer's curve is obtained at a constant current.

2.4.2.2.3 Model validation

The experimental validation done in [34] shows that even if the model parameters are extracted from a steady state curve, the model still produce results accurately, within a 5 % error. When the state of charge (SOC) decreases below 20 %, the error of simulation becomes approximately 10 %. The applications investigated in this study typical only discharge to minimum of 50 %, and therefore the model percentage error is acceptable.

The proposed battery model, as validated in [34], is also used as the MATLAB ® SimPowerSystems™ battery model. The SimPowerSystems™ battery model, therefore, allows for an adequate representation of a NiCd battery real behavior, based on the information extracted from the manufacturer's datasheet.

2.5 CRITICAL LITERATURE REVIEW

Throughout the literature there are numerous studies pertaining to stochastic methodologies which are used to define the load profiles for a specific system. The applications include UPS systems, renewable energies as well as electric vehicles. No studies could be found, however, that addresses the exact same problem which this study investigates.

The study conducted in [18] presents a stochastic simulation to size a battery using the Monte Carlo theory. In the study, the non-deterministic factors includes weather conditions, demand peaks, and outage events. Due to the non-deterministic nature of the load, this study suggest that the battery capacity calculations should be based on a probabilistic approach, rather than a deterministic approach.

For the study in [18], the consumer has to weigh the percentage of the risk of the system not being able to sustain the power requirements, compared to the cost of the battery investment. If the consumer decide that its application only has to survive 90 % of power interruptions, the battery can be sized accordingly.

The study in [18] also compares the stochastic method of sizing batteries to the traditional technique of sizing batteries for UPS applications. The traditional technique mentioned in the study is were the battery capacity is sized by defining the load profile based on the worst case demand. The study found that consumers may save as much 45 % of battery capacity when using the stochastic method, compared to the traditional method. The authors of the study does stress the fact that consumers will carry the additional risk of the system not being able to supply the full load in a worst case scenario.

Using a stochastic method, the cost of damages or losses due to an outage is also estimated in [18]. As this study researched UPS systems for commercial use, the estimations are based on surveys where the customers estimated their cost or losses associated with power interruptions. The lifecycle cost in [18] considers factors including the capital cost, installation and engineering costs, operational and maintenance cost, replacement cost, utility electricity cost, battery cost, and any revenue or incentives offered by the government.

The study conducted in [35] presents an advanced statistical method for wind power forecasting that is based on artificial intelligence. The method explained in the study requires historical data of power measurements and meteorological forecasts of wind speeds and direction. The meteorological data used in the study is obtained from numerical wind predicitions. These predictions are used for the first hour of simulation. The results from the simulation is then used as past wind power for the next prediction.

Because this process runs iteratively, the error in wind power prediction increases as the prediction period increases. In order to decrease the percentage error, the study introduces a radial basis function network to the system, which estimates the quality of the numerical wind predictions. The maximum percentage error decreased from as much as 50 %, down to 30 %. Although the authors of [35] managed to improve the percentage error of the simulation, implementing a methodology such as the the Markov Chain Monte Carlo simulation methodology may prove to be more advantageous. The criteria for a state change will be defined and, thus, the percentage error will not increase as the prediction period increases.

Similar to the studies in [18] and [35], the load profile definition in this present study is also based on a stochastic methodology. The studies differ from this one in that the profiles created in [18] and [35] use historical data as input to their simulation models. In the present study, there are no historical data available, nor is it allowed to measure data from a live plant. The target distribution used as input to the simulations are based on the operating philosophies of the plant.

Furthermore, the study in [18] makes use of only the Monte Carlo theory. The present study introduces the Markov Chain Monte Carlo simulation methodology. This decision is made because the simulations are of a dynamic process, which is greatly dependent on its current state. The Markov Chain Monte Carlo simulation theory introduces a more accurate result when approximating the load profiles of a dynamic system.

The literature also contains numerous studies on the influence which supercapacitors have on batteries in terms of life cycle costs. The study in [36] investigates the expected life cycle cost of a battery-supercapacitor energy storage system for a wind farm. Due to the level of wind farm output fluctuations, caused by the rapid changing of wind conditions, the authors believed that supercapacitors will have a positive effect on the life cycle costs for wind farm applications.

The authors of [36] briefly investigated three types of hybrid energy systems in order to determine the most cost effective solution. The systems investigated were superconducting magnetic energy storage, flywheel energy storage, and supercapacitor energy storage. Out of these three energy storage systems, supercapacitors proved to be the most suitable as its cost per kilowatt-hour is the lowest.

The life cycle cost calculation in [36] only included capital costs and replacement costs. The replacement costs is based on the expected life of the battery and supercapacitor. The authors did not include the H_2 extraction systems, or required space in the battery rooms as part of their calculations. Furthermore, the authors from [36] state that a supercapacitor has characteristics similar to that of a conventional capacitor, and have therefore used a conventional supercapacitor when modelling the system. In reality supercapacitors exhibit a non-ideal behavior due to the porous materials used to make the electrodes. This causes supercapacitors to exhibit behavior more closely to transmission lines than conventional capacitors [37],

[38], [39], [40], [41]. Using a more accurate supercapacitor model may have an effect on the study in [36].

The study in [36] found that the use of supercapacitors is not a viable long term solution for the wind farm application. The frequency of charge and discharge cycles for wind farms is, however, much higher than what is expected for the applications in the present study.

The study in [42] investigates the possible increase in battery life in electric vehicles. The study entails maximizing the efficiency and minimizing the peak battery currents. Maximizing the efficiency was measured by the distance the vehicle can travel per kilowatt-hour. Two scenarios were compared. Firstly, a supercapacitor bank added to the vehicle and the range was tested. Secondly, an additional battery was added to the vehicle and the test repeated. The range extension provided by the the extra batteries far exceeded that of the supercapacitors. It was confirmed that supercapacitors are not cost-effective for the purpose of range extension.

The addition of the supercapacitors caused a significant battery peak power reduction. To gain the same peak power reduction benefit without supercapacitors, battery pack size has to increase quite significantly. The study suggests that a battery life extension of at least 50 % is necessary in order to render the supercapacitors a cost effective solution. The study proves that under the correct control strategies, a reduction of up to 80 % in battery current is observed when using supercapacitors.

Similar to the study in [36], the frequency of charge and discharge for electric vehicles are much higher than what is expected during the present study. This is due to the frequent requirement to accelerate and decelerate.

In the present study, the feasibility of using supercapacitors in conjunction with batteries is investigated for the application of industrial auxiliary systems. In particular, the load profiles required for industrial control and monitoring systems are investigated. The discharge periods of the profiles in this study include two and four hour periods. Typically, the charge and discharge frequency of the applications in this study may be as little as monthly. In some instances, the frequency may even be less than monthly. In these cases, the battery bank voltage is raised to a higher preset voltage, referred to as the auto boost voltage, every 28 days [16].

2.6 CONCLUSION

The main focus of the present study is to investigate whether the addition of a supercapacitor to an auxiliary power system has cost saving implications. The factors considered during the study are the battery size, the charger size, the H_2 extraction system, the battery end-of-life time, and the required maintenance practices. The standards developed and published by the IEEE and SANS for calculating these factors are adequate for the purpose of the present study.
In order to test the influence of the supercapacitor, detailed load profiles have to be defined. Since there are no historic load data available for the applications investigated in the present study, load profiles are approximated using a stochastic approach. The Markov Chain Monte Carlo simulation theory is the selected for the purpose of the load profile approximations as the profiles generated through this methodology will be reasonably accurate and realistic.

The influence of the supercapacitor is measured through comparing software simulations. The software models investigated in this chapter are existing validated models which fit in the parameters of the present study. The validated battery model includes parameters for various types of battery technologies. Since the main focus of the present study is cost, the NiCd battery technology is used during simulations as it has the lowest lifecycle cost.

CHAPTER 3: **DEFINING LOAD PROFILES**

The load of the industrial applications investigated in this dissertation is made up of the loads of different equipment and devices. These equipment and devices have different influences on the load approximation, and are broken down into two categories namely, static loads and variable loads. Items that will have a constant effect on the load calculation are classified as continuous loads. Items that have a fluctuating impact on the load calculation are classified as momentary loads.

Table 7: Load components

Item	Classification	Load (A)
DCS	Static	96.700[NOTE1]
Light Bulb in Cabinets	Variable	0.600
MTL5517 for line fault detection	Static	0.035
L2 GRVSA-660FA switch	Static	0.833
L3 GRVSW-670FA (Bus 1) switch	Static	1.083
L3 GRVSW-673FA (Bus 2) switch	Static	1.083
HP4-DC24V-F Relay (IPR and IPS)	Variable	0.063
Beckhoff Touch Screen CP6903 19"	Static	0.649
Beckhoff Cabinet PC C6920	Static	2.917
Burkert Solenoids	Variable	0.075
Phoenix Relays (Solenoids and limits)	Variable	0.010

NOTE1: The DCS load and its inrush current will differ from application to application as the number of controllers and the number of I/O is different for each application.

The control and operation of drives, pumps, actuators and valves for the applications investigated in this dissertation are managed by energizing the relevant switchgear relays or solenoids for the relevant equipment. This study only examines the load required to operate the individual devices through the control system (i.e. the relays, solenoids, etc.), and not the load of the equipment itself.

In order to test the influence that a supercapacitor has on the required battery size, the load profiles are broken into the two components shown in Figure 19.

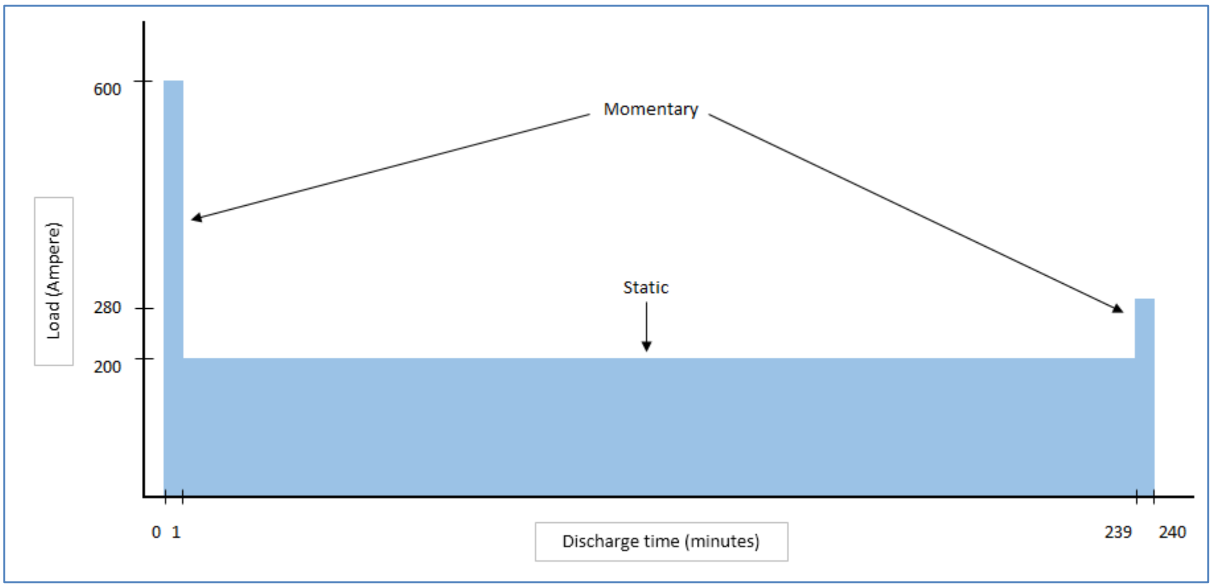

Figure 19: Classification of components that make up a typical DC load profile

Firstly, the static component of the profile is examined. The static component in Figure 19 illustrates the profile during normal operation. Determining this component's load profile depend on the worst case load profile methodology. Supercapacitors, however, only offer a possible advantage when the load varies. Therefore, more detailed and complex load profiles are approximated in the following section in order to determine the possible influence the supercapacitor may have during this component of the profile.

Secondly, the momentary loads at the start and end of the profiles are examined. Because of the sudden increase in load, the supercapacitor may provide an advantage by lowering the magnitude of these momentary loads which the battery has to supply. The influence of the supercapacitor during these periods is therefore also examined.

3.1 LOAD PROFILE DURING NORMAL OPERATION

In this section, various approximations for battery load profiles are generated. The generation method is based on the Markov Chain Monte Carlo simulation theory, as described in Section 2.2.3. The load data used for the generation is from actual industrial applications. The approximated load profiles are compared to worst-case scenario load profiles and are indicated graphically.

The Markov Chain Monte Carlo method assume a random number generator which generates uniform random numbers over the interval [0, 1]. The random numbers are generated by a computer and uses a numerical algorithm and, therefore, are not truly random but are pseudorandom numbers [43].

During simulations, it is possible for the equipment to stop or start at any time during the simulation. Changing a state during the simulation is also dependent on the current state of the equipment. Hence, a uniform probability density function is used for each state of the equipment during the simulation.

To illustrate how the probabilities are determined, consider the following example:
If a device experience a trip condition, it is assumed that the maintenance processes will ensure that the fault is corrected at any time within the following 12 hours. The device may therefore return to duty at any time during the 12 hours. The probability density function for the above example is illustrated in Figure 20 [44].

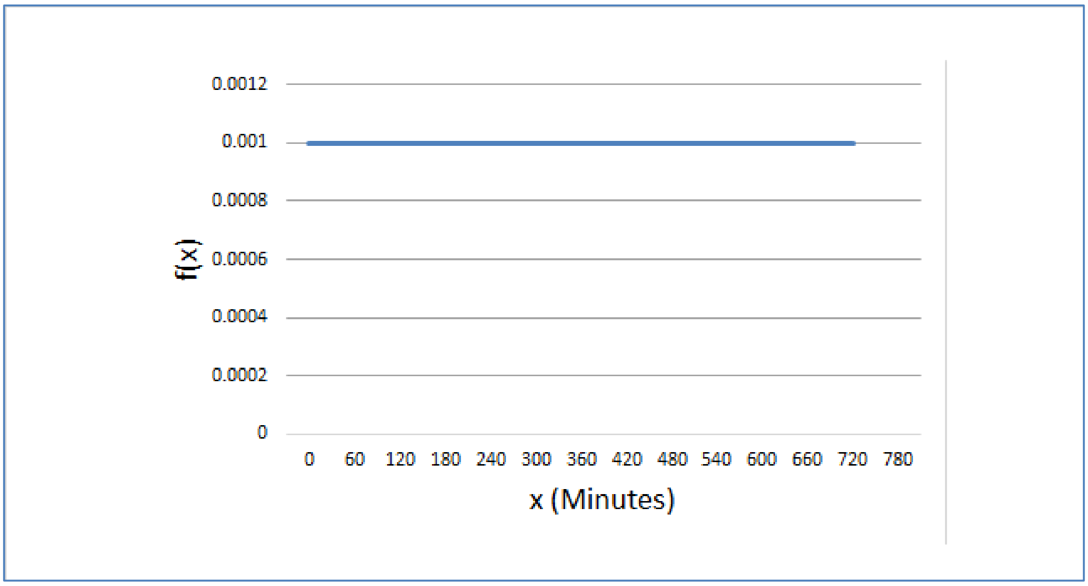

Figure 20: Example of a probability density function [44]

3.1.1 **Approximation methodology**

The IEEE recommended practice for sizing batteries, as explained in Section 2.3.1, breaks down the load profile into different sections throughout the required standby period. Whenever the load changes, a new section is created.

For this dissertation, applications for both two and four hour standby periods are investigated. Due to the dynamic nature, and therefore possibility of rapid change in the load of a control system, the load profiles are broken down in one minute intervals.

When generating the load profile for a specific application, all the equipment that forms part of the system in that application is simulated in isolation. The sum of the loads of all the simulated equipment is the resulting load.

The operation of the pumps, drives and valves are part of a dynamic process and therefore a load profile for each minute of operation cannot be defined as a certainty. For the purpose of this study, a probabilistic load profile for these scenarios is determined. Using Markov chains, the operation for this equipment is simulated by using the state the equipment is in at any given time, and either remaining in that state, or changing the state depending on the probability of change. The probabilities are approximated based on normal operation of the system, and do not cater for the rare occurrence of manual operator intervention.

3.1.2 **Approximated load Profiles**

In this section, the load profiles for four different, actual industrial applications are generated and graphically indicated. The four different applications are chosen in order to obtain data for different sizes of required batteries. It is important to note that the simulations are based on the operating philosophies of the various applications.

The simulations in this study are based on a four, or two hour time window, depending on the standby time specified for the specific application. The simulation is broken down into one minute intervals over the relevant time period. This mindset is required to logically determine realistic probability values. Whenever relevant, certain abnormal operating conditions, such as equipment trips, will be induced during the simulation in order to obtain data for all possible scenarios.

The different applications are listed in order from largest load value to smallest load value.

3.1.2.1 Application 1

The system in Application 1 is used for handling a byproduct, generated during the process. The product handling section applicable to Application 1 consists of four identical systems. Each system consists of a byproduct conditioner, conveyors, an aeration system and multiple valves. The section below explains only one of these systems. The simulation, however, includes all the systems.

The byproduct is transported from a bunker to the conditioners via an air slide, where the product is treated. The aeration system is used to ensure that all the product is transported and does not build up and block along the way. Once inside the conditioner, the product is sprayed with water. The treated product then exits the conditioner onto a conveyor. The conveyor system then conveys the treated product to a disposal site.

The equipment for Application 1, as indicated in Figure 21, is listed below:

1) Conditioning Conveyor
2) Product conditioning drive
3) Vent valve
4) Product isolating valve
5) Product flow valve
6) Rotary air distributor
7) Motorized isolation valves
8) Water isolating valve

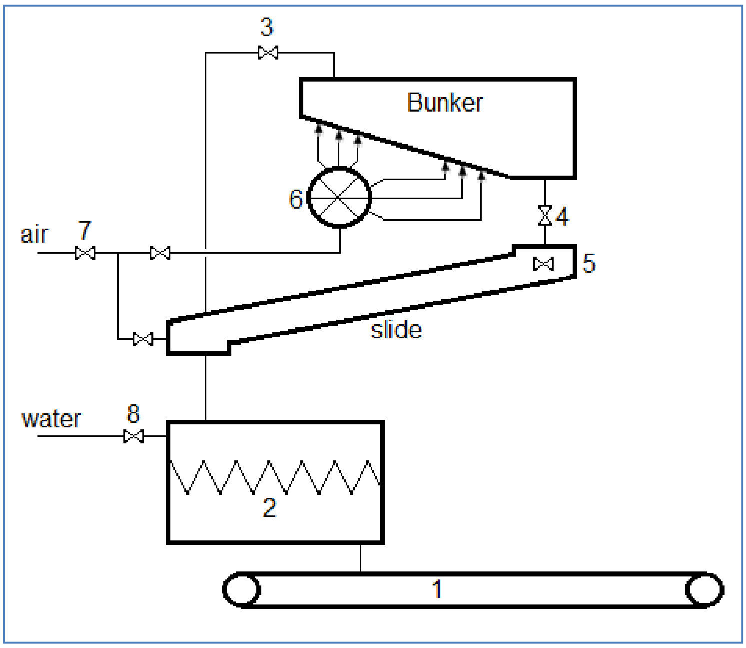

Figure 21: Simplified representation for Application 1

The following section indicates the probabilities for each of the equipment that influences the load for Application 1. These probabilities will be used for generating a load profile for the entire system under the simulated operating conditions.

3.1.2.1.1 Conditioning Conveyor

The conditioning conveyor has the capability to operate in forward and reverse mode. The conveyor operates in forward mode under normal conditions, and in reverse mode during emergencies. Due to this forward and reverse capability, it is highly probable that the conveyor will receive a start signal shortly after it has stopped. However, although it should very rarely occur, an operator may also stop the conveyor entirely for a specific reason. The simulation should, therefore, also include a small probability of not starting the conveyor immediately after it has stopped.

The system in Application 1 has a four hour standby period. The probability of the conveyor experiencing a trip condition in this period of time is very low. Under optimal operating conditions, the conveyors should be able to run for several days without stopping. Due to specific conditions, such as maintenance negligence for example, a small probability of a conveyor trip should still be included. In the event of a conveyor experience a trip condition, however, the probability of starting the conveyor within the 240 minutes is almost zero. This low probability is due to the investigations, and safety considerations associated with such as a trip.

The probabilities used for the conditioning conveyors are illustrated in Figure 22.

In the figure below, “R”, “S”, and “T” represents a running condition, stop condition, and a trip condition respectively. All arrows flowing out of the various conditions indicate a condition change. The change indicated is from the current condition, to which ever condition the arrow is pointing at. The values observed at the various arrows indicate the probability of that specific change in condition. The totalized value of all the arrows flowing out of any condition should be one, or 100%.

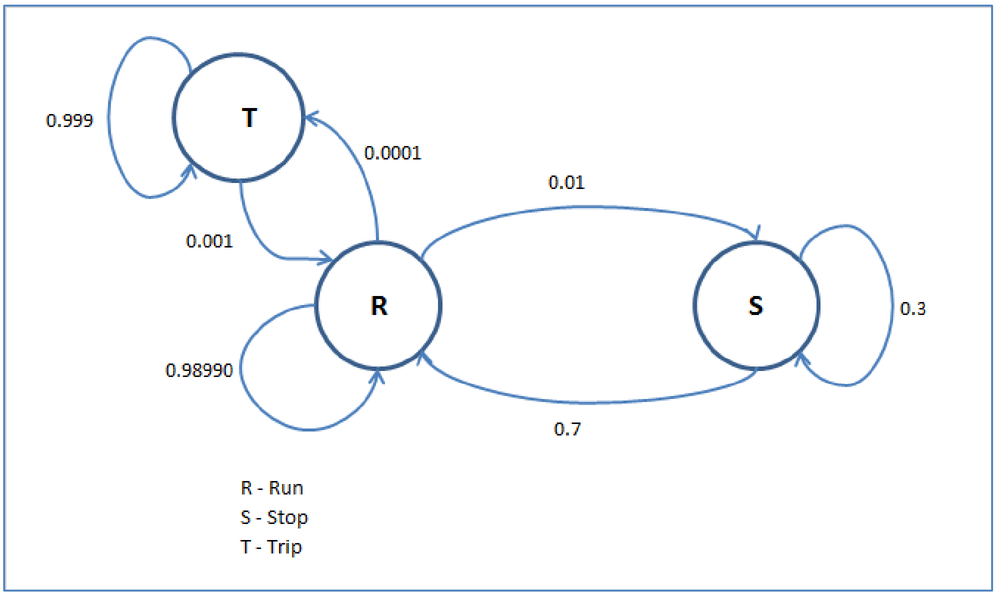

Figure 22: Conditioning conveyor operating probabilities

3.1.2.1.2 Product conditioning drive

The product conditioning drive mixes the product inside the conditioner. The drive also conveys the treated product to the outlet of the conditioner. Under normal operating conditions, the conditioning drive is always running. It is possible for an operator to stop the drive for a specific reason, but this should rarely occur. Should an operator stop the drive, however, it would have been stopped for a definite reason and therefore the drive has a low probability of starting up again within the standby period.

Under optimal operating conditions, the drive operates for days without stopping. Therefore, the probability of the drive experiencing a trip condition is very low.
If the drive has experienced a trip, it is highly improbable to start-up again within the standby period.
The probabilities used for the conditioning drive are illustrated in Figure 23.

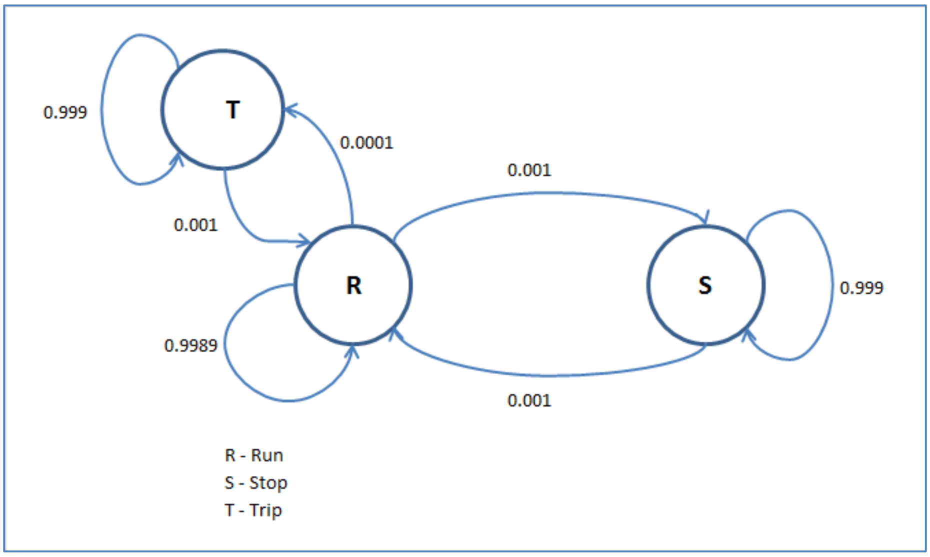

Figure 23: Conditioning drive operating probabilities

3.1.2.1.3 Vent valve

The vent valve is a safety valve that triggers during an over pressure occurrence. Under normal operating conditions the valve is closed. As this valve's function is for safety / abnormal conditions, the probability of the valve opening is very low. Should the valve open, it will only stay opened until the high pressure is relieved and would then close again. Pressure normalization happens in a relatively short period of time, and therefore the probability of the valve closing within the next minute and a half after opening, is high.

The probabilities used for the vent valve are illustrated in Figure 24.

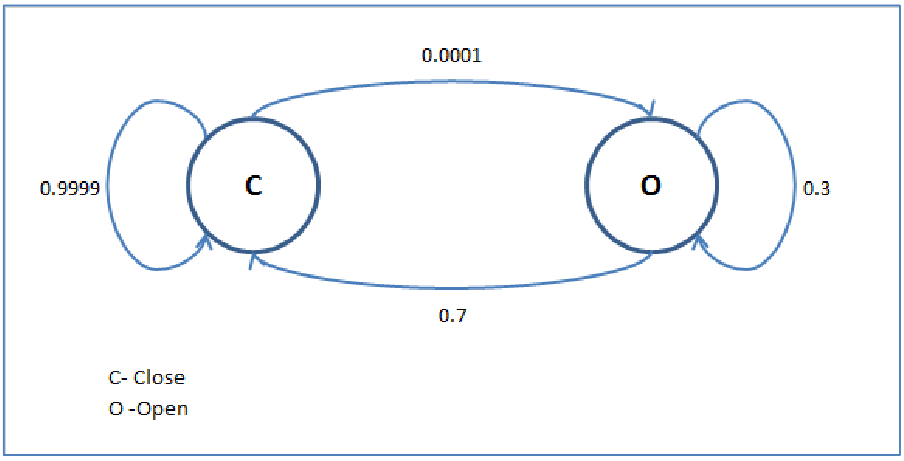

Figure 24: Dust vent valve operating probabilities

3.1.2.1.4 Product isolating, water isolating and product flow valves

The product isolating, water isolating and product flow valves are linked to the starting and stopping of the conditioning drive. Should the drive stop, the valves will close. Under normal operating conditions the valves are all open. The valves may be closed irrespective of the status of the conditioning drive for maintenance purposes. For this study, however, maintenance procedures are discarded as maintenance will not be initiated while auxiliary systems are in standby mode.

3.1.2.1.5 Rotary air distributor

The air distributor is a six way outlet rotary air distributor supplying air to the bottom of the bunkers, at specific intervals, for aeration purposes. The turning speed of the air distributor varies with changes in the rotary speed. For simulation purposes, the rotary distributor is pulsed in even one minute intervals. The distributors for each system operate independent of the other. The pulsing of distributors may therefore not be in sequence with one another.

3.1.2.1.6 Motorized isolation valves

The air supplied to the rotary air distributor, air slides and bunker passes through and is controlled by the following valves:

1) Air to rotary valve
2) Air to silo valve
3) Air to air slide valve

The valves are linked to the operation of the aeration blowers. Should the blowers stop, the valves will close. Under normal operating conditions the valves are open. The valves are closed during the start-up of the aeration blowers while pressure builds up. The pressure for this application normally reaches its operating value before or on approximately 10 minutes. Should the pressure drop below the required value during operation, the valves will close. Low pressure conditions are only experienced in rare abnormal conditions and are therefore deemed as improbable. Should the pressure drop below the requirement, and the valves are closed, the pressure will return to normal in a relatively short period of time. This short period of time will, however, most probably not be within the next interval of simulation, i.e. one minute. The maximum time before pressure is restored is around 10 minutes. Therefore, the probability of the valves opening during the next interval of simulation is low, but should open within the next 10 intervals of simulation.

The probabilities used for the above mentioned valves are illustrated in Figure 25.

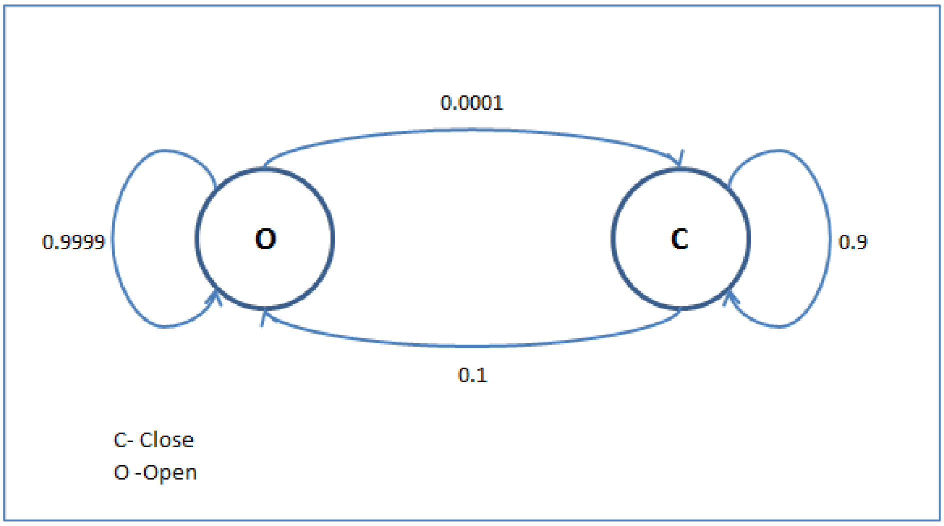

Figure 25: Motorized isolation valves operating probabilities

3.1.2.1.7 Operating principles

Starting and stopping the conveyors involves pulsing an interposing run (IPR) relay, or an interposing stop (IPS) relay. When a fault occurs, and the conveyor is stopped, there are 2 fault lamps that indicate the fault condition. When starting a conveyor, two sirens are used to warn nearby people that the conveyor is about to start. Emergency trips are managed through an emergency trip relay (ETR).

Starting and stopping conditioner drives involves pulsing either a forward or reverse IPR or IPS relay. When a fault occurs, and the drive is stopped, there are 2 fault lamps that indicate the fault condition. Emergency trips are also managed through an emergency trip relay (ETR).

All valve operation also involves pulsing either the IPS or IPR relay to open or close the valves. When a fault occurs, there are 2 fault lamps that indicate the fault condition. The valve has both an open and a closed limit in order to feed back its position.

The operation of the air distributor involves pulsing the IPS or IPR relay for each interval. When a fault occurs, there are 2 fault lamps that indicate the fault condition.

3.1.2.1.8 Application 1 approximated load profile

In order to convert the simulated results, as defined by sections above, into current (Amp) or load values, the load data for all individual equipment are linked to its operation. For example, if a conveyor has to start, it requires a pulse to the IPR relay, and two individual relays have to be energized for the two sirens to sound. The current, or load, involved for starting a conveyor then becomes the combined current required for all the above mentioned devices. Section 3.1.2.1.7 indicates the devices required for Application 1, while Table 7 indicates the typical load values.

Application 1 has a required standby period of four hours. The probabilities, as explained in the sections above, are therefore simulated for 240 intervals or minutes. Calculating all the loads required for the individual equipment yields the results in Figure 26.

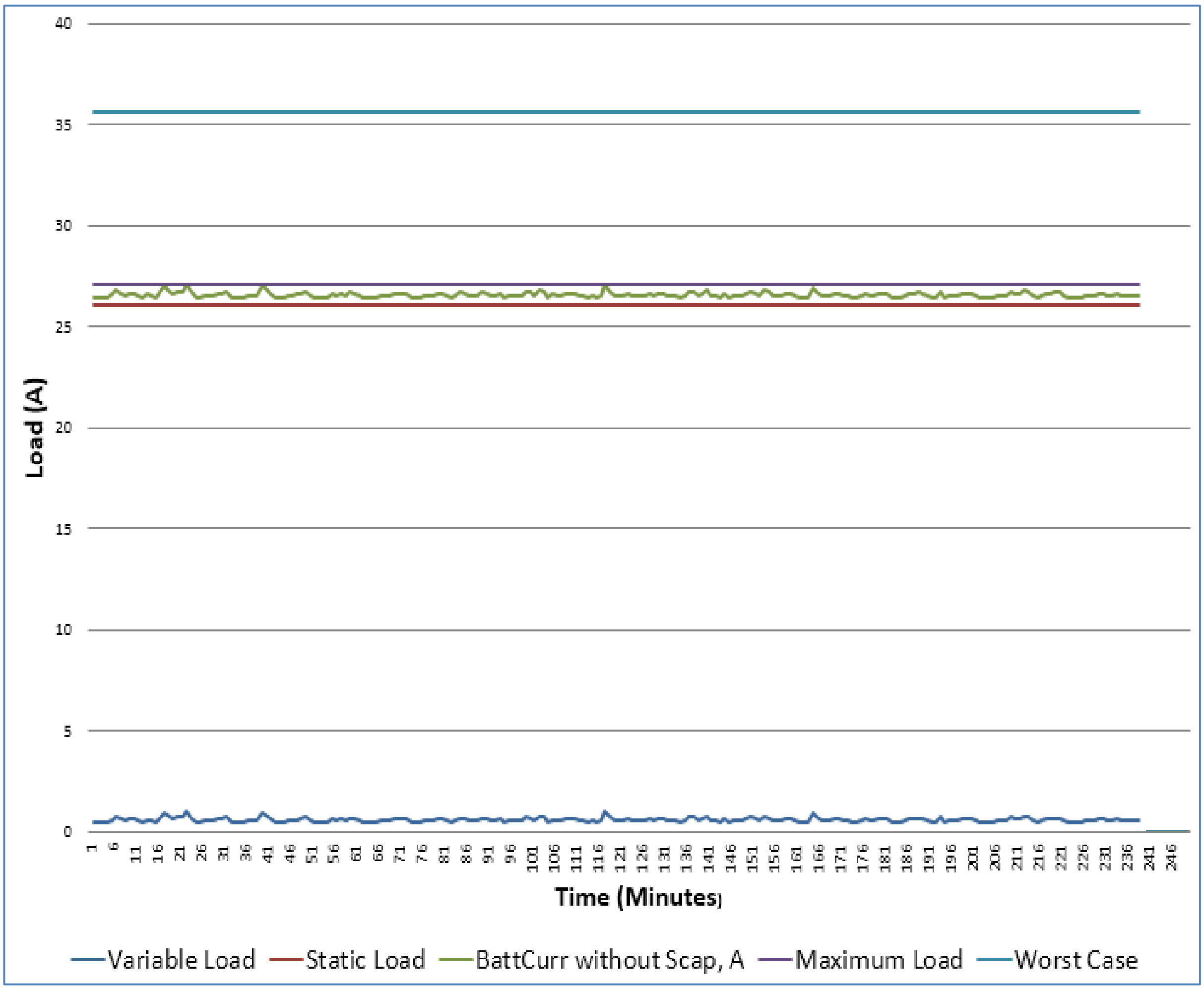

Figure 26: Application 1 approximated load profile

Variable load

The variable load component in Figure 26 is obtained from simulating the system with its probabilities, as defined in the sections above. This component is also the main focus of this study, as it is the component that the supercapacitors will be designed for.

Static load

It is important to note the static load component in Figure 26. This load component value is obtained from all equipment relevant to the application, which will be using current constantly. This equipment is indicated in Table 7.

Total load

Total load is the values obtained when combining the variable and static load components. Therefore, it is the total (simulated) load that the system will use.

Maximum load

The maximum load component in Figure 26 indicates the maximum load value which the total load reaches at any given point during the simulation.

Worst case

The worst case value indicated in Figure 26 is based on the sizing methodology used for industrial applications, as explained in Chapter 1. The value is calculated by assuming that all current consuming equipment is active at any given time, thus resulting in a worst case value.

In Figure 26, a large difference is observed between the worst case profile, and the "Total Load" profile. This is due to the methodology followed when calculating the worst case load. For example, during the worst case calculation, each load value for all the relays in the system are added, irrespective of its operating philosophy. It is assumed that at any given time, all relays may be energized, resulting in the worst case load. In the simulated, or total load profile calculation, there are start and stop relays. A start relay will be pulsed, or energized to start a drive. While the drive is running, the stop relay will kept energized. At this point the start relay is no longer energized. A negative, or zero pulse to the stop relay will stop the drive.

Also, the worst case load profile assumes that all drives are active at any point in time. In contrast to the worst case load profile, the simulated load profile take into account if a set of drives is in a duty-standby configuration, which will effectively disregard the load of a drive that is stopped.

Therefore, simulating the system according to its operational philosophy for the multiple drives and devices in the system, yields the lower total load value observed in Figure 26.

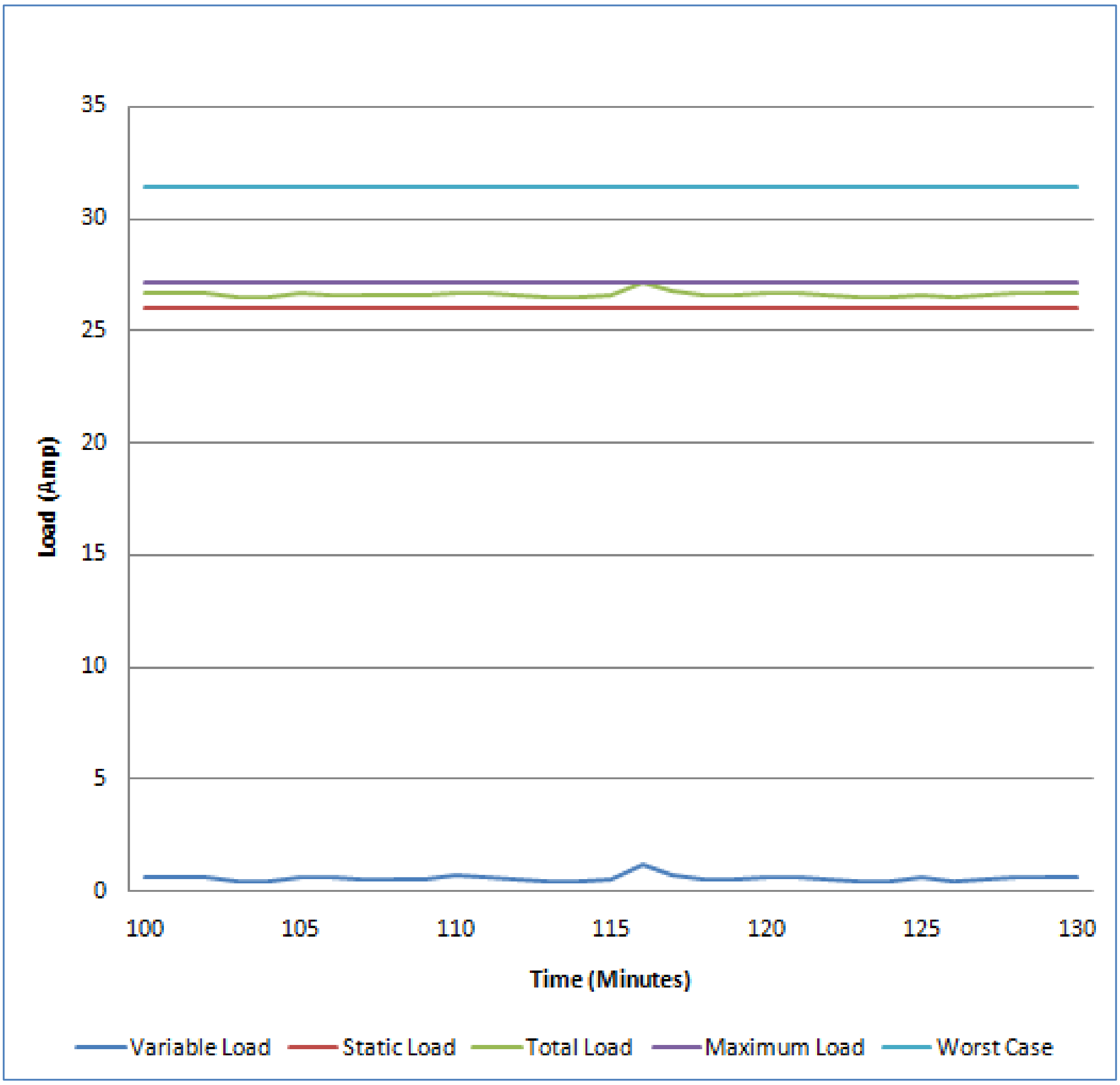

Figure 27: Application 1 load profile extract

Figure 27 indicates an extract from Figure 26. The extract is taken over interval 100 to 130. This 30 minute extract is taken in order to discuss how the simulation is behaving at this time, and why the peaks are forming as they are.

A noticeable peak is visible at interval 116. This peak has a relatively large incline and therefore, indicates a sudden increase in load. When inspecting the simulation, rotary distributor 2 received a pulse during interval 117. During interval 116, both conditioning conveyors received a signal to reverse direction. The resulting load required to energize all the involved equipment for these conditions is the cause for the observed peak in load.

Throughout the load profile the peaks in Application 1 are caused by the combined conditions of the various equipment. In this application the peaks seem relatively low. The maximum increase in load observed during this simulation, at any given interval was 1.145 ampere.

The simulation was repeated 30 times. Each simulation yielded different load peaks. The maximum load variation observed during all simulations for Application 1 was 1.225 ampere.

3.1.2.2 Application 2

The probabilities for Application 2 are determined in a similar fashion as Application 1. A more detailed discussion of Application 2 and its probabilities are discussed in APPENDIX A.

The system in Application 2 is used to fill storage bunkers. The system consists of a series of conveyors as well as distribution chutes. There are two streams of conveyors which transport the product from source to destination.

3.1.2.2.1 Application 2 approximated load profile

Application 2 has a required standby period of 2 hours. The system is therefore simulated for 120 minutes.

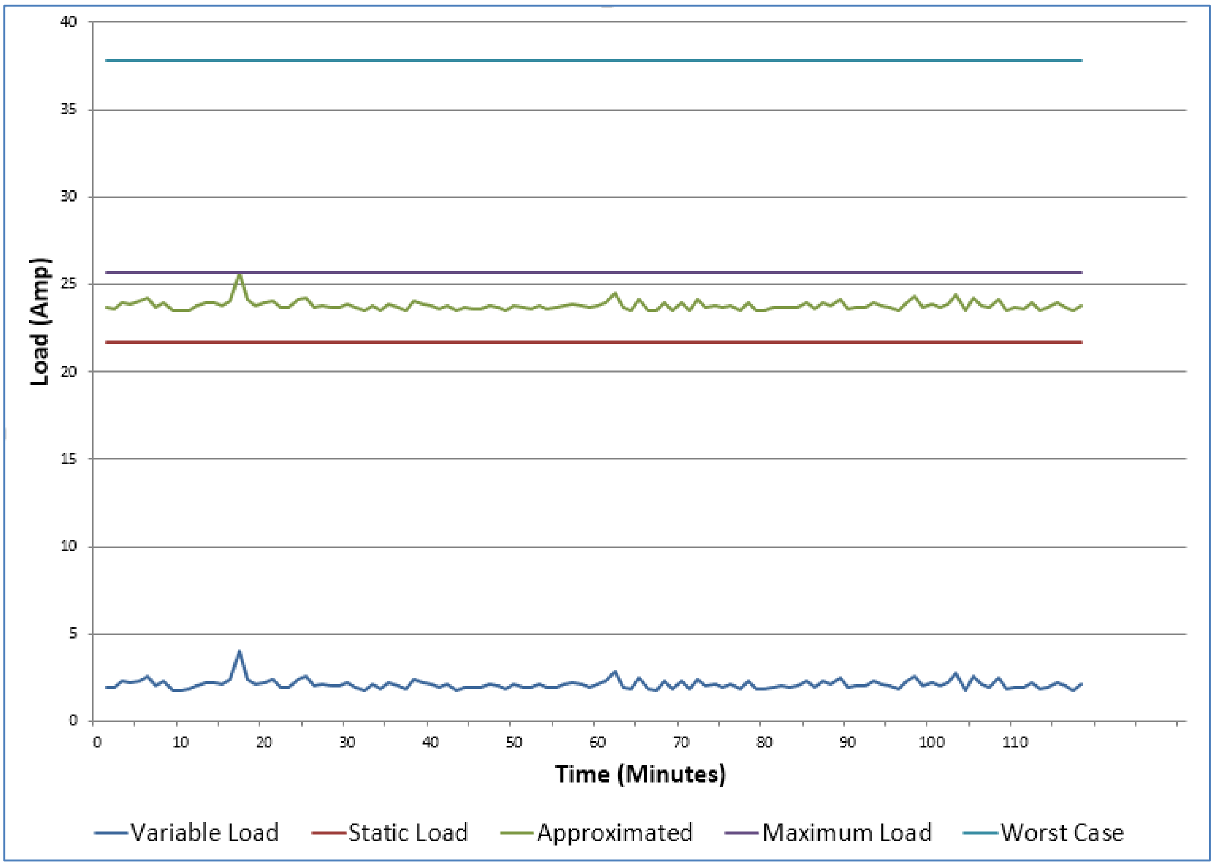

Figure 28: Application 2 approximated load profile

The system in Application 2 is designed so that minimal impact is made should a trip occur. For example, the feed conveyors are the last conveyors in the stream. Should one of these conveyors trip, only one additional conveyor as well as one chute will be affected. In the case that two feed conveyors trip, given they are fed from the same reclaim stream, three additional conveyors as well as the two chutes will be affected. This design is better understood when examining Figure 50 in Appendix A.

Although it is very unlikely to occur, the above mentioned situation is induced during the simulation to test how the system will behave. The trip for both conveyors is induced during interval 18 of the simulation.

In order to investigate other peaks observed throughout the profile, intervals 30 through 60 of the profile is examined.

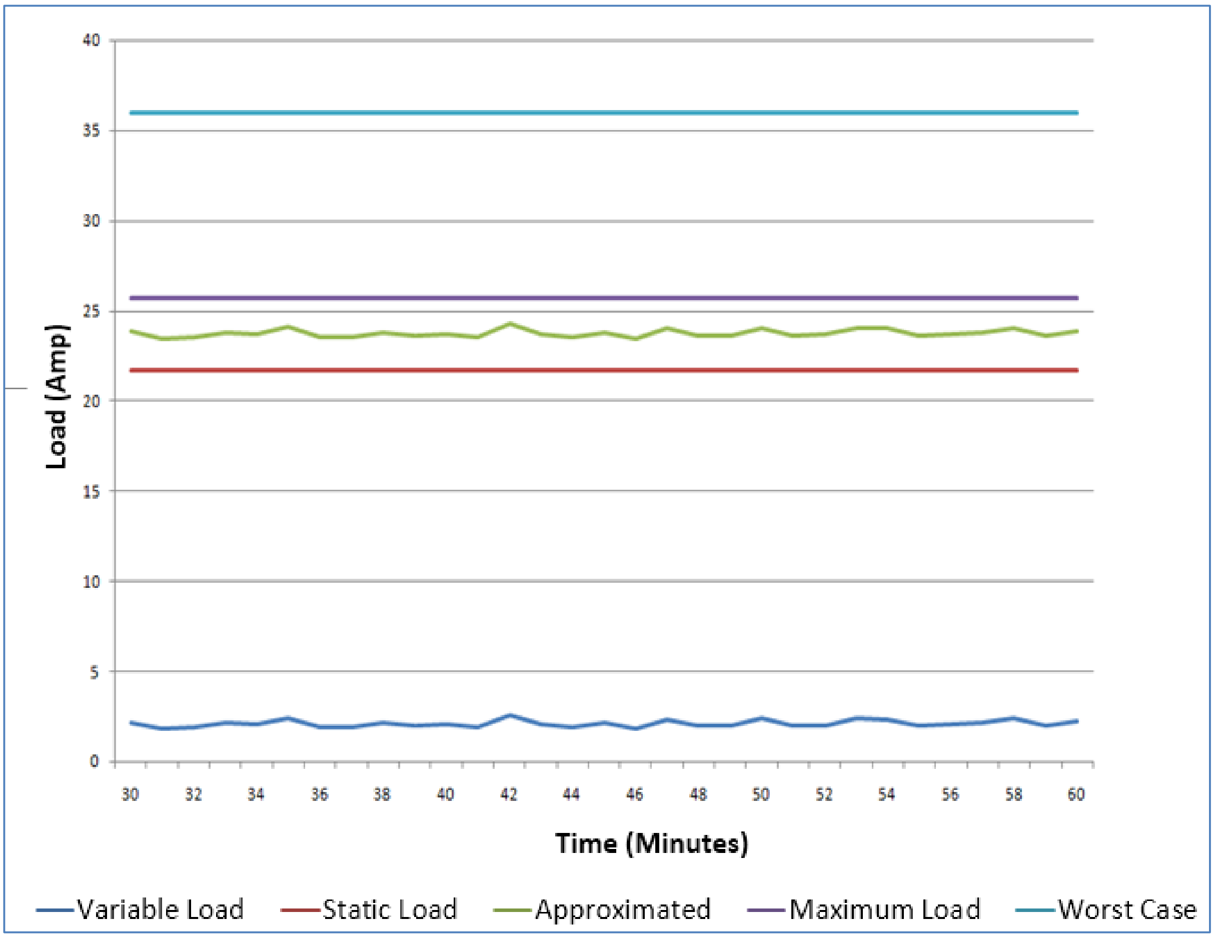

Figure 29: Application 2 load profile extract

In Figure 29, one of the largest peaks observed is at interval 42. Examining the simulation yielded that one distribution chute changed position during interval 41. It reached its destination and the limit switch was activated. During interval 42 a second distribution chute changed position. The relay associated with this action was energized during this interval.

Similar to Application 1, the peaks in Application 2 are caused by the combined conditions of the various equipment. The load increase observed during the induced trip is 4.057 ampere. The maximum load variation throughout the rest of the profile is 2.665 ampere.

3.1.2.3 Application 3

The system in Application 3 uses six different pumps to pump water from a central point, through a heat exchange process. The water finally ends in one of three different reservoirs. Each pump has its own auto closing and back-up valve. The system also comprises of six sump pumps. These sump pumps are used to drain the pump housing, should it be filled with water.

Similar to Application 2, a more detailed description of Application 3 and its probabilities are discussed in APPENDIX A. The probabilities for the different equipment are determined in a similar fashion as Application 1.

3.1.2.3.1 Application 3 approximated load profile

Application 3 has a required standby period of 4 hours. The system simulated for 240 minutes.

Figure 30 indicates very small variation in load. This is due to the small amount of change that occur during operation. Although it should rarely occur, one reservoir is deliberately taken out of service in order to investigate the simulation behavior. The reservoir is taken out of service during interval 100. The small load increase observed is due to one of the pumps that is stopped as a result of the reservoir condition. The relative auto closing valve is also closed due the pump that has stopped.

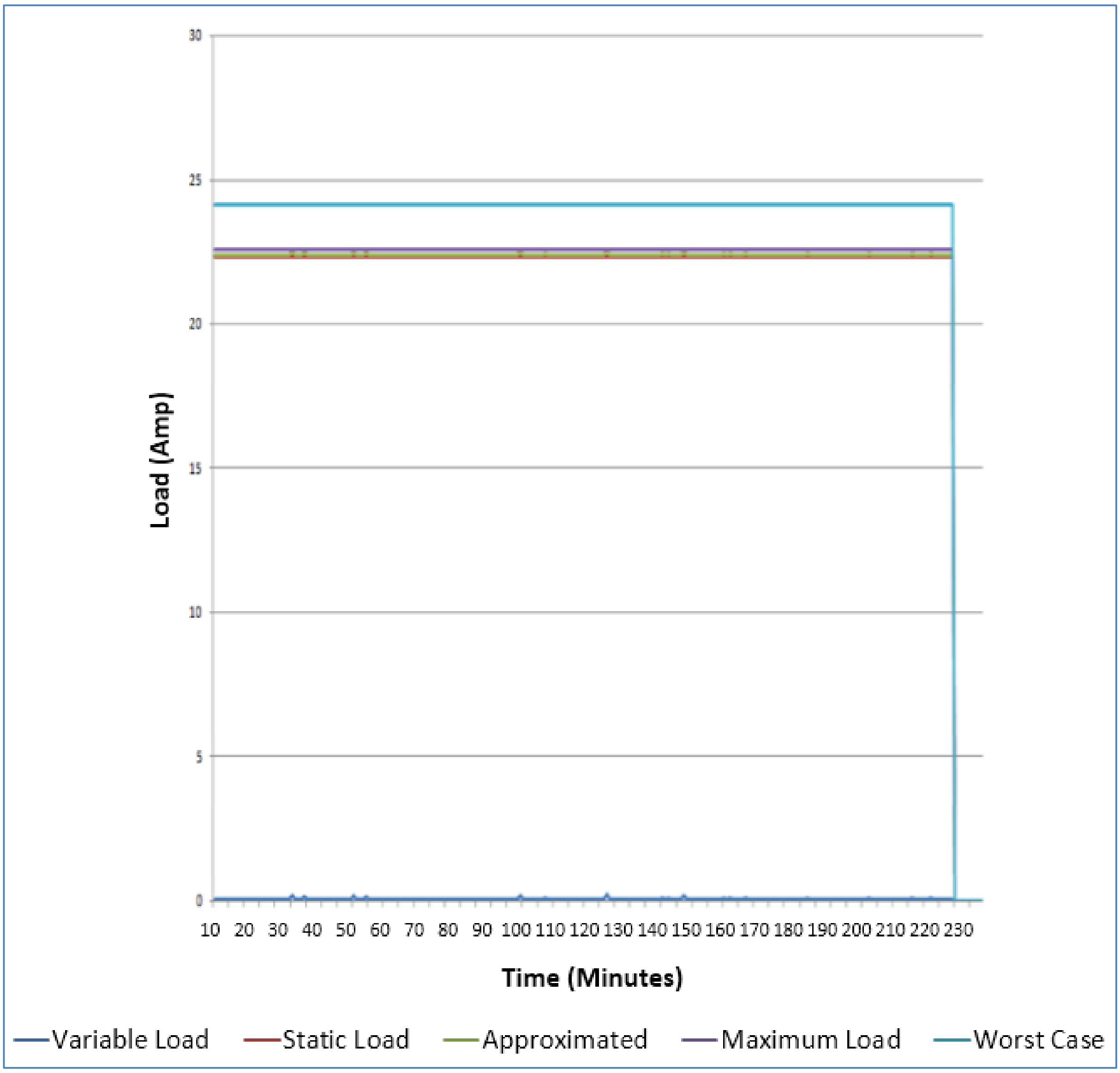

Figure 30: Application 3 approximated load profile

Other than the load increase observed due the reservoir that is purposefully taken out of service, other small load increases are also observed throughout the profile. These load increases are caused by the starting and stopping of the various sump pumps. From Figure 30, it can be observed that when the load increases as a specific sump pump starts, a second load increase is visible 20 intervals or minutes later, when the sump pump stops. The maximum load variation observed throughout the profile is 0.259 ampere.

3.1.2.4 Application 4

The system in Application 4 is used to pump fluid from storage tanks. The system contains three booster pumps which manages the flow at the required pressure. The storage tanks must also be in equilibrium with one another. This is managed by two transfer pumps. A more detailed description of Application 4 and its probabilities are discussed in APPENDIX A.

3.1.2.4.1 Application 4 approximated load profile

Application 4 has a required standby period of two hours. The system is therefore simulated for 120 minutes. Summing the loads required for the individual equipment yields the results in Figure 31.

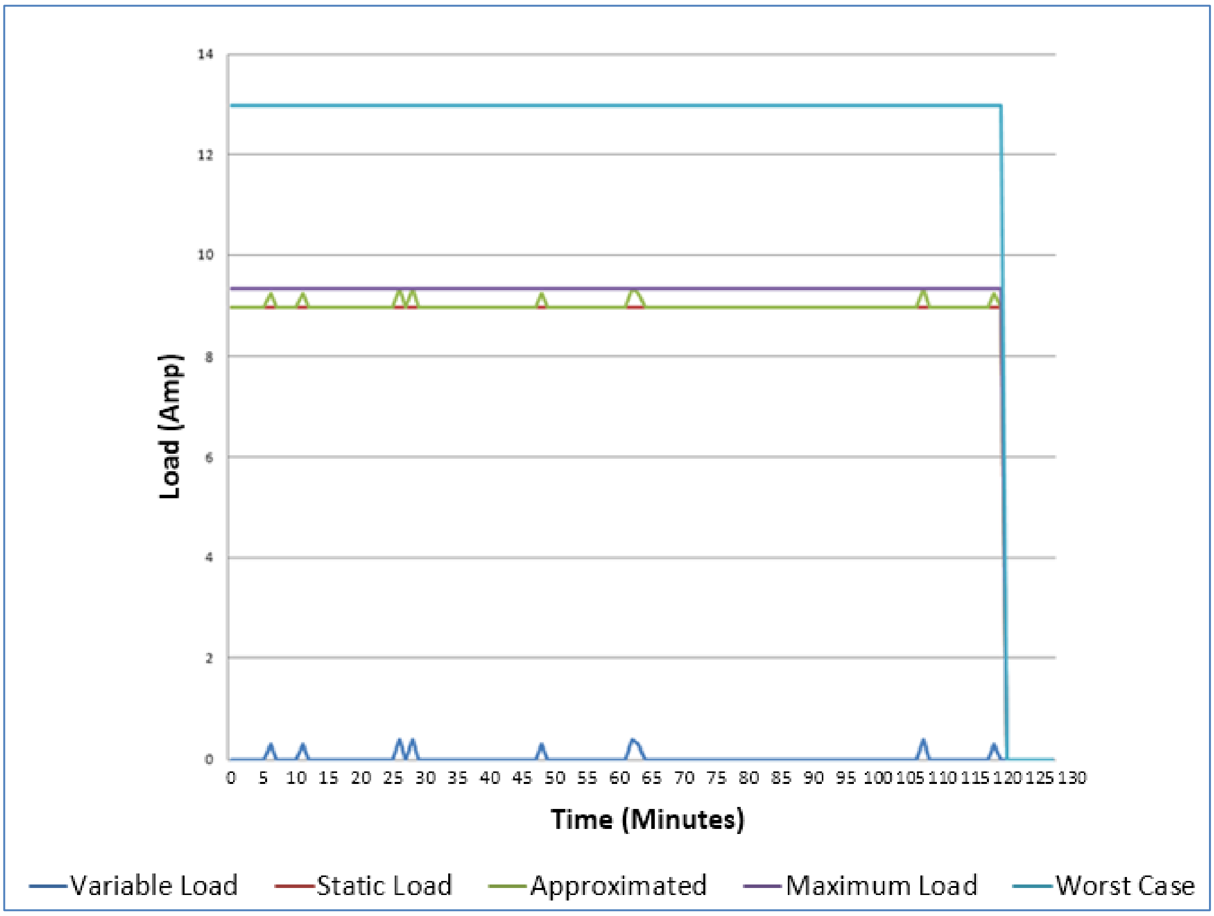

Figure 31: Application 4 approximated load profile

In Figure 31, only a few load peaks are observed. The peaks at both interval 7 and interval 13 are due to booster pump 1 and booster pump 2 starting up respectively. The pressure demand decreased during interval 27. The peaks observed during interval 27 and interval 29 is due to the stopping of the pumps.

During the simulation, the transfer pumps did not start. All the peaks observed are due to the various booster pumps stopping and starting. The effect of a transfer pump starting would have caused a similar load increase observed when a booster pump started. Therefore, even if one of the transfer pumps had started, it would not have caused any significant change in the overall load current.

The maximum load variation observed throughout the profile is 0.373 ampere.

3.2 FINAL APPROXIMATED LOAD PROFILES

To finalize the required load profile for each application, the momentary loads present during each application are added to the approximated profiles.

3.2.1 **Application 1**

Table 8 indicates the equipment that will influence the momentary loads for application 1. The “Count” column represents the number of items present in the system. Inrush currents influence the first minute of operation, while the collective currents of switchgear relays that are energized to take the process to a safe state influence the last minute of operation.

Table 8: Application 1 Momentary loads

Item	Count	Classification	Load (A)
DCS inrush current	1	Momentary	60
HP4-DC24V-F Relay (IPR and IPS)	128	Momentary	0.063

The final momentary load results in an 8.064 A increase in load. The approximated final load profile then becomes as indicated in Figure 32. The figure also illustrate the difference between the approximated load profile and the worst case load profile.

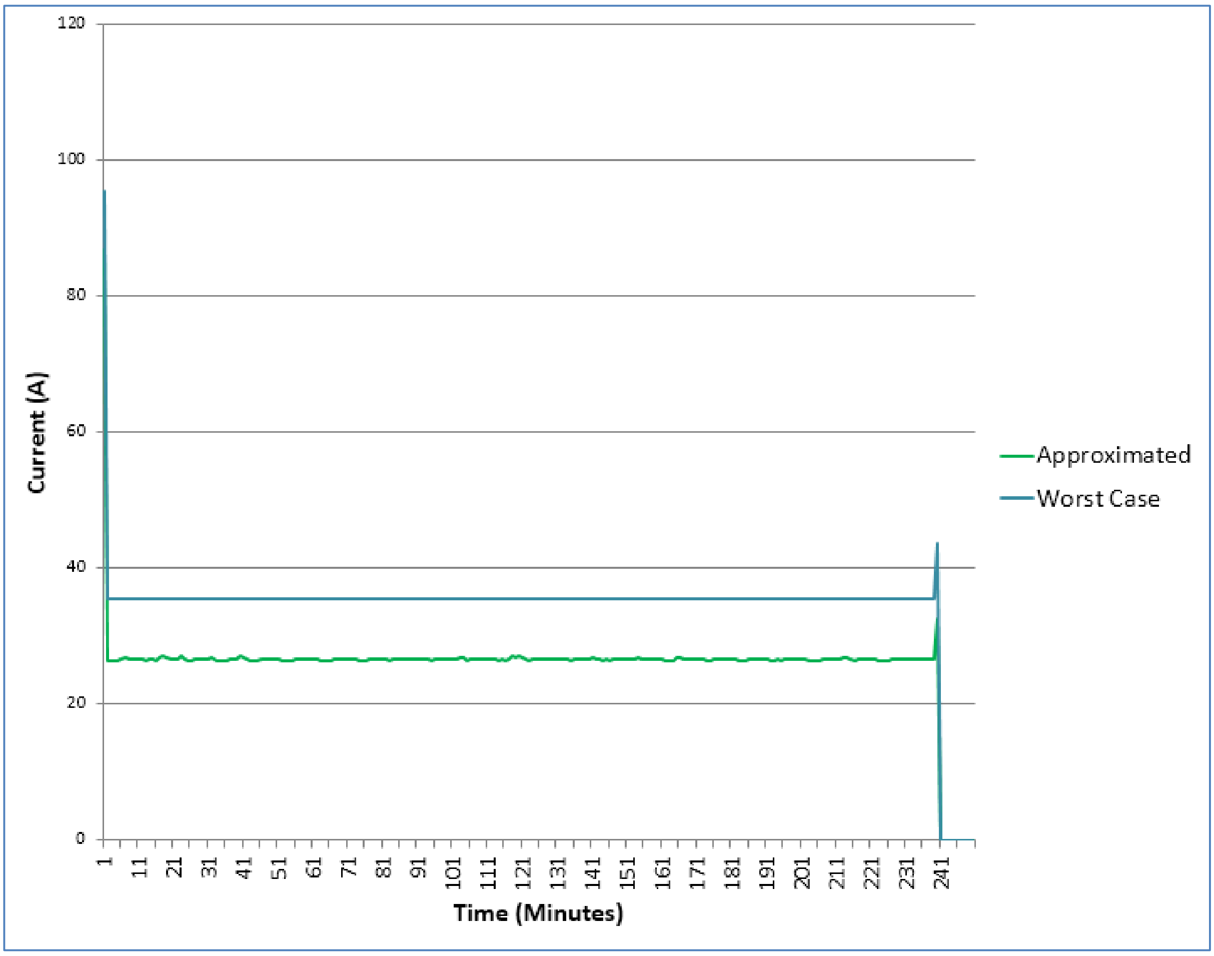

Figure 32: Application 1 final approximated load profile

3.2.1 **Application 2**

Table 9 indicates the equipment that will influence the momentary loads for application 2.

Table 9: Application 2 Momentary loads

Item	Count	Classification	Load (A)
DCS inrush current	1	Momentary	60
HP4-DC24V-F Relay (IPR and IPS)	256	Momentary	0.063

The momentary loads results in a 16.128A increase in load. The approximated load profile for the purpose of this study then becomes as indicated in Figure 33. The figure also illustrates the difference between the approximated load profile and the worst case load profile.

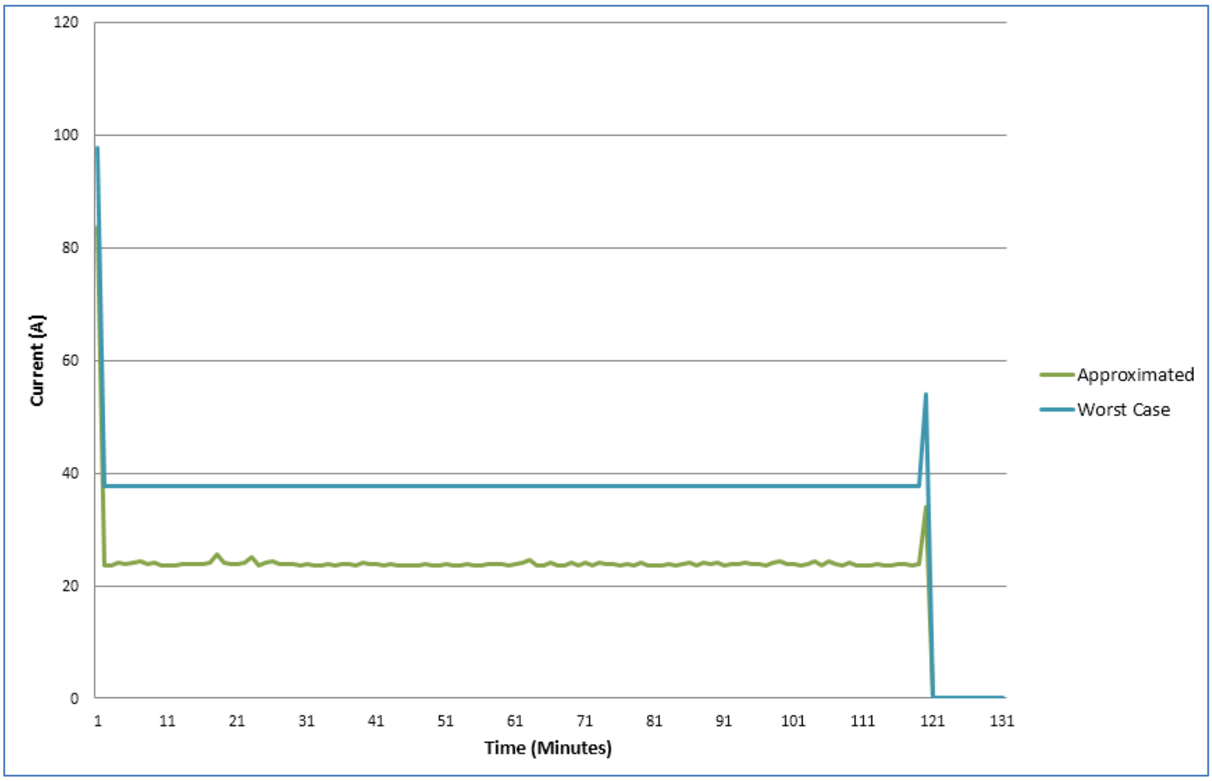

Figure 33: Application 2 final approximated load profile

3.2.1 **Application 3**

Table 10 indicates the equipment that will influence the momentary loads for application 3.

Table 10: Application 3 Momentary loads

Item	Count	Classification	Load (A)
DCS inrush current	1	Momentary	60
HP4-DC24V-F Relay (IPR and IPS)	64	Momentary	0.063
Burkert Solenoids	2	Momentary	0.1
Phoenix relays	2	Momentary	0.01

The momentary loads results in a 4.252A increase in load. The approximated load profile for the purpose of this study then becomes as indicated in Figure 34. The figure also illustrate the difference between the approximated load profile and the worst case load profile.

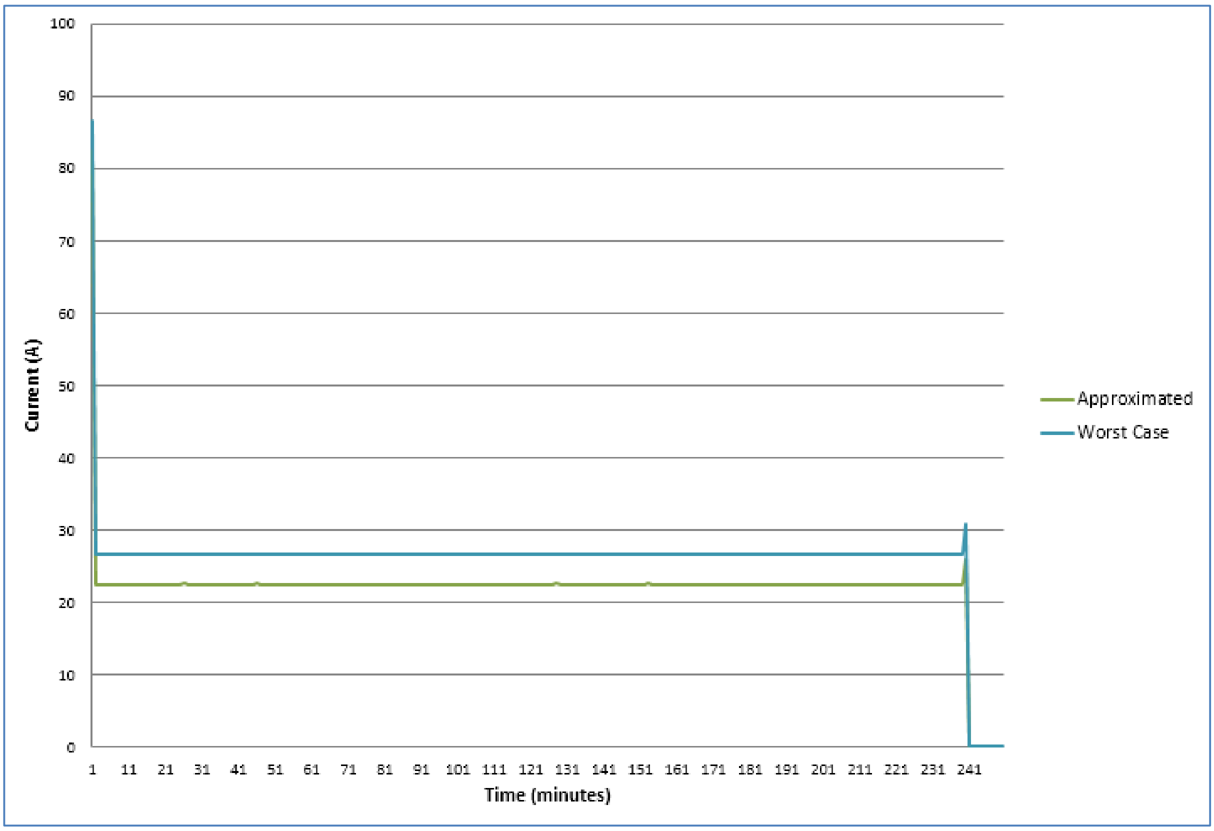

Figure 34: Application 3 final approximated load profile

3.2.1 **Application 4**

Table 11 indicates the equipment that will influence the momentary loads for application 4.

Table 11: Application 4 Momentary loads

Item	Count	Classification	Load (A)
DCS inrush current	1	Momentary	30
HP4-DC24V-F Relay (IPR and IPS)	64	Momentary	0.063

The momentary loads results in a 4.032A increase in load. The approximated load profile for the purpose of this study then becomes as indicated in Figure 35. The figure also illustrate the difference between the approximated load profile and the worst case load profile.

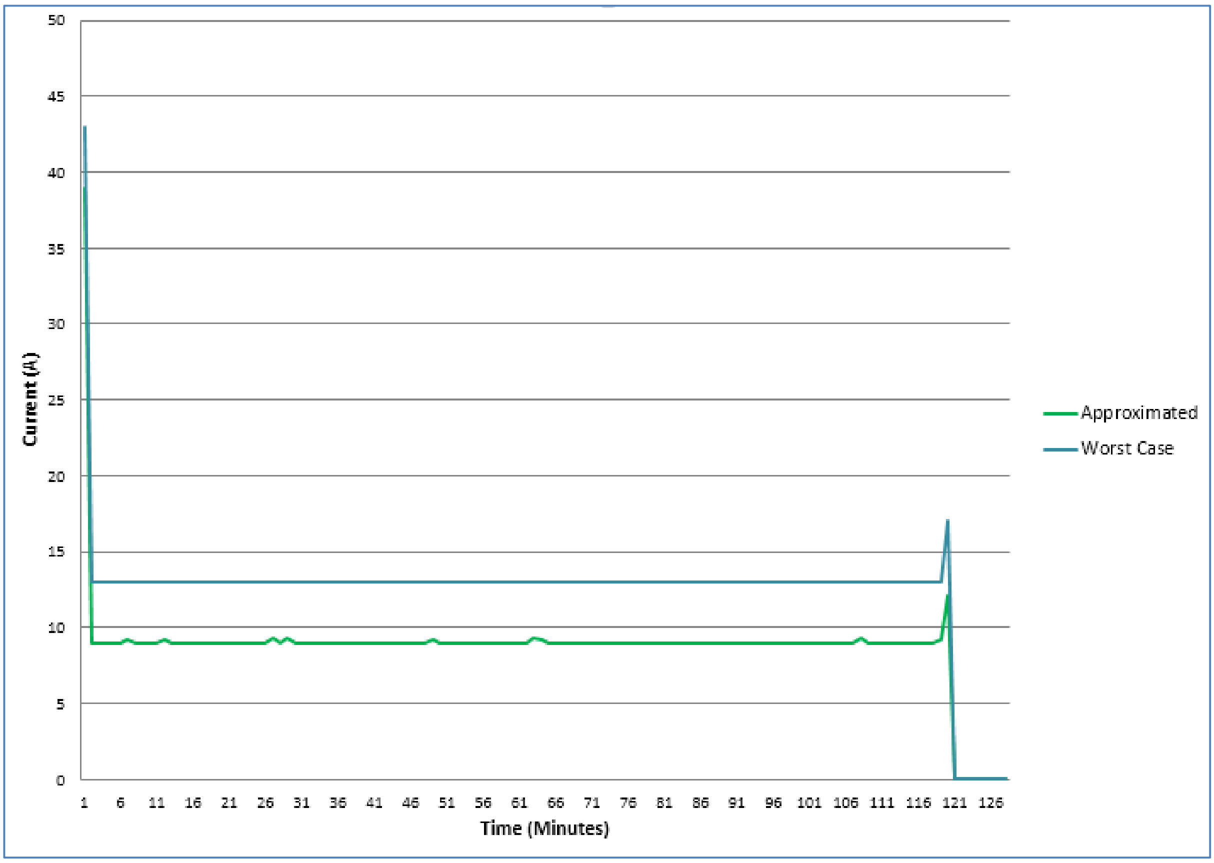

Figure 35: Application 4 final approximated load profile

3.3 CONCLUSION

The load profiles created in Chapter 3 illustrate the required load of specific processes through a set discharge time. In the following chapters these profiles are used to determine the influence, and possible advantages a supercapacitor may offer in terms of a required battery capacity reduction.

From the comparisons between the worst case and approximated profiles as indicated above, it is clear that there is potential saving in battery capacity when the methodology for sizing batteries is changed from the worst case methodology, to a methodology where the load profile for the system is approximated. Using the approximated load profile methodology does, however, involve much more engineering, and therefore the additional cost in terms of engineering hours also has to be considered.

The focus of this study, however, is to test the feasibility of using supercapacitors in conjunction with batteries, and not to explore the advantages of different sizing methodologies. The remainder of this study therefore focusses on the approximated profiles in order to test the influence of the supercapacitor during the momentary loads, as well as the fluctuating loads that occur during normal control system operations.

As mentioned in earlier chapters, a decrease in the size of the required battery capacity not only influence the cost of the battery itself, but also the cost of the hydrogen emissions extraction systems, the cost of required battery rooms due to physical space requirements, as well required size battery chargers.

CHAPTER 4: **VALIDATION OF APPROXIMATED LOAD PROFILES**

Due to the unavailability of, and the impracticality of obtaining practical load data for the purpose of this study, certain approximations are made in Chapter 3. The approximations are validated by means of qualitative research in the form of a structured interview. Industry experts are approached and asked to complete a questionnaire. The main focus of the questionnaire is to gather the expert's opinions on the validity of the approximation methodology, and the results thereof.

Three experts were specifically chosen for the purpose of this qualitative research questionnaire. The first expert is chosen due to his direct involvement in developing a very similar control system as is used in the example of the questionnaire. This expert also has academic qualifications on a master's level.

The second expert is chosen for his extensive experience with both control systems, as well as auxiliary DC systems. This expert is a lead engineer in the control and automation sector and also has academic qualifications on a magister level.

The third expert is chosen for his extensive and direct involvement with industrial DC auxiliary systems. This expert is a senior, and professional engineer in his field, and he is responsible for the design and implementation of all the auxiliary DC systems on more than 3 plants.

The completed questionnaires from the respective experts are indicated in raw format in Appendix D.

4.1 QUESTIONNAIRE FEEDBACK ANALYSIS

This sections discusses the answers and feedback received from the experts. The questions from the questionnaire are indicated, followed by the answers received from the experts. Where applicable, the concerns of the experts are discussed.
The main purpose of this questionnaire is to determine if the load profile approximation methodology followed in Chapter 3 is valid and if the profiles that are generated are realistic.

Questions 1a and 1b of the questionnaire are used to determine the level of the individual expert's exposure, relevant to this study. Table 12 and Table 13 indicate the responses from the experts for question 1a and question 1b.

QUESTION 1a:

Indicate on the scale below how many auxiliary DC systems you have had exposure to throughout your career.

Table 12: Question 1a responses

Lickert scale	1	2	3	4	5
	x < 5	5 < x < 10	10 < x < 20	20 < x < 30	x > 30
Expert 1	X				
Expert 2					X
Expert 3					X

QUESTION 1b:

Indicate on the scale below how many control and automation systems you have had exposure to throughout your career.

Table 13: Question 1b responses

Lickert scale	1	2	3	4	5
	x < 5	5 < x < 10	10 < x < 20	20 < x < 30	x > 30
Expert 1	X				
Expert 2					X
Expert 3				X	

Question 2a

Figure 36 Illustrates a typical DC load profile found in industry. The value “C”, represents the static, or continuous load of the system. The factors indicated in the figure represent the relationship of the momentary loads in relation to the continuous load. On the scale provided, please indicate the accuracy of these factors.

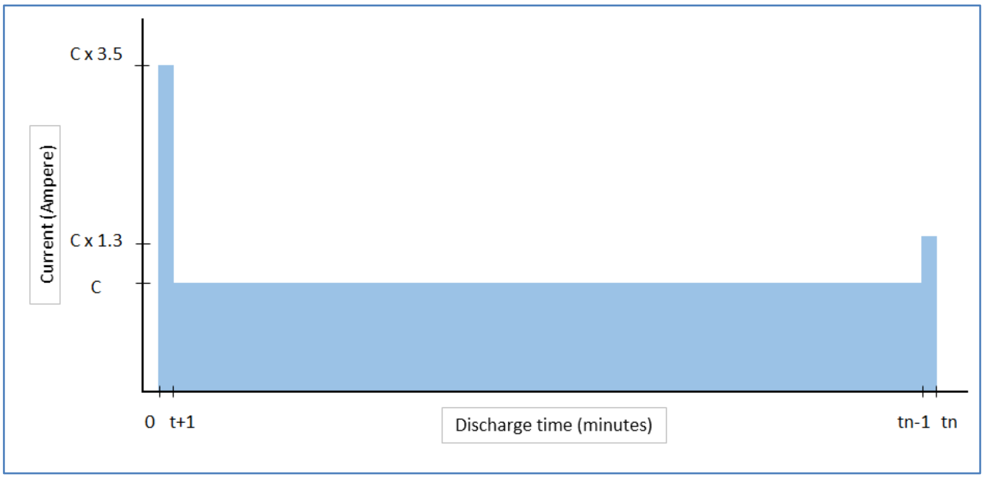

Figure 36: Typical load profile

Table 14 indicates the responses from the experts for question 2a.

Table 14: Question 2a responses

Lickert scale	1	2	3	4	5
	Strongly Disagree	Disagree	Unsure	Agree	Strongly Agree
Expert 1				X	
Expert 2		X			
Expert 3					X

QUESTION 2b:

If you disagree with any of the statements or values in Figure 36, please indicate what you are in disagreement about. Please also elaborate on your answer.

One expert commented that the factor for the initial momentary load will be much higher, depending on the bulk capacitors utilized in that specific application. It is the belief of this expert that the initial inrush current may have a much higher factor than

3.5. It should, therefore, be noted that the intention of this profile is to serve as a guideline when defining a typical load profile, and that the factors should not be considered as the actual profile values.

<u>QUESTION 3:</u>

When sizing a new auxiliary system for a dynamic process, and a specific load profile is not defined, it is assumed that all equipment and devices in the system can be active or energized at any given moment. The continuous load is therefore determined by calculating the collective loads of all the equipment and devices that are present in the system.

Table 15 indicates the responses from the experts for question 3.

Table 15: Question 3 responses

Lickert scale	1	2	3	4	5
	Strongly Disagree	Disagree	Unsure	Agree	Strongly Agree
Expert 1	X				
Expert 2				X	
Expert 3				X	

In Chapter 2, it is mentioned that industry applications typically design auxiliary DC systems using the worst case sizing methodology. In question 3, the experts are asked their opinion in this matter.

One expert strongly disagreed with the statement in question 3. Upon examining the comments from this expert regarding question 3, he mentions that momentary loads can be assumed to all become active, which supports the worst case methodology. When taking this comment into consideration, all the experts agrees that a worst case methodlogy is typically followed when defining load profiles.

Question 4 is pertinent to the approximation methodology followed in Chapter 3. One of the applications from the Chapter is explained, together with the methodology followed while determining its load profile. In question 4a, the experts are asked to indicate how accurate they deem the approximation methodology to be.

QUESTION 4a:

Considering the example above, please indicate on the scale below how accurate you deem the load approximation methodology.

Table 16 indicates the responses from the experts for question 4a.

Table 16: Question 4a responses

Lickert scale	1	2	3	4	5
	Highly Inaccurate	Inaccurate	Unsure	Accurate	Highly Accurate
Expert 1				X	
Expert 2				X	
Expert 3				X	

QUESTION 4b:

Please raise your concerns, if any, regarding the approximation methodology.

Expert 1 commented that the probabilities of a state change is not clear with respect to the values of the probabilities that are assigned. Throughout the study, assigning the probabilities proved to be a challenge as there are no historic data which could be used as reference. For this reason, the probabilities are based on plant operating procedures and assigned through deductive reasoning. This expert did, however, indicate that the methodology followed is accurate and that he deems the approach to be scientific.

Expert 2 also deemed the methodology as accurate. A comment was made enquiring about the possibility of applying this methodology linearly, irrespective of the number and types of loads that are connected. In different applications, different types of devices are simulated. Each device is seen as a separate entity, although it contributes collectively to the final profile.

Expert 3 indicated that the probabilities used in during the methodology relates to equipment for which good maintenance practices are applied. During the interview, this expert stated that the methodology would prove to be less of a risk if the simulation included higher probabilities of a state change than one would expect in reality. This would simulate the worst conditions that the plant would experience.

Despite the the different comments received from the experts, they are in agreement that the methodology followed is accurate. Question 4c is pertinent to the load profile that is formed as a result of the methodololgy.

QUESTION 4c:

Please indicate on the scale below how realistic you deem the approximated load profile in Figure 35.

Table 17 indicates the responses from the experts for question 4c.

Table 17: Question 4c responses

Lickert scale	1	2	3	4	5
	Highly Unrealistic	Unrealistic	Unsure	Realistic	Highly Realistic
Expert 1				X	
Expert 2				X	
Expert 3				X	

All of the experts deemed the load profile that was presented as realistic. There where no specific concerns raised about the profile. The experts did, however, refer back to the comments made during the previous question.

QUESTION 5a:

A reduction in the required battery size of a system also affects the required H_2 extraction system, the physical battery room size, as well the required charger size. Considering the potential saving due to the reduction in battery size, but also considering any possible risk involved, how likely will you implement the method of defining a system's load profile, as described in QUESTION 4.

Table 18 indicates the responses from the experts for question 5a.

Table 18: Question 5a responses

Lickert scale	1	2	3	4	5
	Highly Unlikely	Unlikely	Unsure	Likely	Highly Likely
Expert 1					X
Expert 2				X	
Expert 3				X	

QUESTION 5b:

Please elaborate on your answer in QUESTION 5b:

All the experts indicated that they would either likely, or highly likely implement the methodlogy descibed. The biggest contribution to their decision is the potential cost saving due of the methodology.

4.2 CONCLUSION

The interviews with the experts indicated that the experts would be likely to implement the approximation methodology for defining load profiles. The potential savings in cost is the biggest contributing factor towards their decision. The savings in cost as a result of this methodology is separate from the potential savings in cost due the addition of supercapacitors.

This study specifically focus on the influence of supercapacitors on an auxiliary design, and therefore requires more detailed profiles. Since the predominant factors of the battery calculations are the initial and final momentary loads, the profile during normal operation only needs to be defined to a reasonable accuracy in order to obtain adequate results. The interviews with the various experts confirms that the methodology followed for the load profile approximation yields accurate results within reasonable limits. From the feedback obtained during this chapter, the approximation methodology is considered accurate to the extent of satisfying the outcomes of this study.

CHAPTER 5: **SIMULATION**

In this chapter, the battery and supercapacitor models as discussed in section 2.4 are used to test the influence that the supercapacitor has on the required discharge battery loads as approximated in Chapter 3.

This section begins by calculating the parameters of the different models. For each application, the required battery as per the IEEE recommended practice is calculated according to its load profile. A preliminary size supercapacitor is then calculated for the same load profile. The parameters of the calculated components are used as inputs to the simulation models.

The simulation model used is indicated in Figure 37. The model is the same through all the applications, with the only difference being the battery and supercapacitor parameters, as well as the load profiles pertaining to each application.

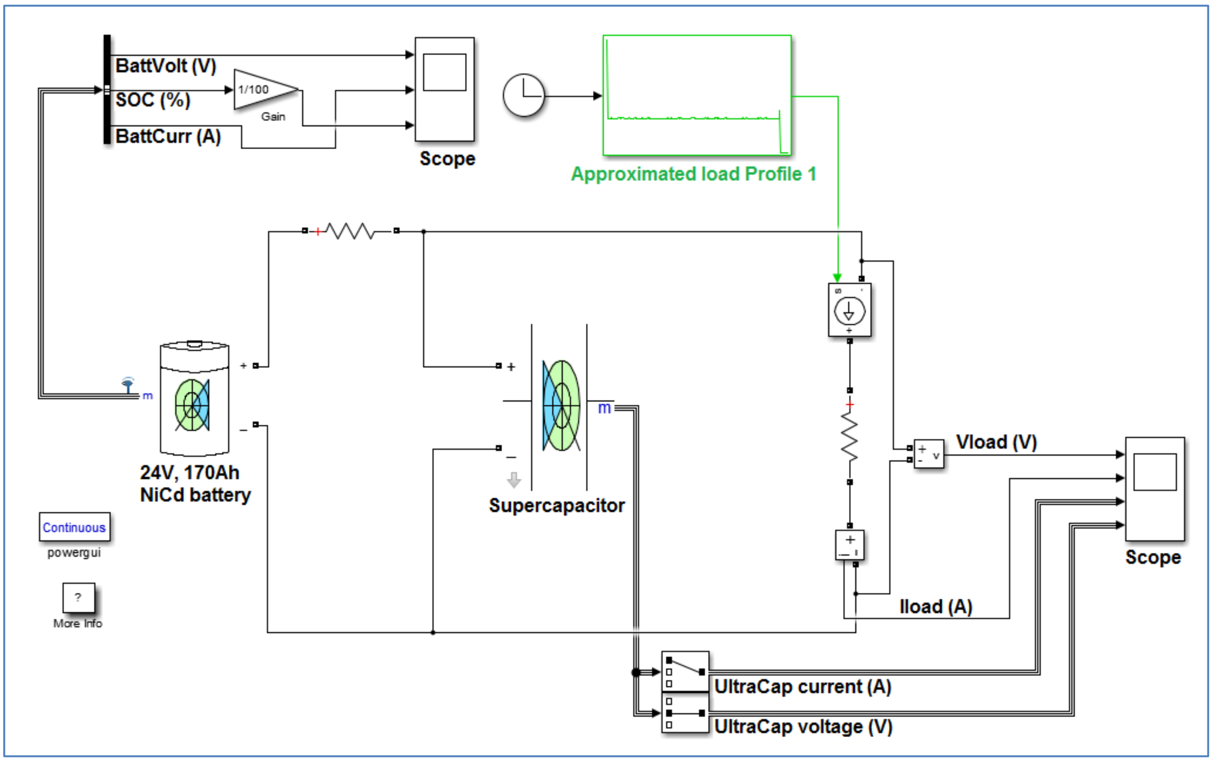

Figure 37: Simulation model

In this study, the nominal voltage for the systems examined is 24VDC, with tolerances of +20% and -10%. The allowable voltage window thus becomes 22.6 – 28.8VDC. The supercapacitors are therefore also sized to operate within these limits.

The battery and supercapacitor models in the simulation model requires the inputs indicated in Table 19. These parameters are obtained from the various supplier technical datasheets. The battery model allows for an option to either input the exact battery parameters, or to have the model use parameters based on the battery type and nominal values. During the simulations, the latter is used.

Table 19: Parameters required for simulation model

Supercapacitor	Battery
Rated capacitance (F)	Battery type (e.g. NiCd)
Equivalent DC series resistance (Ω)	Nominal Voltage (V)
Rated voltage (V)	Rated Capacity (Ah)
Surge Voltage (V)	Maximum Capacity (Ah), optional
Number of series capacitors	Fully charged voltage (V), optional
Number of parallel capacitors	Nominal discharge current (A), optional
Initial voltage (V)	Internal resistance (Ω), optional
Leakage current (A)	Capacity at nominal Voltage (Ah), optional
Operating temperature (°C)	Exponential zone [Voltage (V), Capacity (Ah)], optional

Simulation methodology

The main focus of this study is to research the possibility of a battery size reduction due to the addition of a supercapacitor and therefore, all comparison data is measured over the battery.

Firstly, the simulation is conducted without the supercapacitor in the circuit, in order to obtain benchmark data. The simulation is then repeated with the supercapacitor in the circuit to test the influence of the supercapacitor on the system. The portion of the load which the battery has to supply, as measured during this second simulation, is then used to recalculate the required battery size when the supercapacitor is present.

Lastly, the simulation is repeated iteratively, each time decreasing the size of the supercapacitor to a point where the battery has to supply a portion of the initial momentary load. This is done in attempt to determine the optimum battery and supercapacitor sizes.

5.1 APPLICATION 1

In this section, battery and supercapacitor sizes for application 1 are calculated. The results from the calculations are used in the simulation model for this application.

5.1.1 Preliminary sizing calculations for application 1

The calculations for the battery and supercapacitor sizes required for application 1 are indicated in the following sections.

5.1.1.1 Approximated battery sizing calculation

The approximated load profile, as determined in section 3.1.2.1, has a value change in the load during each minute of simulation. Therefore, 240 different sections/ periods are required when defining the load as per the IEEE recommended practice for sizing batteries. The calculation tables for application 1 are indicated in APPENDIX B.

From the calculations, the system requires a battery with a capacity of 168.037 Ah. The next available size battery in the ALCAD VANTEX range is the VTX1M170.

5.1.1.2 Preliminary supercapacitor sizing calculation

Table 20 indicates the parameters required from application 1 for the purpose of calculating the required supercapacitor. The required power is derived from the relevant load profile. The methodology explained in section 2.3.2 is used when determining the preliminary size supercapacitor.

Table 20: Parameters for preliminary sizing of supercapacitor for approximated profile, Application 1

Variable	Description
V_{max}	28.8 (V)
V_w	24 (V)
V_{min}	22.6 (V)
Power	86.73 x 24 = 2081.52 (W)
Δ_t	60 (s)

V_w is the operating voltage at the beginning of discharge. In this study, this value will be equal to V_{max}. V_w is the nominal voltage of the system.

$$\boldsymbol{\Delta V = V_w - V_{min}} \tag{5.1}$$

$$\Delta V = 6.2\ V$$

$$\boldsymbol{i_{max} = \frac{Power}{V_{min}}} \tag{5.2}$$

$$i_{max} = 92.103\ A$$

$$\boldsymbol{i_{min} = \frac{Power}{V_{max}}} \tag{5.3}$$

$$i_{max} = 72.275\ A$$

$$\boldsymbol{i_{avg} = \frac{i_{max} + i_{min}}{2}} \tag{5.4}$$

$$i_{avg} = 82.189\ A$$

As the required size supercapacitor is unknown at this point, a value of 1 second is used for the RC constant. (Refer to section 2.3.2)

$$\boldsymbol{\tau = R \cdot C = 1} \tag{5.5}$$

$$R = \frac{1}{C}$$

Having all the variables defined, C can be solved as follows:

$$\boldsymbol{dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot R} \tag{5.6}$$

$$dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot \frac{1}{C}$$

$$dV = \frac{i_{avg}}{C}(dt + 1)$$

$$C = \frac{i_{avg}}{dV}(dt + 1)$$

$$C = 808.634\ F$$

For this study, the Maxwell range of supercapacitors is considered. The MC series of cells has a cell voltage of 2.7 V. The required number of cells then becomes:

$$\boldsymbol{Number\ of\ series\ cells} = \frac{\mathbf{28.8}}{\mathbf{2.7}} \tag{5.7}$$

$$Number\ of\ series\ cells = \ 10.667$$

$$\therefore Number\ of\ series\ cells = \ 11$$

$$\boldsymbol{C_{Total}} = \boldsymbol{C_{Cell}} \cdot \frac{\boldsymbol{nCells_p}}{\boldsymbol{nCells_s}} \tag{5.8}$$

$$C_{cell} = C_{Total} \cdot \frac{nCells_s}{nCells_p}$$

$$C_{cell} = 808.634 \cdot \frac{11}{1}$$

$$C_{cell} = 8894.974\ \mathrm{F}$$

The available supercapacitor in the Maxwell range is either the BCAP3000, with rated capacitance of 3000F, or the BCAP2000, with rated capacitance of 2000F. The above calculation therefore has to be revisited.

$$\boldsymbol{C_{cell}} = \boldsymbol{C_{Total}} \cdot \frac{\boldsymbol{nCells_s}}{\boldsymbol{nCells_p}} \tag{5.9}$$

$$C_{cell} = 891.333 \cdot \frac{11}{3}$$

$$C_{cell} = 2964.991\ \mathrm{F}$$

The BCAP3000 capacitor has an ESR value of 0.29mΩ. The process above is repeated with the actual capacitor values in order to verify the selected capacitor.

$$BCAP3000\ cell\ capacitance = 3000\ F$$

$$Number\ of\ series\ cells = \ 11$$

$$Number\ of\ parallel\ cells = \ 3$$

$$Total\ stack\ capacitance = \ \frac{3000\ \cdot 3}{11}$$

$$Total\ stack\ capacitance = \ 818.1818\ F$$

$$BCAP3000\ cell\ resistance = 0.00029\ \Omega$$

$$Total\ stack\ resistance = \ \frac{0.00029\ \cdot 11}{3}$$

$$Total\ stack\ resistance = \ 0.00106\ \Omega$$

$$\boldsymbol{dV} = \boldsymbol{i_{avg}} \cdot \frac{\boldsymbol{dt}}{\boldsymbol{C}} + \boldsymbol{i_{avg}} \cdot \boldsymbol{R} \tag{5.10}$$

$$dV = 6.1143$$

The original $\Delta V = 6.2\,V$. The calculated required capacitor has 98.62% of the allowed voltage drop.

BCAP3000 time constant is given by

$$\tau = 3000 \cdot \frac{3}{11} \cdot 0.00029$$

$$\tau = 0.2373$$

$$\tau = R \cdot C$$

$$R = \frac{0.2373}{C}$$

$$\boldsymbol{dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot R} \tag{5.11}$$

$$dV = \frac{i_{avg}}{C}(dt + 0.2373)$$

$$C = \frac{82.189}{6.2}(60 + 0.2373)$$

$$C = 798.523\,F$$

$$Number\ of\ series\ cells = \ 11$$

$$Number\ of\ parallel\ cells = \ 3$$

$$\boldsymbol{C_{cell} = C_{Total} \cdot \frac{nCells_s}{nCells_p}} \tag{5.12}$$

$$C_{cell} = 798.523 \cdot \frac{11}{3}$$

$$C_{cell} = 2927.918\ \mathrm{F}$$

It is concluded that 11 series, and 3 parallel BCAP3000 supercapacitors is the optimum supercapacitor stack for the approximated profile of application 1.

5.1.2 **Simulation results for application 1**

Figure 38 indicates the measurements across the battery during the simulation. From the figure, it is observed that the supercapacitor supplies the first momentary load of the profile. The battery has sufficient current to recharge the supercapacitor directly after this initial momentary load. It is also observed that the supercapacitor supplies all the small peaks in the load during the continuous operation of the system. The final momentary load is again supplied by the supercapacitor.

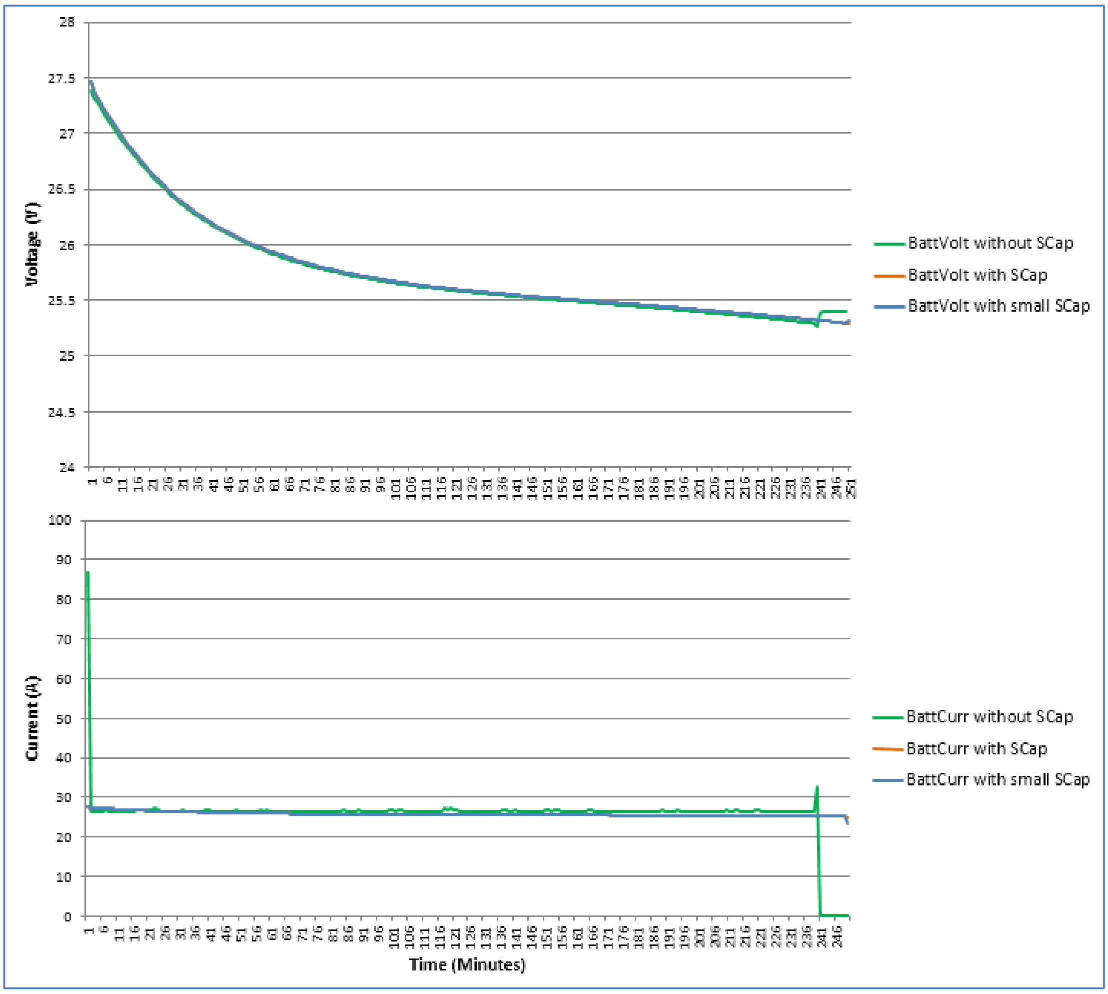

Figure 38: Application 1 battery measurements

After the initial momentary load, the battery has to re-energize the supercapacitor, and therefore the load is slightly higher than the approximated load when the supercapacitor is absent. The battery load decreases towards the end of the discharge period. This is due to the supercapacitor starting to supply a portion of the load.

The “BattCurr with SCap” curve in Figure 38 is used to recalculate the required battery size when the preliminary sized supercapacitor is present in the circuit. The IEEE calculation tables is indicated in Appendix B.

To test the optimum battery and supercapacitor sizes for the application, the supercapacitor size is iteratively decreased. The “BattCurr with small SCap” curve in Figure 38 indicates the battery current with the smaller, or undersized, supercapacitor. The different battery measurements when used in conjunction with the two different capacitors are indicated in Figure 39.

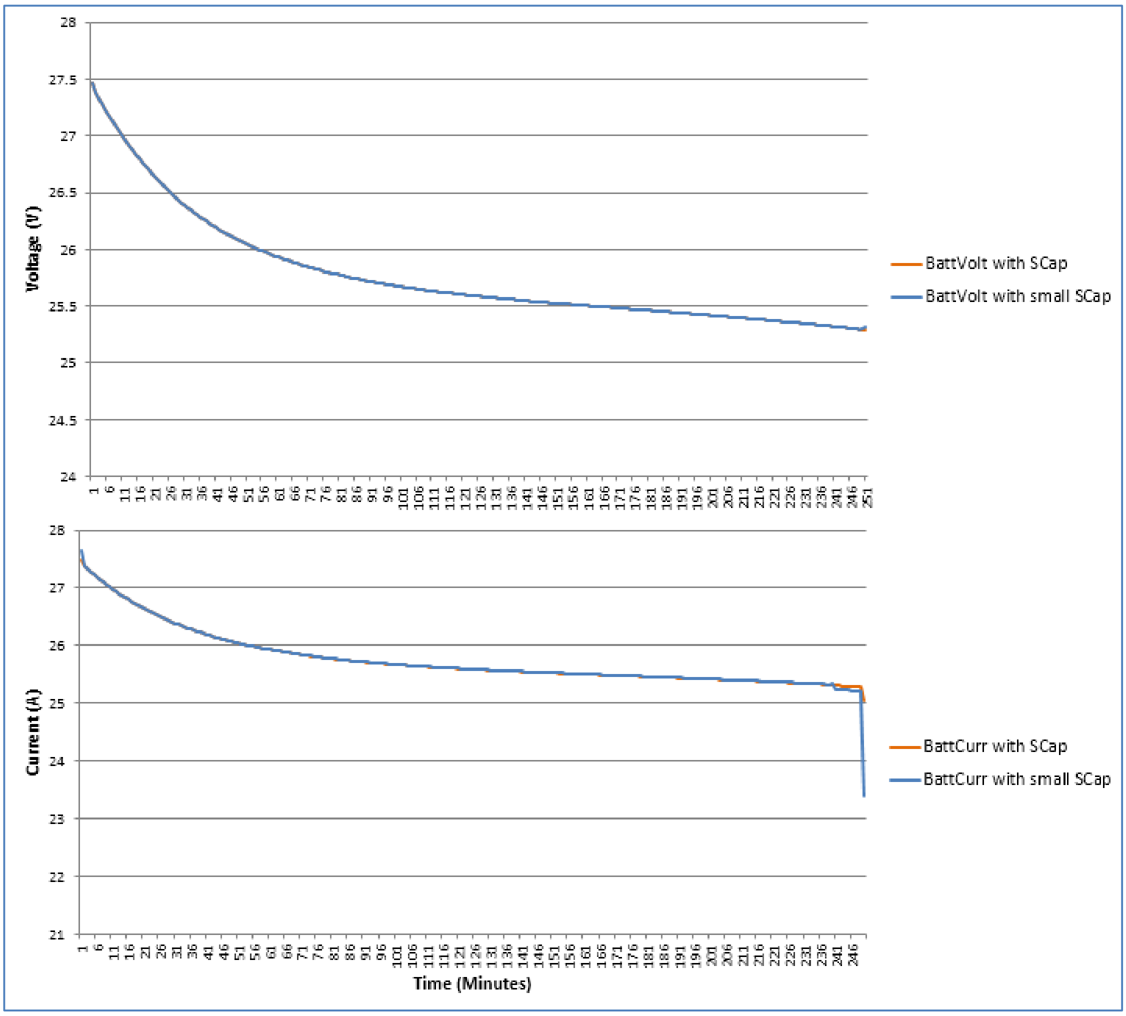

Figure 39: Battery measurements with undersized supercapacitor versus preliminary sized supercapacitor, application 1

From Figure 39 it is observed that the required battery current very nearly follows its original discharge curve when either of the supercapacitors are used. The only difference is the portion of the initial momentary load which the battery has to supply when the smaller supercapacitor is used.

When recalculating the required battery when used in conjunction with the supercapacitor, it is found that the required battery capacity becomes ±154Ah. The next available size battery in the supplier range is a 170Ah battery. From Figure 39, it seems that the supercapacitors have very little influence on the battery discharge curves other than relieving the battery of the momentary loads. The supercapacitors follow the battery discharge curve because of the fact that the battery has ample spare capacity to supply both the load, and recharge the supercapacitors.

The battery sizing tables are indicated in Appendix B.

5.1.3 Comparison

Using the calculations indicated in section 2.3, the required battery, supercapacitor, charger size, and H_2 extraction fan for this application is calculated. The battery dimensions for the purpose of these calculations are obtained from the relevant datasheets. Table 21 summarizes the required equipment required for Application 1.

Table 21: Summary of required battery and supercapacitor sizes for Application 1

Description	Required supercapacitors		Required battery capacity as per IEEE recommended practice		Required extraction fan	Required battery charger	Next available size: Battery; supercapacitor; charger; extraction fan
	Size (F)	Count	Size (Ah)	Count	Size (m^3/h)	Size (A)	Size
Required battery without supercapacitor	N/A	N/A	168.037	20	0.0531	50.52	VTX1M170, 170Ah; N/A; 60A; RVK315Y4, 16.8 m^3/h
Required battery with preliminary sized supercapacitor	Cell 2927.918; stack 798.523	11 series, 3 parallel	153.99	20	0.0531	48.56	VTX1M170, 170Ah; BCAP3000, 3000F; 60A; RVK315Y4, 16.8 m^3/h
Required battery with undersized supercapacitor	BCAP350, 350F; stack 31.82F	11 series, 1 parallel	153.96	20	0.0531	48.55	VTX1M170, 170Ah; BCAP350, 350F; 60A; RVK315Y4, 16.8 m^3/h

5.2 APPLICATION 2

The preliminary battery and supercapacitor sizes for application 2 are calculated similarly to application 1. In this section, only the results from the simulation are discussed. The battery sizing tables for application 2 are indicated in Appendix B, while the preliminary supercapacitor sizing is indicated in Appendix C.

5.2.1 **Simulation results for application 2**

Figure 40 indicates the measurements across the battery during the simulation for application 2. From the figure it is observed that both the preliminary and undersized supercapacitor supplies the predominant portion of the initial momentary load. The undersized sized supercapacitor, however, is not adequate to supply the total final momentary load.

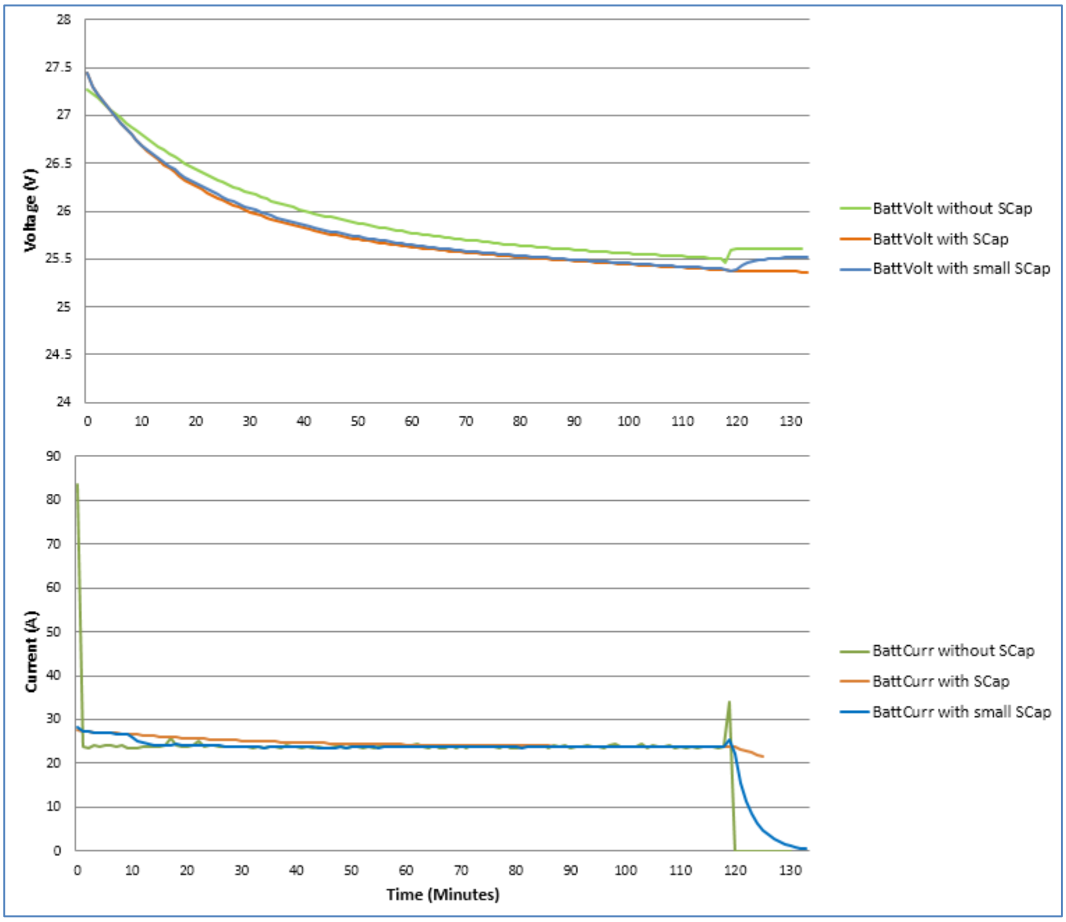

Figure 40: Application 2 battery measurements

Although the supercapacitor relieves the battery of the initial and final momentary loads, it adds additional load to the battery during normal operation as the supercapacitor recharge. As with application 1, it seems that the supercapacitors introduce no advantage during discharge other than relieving the battery of the momentary loads.

The supercapacitor size is again iteratively decreased to test the optimum battery and supercapacitor sizes. The “BattCurr with small SCap” curve in Figure 40 indicates the battery current with the smaller supercapacitor. The different battery measurements when used in conjunction with the two different capacitors are indicated in Figure 41.

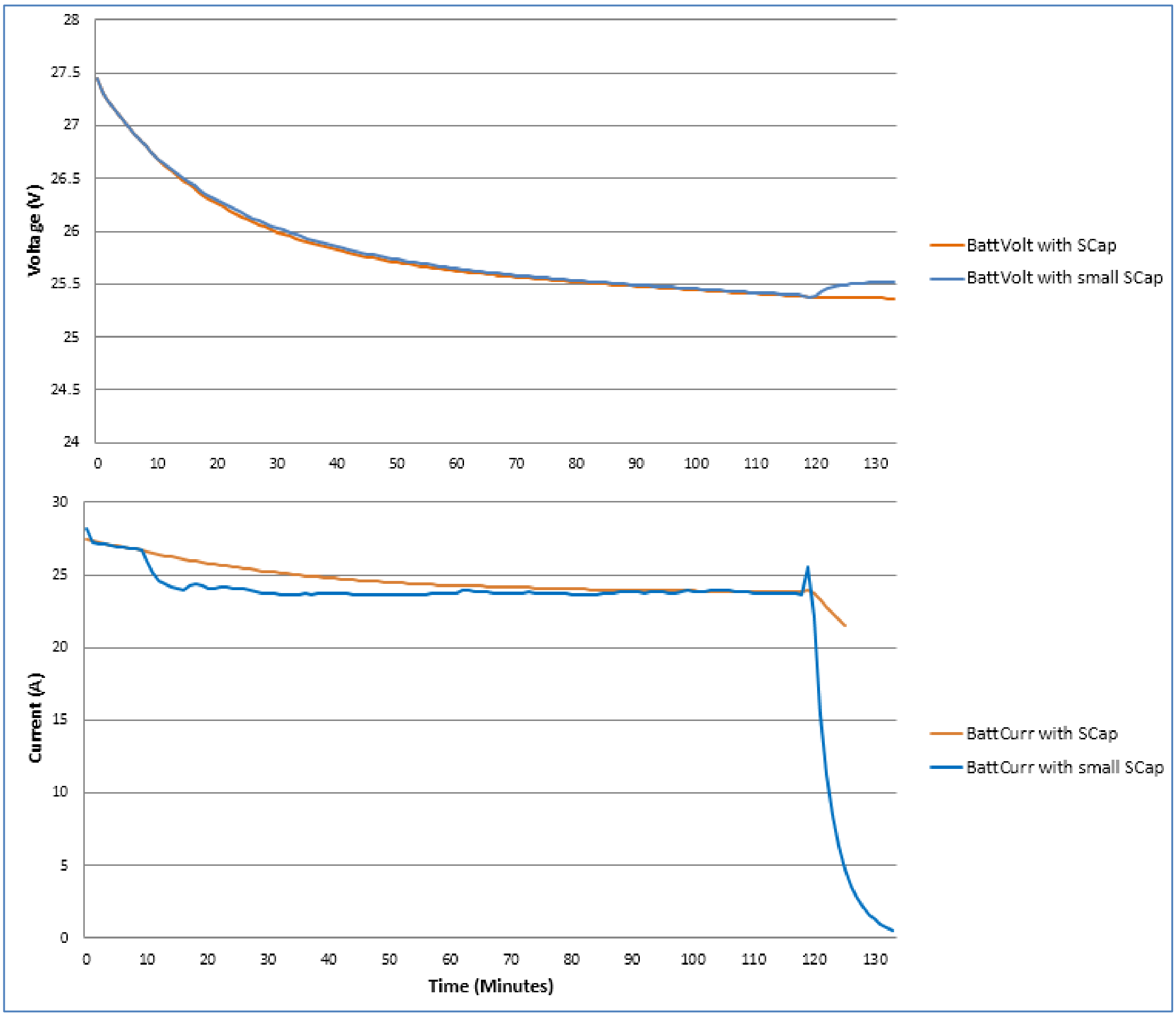

Figure 41: Battery measurements with undersized supercapacitor versus preliminary sized supercapacitor, application 2

From Figure 41 it is observed that the battery has to supply a portion of the load when using the smaller, or undersized, supercapacitor. It is also observed that the smaller supercapacitor adds much less load on the battery, as it recharges in a much shorter period of time. The battery does, however, have to supply a large portion of the final momentary load when the undersized supercapacitor is used.

When recalculating the required battery when used in conjunction with the supercapacitor, it is found that the required battery capacity becomes ±92 Ah. The next available size battery in the supplier range is a 100 Ah battery.

The required battery when used in conjunction with the preliminary size supercapacitor, compared to that of application 1, has the same amount of spare capacity when calculated as a percentage of the total battery. The battery itself, however, is smaller and has less capacity, but the supercapacitors are identical.

Although the supercapacitor is smaller and requires less energy to recharge, the battery has to supply portions of the momentary loads when the smaller supercapacitor is used. When recalculating the required battery for the two different discharge curves in Figure 41, it is found that the smaller supercapacitor is slightly more taxing on the battery than the preliminary sized supercapacitor.

The battery sizing tables are indicated in Appendix B.

5.2.2 **Comparison**

Using the calculations indicated in section 2.3, the required battery, supercapacitor, charger size, and H_2 extraction fan for this application is calculated. The battery dimensions for the purpose of these calculations are obtained from the relevant datasheets. Table 22 summarizes the required equipment required for Application 2.

Table 22: Summary of required battery and supercapacitor sizes for Application 2

Description	Required supercapacitors		Required battery capacity as per IEEE recommended practice		Required extraction fan	Required battery charger	Next available size: Battery; supercapacitor; charger; extraction fan
	Size (F)	Count	Size (Ah)	Count	Size (m^3/h)	Size (A)	Size
Required battery without supercapacitor	N/A	N/A	117.845	20	0.03906	40.49	VTX1M125, 125Ah; N/A; 60A; RVK315Y4, 16.8 m^3/h
Required battery with preliminary sized supercapacitor	Cell 2823.682; stack 770.095	11 series, 3 parallel	91.561	20	0.03125	36.82	VTX1M100, 100Ah; BCAP3000, 3000F; 60A; RVK315Y4, 16.8 m^3/h

Required battery with undersized supercapacitor	BCAP150, 150; stack 13.64	11 series, 1 parallel	92.466	20	0.03125	36.95	VTX1M100, 100Ah; BCAP150, 150F; 60A; RVK315Y4, 16.8 m³/h

5.3 APPLICATION 3

Similarly to application 2, this section only indicates the results of the simulations and a discussion thereof. The battery sizing tables for application 3 are indicated in Appendix B, while the preliminary supercapacitor sizing is indicated in Appendix C.

5.3.1 Simulation results for application 3

Figure 42 indicates the measurements across the battery during the simulation for application 3. As with the application 2, the supercapacitors supplies the predominant portion of the initial momentary load. The undersized sized supercapacitor, however, does not totally relieve the battery of the final momentary load.

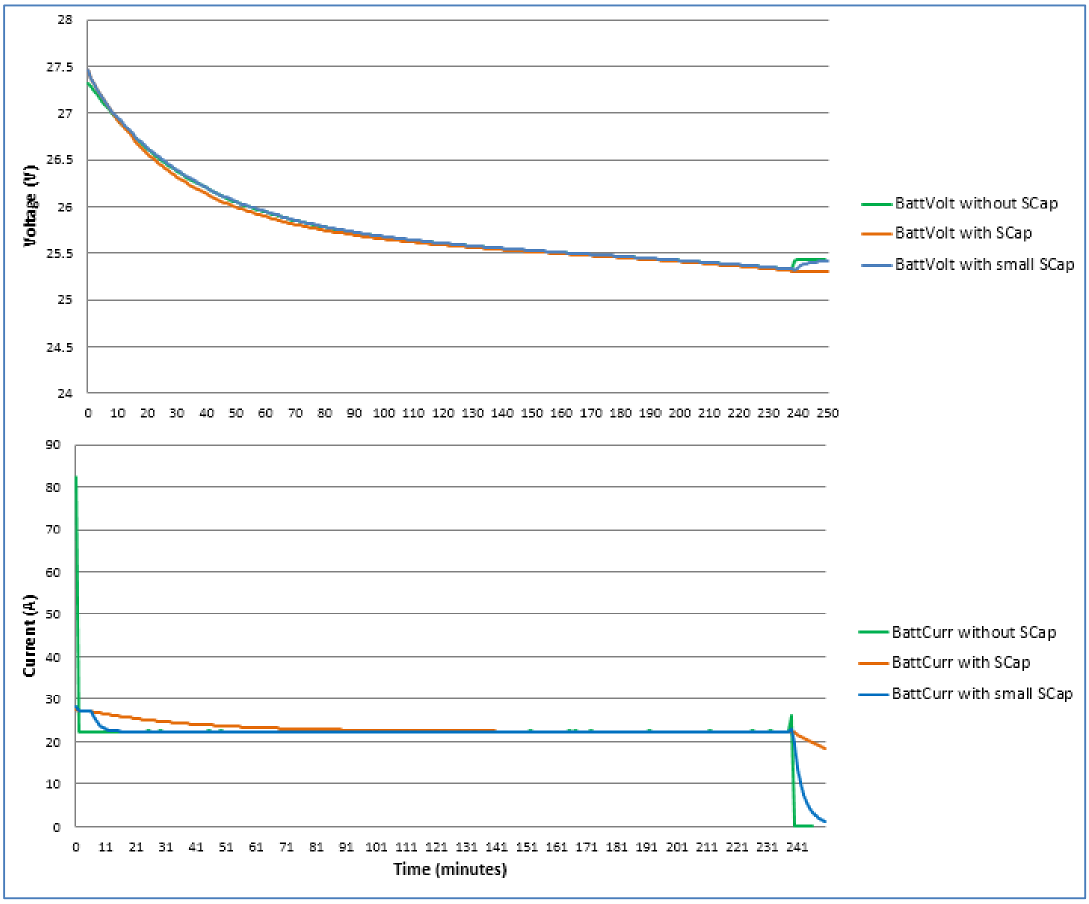

Figure 42: Application 3 battery measurements

Although the supercapacitors partially relieves the battery of the initial and final momentary loads, it adds additional load to the battery during normal operation. As with the previous applications, the supercapacitors introduce no advantage during discharge other than relieving the battery of the momentary loads.

Figure 43 represents the difference in battery measurements during simulation with the preliminary and undersized supercapacitors.

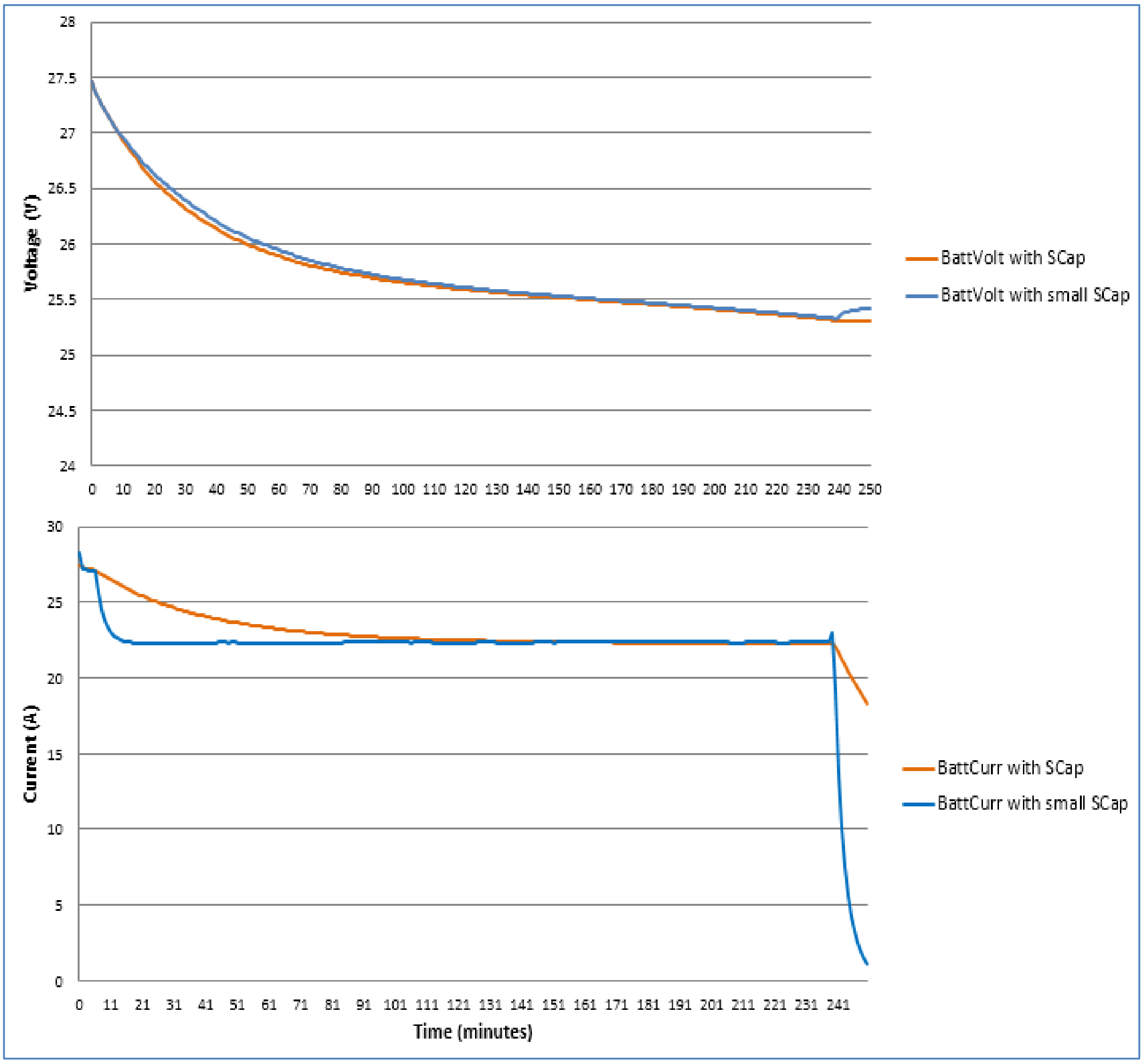

Figure 43: Battery measurements with undersized supercapacitor versus preliminary sized supercapacitor, application 3

From the “BattCurr with small SCap” curve in Figure 43, it is clearly observed that the battery has to supply a portion of the initial momentary load. The smaller supercapacitor, however, recharge much quicker than the preliminary sized capacitor.

Calculating the required battery sized for both the discharge curves in Figure 43 proves that the current required to recharge the preliminary sized supercapacitor is substantially more than to supply the partial momentary load when using the undersized supercapacitor.

The battery sizing tables are indicated in Appendix B.

5.3.2 Comparison

Using the calculations indicated in section 2.3, the required battery, supercapacitor, charger size, and H_2 extraction fan for this application is calculated. The battery dimensions for the purpose of these calculations are obtained from the relevant datasheets. Table 23 summarizes the required equipment required for Application 3.

Table 23: Summary of required battery and supercapacitor sizes for Application 3

Description	Required supercapacitors		Required battery capacity as per IEEE recommended practice		Required extraction fan	Required battery charger	Next available size: Battery; supercapacitor; charger; extraction fan
	Size (F)	Count	Size (Ah)	Count	Size (m^3/h)	Size (A)	Size
Required battery without supercapacitor	N/A	N/A	139.1856	20	0.046875	46.486	VTX1M150, 150Ah; N/A; 60A; RVK315Y4, 16.8 m^3/h
Required battery with preliminary sized supercapacitor	Cell 2780.327, stack 758.271	11 series, 3 parallel	136.762	20	0.046875	46.147	VTX1M150, 150Ah; BCAP3000, 3000F; 60A; RVK315Y4, 16.8 m^3/h
Required battery with undersized supercapacitor	BCAP150, 150; stack 31.82	11 series, 1 parallel	134.65	20	0.046875	45.851	VTX1M150, 150Ah; BCAP150, 150F; 60A; RVK315Y4, 16.8 m^3/h

5.4 APPLICATION 4

Similarly to application 2, this section only indicates the results of the simulations and a discussion thereof. The battery sizing tables for application 3 are indicated in Appendix B, while the preliminary supercapacitor sizing is indicated in Appendix C.

5.4.1 Simulation results for application 4

Figure 44 indicates the measurements across the battery during the simulation for application 4. From the figure, it seems as if the supercapacitors only supply approximately half of the initial momentary load. In actual fact, the supercapacitors supply the full momentary load, but add an enormous amount of additional load to the battery as they recharge.

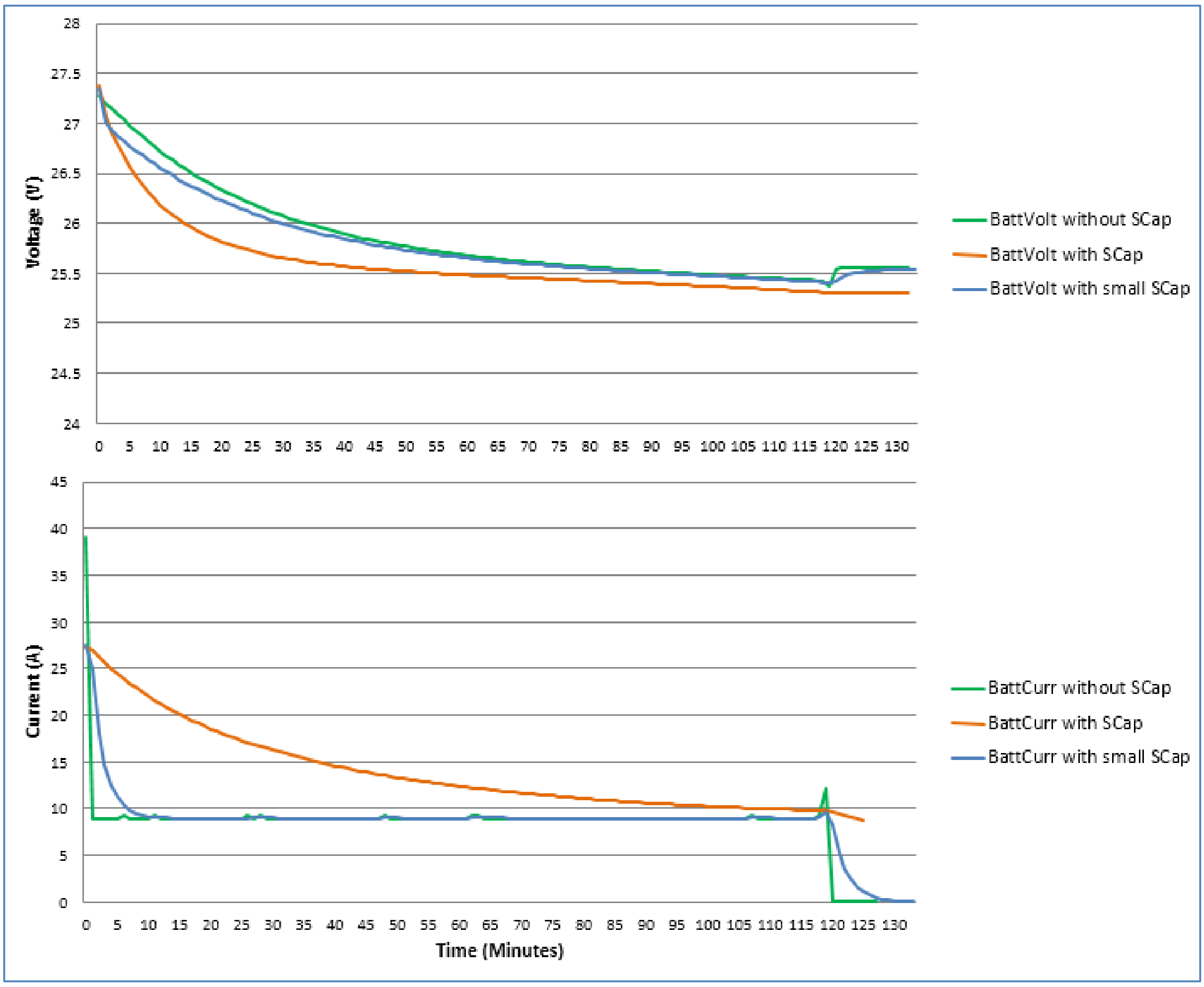

Figure 44: Application 4 battery measurements

Due to the large current requirement observed after the initial load, the assumption is made that the supercapacitors are oversized for this application. The reality is that the supercapacitors are correctly sized to supply the initial momentary load. In this application, the ratio between the initial load and the continuous load is much higher than with the previous applications. This higher ration creates the effect that the supercapacitors are oversized for the application.

Figure 45 concentrates on the difference in battery measurements during the preliminary and undersized supercapacitor simulations.

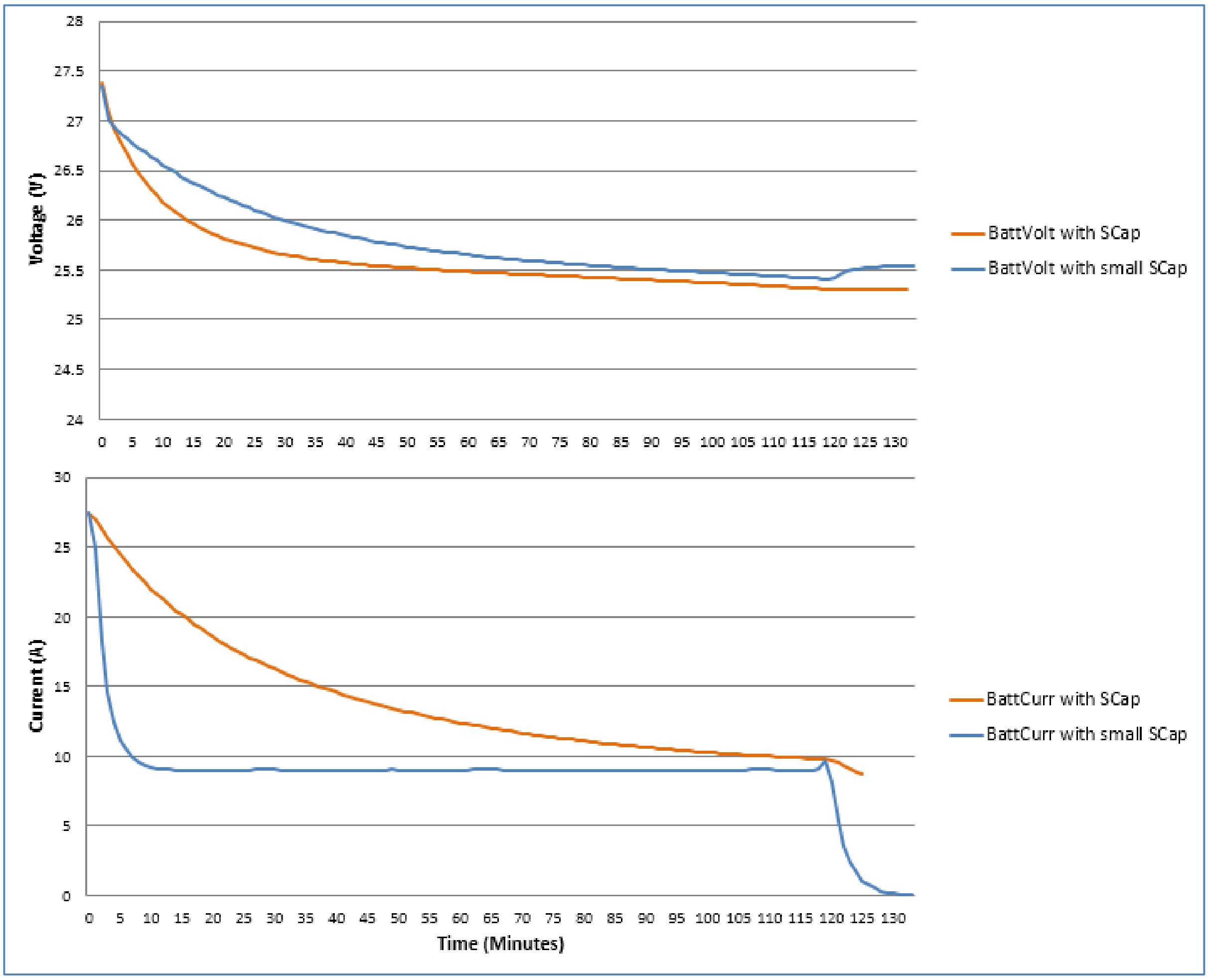

Figure 45: Battery measurements with undersized supercapacitor versus preliminary sized supercapacitor, application 4

From Figure 45 it is clear that, as with the previous applications, the supercapacitors introduce no advantage during discharge other than relieving the battery of the momentary loads. It is also clearly illustrated that the preliminary sized battery requires significantly more current to recharge than the undersized supercapacitor.

Calculating the required battery size for the discharge curve where the preliminary sized supercapacitor is used, proves that this supercapacitor is much more taxing on the battery. The required battery size becomes more than what is required when no supercapacitor is used.

The calculations above are repeated for the discharge curve where the smaller, or undersized supercapacitor is used. The results show some advantage when using this supercapacitor, although the battery has to supply a portion of the momentary loads.

The battery sizing tables for application 4 are indicated in Appendix B.

5.4.2 Comparison

Using the calculations indicated in section 2.3, the required battery, supercapacitor, charger size, and H_2 extraction fan for this application are calculated. The battery dimensions for the purpose of these calculations are obtained from the relevant datasheets. Table 24 summarizes the required equipment required for Application 4.

Table 24: Summary of required battery and supercapacitor sizes for Application 4

Description	Required supercapacitors		Required battery capacity as per IEEE recommended practice		Required extraction fan	Required battery charger	Next available size: Battery; supercapacitor; charger; extraction fan
	Size (F)	Count	Size (Ah)	Count	Size (m^3/h)	Size (A)	Size
Required battery without supercapacitor	N/A	N/A	43.3946 Ah	20	0.015	15.075	VTX1M48, 48Ah; N/A; 30A; RVK315Y4, 16.8 m^3/h
Required battery with preliminary sized supercapacitor	Cell 1969.773F, stack 358.114F	11 series, 2 parallel	49.148Ah	20	0.015	15.881	VTX1M48, 48Ah*; BCAP2000, 2000F; 30A; RVK315Y4, 16.8 m^3/h

Required battery with undersized supercapacitor	BCAP100, 100F; stack 9.1F	11 series, 1 parallel	36.303Ah	20	0.0125	14.082	VTX1M40, 40Ah; BCAP100, 100F; 30A; RVK315Y4, 16.8 m^3/h

*NOTE: See Appendix B for discussion on cell selection

5.5 CONCLUSION

The applications in this study are chosen specifically to study the influence of supercapacitors over a range of required battery sizes. From the results obtained, it is evident that the supercapacitor-battery combination becomes less efficient as the required size battery decreases.

Table 25 indicate data for five different load profiles. The first profile is from literature, while the other four are from the applications in this study. The values of the initial and final momentary loads are displayed in the table. The load profiles in this study imitate a constant discharge current during normal operation. The average value during discharge, disregarding the momentary loads, are therefore indicated in the table as the "static load".

Table 25: Average factor for defining a typical load profile when momentary loads are unknown

	Static Load	Initial Momentary load	Final Momentary load	Factor (Initial / Static)	Factor (Final / Static)
Typical load from literature	300	900	425	3.00	1.42
Application 1	26.59	86.73	32.56	3.26	1.22
Application 2	23.81	83.643	33.98	3.51	1.43
Application 3	22.36	82.36	25.93	3.68	1.16
Application 4	8.99	38.97	12.12	4.33	1.35
			Average	3.55	1.32

The last two columns of the table indicate the values when computing the momentary loads as a factor of the static loads. The individual factors are used to calculate the average factor for the relevant category.

Table 25 clearly illustrates the fact that the load requirements and momentary loads throughout industry differ from application to application. However, from examining Table 25, and assuming the law of averages, the profile and factors as indicated in

Figure 46 seem to correlate throughout the different applications. These average factors represent a good estimate for defining a typical DC control system load profile in the case where the momentary loads are unknown.

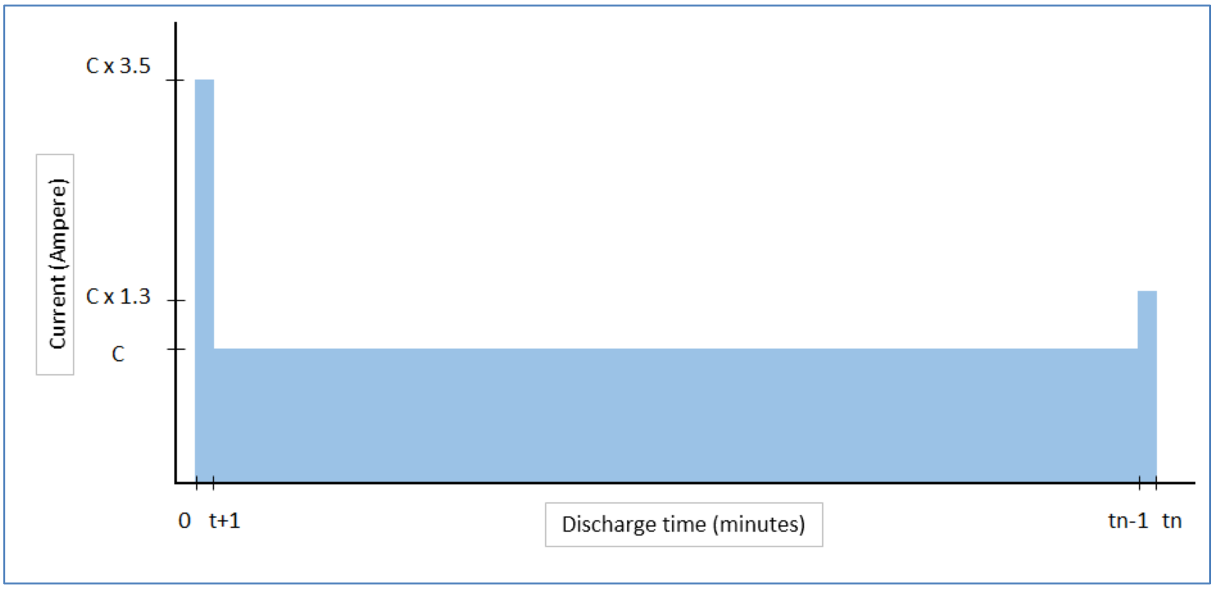

Figure 46: Typical load profile estimation when the momentary loads are unknown

The results from the section above clearly indicates that the supercapacitor has very little, if not zero effect on the required battery load during normal operation. The variations in the load of the control systems are simply too small for the supercapacitor to have a mentionable influence on the required battery size.

The addition of the supercapacitor also does not affect the selection of a specific size charger, nor does it affect the selection of an extraction fan. This is because of the ranges available from manufacturers. The influence of the supercapacitor on these parameters are again too small to cause a decrease in the selection of these devices.

It is therefore concluded that supercapacitors add no benefit in terms of the battery sizing during normal operations of a typical control and monitoring system. The apparent benefit of using a supercapacitor in conjunction with batteries is to minimize the momentary loads at the start and end of the profiles.

CHAPTER 6: **COST IMPACT**

In this chapter, the financial impact of using a supercapacitor in conjunction with a battery for an auxiliary power system is indicated. The quotations obtained are reflected in this chapter, and are based on the foreign exchange rates at the time of the study.

In order to conduct a thorough cost comparison, this section also compares the costs associated with required charger sizes, physical space requirements, as well as H_2 ventilation system requirements.

6.1 APPLICATION 1

In Section 5.1.3, the impact that the supercapacitor has on the required battery size is indicated. A reduction from 168.037 Ah to 153.99 Ah is noticed in the required battery capacity. For both these values, the next available battery size in the supplier catalog is a 170 Ah battery. Although the supercapacitor reduces the required battery capacity, the reduction is not sufficient enough to drop one battery size.

The addition of the supercapacitor to the system also has no influence on the selected charger and H_2 extraction system. The exact same equipment is required throughout the scenarios of this application. Thus, the addition of the supercapacitor only has a negative cost impact on this application. For this reason, the costs for this application are not compared. Adding a supercapacitor to the design of application 1 is, therefore, not a feasible solution.

6.2 APPLICATION 2

In Section 5.2.2, a reduction from 117.845 Ah to 91.561 Ah is noticed in the required battery capacity when the preliminary sized supercapacitor is added to the circuit. When an undersized supercapacitor is used, the required battery capacity becomes 92.466 Ah. Table 26 indicates a cost breakdown and comparison for application 2.

The addition of the supercapacitor to the system also has no influence on the selected charger and H_2 extraction system. The exact same equipment is required throughout the scenarios of this application. The cost of these specific equipment is, therefore, disregarded and not shown in Table 26.

Table 26: Application 2 cost comparison

Description	Item	QTY	Cost per item, ZAR	Total cost, ZAR
Battery without supercapacitor	VTX1M125	20	1620.00	32,400.00
	TOTAL			32,400.00
Battery with preliminary sized supercapacitor	VTX1M100	20	1304.00	26,080.00
	BCAP3000	14	664.40	9,301.60
	TOTAL			35,381.60
Battery with undersized supercapacitor	VTX1M100	20	1304.00	26,080.00
	BCAP0150	12	171.49	1,886.39
	TOTAL			27,966.39

From Table 26 it is noted that using the undersized supercapacitor yields the most cost effective result. A cost saving of R4433.61 is possible when using this supercapacitor in conjunction with the battery.

6.3 APPLICATION 3

In Section 5.3.2, the impact that the supercapacitor has on the required battery size is indicated. Similarly to application 1, the reduction in battery size due to the supercapacitor is not sufficient enough to drop a battery size.

It is again observed that the addition of the supercapacitor to the system also has no influence on the selected charger and H_2 extraction system. Thus, the addition of the supercapacitor only has a negative cost impact on this application. For this reason, the costs for this application are not compared. Adding a supercapacitor to the design of application 3 is, therefore, not a feasible solution.

6.4 APPLICATION 4

In Section 5.4.2, an increase from 43.3946 Ah to 49.148Ah Ah is noticed in the required battery capacity when the preliminary sized supercapacitor is added to the circuit. When an undersized supercapacitor is used, the required battery capacity becomes 36.303 Ah. Table 27 indicates a cost breakdown and comparison for application 2.

The addition of the supercapacitor to the system also has no influence on the selected charger and H_2 extraction system. The exact same equipment is required throughout the scenarios of this application. The cost of these specific equipment is, therefore, disregarded and not shown in Table 27.

Table 27: Application 4 cost comparison

Description	Item	QTY	Cost per item, ZAR	Total cost, ZAR
Battery without supercapacitor	VTX1M48	20	752.00	15,040.00
	TOTAL			15,040.00
Battery with preliminary sized supercapacitor	VTX1M48	20	752.00	15,040.00
	BCAP2000	13	601.70	7822.10
	TOTAL			22,862.10
Battery with undersized supercapacitor	VTX1M40	20	645.00	12,900.00
	BCAP0100	12	117.70	1412.40
	TOTAL			14312.40

From Table 27 it is noted that using the undersized supercapacitor again yields the most cost effective result. A cost saving of R727.60 is possible when using this supercapacitor in conjunction with the battery.

6.5 CONCLUSION

In order to investigate the full influence that the addition of a supercapacitor has on an auxiliary DC supply system, the impact on various factors are considered. These factors include the battery size, charger size, H_2 extraction system, as well as maintenance requirements and the life of the battery.

From the comparisons in the previous sections, it is clear that the addition supercapacitors have no major cost saving in terms of a battery size decrease. In the instances where there is a visible cost saving, the amount saved is so little that the engineering time required to calculate the required supercapacitor, and optimizing the design, will result in at least an equal cost to that which can be saved.

When additional factors, such as the required charger size and the influence on the required H_2 extraction system are calculated, it is again observed that the addition of the supercapacitor has no cost saving implications.

It is important to note that this study is based on the NiCd battery technology due to economic reasons as stated in section 2.4.2.1. Lead acid batteries have a higher H_2 emission rate and may indicate different gas evolution results. When sizing an H_2 extraction system, however, only the cell type, the number of cells, the overcharge current and volume of air is considered. Only if the influence of the supercapacitor is such that a reduction in cell size is achieved, may it affect the H_2 extraction system. Even if the rare occurrence of a reduction in the required extraction system is assumed, the cost saving will be of little or no value due to the fixed range of units available from manufacturers.

The recommended maintenance procedures as per the IEEE recommended practice is not dependent on cell sizing [45], [46]. Factors that influence the maintenance of battery are the overall float voltage, charger output current and voltage, ambient temperature, ventilation and monitoring equipment, physical condition of the cell containers and battery racks, terminal corrosion, and leakage of electrolyte.

The above mentioned standard recommends that a battery is inspected if it has experienced an abnormal condition such as a severe discharge, overcharge, or an extreme ambient temperature [45], [46]. Supercapacitors may temporarily relieve the battery of a large sudden discharge, but will not safeguard the battery in the event of a severe discharge.

The capacity of a NiCd battery gradually decrease through the life of the battery. There is no sudden capacity loss encountered under normal operating conditions.

The rate of capacity loss is dependent on the operating temperature, electrolyte-specific gravity, and the depth and frequency of discharge [5]. When a NiCd battery is subjected to repetitive deep discharges, its available capacity may be reduced. This capacity loss is temporary however. The capacity can be recovered to its original level by applying a reconditioning charge [45].

The addition of supercapacitor may, therefore, provide some advantage to the end-of-life time of the battery by relieving the battery of some deep discharges. However, it does not influence the calculation parameters when sizing a new NiCd battery.

Lead Acid batteries with Planté, modified Planté, or rounded plate designs are replaced when the measured capacity of the battery drops below 100% of the rated capacity. Thus, these batteries have an aging factor of 1.00. When these batteries are used, the battery maintains a constant capacity throughout its designed life time [4]. The addition of a supercapacitor to the design, therefore, will not prove beneficial.

CHAPTER 7: **CONCLUSION AND RECOMMENDATIONS**

In this chapter, the findings of the study is concluded. The chapter also include recommendations for possible future studies.

7.1 APPROXIMATED PROFILES

In Chapter 3, approximated profiles for dynamic processes were created by means of determining and simulating a probabilistic load profile. These simulations are based on the various plant operating philosophies.

Interviews with the various experts confirmed that the methodlogy followed for the load profile approximation yields accurate results within reasonable limits. The interviews with the experts indicated that the experts would be likely to implement the approximation methodology for defining load profiles.

The results from the simulations, however, proved that the variation in load as a result from the simulations are minute. The intention of the approximation methodology is to define a more complex load profile in order to fully test the influence of the supercapacitor. Considering the time to develop the simulations, the possible inaccuracy of the probabilistic approach, and most importantly, the small result as a function of the simulation, it is recommended that load profile definitions follow a constant current profile. This recommendation is specific to a control and monitoring application, and conforms to the existing practices as discussed during this dissertation.

Furthermore, in the event where the momentary loads of a load profile are unknown, the factors indicated in Figure 46, as discussed in section 5.5, are good estimates to follow when defining any application’s load profile.

7.2 USING SUPERCAPACITORS IN CONJUNCTION WITH BATTERIES

The calculations performed in Chapter 6 indicate that the addition of supercapacitors have no major cost saving in terms of a battery size decrease. When the cost of additional engineering hours are considered, the design may in actual fact prove more costly.

The addition of the supercapacitors to the design does, however, relieve the battery, and its relevant charger of some load. Unfortunately, due to the fact that equipment are manufactured in a specific range of sizes, the reduction in load is too small to cause a drop in the required selection, and therefore no cost benefit is gained.

The influence of the supercapacitor on the H_2 extraction system, battery end-of-life time, and maintenance processes also have no cost saving implications.

It can therefore be concluded that the savings in cost when using supercapacitors in conjunction with batteries is too little (if not zero), and it is therefore not a feasible solution. This finding is specific to control and automation systems. It is believed that a larger cost saving will be visible is applications where the profile contains larger momentary loads. A typical application may be the UPS system which directly powers sets of large motors and drives. The application differs from this study in the fact that control and monitoring sytems start and stop motors and drives through devices such as relays.

7.3 RECOMMENDATIONS

This study specifically investigates the load profiles of control and automation systems. For these types of applications, it is not feasible to use supercapacitors in conjunction with batteries.

In the section below, some hypothetical load profiles are created. For the profile indicated in Figure 47, some additional load peaks are manually added to the profile. For this example, the battery calculation table indicates that the initial momentary load is the limiting factor. The three additional peaks do not cause an increase in the required battery size.

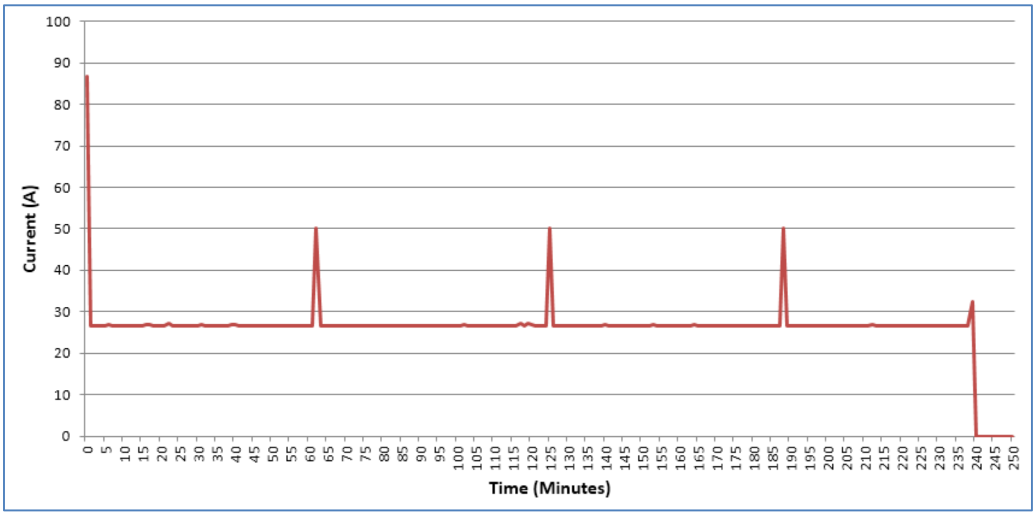

Figure 47: Hypothetical load profile 1

For the hypothetical profile created in Figure 48, the random loads induced do influence the required battery size.

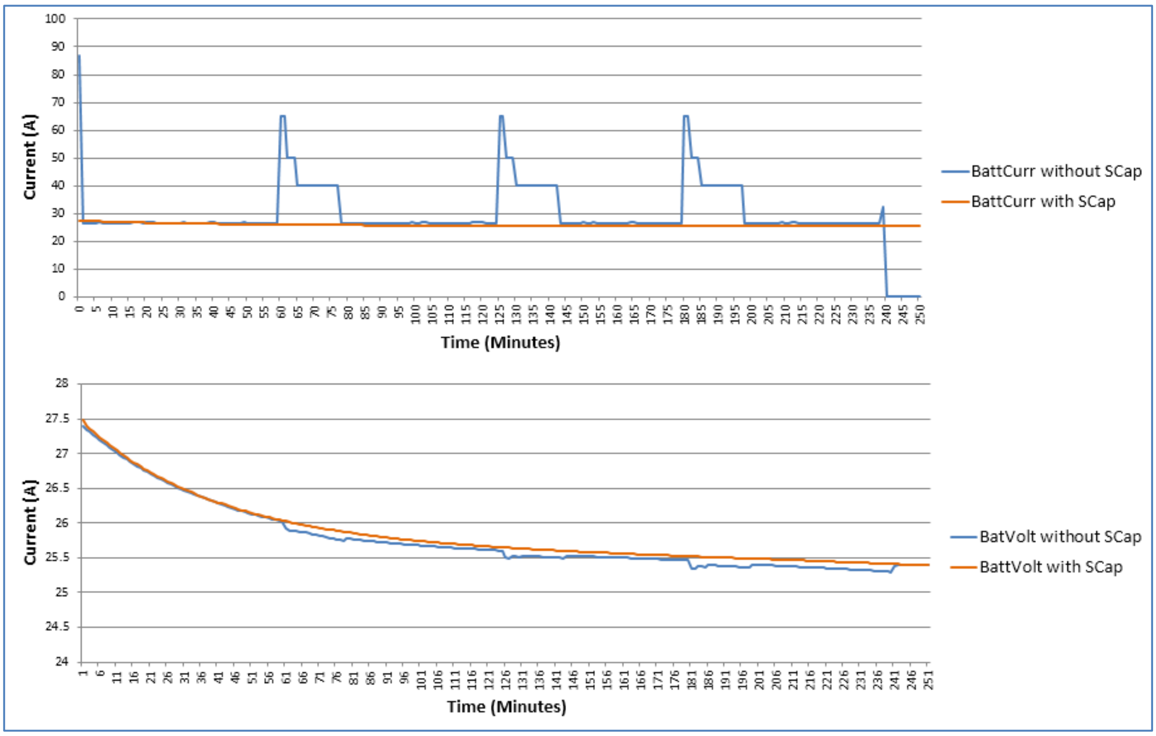

Figure 48: Hypothetical load profile 2

The required battery capacity for this profile is 194.06 Ah. The next available battery from the manufacturer catalogue is a VTX1M195 cell. Adding 11 series, and 3 parallel BCAP3000 capacitors to the circuit reduces the required battery capacity to 154.20 Ah. Available battery sizes in this vicinity are the VTX1M150 and the

VTX1M170. It can be argued that the VTX1M150 battery will suffice for this application, in which case the battery size drops by two interval sizes. The addition of the supercapacitor will still not have a major cost impact.

Figure 49 indicate the European (EUCAR) power-assist profile which is commonly used to simulate driving conditions of an electric vehicle. The profile indicate a two minute cycle and comprises of a discharge to simulate the power assist, a rest period, and a recharge period to simulate regenerative breaking. The profile indicate all values as a factor of the C_2 (two hour capacity) capacity of the battery [47], [48].

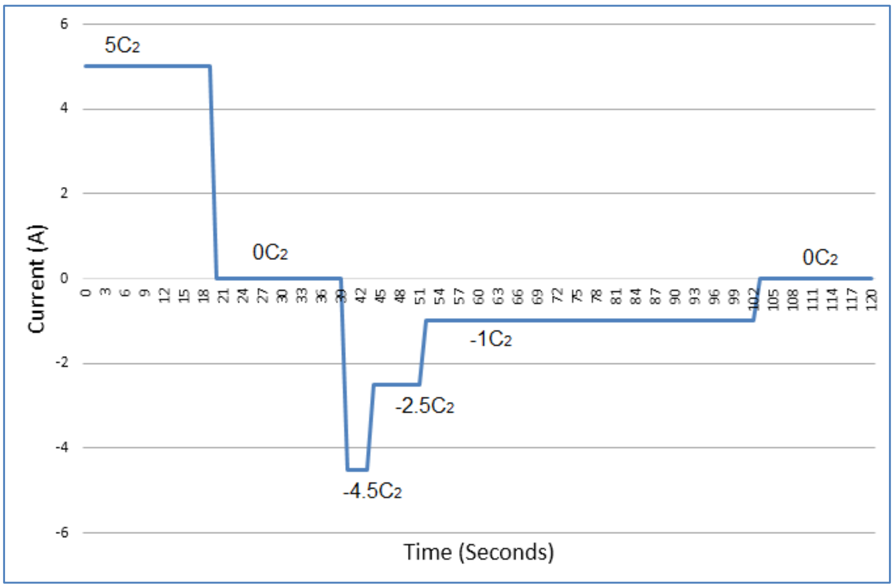

Figure 49: EUCAR power-assist profile [47], [48]

From Figure 49 it is apparent that the load profiles for electric vehicles have much more frequent, large current peaks in comparison to load profiles of the present study. The literature indicate great advantageous when combining supercapacitors and batteries in electric vehicles. This can be attributed to the high charge and discharge frequency of a typical electric vehicle load profile.

It is recommended that further studies are conducted to investigate various types of load profiles from different application and industries, in order to determine the conditions under which the use of supercapacitors become feasible.

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APPENDIXES

This section details the appendixes relevant to this study.

1. APPENDIX A

Appendix A details the approximation methodologies, as used in Chapter 3, for Application 2 through Application 4.

1.1. Application 2

The system in Application 2 is a conveyor system used to transport a specific product. The system consists of a series of conveyors as well as distribution chutes. There are two streams of conveyors which transport the product from source to destination. The conveyor system operates in an upstream methodology. If any one of the conveyors stops or experience a trip, all the conveyors upstream of that conveyor will also trip.

The equipment for Application 2 is listed below:

1) Reclaim conveyor
2) Incline conveyor
3) Shuttle conveyor
4) Distribution chutes
5) Cross conveyors
6) Vibro chutes
7) Feed conveyors

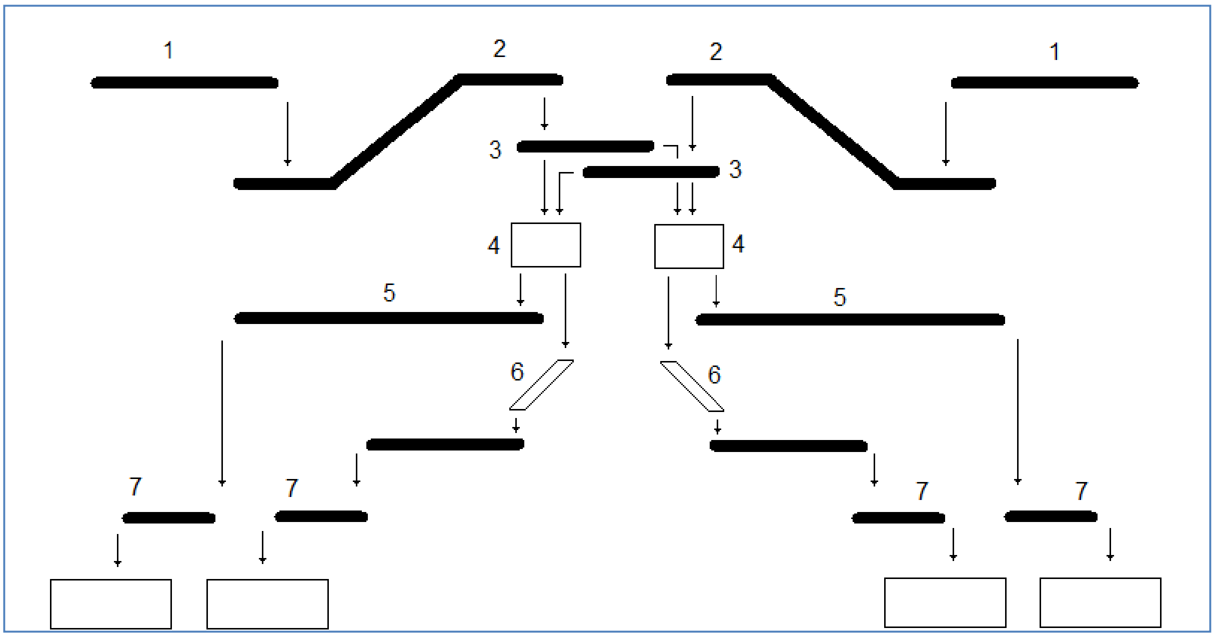


Figure 50: Simplified representation of Application 2

1.1.1. **Conveyors**

This section is applicable to all conveyors in the system except the shuttle conveyors. Under normal operating conditions the entire system is in operation for days on end. Trips and conveyor stops are therefore very improbable during the standby period. Although it is possible for an operator to stop the any of the conveyors, it should very rarely be required. Should a conveyor experience a trip condition, however, it is very improbable that the conveyor start again within the standby period. This is due to safety consideration and procedures applicable to the system.

The probabilities used for the reclaim conveyors are illustrated in Figure 51.

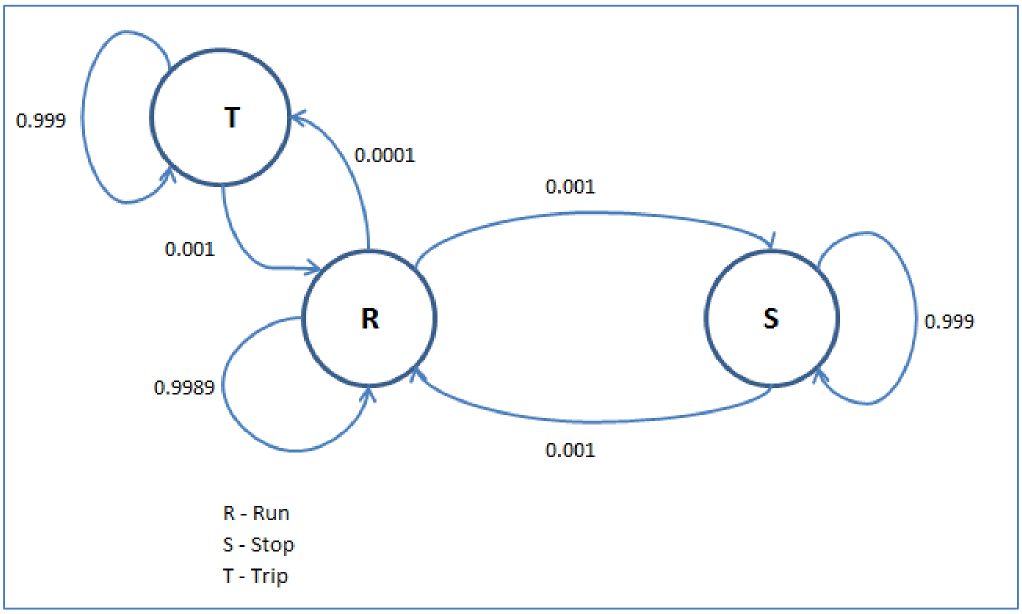


Figure 51: Conveyor operation probabilities

1.1.2. Shuttle conveyor

The shuttle conveyor can be used to transfer product between the two streams. This will only be required in the unlikely event that any one of the reclaim or incline conveyors have stopped or tripped. The shuttle conveyors operations are therefore linked to trip occurrences in any one (1) of the above mentioned conveyors.

Conveyor positioners are used to manipulate the destination of the product. Under normal operating conditions, the conveyors feed to its respective streams. The shuttle position can be changed within 1 to 2 minutes. Once the position has changed, the reason for the upstream trip will have to be investigated. It is therefore very improbable to revert position within the standby period.

The shuttle conveyors will add additional load to the system during a position change. The operation of the conveyors itself is similar to the conveyors in the previous section. The probabilities used for the shuttle conveyor positioners are illustrated in Figure 52.

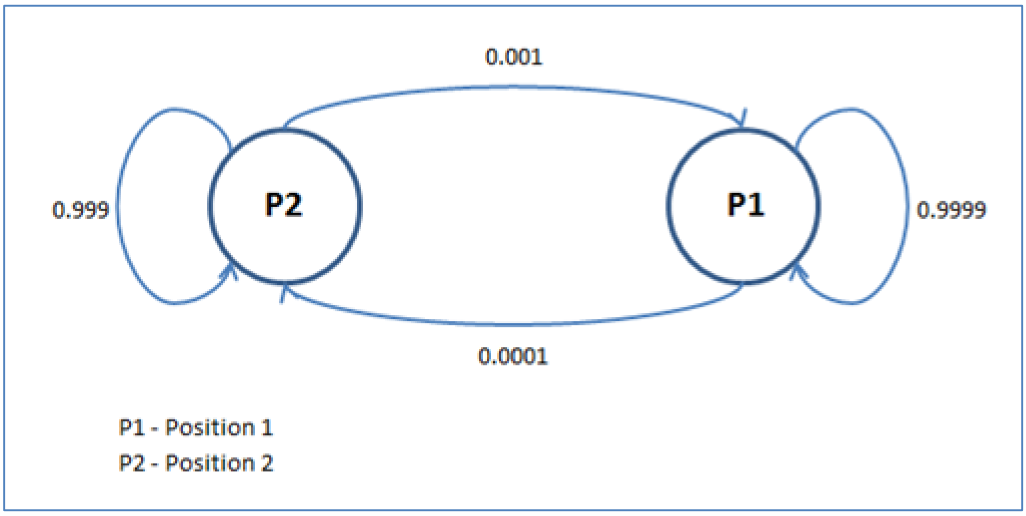


Figure 52: Shuttle conveyor positioner's operation probabilities

1.1.3. **Distribution chutes**

The shuttle conveyors feed into distribution chutes, which directs the product either to another conveyor, or a vibro chute, depending on the demand at the end of the stream. The chute output direction is changed in order to manipulate the product path. It is therefore relatively likely for the chute position to receive a change input. The probability of the chute experiencing a trip condition within the simulation period is also very low. The probabilities used for the distribution chutes are illustrated in Figure 53.

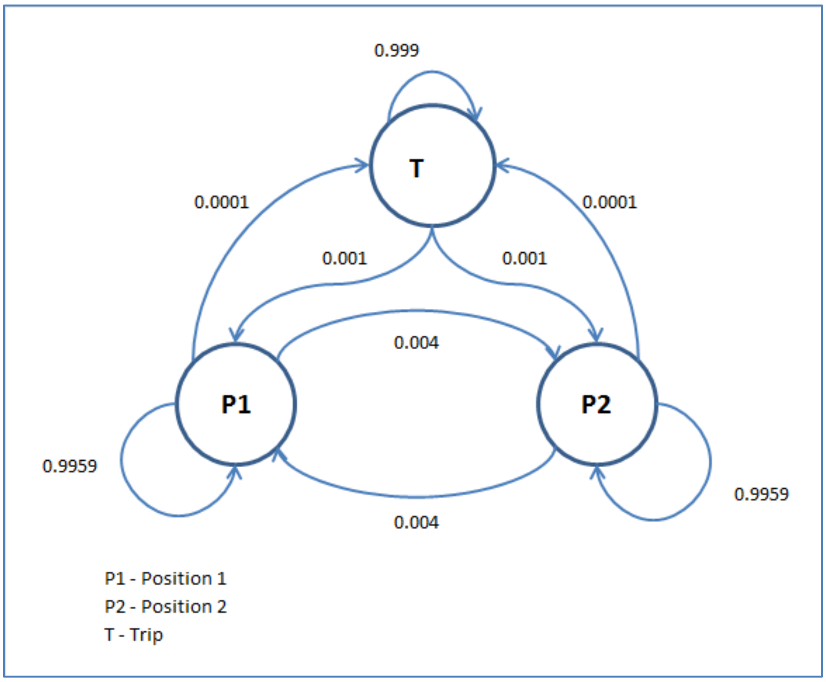


Figure 53: Distribution chutes operation probabilities

1.1.4. **Vibro chutes**

The vibro chutes receives product from the distribution chutes. The probability of the chute blocking and experiencing a trip condition within the simulation period is very low. Should it trip, however, the reason for the trip will have to be investigated. Should the investigation show that the chute is blocked, it will have to be unblocked manually. Unblocking a chute may take up to 24 hours. The probability of the chute going back online within the simulation period is therefore low. The probabilities used for the distribution chutes are illustrated in Figure 54.

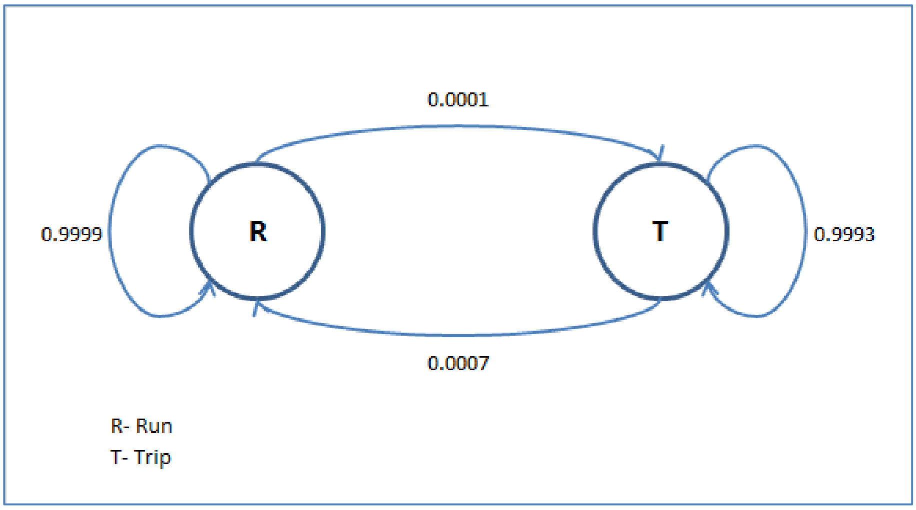


Figure 54: Vibro chutes operation probabilities

1.1.5. **Operating principles**

Starting and stopping the conveyors involves pulsing an interposing run (IPR) relay, or an interposing stop (IPS) relay. When a fault occurs, and the conveyor is stopped, there are 2 fault lamps that indicate the fault condition. When starting a conveyor, two sirens are used to warn nearby people that the conveyor is about to start. Emergency trips are managed through an emergency trip relay (ETR).

Starting and stopping distribution chutes involves pulsing either a forward or reverse IPR or IPS relay. When a fault occurs, and the drive is stopped, there are 2 fault lamps that indicate the fault condition. Vibro chutes only have fault indication, as no direction can be set on these chutes.

The conveyor system feed from one conveyor to the next. Should any one (1) conveyor trip, all the conveyors upstream of that specific conveyor will also trip.

1.2. Application 3

The system in Application 3 is used to pump water from a central point, through a heat exchange process, and finally end in one of three different reservoirs.

The equipment for Application 3 is listed below:

1) Pumps
2) Auto closing valves
3) Back-up valves
4) Sump pumps

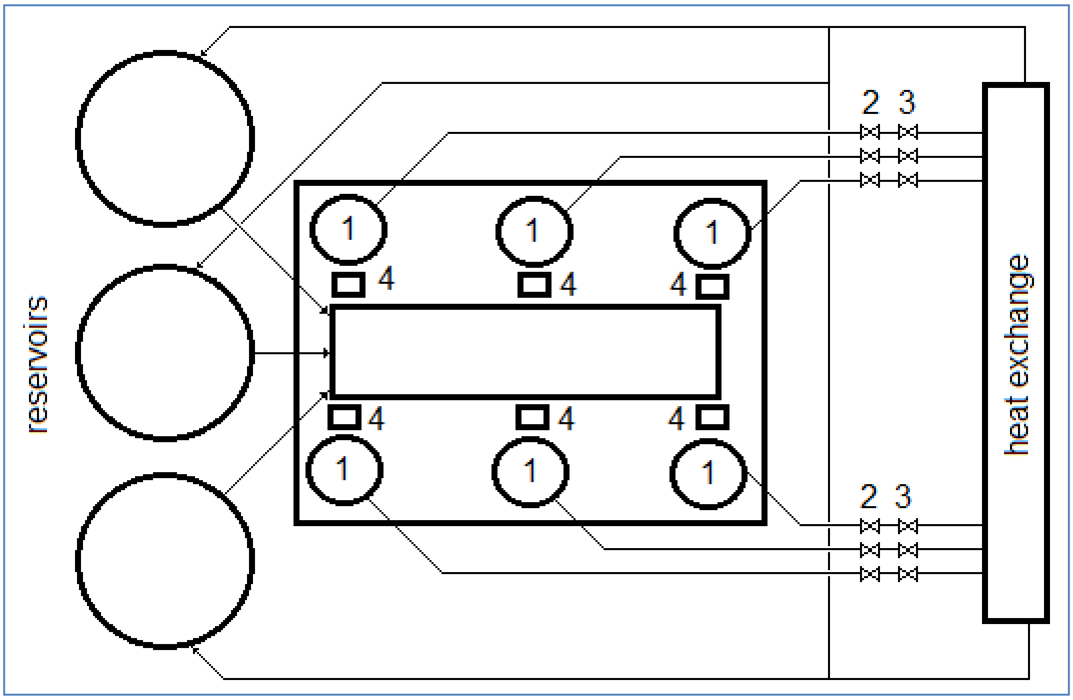


Figure 55: Simplified representation of Application 3

1.2.1. Pumps

There are six pumps in the system. The number of active pumps required is dependent on the number of reservoirs in service. Three reservoirs in service will require all six pumps to be active. When two reservoirs are in service, the system requires five pumps to be active. When only one reservoir is in service, the system requires only two pumps to be active. The pump operation is therefore linked to the operation of the reservoirs.

When a certain number of pumps are required, and one of the online pumps experiences a trip condition, one of the standby pumps will start. However, normally these pumps run several days without stopping. The probability of a pump experiencing a trip condition within the standby period is therefore low.

The reservoirs are also very rarely out of service. Typically they will be in service for days on end. The probability of a reservoir going out of service during the standby period is therefore also extremely low. Should a reservoir go out of service, however, the probability of the reservoir returning to an online status within the standby period is close to zero.

The probabilities used for the reservoirs are illustrated in Figure 56.

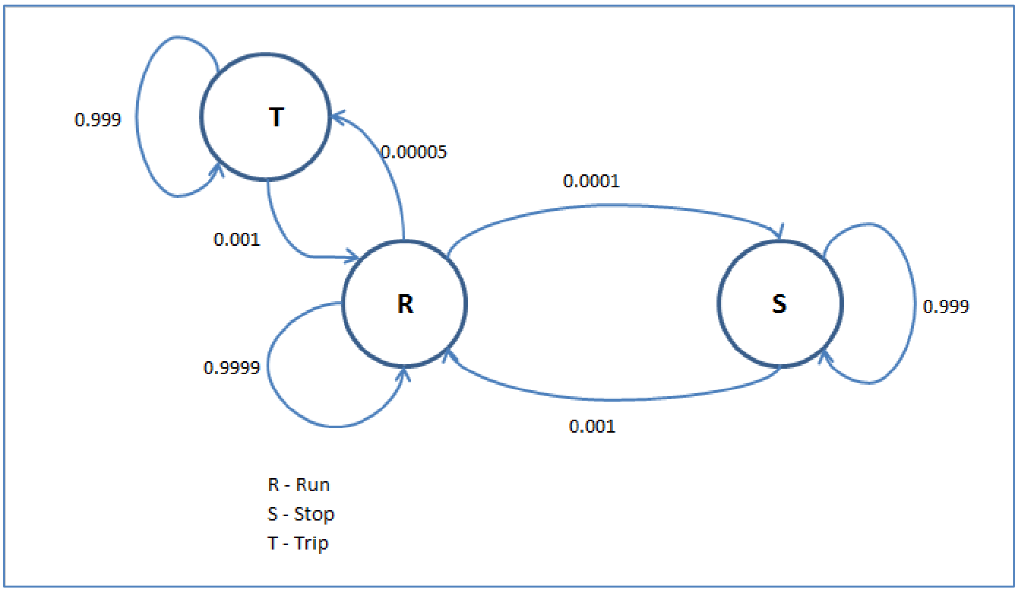


Figure 56: Probabilities for reservoirs

1.2.2. **Auto closing valves**

When any one of the pumps experiences a trip condition, a valve closes automatically to prevent water from flowing backward into the system. Should any one of the pumps trip or stop, its accompanying auto closing valve will close. The auto closing valve is therefore linked to operation of the pumps.

The probabilities used for the pumps are illustrated in Figure 57.

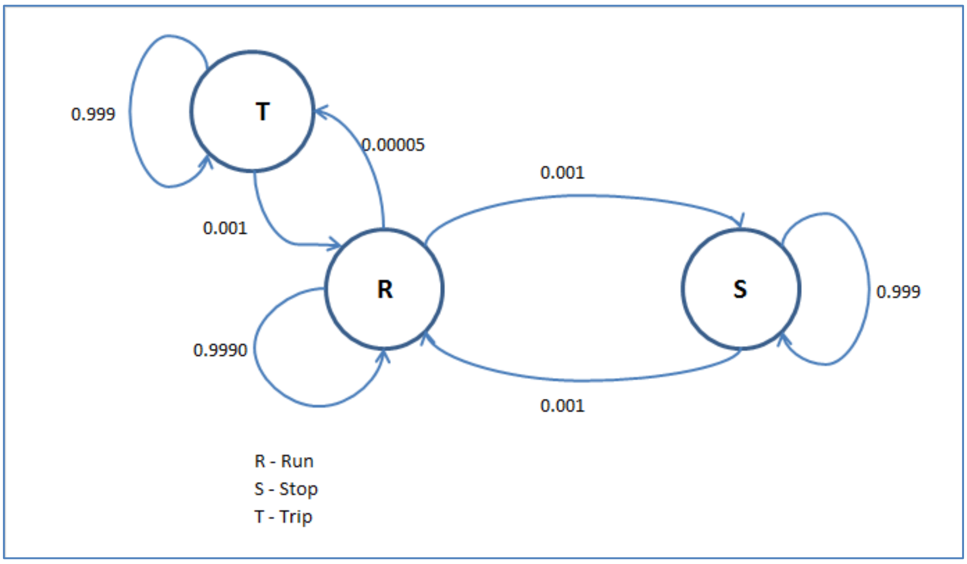


Figure 57: Probabilities for pumps

1.2.3. **Back-up valves**

Every auto closing valve has an in-line back-up valve. Should the system require the auto closing valve to close, and the valve fails, the back-up valve for that auto closing valve will close. Under normal operating conditions the back-up valve is open. The probability of the auto closing valve failing while it is required to close, is almost zero.

The probabilities used for the auto closing valves are illustrated in Figure 58.

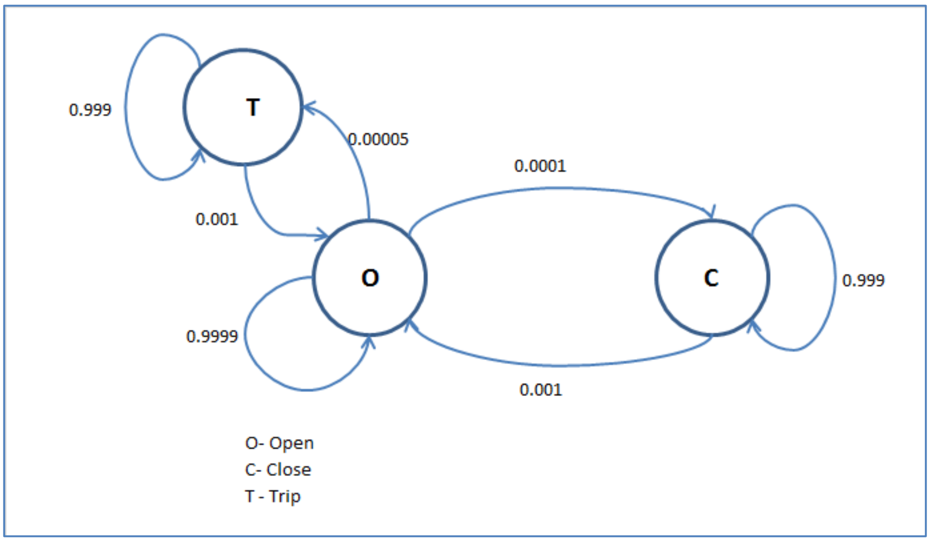


Figure 58: Probabilities of Auto closing valves

1.2.4. **Sump pumps**

The pumps have glands that leak, and eventually start to fill the housing of the pump. This water then seeps into the pump bearing housing, thereby contaminating the bearing oil. The sump pumps are used to drain leakage water from the housing/ sump.

The sump pumps are level controlled. Once a sump is full and requires the pump to start, it takes the pump approximately 20 minutes to fully drain the sump. The simulation uses a probability of the sump reaching a high level. Should it reach this level, the pump is kept active for 20 minutes or intervals. The sump will most probably not reach the high level twice within the standby period.

The probabilities used for the sump levels are illustrated in Figure 59.

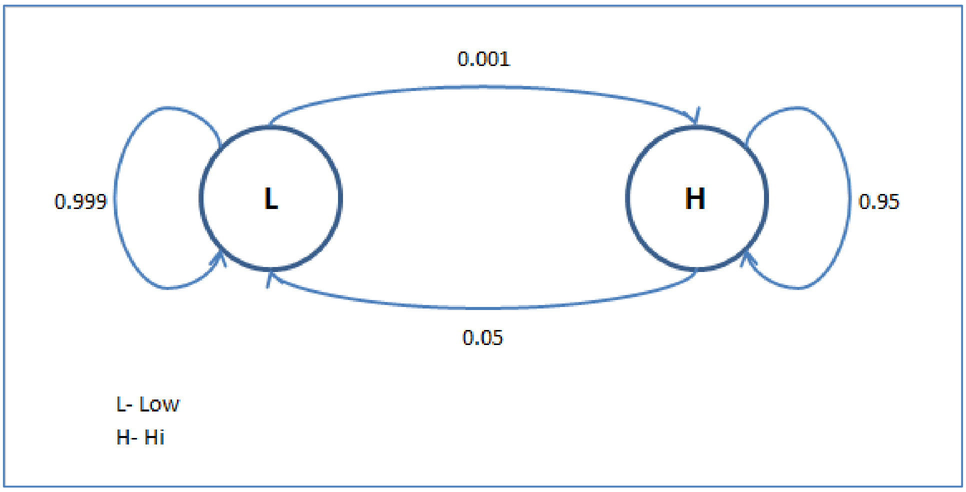


Figure 59: Probabilities for sump levels

1.2.5. **Operating principles**

Starting and stopping the pumps involves pulsing an interposing run (IPR) relay, or an interposing stop (IPS) relay. When a fault occurs, and the pump is stopped, there are 2 fault lamps that indicate the fault condition.

The auto closing and back-up valves, as well as the sump pumps operate similar to the pumps. The back-up valve and sump pumps, however, have no fault indicating lamps.

1.3. Application 4

Application 4 consist of two identical systems. For this study, each system will have its own auxiliary back-up system. The systems are used to pump a fluid from storage tanks to its destination. The fluid has to be pumped at a specific pressure. Each system contains 3 booster pumps which manages the fluid flow at the required pressure. The storage tanks must also be in equilibrium with one another. Equilibrium is maintained by pumping the fluid between the storage tanks. This is managed by 2 transfer pumps.

The equipment for Application 4 is listed below:

1) Transfer pumps
2) Booster pumps

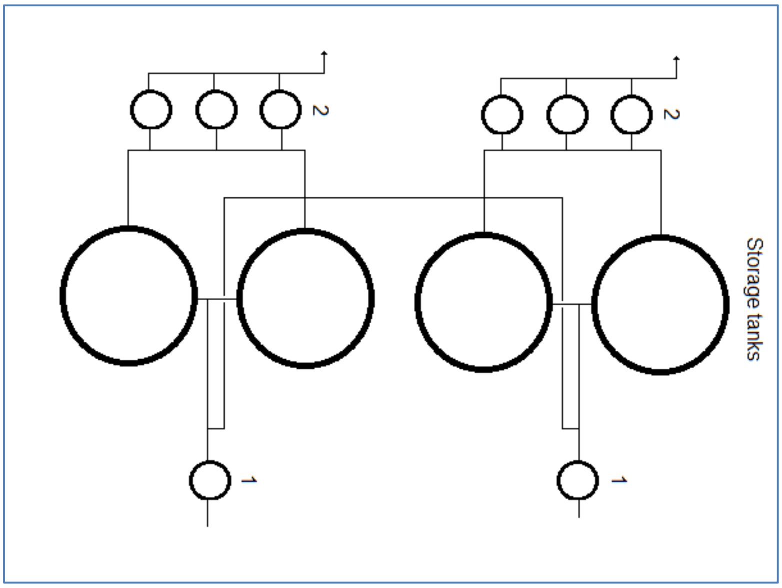


Figure 60: Simplified representation of Application 4

1.3.1. Transfer pumps

The fluid can be directed between any of the four storage tanks. The tanks are normally unbalanced during off-loading / re-filling of the tanks and require equalization. This should very rarely be required during the standby period. It is estimated that the tanks will be refilled monthly. The simulation, however, does cater for the possibility of an abnormal situation where filling is required and the tanks will have to be equalized. Should this situation occur during simulation, the transfer pumps will most probably run throughout the remainder of the simulation period. This is due to the time it will take to fill the large storage tanks.

At the beginning of the simulation, a stop condition is assumed for the pump. The probabilities used for the transfer pumps are illustrated in Figure 61.

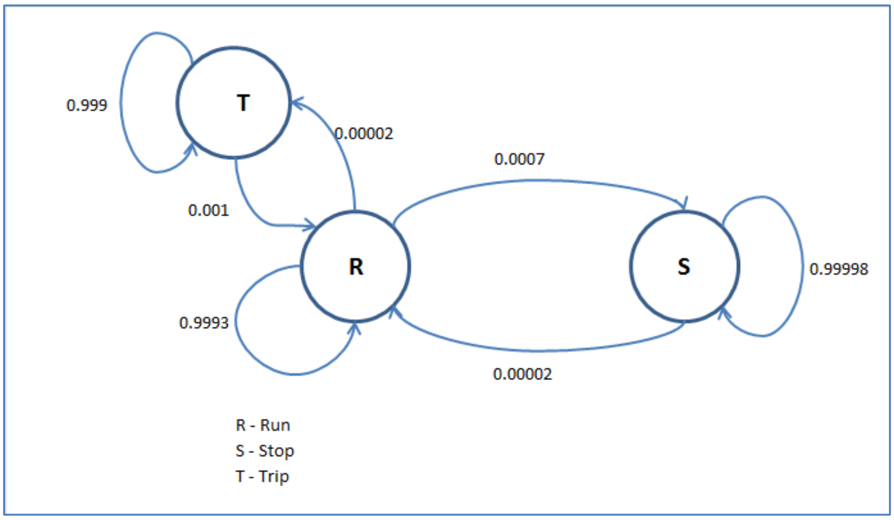


Figure 61: Probabilities of transfer pumps

1.3.2. **Booster pumps**

There are three booster pumps installed, which supply fluid at high pressure. Under normal operating conditions, only one of the three booster pumps is in service at a time. The second booster pump is on standby and will start automatically when the demand increase, or when the first pump has tripped. The third pump is a reserve pump and will only be used if one of the other pumps is out of service, or upon high demand.

The simulation starts with the first pump running, and the second and third pumps stopped. Should the first pump reach 90% of its capacity, the second pump will start. The third pump will start if either of the first two pumps fail, or if both the first and second pump reaches a combined capacity of 90%. The third and second pumps will stop once the demand decreases to 80% of the relevant capacity.

Pump1:

Pump 1 is in a run condition when the simulation starts.

Pump 2:

Pump 2 is in a stop or standby condition when the simulation starts. Should Pump 1 fail, or the demand increase to 90% of the first pumps' capacity, the simulation will put Pump 2 in a run condition.

Pump 2:

Pump 3 is also in a stop or standby condition when the simulation starts. Should either of Pump 1 or Pump 2 fail whilst they are in operation, or the demand increase to 90% of combined capacity of both Pump 1 and Pump 2, the simulation will put Pump 3 in a run condition.

The probabilities for each individual pump, disregarding the status of the pressure and condition of the other two pumps, are illustrated in Figure 62.

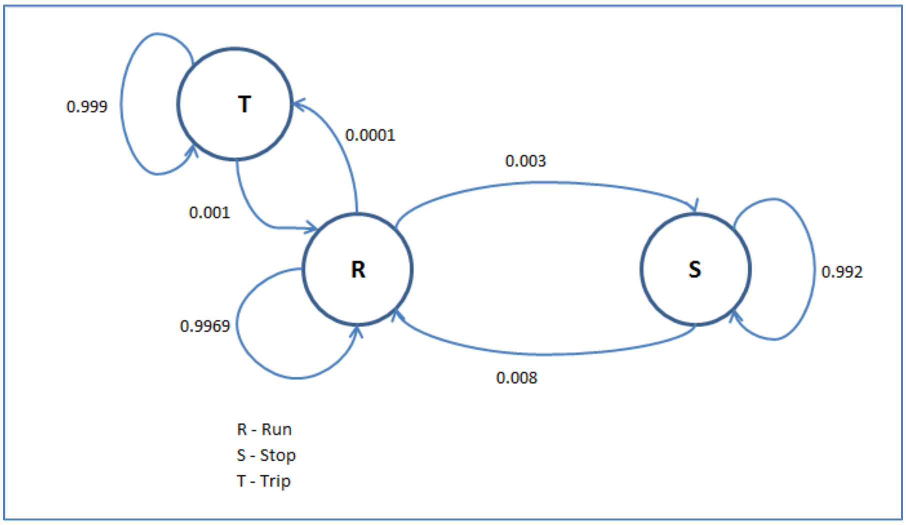


Figure 62: Probabilities of booster Pumps

1.3.3. **Operating principles**

Starting and stopping the pumps involves pulsing an interposing run (IPR) relay, or an interposing stop (IPS) relay. When a fault occurs, and the pump is stopped, there are 2 fault lamps that indicate the fault condition.

2. APPENDIX B

Appendix B indicates extractions of the calculation tables, as per the IEEE recommended practice for sizing NiCd batteries, for all applications pertinent to this study. Only the last section of the battery sizing tables are indicated due to the massive size of these tables.

2.1. Application 1

The required standby period for Application 1 is 240 minutes. The calculation starts two minutes prior the introduction of the inrush current, and ends two minutes after the momentary loads at the end of the profile.

2.1.1. IEEE recommended sizing for approximated load profile without supercapacitor

The largest load was observed during section 242 and therefore the table indicates this section.

Table 28: IEEE recommended practice for approximated load profile without supercapacitor, Application 1

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt) 1.1	Required size (3)x(6)x(7) (Rated Ah)	
							Pos	Neg
Section 242 - If A243 is greater than A242, go to section 243						1.1		
1	0	0	1	242	4.326993897	1.1	0	
2	0	0	1	241	4.311618792	1.1	0	
3	86.73	86.73	1	240	4.296243687	1.1	409.8745365	
4	26.73	-60	1	239	4.280868582	1.1	-282.5373264	
5	26.471	-0.259	1	238	4.265493476	1.1	-1.215239091	
6	26.471	0	1	237	4.250118371	1.1	0	
7	26.471	0	1	236	4.234743266	1.1	0	
8	26.617	0.146	1	235	4.219368161	1.1	0.677630527	
9	26.803	0.186	1	234	4.203993056	1.1	0.860136979	
10	26.637	-0.166	1	233	4.18861795	1.1	-0.764841638	

11	26.544	-0.093	1	232	4.173242845	1.1	-0.426922743	
12	26.637	0.093	1	231	4.15786774	1.1	0.42534987	
13	26.637	0	1	230	4.142492635	1.1	0	
14	26.564	-0.073	1	229	4.127117529	1.1	-0.331407538	
15	26.471	-0.093	1	228	4.111742424	1.1	-0.42063125	
16	26.617	0.146	1	227	4.096367319	1.1	0.657876591	
17	26.564	-0.053	1	226	4.080992214	1.1	-0.237921846	
18	26.471	-0.093	1	225	4.065617109	1.1	-0.41591263	
19	26.803	0.332	1	224	4.050242003	1.1	1.47914838	
20	27.003	0.2	1	223	4.034866898	1.1	0.887670718	
21	26.737	-0.266	1	222	4.019491793	1.1	-1.176103299	
22	26.637	-0.1	1	221	4.004116688	1.1	-0.440452836	
23	26.73	0.093	1	220	3.988741582	1.1	0.408048264	
24	26.73	0	1	219	3.973366477	1.1	0	
25	27.056	0.326	1	218	3.957991372	1.1	1.419335706	
26	26.664	-0.392	1	217	3.942616267	1.1	-1.700056134	
27	26.471	-0.193	1	216	3.927241162	1.1	-0.833753299	
28	26.471	0	1	215	3.911866056	1.1	0	
29	26.544	0.073	1	214	3.896490951	1.1	0.312888223	
30	26.564	0.02	1	213	3.881115846	1.1	0.085384549	
31	26.544	-0.02	1	212	3.865740741	1.1	-0.085046296	
32	26.637	0.093	1	211	3.850365636	1.1	0.393892405	
33	26.637	0	1	210	3.83499053	1.1	0	
34	26.75	0.113	1	209	3.819615425	1.1	0.474778197	
35	26.471	-0.279	1	208	3.80424032	1.1	-1.167521354	
36	26.471	0	1	207	3.788865215	1.1	0	
37	26.544	0.073	1	206	3.773490109	1.1	0.303011256	
38	26.471	-0.073	1	205	3.758115004	1.1	-0.301776635	
39	26.544	0.073	1	204	3.742739899	1.1	0.300542014	
40	26.564	0.02	1	203	3.727364794	1.1	0.082002025	
41	26.544	-0.02	1	202	3.711989689	1.1	-0.081663773	
42	26.983	0.439	1	201	3.696614583	1.1	1.785095182	
43	26.903	-0.08	1	200	3.681239478	1.1	-0.323949074	
44	26.637	-0.266	1	199	3.665864373	1.1	-1.072631916	
45	26.471	-0.166	1	198	3.650489268	1.1	-0.66657934	
46	26.471	0	1	197	3.635114162	1.1	0	
47	26.471	0	1	196	3.619739057	1.1	0	
48	26.471	0	1	195	3.604363952	1.1	0	
49	26.544	0.073	1	194	3.588988847	1.1	0.288195804	
50	26.564	0.02	1	193	3.573613742	1.1	0.078619502	
51	26.617	0.053	1	192	3.558238636	1.1	0.207445312	
52	26.637	0.02	1	191	3.542863531	1.1	0.077942998	
53	26.73	0.093	1	190	3.527488426	1.1	0.360862066	
54	26.564	-0.166	1	189	3.512113321	1.1	-0.641311892	
55	26.471	-0.093	1	188	3.496738215	1.1	-0.357716319	
56	26.471	0	1	187	3.48136311	1.1	0	

57	26.471	0	1	186	3.465988005	1.1	0	
58	26.637	0.166	1	185	3.4506129	1.1	0.630081916	
59	26.544	-0.093	1	184	3.435237795	1.1	-0.351424826	
60	26.657	0.113	1	183	3.419862689	1.1	0.425088932	
61	26.544	-0.113	1	182	3.404487584	1.1	-0.423177807	
62	26.71	0.166	1	181	3.389112479	1.1	0.618851939	
63	26.637	-0.073	1	180	3.373737374	1.1	-0.270911111	
64	26.564	-0.073	1	179	3.362839579	1.1	-0.270036018	
65	26.471	-0.093	1	178	3.351941785	1.1	-0.342903645	
66	26.471	0	1	177	3.34104399	1.1	0	
67	26.471	0	1	176	3.330146196	1.1	0	
68	26.471	0	1	175	3.319248401	1.1	0	
69	26.544	0.073	1	174	3.308350607	1.1	0.265660554	
70	26.564	0.02	1	173	3.297452813	1.1	0.072543962	
71	26.544	-0.02	1	172	3.286555018	1.1	-0.07230421	
72	26.637	0.093	1	171	3.275657224	1.1	0.335099734	
73	26.637	0	1	170	3.264759429	1.1	0	
74	26.637	0	1	169	3.253861635	1.1	0	
75	26.471	-0.166	1	168	3.24296384	1.1	-0.592165197	
76	26.471	0	1	167	3.232066046	1.1	0	
77	26.471	0	1	166	3.221168251	1.1	0	
78	26.471	0	1	165	3.210270457	1.1	0	
79	26.544	0.073	1	164	3.199372663	1.1	0.256909625	
80	26.564	0.02	1	163	3.188474868	1.1	0.070146447	
81	26.544	-0.02	1	162	3.177577074	1.1	-0.069906696	
82	26.637	0.093	1	161	3.166679279	1.1	0.32395129	
83	26.637	0	1	160	3.155781485	1.1	0	
84	26.564	-0.073	1	159	3.14488369	1.1	-0.25253416	
85	26.471	-0.093	1	158	3.133985896	1.1	-0.320606757	
86	26.544	0.073	1	157	3.123088101	1.1	0.250783975	
87	26.71	0.166	1	156	3.112190307	1.1	0.56828595	
88	26.637	-0.073	1	155	3.101292513	1.1	-0.249033789	
89	26.544	-0.093	1	154	3.090394718	1.1	-0.31614738	
90	26.564	0.02	1	153	3.079496924	1.1	0.067748932	
91	26.544	-0.02	1	152	3.068599129	1.1	-0.067509181	
92	26.71	0.166	1	151	3.057701335	1.1	0.558336264	
93	26.637	-0.073	1	150	3.04680354	1.1	-0.244658324	
94	26.564	-0.073	1	149	3.035905746	1.1	-0.243783231	
95	26.544	-0.02	1	148	3.025007951	1.1	-0.066550175	
96	26.637	0.093	1	147	3.014110157	1.1	0.308343469	
97	26.471	-0.166	1	146	3.003212362	1.1	-0.548386577	
98	26.544	0.073	1	145	2.992314568	1.1	0.24028286	
99	26.544	0	1	144	2.981416774	1.1	0	
100	26.564	0.02	1	143	2.970518979	1.1	0.065351418	
101	26.544	-0.02	1	142	2.959621185	1.1	-0.065111666	
102	26.73	0.186	1	141	2.94872339	1.1	0.603308806	

103	26.71	-0.02	1	140	2.937825596	1.1	-0.064632163	
104	26.564	-0.146	1	139	2.926927801	1.1	-0.470064605	
105	26.817	0.253	1	138	2.916030007	1.1	0.811531151	
106	26.737	-0.08	1	137	2.905132212	1.1	-0.255651635	
107	26.737	0	1	136	2.894234418	1.1	0	
108	26.471	-0.266	1	135	2.883336624	1.1	-0.843664296	
109	26.617	0.146	1	134	2.872438829	1.1	0.461313676	
110	26.564	-0.053	1	133	2.861541035	1.1	-0.166827842	
111	26.544	-0.02	1	132	2.85064324	1.1	-0.062714151	
112	26.637	0.093	1	131	2.839745446	1.1	0.290505959	
113	26.637	0	1	130	2.828847651	1.1	0	
114	26.564	-0.073	1	129	2.817949857	1.1	-0.226281374	
115	26.564	0	1	128	2.807052062	1.1	0	
116	26.471	-0.093	1	127	2.796154268	1.1	-0.286046582	
117	26.544	0.073	1	126	2.785256474	1.1	0.223656095	
118	26.471	-0.073	1	125	2.774358679	1.1	-0.222781002	
119	26.544	0.073	1	124	2.763460885	1.1	0.221905909	
120	27.076	0.532	1	123	2.75256309	1.1	1.61079992	
121	26.737	-0.339	1	122	2.741665296	1.1	-1.022366989	
122	27.076	0.339	1	121	2.730767501	1.1	1.018303201	
123	26.83	-0.246	1	120	2.719869707	1.1	-0.735996743	
124	26.71	-0.12	1	119	2.709286776	1.1	-0.357625854	
125	26.471	-0.239	1	118	2.698703846	1.1	-0.709489241	
126	26.471	0	1	117	2.688120916	1.1	0	
127	26.564	0.093	1	116	2.677537985	1.1	0.273912136	
128	26.544	-0.02	1	115	2.666955055	1.1	-0.058673011	
129	26.544	0	1	114	2.656372124	1.1	0	
130	26.564	0.02	1	113	2.645789194	1.1	0.058207362	
131	26.544	-0.02	1	112	2.635206264	1.1	-0.057974538	
132	26.637	0.093	1	111	2.624623333	1.1	0.268498967	
133	26.637	0	1	110	2.614040403	1.1	0	
134	26.564	-0.073	1	109	2.603457472	1.1	-0.209057635	
135	26.564	0	1	108	2.592874542	1.1	0	
136	26.544	-0.02	1	107	2.582291612	1.1	-0.056810415	
137	26.471	-0.073	1	106	2.571708681	1.1	-0.206508207	
138	26.471	0	1	105	2.561125751	1.1	0	
139	26.544	0.073	1	104	2.55054282	1.1	0.204808588	
140	26.73	0.186	1	103	2.53995989	1.1	0.519675793	
141	26.544	-0.186	1	102	2.52937696	1.1	-0.517510526	
142	26.637	0.093	1	101	2.518794029	1.1	0.257672629	
143	26.803	0.166	1	100	2.508211099	1.1	0.457999347	
144	26.564	-0.239	1	99	2.497628168	1.1	-0.656626445	
145	26.544	-0.02	1	98	2.487045238	1.1	-0.054714995	
146	26.471	-0.073	1	97	2.476462308	1.1	-0.198859923	
147	26.637	0.166	1	96	2.465879377	1.1	0.450269574	
148	26.471	-0.166	1	95	2.455296447	1.1	-0.448337131	

149	26.544	0.073	1	94	2.444713516	1.1	0.196310495	
150	26.564	0.02	1	93	2.434130586	1.1	0.053550873	
151	26.544	-0.02	1	92	2.423547656	1.1	-0.053318048	
152	26.637	0.093	1	91	2.412964725	1.1	0.246846291	
153	26.73	0.093	1	90	2.402381795	1.1	0.245763658	
154	26.657	-0.073	1	89	2.391798864	1.1	-0.192061449	
155	26.544	-0.113	1	88	2.381215934	1.1	-0.295985141	
156	26.817	0.273	1	87	2.370633004	1.1	0.711901091	
157	26.664	-0.153	1	86	2.360050073	1.1	-0.397196427	
158	26.544	-0.12	1	85	2.349467143	1.1	-0.310129663	
159	26.544	0	1	84	2.338884212	1.1	0	
160	26.564	0.02	1	83	2.328301282	1.1	0.051222628	
161	26.544	-0.02	1	82	2.317718352	1.1	-0.050989804	
162	26.637	0.093	1	81	2.307135421	1.1	0.236019954	
163	26.637	0	1	80	2.296552491	1.1	0	
164	26.564	-0.073	1	79	2.28596956	1.1	-0.183563356	
165	26.471	-0.093	1	78	2.27538663	1.1	-0.232772052	
166	26.471	0	1	77	2.2648037	1.1	0	
167	26.91	0.439	1	76	2.254220769	1.1	1.088563209	
168	26.737	-0.173	1	75	2.243637839	1.1	-0.426964281	
169	26.544	-0.193	1	74	2.233054908	1.1	-0.474077557	
170	26.564	0.02	1	73	2.222471978	1.1	0.048894384	
171	26.544	-0.02	1	72	2.211889047	1.1	-0.048661559	
172	26.637	0.093	1	71	2.201306117	1.1	0.225193616	
173	26.637	0	1	70	2.190723187	1.1	0	
174	26.564	-0.073	1	69	2.180140256	1.1	-0.175065263	
175	26.544	-0.02	1	68	2.169557326	1.1	-0.047730261	
176	26.471	-0.073	1	67	2.158974395	1.1	-0.173365644	
177	26.471	0	1	66	2.148391465	1.1	0	
178	26.544	0.073	1	65	2.137808535	1.1	0.171666025	
179	26.637	0.093	1	64	2.127225604	1.1	0.217615179	
180	26.564	-0.073	1	63	2.116642674	1.1	-0.169966407	
181	26.544	-0.02	1	62	2.106059743	1.1	-0.046333314	
182	26.637	0.093	1	61	2.095476813	1.1	0.214367278	
183	26.637	0	1	60	2.084893883	1.1	0	
184	26.637	0	1	59	2.067843272	1.1	0	
185	26.471	-0.166	1	58	2.050792661	1.1	-0.37447474	
186	26.471	0	1	57	2.03374205	1.1	0	
187	26.471	0	1	56	2.016691439	1.1	0	
188	26.564	0.093	1	55	1.999640829	1.1	0.204563257	
189	26.637	0.073	1	54	1.982590218	1.1	0.159201994	
190	26.637	0	1	53	1.965539607	1.1	0	
191	26.69	0.053	1	52	1.948488996	1.1	0.113596908	
192	26.637	-0.053	1	51	1.931438385	1.1	-0.112602858	
193	26.637	0	1	50	1.914387775	1.1	0	
194	26.564	-0.073	1	49	1.897337164	1.1	-0.152356174	

195	26.471	-0.093	1	48	1.880286553	1.1	-0.192353314	
196	26.471	0	1	47	1.863235942	1.1	0	
197	26.73	0.259	1	46	1.846185331	1.1	0.525978201	
198	26.471	-0.259	1	45	1.829134721	1.1	-0.521120482	
199	26.544	0.073	1	44	1.815283021	1.1	0.145767227	
200	26.564	0.02	1	43	1.801431321	1.1	0.039631489	
201	26.544	-0.02	1	42	1.787579621	1.1	-0.039326752	
202	26.637	0.093	1	41	1.773727921	1.1	0.181452366	
203	26.637	0	1	40	1.759876222	1.1	0	
204	26.564	-0.073	1	39	1.746024522	1.1	-0.140205769	
205	26.471	-0.093	1	38	1.732172822	1.1	-0.17720128	
206	26.471	0	1	37	1.718321122	1.1	0	
207	26.471	0	1	36	1.704469422	1.1	0	
208	26.471	0	1	35	1.690617722	1.1	0	
209	26.544	0.073	1	34	1.676766023	1.1	0.134644312	
210	26.564	0.02	1	33	1.662914323	1.1	0.036584115	
211	26.544	-0.02	1	32	1.649062623	1.1	-0.036279378	
212	26.73	0.186	1	31	1.635210923	1.1	0.334564155	
213	26.637	-0.093	1	30	1.621359223	1.1	-0.165865049	
214	26.637	0	1	29	1.604440692	1.1	0	
215	26.817	0.18	1	28	1.587522161	1.1	0.314329388	
216	26.737	-0.08	1	27	1.57060363	1.1	-0.138213119	
217	26.544	-0.193	1	26	1.553685099	1.1	-0.329847347	
218	26.471	-0.073	1	25	1.536766568	1.1	-0.123402355	
219	26.544	0.073	1	24	1.519848037	1.1	0.122043797	
220	26.637	0.093	1	23	1.502929506	1.1	0.153749688	
221	26.637	0	1	22	1.486010975	1.1	0	
222	26.71	0.073	1	21	1.469092444	1.1	0.117968123	
223	26.71	0	1	20	1.452173913	1.1	0	
224	26.564	-0.146	1	19	1.437772188	1.1	-0.230906213	
225	26.471	-0.093	1	18	1.423370464	1.1	-0.145610798	
226	26.471	0	1	17	1.408968739	1.1	0	
227	26.471	0	1	16	1.394567014	1.1	0	
228	26.471	0	1	15	1.380165289	1.1	0	
229	26.544	0.073	1	14	1.353385963	1.1	0.108676893	
230	26.564	0.02	1	13	1.326606636	1.1	0.029185346	
231	26.544	-0.02	1	12	1.29982731	1.1	-0.028596201	
232	26.637	0.093	1	11	1.273047983	1.1	0.130232809	
233	26.637	0	1	10	1.246268657	1.1	0	
234	26.564	-0.073	1	9	1.22422581	1.1	-0.098305333	
235	26.564	0	1	8	1.202182963	1.1	0	
236	26.637	0.073	1	7	1.180140116	1.1	0.094765251	
237	26.544	-0.093	1	6	1.158097269	1.1	-0.118473351	
238	26.544	0	1	5	1.136054422	1.1	0	
239	26.544	0	1	4	1.106613987	1.1	0	
240	26.564	0.02	1	3	1.077173552	1.1	0.023697818	

241	26.544	-0.02	1	2	1.047733118	1.1	-0.023050129	
242	32.55751	6.01350796	1	1	1.018292683	1.1	6.735862275	
Total						1.1	133.3631373	***

The required battery size is the product of the maximum section from the table above, the design margin, as well as the aging factor for NiCd batteries.

I.e. Maximum size * design margin * aging factor = required battery size

133.3631 * 1.05 * 1.2 = 168.037 Ah

2.1.2. **IEEE recommended sizing for approximated load profile with preliminary sized supercapacitor**

The largest load was observed during section 241 and therefore the table indicates this section.

Table 29: IEEE recommended practice for approximated load profile with preliminary sized supercapacitor, Application 1

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 241 - If A242 is greater than A241, go to section 242						1.1		
1	0	0	1	241	4.311618792	1.1	0	
2	27.5	27.5	1	240	4.296243687	1.1	129.9613715	
3	27.46429	-0.035714	1	239	4.280868582	1.1	-0.168175635	
4	27.42857	-0.035714	1	238	4.265493476	1.1	-0.167571617	
5	27.39286	-0.035714	1	237	4.250118371	1.1	-0.1669676	
6	27.35714	-0.035714	1	236	4.234743266	1.1	-0.166363583	
7	27.32143	-0.035714	1	235	4.219368161	1.1	-0.165759566	
8	27.28572	-0.035714	1	234	4.203993056	1.1	-0.165155549	
9	27.25	-0.035714	1	233	4.18861795	1.1	-0.164551532	
10	27.21429	-0.035714	1	232	4.173242845	1.1	-0.163947514	
11	27.17857	-0.035714	1	231	4.15786774	1.1	-0.163343497	
12	27.14286	-0.035714	1	230	4.142492635	1.1	-0.16273948	
13	27.10715	-0.035714	1	229	4.127117529	1.1	-0.162135463	
14	27.07143	-0.035714	1	228	4.111742424	1.1	-0.161531446	
15	27.03572	-0.035714	1	227	4.096367319	1.1	-0.160927429	
16	27	-0.035714	1	226	4.080992214	1.1	-0.160323412	

17	26.97778	-0.0222222	1	225	4.065617109	1.1	-0.099381652	
18	26.95556	-0.0222222	1	224	4.050242003	1.1	-0.099005817	
19	26.93334	-0.0222222	1	223	4.034866898	1.1	-0.098629981	
20	26.91112	-0.0222222	1	222	4.019491793	1.1	-0.098254146	
21	26.88889	-0.0222222	1	221	4.004116688	1.1	-0.09787831	
22	26.86667	-0.0222222	1	220	3.988741582	1.1	-0.097502475	
23	26.84445	-0.0222222	1	219	3.973366477	1.1	-0.097126639	
24	26.82223	-0.0222222	1	218	3.957991372	1.1	-0.096750803	
25	26.8	-0.0222222	1	217	3.942616267	1.1	-0.096374968	
26	26.77778	-0.0222222	1	216	3.927241162	1.1	-0.095999132	
27	26.75679	-0.0209889	1	215	3.911866056	1.1	-0.090316256	
28	26.7358	-0.0209889	1	214	3.896490951	1.1	-0.089961279	
29	26.71482	-0.0209889	1	213	3.881115846	1.1	-0.089606302	
30	26.69383	-0.0209889	1	212	3.865740741	1.1	-0.089251325	
31	26.67284	-0.0209889	1	211	3.850365636	1.1	-0.088896349	
32	26.65185	-0.0209889	1	210	3.83499053	1.1	-0.088541372	
33	26.63086	-0.0209889	1	209	3.819615425	1.1	-0.088186395	
34	26.60987	-0.0209889	1	208	3.80424032	1.1	-0.087831418	
35	26.58888	-0.0209889	1	207	3.788865215	1.1	-0.087476441	
36	26.56789	-0.0209889	1	206	3.773490109	1.1	-0.087121464	
37	26.5469	-0.0209889	1	205	3.758115004	1.1	-0.086766487	
38	26.52592	-0.0209889	1	204	3.742739899	1.1	-0.08641151	
39	26.50493	-0.0209889	1	203	3.727364794	1.1	-0.086056534	
40	26.48394	-0.0209889	1	202	3.711989689	1.1	-0.085701557	
41	26.46295	-0.0209889	1	201	3.696614583	1.1	-0.08534658	
42	26.44196	-0.0209889	1	200	3.681239478	1.1	-0.084991603	
43	26.42097	-0.0209889	1	199	3.665864373	1.1	-0.084636626	
44	26.39998	-0.0209889	1	198	3.650489268	1.1	-0.084281649	
45	26.38332	-0.01666	1	197	3.635114162	1.1	-0.066617102	
46	26.36666	-0.01666	1	196	3.619739057	1.1	-0.066335338	
47	26.35	-0.01666	1	195	3.604363952	1.1	-0.066053574	
48	26.33334	-0.01666	1	194	3.588988847	1.1	-0.06577181	
49	26.31668	-0.01666	1	193	3.573613742	1.1	-0.065490045	
50	26.30002	-0.01666	1	192	3.558238636	1.1	-0.065208281	
51	26.28336	-0.01666	1	191	3.542863531	1.1	-0.064926517	
52	26.27145	-0.0119143	1	190	3.527488426	1.1	-0.046230311	
53	26.25953	-0.0119143	1	189	3.512113321	1.1	-0.046028809	
54	26.24762	-0.0119143	1	188	3.496738215	1.1	-0.045827307	
55	26.2357	-0.0119143	1	187	3.48136311	1.1	-0.045625805	
56	26.22379	-0.0119143	1	186	3.465988005	1.1	-0.045424303	
57	26.21188	-0.0119143	1	185	3.4506129	1.1	-0.045222801	
58	26.19996	-0.0119143	1	184	3.435237795	1.1	-0.045021299	
59	26.18967	-0.0102941	1	183	3.419862689	1.1	-0.038724913	
60	26.17937	-0.0102941	1	182	3.404487584	1.1	-0.038550813	
61	26.16908	-0.0102941	1	181	3.389112479	1.1	-0.038376712	
62	26.15879	-0.0102941	1	180	3.373737374	1.1	-0.038202612	

63	26.14849	-0.0102941	1	179	3.362839579	1.1	-0.03807921	
64	26.1382	-0.0102941	1	178	3.351941785	1.1	-0.037955809	
65	26.1279	-0.0102941	1	177	3.34104399	1.1	-0.037832408	
66	26.11761	-0.0102941	1	176	3.330146196	1.1	-0.037709006	
67	26.10732	-0.0102941	1	175	3.319248401	1.1	-0.037585605	
68	26.09702	-0.0102941	1	174	3.308350607	1.1	-0.037462203	
69	26.08673	-0.0102941	1	173	3.297452813	1.1	-0.037338802	
70	26.07643	-0.0102941	1	172	3.286555018	1.1	-0.0372154	
71	26.06614	-0.0102941	1	171	3.275657224	1.1	-0.037091999	
72	26.05584	-0.0102941	1	170	3.264759429	1.1	-0.036968597	
73	26.04555	-0.0102941	1	169	3.253861635	1.1	-0.036845196	
74	26.03526	-0.0102941	1	168	3.24296384	1.1	-0.036721794	
75	26.02496	-0.0102941	1	167	3.232066046	1.1	-0.036598393	
76	26.01996	-0.005	1	166	3.221168251	1.1	-0.017716425	
77	26.01496	-0.005	1	165	3.210270457	1.1	-0.017656488	
78	26.00996	-0.005	1	164	3.199372663	1.1	-0.01759655	
79	26.00496	-0.005	1	163	3.188474868	1.1	-0.017536612	
80	25.99996	-0.005	1	162	3.177577074	1.1	-0.017476674	
81	25.99371	-0.00625	1	161	3.166679279	1.1	-0.02177092	
82	25.98746	-0.00625	1	160	3.155781485	1.1	-0.021695998	
83	25.98121	-0.00625	1	159	3.14488369	1.1	-0.021621075	
84	25.97496	-0.00625	1	158	3.133985896	1.1	-0.021546153	
85	25.96871	-0.00625	1	157	3.123088101	1.1	-0.021471231	
86	25.96246	-0.00625	1	156	3.112190307	1.1	-0.021396308	
87	25.95621	-0.00625	1	155	3.101292513	1.1	-0.021321386	
88	25.94996	-0.00625	1	154	3.090394718	1.1	-0.021246464	
89	25.94353	-0.0064286	1	153	3.079496924	1.1	-0.021776441	
90	25.9371	-0.0064286	1	152	3.068599129	1.1	-0.021699378	
91	25.93068	-0.0064286	1	151	3.057701335	1.1	-0.021622315	
92	25.92425	-0.0064286	1	150	3.04680354	1.1	-0.021545252	
93	25.91782	-0.0064286	1	149	3.035905746	1.1	-0.021468189	
94	25.91139	-0.0064286	1	148	3.025007951	1.1	-0.021391126	
95	25.90496	-0.0064286	1	147	3.014110157	1.1	-0.021314063	
96	25.89853	-0.0064286	1	146	3.003212362	1.1	-0.021237	
97	25.8921	-0.0064286	1	145	2.992314568	1.1	-0.021159937	
98	25.88568	-0.0064286	1	144	2.981416774	1.1	-0.021082874	
99	25.87925	-0.0064286	1	143	2.970518979	1.1	-0.021005811	
100	25.87282	-0.0064286	1	142	2.959621185	1.1	-0.020928748	
101	25.86639	-0.0064286	1	141	2.94872339	1.1	-0.020851685	
102	25.85996	-0.0064286	1	140	2.937825596	1.1	-0.020774622	
103	25.8553	-0.0046666	1	139	2.926927801	1.1	-0.015024681	
104	25.85063	-0.0046666	1	138	2.916030007	1.1	-0.01496874	
105	25.84596	-0.0046666	1	137	2.905132212	1.1	-0.014912799	
106	25.8413	-0.0046666	1	136	2.894234418	1.1	-0.014856858	
107	25.83663	-0.0046666	1	135	2.883336624	1.1	-0.014800917	
108	25.83196	-0.0046666	1	134	2.872438829	1.1	-0.014744975	

109	25.8273	-0.0046666	1	133	2.861541035	1.1	-0.014689034	
110	25.82263	-0.0046666	1	132	2.85064324	1.1	-0.014633093	
111	25.818	-0.0046293	1	131	2.839745446	1.1	-0.014460565	
112	25.81371	-0.0042857	1	130	2.828847651	1.1	-0.013335995	
113	25.80943	-0.0042857	1	129	2.817949857	1.1	-0.01328462	
114	25.80514	-0.0042857	1	128	2.807052062	1.1	-0.013233245	
115	25.80086	-0.0042857	1	127	2.796154268	1.1	-0.013181869	
116	25.79657	-0.0042857	1	126	2.785256474	1.1	-0.013130494	
117	25.79229	-0.0042857	1	125	2.774358679	1.1	-0.013079119	
118	25.788	-0.0042857	1	124	2.763460885	1.1	-0.013027749	
119	25.78438	-0.0036176	1	123	2.75256309	1.1	-0.010953591	
120	25.78076	-0.0036176	1	122	2.741665296	1.1	-0.010910224	
121	25.77715	-0.0036176	1	121	2.730767501	1.1	-0.010866857	
122	25.77353	-0.0036176	1	120	2.719869707	1.1	-0.01082349	
123	25.76991	-0.0036176	1	119	2.709286776	1.1	-0.010781376	
124	25.76629	-0.0036176	1	118	2.698703846	1.1	-0.010739263	
125	25.76268	-0.0036176	1	117	2.688120916	1.1	-0.010697149	
126	25.75906	-0.0036176	1	116	2.677537985	1.1	-0.010655035	
127	25.75544	-0.0036176	1	115	2.666955055	1.1	-0.010612921	
128	25.75182	-0.0036176	1	114	2.656372124	1.1	-0.010570807	
129	25.74821	-0.0036176	1	113	2.645789194	1.1	-0.010528693	
130	25.74459	-0.0036176	1	112	2.635206264	1.1	-0.010486579	
131	25.74097	-0.0036176	1	111	2.624623333	1.1	-0.010444465	
132	25.73735	-0.0036176	1	110	2.614040403	1.1	-0.010402352	
133	25.73374	-0.0036176	1	109	2.603457472	1.1	-0.010360238	
134	25.73012	-0.0036176	1	108	2.592874542	1.1	-0.010318124	
135	25.7265	-0.0036176	1	107	2.582291612	1.1	-0.010275868	
136	25.72328	-0.00322	1	106	2.571708681	1.1	-0.009108992	
137	25.72006	-0.00322	1	105	2.561125751	1.1	-0.009071507	
138	25.71684	-0.00322	1	104	2.55054282	1.1	-0.009034023	
139	25.71362	-0.00322	1	103	2.53995989	1.1	-0.008996538	
140	25.7104	-0.00322	1	102	2.52937696	1.1	-0.008959053	
141	25.70718	-0.00322	1	101	2.518794029	1.1	-0.008921568	
142	25.70396	-0.00322	1	100	2.508211099	1.1	-0.008884084	
143	25.70074	-0.00322	1	99	2.497628168	1.1	-0.008846599	
144	25.69752	-0.00322	1	98	2.487045238	1.1	-0.008809114	
145	25.6943	-0.00322	1	97	2.476462308	1.1	-0.008771629	
146	25.69108	-0.00322	1	96	2.465879377	1.1	-0.008734145	
147	25.68786	-0.00322	1	95	2.455296447	1.1	-0.00869666	
148	25.68464	-0.00322	1	94	2.444713516	1.1	-0.008659175	
149	25.68142	-0.00322	1	93	2.434130586	1.1	-0.008621691	
150	25.6782	-0.00322	1	92	2.423547656	1.1	-0.008584206	
151	25.6782	0	1	91	2.412964725	1.1	0	
152	25.6759	-0.0023	1	90	2.402381795	1.1	-0.006078026	
153	25.6736	-0.0023	1	89	2.391798864	1.1	-0.006051251	
154	25.6713	-0.0023	1	88	2.381215934	1.1	-0.006024476	

155	25.669	-0.0023	1	87	2.370633004	1.1	-0.005997701	
156	25.6667	-0.0023	1	86	2.360050073	1.1	-0.005970927	
157	25.6644	-0.0023	1	85	2.349467143	1.1	-0.005944152	
158	25.6621	-0.0023	1	84	2.338884212	1.1	-0.005917377	
159	25.6598	-0.0023	1	83	2.328301282	1.1	-0.005890602	
160	25.6575	-0.0023	1	82	2.317718352	1.1	-0.005863827	
161	25.6552	-0.0023	1	81	2.307135421	1.1	-0.005837053	
162	25.6529	-0.0023	1	80	2.296552491	1.1	-0.005810278	
163	25.6506	-0.0023	1	79	2.28596956	1.1	-0.005783503	
164	25.6483	-0.0023	1	78	2.27538663	1.1	-0.005756728	
165	25.646	-0.0023	1	77	2.2648037	1.1	-0.005729953	
166	25.6437	-0.0023	1	76	2.254220769	1.1	-0.005703179	
167	25.6414	-0.0023	1	75	2.243637839	1.1	-0.005676404	
168	25.6391	-0.0023	1	74	2.233054908	1.1	-0.005649629	
169	25.6368	-0.0023	1	73	2.222471978	1.1	-0.005622854	
170	25.6345	-0.0023	1	72	2.211889047	1.1	-0.005596079	
171	25.6322	-0.0023	1	71	2.201306117	1.1	-0.005569304	
172	25.6299	-0.0023	1	70	2.190723187	1.1	-0.00554253	
173	25.6276	-0.0023	1	69	2.180140256	1.1	-0.005515755	
174	25.6253	-0.0023	1	68	2.169557326	1.1	-0.00548898	
175	25.623	-0.0023	1	67	2.158974395	1.1	-0.005462205	
176	25.6207	-0.0023	1	66	2.148391465	1.1	-0.00543543	
177	25.6184	-0.0023	1	65	2.137808535	1.1	-0.005408656	
178	25.6161	-0.0023	1	64	2.127225604	1.1	-0.005381881	
179	25.6138	-0.0023	1	63	2.116642674	1.1	-0.005355106	
180	25.6115	-0.0023	1	62	2.106059743	1.1	-0.005328331	
181	25.6092	-0.0023	1	61	2.095476813	1.1	-0.005301556	
182	25.6069	-0.0023	1	60	2.084893883	1.1	-0.005274782	
183	25.6046	-0.0023	1	59	2.067843272	1.1	-0.005231643	
184	25.6023	-0.0023	1	58	2.050792661	1.1	-0.005188505	
185	25.6	-0.0023	1	57	2.03374205	1.1	-0.005145367	
186	25.59808	-0.0019161	1	56	2.016691439	1.1	-0.004250536	
187	25.59617	-0.0019161	1	55	1.999640829	1.1	-0.004214599	
188	25.59425	-0.0019161	1	54	1.982590218	1.1	-0.004178662	
189	25.59234	-0.0019161	1	53	1.965539607	1.1	-0.004142725	
190	25.59042	-0.0019161	1	52	1.948488996	1.1	-0.004106788	
191	25.5885	-0.0019161	1	51	1.931438385	1.1	-0.00407085	
192	25.58659	-0.0019161	1	50	1.914387775	1.1	-0.004034913	
193	25.58467	-0.0019161	1	49	1.897337164	1.1	-0.003998976	
194	25.58276	-0.0019161	1	48	1.880286553	1.1	-0.003963039	
195	25.58084	-0.0019161	1	47	1.863235942	1.1	-0.003927102	
196	25.57892	-0.0019161	1	46	1.846185331	1.1	-0.003891164	
197	25.57701	-0.0019161	1	45	1.829134721	1.1	-0.003855227	
198	25.57509	-0.0019161	1	44	1.815283021	1.1	-0.003826032	
199	25.57318	-0.0019161	1	43	1.801431321	1.1	-0.003796837	
200	25.57126	-0.0019161	1	42	1.787579621	1.1	-0.003767642	

201	25.56934	-0.0019161	1	41	1.773727921	1.1	-0.003738447	
202	25.56743	-0.0019161	1	40	1.759876222	1.1	-0.003709253	
203	25.56551	-0.0019161	1	39	1.746024522	1.1	-0.003680058	
204	25.56359	-0.0019161	1	38	1.732172822	1.1	-0.003650863	
205	25.56168	-0.0019161	1	37	1.718321122	1.1	-0.003621668	
206	25.55976	-0.0019161	1	36	1.704469422	1.1	-0.003592473	
207	25.55785	-0.0019161	1	35	1.690617722	1.1	-0.003563278	
208	25.55593	-0.0019161	1	34	1.676766023	1.1	-0.003534083	
209	25.55401	-0.0019161	1	33	1.662914323	1.1	-0.003504888	
210	25.5521	-0.0019161	1	32	1.649062623	1.1	-0.003475693	
211	25.55018	-0.0019161	1	31	1.635210923	1.1	-0.003446498	
212	25.54827	-0.0019161	1	30	1.621359223	1.1	-0.003417303	
213	25.54635	-0.0019161	1	29	1.604440692	1.1	-0.003381645	
214	25.54443	-0.0019161	1	28	1.587522161	1.1	-0.003345986	
215	25.54252	-0.0019161	1	27	1.57060363	1.1	-0.003310327	
216	25.5406	-0.0019161	1	26	1.553685099	1.1	-0.003274668	
217	25.53869	-0.0019161	1	25	1.536766568	1.1	-0.003239009	
218	25.53677	-0.0019161	1	24	1.519848037	1.1	-0.00320335	
219	25.53485	-0.0019161	1	23	1.502929506	1.1	-0.003167692	
220	25.53294	-0.0019161	1	22	1.486010975	1.1	-0.003132033	
221	25.53102	-0.0019161	1	21	1.469092444	1.1	-0.003096374	
222	25.52911	-0.0019161	1	20	1.452173913	1.1	-0.003060715	
223	25.52719	-0.0019161	1	19	1.437772188	1.1	-0.003030361	
224	25.52527	-0.0019161	1	18	1.423370464	1.1	-0.003000007	
225	25.52336	-0.0019161	1	17	1.408968739	1.1	-0.002969653	
226	25.52144	-0.0019161	1	16	1.394567014	1.1	-0.002939298	
227	25.51953	-0.0019161	1	15	1.380165289	1.1	-0.002908944	
228	25.51761	-0.0019161	1	14	1.353385963	1.1	-0.002852502	
229	25.51569	-0.0019161	1	13	1.326606636	1.1	-0.00279606	
230	25.51378	-0.0019161	1	12	1.29982731	1.1	-0.002739618	
231	25.51186	-0.0019161	1	11	1.273047983	1.1	-0.002683175	
232	25.50994	-0.0019161	1	10	1.246268657	1.1	-0.002626733	
233	25.50803	-0.0019161	1	9	1.22422581	1.1	-0.002580274	
234	25.50611	-0.0019161	1	8	1.202182963	1.1	-0.002533815	
235	25.5042	-0.0019161	1	7	1.180140116	1.1	-0.002487355	
236	25.50228	-0.0019161	1	6	1.158097269	1.1	-0.002440896	
237	25.50036	-0.0019161	1	5	1.136054422	1.1	-0.002394437	
238	25.49845	-0.0019161	1	4	1.106613987	1.1	-0.002332386	
239	25.49653	-0.0019161	1	3	1.077173552	1.1	-0.002270335	
240	25.49462	-0.0019161	1	2	1.047733118	1.1	-0.002208284	
241	25.4927	-0.0019161	1	1	1.018292683	1.1	-0.00214626	
Total						1.1	122.221504	***

Maximum size * design margin * aging factor = required battery size

122.221 * 1.05 * 1.2 = 153.999 Ah

2.1.3. IEEE recommended sizing for approximated load profile with undersized supercapacitor

The largest load was observed during section 243 and therefore the table indicates this section.

Table 30: IEEE recommended practice for approximated load profile with undersized supercapacitor, Application 1

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 243 - If A244 is greater than A243, go to section 244						1.1		
1	0	0	1	243	4.342369003	1.1	0	
2	27.38213	27.38213	1	242	4.326993897	1.1	130.3305403	
3	27.33187	-0.050258	1	241	4.311618792	1.1	-0.238362671	
4	27.28318	-0.048693	1	240	4.296243687	1.1	-0.230116693	
5	27.23593	-0.047254	1	239	4.280868582	1.1	-0.22251698	
6	27.19006	-0.045863	1	238	4.265493476	1.1	-0.21519116	
7	27.14555	-0.044517	1	237	4.250118371	1.1	-0.208122771	
8	27.10233	-0.043215	1	236	4.234743266	1.1	-0.201304873	
9	27.06037	-0.041957	1	235	4.219368161	1.1	-0.194735233	
10	27.01963	-0.040739	1	234	4.203993056	1.1	-0.18839312	
11	26.98007	-0.039561	1	233	4.18861795	1.1	-0.182276506	
12	26.94165	-0.03842	1	232	4.173242845	1.1	-0.176369589	
13	26.90434	-0.037316	1	231	4.15786774	1.1	-0.170670492	
14	26.86809	-0.036248	1	230	4.142492635	1.1	-0.16517278	
15	26.83288	-0.035212	1	229	4.127117529	1.1	-0.159856469	
16	26.79867	-0.034211	1	228	4.111742424	1.1	-0.154733502	
17	26.76543	-0.03324	1	227	4.096367319	1.1	-0.149779575	
18	26.73313	-0.0323	1	226	4.080992214	1.1	-0.144997653	
19	26.70174	-0.03139	1	225	4.065617109	1.1	-0.140381693	
20	26.67123	-0.030508	1	224	4.050242003	1.1	-0.135921261	
21	26.64158	-0.029652	1	223	4.034866898	1.1	-0.131606061	
22	26.61275	-0.028825	1	222	4.019491793	1.1	-0.127448036	
23	26.58473	-0.028021	1	221	4.004116688	1.1	-0.123419289	
24	26.55749	-0.027243	1	220	3.988741582	1.1	-0.119531816	
25	26.531	-0.026489	1	219	3.973366477	1.1	-0.115775555	
26	26.50524	-0.025758	1	218	3.957991372	1.1	-0.112144936	
27	26.48019	-0.025048	1	217	3.942616267	1.1	-0.108630117	

28	26.45583	-0.024361	1	216	3.927241162	1.1	-0.105238674	
29	26.43214	-0.023694	1	215	3.911866056	1.1	-0.10195653	
30	26.40909	-0.023047	1	214	3.896490951	1.1	-0.09878267	
31	26.38667	-0.022421	1	213	3.881115846	1.1	-0.095720348	
32	26.36486	-0.021811	1	212	3.865740741	1.1	-0.092747238	
33	26.34364	-0.021222	1	211	3.850365636	1.1	-0.089883705	
34	26.32299	-0.020649	1	210	3.83499053	1.1	-0.087107591	
35	26.30289	-0.020093	1	209	3.819615425	1.1	-0.084422286	
36	26.28334	-0.019554	1	208	3.80424032	1.1	-0.081826927	
37	26.26431	-0.019031	1	207	3.788865215	1.1	-0.079316483	
38	26.24579	-0.018524	1	206	3.773490109	1.1	-0.076890144	
39	26.22775	-0.018031	1	205	3.758115004	1.1	-0.074538829	
40	26.2102	-0.017552	1	204	3.742739899	1.1	-0.072261828	
41	26.19311	-0.017089	1	203	3.727364794	1.1	-0.070066631	
42	26.17648	-0.016638	1	202	3.711989689	1.1	-0.067936093	
43	26.16028	-0.0162	1	201	3.696614583	1.1	-0.065873672	
44	26.1445	-0.015777	1	200	3.681239478	1.1	-0.063886807	
45	26.12913	-0.015364	1	199	3.665864373	1.1	-0.061954574	
46	26.11417	-0.014963	1	198	3.650489268	1.1	-0.060084498	
47	26.0996	-0.014576	1	197	3.635114162	1.1	-0.058283966	
48	26.0854	-0.014198	1	196	3.619739057	1.1	-0.056532361	
49	26.07157	-0.013831	1	195	3.604363952	1.1	-0.054837154	
50	26.05809	-0.013476	1	194	3.588988847	1.1	-0.053201735	
51	26.04496	-0.013131	1	193	3.573613742	1.1	-0.051617634	
52	26.03216	-0.012795	1	192	3.558238636	1.1	-0.05008043	
53	26.0197	-0.012469	1	191	3.542863531	1.1	-0.048593562	
54	26.00754	-0.012153	1	190	3.527488426	1.1	-0.047156524	
55	25.9957	-0.011845	1	189	3.512113321	1.1	-0.045761081	
56	25.98415	-0.011548	1	188	3.496738215	1.1	-0.044418366	
57	25.97289	-0.011257	1	187	3.48136311	1.1	-0.043108675	
58	25.96192	-0.010975	1	186	3.465988005	1.1	-0.04184314	
59	25.95122	-0.010702	1	185	3.4506129	1.1	-0.040621305	
60	25.94078	-0.010437	1	184	3.435237795	1.1	-0.039438935	
61	25.9306	-0.010178	1	183	3.419862689	1.1	-0.038288099	
62	25.92067	-0.009928	1	182	3.404487584	1.1	-0.037179728	
63	25.91099	-0.009684	1	181	3.389112479	1.1	-0.036102182	
64	25.90154	-0.009447	1	180	3.373737374	1.1	-0.035058867	
65	25.89232	-0.009218	1	179	3.362839579	1.1	-0.034098521	
66	25.88333	-0.008994	1	178	3.351941785	1.1	-0.033162101	
67	25.87455	-0.008778	1	177	3.34104399	1.1	-0.032260453	
68	25.86598	-0.008567	1	176	3.330146196	1.1	-0.031382299	
69	25.85762	-0.008362	1	175	3.319248401	1.1	-0.030531111	
70	25.84946	-0.008164	1	174	3.308350607	1.1	-0.029710312	
71	25.84149	-0.00797	1	173	3.297452813	1.1	-0.028908769	
72	25.83371	-0.007782	1	172	3.286555018	1.1	-0.028133568	
73	25.82611	-0.007601	1	171	3.275657224	1.1	-0.027388098	

74	25.81868	-0.007423	1	170	3.264759429	1.1	-0.02665774	
75	25.81143	-0.007251	1	169	3.253861635	1.1	-0.025953126	
76	25.80435	-0.007084	1	168	3.24296384	1.1	-0.025270471	
77	25.79743	-0.006922	1	167	3.232066046	1.1	-0.024609597	
78	25.79066	-0.006764	1	166	3.221168251	1.1	-0.02396678	
79	25.78405	-0.00661	1	165	3.210270457	1.1	-0.023341876	
80	25.77759	-0.006462	1	164	3.199372663	1.1	-0.022741781	
81	25.77127	-0.006318	1	163	3.188474868	1.1	-0.022159263	
82	25.7651	-0.006176	1	162	3.177577074	1.1	-0.021587188	
83	25.75905	-0.006041	1	161	3.166679279	1.1	-0.0210429	
84	25.75315	-0.005908	1	160	3.155781485	1.1	-0.020508793	
85	25.74737	-0.005779	1	159	3.14488369	1.1	-0.019991711	
86	25.74171	-0.005655	1	158	3.133985896	1.1	-0.019494959	
87	25.73618	-0.005533	1	157	3.123088101	1.1	-0.019008051	
88	25.73076	-0.005415	1	156	3.112190307	1.1	-0.018537762	
89	25.72546	-0.0053	1	155	3.101292513	1.1	-0.018080535	
90	25.72027	-0.00519	1	154	3.090394718	1.1	-0.017643063	
91	25.71519	-0.005081	1	153	3.079496924	1.1	-0.017211616	
92	25.71022	-0.004977	1	152	3.068599129	1.1	-0.01679966	
93	25.70534	-0.004874	1	151	3.057701335	1.1	-0.01639356	
94	25.70057	-0.004776	1	150	3.04680354	1.1	-0.016006687	
95	25.69589	-0.00468	1	149	3.035905746	1.1	-0.015628843	
96	25.6913	-0.004587	1	148	3.025007951	1.1	-0.015263283	
97	25.6868	-0.004497	1	147	3.014110157	1.1	-0.014909899	
98	25.68239	-0.004409	1	146	3.003212362	1.1	-0.01456528	
99	25.67807	-0.004323	1	145	2.992314568	1.1	-0.014229353	
100	25.67383	-0.004241	1	144	2.981416774	1.1	-0.013908607	
101	25.66967	-0.004161	1	143	2.970518979	1.1	-0.013596362	
102	25.66559	-0.004083	1	142	2.959621185	1.1	-0.013292547	
103	25.66158	-0.004007	1	141	2.94872339	1.1	-0.012997088	
104	25.65764	-0.003934	1	140	2.937825596	1.1	-0.012713146	
105	25.65378	-0.003863	1	139	2.926927801	1.1	-0.012437394	
106	25.64999	-0.003794	1	138	2.916030007	1.1	-0.01216976	
107	25.64626	-0.003727	1	137	2.905132212	1.1	-0.011910171	
108	25.6426	-0.003663	1	136	2.894234418	1.1	-0.011661739	
109	25.639	-0.003599	1	135	2.883336624	1.1	-0.011414841	
110	25.63546	-0.003539	1	134	2.872438829	1.1	-0.011182117	
111	25.63198	-0.003479	1	133	2.861541035	1.1	-0.010950831	
112	25.62856	-0.003423	1	132	2.85064324	1.1	-0.010733527	
113	25.62519	-0.003366	1	131	2.839745446	1.1	-0.010514441	
114	25.62188	-0.003313	1	130	2.828847651	1.1	-0.010309169	
115	25.61862	-0.003261	1	129	2.817949857	1.1	-0.010108268	
116	25.61541	-0.003211	1	128	2.807052062	1.1	-0.009914789	
117	25.61225	-0.003161	1	127	2.796154268	1.1	-0.009722508	
118	25.60913	-0.003115	1	126	2.785256474	1.1	-0.009543681	
119	25.60606	-0.003068	1	125	2.774358679	1.1	-0.009362906	

120	25.60304	-0.003024	1	124	2.763460885	1.1	-0.009192376	
121	25.60006	-0.002982	1	123	2.75256309	1.1	-0.009028957	
122	25.59712	-0.002939	1	122	2.741665296	1.1	-0.00886353	
123	25.59422	-0.0029	1	121	2.730767501	1.1	-0.008711148	
124	25.59136	-0.002861	1	120	2.719869707	1.1	-0.008559702	
125	25.58853	-0.002824	1	119	2.709286776	1.1	-0.008416128	
126	25.58575	-0.002787	1	118	2.698703846	1.1	-0.008273416	
127	25.58299	-0.002752	1	117	2.688120916	1.1	-0.00813748	
128	25.58027	-0.002719	1	116	2.677537985	1.1	-0.008008248	
129	25.57759	-0.002686	1	115	2.666955055	1.1	-0.007879785	
130	25.57493	-0.002654	1	114	2.656372124	1.1	-0.007755013	
131	25.57231	-0.002624	1	113	2.645789194	1.1	-0.007636806	
132	25.56972	-0.002595	1	112	2.635206264	1.1	-0.007522196	
133	25.56715	-0.002567	1	111	2.624623333	1.1	-0.007411149	
134	25.56461	-0.002539	1	110	2.614040403	1.1	-0.007300753	
135	25.5621	-0.002514	1	109	2.603457472	1.1	-0.007199601	
136	25.55961	-0.002488	1	108	2.592874542	1.1	-0.007096179	
137	25.55714	-0.002464	1	107	2.582291612	1.1	-0.006999043	
138	25.5547	-0.00244	1	106	2.571708681	1.1	-0.006902466	
139	25.55228	-0.002419	1	105	2.561125751	1.1	-0.0068149	
140	25.54989	-0.002396	1	104	2.55054282	1.1	-0.006722211	
141	25.54751	-0.002377	1	103	2.53995989	1.1	-0.006641233	
142	25.54516	-0.002356	1	102	2.52937696	1.1	-0.006555133	
143	25.54282	-0.002338	1	101	2.518794029	1.1	-0.006477834	
144	25.5405	-0.002319	1	100	2.508211099	1.1	-0.006398196	
145	25.5382	-0.002302	1	99	2.497628168	1.1	-0.006324494	
146	25.53591	-0.002286	1	98	2.487045238	1.1	-0.006253924	
147	25.53364	-0.00227	1	97	2.476462308	1.1	-0.006183726	
148	25.53139	-0.002255	1	96	2.465879377	1.1	-0.006116614	
149	25.52915	-0.00224	1	95	2.455296447	1.1	-0.00604985	
150	25.52692	-0.002227	1	94	2.444713516	1.1	-0.005988815	
151	25.5247	-0.002214	1	93	2.434130586	1.1	-0.005928082	
152	25.5225	-0.002202	1	92	2.423547656	1.1	-0.005870317	
153	25.52031	-0.00219	1	91	2.412964725	1.1	-0.005812832	
154	25.51813	-0.00218	1	90	2.402381795	1.1	-0.005760912	
155	25.51596	-0.002169	1	89	2.391798864	1.1	-0.005706593	
156	25.5138	-0.002159	1	88	2.381215934	1.1	-0.00565515	
157	25.51165	-0.002151	1	87	2.370633004	1.1	-0.005609155	
158	25.50951	-0.002142	1	86	2.360050073	1.1	-0.00556075	
159	25.50738	-0.002134	1	85	2.349467143	1.1	-0.005515139	
160	25.50525	-0.002127	1	84	2.338884212	1.1	-0.005472287	
161	25.50313	-0.00212	1	83	2.328301282	1.1	-0.005429599	
162	25.50102	-0.002114	1	82	2.317718352	1.1	-0.005389622	
163	25.49891	-0.002109	1	81	2.307135421	1.1	-0.005352323	
164	25.4968	-0.002103	1	80	2.296552491	1.1	-0.005312615	
165	25.49471	-0.002099	1	79	2.28596956	1.1	-0.005278075	

166	25.49261	-0.002095	1	78	2.27538663	1.1	-0.005243628	
167	25.49052	-0.002091	1	77	2.2648037	1.1	-0.005209275	
168	25.48843	-0.002088	1	76	2.254220769	1.1	-0.005177494	
169	25.48635	-0.002086	1	75	2.243637839	1.1	-0.005148251	
170	25.48426	-0.002083	1	74	2.233054908	1.1	-0.005116599	
171	25.48218	-0.002082	1	73	2.222471978	1.1	-0.005089905	
172	25.4801	-0.002081	1	72	2.211889047	1.1	-0.005063235	
173	25.47802	-0.002079	1	71	2.201306117	1.1	-0.005034167	
174	25.47594	-0.00208	1	70	2.190723187	1.1	-0.005012375	
175	25.47386	-0.00208	1	69	2.180140256	1.1	-0.004988161	
176	25.47178	-0.00208	1	68	2.169557326	1.1	-0.004963947	
177	25.4697	-0.002082	1	67	2.158974395	1.1	-0.004944483	
178	25.46762	-0.002083	1	66	2.148391465	1.1	-0.004922609	
179	25.46553	-0.002085	1	65	2.137808535	1.1	-0.004903064	
180	25.46344	-0.002087	1	64	2.127225604	1.1	-0.004883472	
181	25.46135	-0.002089	1	63	2.116642674	1.1	-0.004863833	
182	25.45926	-0.002093	1	62	2.106059743	1.1	-0.004848781	
183	25.45717	-0.002096	1	61	2.095476813	1.1	-0.004831331	
184	25.45507	-0.0021	1	60	2.084893883	1.1	-0.004816105	
185	25.45296	-0.002104	1	59	2.067843272	1.1	-0.004785816	
186	25.45085	-0.002109	1	58	2.050792661	1.1	-0.004757634	
187	25.44874	-0.002114	1	57	2.03374205	1.1	-0.004729264	
188	25.44662	-0.002119	1	56	2.016691439	1.1	-0.004700706	
189	25.44449	-0.002125	1	55	1.999640829	1.1	-0.00467416	
190	25.44236	-0.002131	1	54	1.982590218	1.1	-0.00464739	
191	25.44023	-0.002138	1	53	1.965539607	1.1	-0.004622556	
192	25.43808	-0.002144	1	52	1.948488996	1.1	-0.004595316	
193	25.43593	-0.002151	1	51	1.931438385	1.1	-0.004569976	
194	25.43377	-0.002159	1	50	1.914387775	1.1	-0.00454648	
195	25.4316	-0.002167	1	49	1.897337164	1.1	-0.004522683	
196	25.42943	-0.002174	1	48	1.880286553	1.1	-0.004496517	
197	25.42725	-0.002184	1	47	1.863235942	1.1	-0.004476238	
198	25.42505	-0.002192	1	46	1.846185331	1.1	-0.004451522	
199	25.42285	-0.002201	1	45	1.829134721	1.1	-0.004428518	
200	25.42064	-0.002211	1	44	1.815283021	1.1	-0.00441495	
201	25.41842	-0.002221	1	43	1.801431321	1.1	-0.004401077	
202	25.41619	-0.002231	1	42	1.787579621	1.1	-0.004386899	
203	25.41395	-0.002242	1	41	1.773727921	1.1	-0.004374368	
204	25.4117	-0.002253	1	40	1.759876222	1.1	-0.004361501	
205	25.40943	-0.002263	1	39	1.746024522	1.1	-0.004346379	
206	25.40716	-0.002276	1	38	1.732172822	1.1	-0.004336668	
207	25.40487	-0.002287	1	37	1.718321122	1.1	-0.00432278	
208	25.40257	-0.002299	1	36	1.704469422	1.1	-0.004310433	
209	25.40026	-0.002312	1	35	1.690617722	1.1	-0.004299579	
210	25.39793	-0.002325	1	34	1.676766023	1.1	-0.004288329	
211	25.3956	-0.002338	1	33	1.662914323	1.1	-0.004276683	

212	25.39324	-0.002351	1	32	1.649062623	1.1	-0.004264641	
213	25.39088	-0.002366	1	31	1.635210923	1.1	-0.0042558	
214	25.3885	-0.002379	1	30	1.621359223	1.1	-0.004242935	
215	25.38611	-0.002394	1	29	1.604440692	1.1	-0.004225134	
216	25.3837	-0.002409	1	28	1.587522161	1.1	-0.004206775	
217	25.38127	-0.002424	1	27	1.57060363	1.1	-0.004187858	
218	25.37883	-0.00244	1	26	1.553685099	1.1	-0.004170091	
219	25.37638	-0.002456	1	25	1.536766568	1.1	-0.004151729	
220	25.37391	-0.002471	1	24	1.519848037	1.1	-0.004131099	
221	25.37142	-0.002488	1	23	1.502929506	1.1	-0.004113217	
222	25.36891	-0.002506	1	22	1.486010975	1.1	-0.004096338	
223	25.36639	-0.002522	1	21	1.469092444	1.1	-0.004075556	
224	25.36385	-0.00254	1	20	1.452173913	1.1	-0.004057374	
225	25.36129	-0.002557	1	19	1.437772188	1.1	-0.004044022	
226	25.35872	-0.002576	1	18	1.423370464	1.1	-0.004033263	
227	25.35612	-0.002595	1	17	1.408968739	1.1	-0.004021901	
228	25.35351	-0.002614	1	16	1.394567014	1.1	-0.004009938	
229	25.35087	-0.002633	1	15	1.380165289	1.1	-0.003997373	
230	25.34822	-0.002652	1	14	1.353385963	1.1	-0.003948098	
231	25.34555	-0.002673	1	13	1.326606636	1.1	-0.003900621	
232	25.34286	-0.002693	1	12	1.29982731	1.1	-0.003850478	
233	25.34014	-0.002714	1	11	1.273047983	1.1	-0.003800557	
234	25.33741	-0.002735	1	10	1.246268657	1.1	-0.003749399	
235	25.33465	-0.002756	1	9	1.22422581	1.1	-0.003711363	
236	25.33187	-0.002778	1	8	1.202182963	1.1	-0.003673631	
237	25.32907	-0.002801	1	7	1.180140116	1.1	-0.00363613	
238	25.32625	-0.002824	1	6	1.158097269	1.1	-0.003597513	
239	25.3234	-0.002846	1	5	1.136054422	1.1	-0.003556532	
240	25.32051	-0.002894	1	4	1.106613987	1.1	-0.003522795	
241	25.31774	-0.002766	1	3	1.077173552	1.1	-0.003277408	
242	25.31484	-0.002899	1	2	1.047733118	1.1	-0.003341116	
243	25.3119	-0.002939	1	1	1.018292683	1.1	-0.003292038	
Total							122.1924371	***

Maximum size * design margin * aging factor = required battery size

122.1924 * 1.05 * 1.2 = 153.9624 Ah

2.2. Application 2

The required standby period for Application 2 is 120 minutes. The calculation starts two minutes prior the introduction of the inrush current, and ends two minutes after the momentary loads at the end of the standby period.

2.2.1. **IEEE recommended sizing for approximated load profile without supercapacitor**

The largest load was observed during section 3 and therefore the table indicates this section.

Table 31: IEEE recommended practice for approximated load profile without supercapacitor, Application 2

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 3 - If A4 is greater than A3, go to section 4						1.1		
1	0	0	1	3	1.077708907	1.1	0	
2	0	0	1	2	1.047118916	1.1	0	
3	83.643	83.643	1	1	1.016528926	1.1	93.52808182	
Total						1.1	93.52808182	***

The required battery size is the product of the maximum section from the table above, the design margin, as well as the aging factor for NiCd batteries. For the above profile, the largest load value is observed in section 3, which is the section where the inrush current is introduced. For this reason, the entire calculation table is not shown.

I.e. Maximum size * design margin * aging factor = required battery size

93.528 * 1.05 * 1.2 = 117.845 Ah

2.2.2. **IEEE recommended sizing for approximated load profile with preliminary sized supercapacitor**

The largest load was observed during section 122 and therefore the table indicates this section.

Table 32: IEEE recommended practice for approximated load profile with preliminary sized supercapacitor, Application 2

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 122 - If A123 is greater than A122, go to section 123						1.1		
1	0	0	1	122	2.736448646	1.1	0	
2	27.45854	27.458544	1	121	2.725565043	1.1	82.32405242	
3	27.29428	-0.164267	1	120	2.71468144	1.1	-0.490525834	
4	27.21172	-0.082558	1	119	2.70411474	1.1	-0.245570935	
5	27.13349	-0.078225	1	118	2.693548039	1.1	-0.231773075	
6	27.05899	-0.074508	1	117	2.682981339	1.1	-0.219893931	
7	26.98818	-0.070802	1	116	2.672414638	1.1	-0.208133531	
8	26.92085	-0.067333	1	115	2.661847938	1.1	-0.197153228	
9	26.85656	-0.064289	1	114	2.651281237	1.1	-0.187493041	
10	26.79557	-0.060988	1	113	2.640714536	1.1	-0.177157088	
11	26.73729	-0.058282	1	112	2.630147836	1.1	-0.168619304	
12	26.64301	-0.094283	1	111	2.619581135	1.1	-0.271680165	
13	26.52865	-0.11436	1	110	2.609014435	1.1	-0.32820358	
14	26.42187	-0.106778	1	109	2.598447734	1.1	-0.305202757	
15	26.32331	-0.098559	1	108	2.587881033	1.1	-0.280564863	
16	26.23063	-0.092678	1	107	2.577314333	1.1	-0.262746372	
17	26.14091	-0.089723	1	106	2.566747632	1.1	-0.253325928	
18	26.05656	-0.084351	1	105	2.556180932	1.1	-0.23717806	
19	25.99448	-0.062076	1	104	2.545614231	1.1	-0.173823704	
20	25.93461	-0.059874	1	103	2.535047531	1.1	-0.166961779	
21	25.85955	-0.075058	1	102	2.52448083	1.1	-0.20843073	
22	25.78604	-0.073509	1	101	2.513914129	1.1	-0.203274845	
23	25.71825	-0.067792	1	100	2.503347429	1.1	-0.186677622	
24	25.66409	-0.054165	1	99	2.492780728	1.1	-0.148523615	
25	25.60744	-0.056644	1	98	2.482214028	1.1	-0.154662785	
26	25.54499	-0.062448	1	97	2.471647327	1.1	-0.169784376	
27	25.4908	-0.054192	1	96	2.461080626	1.1	-0.146707969	
28	25.43494	-0.055861	1	95	2.450513926	1.1	-0.150576974	
29	25.37737	-0.05757	1	94	2.439947225	1.1	-0.154514538	
30	25.32195	-0.055424	1	93	2.429380525	1.1	-0.148110585	
31	25.26741	-0.05454	1	92	2.418813824	1.1	-0.145114317	
32	25.21624	-0.051171	1	91	2.408247124	1.1	-0.135555655	
33	25.16642	-0.049815	1	90	2.397680423	1.1	-0.131384495	
34	25.11478	-0.051638	1	89	2.387113722	1.1	-0.135592356	
35	25.06689	-0.047891	1	88	2.376547022	1.1	-0.125196735	
36	25.02125	-0.04564	1	87	2.365980321	1.1	-0.118781676	
37	24.9782	-0.043053	1	86	2.355413621	1.1	-0.111548385	

38	24.93825	-0.039951	1	85	2.34484692	1.1	-0.103046877	
39	24.89634	-0.041906	1	84	2.334280219	1.1	-0.107602382	
40	24.85957	-0.036771	1	83	2.323713519	1.1	-0.093989797	
41	24.82686	-0.032714	1	82	2.313146818	1.1	-0.083239514	
42	24.793	-0.033854	1	81	2.302580118	1.1	-0.085746702	
43	24.75807	-0.034933	1	80	2.292013417	1.1	-0.088073595	
44	24.72449	-0.033576	1	79	2.281446717	1.1	-0.08426204	
45	24.69046	-0.034036	1	78	2.270880016	1.1	-0.085020839	
46	24.65604	-0.034415	1	77	2.260313315	1.1	-0.085567551	
47	24.62414	-0.0319	1	76	2.249746615	1.1	-0.078943609	
48	24.59305	-0.031091	1	75	2.239179914	1.1	-0.076580177	
49	24.56504	-0.028016	1	74	2.228613214	1.1	-0.068680511	
50	24.53858	-0.026459	1	73	2.218046513	1.1	-0.064556022	
51	24.51031	-0.028264	1	72	2.207479813	1.1	-0.06863143	
52	24.48436	-0.02595	1	71	2.196913112	1.1	-0.062710885	
53	24.4601	-0.02426	1	70	2.186346411	1.1	-0.05834484	
54	24.43472	-0.025383	1	69	2.175779711	1.1	-0.060750598	
55	24.41193	-0.022786	1	68	2.16521301	1.1	-0.054270198	
56	24.38929	-0.022648	1	67	2.15464631	1.1	-0.053678273	
57	24.36577	-0.02352	1	66	2.144079609	1.1	-0.055471628	
58	24.34517	-0.020601	1	65	2.133512908	1.1	-0.048347749	
59	24.32764	-0.01753	1	64	2.122946208	1.1	-0.040936772	
60	24.3109	-0.016736	1	63	2.112379507	1.1	-0.038888062	
61	24.29226	-0.018639	1	62	2.101812807	1.1	-0.043093258	
62	24.27405	-0.01821	1	61	2.091246106	1.1	-0.041889751	
63	24.25956	-0.014486	1	60	2.080679406	1.1	-0.033154794	
64	24.25305	-0.00651	1	59	2.063631008	1.1	-0.014777662	
65	24.24321	-0.009842	1	58	2.046582611	1.1	-0.022156713	
66	24.22423	-0.018986	1	57	2.029534213	1.1	-0.04238601	
67	24.21115	-0.013076	1	56	2.012485816	1.1	-0.028946791	
68	24.19807	-0.013078	1	55	1.995437419	1.1	-0.028705964	
69	24.17877	-0.019304	1	54	1.978389021	1.1	-0.042009904	
70	24.16459	-0.014177	1	53	1.961340624	1.1	-0.030586519	
71	24.15123	-0.013366	1	52	1.944292227	1.1	-0.028586151	
72	24.13828	-0.012944	1	51	1.927243829	1.1	-0.027440869	
73	24.12543	-0.012849	1	50	1.910195432	1.1	-0.026998511	
74	24.11454	-0.010897	1	49	1.893147035	1.1	-0.022692586	
75	24.10536	-0.009178	1	48	1.876098637	1.1	-0.018940717	
76	24.09366	-0.011697	1	47	1.85905024	1.1	-0.023919842	
77	24.0815	-0.012159	1	46	1.842001842	1.1	-0.02463659	
78	24.06978	-0.011725	1	45	1.824953445	1.1	-0.023537337	
79	24.05726	-0.012521	1	44	1.810746022	1.1	-0.024939586	
80	24.04727	-0.009984	1	43	1.7965386	1.1	-0.019730306	
81	24.03726	-0.010011	1	42	1.782331177	1.1	-0.019627209	
82	24.02328	-0.013979	1	41	1.768123754	1.1	-0.027188262	
83	24.01067	-0.012612	1	40	1.753916332	1.1	-0.024332432	

84	24.00007	-0.010601	1	39	1.739708909	1.1	-0.02028692	
85	23.98969	-0.010379	1	38	1.725501486	1.1	-0.019699878	
86	23.97962	-0.010065	1	37	1.711294064	1.1	-0.018946592	
87	23.97301	-0.006613	1	36	1.697086641	1.1	-0.012345117	
88	23.96539	-0.007618	1	35	1.682879219	1.1	-0.014102191	
89	23.95821	-0.007184	1	34	1.668671796	1.1	-0.013186512	
90	23.95301	-0.005197	1	33	1.654464373	1.1	-0.009458076	
91	23.95009	-0.002918	1	32	1.640256951	1.1	-0.005264897	
92	23.945	-0.005096	1	31	1.626049528	1.1	-0.009114983	
93	23.93587	-0.009131	1	30	1.611842105	1.1	-0.016189503	
94	23.9279	-0.007968	1	29	1.59584308	1.1	-0.013987245	
95	23.92262	-0.005276	1	28	1.579844055	1.1	-0.009168783	
96	23.91833	-0.004295	1	27	1.563845029	1.1	-0.007388386	
97	23.91174	-0.006593	1	26	1.547846004	1.1	-0.011225444	
98	23.90258	-0.009152	1	25	1.531846979	1.1	-0.01542141	
99	23.89653	-0.006055	1	24	1.515847953	1.1	-0.010096305	
100	23.8979	0.001373	1	23	1.499848928	1.1	0.002265222	
101	23.89628	-0.001626	1	22	1.483849903	1.1	-0.002654014	
102	23.89101	-0.005264	1	21	1.467850877	1.1	-0.008499444	
103	23.88547	-0.005543	1	20	1.451851852	1.1	-0.008852376	
104	23.88018	-0.005289	1	19	1.43753782	1.1	-0.008363451	
105	23.88246	0.00228	1	18	1.423223787	1.1	0.003569445	
106	23.88006	-0.002401	1	17	1.408909755	1.1	-0.003721072	
107	23.87633	-0.00373	1	16	1.394595722	1.1	-0.005722026	
108	23.8754	-0.00093	1	15	1.38028169	1.1	-0.001412028	
109	23.86876	-0.006638	1	14	1.352956317	1.1	-0.009879016	
110	23.86615	-0.002612	1	13	1.325630943	1.1	-0.003808803	
111	23.86221	-0.003938	1	12	1.298305569	1.1	-0.005624	
112	23.85348	-0.008729	1	11	1.270980196	1.1	-0.012203825	
113	23.84559	-0.007889	1	10	1.243654822	1.1	-0.010792312	
114	23.84065	-0.004945	1	9	1.22177571	1.1	-0.006645849	
115	23.83484	-0.005808	1	8	1.199896597	1.1	-0.007665899	
116	23.82661	-0.00823	1	7	1.178017484	1.1	-0.010664592	
117	23.82226	-0.004354	1	6	1.156138372	1.1	-0.005537209	
118	23.81853	-0.003728	1	5	1.134259259	1.1	-0.00465137	
119	23.81045	-0.008075	1	4	1.104055354	1.1	-0.009806772	
120	23.80371	-0.006746	1	3	1.07385145	1.1	-0.007968622	
121	23.90382	0.100116	1	2	1.043647545	1.1	0.114934399	
122	23.75251	-0.151309	1	1	1.01344364	1.1	-0.168677458	
Total						1.1	72.66772646	***

Maximum size * design margin * aging factor = required battery size

72.6677 * 1.05 * 1.2 = 91.561 Ah

2.2.3. IEEE recommended sizing for approximated load profile with undersized supercapacitor

The largest load was observed during section 121 and therefore the table indicates this section.

Table 33: IEEE recommended practice for approximated load profile with undersized supercapacitor, Application 2

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 121 - If A122 is greater than A121, go to section 122						1.1		
1	0	0	1	121	2.725565043	1.1	0	
2	28.21578	28.215776	1	120	2.71468144	1.1	84.25652778	
3	27.24315	-0.97263	1	119	2.70411474	1.1	-2.893113431	
4	27.16183	-0.081321	1	118	2.693548039	1.1	-0.240946222	
5	27.08984	-0.071987	1	117	2.682981339	1.1	-0.212453755	
6	27.01514	-0.0747	1	116	2.672414638	1.1	-0.219592311	
7	26.94714	-0.068003	1	115	2.661847938	1.1	-0.19911501	
8	26.88376	-0.063379	1	114	2.651281237	1.1	-0.184839109	
9	26.81346	-0.070292	1	113	2.640714536	1.1	-0.204183217	
10	26.7567	-0.056766	1	112	2.630147836	1.1	-0.164233269	
11	26.69268	-0.064022	1	111	2.619581135	1.1	-0.184481906	
12	25.96397	-0.728707	1	110	2.609014435	1.1	-2.09132779	
13	25.12419	-0.839775	1	109	2.598447734	1.1	-2.40032259	
14	24.61018	-0.514019	1	108	2.587881033	1.1	-1.463242023	
15	24.32563	-0.284542	1	107	2.577314333	1.1	-0.806689592	
16	24.15915	-0.166485	1	106	2.566747632	1.1	-0.470057478	
17	24.02972	-0.129433	1	105	2.556180932	1.1	-0.363939583	
18	23.97458	-0.055132	1	104	2.545614231	1.1	-0.154379284	
19	24.26429	0.289704	1	103	2.535047531	1.1	0.807854751	
20	24.39647	0.13218	1	102	2.52448083	1.1	0.367054464	
21	24.21388	-0.182588	1	101	2.513914129	1.1	-0.504911608	
22	24.07332	-0.140555	1	100	2.503347429	1.1	-0.387043798	
23	24.02381	-0.04951	1	99	2.492780728	1.1	-0.135759331	
24	24.18028	0.156464	1	98	2.482214028	1.1	0.427214849	
25	24.16946	-0.010815	1	97	2.471647327	1.1	-0.029403952	
26	24.05865	-0.110809	1	96	2.461080626	1.1	-0.299980871	
27	24.07356	0.014909	1	95	2.450513926	1.1	0.040188183	
28	24.00954	-0.064027	1	94	2.439947225	1.1	-0.171844751	

29	23.91319	-0.096345	1	93	2.429380525	1.1	-0.257464533	
30	23.8444	-0.068795	1	92	2.418813824	1.1	-0.183042527	
31	23.77974	-0.064652	1	91	2.408247124	1.1	-0.171267792	
32	23.76116	-0.018583	1	90	2.397680423	1.1	-0.049011705	
33	23.73401	-0.027155	1	89	2.387113722	1.1	-0.07130428	
34	23.65679	-0.077215	1	88	2.376547022	1.1	-0.201855586	
35	23.64446	-0.012327	1	87	2.365980321	1.1	-0.032081983	
36	23.63477	-0.009696	1	86	2.355413621	1.1	-0.0251219	
37	23.65422	0.01945	1	85	2.34484692	1.1	0.050168	
38	23.68434	0.030118	1	84	2.334280219	1.1	0.077334237	
39	23.64949	-0.034848	1	83	2.323713519	1.1	-0.089074446	
40	23.6975	0.048008	1	82	2.313146818	1.1	0.122154508	
41	23.76256	0.065064	1	81	2.302580118	1.1	0.16479658	
42	23.77162	0.009061	1	80	2.292013417	1.1	0.022844727	
43	23.73771	-0.033908	1	79	2.281446717	1.1	-0.085095225	
44	23.72406	-0.013654	1	78	2.270880016	1.1	-0.034107255	
45	23.67955	-0.044506	1	77	2.260313315	1.1	-0.110657255	
46	23.63341	-0.046142	1	76	2.249746615	1.1	-0.114188589	
47	23.62167	-0.01174	1	75	2.239179914	1.1	-0.028916769	
48	23.61031	-0.011357	1	74	2.228613214	1.1	-0.027841396	
49	23.63966	0.029347	1	73	2.218046513	1.1	0.071602312	
50	23.66439	0.024729	1	72	2.207479813	1.1	0.060047645	
51	23.63694	-0.027446	1	71	2.196913112	1.1	-0.066326125	
52	23.64846	0.011512	1	70	2.186346411	1.1	0.027686142	
53	23.66279	0.014331	1	69	2.175779711	1.1	0.034299209	
54	23.6437	-0.019092	1	68	2.16521301	1.1	-0.045472071	
55	23.66401	0.020313	1	67	2.15464631	1.1	0.048144064	
56	23.66068	-0.003332	1	66	2.144079609	1.1	-0.007858481	
57	23.63779	-0.022887	1	65	2.133512908	1.1	-0.053712681	
58	23.65953	0.021738	1	64	2.122946208	1.1	0.050763465	
59	23.71319	0.053667	1	63	2.112379507	1.1	0.124701578	
60	23.75025	0.037054	1	62	2.101812807	1.1	0.085668629	
61	23.73351	-0.016743	1	61	2.091246106	1.1	-0.038515107	
62	23.72509	-0.008411	1	60	2.080679406	1.1	-0.019250654	
63	23.77179	0.0467	1	59	2.063631008	1.1	0.106008725	
64	23.93327	0.161477	1	58	2.046582611	1.1	0.363523622	
65	23.95836	0.025091	1	57	2.029534213	1.1	0.056015347	
66	23.83237	-0.12599	1	56	2.012485816	1.1	-0.278908397	
67	23.84747	0.015097	1	55	1.995437419	1.1	0.033137631	
68	23.83028	-0.017192	1	54	1.978389021	1.1	-0.03741371	
69	23.71893	-0.111349	1	53	1.961340624	1.1	-0.240232649	
70	23.72912	0.010196	1	52	1.944292227	1.1	0.021806404	
71	23.72651	-0.002614	1	51	1.927243829	1.1	-0.005541597	
72	23.73971	0.013196	1	50	1.910195432	1.1	0.027727633	
73	23.73012	-0.009582	1	49	1.893147035	1.1	-0.019954148	
74	23.76575	0.035628	1	48	1.876098637	1.1	0.073525806	

75	23.79753	0.031776	1	47	1.85905024	1.1	0.064980498	
76	23.78044	-0.017087	1	46	1.842001842	1.1	-0.034621714	
77	23.7523	-0.028139	1	45	1.824953445	1.1	-0.056487601	
78	23.73986	-0.012444	1	44	1.810746022	1.1	-0.024786216	
79	23.70663	-0.033225	1	43	1.7965386	1.1	-0.065658994	
80	23.73199	0.025361	1	42	1.782331177	1.1	0.049721871	
81	23.72939	-0.002609	1	41	1.768123754	1.1	-0.005074338	
82	23.66543	-0.063957	1	40	1.753916332	1.1	-0.12339275	
83	23.64067	-0.02476	1	39	1.739708909	1.1	-0.047382712	
84	23.65137	0.010697	1	38	1.725501486	1.1	0.020303458	
85	23.65541	0.004048	1	37	1.711294064	1.1	0.00762005	
86	23.66145	0.00604	1	36	1.697086641	1.1	0.011275444	
87	23.72106	0.059608	1	35	1.682879219	1.1	0.110344371	
88	23.73208	0.011014	1	34	1.668671796	1.1	0.020216626	
89	23.75496	0.022887	1	33	1.654464373	1.1	0.041652299	
90	23.79194	0.036973	1	32	1.640256951	1.1	0.066709742	
91	23.86033	0.068399	1	31	1.626049528	1.1	0.122342178	
92	23.85432	-0.006011	1	30	1.611842105	1.1	-0.010657661	
93	23.7924	-0.061921	1	29	1.59584308	1.1	-0.108697819	
94	23.76459	-0.027811	1	28	1.579844055	1.1	-0.048330747	
95	23.79115	0.026556	1	27	1.563845029	1.1	0.045682415	
96	23.8166	0.025454	1	26	1.547846004	1.1	0.043338759	
97	23.79499	-0.021615	1	25	1.531846979	1.1	-0.03642196	
98	23.73457	-0.06042	1	24	1.515847953	1.1	-0.100746287	
99	23.75175	0.017186	1	23	1.499848928	1.1	0.028354044	
100	23.88104	0.12929	1	22	1.483849903	1.1	0.211031649	
101	23.90475	0.023705	1	21	1.467850877	1.1	0.038274946	
102	23.87253	-0.032217	1	20	1.451851852	1.1	-0.051451742	
103	23.83811	-0.034421	1	19	1.43753782	1.1	-0.054429638	
104	23.82378	-0.014327	1	18	1.423223787	1.1	-0.02242958	
105	23.94279	0.119009	1	17	1.408909755	1.1	0.184440235	
106	23.92156	-0.021234	1	16	1.394595722	1.1	-0.03257413	
107	23.91334	-0.008213	1	15	1.38028169	1.1	-0.012469879	
108	23.93256	0.019219	1	14	1.352956317	1.1	0.028602714	
109	23.85621	-0.076358	1	13	1.325630943	1.1	-0.11134478	
110	23.87995	0.023744	1	12	1.298305569	1.1	0.033909664	
111	23.85441	-0.025543	1	11	1.270980196	1.1	-0.035711112	
112	23.76905	-0.08536	1	10	1.243654822	1.1	-0.116774213	
113	23.72041	-0.048638	1	9	1.22177571	1.1	-0.0653672	
114	23.73903	0.018621	1	8	1.199896597	1.1	0.024577602	
115	23.7248	-0.014233	1	7	1.178017484	1.1	-0.018443395	
116	23.68149	-0.043306	1	6	1.156138372	1.1	-0.055074501	
117	23.71647	0.034978	1	5	1.134259259	1.1	0.043641532	
118	23.74139	0.024926	1	4	1.104055354	1.1	0.030271652	
119	23.68497	-0.056427	1	3	1.07385145	1.1	-0.066653637	
120	23.6763	-0.00867	1	2	1.043647545	1.1	-0.009953267	

121	25.49786	1.821561	1	1	1.01344364	1.1	2.030654352	
Total						1.1	73.38772877	***

Maximum size * design margin * aging factor = required battery size

73.3877 * 1.05 * 1.2 = 92.466 Ah

2.3. Application 3

The required standby period for Application 3 is 240 minutes. The calculation starts two minutes prior the introduction of the inrush current, and ends two minutes after the momentary loads at the end of the profile.

2.3.1. IEEE recommended sizing for approximated load profile without supercapacitor

The largest load was observed during section 242 and therefore the table indicates this section.

Table 34: IEEE recommended practice for approximated load profile without supercapacitor, Application 3

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 242 - If A243 is greater than A242, go to section 243						1.1		
1	0	0	1	242	4.319120535	1.1	0	
2	0	0	1	241	4.303712855	1.1	0	
3	82.3577	82.3577	1	240	4.288305176	1.1	388.4924463	
4	22.3577	-60	1	239	4.272897496	1.1	-282.0112347	
5	22.3577	0	1	238	4.257489816	1.1	0	
6	22.3577	0	1	237	4.242082136	1.1	0	
7	22.3577	0	1	236	4.226674457	1.1	0	
8	22.3577	0	1	235	4.211266777	1.1	0	
9	22.3577	0	1	234	4.195859097	1.1	0	
10	22.3577	0	1	233	4.180451418	1.1	0	
11	22.3577	0	1	232	4.165043738	1.1	0	
12	22.3577	0	1	231	4.149636058	1.1	0	
13	22.3577	0	1	230	4.134228379	1.1	0	
14	22.3577	0	1	229	4.118820699	1.1	0	

15	22.3577	0	1	228	4.103413019	1.1	0	
16	22.3577	0	1	227	4.088005339	1.1	0	
17	22.3577	0	1	226	4.07259766	1.1	0	
18	22.3577	0	1	225	4.05718998	1.1	0	
19	22.3577	0	1	224	4.0417823	1.1	0	
20	22.3577	0	1	223	4.026374621	1.1	0	
21	22.3577	0	1	222	4.010966941	1.1	0	
22	22.3577	0	1	221	3.995559261	1.1	0	
23	22.3577	0	1	220	3.980151582	1.1	0	
24	22.3577	0	1	219	3.964743902	1.1	0	
25	22.3577	0	1	218	3.949336222	1.1	0	
26	22.3577	0	1	217	3.933928542	1.1	0	
27	22.3577	0	1	216	3.918520863	1.1	0	
28	22.5037	0.146	1	215	3.903113183	1.1	0.626839977	
29	22.3577	-0.146	1	214	3.887705503	1.1	-0.624365504	
30	22.3577	0	1	213	3.872297824	1.1	0	
31	22.3577	0	1	212	3.856890144	1.1	0	
32	22.4307	0.073	1	211	3.841482464	1.1	0.308471042	
33	22.3577	-0.073	1	210	3.826074785	1.1	-0.307233805	
34	22.3577	0	1	209	3.810667105	1.1	0	
35	22.3577	0	1	208	3.795259425	1.1	0	
36	22.3577	0	1	207	3.779851745	1.1	0	
37	22.3577	0	1	206	3.764444066	1.1	0	
38	22.3577	0	1	205	3.749036386	1.1	0	
39	22.3577	0	1	204	3.733628706	1.1	0	
40	22.3577	0	1	203	3.718221027	1.1	0	
41	22.3577	0	1	202	3.702813347	1.1	0	
42	22.3577	0	1	201	3.687405667	1.1	0	
43	22.3577	0	1	200	3.671997988	1.1	0	
44	22.3577	0	1	199	3.656590308	1.1	0	
45	22.3577	0	1	198	3.641182628	1.1	0	
46	22.3577	0	1	197	3.625774948	1.1	0	
47	22.3577	0	1	196	3.610367269	1.1	0	
48	22.5037	0.146	1	195	3.594959589	1.1	0.57735051	
49	22.3577	-0.146	1	194	3.579551909	1.1	-0.574876037	
50	22.3577	0	1	193	3.56414423	1.1	0	
51	22.3577	0	1	192	3.54873655	1.1	0	
52	22.4307	0.073	1	191	3.53332887	1.1	0.283726308	
53	22.3577	-0.073	1	190	3.517921191	1.1	-0.282489072	
54	22.3577	0	1	189	3.502513511	1.1	0	
55	22.3577	0	1	188	3.487105831	1.1	0	
56	22.3577	0	1	187	3.471698151	1.1	0	
57	22.3577	0	1	186	3.456290472	1.1	0	
58	22.3577	0	1	185	3.440882792	1.1	0	
59	22.3577	0	1	184	3.425475112	1.1	0	
60	22.3577	0	1	183	3.410067433	1.1	0	

61	22.3577	0	1	182	3.394659753	1.1	0	
62	22.3577	0	1	181	3.379252073	1.1	0	
63	22.3577	0	1	180	3.363844394	1.1	0	
64	22.3577	0	1	179	3.352983272	1.1	0	
65	22.3577	0	1	178	3.342122151	1.1	0	
66	22.3577	0	1	177	3.33126103	1.1	0	
67	22.3577	0	1	176	3.320399909	1.1	0	
68	22.3577	0	1	175	3.309538788	1.1	0	
69	22.3577	0	1	174	3.298677666	1.1	0	
70	22.3577	0	1	173	3.287816545	1.1	0	
71	22.3577	0	1	172	3.276955424	1.1	0	
72	22.3577	0	1	171	3.266094303	1.1	0	
73	22.3577	0	1	170	3.255233182	1.1	0	
74	22.3577	0	1	169	3.24437206	1.1	0	
75	22.3577	0	1	168	3.233510939	1.1	0	
76	22.3577	0	1	167	3.222649818	1.1	0	
77	22.3577	0	1	166	3.211788697	1.1	0	
78	22.3577	0	1	165	3.200927576	1.1	0	
79	22.3577	0	1	164	3.190066454	1.1	0	
80	22.3577	0	1	163	3.179205333	1.1	0	
81	22.3577	0	1	162	3.168344212	1.1	0	
82	22.3577	0	1	161	3.157483091	1.1	0	
83	22.3577	0	1	160	3.14662197	1.1	0	
84	22.3577	0	1	159	3.135760848	1.1	0	
85	22.3577	0	1	158	3.124899727	1.1	0	
86	22.3577	0	1	157	3.114038606	1.1	0	
87	22.3577	0	1	156	3.103177485	1.1	0	
88	22.3577	0	1	155	3.092316364	1.1	0	
89	22.3577	0	1	154	3.081455242	1.1	0	
90	22.3577	0	1	153	3.070594121	1.1	0	
91	22.3577	0	1	152	3.059733	1.1	0	
92	22.3577	0	1	151	3.048871879	1.1	0	
93	22.3577	0	1	150	3.038010758	1.1	0	
94	22.3577	0	1	149	3.027149636	1.1	0	
95	22.3577	0	1	148	3.016288515	1.1	0	
96	22.3577	0	1	147	3.005427394	1.1	0	
97	22.3577	0	1	146	2.994566273	1.1	0	
98	22.3577	0	1	145	2.983705152	1.1	0	
99	22.3577	0	1	144	2.97284403	1.1	0	
100	22.3577	0	1	143	2.961982909	1.1	0	
101	22.3577	0	1	142	2.951121788	1.1	0	
102	22.4937	0.136	1	141	2.940260667	1.1	0.439862996	
103	22.3477	-0.146	1	140	2.929399546	1.1	-0.470461567	
104	22.3477	0	1	139	2.918538425	1.1	0	
105	22.3477	0	1	138	2.907677303	1.1	0	
106	22.3477	0	1	137	2.896816182	1.1	0	

107	22.3477	0	1	136	2.885955061	1.1	0	
108	22.3477	0	1	135	2.87509394	1.1	0	
109	22.3477	0	1	134	2.864232819	1.1	0	
110	22.4207	0.073	1	133	2.853371697	1.1	0.229125747	
111	22.3477	-0.073	1	132	2.842510576	1.1	-0.228253599	
112	22.3477	0	1	131	2.831649455	1.1	0	
113	22.3477	0	1	130	2.820788334	1.1	0	
114	22.3477	0	1	129	2.809927213	1.1	0	
115	22.3477	0	1	128	2.799066091	1.1	0	
116	22.3477	0	1	127	2.78820497	1.1	0	
117	22.3477	0	1	126	2.777343849	1.1	0	
118	22.3477	0	1	125	2.766482728	1.1	0	
119	22.3477	0	1	124	2.755621607	1.1	0	
120	22.3477	0	1	123	2.744760485	1.1	0	
121	22.3477	0	1	122	2.733899364	1.1	0	
122	22.3477	0	1	121	2.723038243	1.1	0	
123	22.3477	0	1	120	2.712177122	1.1	0	
124	22.3477	0	1	119	2.701627635	1.1	0	
125	22.3477	0	1	118	2.691078148	1.1	0	
126	22.3477	0	1	117	2.680528662	1.1	0	
127	22.3477	0	1	116	2.669979175	1.1	0	
128	22.3477	0	1	115	2.659429688	1.1	0	
129	22.3477	0	1	114	2.648880202	1.1	0	
130	22.5567	0.209	1	113	2.638330715	1.1	0.606552231	
131	22.3377	-0.219	1	112	2.627781228	1.1	-0.633032498	
132	22.3377	0	1	111	2.617231742	1.1	0	
133	22.3377	0	1	110	2.606682255	1.1	0	
134	22.3377	0	1	109	2.596132768	1.1	0	
135	22.3377	0	1	108	2.585583282	1.1	0	
136	22.3377	0	1	107	2.575033795	1.1	0	
137	22.3377	0	1	106	2.564484308	1.1	0	
138	22.3377	0	1	105	2.553934822	1.1	0	
139	22.3377	0	1	104	2.543385335	1.1	0	
140	22.3377	0	1	103	2.532835848	1.1	0	
141	22.3377	0	1	102	2.522286361	1.1	0	
142	22.3377	0	1	101	2.511736875	1.1	0	
143	22.3377	0	1	100	2.501187388	1.1	0	
144	22.3377	0	1	99	2.490637901	1.1	0	
145	22.3377	0	1	98	2.480088415	1.1	0	
146	22.3377	0	1	97	2.469538928	1.1	0	
147	22.3377	0	1	96	2.458989441	1.1	0	
148	22.4107	0.073	1	95	2.448439955	1.1	0.196609728	
149	22.3377	-0.073	1	94	2.437890468	1.1	-0.195762605	
150	22.4107	0.073	1	93	2.427340981	1.1	0.194915481	
151	22.3377	-0.073	1	92	2.416791495	1.1	-0.194068357	
152	22.3377	0	1	91	2.406242008	1.1	0	

153	22.3377	0	1	90	2.395692521	1.1	0	
154	22.3377	0	1	89	2.385143035	1.1	0	
155	22.5207	0.183	1	88	2.374593548	1.1	0.478005681	
156	22.3477	-0.173	1	87	2.364044061	1.1	-0.449877585	
157	22.3477	0	1	86	2.353494575	1.1	0	
158	22.3477	0	1	85	2.342945088	1.1	0	
159	22.3477	0	1	84	2.332395601	1.1	0	
160	22.3477	0	1	83	2.321846115	1.1	0	
161	22.3477	0	1	82	2.311296628	1.1	0	
162	22.3477	0	1	81	2.300747141	1.1	0	
163	22.3477	0	1	80	2.290197654	1.1	0	
164	22.3477	0	1	79	2.279648168	1.1	0	
165	22.3477	0	1	78	2.269098681	1.1	0	
166	22.3477	0	1	77	2.258549194	1.1	0	
167	22.3477	0	1	76	2.247999708	1.1	0	
168	22.4207	0.073	1	75	2.237450221	1.1	0.179667253	
169	22.3477	-0.073	1	74	2.226900734	1.1	-0.178820129	
170	22.4207	0.073	1	73	2.216351248	1.1	0.177973005	
171	22.3477	-0.073	1	72	2.205801761	1.1	-0.177125881	
172	22.3477	0	1	71	2.195252274	1.1	0	
173	22.3477	0	1	70	2.184702788	1.1	0	
174	22.3477	0	1	69	2.174153301	1.1	0	
175	22.4207	0.073	1	68	2.163603814	1.1	0.173737386	
176	22.3477	-0.073	1	67	2.153054328	1.1	-0.172890263	
177	22.3477	0	1	66	2.142504841	1.1	0	
178	22.3477	0	1	65	2.131955354	1.1	0	
179	22.3477	0	1	64	2.121405868	1.1	0	
180	22.3477	0	1	63	2.110856381	1.1	0	
181	22.3477	0	1	62	2.100306894	1.1	0	
182	22.3477	0	1	61	2.089757407	1.1	0	
183	22.3477	0	1	60	2.079207921	1.1	0	
184	22.3477	0	1	59	2.062182149	1.1	0	
185	22.3477	0	1	58	2.045156377	1.1	0	
186	22.3477	0	1	57	2.028130605	1.1	0	
187	22.3477	0	1	56	2.011104833	1.1	0	
188	22.3477	0	1	55	1.994079061	1.1	0	
189	22.3477	0	1	54	1.977053288	1.1	0	
190	22.3477	0	1	53	1.960027516	1.1	0	
191	22.3477	0	1	52	1.943001744	1.1	0	
192	22.3477	0	1	51	1.925975972	1.1	0	
193	22.3477	0	1	50	1.9089502	1.1	0	
194	22.3477	0	1	49	1.891924428	1.1	0	
195	22.4207	0.073	1	48	1.874898656	1.1	0.150554362	
196	22.3477	-0.073	1	47	1.857872884	1.1	-0.149187193	
197	22.3477	0	1	46	1.840847112	1.1	0	
198	22.3477	0	1	45	1.82382134	1.1	0	

199	22.3477	0	1	44	1.809807345	1.1	0	
200	22.3477	0	1	43	1.79579335	1.1	0	
201	22.3477	0	1	42	1.781779355	1.1	0	
202	22.3477	0	1	41	1.76776536	1.1	0	
203	22.3477	0	1	40	1.753751365	1.1	0	
204	22.3477	0	1	39	1.73973737	1.1	0	
205	22.3477	0	1	38	1.725723375	1.1	0	
206	22.3477	0	1	37	1.711709381	1.1	0	
207	22.3477	0	1	36	1.697695386	1.1	0	
208	22.3477	0	1	35	1.683681391	1.1	0	
209	22.3477	0	1	34	1.669667396	1.1	0	
210	22.3477	0	1	33	1.655653401	1.1	0	
211	22.3477	0	1	32	1.641639406	1.1	0	
212	22.3477	0	1	31	1.627625411	1.1	0	
213	22.3477	0	1	30	1.613611416	1.1	0	
214	22.3477	0	1	29	1.597794829	1.1	0	
215	22.4207	0.073	1	28	1.581978242	1.1	0.127032853	
216	22.3477	-0.073	1	27	1.566161655	1.1	-0.125762781	
217	22.3477	0	1	26	1.550345067	1.1	0	
218	22.3477	0	1	25	1.53452848	1.1	0	
219	22.3477	0	1	24	1.518711893	1.1	0	
220	22.3477	0	1	23	1.502895306	1.1	0	
221	22.3477	0	1	22	1.487078719	1.1	0	
222	22.3477	0	1	21	1.471262132	1.1	0	
223	22.3477	0	1	20	1.455445545	1.1	0	
224	22.3477	0	1	19	1.439122791	1.1	0	
225	22.3477	0	1	18	1.422800037	1.1	0	
226	22.3477	0	1	17	1.406477283	1.1	0	
227	22.3477	0	1	16	1.390154529	1.1	0	
228	22.3477	0	1	15	1.373831776	1.1	0	
229	22.4207	0.073	1	14	1.348217963	1.1	0.108261902	
230	22.3477	-0.073	1	13	1.32260415	1.1	-0.106205113	
231	22.3477	0	1	12	1.296990337	1.1	0	
232	22.3477	0	1	11	1.271376525	1.1	0	
233	22.3477	0	1	10	1.245762712	1.1	0	
234	22.3477	0	1	9	1.222764016	1.1	0	
235	22.4207	0.073	1	8	1.199765319	1.1	0.096341155	
236	22.3477	-0.073	1	7	1.176766623	1.1	-0.09449436	
237	22.3477	0	1	6	1.153767927	1.1	0	
238	22.3477	0	1	5	1.130769231	1.1	0	
239	22.3477	0	1	4	1.101525199	1.1	0	
240	22.3477	0	1	3	1.072281167	1.1	0	
241	22.3477	0	1	2	1.043037135	1.1	0	
242	25.92872	3.58102206	1	1	1.013793103	1.1	3.993457016	
Total						1.1	110.4647898	***

The required battery size is the product of the maximum section from the table above, the design margin, as well as the aging factor for NiCd batteries.

I.e. Maximum size * design margin * aging factor = required battery size

110.4648 * 1.05 * 1.2 = 139.1856 Ah

2.3.2. **IEEE recommended sizing for approximated load profile with preliminary sized supercapacitor**

The largest load was observed during section 242 and therefore the table indicates this section.

Table 35: IEEE recommended practice for approximated load profile with preliminary sized supercapacitor, Application 3

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 242 - If A243 is greater than A242, go to section 243						1.1		
1	0	0	1	242	4.319120535	1.1	0	
2	27.4801	27.480097	1	241	4.303712855	1.1	130.0930914	
3	27.36409	-0.116005	1	240	4.288305176	1.1	-0.547211326	
4	27.30753	-0.056567	1	239	4.272897496	1.1	-0.265875492	
5	27.25294	-0.054581	1	238	4.257489816	1.1	-0.255615857	
6	27.20018	-0.052761	1	237	4.242082136	1.1	-0.246198145	
7	27.14918	-0.051008	1	236	4.226674457	1.1	-0.237153632	
8	27.09985	-0.049321	1	235	4.211266777	1.1	-0.228474278	
9	26.97005	-0.129809	1	234	4.195859097	1.1	-0.599126301	
10	26.83285	-0.137192	1	233	4.180451418	1.1	-0.63087694	
11	26.70002	-0.13283	1	232	4.165043738	1.1	-0.608567036	
12	26.5714	-0.128621	1	231	4.149636058	1.1	-0.587103373	
13	26.44684	-0.124562	1	230	4.134228379	1.1	-0.566464531	
14	26.3262	-0.120644	1	229	4.118820699	1.1	-0.546602105	
15	26.20933	-0.116864	1	228	4.103413019	1.1	-0.527495385	
16	26.09612	-0.113216	1	227	4.088005339	1.1	-0.509110374	
17	25.98642	-0.109692	1	226	4.07259766	1.1	-0.491404521	
18	25.88013	-0.106292	1	225	4.05718998	1.1	-0.474371521	
19	25.77713	-0.103007	1	224	4.0417823	1.1	-0.457965056	
20	25.67729	-0.099835	1	223	4.026374621	1.1	-0.442170421	

21	25.58052	-0.096771	1	222	4.010966941	1.1	-0.42695981	
22	25.48671	-0.093809	1	221	3.995559261	1.1	-0.412301361	
23	25.39576	-0.090949	1	220	3.980151582	1.1	-0.398189887	
24	25.30758	-0.088184	1	219	3.964743902	1.1	-0.384589674	
25	25.22207	-0.085511	1	218	3.949336222	1.1	-0.371482859	
26	25.13914	-0.082928	1	217	3.933928542	1.1	-0.358856109	
27	25.0602	-0.078937	1	216	3.918520863	1.1	-0.340247909	
28	24.98355	-0.076655	1	215	3.903113183	1.1	-0.329112455	
29	24.90781	-0.075738	1	214	3.887705503	1.1	-0.323891743	
30	24.83433	-0.073476	1	213	3.872297824	1.1	-0.31297305	
31	24.76379	-0.070544	1	212	3.856890144	1.1	-0.299288504	
32	24.69529	-0.068494	1	211	3.841482464	1.1	-0.28943035	
33	24.62814	-0.067154	1	210	3.826074785	1.1	-0.282629849	
34	24.56297	-0.06517	1	209	3.810667105	1.1	-0.273175293	
35	24.49972	-0.063251	1	208	3.795259425	1.1	-0.264059349	
36	24.43833	-0.061393	1	207	3.779851745	1.1	-0.255262082	
37	24.37873	-0.059593	1	206	3.764444066	1.1	-0.246767967	
38	24.32088	-0.057851	1	205	3.749036386	1.1	-0.238574054	
39	24.26472	-0.056164	1	204	3.733628706	1.1	-0.230665075	
40	24.21019	-0.054529	1	203	3.718221027	1.1	-0.223025962	
41	24.15724	-0.052947	1	202	3.702813347	1.1	-0.215658144	
42	24.10583	-0.051413	1	201	3.687405667	1.1	-0.208538646	
43	24.0559	-0.049927	1	200	3.671997988	1.1	-0.201665028	
44	24.00741	-0.048488	1	199	3.656590308	1.1	-0.195030826	
45	23.96032	-0.047092	1	198	3.641182628	1.1	-0.18861763	
46	23.91458	-0.045739	1	197	3.625774948	1.1	-0.182423252	
47	23.87163	-0.042949	1	196	3.610367269	1.1	-0.17056783	
48	23.82982	-0.04181	1	195	3.594959589	1.1	-0.165335786	
49	23.78784	-0.041985	1	194	3.579551909	1.1	-0.165316236	
50	23.74705	-0.040788	1	193	3.56414423	1.1	-0.159911746	
51	23.70816	-0.03889	1	192	3.54873655	1.1	-0.151811401	
52	23.67033	-0.037831	1	191	3.53332887	1.1	-0.147036301	
53	23.63289	-0.037443	1	190	3.517921191	1.1	-0.144893675	
54	23.5965	-0.036384	1	189	3.502513511	1.1	-0.140178997	
55	23.56115	-0.035357	1	188	3.487105831	1.1	-0.135622961	
56	23.52679	-0.034361	1	187	3.471698151	1.1	-0.131220122	
57	23.49339	-0.033395	1	186	3.456290472	1.1	-0.126965102	
58	23.46093	-0.032457	1	185	3.440882792	1.1	-0.122848806	
59	23.42939	-0.031547	1	184	3.425475112	1.1	-0.11886981	
60	23.39872	-0.030664	1	183	3.410067433	1.1	-0.115022939	
61	23.36891	-0.029808	1	182	3.394659753	1.1	-0.11130682	
62	23.33994	-0.028975	1	181	3.379252073	1.1	-0.107705212	
63	23.31177	-0.028169	1	180	3.363844394	1.1	-0.104231746	
64	23.28439	-0.027384	1	179	3.352983272	1.1	-0.100999903	
65	23.25776	-0.026624	1	178	3.342122151	1.1	-0.097878726	
66	23.23188	-0.025886	1	177	3.33126103	1.1	-0.094856325	

67	23.20671	-0.025168	1	176	3.320399909	1.1	-0.091924607	
68	23.18224	-0.024472	1	175	3.309538788	1.1	-0.089090137	
69	23.15844	-0.023796	1	174	3.298677666	1.1	-0.086344867	
70	23.1353	-0.02314	1	173	3.287816545	1.1	-0.083688082	
71	23.1128	-0.022503	1	172	3.276955424	1.1	-0.081115461	
72	23.09091	-0.021883	1	171	3.266094303	1.1	-0.078619136	
73	23.06963	-0.021281	1	170	3.255233182	1.1	-0.076202079	
74	23.04894	-0.020698	1	169	3.24437206	1.1	-0.073867214	
75	23.0288	-0.020131	1	168	3.233510939	1.1	-0.07160319	
76	23.00923	-0.019579	1	167	3.222649818	1.1	-0.069405887	
77	22.99018	-0.019045	1	166	3.211788697	1.1	-0.067285367	
78	22.97166	-0.018524	1	165	3.200927576	1.1	-0.065223381	
79	22.95364	-0.018019	1	164	3.190066454	1.1	-0.063229988	
80	22.93611	-0.017528	1	163	3.179205333	1.1	-0.061297622	
81	22.91906	-0.017051	1	162	3.168344212	1.1	-0.059425781	
82	22.90247	-0.016588	1	161	3.157483091	1.1	-0.057613962	
83	22.88633	-0.016138	1	160	3.14662197	1.1	-0.055858204	
84	22.87063	-0.0157	1	159	3.135760848	1.1	-0.05415459	
85	22.85536	-0.015276	1	158	3.124899727	1.1	-0.052509565	
86	22.84049	-0.014862	1	157	3.114038606	1.1	-0.050908926	
87	22.82603	-0.014461	1	156	3.103177485	1.1	-0.049362555	
88	22.81196	-0.01407	1	155	3.092316364	1.1	-0.04785978	
89	22.79827	-0.013692	1	154	3.081455242	1.1	-0.046410414	
90	22.78495	-0.013323	1	153	3.070594121	1.1	-0.045000478	
91	22.77198	-0.012964	1	152	3.059733	1.1	-0.043633016	
92	22.75937	-0.012617	1	151	3.048871879	1.1	-0.042314378	
93	22.74709	-0.012279	1	150	3.038010758	1.1	-0.041034108	
94	22.73514	-0.011949	1	149	3.027149636	1.1	-0.039788552	
95	22.72351	-0.01163	1	148	3.016288515	1.1	-0.038587379	
96	22.71219	-0.011319	1	147	3.005427394	1.1	-0.037420276	
97	22.70117	-0.011017	1	146	2.994566273	1.1	-0.03629025	
98	22.69045	-0.010724	1	145	2.983705152	1.1	-0.035196979	
99	22.68001	-0.010438	1	144	2.97284403	1.1	-0.034133601	
100	22.66985	-0.010161	1	143	2.961982909	1.1	-0.033106379	
101	22.66132	-0.008529	1	142	2.951121788	1.1	-0.02768713	
102	22.65283	-0.008488	1	141	2.940260667	1.1	-0.027452626	
103	22.64322	-0.009617	1	140	2.929399546	1.1	-0.030989239	
104	22.63385	-0.009363	1	139	2.918538425	1.1	-0.030058903	
105	22.62473	-0.009119	1	138	2.907677303	1.1	-0.02916662	
106	22.61586	-0.008879	1	137	2.896816182	1.1	-0.028292914	
107	22.60721	-0.008647	1	136	2.885955061	1.1	-0.027450339	
108	22.59879	-0.008422	1	135	2.87509394	1.1	-0.026635445	
109	22.59132	-0.007471	1	134	2.864232819	1.1	-0.023538552	
110	22.58399	-0.007323	1	133	2.853371697	1.1	-0.022984765	
111	22.57618	-0.007808	1	132	2.842510576	1.1	-0.024413755	
112	22.56858	-0.007606	1	131	2.831649455	1.1	-0.023691278	

113	22.56117	-0.007409	1	130	2.820788334	1.1	-0.022989143	
114	22.55395	-0.007218	1	129	2.809927213	1.1	-0.02231026	
115	22.54692	-0.007031	1	128	2.799066091	1.1	-0.021648257	
116	22.54007	-0.006851	1	127	2.78820497	1.1	-0.021012191	
117	22.53339	-0.006675	1	126	2.777343849	1.1	-0.020392647	
118	22.52689	-0.006503	1	125	2.766482728	1.1	-0.019789481	
119	22.52055	-0.006337	1	124	2.755621607	1.1	-0.019208612	
120	22.51438	-0.006176	1	123	2.744760485	1.1	-0.018646805	
121	22.50836	-0.006018	1	122	2.733899364	1.1	-0.018097867	
122	22.5025	-0.005865	1	121	2.723038243	1.1	-0.017567681	
123	22.49678	-0.005717	1	120	2.712177122	1.1	-0.017056068	
124	22.49121	-0.005572	1	119	2.701627635	1.1	-0.016558816	
125	22.48578	-0.005431	1	118	2.691078148	1.1	-0.01607677	
126	22.48048	-0.005294	1	117	2.680528662	1.1	-0.015609791	
127	22.47532	-0.005162	1	116	2.669979175	1.1	-0.015160676	
128	22.47029	-0.005032	1	115	2.659429688	1.1	-0.014720475	
129	22.46747	-0.002818	1	114	2.648880202	1.1	-0.008210999	
130	22.46449	-0.00298	1	113	2.638330715	1.1	-0.008648448	
131	22.45955	-0.004935	1	112	2.627781228	1.1	-0.01426491	
132	22.45474	-0.004813	1	111	2.617231742	1.1	-0.01385641	
133	22.45005	-0.004696	1	110	2.606682255	1.1	-0.013465078	
134	22.44546	-0.004581	1	109	2.596132768	1.1	-0.013082173	
135	22.44099	-0.004471	1	108	2.585583282	1.1	-0.012716157	
136	22.43663	-0.004362	1	107	2.575033795	1.1	-0.012355527	
137	22.43237	-0.004257	1	106	2.564484308	1.1	-0.012008711	
138	22.42822	-0.004156	1	105	2.553934822	1.1	-0.011675568	
139	22.42416	-0.004055	1	104	2.543385335	1.1	-0.01134477	
140	22.4202	-0.003959	1	103	2.532835848	1.1	-0.011030247	
141	22.41634	-0.003865	1	102	2.522286361	1.1	-0.0107235	
142	22.41257	-0.003774	1	101	2.511736875	1.1	-0.010427224	
143	22.40888	-0.003685	1	100	2.501187388	1.1	-0.010138563	
144	22.40528	-0.003598	1	99	2.490637901	1.1	-0.009857447	
145	22.40177	-0.003515	1	98	2.480088415	1.1	-0.009589262	
146	22.39833	-0.003433	1	97	2.469538928	1.1	-0.00932572	
147	22.39571	-0.002624	1	96	2.458989441	1.1	-0.007097627	
148	22.3931	-0.002612	1	95	2.448439955	1.1	-0.007034858	
149	22.3906	-0.002499	1	94	2.437890468	1.1	-0.006701517	
150	22.38811	-0.00249	1	93	2.427340981	1.1	-0.006648487	
151	22.385	-0.003111	1	92	2.416791495	1.1	-0.008270502	
152	22.38196	-0.00304	1	91	2.406242008	1.1	-0.008046473	
153	22.37899	-0.002973	1	90	2.395692521	1.1	-0.007834633	
154	22.37791	-0.001079	1	89	2.385143035	1.1	-0.002830926	
155	22.37683	-0.001077	1	88	2.374593548	1.1	-0.002813181	
156	22.37417	-0.002657	1	87	2.364044061	1.1	-0.006909392	
157	22.37157	-0.002598	1	86	2.353494575	1.1	-0.006725817	
158	22.36903	-0.002542	1	85	2.342945088	1.1	-0.006551343	

159	22.36654	-0.002488	1	84	2.332395601	1.1	-0.0063833	
160	22.36411	-0.002433	1	83	2.321846115	1.1	-0.006213957	
161	22.36173	-0.002382	1	82	2.311296628	1.1	-0.006056059	
162	22.3594	-0.002332	1	81	2.300747141	1.1	-0.005901877	
163	22.35711	-0.002283	1	80	2.290197654	1.1	-0.005751373	
164	22.35488	-0.002236	1	79	2.279648168	1.1	-0.005607023	
165	22.35269	-0.002189	1	78	2.269098681	1.1	-0.005463763	
166	22.35054	-0.002145	1	77	2.258549194	1.1	-0.005329047	
167	22.34917	-0.001373	1	76	2.247999708	1.1	-0.003395154	
168	22.34778	-0.001395	1	75	2.237450221	1.1	-0.003433367	
169	22.34646	-0.001317	1	74	2.226900734	1.1	-0.003226111	
170	22.34512	-0.001342	1	73	2.216351248	1.1	-0.003271778	
171	22.34312	-0.001994	1	72	2.205801761	1.1	-0.004838206	
172	22.34117	-0.001955	1	71	2.195252274	1.1	-0.00472089	
173	22.33925	-0.001919	1	70	2.184702788	1.1	-0.004611689	
174	22.3381	-0.001154	1	69	2.174153301	1.1	-0.00275987	
175	22.33691	-0.001184	1	68	2.163603814	1.1	-0.002817878	
176	22.33507	-0.001841	1	67	2.153054328	1.1	-0.00436015	
177	22.33326	-0.001808	1	66	2.142504841	1.1	-0.004261014	
178	22.33149	-0.001776	1	65	2.131955354	1.1	-0.004164988	
179	22.32974	-0.001745	1	64	2.121405868	1.1	-0.004072039	
180	22.32803	-0.001715	1	63	2.110856381	1.1	-0.003982131	
181	22.32634	-0.001685	1	62	2.100306894	1.1	-0.003892919	
182	22.32468	-0.001657	1	61	2.089757407	1.1	-0.003809001	
183	22.32305	-0.00163	1	60	2.079207921	1.1	-0.00372802	
184	22.32145	-0.001603	1	59	2.062182149	1.1	-0.003636246	
185	22.31987	-0.001578	1	58	2.045156377	1.1	-0.003549982	
186	22.31832	-0.001553	1	57	2.028130605	1.1	-0.003464656	
187	22.31679	-0.001529	1	56	2.011104833	1.1	-0.003382477	
188	22.31529	-0.001506	1	55	1.994079061	1.1	-0.003303391	
189	22.3138	-0.001483	1	54	1.977053288	1.1	-0.003225167	
190	22.31234	-0.001462	1	53	1.960027516	1.1	-0.003152116	
191	22.3109	-0.001442	1	52	1.943001744	1.1	-0.003081989	
192	22.30948	-0.001421	1	51	1.925975972	1.1	-0.003010493	
193	22.30808	-0.001402	1	50	1.9089502	1.1	-0.002943983	
194	22.30742	-0.000654	1	49	1.891924428	1.1	-0.00136105	
195	22.30672	-0.000701	1	48	1.874898656	1.1	-0.001445734	
196	22.30535	-0.001375	1	47	1.857872884	1.1	-0.002810033	
197	22.30399	-0.001358	1	46	1.840847112	1.1	-0.002749857	
198	22.30265	-0.001342	1	45	1.82382134	1.1	-0.002692325	
199	22.30132	-0.001326	1	44	1.809807345	1.1	-0.002639785	
200	22.30001	-0.001311	1	43	1.79579335	1.1	-0.002589714	
201	22.29871	-0.001296	1	42	1.781779355	1.1	-0.002540105	
202	22.29743	-0.001282	1	41	1.76776536	1.1	-0.002492903	
203	22.29616	-0.001269	1	40	1.753751365	1.1	-0.002448062	
204	22.29491	-0.001256	1	39	1.73973737	1.1	-0.002403621	

205	22.29366	-0.001244	1	38	1.725723375	1.1	-0.00236148	
206	22.29243	-0.001232	1	37	1.711709381	1.1	-0.002319709	
207	22.29121	-0.001221	1	36	1.697695386	1.1	-0.002280175	
208	22.29	-0.001211	1	35	1.683681391	1.1	-0.002242832	
209	22.2888	-0.001201	1	34	1.669667396	1.1	-0.002205798	
210	22.28761	-0.001191	1	33	1.655653401	1.1	-0.002169072	
211	22.28642	-0.001182	1	32	1.641639406	1.1	-0.00213446	
212	22.28525	-0.001174	1	31	1.627625411	1.1	-0.002101915	
213	22.28408	-0.001165	1	30	1.613611416	1.1	-0.002067843	
214	22.28366	-0.000429	1	29	1.597794829	1.1	-0.000753999	
215	22.28317	-0.000487	1	28	1.581978242	1.1	-0.000847466	
216	22.282	-0.001171	1	27	1.566161655	1.1	-0.002017373	
217	22.28083	-0.001165	1	26	1.550345067	1.1	-0.001986767	
218	22.27967	-0.001159	1	25	1.53452848	1.1	-0.00195637	
219	22.27852	-0.001153	1	24	1.518711893	1.1	-0.001926182	
220	22.27737	-0.001148	1	23	1.502895306	1.1	-0.001897856	
221	22.27623	-0.001143	1	22	1.487078719	1.1	-0.001869704	
222	22.27509	-0.001138	1	21	1.471262132	1.1	-0.001841726	
223	22.27396	-0.001135	1	20	1.455445545	1.1	-0.001817124	
224	22.27283	-0.001131	1	19	1.439122791	1.1	-0.001790413	
225	22.2717	-0.001127	1	18	1.422800037	1.1	-0.001763845	
226	22.27057	-0.001125	1	17	1.406477283	1.1	-0.001740516	
227	22.26945	-0.001123	1	16	1.390154529	1.1	-0.001717258	
228	22.26906	-0.000392	1	15	1.373831776	1.1	-0.000592396	
229	22.2686	-0.000455	1	14	1.348217963	1.1	-0.000674783	
230	22.26746	-0.001145	1	13	1.32260415	1.1	-0.00166582	
231	22.26631	-0.001144	1	12	1.296990337	1.1	-0.001632133	
232	22.26517	-0.001143	1	11	1.271376525	1.1	-0.001598502	
233	22.26403	-0.001143	1	10	1.245762712	1.1	-0.001566297	
234	22.26361	-0.000414	1	9	1.222764016	1.1	-0.000556847	
235	22.26314	-0.000478	1	8	1.199765319	1.1	-0.000630837	
236	22.26197	-0.001171	1	7	1.176766623	1.1	-0.001515793	
237	22.26079	-0.001171	1	6	1.153767927	1.1	-0.001486168	
238	22.25962	-0.001173	1	5	1.130769231	1.1	-0.001459032	
239	22.25845	-0.001173	1	4	1.101525199	1.1	-0.001421298	
240	22.25727	-0.001175	1	3	1.072281167	1.1	-0.001385923	
241	22.29189	0.034613	1	2	1.043037135	1.1	0.039712909	
242	22.10015	-0.191736	1	1	1.013793103	1.1	-0.213818698	
Total						1.1	108.5413322	***

Maximum size * design margin * aging factor = required battery size

108.541 * 1.05 * 1.2 = 136.762 Ah

2.3.3. IEEE recommended sizing for approximated load profile with undersized supercapacitor

The largest load was observed during section 241 and therefore the table indicates this section.

Table 36: IEEE recommended practice for approximated load profile with undersized supercapacitor, Application 3

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 241 - If A242 is greater than A241, go to section 242						1.1		
1	0	0	1	241	4.303712855	1.1	0	
2	28.22028	28.220284	1	240	4.288305176	1.1	133.1189089	
3	27.2951	-0.925188	1	239	4.272897496	1.1	-4.348556837	
4	27.23964	-0.055455	1	238	4.257489816	1.1	-0.259709008	
5	27.18594	-0.053697	1	237	4.242082136	1.1	-0.250565793	
6	27.13403	-0.051912	1	236	4.226674457	1.1	-0.241356637	
7	27.08384	-0.050193	1	235	4.211266777	1.1	-0.232513725	
8	27.0353	-0.048537	1	234	4.195859097	1.1	-0.224019854	
9	25.63108	-1.404226	1	233	4.180451418	1.1	-6.45732843	
10	24.53606	-1.095013	1	232	4.165043738	1.1	-5.016854742	
11	23.80506	-0.731005	1	231	4.149636058	1.1	-3.336745177	
12	23.31389	-0.491166	1	230	4.134228379	1.1	-2.233651657	
13	22.98201	-0.331884	1	229	4.118820699	1.1	-1.503667758	
14	22.7569	-0.225111	1	228	4.103413019	1.1	-1.016095749	
15	22.60391	-0.152988	1	227	4.088005339	1.1	-0.687957337	
16	22.49991	-0.103997	1	226	4.07259766	1.1	-0.465891733	
17	22.42932	-0.070594	1	225	4.05718998	1.1	-0.315054596	
18	22.38156	-0.047761	1	224	4.0417823	1.1	-0.212343521	
19	22.34943	-0.03213	1	223	4.026374621	1.1	-0.142304158	
20	22.328	-0.021425	1	222	4.010966941	1.1	-0.094528463	
21	22.31391	-0.014091	1	221	3.995559261	1.1	-0.061931568	
22	22.30484	-0.00907	1	220	3.980151582	1.1	-0.039709972	
23	22.2992	-0.005638	1	219	3.964743902	1.1	-0.024588549	
24	22.29591	-0.003295	1	218	3.949336222	1.1	-0.014314369	
25	22.29421	-0.001702	1	217	3.933928542	1.1	-0.007365101	
26	22.29359	-0.00062	1	216	3.918520863	1.1	-0.002672431	
27	22.31973	0.02614	1	215	3.903113183	1.1	0.112230116	
28	22.33188	0.012153	1	214	3.887705503	1.1	0.051972013	
29	22.32097	-0.010909	1	213	3.872297824	1.1	-0.046467187	

30	22.31398	-0.006989	1	212	3.856890144	1.1	-0.029651386	
31	22.32271	0.008724	1	211	3.841482464	1.1	0.036864402	
32	22.32599	0.003287	1	210	3.826074785	1.1	0.013833939	
33	22.31881	-0.007185	1	209	3.810667105	1.1	-0.030117607	
34	22.31432	-0.004486	1	208	3.795259425	1.1	-0.018728087	
35	22.31168	-0.002646	1	207	3.779851745	1.1	-0.011001636	
36	22.31028	-0.001398	1	206	3.764444066	1.1	-0.005788962	
37	22.30972	-0.000553	1	205	3.749036386	1.1	-0.002280539	
38	22.30974	1.5E-05	1	204	3.733628706	1.1	6.16049E-05	
39	22.31013	0.000394	1	203	3.718221027	1.1	0.001611477	
40	22.31078	0.000642	1	202	3.702813347	1.1	0.002614927	
41	22.31158	0.000803	1	201	3.687405667	1.1	0.003257085	
42	22.31248	0.000903	1	200	3.671997988	1.1	0.003647396	
43	22.31344	0.000962	1	199	3.656590308	1.1	0.003869404	
44	22.31444	0.000993	1	198	3.641182628	1.1	0.003977264	
45	22.31544	0.001005	1	197	3.625774948	1.1	0.004008294	
46	22.31645	0.001007	1	196	3.610367269	1.1	0.003999204	
47	22.34366	0.027214	1	195	3.594959589	1.1	0.107616553	
48	22.35624	0.012576	1	194	3.579551909	1.1	0.049518089	
49	22.34524	-0.010995	1	193	3.56414423	1.1	-0.043106542	
50	22.33801	-0.007232	1	192	3.54873655	1.1	-0.028230909	
51	22.34647	0.008454	1	191	3.53332887	1.1	0.032857838	
52	22.34934	0.002874	1	190	3.517921191	1.1	0.011121556	
53	22.34161	-0.007727	1	189	3.502513511	1.1	-0.029770314	
54	22.33659	-0.005026	1	188	3.487105831	1.1	-0.019278813	
55	22.3334	-0.003187	1	187	3.471698151	1.1	-0.012170732	
56	22.33146	-0.001938	1	186	3.456290472	1.1	-0.00736812	
57	22.33037	-0.00109	1	185	3.440882792	1.1	-0.004125618	
58	22.32986	-0.000516	1	184	3.425475112	1.1	-0.0019443	
59	22.32972	-0.000131	1	183	3.410067433	1.1	-0.000491391	
60	22.32985	0.000127	1	182	3.394659753	1.1	0.000474234	
61	22.33015	0.000297	1	181	3.379252073	1.1	0.001104002	
62	22.33056	0.000407	1	180	3.363844394	1.1	0.001505993	
63	22.33103	0.000478	1	179	3.352983272	1.1	0.001762999	
64	22.33155	0.00052	1	178	3.342122151	1.1	0.001911694	
65	22.3321	0.000543	1	177	3.33126103	1.1	0.001989762	
66	22.33265	0.000555	1	176	3.320399909	1.1	0.002027104	
67	22.33321	0.000558	1	175	3.309538788	1.1	0.002031395	
68	22.33376	0.000554	1	174	3.298677666	1.1	0.002010214	
69	22.33431	0.000547	1	173	3.287816545	1.1	0.001978279	
70	22.33485	0.000538	1	172	3.276955424	1.1	0.001939302	
71	22.33538	0.000528	1	171	3.266094303	1.1	0.001896948	
72	22.33589	0.000515	1	170	3.255233182	1.1	0.00184409	
73	22.3364	0.000504	1	169	3.24437206	1.1	0.00179868	
74	22.33689	0.00049	1	168	3.233510939	1.1	0.001742862	
75	22.33736	0.000478	1	167	3.222649818	1.1	0.001694469	

76	22.33783	0.000466	1	166	3.211788697	1.1	0.001646363	
77	22.33828	0.000453	1	165	3.200927576	1.1	0.001595022	
78	22.33872	0.000441	1	164	3.190066454	1.1	0.001547501	
79	22.33915	0.00043	1	163	3.179205333	1.1	0.001503764	
80	22.33957	0.000417	1	162	3.168344212	1.1	0.001453319	
81	22.33998	0.000406	1	161	3.157483091	1.1	0.001410132	
82	22.34037	0.000395	1	160	3.14662197	1.1	0.001367207	
83	22.34076	0.000384	1	159	3.135760848	1.1	0.001324545	
84	22.34113	0.000374	1	158	3.124899727	1.1	0.001285584	
85	22.34149	0.000363	1	157	3.114038606	1.1	0.001243436	
86	22.34185	0.000353	1	156	3.103177485	1.1	0.001204964	
87	22.34219	0.000344	1	155	3.092316364	1.1	0.001170133	
88	22.34252	0.000334	1	154	3.081455242	1.1	0.001132127	
89	22.34285	0.000324	1	153	3.070594121	1.1	0.00109436	
90	22.34316	0.000316	1	152	3.059733	1.1	0.001063563	
91	22.34347	0.000307	1	151	3.048871879	1.1	0.001029604	
92	22.34377	0.000298	1	150	3.038010758	1.1	0.00099586	
93	22.34406	0.00029	1	149	3.027149636	1.1	0.000965661	
94	22.34434	0.000282	1	148	3.016288515	1.1	0.000935653	
95	22.34461	0.000273	1	147	3.005427394	1.1	0.00090253	
96	22.34488	0.000267	1	146	2.994566273	1.1	0.000879504	
97	22.34514	0.000258	1	145	2.983705152	1.1	0.000846776	
98	22.34539	0.000252	1	144	2.97284403	1.1	0.000824072	
99	22.34563	0.000244	1	143	2.961982909	1.1	0.000794996	
100	22.34587	0.000238	1	142	2.951121788	1.1	0.000772604	
101	22.37071	0.024838	1	141	2.940260667	1.1	0.080333214	
102	22.37995	0.009242	1	140	2.929399546	1.1	0.029780862	
103	22.36628	-0.01367	1	139	2.918538425	1.1	-0.043886062	
104	22.35703	-0.009253	1	138	2.907677303	1.1	-0.029595212	
105	22.35078	-0.006246	1	137	2.896816182	1.1	-0.019902865	
106	22.34658	-0.004199	1	136	2.885955061	1.1	-0.013329938	
107	22.34378	-0.002805	1	135	2.87509394	1.1	-0.008871102	
108	22.34192	-0.001856	1	134	2.864232819	1.1	-0.005847618	
109	22.35392	0.012001	1	133	2.853371697	1.1	0.037667645	
110	22.35896	0.005039	1	132	2.842510576	1.1	0.015755752	
111	22.35243	-0.006534	1	131	2.831649455	1.1	-0.020352197	
112	22.34803	-0.004403	1	130	2.820788334	1.1	-0.013661924	
113	22.34507	-0.002954	1	129	2.809927213	1.1	-0.009130577	
114	22.34311	-0.001966	1	128	2.799066091	1.1	-0.00605326	
115	22.34181	-0.001295	1	127	2.78820497	1.1	-0.003971798	
116	22.34097	-0.000839	1	126	2.777343849	1.1	-0.002563211	
117	22.34044	-0.00053	1	125	2.766482728	1.1	-0.001612859	
118	22.34012	-0.00032	1	124	2.755621607	1.1	-0.000969979	
119	22.33994	-0.000178	1	123	2.744760485	1.1	-0.000537424	
120	22.33986	-8.2E-05	1	122	2.733899364	1.1	-0.000246598	
121	22.33984	-1.9E-05	1	121	2.723038243	1.1	-5.69115E-05	

122	22.33987	2.3E-05	1	120	2.712177122	1.1	6.86181E-05	
123	22.33992	5.2E-05	1	119	2.701627635	1.1	0.000154533	
124	22.33999	6.8E-05	1	118	2.691078148	1.1	0.000201293	
125	22.34007	8E-05	1	117	2.680528662	1.1	0.000235887	
126	22.34015	8.7E-05	1	116	2.669979175	1.1	0.000255517	
127	22.34024	8.9E-05	1	115	2.659429688	1.1	0.000260358	
128	22.34034	9.4E-05	1	114	2.648880202	1.1	0.000273894	
129	22.37829	0.037958	1	113	2.638330715	1.1	0.110160333	
130	22.39322	0.014927	1	112	2.627781228	1.1	0.043147379	
131	22.37332	-0.019902	1	111	2.617231742	1.1	-0.057296961	
132	22.35979	-0.013526	1	110	2.606682255	1.1	-0.038783783	
133	22.3506	-0.00919	1	109	2.596132768	1.1	-0.026244306	
134	22.34437	-0.006236	1	108	2.585583282	1.1	-0.017736067	
135	22.34014	-0.004226	1	107	2.575033795	1.1	-0.011970302	
136	22.33728	-0.002857	1	106	2.564484308	1.1	-0.008059405	
137	22.33536	-0.001925	1	105	2.553934822	1.1	-0.005407957	
138	22.33407	-0.001291	1	104	2.543385335	1.1	-0.003611862	
139	22.33321	-0.00086	1	103	2.532835848	1.1	-0.002396063	
140	22.33264	-0.000566	1	102	2.522286361	1.1	-0.001570375	
141	22.33228	-0.000367	1	101	2.511736875	1.1	-0.001013988	
142	22.33204	-0.000233	1	100	2.501187388	1.1	-0.000641054	
143	22.3319	-0.000141	1	99	2.490637901	1.1	-0.000386298	
144	22.33182	-7.9E-05	1	98	2.480088415	1.1	-0.00021552	
145	22.33178	-3.9E-05	1	97	2.469538928	1.1	-0.000105943	
146	22.33177	-1E-05	1	96	2.458989441	1.1	-2.70489E-05	
147	22.34501	0.013237	1	95	2.448439955	1.1	0.035651	
148	22.35084	0.005834	1	94	2.437890468	1.1	0.015644918	
149	22.35803	0.007188	1	93	2.427340981	1.1	0.0191925	
150	22.35974	0.001708	1	92	2.416791495	1.1	0.004540668	
151	22.35088	-0.008858	1	91	2.406242008	1.1	-0.023445941	
152	22.34486	-0.006021	1	90	2.395692521	1.1	-0.015866911	
153	22.34077	-0.004089	1	89	2.385143035	1.1	-0.010728135	
154	22.37118	0.030405	1	88	2.374593548	1.1	0.079419469	
155	22.38569	0.014511	1	87	2.364044061	1.1	0.037735108	
156	22.37179	-0.013899	1	86	2.353494575	1.1	-0.035982343	
157	22.36234	-0.009454	1	85	2.342945088	1.1	-0.024365223	
158	22.35591	-0.006429	1	84	2.332395601	1.1	-0.016494468	
159	22.35153	-0.004372	1	83	2.321846115	1.1	-0.011166222	
160	22.34856	-0.00297	1	82	2.311296628	1.1	-0.007551006	
161	22.34655	-0.002016	1	81	2.300747141	1.1	-0.005102137	
162	22.34518	-0.001367	1	80	2.290197654	1.1	-0.00344377	
163	22.34426	-0.000925	1	79	2.279648168	1.1	-0.002319542	
164	22.34363	-0.000625	1	78	2.269098681	1.1	-0.001560005	
165	22.34321	-0.000421	1	77	2.258549194	1.1	-0.001045934	
166	22.34293	-0.000281	1	76	2.247999708	1.1	-0.000694857	
167	22.35598	0.013052	1	75	2.237450221	1.1	0.03212352	

168	22.36167	0.005692	1	74	2.226900734	1.1	0.013943071	
169	22.36876	0.007082	1	73	2.216351248	1.1	0.017265819	
170	22.37038	0.001623	1	72	2.205801761	1.1	0.003938018	
171	22.36144	-0.008934	1	71	2.195252274	1.1	-0.021573622	
172	22.35537	-0.006079	1	70	2.184702788	1.1	-0.014608889	
173	22.35123	-0.004138	1	69	2.174153301	1.1	-0.009896311	
174	22.36165	0.010426	1	68	2.163603814	1.1	0.024813507	
175	22.36555	0.003897	1	67	2.153054328	1.1	0.009229498	
176	22.35816	-0.007387	1	66	2.142504841	1.1	-0.017409352	
177	22.35314	-0.005028	1	65	2.131955354	1.1	-0.011791419	
178	22.34971	-0.003425	1	64	2.121405868	1.1	-0.007992397	
179	22.34738	-0.002332	1	63	2.110856381	1.1	-0.005414769	
180	22.34579	-0.001589	1	62	2.100306894	1.1	-0.003671126	
181	22.34471	-0.001084	1	61	2.089757407	1.1	-0.002491827	
182	22.34397	-0.000739	1	60	2.079207921	1.1	-0.001690188	
183	22.34346	-0.000505	1	59	2.062182149	1.1	-0.001145542	
184	22.34312	-0.000346	1	58	2.045156377	1.1	-0.000778387	
185	22.34288	-0.000239	1	57	2.028130605	1.1	-0.000533196	
186	22.34271	-0.000165	1	56	2.011104833	1.1	-0.000365016	
187	22.3426	-0.000115	1	55	1.994079061	1.1	-0.000252251	
188	22.34251	-8.2E-05	1	54	1.977053288	1.1	-0.00017833	
189	22.34246	-5.9E-05	1	53	1.960027516	1.1	-0.000127206	
190	22.34241	-4.5E-05	1	52	1.943001744	1.1	-9.61786E-05	
191	22.34238	-3.5E-05	1	51	1.925975972	1.1	-7.41501E-05	
192	22.34235	-2.8E-05	1	50	1.9089502	1.1	-5.87957E-05	
193	22.34232	-2.3E-05	1	49	1.891924428	1.1	-4.78657E-05	
194	22.35555	0.013227	1	48	1.874898656	1.1	0.027279213	
195	22.36135	0.005795	1	47	1.857872884	1.1	0.011843011	
196	22.35524	-0.006105	1	46	1.840847112	1.1	-0.012362209	
197	22.35108	-0.004162	1	45	1.82382134	1.1	-0.008349819	
198	22.34824	-0.002839	1	44	1.809807345	1.1	-0.005651847	
199	22.3463	-0.00194	1	43	1.79579335	1.1	-0.003832223	
200	22.34497	-0.001328	1	42	1.781779355	1.1	-0.002602823	
201	22.34406	-0.000911	1	41	1.76776536	1.1	-0.001771478	
202	22.34343	-0.000628	1	40	1.753751365	1.1	-0.001211491	
203	22.343	-0.000435	1	39	1.73973737	1.1	-0.000832464	
204	22.34269	-0.000305	1	38	1.725723375	1.1	-0.00057898	
205	22.34248	-0.000215	1	37	1.711709381	1.1	-0.000404819	
206	22.34232	-0.000155	1	36	1.697695386	1.1	-0.000289457	
207	22.34221	-0.000115	1	35	1.683681391	1.1	-0.000212986	
208	22.34212	-8.7E-05	1	34	1.669667396	1.1	-0.000159787	
209	22.34205	-6.9E-05	1	33	1.655653401	1.1	-0.000125664	
210	22.342	-5.6E-05	1	32	1.641639406	1.1	-0.000101125	
211	22.34195	-4.8E-05	1	31	1.627625411	1.1	-8.59386E-05	
212	22.34191	-4.3E-05	1	30	1.613611416	1.1	-7.63238E-05	
213	22.34187	-3.9E-05	1	29	1.597794829	1.1	-6.85454E-05	

214	22.35508	0.013218	1	28	1.581978242	1.1	0.023001647	
215	22.36086	0.005778	1	27	1.566161655	1.1	0.00995421	
216	22.35474	-0.006127	1	26	1.550345067	1.1	-0.010448861	
217	22.35055	-0.004181	1	25	1.53452848	1.1	-0.00705745	
218	22.3477	-0.002858	1	24	1.518711893	1.1	-0.004774526	
219	22.34574	-0.001957	1	23	1.502895306	1.1	-0.003235283	
220	22.34439	-0.001345	1	22	1.487078719	1.1	-0.002200133	
221	22.34347	-0.000928	1	21	1.471262132	1.1	-0.001501864	
222	22.34282	-0.000644	1	20	1.455445545	1.1	-0.001031038	
223	22.34237	-0.000452	1	19	1.439122791	1.1	-0.000715532	
224	22.34205	-0.000321	1	18	1.422800037	1.1	-0.000502391	
225	22.34182	-0.000232	1	17	1.406477283	1.1	-0.000358933	
226	22.34164	-0.000173	1	16	1.390154529	1.1	-0.000264546	
227	22.34151	-0.00013	1	15	1.373831776	1.1	-0.000196458	
228	22.35467	0.013156	1	14	1.348217963	1.1	0.019510871	
229	22.3604	0.005729	1	13	1.32260415	1.1	0.008334919	
230	22.35423	-0.006168	1	12	1.296990337	1.1	-0.00879982	
231	22.35002	-0.004212	1	11	1.271376525	1.1	-0.005890542	
232	22.34714	-0.002882	1	10	1.245762712	1.1	-0.003949317	
233	22.34516	-0.001977	1	9	1.222764016	1.1	-0.002659145	
234	22.35706	0.0119	1	8	1.199765319	1.1	0.015704928	
235	22.36193	0.004871	1	7	1.176766623	1.1	0.006305233	
236	22.35518	-0.006756	1	6	1.153767927	1.1	-0.008574342	
237	22.35056	-0.004614	1	5	1.130769231	1.1	-0.005739106	
238	22.3474	-0.003157	1	4	1.101525199	1.1	-0.003825267	
239	22.34524	-0.002166	1	3	1.072281167	1.1	-0.002554817	
240	22.34379	-0.001452	1	2	1.043037135	1.1	-0.001665939	
241	22.99603	0.65224	1	1	1.013793103	1.1	0.727360055	
Total						1.1	106.8688255	***

Maximum size * design margin * aging factor = required battery size

106.869 * 1.05 * 1.2 = 134.655 Ah

2.4. Application 4

The required standby period for Application 4 is 120 minutes. The calculation starts two minutes prior the introduction of the inrush current, and ends two minutes after the momentary loads at the end of the required standby period.

2.4.1. **IEEE recommended sizing for approximated load profile without supercapacitor**

The largest load was observed during section 3 and therefore the table indicates this section.

Table 37: IEEE recommended practice for approximated load profile without supercapacitor, Application 4

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 3 - If A4 is greater than A3, go to section 4						1.1		
1	0	0	1	3	0.873596952	1.1	0	
2	0	0	1	2	0.838507878	1.1	0	
3	38.97	38.97	1	1	0.803418803	1.1	34.44015385	
Total						1.1	34.44015385	***

The required battery size is the product of the maximum section from the table above, the design margin, as well as the aging factor for NiCd batteries. For the above profile, the largest load value is observed in section 3, which is the section where the inrush current is introduced. For this reason, the entire calculation table is not shown.

The required battery for this application is therefore calculated as follows:
Maximum size * design margin * aging factor = required battery size

34.4402 * 1.05 * 1.2 = 43.3946 Ah

2.4.2. IEEE recommended sizing for approximated load profile with preliminary sized supercapacitor

The IEEE recommended calculation for this particular instance yields a borderline result. When a VTX1M65 battery's data table is used during the calculation, a battery of 46.711Ah is required. The VTX1M range has an available battery, VTX1M48, which has a rated capacity of 48Ah. When the calculation is repeated with the VTX1M48 data table, however, a battery of 49.14Ah is required. For this application, the VTX1M48 will be adequate and is selected as the required battery.

The largest load was observed during section 121 and therefore the table indicates this section.

Table 38: IEEE recommended practice for approximated load profile with supercapacitor, Application 4

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 121 - If A122 is greater than A121, go to section 122						1.1		
1	0	0	1	121	2.79189162	1.1	0	
2	27.37532	27.375316	1	120	2.781065089	1.1	83.74578918	
3	26.96919	-0.406128	1	119	2.764162625	1.1	-1.234864223	
4	26.2853	-0.683884	1	118	2.747260162	1.1	-2.066687996	
5	25.64055	-0.644755	1	117	2.730357699	1.1	-1.936452956	
6	25.03161	-0.608942	1	116	2.713455236	1.1	-1.817570544	
7	24.45586	-0.575743	1	115	2.696552772	1.1	-1.707773521	
8	23.91498	-0.540881	1	114	2.679650309	1.1	-1.594309133	
9	23.40223	-0.51275	1	113	2.662747846	1.1	-1.501856354	
10	22.91209	-0.490146	1	112	2.645845383	1.1	-1.426535584	
11	22.44658	-0.465503	1	111	2.628942919	1.1	-1.346158897	
12	22.00397	-0.442611	1	110	2.612040456	1.1	-1.271729622	
13	21.58656	-0.417414	1	109	2.595137993	1.1	-1.191571623	
14	21.18851	-0.39805	1	108	2.57823553	1.1	-1.128893318	
15	20.80513	-0.38338	1	107	2.561333066	1.1	-1.080160258	
16	20.43895	-0.36618	1	106	2.544430603	1.1	-1.024891558	
17	20.08882	-0.350127	1	105	2.52752814	1.1	-0.97345143	
18	19.7537	-0.335124	1	104	2.510625677	1.1	-0.925508011	

19	19.43261	-0.321084	1	103	2.493723213	1.1	-0.880764087	
20	19.12469	-0.307924	1	102	2.47682075	1.1	-0.838939808	
21	18.82912	-0.295573	1	101	2.459918287	1.1	-0.799793971	
22	18.54515	-0.283964	1	100	2.443015824	1.1	-0.7631014	
23	18.27212	-0.273038	1	99	2.42611336	1.1	-0.728663254	
24	18.00938	-0.262736	1	98	2.409210897	1.1	-0.696285078	
25	17.75637	-0.253014	1	97	2.392308434	1.1	-0.665816279	
26	17.51254	-0.243822	1	96	2.375405971	1.1	-0.637093858	
27	17.27742	-0.235123	1	95	2.358503507	1.1	-0.609992262	
28	17.0554	-0.222016	1	94	2.341601044	1.1	-0.571860187	
29	16.84071	-0.214697	1	93	2.324698581	1.1	-0.549016392	
30	16.63362	-0.207083	1	92	2.307796118	1.1	-0.525695878	
31	16.43313	-0.200496	1	91	2.290893654	1.1	-0.505246516	
32	16.23478	-0.198346	1	90	2.273991191	1.1	-0.496140762	
33	16.04288	-0.191904	1	89	2.257088728	1.1	-0.476458791	
34	15.85712	-0.185758	1	88	2.240186264	1.1	-0.457745772	
35	15.67723	-0.179887	1	87	2.223283801	1.1	-0.439933838	
36	15.50296	-0.174275	1	86	2.206381338	1.1	-0.422968818	
37	15.33406	-0.168903	1	85	2.189478875	1.1	-0.406790505	
38	15.1703	-0.163759	1	84	2.172576411	1.1	-0.391356835	
39	15.01147	-0.158828	1	83	2.155673948	1.1	-0.37661952	
40	14.85737	-0.154096	1	82	2.138771485	1.1	-0.362533744	
41	14.70782	-0.149555	1	81	2.121869022	1.1	-0.349069734	
42	14.56263	-0.14519	1	80	2.104966558	1.1	-0.336182104	
43	14.42163	-0.140995	1	79	2.088064095	1.1	-0.323847257	
44	14.28467	-0.136958	1	78	2.071161632	1.1	-0.31202837	
45	14.1516	-0.133072	1	77	2.054259169	1.1	-0.300700814	
46	14.02227	-0.12933	1	76	2.037356705	1.1	-0.289840477	
47	13.89655	-0.125721	1	75	2.020454242	1.1	-0.279414881	
48	13.77431	-0.122243	1	74	2.003551779	1.1	-0.269412198	
49	13.65542	-0.118886	1	73	1.986649316	1.1	-0.25980327	
50	13.54309	-0.112328	1	72	1.969746852	1.1	-0.243383497	
51	13.43356	-0.10953	1	71	1.952844389	1.1	-0.235284551	
52	13.32391	-0.109656	1	70	1.935941926	1.1	-0.233516413	
53	13.21718	-0.106728	1	69	1.919039463	1.1	-0.225296768	
54	13.11328	-0.103896	1	68	1.902136999	1.1	-0.217386868	
55	13.01213	-0.101158	1	67	1.885234536	1.1	-0.209777211	
56	12.91362	-0.098506	1	66	1.868332073	1.1	-0.202446111	
57	12.81768	-0.09594	1	65	1.85142961	1.1	-0.195388772	
58	12.72423	-0.093455	1	64	1.834527146	1.1	-0.188590308	
59	12.63318	-0.091047	1	63	1.817624683	1.1	-0.182038202	
60	12.54447	-0.088713	1	62	1.80072222	1.1	-0.175722217	
61	12.45801	-0.086451	1	61	1.783819756	1.1	-0.169634302	
62	12.37376	-0.084258	1	60	1.766917293	1.1	-0.163764609	
63	12.29163	-0.08213	1	59	1.770569835	1.1	-0.159958591	
64	12.21599	-0.075634	1	58	1.774222378	1.1	-0.147610689	

65	12.14516	-0.070831	1	57	1.77787492	1.1	-0.138521524	
66	12.07176	-0.073406	1	56	1.781527462	1.1	-0.143852285	
67	11.99718	-0.07458	1	55	1.785180004	1.1	-0.146452597	
68	11.92444	-0.072736	1	54	1.788832546	1.1	-0.143123777	
69	11.85349	-0.070945	1	53	1.792485089	1.1	-0.13988464	
70	11.78429	-0.069206	1	52	1.796137631	1.1	-0.136733851	
71	11.71677	-0.067516	1	51	1.799790173	1.1	-0.133666097	
72	11.6509	-0.065872	1	50	1.803442715	1.1	-0.130676016	
73	11.58663	-0.064275	1	49	1.807095258	1.1	-0.127766152	
74	11.5239	-0.062723	1	48	1.8107478	1.1	-0.124933088	
75	11.46269	-0.061212	1	47	1.814400342	1.1	-0.122169381	
76	11.40295	-0.059744	1	46	1.818052884	1.1	-0.119479527	
77	11.34463	-0.058315	1	45	1.821705426	1.1	-0.116856027	
78	11.28771	-0.056924	1	44	1.805052155	1.1	-0.113025868	
79	11.23213	-0.055573	1	43	1.788398883	1.1	-0.10932536	
80	11.17788	-0.054256	1	42	1.771745612	1.1	-0.105740613	
81	11.1249	-0.052974	1	41	1.755092341	1.1	-0.102271688	
82	11.07318	-0.051728	1	40	1.738439069	1.1	-0.098918574	
83	11.02266	-0.050514	1	39	1.721785798	1.1	-0.095671717	
84	10.97333	-0.049331	1	38	1.705132526	1.1	-0.092527482	
85	10.92515	-0.048181	1	37	1.688479255	1.1	-0.089487881	
86	10.87809	-0.047059	1	36	1.671825983	1.1	-0.086541905	
87	10.83212	-0.045967	1	35	1.655172712	1.1	-0.083691656	
88	10.78722	-0.044904	1	34	1.63851944	1.1	-0.080933685	
89	10.74335	-0.043868	1	33	1.621866169	1.1	-0.078262828	
90	10.70049	-0.042858	1	32	1.605212897	1.1	-0.075675836	
91	10.65862	-0.041875	1	31	1.588559626	1.1	-0.073173028	
92	10.6177	-0.040917	1	30	1.571906355	1.1	-0.070749462	
93	10.57772	-0.039982	1	29	1.551741958	1.1	-0.068245922	
94	10.53865	-0.039073	1	28	1.531577562	1.1	-0.065827663	
95	10.50046	-0.038186	1	27	1.511413165	1.1	-0.063486305	
96	10.46314	-0.037321	1	26	1.491248769	1.1	-0.061220385	
97	10.42666	-0.036479	1	25	1.471084373	1.1	-0.059030056	
98	10.391	-0.035657	1	24	1.450919976	1.1	-0.056908999	
99	10.35615	-0.034856	1	23	1.43075558	1.1	-0.054857458	
100	10.32207	-0.034076	1	22	1.410591183	1.1	-0.052874036	
101	10.28876	-0.033315	1	21	1.390426787	1.1	-0.050954275	
102	10.25618	-0.032573	1	20	1.370262391	1.1	-0.049096913	
103	10.22434	-0.031849	1	19	1.35095246	1.1	-0.047329133	
104	10.19319	-0.031143	1	18	1.331642529	1.1	-0.045618478	
105	10.16274	-0.030456	1	17	1.312332599	1.1	-0.043965242	
106	10.13295	-0.029785	1	16	1.293022668	1.1	-0.042363948	
107	10.10382	-0.029131	1	15	1.273712737	1.1	-0.040814978	
108	10.07533	-0.028493	1	14	1.248238482	1.1	-0.039122665	
109	10.05174	-0.023583	1	13	1.222764228	1.1	-0.031720094	
110	10.02834	-0.023402	1	12	1.197289973	1.1	-0.030820878	

111	10.00148	-0.02686	1	11	1.171815718	1.1	-0.034622467	
112	9.975205	-0.026277	1	10	1.146341463	1.1	-0.033134656	
113	9.949494	-0.025711	1	9	1.105828191	1.1	-0.031275143	
114	9.924336	-0.025158	1	8	1.065314918	1.1	-0.029481312	
115	9.899718	-0.024618	1	7	1.024801646	1.1	-0.027751424	
116	9.875625	-0.024093	1	6	0.984288373	1.1	-0.026085906	
117	9.852046	-0.023579	1	5	0.9437751	1.1	-0.0244786	
118	9.828966	-0.02308	1	4	0.908686026	1.1	-0.023069721	
119	9.806374	-0.022592	1	3	0.873596952	1.1	-0.021709933	
120	9.787386	-0.018988	1	2	0.838507878	1.1	-0.017513746	
121	9.804633	0.017247	1	1	0.803418803	1.1	0.015242221	
Total						1.1	39.00620773	***

Maximum size * design margin * aging factor = required battery size

39.006 * 1.05 * 1.2 = 49.1478 Ah

2.4.3. **IEEE recommended sizing for approximated load profile with undersized supercapacitor**

The largest load was observed during section 121 and therefore the table indicates this section.

Table 39: IEEE recommended practice for approximated load profile with undersized supercapacitor, Application 4

1	2	3	4	5	6	7	8	
Period	Load (amp)	Change in Load (amp)	Duration (minutes)	Time to end of section (minutes)	Capacity rating Factor (Kt)	Temp derating factor (Tt)	Required size (3)x(6)x(7) (Rated Ah) Pos	
Section 121 - If A122 is greater than A121, go to section 122						1.1		
1	0	0	1	121	2.791116088	1.1	0	
2	27.51393	27.513934	1	120	2.780141844	1.1	84.14190313	
3	24.99975	-2.514188	1	119	2.76855792	1.1	-7.656742609	
4	18.19617	-6.803576	1	118	2.756973995	1.1	-20.63301032	
5	14.59318	-3.602992	1	117	2.745390071	1.1	-10.88078031	
6	12.47221	-2.120964	1	116	2.733806147	1.1	-6.378134862	
7	11.16509	-1.307121	1	115	2.722222222	1.1	-3.914101217	
8	10.39717	-0.767919	1	114	2.710638298	1.1	-2.289705716	
9	9.894926	-0.502248	1	113	2.699054374	1.1	-1.491154127	
10	9.532928	-0.361998	1	112	2.687470449	1.1	-1.07014482	
11	9.300958	-0.23197	1	111	2.675886525	1.1	-0.682797937	
12	9.152324	-0.148634	1	110	2.6643026	1.1	-0.435606548	

13	9.111637	-0.040687	1	109	2.652718676	1.1	-0.118724281	
14	9.072917	-0.03872	1	108	2.641134752	1.1	-0.112491211	
15	9.008182	-0.064735	1	107	2.629550827	1.1	-0.18724637	
16	8.9673	-0.040882	1	106	2.617966903	1.1	-0.117730495	
17	8.941818	-0.025482	1	105	2.606382979	1.1	-0.073057436	
18	8.926278	-0.01554	1	104	2.594799054	1.1	-0.044355495	
19	8.917147	-0.009131	1	103	2.58321513	1.1	-0.025946071	
20	8.912138	-0.005009	1	102	2.571631206	1.1	-0.014169431	
21	8.909767	-0.002371	1	101	2.560047281	1.1	-0.006676859	
22	8.909074	-0.000693	1	100	2.548463357	1.1	-0.001942694	
23	8.909436	0.000362	1	99	2.536879433	1.1	0.001010185	
24	8.910451	0.001015	1	98	2.525295508	1.1	0.002819492	
25	8.911859	0.001408	1	97	2.513711584	1.1	0.003893237	
26	8.913493	0.001634	1	96	2.50212766	1.1	0.004497324	
27	8.915247	0.001754	1	95	2.490543735	1.1	0.004805255	
28	8.991504	0.076257	1	94	2.478959811	1.1	0.207941842	
29	9.023104	0.0316	1	93	2.467375887	1.1	0.085765986	
30	9.062796	0.039692	1	92	2.455791962	1.1	0.107222824	
31	9.070585	0.007789	1	91	2.444208038	1.1	0.02094173	
32	9.020191	-0.050394	1	90	2.432624113	1.1	-0.134848626	
33	8.988092	-0.032099	1	89	2.421040189	1.1	-0.085484266	
34	8.967803	-0.020289	1	88	2.409456265	1.1	-0.053774004	
35	8.955146	-0.012657	1	87	2.39787234	1.1	-0.033384857	
36	8.947417	-0.007729	1	86	2.386288416	1.1	-0.020287985	
37	8.942865	-0.004552	1	85	2.374704492	1.1	-0.01189062	
38	8.940354	-0.002511	1	84	2.363120567	1.1	-0.006527175	
39	8.939149	-0.001205	1	83	2.351536643	1.1	-0.003116962	
40	8.938775	-0.000374	1	82	2.339952719	1.1	-0.000962657	
41	8.938923	0.000148	1	81	2.328368794	1.1	0.000379058	
42	8.939394	0.000471	1	80	2.31678487	1.1	0.001200326	
43	8.940059	0.000665	1	79	2.305200946	1.1	0.001686254	
44	8.940836	0.000777	1	78	2.293617021	1.1	0.001960354	
45	8.941671	0.000835	1	77	2.282033097	1.1	0.002096047	
46	8.942531	0.00086	1	76	2.270449173	1.1	0.002147845	
47	8.943394	0.000863	1	75	2.258865248	1.1	0.002144341	
48	8.944246	0.000852	1	74	2.247281324	1.1	0.002106152	
49	8.945081	0.000835	1	73	2.2356974	1.1	0.002053488	
50	9.000585	0.055504	1	72	2.224113475	1.1	0.135791914	
51	9.023228	0.022643	1	71	2.212529551	1.1	0.055108137	
52	8.99705	-0.026178	1	70	2.200945626	1.1	-0.06337799	
53	8.980334	-0.016716	1	69	2.189361702	1.1	-0.040257107	
54	8.969726	-0.010608	1	68	2.177777778	1.1	-0.025412053	
55	8.963066	-0.00666	1	67	2.166193853	1.1	-0.015869536	
56	8.958958	-0.004108	1	66	2.154609929	1.1	-0.009736251	
57	8.956495	-0.002463	1	65	2.143026005	1.1	-0.0058061	
58	8.955089	-0.001406	1	64	2.13144208	1.1	-0.003296488	

59	8.954362	-0.000727	1	63	2.119858156	1.1	-0.001695251	
60	8.954067	-0.000295	1	62	2.108274232	1.1	-0.000684135	
61	8.954044	-2.3E-05	1	61	2.096690307	1.1	-5.30463E-05	
62	8.954191	0.000147	1	60	2.085106383	1.1	0.000337162	
63	8.954444	0.000253	1	59	2.067649678	1.1	0.000575427	
64	9.029577	0.075133	1	58	2.050192974	1.1	0.169440864	
65	9.114632	0.085055	1	57	2.032736269	1.1	0.190183822	
66	9.09997	-0.014662	1	56	2.015279565	1.1	-0.032502832	
67	9.049449	-0.050521	1	55	1.99782286	1.1	-0.11102521	
68	9.016865	-0.032584	1	54	1.980366155	1.1	-0.070981076	
69	8.995873	-0.020992	1	53	1.962909451	1.1	-0.045325935	
70	8.982381	-0.013492	1	52	1.945452746	1.1	-0.028872853	
71	8.973744	-0.008637	1	51	1.927996042	1.1	-0.018317312	
72	8.968248	-0.005496	1	50	1.910539337	1.1	-0.011550357	
73	8.964784	-0.003464	1	49	1.893082632	1.1	-0.007213402	
74	8.962632	-0.002152	1	48	1.875625928	1.1	-0.004439982	
75	8.961327	-0.001305	1	47	1.858169223	1.1	-0.002667402	
76	8.960566	-0.000761	1	46	1.840712519	1.1	-0.00154086	
77	8.960154	-0.000412	1	45	1.823255814	1.1	-0.0008263	
78	8.959964	-0.00019	1	44	1.806658572	1.1	-0.000377592	
79	8.959915	-4.9E-05	1	43	1.790061331	1.1	-9.64843E-05	
80	8.959954	3.9E-05	1	42	1.773464089	1.1	7.60816E-05	
81	8.960045	9.1E-05	1	41	1.756866847	1.1	0.000175862	
82	8.960168	0.000123	1	40	1.740269606	1.1	0.000235458	
83	8.960308	0.00014	1	39	1.723672364	1.1	0.000265446	
84	8.960456	0.000148	1	38	1.707075122	1.1	0.000277912	
85	8.960607	0.000151	1	37	1.690477881	1.1	0.000280788	
86	8.960755	0.000148	1	36	1.673880639	1.1	0.000272508	
87	8.9609	0.000145	1	35	1.657283397	1.1	0.000264337	
88	8.96104	0.00014	1	34	1.640686155	1.1	0.000252666	
89	8.961174	0.000134	1	33	1.624088914	1.1	0.000239391	
90	8.961301	0.000127	1	32	1.607491672	1.1	0.000224567	
91	8.961422	0.000121	1	31	1.59089443	1.1	0.000211748	
92	8.961537	0.000115	1	30	1.574297189	1.1	0.000199149	
93	8.961645	0.000108	1	29	1.553930407	1.1	0.000184607	
94	8.961747	0.000102	1	28	1.533563625	1.1	0.000172066	
95	8.961842	9.5E-05	1	27	1.513196843	1.1	0.000158129	
96	8.961931	8.9E-05	1	26	1.492830062	1.1	0.000146148	
97	8.962015	8.4E-05	1	25	1.47246328	1.1	0.000136056	
98	8.962093	7.8E-05	1	24	1.452096498	1.1	0.00012459	
99	8.962165	7.2E-05	1	23	1.431729716	1.1	0.000113393	
100	8.962231	6.6E-05	1	22	1.411362934	1.1	0.000102465	
101	8.962293	6.2E-05	1	21	1.390996152	1.1	9.48659E-05	
102	8.962349	5.6E-05	1	20	1.370629371	1.1	8.44308E-05	
103	8.962401	5.2E-05	1	19	1.351048951	1.1	7.728E-05	
104	8.962448	4.7E-05	1	18	1.331468531	1.1	6.88369E-05	

105	8.96249	4.2E-05	1	17	1.311888112	1.1	6.06092E-05	
106	8.962527	3.7E-05	1	16	1.292307692	1.1	5.25969E-05	
107	8.962561	3.4E-05	1	15	1.272727273	1.1	4.76E-05	
108	8.962592	3.1E-05	1	14	1.247421584	1.1	4.25371E-05	
109	9.037527	0.074935	1	13	1.222115896	1.1	0.10073718	
110	9.067429	0.029902	1	12	1.196810207	1.1	0.039365721	
111	9.030539	-0.03689	1	11	1.171504519	1.1	-0.047538482	
112	9.006666	-0.023873	1	10	1.14619883	1.1	-0.030099525	
113	8.991197	-0.015469	1	9	1.105874727	1.1	-0.018817454	
114	8.981171	-0.010026	1	8	1.065550624	1.1	-0.011751532	
115	8.97467	-0.006501	1	7	1.02522652	1.1	-0.007331497	
116	8.970453	-0.004217	1	6	0.984902417	1.1	-0.004568667	
117	8.967716	-0.002737	1	5	0.944578313	1.1	-0.002843842	
118	8.965936	-0.00178	1	4	0.909665768	1.1	-0.001781126	
119	8.964778	-0.001158	1	3	0.874753222	1.1	-0.001114261	
120	9.018863	0.054085	1	2	0.839840677	1.1	0.049965061	
121	9.675499	0.656636	1	1	0.804928131	1.1	0.581399267	
Total						1.1	28.81155365	***

Maximum size * design margin * aging factor = required battery size

28.8116 * 1.05 * 1.2 = 36.303 Ah

3. APPENDIX C

This section details the calculations of the preliminary supercapacitors required for application 2 through application 4. The method as explained in section 2.3.2 is used complete the said calculations.

3.1. Application 2

Table 40 indicates the parameters required from application 2 for the purpose of calculating an adequately sized supercapacitor. The required power is derived from the relevant load profile.

Table 40: Parameters for preliminary sizing of supercapacitor for approximated profile, Application 2

Variable	Description
V_{max}	28.8 (V)
V_w	24 (V)
V_{min}	22.6 (V)
Power	83.643 x 24 = 2007.432 (W)
Δ_t	60 (s)

V_w is the operating voltage at the beginning of discharge. In this study, this value will be equal to V_{max}. V_w is the nominal voltage of the system.

$$\Delta \boldsymbol{V} = \boldsymbol{V_w} - \boldsymbol{V_{min}} \tag{7.1}$$

$$\Delta V = 6.2\ V$$

$$\boldsymbol{i_{max}} = \frac{\boldsymbol{Power}}{\boldsymbol{V_{min}}} \tag{7.2}$$

$$i_{max} = 88.824\ A$$

$$\boldsymbol{i_{min}} = \frac{\boldsymbol{Power}}{\boldsymbol{V_{max}}} \tag{7.3}$$

$$i_{max} = 69.703\ A$$

$$\boldsymbol{i_{avg}} = \frac{\boldsymbol{i_{max}} + \boldsymbol{i_{min}}}{\boldsymbol{2}} \tag{7.4}$$

$$i_{avg} = 79.263\ A$$

As the required size supercapacitor is unknown at this point, a value of 1 second is used for the RC constant.

$$\boldsymbol{\tau = R \cdot C = 1} \tag{7.5}$$

$$R = \frac{1}{C}$$

Having all the variables defined, C can be solved as follows:

$$\boldsymbol{dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot R} \tag{7.6}$$

$$dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot \frac{1}{C}$$

$$dV = \frac{i_{avg}}{C}(dt + 1)$$

$$C = \frac{i_{avg}}{dV}(dt + 1)$$

$$C = \frac{79.263}{6.2}(60 + 1)$$

$$C = 779.848\ F$$

For this study, the Maxwell range of supercapacitors is considered. The MC series of cells has a cell voltage of 2.7 V. The required number of cells then becomes:

$$Number\ of\ series\ cells = \frac{28.8}{2.7}$$

$$Number\ of\ series\ cells = \ 10.667$$

$$\therefore Number\ of\ series\ cells = \ 11$$

$$\boldsymbol{C_{Total} = C_{Cell} \cdot \frac{nCells_p}{nCells_s}} \tag{7.7}$$

$$C_{cell} = C_{Total} \cdot \frac{nCells_s}{nCells_p}$$

$$C_{cell} = 779.848 \cdot \frac{11}{1}$$

$$C_{cell} = 8578.329\ \mathrm{F}$$

The available supercapacitor in the Maxwell range is either the BCAP3000, with rated capacitance of 3000F, or the BCAP2000, with rated capacitance of 2000F. The above calculation therefore has to be revisited.

$$\boldsymbol{C_{Total}} = \boldsymbol{C_{Cell}} \cdot \frac{\boldsymbol{nCells_p}}{\boldsymbol{nCells_s}} \tag{7.8}$$

$$C_{cell} = 779.848 \cdot \frac{11}{3}$$

$$C_{cell} = 2859.443 \text{ F}$$

The BCAP3000 capacitor has an ESR value of 0.29mΩ. The process above is repeated with the actual capacitor values in order to verify the selected capacitor.

$$BCAP3000\ cell\ capacitance = 3000\ F$$

$$Number\ of\ series\ cells = \ 11$$

$$Number\ of\ parallel\ cells = \ 3$$

$$Total\ stack\ capacitance = \frac{3000\ \cdot 3}{11}$$

$$Total\ stack\ capacitance = \ 818.1818$$

$$BCAP3000\ cell\ resistance = 0.00029\ \Omega$$

$$Total\ stack\ resistance = \frac{0.00029\ \cdot 11}{3}$$

$$Total\ stack\ resistance = \ 0.00106\ \Omega$$

$$\boldsymbol{dV} = \boldsymbol{i_{avg}} \cdot \frac{\boldsymbol{dt}}{\boldsymbol{C}} + \boldsymbol{i_{avg}} \cdot \boldsymbol{R} \tag{7.9}$$

$$dV = 79.263 \cdot \frac{60}{818.1818} + 79.263 \cdot 0.00106$$

$$dV = 5.897$$

The original $\Delta V = 6.2\,V$. The calculated required capacitor has 95.11% of the allowed voltage drop.

BCAP3000 time constant is given by

$$\tau = 3000 \cdot \frac{3}{11} \cdot 0.00029$$

$$\tau = 0.2373$$

$$\tau = R \cdot C$$

$$R = \frac{0.2373}{C}$$

$$\boldsymbol{dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot R} \tag{7.10}$$

$$dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot \frac{0.2373}{C}$$

$$dV = \frac{i_{avg}}{C}(dt + 0.2373)$$

$$C = \frac{i_{avg}}{dV}(dt + 0.2373)$$

$$C = 770.095\ F$$

$$Number\ of\ series\ cells = \ 11$$

$$Number\ of\ parallel\ cells = \ 3$$

$$\boldsymbol{C_{cell} = C_{Total} \cdot \frac{nCells_s}{nCells_p}} \tag{7.11}$$

$$C_{cell} = 770.095 \cdot \frac{11}{3}$$

$$C_{cell} = 2823.682\ \mathrm{F}$$

It can be concluded that 11 series, and 3 parallel BCAP3000 supercapacitors is the optimum supercapacitor stack for approximated profile of application 2.

3.2. Application 3

Table 41 indicates the parameters required from application 3 for the purpose of calculating an adequately sized supercapacitor. The required power is derived from the relevant load profile.

Table 41: Parameters for preliminary sizing of supercapacitor for approximated profile, Application 3

Variable	Description
V_{max}	28.8 (V)
V_w	24 (V)
V_{min}	22.6 (V)

Power	82.358 x 24 = 1976.592 (W)
Δ_t	60 (s)

V_w is the operating voltage at the beginning of discharge. In this study, this value will be equal to V_{max}. V_w is the nominal voltage of the system.

$$\boldsymbol{\Delta V = V_w - V_{min}} \tag{7.12}$$
$$\Delta V = 6.2\,V$$

$$\boldsymbol{i_{max} = \frac{Power}{V_{min}}} \tag{7.13}$$
$$i_{max} = 87.46\,A$$

$$\boldsymbol{i_{min} = \frac{Power}{V_{max}}} \tag{7.14}$$
$$i_{max} = 68.632\,A$$

$$\boldsymbol{i_{avg} = \frac{i_{max} + i_{min}}{2}} \tag{7.15}$$
$$i_{avg} = 78.046\,A$$

As the required size supercapacitor is unknown at this point, a value of 1 second is used for the RC constant.

$$\boldsymbol{\tau = R \cdot C = 1} \tag{7.16}$$
$$R = \frac{1}{C}$$

Having all the variables defined, C can be solved as follows:

$$\boldsymbol{dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot R} \tag{7.17}$$
$$dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot \frac{1}{C}$$
$$dV = \frac{i_{avg}}{C}(dt + 1)$$
$$C = \frac{i_{avg}}{dV}(dt + 1)$$
$$C = \frac{78.046}{6.2}(60 + 1)$$

$C = 767.87\ F$

For this study, the Maxwell range of supercapacitors is considered. The MC series of cells has a cell voltage of 2.7 V. The required number of cells then becomes:

$$Number\ of\ series\ cells = \frac{28.8}{2.7}$$

$$Number\ of\ series\ cells = \ 10.667$$

$$\therefore Number\ of\ series\ cells = \ 11$$

$$\boldsymbol{C_{Total}} = \boldsymbol{C_{Cell}} \cdot \frac{\boldsymbol{nCells_p}}{\boldsymbol{nCells_s}} \tag{7.18}$$

$$C_{cell} = C_{Total} \cdot \frac{nCells_s}{nCells_p}$$

$$C_{cell} = 767.87 \cdot \frac{11}{1}$$

$$C_{cell} = 8446.573\ \mathrm{F}$$

The available supercapacitor in the Maxwell range is either the BCAP3000, with rated capacitance of 3000F, or the BCAP2000, with rated capacitance of 2000F. The above calculation therefore has to be revisited.

$$\boldsymbol{C_{Total}} = \boldsymbol{C_{Cell}} \cdot \frac{\boldsymbol{nCells_p}}{\boldsymbol{nCells_s}} \tag{7.19}$$

$$C_{cell} = 767.87 \cdot \frac{11}{3}$$

$$C_{cell} = 2815.524\ \mathrm{F}$$

The BCAP3000 capacitor has an ESR value of 0.29mΩ. The process above is repeated with the actual capacitor values in order to verify the selected capacitor.

$$BCAP3000\ cell\ capacitance = 3000\ F$$

$$Number\ of\ series\ cells = \ 11$$

$$Number\ of\ parallel\ cells = \ 3$$

$$Total\ stack\ capacitance = \frac{3000\ \cdot 3}{11}$$

$$Total\ stack\ capacitance = \ 818.1818$$

$BCAP3000\ cell\ resistance = 0.00029\ \Omega$

$Total\ stack\ resistance = \dfrac{0.00029\ \cdot 11}{3}$

$Total\ stack\ resistance = \ 0.00106\ \Omega$

$$\boldsymbol{dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot R} \tag{7.20}$$

$dV = 78.046\ \cdot \dfrac{60}{818.1818} + 78.046\ \cdot 0.00106$

$dV = 5.723 + 0.0827$

$dV = 5.806$

The original $\Delta V = 6.2\,V$. The calculated required capacitor has 93.64% of the allowed voltage drop.

BCAP3000 time constant is given by

$\tau = 3000 \cdot \dfrac{3}{11} \cdot 0.00029$

$\tau = 0.2373$

$\tau = R \cdot C$

$R = \dfrac{0.2373}{C}$

$$\boldsymbol{dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot R} \tag{7.21}$$

$dV = i_{avg} \cdot \dfrac{dt}{C} + i_{avg} \cdot \dfrac{0.2373}{C}$

$dV = \dfrac{i_{avg}}{C}(dt + 0.2373)$

$C = \dfrac{i_{avg}}{dV}(dt + 0.2373)$

$C = \dfrac{78.046}{6.2}(60 + 0.2373)$

$C = 758.271\ F$

$Number\ of\ series\ cells = \ \ 11$

$Number\ of\ parallel\ cells = \ \ 3$

$$\boldsymbol{C_{cell}} = \boldsymbol{C_{Total}} \cdot \frac{\boldsymbol{nCells_s}}{\boldsymbol{nCells_p}} \tag{7.22}$$

$$C_{cell} = 758.271 \cdot \frac{11}{3}$$

$$C_{cell} = 2780.327 \text{ F}$$

It can be concluded that 11 series, and 3 parallel BCAP3000 supercapacitors is the optimum supercapacitor stack for approximated profile of application 3.

3.3. Application 4

Table 42 indicates the parameters required from application 4 for the purpose of calculating an adequately sized supercapacitor. The required power is derived from the relevant load profile.

Table 42: Parameters for preliminary sizing of supercapacitor for approximated profile, Application 4

Variable	Description
V_{max}	28.8 (V)
V_w	24 (V)
V_{min}	22.6 (V)
Power	38.97 x 24 = 935.28 (W)
Δ_t	60 (s)

V_w is the operating voltage at the beginning of discharge. In this study, this value will be equal to V_{max}. V_w is the nominal voltage of the system.

$$\Delta\boldsymbol{V} = \boldsymbol{V_w} - \boldsymbol{V_{min}} \tag{7.23}$$

$$\Delta V = 6.2\, V$$

$$\boldsymbol{i_{max}} = \frac{\boldsymbol{Power}}{\boldsymbol{V_{min}}} \tag{7.24}$$

$$i_{max} = 41.384\, A$$

$$\boldsymbol{i_{min}} = \frac{\boldsymbol{Power}}{\boldsymbol{V_{max}}} \tag{7.25}$$

$$i_{max} = 32.475\, A$$

$$\boldsymbol{i_{avg}} = \frac{\boldsymbol{i_{max}} + \boldsymbol{i_{min}}}{\mathbf{2}} \tag{7.26}$$

$$i_{avg} = 36.9295\, A$$

As the required size supercapacitor is unknown at this point, a value of 1 second is used for the RC constant.

$$\boldsymbol{\tau = R \cdot C = 1} \tag{7.27}$$

$$R = \frac{1}{C}$$

Having all the variables defined, C can be solved as follows:

$$\boldsymbol{dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot R} \tag{7.28}$$

$$dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot \frac{1}{C}$$

$$dV = \frac{i_{avg}}{C}(dt + 1)$$

$$C = \frac{i_{avg}}{dV}(dt + 1)$$

$$C = \frac{36.9295}{6.2}(60 + 1)$$

$$C = 363.339\, F$$

For this study, the Maxwell range of supercapacitors is considered. The MC series of cells has a cell voltage of 2.7 V. The required number of cells then becomes:

$$Number\ of\ series\ cells = \frac{28.8}{2.7}$$

$$Number\ of\ series\ cells = 10.667$$

$$\therefore Number\ of\ series\ cells = 11$$

$$\boldsymbol{C_{Total} = C_{Cell} \cdot \frac{nCells_p}{nCells_s}} \tag{7.29}$$

$$C_{cell} = 363.339 \cdot \frac{11}{1}$$

$$C_{cell} = 3996.725\ \mathrm{F}$$

The available supercapacitor in the Maxwell range is either the BCAP3000, with rated capacitance of 3000F, or the BCAP2000, with rated capacitance of 2000F. The above calculation therefore has to be revisited.

$$\boldsymbol{C_{Total}} = \boldsymbol{C_{Cell}} \cdot \frac{\boldsymbol{nCells_p}}{\boldsymbol{nCells_s}} \tag{7.30}$$

$$C_{cell} = 363.339 \cdot \frac{11}{2}$$

$$C_{cell} = 1998.362 \text{ F}$$

The BCAP2000 capacitor has an ESR value of 0.35mΩ. The process above is repeated with the actual capacitor values in order to verify the selected capacitor.

$$BCAP2000\ cell\ capacitance = 2000\ F$$

$$Number\ of\ series\ cells = \ 11$$

$$Number\ of\ parallel\ cells = \ 2$$

$$Total\ stack\ capacitance = \frac{2000\ \cdot 2}{11}$$

$$Total\ stack\ capacitance = \ 363.636$$

$$BCAP2000\ cell\ resistance = 0.00035\ \Omega$$

$$Total\ stack\ resistance = \frac{0.00035\ \cdot 11}{2}$$

$$Total\ stack\ resistance = \ 0.001925\ \Omega$$

$$\boldsymbol{dV} = \boldsymbol{i_{avg}} \cdot \frac{\boldsymbol{dt}}{\boldsymbol{C}} + \boldsymbol{i_{avg}} \cdot \boldsymbol{R} \tag{7.31}$$

$$dV = \ 36.9295 \cdot \frac{60}{363.339} + \ 36.9295 \cdot 0.001925$$

$$dV = 6.0984 + 0.07109$$

$$dV = 6.1695$$

The original $\Delta V = 6.2\,V$. The calculated required capacitor has 99.51% of the allowed voltage drop.

BCAP2000 time constant is given by

$$\tau = 2000 \cdot \frac{2}{11} \cdot 0.00035$$

$$\tau = 0.1273$$

$$\tau = R \cdot C$$

$$R = \ \frac{0.1273}{C}$$

$$\boldsymbol{dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot R} \tag{7.32}$$

$$dV = i_{avg} \cdot \frac{dt}{C} + i_{avg} \cdot \frac{0.1273}{C}$$

$$dV = \frac{i_{avg}}{C}(dt + 0.1273)$$

$$C = \frac{i_{avg}}{dV}(dt + 0.1273)$$

$$C = \frac{36.9295}{6.2}(60 + 0.1273)$$

$$C = 358.141\ F$$

$$Number\ of\ series\ cells = \ \ 11$$

$$Number\ of\ parallel\ cells = \ \ 2$$

$$\boldsymbol{C_{cell} = C_{Total} \cdot \frac{nCells_s}{nCells_p}} \tag{7.33}$$

$$C_{cell} = 358.141 \cdot \frac{11}{2}$$

$$C_{cell} = 1969.773\ \mathrm{F}$$

It can be concluded that 11 series, and 2 parallel BCAP2000 supercapacitors is the optimum supercapacitor stack for approximated profile of application 4.

4. APPENDIX D

This section indicates the raw data obtained from the questionnaires, as completed by industry experts. The intended outcome of the questionnaire is to obtain input from industry experts and use the data for validation purposes.

4.1. Completed questionnaire from expert 1

Battery sizing IEEE 485, 1115 Lead-acid
Nickel-cad

STRUCTURED QUESTIONNAIRE FOR THE PURPOSE OF QUALITATIVE RESEARCH

Preface

Thank you

I would like to thank you in advance for taking the time and completing this questionnaire. Your inputs and comments will go a long way in making this research project a success. I appreciate that everyone has very busy schedules, and therefore your efforts in this regard are especially appreciated.

Kind regards,
Ruan Pekelharing

Introduction

The questions in this questionnaire are pertaining to the design, and specifically the battery sizing, of auxiliary power systems for a DC control and automation system. When using the IEEE recommended practice for sizing batteries, a defined load profile of the system is required. In the case where no specific load profile is defined, it is common practice to use the worst case load the system may experience at any given time.

A typical load profile consists of an initial momentary load, followed by the continuous system load. A final momentary load is typically experienced during the final minute of discharge. The initial momentary load is caused by equipment suddenly changing state as the AC power of the system is lost. This final momentary load is caused by equipment suddenly changing state as the system prepares for shutdown, or as the system regains AC power. The continuous load is observed during normal operations.

A typical control and automation system consists of controllers, network switches, relays, and solenoids. These equipment and devices are used to control the operation of devices such as drives, valves, actuators, etc. It is important to note that the load required to energize these last mentioned devices, does not form part of the control and automation load. Only the collective loads of the control equipment (relays, solenoids, etc.) are considered.

A control and automation system is dynamic of nature, and it is therefore very difficult to define its load profile as an absolute certainty. Devices such as drives, valves and actuators are stopped and started as the process requires. This start and stop actions create a fluctuation in the continuous load section of the load profile.

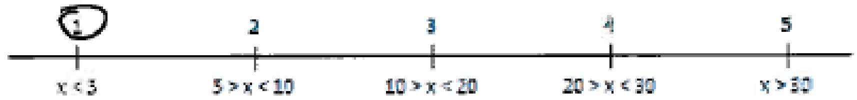
Supercapacitors have good power densities, which make them suitable to provide energy during short power peaks. Supercapacitors may, therefore, prove advantages during momentary loads, as well fluctuating loads. The aim of the research project is to test the feasibility of using supercapacitors in conjunction with batteries, in order to potentially decrease the required battery size. The influence of the supercapacitor is tested on the initial and final momentary loads, as well the continuous loads.

For this study, live plant measurements cannot be taken for the purpose of defining load profiles. Typically, the worst case load profile is assumed during these situations. Testing the influence of a supercapacitor during the fluctuating loads of the dynamic process, however, requires more detailed load profiles.

To obtain more detailed load profiles, probabilistic load profiles from plant operating procedures were created during the study. The aim of this questionnaire is get the opinions and input from leading experts in the field to determine the validity of the reasoning used during the Load profile definition, as well as the validity of the probabilistic load profiles that were created.

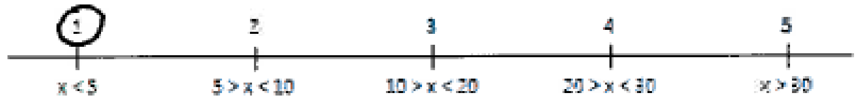
QUESTION 1a:

Indicate on the scale below how many auxiliary DC systems you have had exposure to throughout your career.



QUESTION 1b:

Indicate on the scale below how many control and automation systems you have had exposure to throughout your career.



QUESTION 2a:

Figure 1 illustrates a typical DC load profile found in industry. The value "C", represents the static, or continuous load of the system. The factors indicated in the figure represent the relationship of the momentary loads in relation to the continuous load. On the scale provided, please indicate the accuracy of these factors.

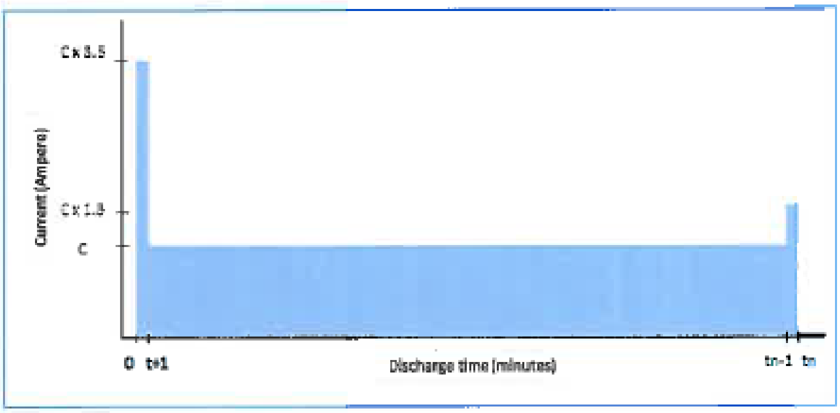
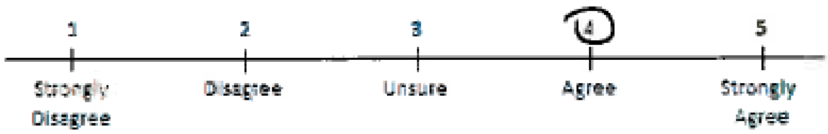


Figure 1: Typical load profile



QUESTION 2b:

If you disagree with any of the statements or values in Figure 1, please indicate what you are in disagreement about. Please also elaborate on your answer.

Comment only: A duty cycle diagram would be more informative than a load profile

QUESTION 3:

When sizing a new auxiliary system for a dynamic process, and a specific load profile is not defined, it is assumed that all equipment and devices in the system can be active or energized at any given moment. The continuous load is therefore determined by calculating the collective loads of all the equipment and devices that are present in the system.

1	2	3	4	5
Strongly Disagree	Disagree	Unsure	Agree	Strongly Agree

Section 4.2. (IEEE 485) requires (recommends) that a load profile is created. In the dynamic process then, classification for continuous and non-continuous loads supports better load profiling. Momentary loading can be assumed to all become active, and it should be loaded onto this profile on the worst case scenario.

QUESTION 4:

In the example below, a load profile for a dynamic process is simulated using the process operating philosophies. From the simulation, a probabilistic load profile for the example is approximated. Figure 2 illustrates equipment of this dynamic process. For this example, assume a required discharge period of two hours.

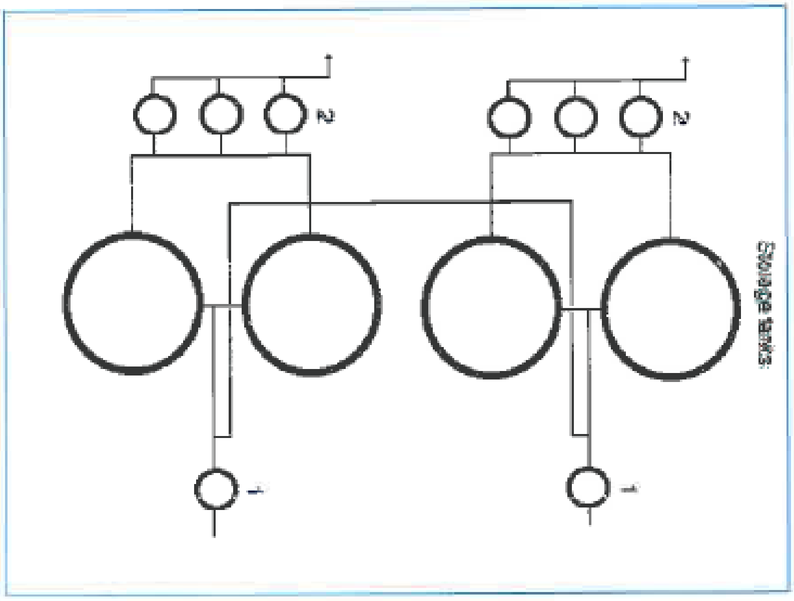


Figure 2: Illustration of equipment in a dynamic process

The equipment marked "1", are transfer pumps, and are used to transfer liquid from one tank another. This transfer is only required when the tank are unbalanced. The tanks are normally unbalanced during off-loading / re-filling of the tanks and require equalization. This should very rarely be required during the standby period. Should equalization occur during the standby period, however, the transfer pumps will most probably run throughout the remainder of the simulation period. This is due to the time it will take to fill the large storage tanks.

From the explanation above, the probability that any of the pumps marked "1" will start, can be illustrated as in Figure 3. The figure illustrates three states – "Stop, Run, and "Trip". The pump is initially is the "Stop" state. When the pumps are in the "Stop" state, it has a

99.9% probability of remaining in this state during the two hour discharge period. Should the pump start, and shift to the "Run" state, it will run for at least two hours, and therefore not return to the "Stop" state within the discharge period. The probability of remaining in the "Run" state becomes 99.99%. Only if the pump has a fault during this time will it change to the "Trip" state.

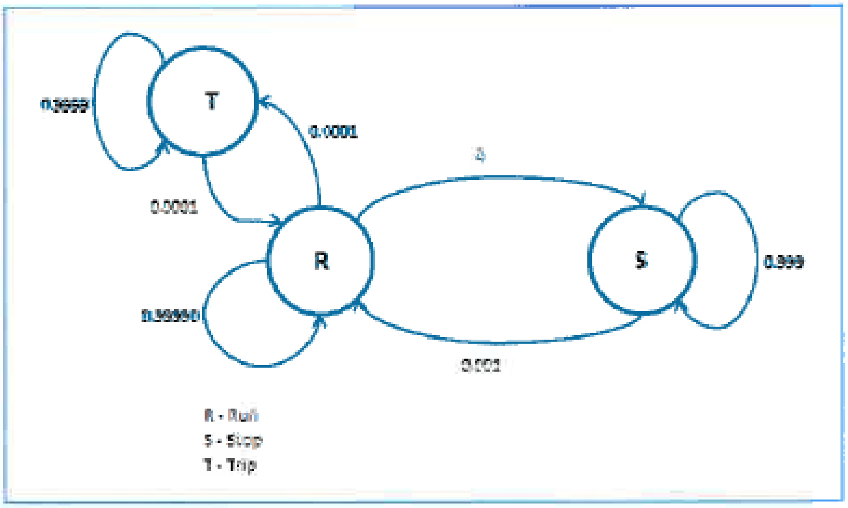


Figure 3: Probability of equipment 1 running

The equipment marked "2" are booster pumps, and are used to transfer liquid out of the relevant tank at high pressure. Under normal operating conditions, only one of the three booster pumps is in service at a time. The second booster pump is on standby and will start automatically when the pressure demand increase, or when the first pump has tripped. The third pump is a reserve pump and will only be used if one of the other pumps is out of service, or upon high pressure demand.

The first pump is initially in a "Run" state, and the second and third pumps stopped. Should the first pump reach 90% of its capacity, the second pump will start. The third pump will start if either of the first two pumps fail, or if both the first and second pump reaches a combined capacity of 90%. The third and second pumps will stop once the demand decreases to 80% of the relevant capacity.

Pump1:

Pump 1 is initially in a run condition.

Pump 2:

Pump 2 is initially in a stop or standby condition. Should Pump 1 fail, or the demand increase to 90% of the first pumps' capacity, the simulation will put Pump 2 in a run condition.

Pump 3:

Similar to pump 2, pump 3 is also initially in a stop or standby. Should either of Pump 1 or Pump 2 fail whilst they are in operation, or the demand increase to 90% of combined capacity of both Pump 1 and Pump 2, the simulation will put Pump 3 in a run condition.

The probabilities for each individual pump, disregarding the status of the pressure and condition of the other two pumps, are illustrated in Figure 4. Random number generators are used to simulate the pressure for each pump. If the random number generator of the pressure for pump exceed 90%, the second pump is started. If second pump is in a "Run" state, and its random number generator exceeds 90%, the third pump is started. Similar logic is used for a decrease in demand.

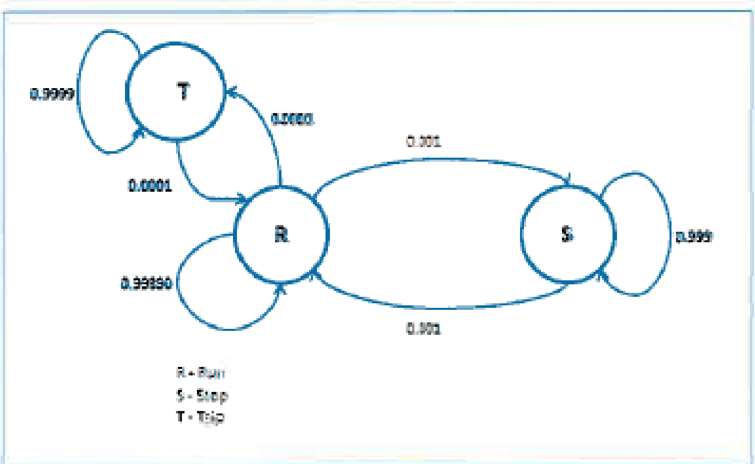


Figure 4: Probability of equipment 2 running

Operating principles:

Table 1 indicates the equipment that forms part of the above example. The controller, or DCS, and the network switches are always active during operation and therefore has a static, or continuous, energy requirement.

1. not regarded as a momentary, but a non-continuous. ? continuous.

Table 1: Components that form part of control system

Item	QTY	Classification	Load per item (A)
DCS inrush	1	Momentary	30
DCS operation	1	Static	6.1
Fault lamps	8	Momentary	0.02
L2 GRVSA-660FA switch	2	Static	1.6667
HP4-DC24V-F Relay (IPR and IPS)	64	Momentary	0.063

Starting and stopping the pumps involves pulsing an interposing run (IPR) relay, or an interposing stop (IPS) relay. When a fault occurs, and the pump is stopped, there are 2 fault lamps that indicate the fault condition. The energy required to energize all the individual devices mentioned above, is used to determine the fluctuating load requirements.

The approximated load profile for this example then becomes as indicated in Figure 5. The figure also illustrate the difference between the approximated load profile and the worst case load profile. The worst case profile represents the load profile when it is assumed that all components of the system may be energized at any given time.

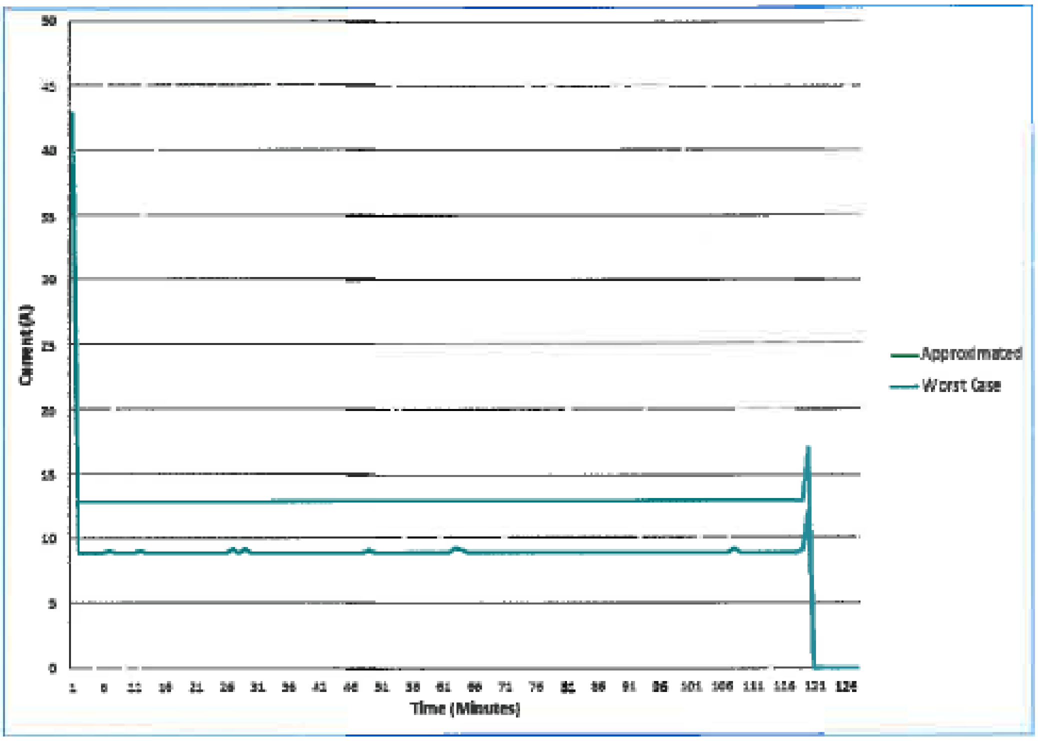


Figure 5: Approximated load profile

Discussion

In Figure 5, only a few load peaks are observed. The peaks at both interval 7 and interval 13 are due to booster pump 1 and booster pump 2 starting up respectively. The pressure demand decreased during interval 27. The peaks observed during interval 27 and interval 29 is due to the stopping of the pumps.

During the simulation, the transfer pumps did not start. All the peaks observed is due to the various booster pumps stopping and starting as the pressure demanded.

The maximum load variation observed throughout the profile is 0.373 ampere.

QUESTION 4a:

Considering the example above, please indicate on the scale below how accurate you deem the load approximation methodology.

1	2	3	4	5
Highly Inaccurate	Inaccurate	Unsure	Accurate	Highly Accurate

QUESTION 4b:

Please raise your concerns, if any, regarding the approximation methodology.

comment 1: The random number generator must be discussed in your work, especially highlight the seed randomness, otherwise it may present a challenge to some examiners.

Comment 2: the probability of state change is not very clear with respect to how the values (probabilities) were assigned. ~~state~~ dedicate a section to that.

Concerning the methodology, the approach is scientific, and can be validated, I support it.

QUESTION 4c:

Please indicate on the scale below how realistic you deem the approximated load profile in Figure 5.

1	2	3	4	5
Highly Unrealistic	Unrealistic	Unsure	Realistic	Highly Realistic

QUESTION 4d:

Please raise your concerns, if any, regarding the approximated load profile as indicated in Figure 5.

Only refer to coment made previously on the duty cycle diagram. This will greatly lower visual interpretation and highlight how the momentary loads and non-continuous loads affect the sizing → Load profile.

QUESTION 5a:

A reduction in the required battery size of a system also affects the required H^2 extraction system, the physical battery room size, as well the required charger size. Considering the potential saving due to the reduction in battery size, but also considering any possible risk involved, how likely will you implement the method of defining a system's load profile, as described in QUESTION 4.

1	2	3	4	5
Highly Unlikely	Unlikely	Unsure	Likely	Very Likely

QUESTION 5b:

Please elaborate on your answer in QUESTION 5b:

1. Mostly for the following reasons:
→ economic feasability trade-off i.e. Sizing based on use or expected use or likely scenario.

→ 2. Limits oversizing → a huge cost in capital and even activities like commissioning

→ The presentation of a design compared to an over size based on unvalidated assumptions.

4.2. Completed questionnaire from expert 2

STRUCTURED QUESTIONNAIRE FOR THE PURPOSE OF QUALITATIVE RESEARCH

Preface

Thank you

I would like to thank you in advance for taking the time and completing this questionnaire. Your inputs and comments will go a long way in making this research project a success. I appreciate that everyone has very busy schedules, and therefore your efforts in this regard are especially appreciated.

Kind regards,
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Introduction

The questions in this questionnaire are pertaining to the design, and specifically the battery sizing, of auxiliary power systems for a DC control and automation system. When using the IEEE recommended practice for sizing batteries, a defined load profile of the system is required. In the case where no specific load profile is defined, it is common practice to use the worst case load the system may experience at any given time.

A typical load profile consists of an initial momentary load, followed by the continuous system load. A final momentary load is typically experienced during the final minute of discharge. The initial momentary load is caused by equipment suddenly changing state as the AC power of the system is lost. This final momentary load is caused by equipment suddenly changing state as the system prepares for shutdown, or as the system regains AC power. The continuous load is observed during normal operations.

A typical control and automation system consists of controllers, network switches, relays, and solenoids. These equipment and devices are used to control the operation of devices such as drives, valves, actuators, etc. It is important to note that the load required to energize these last mentioned devices, does not form part of the control and automation load. Only the collective loads of the control equipment (relays, solenoids, etc.) are considered.

A control and automation system is dynamic of nature, and it is therefore very difficult to define its load profile as an absolute certainty. Devices such as drives, valves and actuators are stopped and started as the process requires. This start and stop actions create a fluctuation in the continuous load section of the load profile.

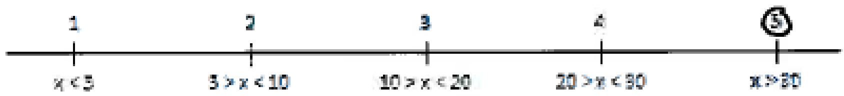
Supercapacitors have good power densities, which make them suitable to provide energy during short power peaks. Supercapacitors may, therefore, prove ~~advantages~~ advantageous during momentary loads, as well fluctuating loads. The aim of the research project is to test the feasibility of using supercapacitors in conjunction with batteries, in order to potentially decrease the required battery size. The influence of the supercapacitor is tested on the initial and final momentary loads, as well the continuous loads.

For this study, live plant measurements cannot be taken for the purpose of defining load profiles. Typically, the worst case load profile is assumed during these situations. Testing the influence of a supercapacitor during the fluctuating loads of the dynamic process, however, requires more detailed load profiles.

To obtain more detailed load profiles, probabilistic load profiles from plant operating procedures were created during the study. The aim of this questionnaire is get the opinions and input from leading experts in the field to determine the validity of the reasoning used during the profile definition, as well as the validity of the probabilistic load profiles that were created.

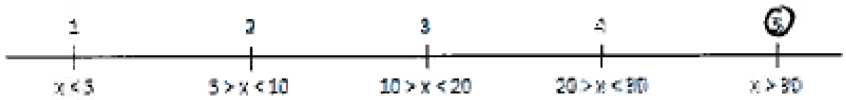
QUESTION 1a:

Indicate on the scale below how many auxiliary DC systems you have had exposure to throughout your career.



QUESTION 1b:

Indicate on the scale below how many control and automation systems you have had exposure to throughout your career.



QUESTION 2a:

Figure 1 illustrates a typical DC load profile found in industry. The value "C", represents the static, or continuous load of the system. The factors indicated in the figure represent the relationship of the momentary loads in relation to the continuous load. On the scale provided, please indicate the accuracy of these factors.

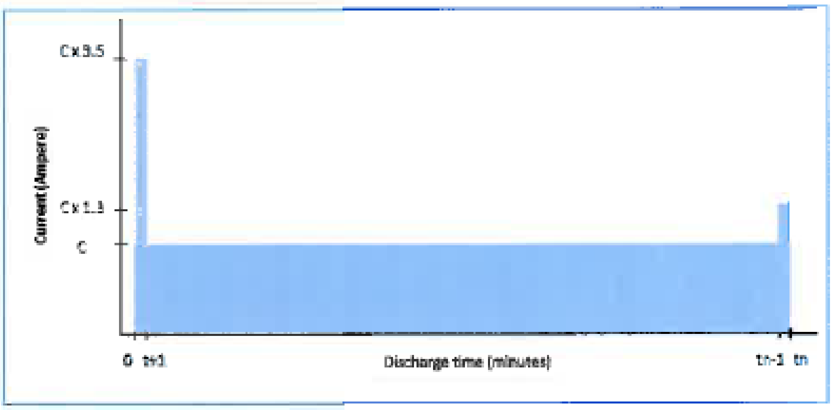
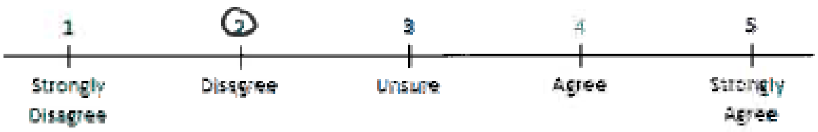


Figure 1: Typical load profile



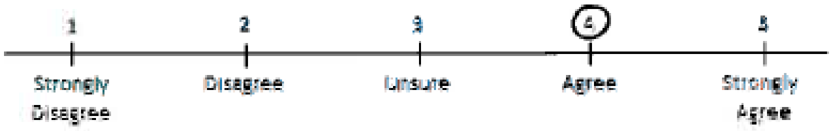
QUESTION 2b:

If you disagree with any of the statements or values in Figure 1, please indicate what you are in disagreement about. Please also elaborate on your answer.

This value is dependant on the time. This will result in a factor higher than 3.5. The start-up load is highly dependant on the bulk capacitors utilized.

QUESTION 3:

When sizing a new auxiliary system for a dynamic process, and a specific load profile is not defined, it is assumed that all equipment and devices in the system can be active or energized at any given moment. The continuous load is therefore determined by calculating the collective loads of all the equipment and devices that are present in the system.



QUESTION 4:

In the example below, a load profile for a dynamic process is simulated using the process operating philosophies. From the simulation, a probabilistic load profile for the example is approximated. Figure 2 illustrates equipment of this dynamic process. For this example, assume a required discharge period of two hours.

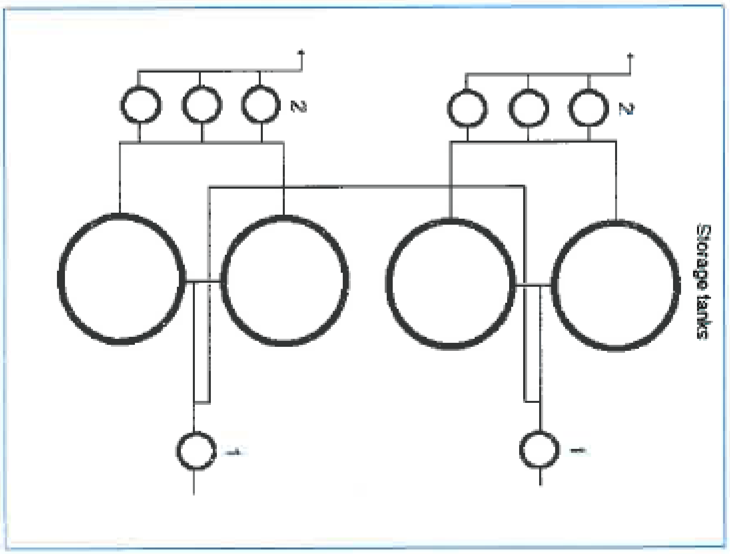


Figure 2: Illustration of equipment in a dynamic process

The equipment marked "1", are transfer pumps, and are used to transfer liquid from one tank another. This transfer is only required when the tank are unbalanced. The tanks are normally unbalanced during off-loading / re-filling of the tanks and require equalization. This should very rarely be required during the standby period. Should equalization occur during the standby period, however, the transfer pumps will most probably run throughout the remainder of the simulation period. This s due to the time it will take to fill the large storage tanks.

From the explanation above, the probability that any of the pumps marked "1' will start, can be illustrated as in Figure 3. The figure illustrates three states – "Stop, Run, and "Trip". The pump is initially is the "Stop" state. When the pumps are in the "Stop" state, it has a

99.9% probability of remaining in this state during the two hour discharge period. Should the pump start, and shift to the "Run" state, it will run for at least two hours, and therefore not return to the "Stop" state within the discharge period. The probability of remaining in the "Run" state becomes 99.99%. Only if the pump has a fault during this time will it change to the "Trip" state.

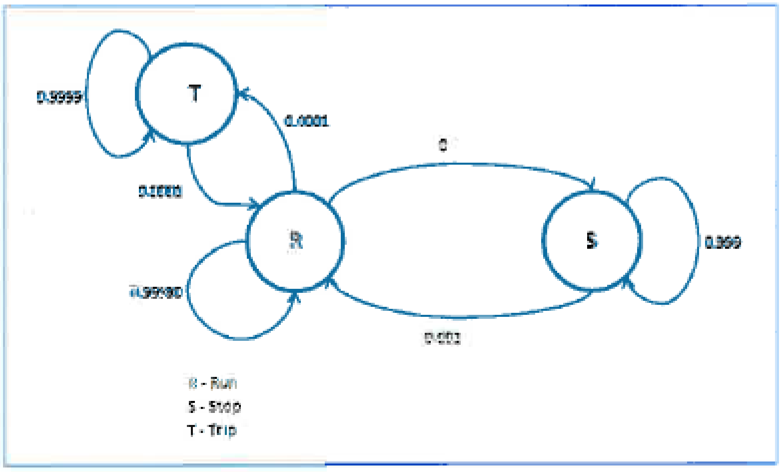


Figure 3: Probability of equipment 1 running

The equipment marked "2" are booster pumps, and are used to transfer liquid out of the relevant tank at high pressure. Under normal operating conditions, only one of the three booster pumps is in service at a time. The second booster pump is on standby and will start automatically when the pressure demand increase, or when the first pump has tripped. The third pump is a reserve pump and will only be used if one of the other pumps is out of service, or upon high pressure demand.

The first pump is initially in a "Run" state, and the second and third pumps stopped. Should the first pump reach 90% of its capacity, the second pump will start. The third pump will start if either of the first two pumps fail, or if both the first and second pump reaches a combined capacity of 90%. The third and second pumps will stop once the demand decreases to 80% of the relevant capacity.

Pump1:

Pump 1 is initially in a run condition.

Pump 2:

Pump 2 is initially in a stop or standby condition. Should Pump 1 fail, or the demand increase to 90% of the first pumps' capacity, the simulation will put Pump 2 in a run condition.

Pump 3:

Similar to pump 2, pump 3 is also initially in a stop or standby. Should either of Pump 1 or Pump 2 fail whilst they are in operation, or the demand increase to 90% of combined capacity of both Pump 1 and Pump 2, the simulation will put Pump 3 in a run condition.

The probabilities for each individual pump, disregarding the status of the pressure and condition of the other two pumps, are illustrated in Figure 4. Random number generators are used to simulate the pressure for each pump. If the random number generator of the pressure for pump exceed 90%, the second pump is started. If second pump is in a "Run" state, and its random number generator exceeds 90%, the third pump is started. Similar logic is used for a decrease in demand.

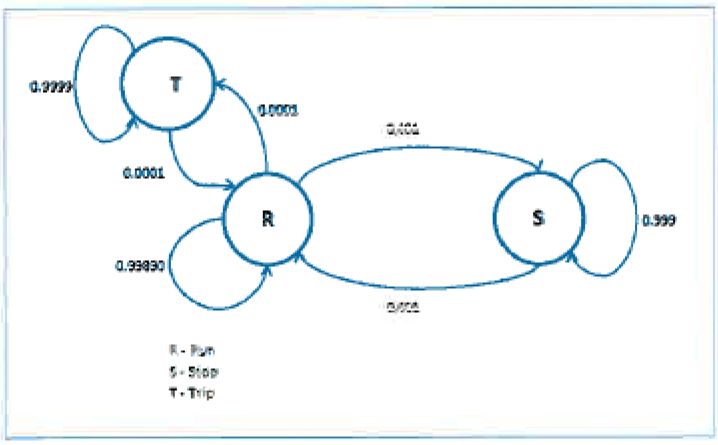


Figure 4: Probability of equipment 2 running

Operating principles:

Table 1 indicates the equipment that forms part of the above example. The controller, or DCS, and the network switches are always active during operation and therefore has a static, or continuous, energy requirement.

Table 1: Components that form part of control system

Item	QTY	Classification	Load per item (A)
DCS inrush	1	Momentary	30
DCS operation	1	Static	6.1
Fault lamps	8	Momentary	0.02
L2 GRVSA-660FA switch	2	Static	1.6667
HP4-DC24V-F Relay (IPR and IPS)	64	Momentary	0.063

Starting and stopping the pumps involves pulsing an interposing run (IPR) relay, or an interposing stop (IPS) relay. When a fault occurs, and the pump is stopped, there are 2 fault lamps that indicate the fault condition. The energy required to energize all the individual devices mentioned above, is used to determine the fluctuating load requirements.

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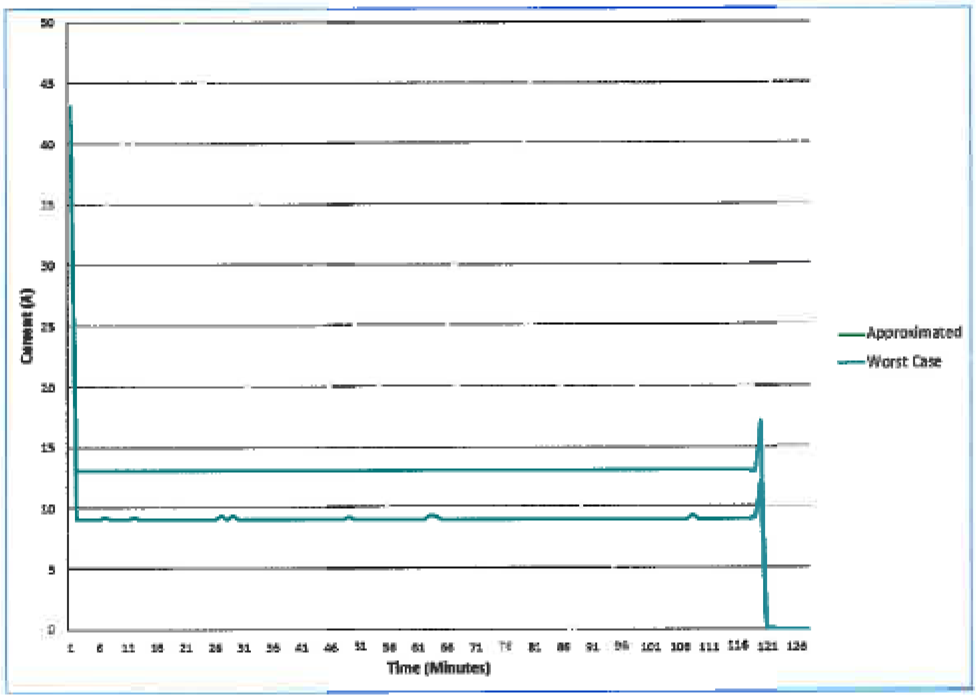

Figure 5: Approximated load profile

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In Figure 5, only a few load peaks are observed. The peaks at both interval 7 and interval 13 are due to booster pump 1 and booster pump 2 starting up respectively. The pressure demand decreased during interval 27. The peaks observed during interval 27 and interval 29 is due to the stopping of the pumps.

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The maximum load variation observed throughout the profile is 0.373 ampere.

QUESTION 4a:

Considering the example above, please indicate on the scale below how accurate you deem the load approximation methodology.

1	2	3	4	5
Highly Inaccurate	Inaccurate	Unsure	Accurate	Highly Accurate

QUESTION 4b:

Please raise your concerns, if any, regarding the approximation methodology.

What is the effect and has it been considered when a load higher than the static load is connected. Is it possible to apply this linearly irrespective of the number and types of loads connected?

QUESTION 4c:

Please indicate on the scale below how realistic you deem the approximated load profile in Figure 5.

1	2	3	4	5
Highly Unrealistic	Unrealistic	Unsure	Realistic	Highly Realistic

QUESTION 4d:

Please raise your concerns, if any, regarding the approximated load profile as indicated in Figure 5.

For this case the profile is realistic. Once again refer to comments on 4a.

QUESTION 5a:

A reduction in the required battery size of a system also affects the required H^2 extraction system, the physical battery room size, as well the required charger size. Considering the potential saving due to the reduction in battery size, but also considering any possible risk involved, how likely will you implement the method of defining a system's load profile, as described in QUESTION 4.

1	2	3	4	5
Highly Unlikely	Unlikely	Unsure	Likely	Very Likely

QUESTION 5b:

Please elaborate on your answer in QUESTION 5b:

Depending on the scalability of the approximation.

4.3. Completed questionnaire from expert 3

STRUCTURED QUESTIONNAIRE FOR THE PURPOSE OF QUALITATIVE RESEARCH

Preface

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QUESTION 1a:

Indicate on the scale below how many auxiliary DC systems you have had exposure to throughout your career.

1	2	3	4	5
x < 5	5 > x < 10	10 > x < 20	20 > x < 30	x > 30

QUESTION 1b.

Indicate on the scale below how many control and automation systems you have had exposure to throughout your career.

1	2	3	4	5
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QUESTION 2a:

Figure 1 illustrates a typical DC load profile found in industry. The value “C”, represents the static, or continuous load of the system. The factors indicated in the figure represent the relationship of the momentary loads in relation to the continuous load. On the scale provided, please indicate the accuracy of these factors.

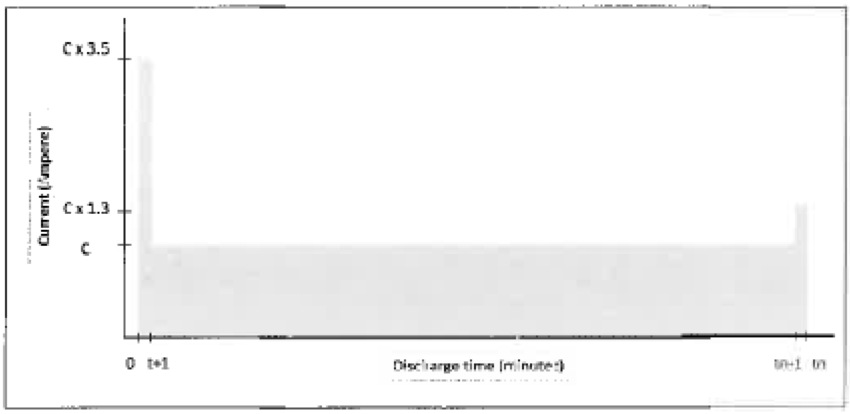

Figure 1: Typical load profile

1	2	3	4	5
Strongly Disagree	Disagree	Unsure	Agree	Strongly Agree

QUESTION 2b:

If you disagree with any of the statements or values in Figure 1, please indicate what you are in disagreement about. Please also elaborate on your answer.

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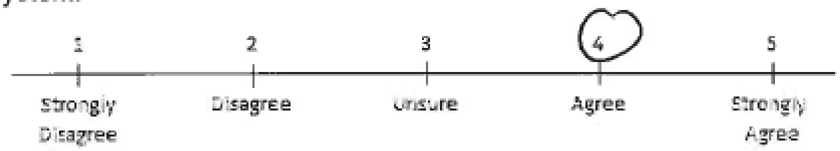
When sizing a new auxiliary system for a dynamic process, and a specific load profile is not defined, it is assumed that all equipment and devices in the system can be active or energized at any given moment. The continuous load is therefore determined by calculating the collective loads of all the equipment and devices that are present in the system.



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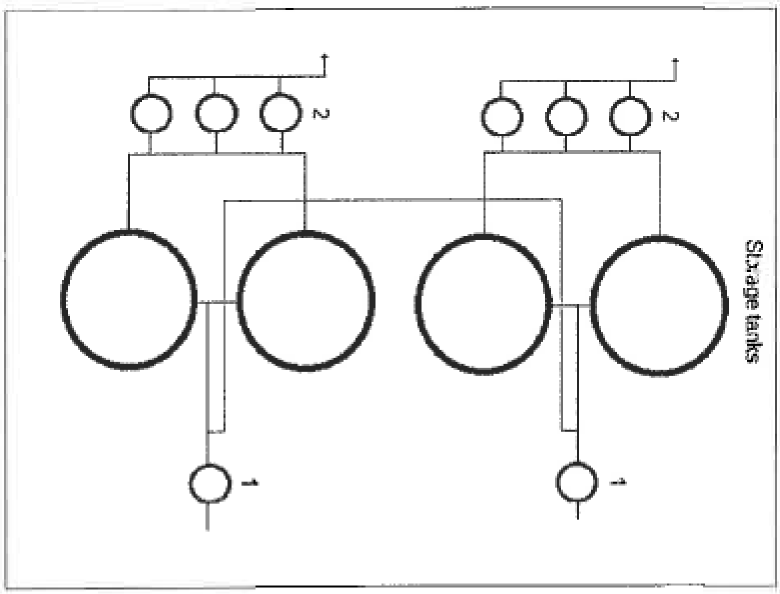

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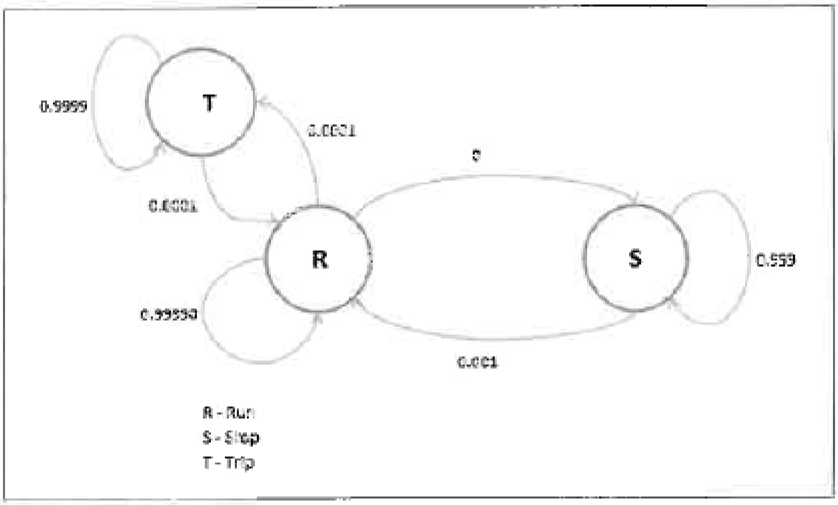

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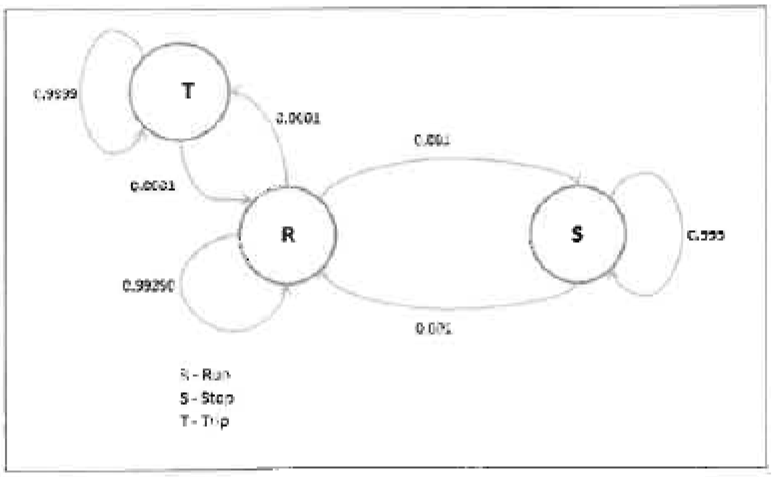

Figure 4: Probability of equipment 2 running

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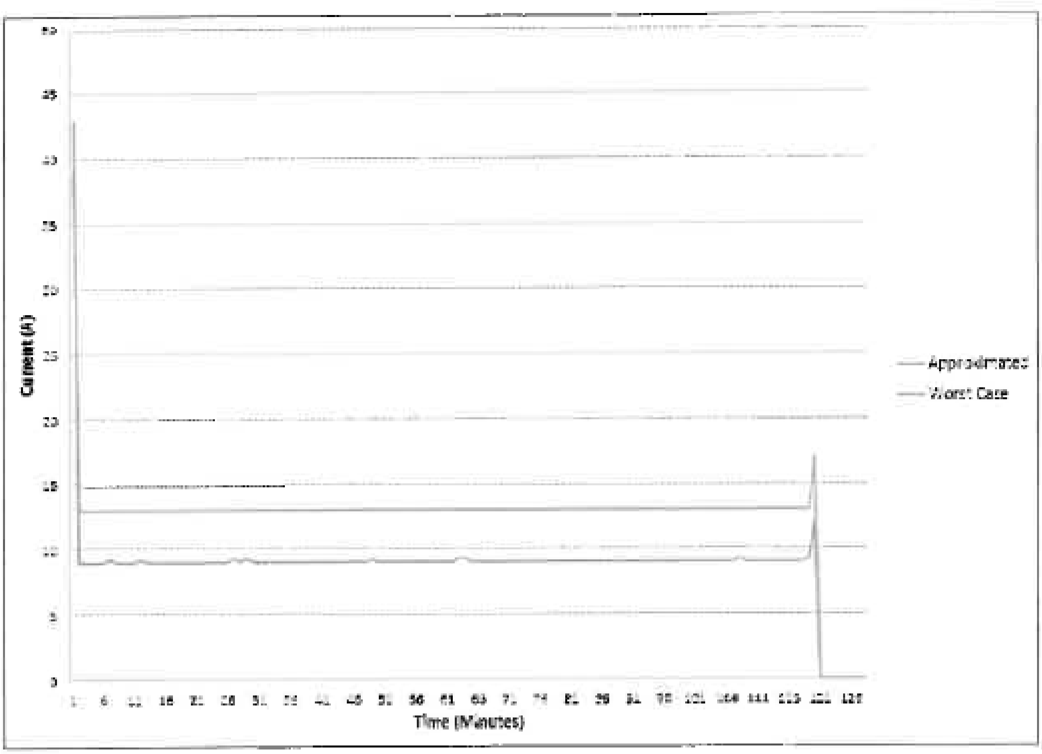

Figure 5: Approximated load profile

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In Figure 5, only a few load peaks are observed. The peaks at both interval 7 and interval 13 are due to booster pump 1 and booster pump 2 starting up respectively. The pressure demand decreased during interval 27. The peaks observed during interval 27 and interval 29 is due to the stopping of the pumps.

During the simulation, the transfer pumps did not start. All the peaks observed is due to the various booster pumps stopping and starting as the pressure demanded.

The maximum load variation observed throughout the profile is 0.373 ampere.

QUESTION 4a:

Considering the example above, please indicate on the scale below how accurate you deem the load approximation methodology.

1	2	3	4	5
Highly Inaccurate	Inaccurate	Unsure	Accurate	Highly Accurate

QUESTION 4b:

Please raise your concerns, if any, regarding the approximation methodology.

The probability figures relates to systems for which good maintenance practices are applied.

QUESTION 4c:

Please indicate on the scale below how realistic you deem the approximated load profile in Figure 5.

1	2	3	4	5
Highly Unrealistic	Unrealistic	Unsure	Realistic	Highly Realistic

QUESTION 4d:

Please raise your concerns, if any, regarding the approximated load profile as indicated in Figure 5.

QUESTION 5a:

A reduction in the required battery size of a system also affects the required H^2 extraction system, the physical battery room size, as well the required charger size. Considering the potential saving due to the reduction in battery size, but also considering any possible risk involved, how likely will you implement the method of defining a system's load profile, as described in QUESTION 4.

1	2	3	4	5
Highly Unlikely	Unlikely	Unsure	Likely	Very Likely

QUESTION 5b:

Please elaborate on your answer in QUESTION 5b:

The benifit of the method would be cost saving due to smaller equipment that will be required to meet the process requirements.