MINIMIZING THE STATE OF HEALTH DEGRADATION OF LI-ION BATTERY FOR LOW EARTH ORBIT SATELLITES

by

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Dedication

To my beloved family

Najat Abdelhameed, Shareef Lami

Abstract

Satellites have a tangible impact on our daily lives; they provide us with many services like communication, global positioning etc. Satellites may be sent to space for prolonged periods of time. There are several mission profiles for satellites i.e. low earth orbit (LEO), middle earth orbit (MEO) or geosynchronous orbit (GEO) missions. Batteries on board satellites are expected to deliver the power demand at any time during the period of an eclipse, or when the power received from the solar panel is not sufficient. The focus of this thesis is to develop a mixed integer nonlinear scheduling model that reduces the state of health (SOH) degradation of a battery in a LEO satellite. This will improve the battery lifetime, thus increasing the length of time a LEO satellite can stay in service. The developed model for a LEO satellite is solved separately for meeting three different objectives, which are minimizing the number of battery switches between charging and discharging, minimizing the sum of products of the battery state switches and battery current, and minimizing the total depth of discharge (DOD). In addition to the model, a heuristic approach is developed and compared with the mathematical model. In this endeavor, data are collected for an existing LEO satellite, Nayif-1, in order to analyze the current battery behavior in space and compare it with the developed model and heuristics. Sensitivity analysis is conducted to observe the effects of altering different parameters of the model. The results presented in this thesis show that minimizing the sum of products of the battery state switches and the battery current, yields the best results by enhancing the lifetime of the battery by 8 days and providing 122 more cycles than that observed in the data from Nayif-1, assuming that the DOD of the battery remains constant throughout all orbits. Therefore, based on the main results comparison and sensitivity analysis, it is concluded that the second objective function provides the best enhancement of the battery lifetime for LEO satellites.

Search Terms: ***Batteries; Scheduling; Satellite; State of Charge; State of Health; Depth of Discharge; Heuristic.***

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Chapter 1. Introduction

This chapter will firstly provide an overview of satellites, batteries, Lithium-ion (Li-ion) batteries, and batteries characteristics. In addition, the problem statement, research objectives and significance, research contribution, and the research methodology, will be highlighted.

1.1. Overview

1.1.1. Satellites

Satellites have revolutionized communication systems in the world. Without satellites, worldwide phone calls would not be possible. Furthermore, satellites have significantly saved human life in many areas around the world due to their great impact on weather forecasting; satellites have made it easy for meteorologists to see a storm coming before visually observing the storm from the area of impact. This would give concerned authorities enough time to alert people so they can evacuate the area. Furthermore, satellites orbit in either a geosynchronous orbit (GEO), Medium Earth orbit (MEO) or in low earth orbit (LEO).

Most satellites use photovoltaic cells in order to obtain power through the sun; however, satellites need an energy storage system in order to provide backup power to the satellite in the absence of sunlight. It is common that batteries provide power for satellites during periods of peak power demands, when the solar power is not enough or during eclipse periods (e.g. the time the sun light is blocked by the moon or the earth blocks the sunlight of the sun) [1, 2]. Consequently, depending on the mission profile, one can determine how long the satellite would face the eclipse.

Based on Table 1, the eclipse season in GEO happens in spring and fall whereas each season faces 45 eclipses up to 72 minutes of maximum duration [1, 2]. It is important to mention that at GEO the satellite makes 90 to 100 charge/discharge cycles per year [1] at a height of 35,800 Km above earth surface [4, 5]. The typical life-cycle requirement for the battery in GEO is 1350 charge/discharge cycles corresponding to approximately 15 years [2]. On the other hand, at the LEO mission profile, the satellite faces eclipse almost every 90 minutes up to 35 minutes of maximum duration for a total of 5000 to 5500 charge/discharge cycles per year [1] and the typical cycle life target of the battery is 30,000 charge/discharge cycles corresponding to 5 years [2] at a height of 500-1500 Km above earth surface [4, 5].

The important parameters in the GEO and LEO mission profiles are summarized in Table 1

Table 1: GEO and LEO Mission Profiles [1, 2, 3, 4]

	GEO	LEO
Number of Eclipses	45 per season. Happens only in two seasons (Spring and Fall)	Faces eclipse every 90 minutes
Maximum duration of Eclipse (Minutes)	72	35
Battery charge/discharge cycles Per Year	90-100	5,000 – 5,500
Typical life requirement (battery charge/discharge cycles)	1,350 corresponding to 15 years	30,000 corresponding to 5 years

Almost all space applications use Li-ion batteries. In 2000, the first space qualified Li-ion battery pack was flown by the STRV satellite [6]. Mazlan et al. [6] mentioned the main reasons and advantages of the Li-ion batteries in space application which will be discussed in Chapter 2.

1.1.2. Batteries

Batteries are used in almost every industry including electronics, renewable energy, transportation, space applications and many others. Many types of batteries have been developed such as the Li-ion, Lead-acid and NiMH batteries etc. However, these batteries have failed to meet the exponential growth in energy demand as well as the size limitations in recent technologies of portable devices [7]. For most portable electronics, the batteries take around 1.5 to 4 hours to fully charge (depending on the current drawn). On the other hand, it takes few hours for it to completely discharge [8]. For each type of battery, scholars concentrated on representing the batteries with an equivalent battery model because the accuracy and efficiency in battery modeling can aid the designers in estimating and optimizing the battery runtime and lifetime. Therefore, the accuracy of the represented battery model is vital for the parameter estimation of the battery characteristics.

1.1.3. Battery characteristics

In all industries, battery runtime and lifetime are very critical factors. The runtime is important even for consumers of electronic devices, such as mobile phones for instance. Consumers have started purchasing portable chargers to recharge their phone batteries due to the short runtime of their phone battery. Therefore, improving the runtime of the batteries can be economically and socially beneficial for consumers in industries. Battery runtime is the amount of time the battery takes to go from 100% state of charge SOC to 0% SOC. The SOC of the battery can be represented as the available capacity in Ampere Hour (Ah) and it is expressed as a percentage of the rated capacity [9]. It can also be defined as the "the percentage of the maximum possible charge that is present inside a rechargeable battery" [10]. An important parameter for the SOC is the open circuit voltage (OCV) of the battery which is the voltage under no load condition [11]; in theory it states that if the OCV is accurately observed, it can be able to accurately estimate the SOC [10]. There are many different SOC estimation techniques that will be discussed and explained further in chapter 2.

The lifetime of the battery is the period of time the battery can deliver the demanded power. This battery lifetime has been critical for the industry; the battery can deliver the expected outcome for a specific period until it goes through an unstable state that can take place due to overcharge or deep discharge of the battery cells [9]. Furthermore, it can be the result of capacity fading which is the outcome of many charge/discharge cycles. In the same manner as runtime, battery lifetime, if improved, can benefit consumers. The lifetime of the battery is directly related to the state of health (SOH) of the battery, which has been a vital factor for many researchers for optimal battery management. The SOH of the battery is stated in [9] to be the measure of the ability of the battery to store and deliver electrical energy compared to a new battery. It is worth mentioning here that the SOH and capacity fading are linked to the depth of discharge (DOD) of the battery. It is stated by Park et al. [12] that as DOD increases the capacity fading also becomes large. The terminology DOD is defined as the "percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity" [13]; it was also stated that the higher DOD, the lower the lifetime of the battery. A clearer example was given in [14], i.e. if a battery has 70% SOC and then cycled down to 40% SOC thus the DOD will be the difference between them giving a value of 30%.

Many challenges, however, can exist in SOC estimation of the battery; such challenges can be caused by the effects of temperature, number of charge-discharge cycles and self-discharge [8, 15]. It is also essential that we try to prevent the overcharge and the deep discharge of the battery which affect its SOH [16]. The reason is that whenever the battery cells are overcharged the active materials are most likely to react with other materials of the electrolyte, which can result in an explosion that damages the cells of the battery [16]. For the deep discharge case, when the terminal voltage reaches below the cut-off voltage, it may result in the battery transitioning into an irreversible condition [16].

1.1.4. Lithium-ion batteries

Li-ion batteries have been used widely in many systems due to many reasons such as the high power and energy density, high voltage, no memory effect, long cycle life and low self-discharge [8, 17]. Other main advantages of the Li-ion battery can be found in [6]. It is important to mention that in the late 90's, Li-ion batteries started getting acceptance to be used for satellite systems [18], and they entered aerospace applications from all aspects including planetary and lunar rovers as well as astronaut suits [18].

Moreover, this thesis will be focusing on the LEO satellite system for implementing the scheduling of Li-ion battery. A brief comparison of the batteries and the system impact of using Li-ion for satellite system can be found in Table 2.

Table 2: Li-ion Comparison [6]

	NiCd	NiH2	Li-ion	System impact
Energy density (Wh/Kg)	30	60	125	Weight saving
Energy efficiency (%)	72	70	96	Reduction of charge power
Self-discharge (%/day)	1	10	0.3	No trickle and charge at the launch pad
Temperature range (˚C)	0-40	- 20 - 30	10 - 30	Management at ambient
Charge management	CC	CC	CCCV +	Parts increase

1.1.5. Problem statement

Battery management has been a topic of interest for many researchers due to the rise of electric vehicles and drones. Liu et al. [19] stated that the challenges of safety management, charging/discharging control and the SOH degradation of the battery have made battery management one of the most challenging issues. However, most researchers have been implementing battery management mainly on electric vehicles, hybrid vehicles, and drones in the pursuit of augmenting the battery lifetime and cycle lifetime. To the best of our knowledge, very limited research was developed on battery management on satellites and space applications. Those few researches illustrated the significance of estimating the health of the batteries such as predicting the remaining cycle life and monitoring the health of the batteries in space application [19, 20].

This work is concerned with battery management for satellites because of the great importance satellites have in everyday life and because of their heavy dependency on batteries. It was stated by Liu et al. [19] that most fatal failures of satellites are due to their power system especially from the batteries side. For example, a battery fault had ended an X-ray satellite mission in 1999 [21]. M. Jun et al. [22] also stated that due to the high cost of launch and the complexity to perform repairs during orbit, battery management is used in order to utilize the battery capacity and diminish the risk. Furthermore, NASA has stated in [23] that the essential metric for any battery operating in LEO is long lifetime. Therefore, there is a great focus on making the power system lighter, cheaper and of a higher cycle life for the battery used [1].

The satellite being studied is a LEO Nayif-1 satellite that incorporates a Li-ion battery and solar panels. The battery is used to supply the demand of the satellite during the period of eclipse and peak power demands.

Thus, the proposed approach will focus on providing scheduling model for Nayif-1 satellite battery in which the main objective of the model is to minimize the state of health (SOH) degradation of the battery for one orbital period which as a result will enhance the lifetime and cycle lifetime of the battery. The model will be subject to several constraints, mainly the SOC of the battery and the demanded power.

The results of the model are based on the Nayif-1 satellite and are applicable to all LEO satellites.

1.2. Research Objectives

The main objective of this thesis is to present a scheduling model for the battery of LEO satellites; the model will be tested and verified on Nayif-1 satellite. The scheduling model will determine the appropriate time instances at which the battery begins charging, terminates charging, begins discharging and terminates discharging. At the instance of charging, the model will also specify how much current is used to charge and how much current is used at the discharge instance; this will result in managing the capacity availability of satellite battery in order to minimize the SOH degradation of the battery for a whole orbital period. The scheduling model will be based on a set of constraints such as the SOC of the battery and the satellite needed power. It is also worth mentioning that the Coulomb counting method will be used for the battery SOC estimation.

The objective of the proposed model is to minimize the SOH degradation. The model will be solved for three different objective functions for further analysis and validation. By scheduling the battery, it is expected to augment the lifetime and cycle lifetime of the battery by allowing the battery to live longer; meaning the capacity fading and the SOH degradation of the battery will be diminished. In this endeavor for scheduling the battery of the satellite, the thesis will use the Chen and Mora circuit model in [7] as a representation of the Li-ion battery because the errors in terminal voltage dynamics are minimal for this specific circuit model representation [7, 15, 24]. LINGO and MATLAB were used to solve and simulate all scenarios.

1.3. Research Contribution and Significance

This research considers using scheduling techniques in order to schedule the battery charge/discharge switches and capacity to augment the battery lifetime by considering the battery SOH degradation factors on the satellite system. There isn’t any existing work that tackles this problem from this perspective; most of the research was based on estimating the remaining health and the SOH for satellite systems. Therefore, in this research the main contributions are:

- Proposing a scheduling model that focuses on enhancing the lifetime and cycle lifetime of LEO satellites battery with respect to specific constraints.
- Solving the scheduling model with three different objective functions and comparing the results in order to provide a wider scope for the results discussion and comparison, which in turn will add to the literature.
- Implementing a sensitivity analysis on different initial SOC of the battery and demand profile in order to have a concrete understanding and conclusion to the results.
- Performing simulation through LINGO and MATLAB that can deliver the simulated results for the LEO satellite battery.

1.4. Research Methodology

The steps stated below are followed to meet the research objectives:

1. Conducting a literature review on batteries, SOC and SOH estimation, scheduling techniques, satellites orbit simulations and battery management system for different systems and satellites.
2. Data collection and analysis for Nayif-1 LEO satellite.
3. Performing and simulating the Coulomb counting SOC estimation technique through MATLAB.
4. Developing the mixed integer nonlinear scheduling model for the LEO Nayif-1 battery.
5. Conducting simulation for the developed model through LINGO.
6. Creating a heuristic model and validating it using simulation through MATLAB.
7. Performing a comparison analysis on the current case used on the Nayif-1 LEO satellite battery and the scheduling model for three different objective functions and the heuristic model.
8. Evaluating the performance and accuracy of the model through carrying out sensitivity analysis.

1.5. Thesis Organization

The rest of the thesis will be organized as follows: Chapter 2 will provide the background and literature review of the circuit models that are going to be represented by the battery. It will also discuss the different techniques of SOC estimation in order to provide a comparison between them. The chapter will also present important factors about satellites in general and their power system in specific. In addition to that, this chapter will introduce the different types of scheduling cases from previous literature for different systems in order to have a better understanding of the scheduling models implemented. Finally, the chapter will give an overview about the satellite under study which is the LEO Nayif-1 satellite. Chapter 3 will include the mathematical model, which will include an introduction of the type of battery currently used by LEO Nayif-1 satellite and specify the important parameters and manufacturer recommendations. It will also include the model assumptions, model parameters, model decision variables and the model objective function along with the model constraints. Moreover, chapter 4 will illustrate the heuristic approach for the model. Furthermore, chapter 5 will include all the results and analysis performed on the scheduling model, the different objective functions and all the implemented calculation and simulations used in the endeavor of this thesis. In addition to that, chapter 6 will include the sensitivity analysis performed on the scheduling model. Finally, chapter 7 concludes the thesis and presents the future work and enhancements.

Chapter 2. Background and Literature Review

This chapter will start by discussing the different battery modeling representations for the Li-ion battery. It will also provide an illustration and comparison between the different SOC estimation techniques used over the past years. The significance of Li-ion batteries and battery management on satellites will be also documented. The chapter will then examine the different types of scheduling schemes for the batteries alongside with the types of systems on which the scheduling scheme of the battery can be implemented. Finally, the chapter will conclude by giving an overview on the LEO satellite under study.

2.1. Lithium-ion Battery

This section of the chapter will consider only the electrical engineering aspects of the batteries such as the circuit model representations of the battery, the different techniques for the SOC estimation, the battery lifetime, and the SOH estimation.

2.1.1. Lithium-ion battery models representations

The first step in an accurate SOC estimation is to develop an accurate battery model that can represent the battery and more specifically the Li-ion battery. There happen to be many different kinds of battery models developed such as the physical models (electrochemical), empirical models, mathematical models (abstract), electrical models (abstract) or even a mixture of models [8]. The use of these models aids researchers in fathoming the battery behavior and helps designers in finding a battery management algorithm [8].

2.1.1.1. Physical models

Physical models or electrochemical modeling can be very accurate and have good value for the designers of the battery. An example of a physical model has been stated in [8] called the isothermal electrochemical model. However, the physical model has many cons; for instance, it is the slowest to produce predictions and is very complex to configure [8]. Furthermore, the model represented in [8] involves solving interdependent partial differential equations that require very complex numerical techniques [15]. Thus, in simulation this will result in a very long time that can reach days for each load profile to be generated [8]. Similarly, it was also noted in [7] that the electrochemical models are very complex and time consuming.

2.1.1.2. Empirical models

The empirical models are regularly the easiest to develop and they quickly produce results; however, they are unfortunately the least accurate. Types of empirical models have been presented in [8] such as the Peukert's law, which is very easy to configure and use, but it does not account for time-varying loads. Another model is the battery efficiency model, which can account for time-varying load and rate dependence. The third model stated in [8] is the Weibull fit model. However, in all of these empirical models the temperature effect is considered while the capacity fading is not.

2.1.1.3. Abstract models

Abstract models try to provide an equivalent representation of the battery. The most important models are the electrical circuit models, discrete time model and the stochastic model [8]. Mathematical models are considered to be abstract, however, they can require heavy computations [15]. They cannot also offer the I-V information of the battery [7]. On the other hand, electrical models' accuracy lies between around 1% to 5% error [7], and they consist of voltage sources, resistors and capacitors. Over the years, scholars have developed many electrical model representations for Li-ion batteries. Many circuits will be presented in the following subsections of this section.

2.1.1.3.1. Thevenin based model

The Thevenin based electrical model is shown in Figure 1. The model consists of series resistance and an RC parallel network that estimates the battery response of the transient loads at a specific SOC, given that the OCV is constant over time [7]. The drawbacks of this model are that it fails in capturing the runtime information of the battery as well as the battery voltage variation at the steady state stage [7]. This model has been tested and it showed close to acceptable results in [24]; however, according to [7], it fails to predict the runtime of the battery accurately in circuit simulators.

2.1.1.3.2. Impedance based electrical model

The same way as the previous Thevenin based electrical model, this impedance model contains the OCV dependent source along with the series resistance. The electrical model is shown in Figure 2. Similar to the previous model in figure 1, this model has its own drawbacks. The main one is that it needs a fixed SOC and temperature settings to be able to operate. This means, that it fails in predicting the dc response and battery runtime [7]. In addition, it was also mentioned in [7] that the fitting process is complex and difficult.

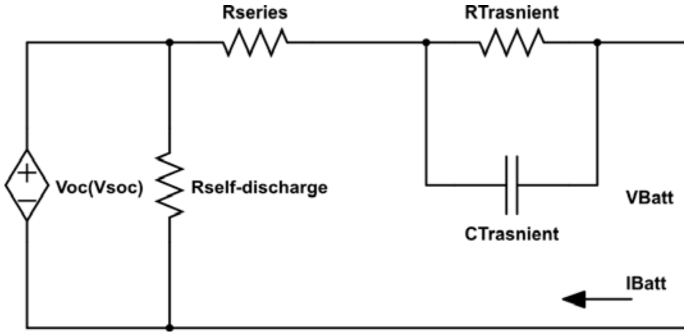

Figure 1: Thevenin based electrical model [7, 12].

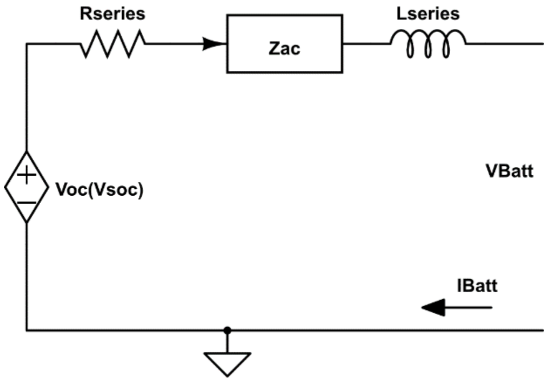

Figure 2: Impedance based electrical model [7]

2.1.1.3.3. Runtime based electrical model

This circuit model as shown in Figure 3 is more complex than the previous two models; this circuit model is used to simulate the battery runtime and dc voltage response using only a constant discharge current in SPICE simulators. However, the drawback in this model is that the runtime and the voltage response for the varying load currents cannot be predicted accurately [7].

2.1.1.3.4. Rint model

This model, as shown in Figure 4, has an ideal voltage source to represent the OCV. The R_o and the OCV are a function of the SOC and temperature [24], whereas the I_L is the load current. However, based on an evaluation accuracy of this model in [25], it was proven that it has significant errors, and it fails in simulating the dynamic performance of the battery.

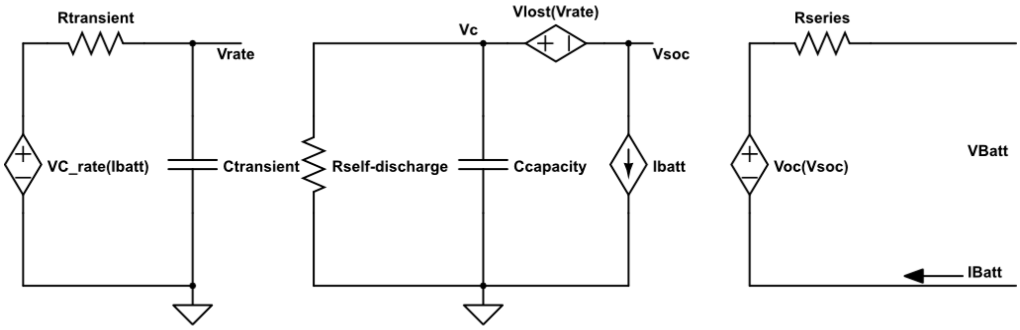

Figure 3: Runtime based electrical model [7]

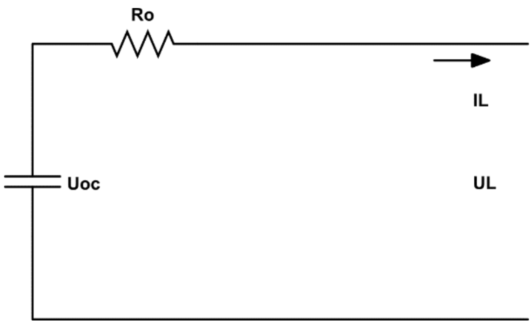

Figure 4: Rint electrical model [24]

2.1.1.3.5. RC model

This RC model has been designed by SAFT battery company, as shown in Figure 5. It contains two capacitors and three resistors. Moreover, the SOC can be obtained from the voltage across C_b [24]. Although the model has shown some useful applications, the evaluation made in [24] has proven that this model causes big errors on the terminal voltage.

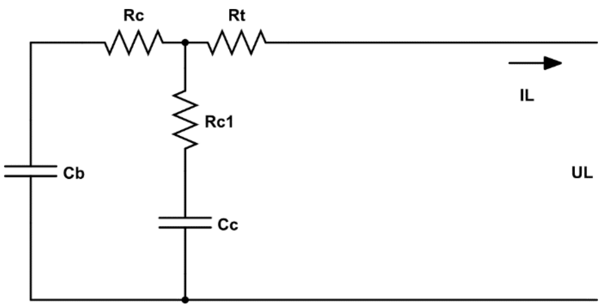

Figure 5: The RC electrical model [24]

2.1.1.3.6. PNGV model

This circuit model is derived from the Thevenin model shown in Figure 1: Thevenin based electrical model [7, 12]. the only difference is the addition of one capacitor in series with the resistor in order to be able to describe the changes of the OCV [24]. Through the evaluation accuracy of the battery models in [24], it was proven that this model can simulate the polarization characteristics, but it produced fluctuation in the terminal voltage calculation of the battery which caused big errors. The model is shown in Figure 6.

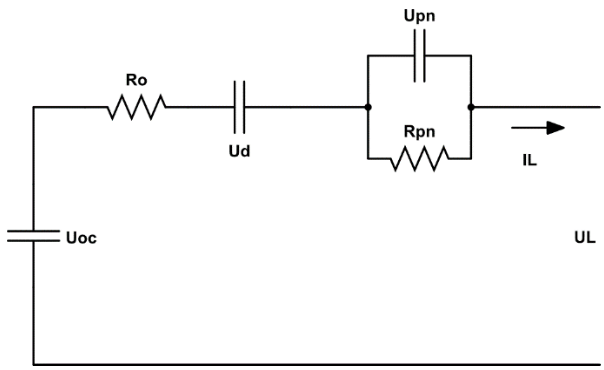

Figure 6: PNGV electrical model [24]

2.1.1.3.7. Chen and Mora electrical model

An integrated electrical model is proposed that is able to combine the transient capabilities of the Thevenin model, the AC features of the impedance model and the runtime information of the runtime model [7]. The model presented in Figure 7, consists of two parts. On the left side, it contains a capacitor and current controlled source, derived from the runtime based model, in order to enable to model the capacity SOC and runtime of the battery [7]. On the right side of the circuit, it contains a voltage-controlled source to bridge the SOC to OCV. It also contains the R_{series} and two RC networks; the series resistance is responsible for the instantaneous voltage drop of the step response [7], where the two RC networks are responsible for the short and long time constants of the step response [7]. This model was validated in [7] where it showed a very close agreement between simulation and experiential results. It was also proven that the proposed model can predict the runtime and both steady state and transient voltage response accurately; Table 3 shows model validation results in [7]. The significance of this model is that M. Chen and G. Mora in [7] were able to provide equations that relate the values of the equivalent circuit to the SOC; this aided in capturing the nonlinear behavior of the Li-ion battery effectively [8].

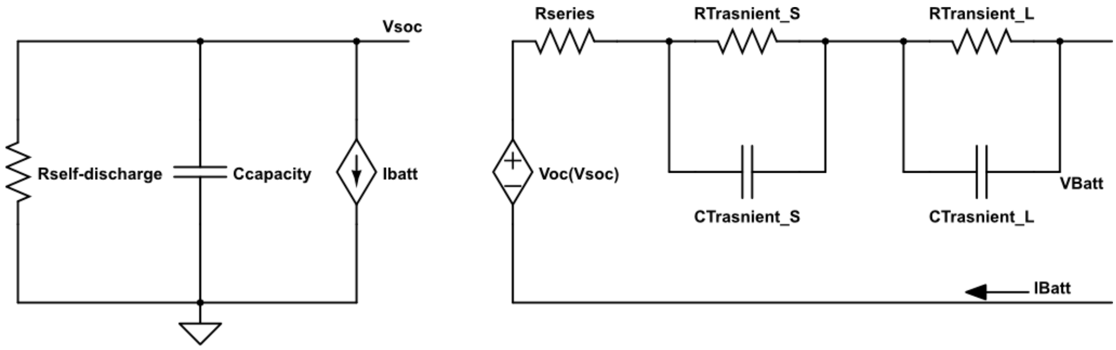

Figure 7: Chen and Mora electrical model [7]

Table 3: Model validation results [7]

Load profiles	Max error voltage (mV)	Runtime error (%)
Continuous discharge	15	0.395%
Pulse charge	30	0.133%
4-step discharge	20	0.338%

This model has been used in many research articles and tests for further battery studies such as the study of battery robustness in [25] and the parameters estimation in [15]. This gives a concrete conclusion that the Chen and Mora model is a very accurate representation of the battery that can predict the steady state, transient, and runtime response collectively, and without the need for too many computational resources for simulation. Thus, the Chen and Mora model is adopted in this thesis.

2.1.2. State of charge estimation techniques

State of charge (SOC) estimation is extremely significant to battery management systems [26]. Scholars have been deriving many different techniques to be able to estimate the SOC with the greatest accuracy. SOC estimation is very complex due to the nonlinear dynamics of the battery characteristics and because the SOC is an inner state of the battery that cannot be measured directly [10]. Accurate estimation of the SOC will aid in improving the system performance, reliability and will also augment the runtime and lifetime of a battery [9]. In addition to that, accurate estimation will enable the battery management system to avoid unexpected interruption that might occur and also prevent batteries from being over or under discharged [9]. The next subsections will provide an overview of the different methods for accurate SOC estimation.

2.1.2.1. Coulomb counting and enhanced Coulomb counting method

Coulomb counting sometimes referred to as ampere-hour counting is the most basic and common method used for SOC estimation. The mathematical formulation is shown in equation (1).

$$SOC(t) = SOC(t_0) + \frac{1}{C}\int_0^t i(t)\,dt \qquad (1)\ [10]$$

$SOC(t_0)$ is the initial state of charge, C is the rated capacity of the battery which is given by the manufacturer, i is the discharge current in the discharging process [10]. Therefore, as it can be seen from equation 1, the method depends on the accurate measurement of the battery current, estimated initial SOC of the battery [9]. However, the method drawback is that it is unable to react against measurement noise or inaccurate initial SOC [17].

Scholars have improved Coulomb counting and the method was called the enhanced Coulomb counting algorithm. In this enhanced method, the initial SOC is estimated from the terminal voltage or the OCV. This method has also considered the charging and discharging efficiencies, and this has compensated the losses [9]. Thus, the method enables researches to have a better estimation of the SOC [9].

M. Murnane and A. Ghazel in [9] have selected the enhanced Coulomb counting method over the Kalman filter (KF) and the Extended Kalman filter (EKF), since the Coulomb counting provides a lot less complexity, fair estimation and accuracy of the SOC.

2.1.2.2. The Kalman filter method

Another important method for the SOC estimation is the Kalman filter (KF). KF was developed in the 1960’s and its objective was to provide an optimal linear filtering for the state observation and prediction problems [9]. Since the KF is used for linear systems and because the Li-ion battery has a nonlinear dynamic characteristic [27], an effort was made by scholars to develop the extended Kalman filter (EKF) and the unscented Kalman filter (UKF), which is suitable for the estimation of the nonlinear Li-ion characteristics [10]. The EKF contains an extra linearization process at every time step in order to approximate the nonlinear system with a linear time varying system [9]. The linearization steps and mechanism as well as the filtering algorithm model are illustrated in detail in [10]. However, the EKF follows the same process as the normal KF in measuring the input and output to obtain the minimum mean squared error of the true state [9]. On the other hand, the UKF provides better performance in terms of accuracy in SOC estimation and robustness [17]. The UKF was used in [20] for the state of charge estimation of the Li-ion battery set for the rover at NASA program and has delivered promising and accurate results. However, the UKF and EKF may be affected by the assumption that any noise has a Gaussian distribution [22] not to forget that the EKF has linearization errors.

Furthermore, there are other types of Kalman filters like the cubature Kalman filter (CKF) [17] and the adaptive cubature Kalman filter (ACKF) [17]. Research has shown that ACKF delivers better results in the SOC estimation than the EKF, UKF and CKF algorithms [17]. However, as expected, there is a high computational cost.

2.1.2.3. Open circuit voltage method

This method is the easiest, most straightforward compared to the previous techniques for the SOC estimation. It involves reading the battery open circuit voltage and then looking the corresponding SOC via interpolation using a given/pre-existing OCV vs SOC curve [9]. While this method has the potential to be accurate, obtaining the OCV curve involves significant effort.

2.2. Battery Lifetime and State of Health Estimation

SOC is not the only important parameter that needs to be estimated. As stated in [27], in order to improve the performance of any battery, the SOC and SOH should be monitored constantly. The state of health estimation is one of the major key points in order to achieve longer lifetime for the battery. Since the SOH is determined by comparing the rated capacity and the maximum estimated capacity [29], the state of health can be formulated as shown in equation (2):

$$SOH = \frac{C_{maximum\ releasable}}{C_{rated}} \times 100 \quad (2)$$

Meaning it is the ratio of the maximum releasable capacity relative to the rated capacity of the battery [9, 27, 29]. The maximum releasable capacity is related to the capacity fading of the battery; thus as the battery cycles increases the more capacity fading occurs, which leads to reduction in releasable capacity by the battery [11].

It is shown in [14, 18, 30] that the battery lifetime and capacity are affected by many factors but mainly by the DOD, the temperature of the battery and the charge/discharge current. Lowering the values for each one of the above factors can extend the battery lifetime and lower the effect of capacity fading. Moreover, temperature has a great effect on capacity loss during the storage of a battery [18]. Furthermore, NASA has published an article [18] specifying important guidelines for the use of Li-ion battery cells in space application. One of the many guidelines they have noted was to have an end of discharge voltage at all times which does not go below 2.5V for a 3.6V battery [18]. In addition to that, the optimum battery temperature should be between 20℃ and 40℃. Most importantly, [18] specifies that the number of charge/discharge cycles affects both the voltage and capacity of the battery which, as a result, effects the SOH of the battery as shown by equation 2 [27].

2.3. Satellites

Since cost is a critical factor for space missions, it has been important for designers to reduce the weight and size of the batteries in order to get the most out of the space investment [2]. Therefore, researchers have noted that Li-ion batteries are expected to currently replace all the batteries used for space applications [2]. The Li-ion battery has been widely used in the new satellites by most of the space agencies in the world such as NASA and European Space Agency (ESA). It has been commonly said that Li-ion batteries are the third generation of satellite power storage batteries instead of other batteries [19]. This has revolutionized the use of Li-ion battery applications due to its high energy density that aids in reducing the system weight of a spacecraft which, as a result, will improve the load efficiency of satellites [6, 19].

Extensive research has been conducted on the remaining useful life estimation of the battery which has been a tough challenge for researchers [19]. It is very critical for satellites to have an intelligent battery management system in order to optimize the use of the battery. D. Liu et al. in [19] have implemented a research to achieve a reliable framework for the remaining useful life (RUL) estimation for the Li-ion batteries. D. Liu et al.[19] have also presented an optimized ensemble echo state (ESN) algorithm to ensure accurate prediction and stability of the RUL [19]. They also implemented an experimental test on three single Li-ion batteries with a rated capacity of 10AH, and they are simulating a condition of LEO of charging/discharging the battery [19]. Finally, the experimental results in [19] proved the high effectiveness of the used RUL framework. Moreover, Wang et al. in [2] conducted a study on a 100Ah Li-ion class battery that is simulated in a GEO satellite operation; the simulation was conducted for 18 eclipse seasons in real time testing with five depths of discharge (DOD) patterns. Data in [2] has shown that the battery successfully operates and meets the requirement of the satellite at GEO mission profile. In addition to that, J. Koo, S. Lee and S. Ra in [31] provide a detailed design for a Li-ion battery for a satellite in GEO which includes cell modules design and the architecture and management during orbit.

The potentials of Li-ion batteries for space application compared to other batteries are illustrated by Mazlan [6] and are as the below:

1. High volume energy density for the battery meaning it needs less space to deliver the required amount of energy.
2. High mass energy density for the battery meaning that it aids in having the satellite mass low as possible.
3. High voltage per cell.
4. Low maintenance.
5. Low self-discharge – long storage/shelf life.

Moreover, in Table 4 the wide usage of Li-ion batteries in the space programs is clearly illustrated.

Table 4: Li-ion battery space applications [5]

Program	Customer	Launch	Energy (Wh)	Satellites
Roland	CNES	2003	73	1
Roland-2	CNES	2003	148.6	1
Beagle2	Matra Marconi Space	2003	291.6	1
Microsoft Bus	CNES	2003	345.6	4
New Millennium ST5	NASA	2003	54	3

2.4. Scheduling Techniques

Different varieties of scheduling techniques and strategies have been developed in the literature due to the high importance of optimization in such systems. One of the main topics that has attracted a lot of attention is battery scheduling [33]. For instance, it has been noted by Yang [33] that a battery energy storage system (BESS) is used to overcome the fluctuations of the distributed energy resources (DER). Consequently, an optimal scheduling strategy for the BESS was performed in order to diminish the active power loss and reduce the electricity cost to the minimum. Two strategies were used by Yang which are the day ahead and real time operation scheduling strategies. Yang has used a fuzzy mathematical method and an improved swarm optimization (IPSO) algorithm for the optimization mean. Finally, Yang performed simulation tests, which proved that the strategies are effective for the enhancement of the distribution network characteristics.

Additionally, many studies have been done on battery scheduling with the objective of extending the lifetime and runtime of the battery. Jongerden et al. [34] stated that battery scheduling over the load enables to exploit the recovery properties, which leads to augmenting the system lifetime. They have evaluated different scheduling schemes such as the round robin schedule, sequential schedule, best of two schedules and finally compared them to an optimal schedule that they developed. The battery behavior is modeled as a linear priced timed automata (LPTA), and it uses the model checker called Cora to generate the optimal schedules. It is important to mention that the complexity of obtaining the optimal schedule depends on the number of scheduling decisions that need to be made. The four different scheduling schemes that have been under study in [34] are:

1. Sequential scheduling: the batteries are scheduled in sequence, meaning that the second battery is used only when the first is completely empty.
2. Round robin scheduling: the battery is chosen depending on the new job. Therefore, a new battery for every new job.
3. Best of two schedules: at the beginning of the job, the battery status is checked and the battery with the most charge (SOC) is chosen to supply the charge for the job.

4. Optimal schedule: is the schedule computed using the Cora and can be referred to in [34].

Simulations for the above scheduling schemes were performed and a comparison was made using different loads for each scheduling method. Based on the results, it was concluded that the sequential scheduling is the worst of all. However, the round robin and best of two result in almost the same lifetime except for some cases of alternating jobs. This shows that for such a case round robin is not efficient enough. The best two schemes, however, balances the load between two batteries better which leads to a longer lifetime. Finally, the optimal scheduler had given a better result than all the others with a 32% improvement in the lifetime [34].

The use of battery models is essential for developing an optimized battery scheduling model [8]. A real time static task scheduling seeks to reduce the mean value of discharge current and shape the discharge profile in order to maximize the battery lifetime. In the same manner as in [34], three types of scheduling were proposed by Ravishankar et al. [8] which are:

1. Sequentially discharging scheme: same as the previous sequential scheduling discussed.
2. Static switching: the discharging of the battery happens for a fixed duration.
3. Dynamic switching: selecting the healthiest battery to discharge at any time instant dynamically while the others rest.

In order to compare the results, a monolithic equivalent of the multi battery system was used for comparison. The performed comparison stated that monolithic is the best of all, followed by the dynamic scheduling, then static scheduling and finally the sequential. It was also noted that as the frequency increased in the static switching model, it came very close to the monolithic battery case. Ravishankar et al. [8] have also proposed another approach for augmenting the lifetime of the battery by having a parallel discharge of multiple batteries; a nonlinear optimization model was used for this. This has been implemented with the multiple batteries connected in series which resulted in a good improvement in system lifetime for high current loads. Therefore, having multiple battery discharge sequentially is nothing close to better to the monolithic battery discharge. Having batteries in parallel simultaneously discharge is very equivalent to the monolithic scenario. The same was noted by Benini [35] who used three artificial workloads and one real life workload on 4 different battery cases. The first one is with two battery packs; the second is with four battery packs each with the same capacity; the third one has four packs, but one of them is for back up purpose and finally four batteries each with different capacities. However, in all cases the total capacity is the same, that is 1.5 Ah. The analysis was performed on the sequence, static and dynamic scheduling, same as [8] they were compared with the monolithic case of battery. The results have given the same conclusion as in [8]; however they have additionally stated that static scheduling is preferred for homogenous battery packs while dynamic is preferred for the asymmetric cells and non-uniform workloads. Further elaboration on the testing can be referred to in [35].

Another important battery scheduling case has been proposed by Miliche [32] in which battery scheduling is used to optimize the lifetime of mobile devices. The paper also illustrates three scheduling schemes, which are exactly the same ones as in [34]. However, the better of the two is renamed to pick the best scheduling. It is important to mention that all battery-scheduling techniques are limited to simple deterministic scheduling schemes; however, all of them augment the lifetime of the battery compared to the sequential case [32]. In addition to all that, an experimental setup was performed in [32] which had the objective of augmenting the lifetime of Thales communication system called CIM. The scheduling algorithm that was implemented for this experiment was the round robin method since it is the simplest to implement. The paper had concluded that the output gained from round robin is unpredictable, and it is not as high as predictable.

Kim and Shin [16] have proposed a new policy for scheduling battery cell activities which was called the weighted-k-round-robin (KRR) scheduling framework. The KRR dynamically adapts battery cell activities to load demands and the condition of each cell and thus augments the battery lifetime and make them robust to voltage imbalances [16]. In order to implement this, two main components are used, the first one is an adaptive filter to estimate the upcoming load demand, and the second is based on the load demand. The KRR scheduler determines k which is the number of parallel connected cells to be discharged simultaneously. The weighted KRR algorithm and architecture can be found in article [16] for further elaboration. In order to evaluate this new scheduling technique H. Kim and K. Shin [16] have performed simulation between 4 different scheduling schemes which include KRR,1RR (k=1), nRR and 1+ 1RR (sequential scheduling) and the results have proved that KRR allows the battery to last 56% longer than 1RR, and be 50% more fault tolerant of voltage imbalance than the nRR scheduling [16].

Many scheduling models that have been implemented on systems battery; Honarmand et al. [36] proposed a scheduling model for large number of EV parked in an urban parking lot. The model considered constraints such as the electricity price, remaining batter capacity, remaining charge time and the age of the battery. The energy management system will be managing the charging/discharging scheduling of the EV in the parking lots [36]. The main objective of the scheduling model is to maximize profit to each EV owner by means of charging and discharging at the right time. Of course this objective function is subject to some constraints such as the limits for the SOC for each battery etc. The mathematical formulation for the objective function and the constraints can be found and elaborated more in [36]. This model was solved through the use of nonlinear programming (NLP) solver. The article shows a simulation of the model and had concluded that it satisfies both financial and the electrical goals. In addition to this, Zakariazadeh et al. [37] have also added to the literature a new multi-objective scheduling method for charging/discharging the EV in a smart distribution system. The main objective of the scheduling method is to minimize the total operational cost and reduce the emission amount. The objective functions are subjected to constraints such as the load balancing etc [37]. The model has been solved through the use of mixed integer nonlinear programming (MINLP). The results of the model have been validated. It was concluded that the model can reduce both the cost and emissions [37]. Moreover, E. Limouzadeh and A.Kargar [38] implemented an optimal charge/discharge scheduling for electric vehicles by considering their battery lifetime. In this model the objective was to minimize the total operational costs of the EV subjected to constraints related to the battery lifetime of each EV. The mathematical formulation for the model is referred to in [38]. Another important article by C. Cao, M. Cheng and B, Chen [39] illustrates an optimization model for charging/discharging schedule of plug in electric vehicle (PEV) to reduce customer cost and improve grid performance. The model considered three cases: minimizing the cost, minimizing the power deviation from a pre-defined power profile and finally a combined objective function between the two. In the same manner, the mathematical formulation for the cases can be referred to in [39].

Finally, Park et al. [24] have performed a battery scheduling and battery assignment model on commercial drones with the objective of minimizing the SOH degradation of the battery. They noted that the two main factors affecting the SOH of the battery are the average SOC and the SOC swing of the batteries. The method for performing the models was divided into two stages: the first is the battery assignment which will be tackled through a heuristic algorithm and the second is the battery scheduling which will be solved through mixed integer linear programming (MILP). They have used the Chen and Mora circuit model [7] which is the one adopted in this thesis for simulating the short and long term degradation of the SOH. It is important to note that the scheduling model adopted by Park et al. [24] is very similar to the work we are conducting for the satellites in this thesis. It should be noted here that the scheduling problem will be obtaining the time instances at which a battery begins charging, terminates charging, begins discharging, and terminates discharging. The result of the test has shown that the model resulted in diminishing the electricity and battery purchasing cost by 25%, and the average packing waiting time by more than 50%.

2.5. Nayif-1 Overview

Nayif-1 is a 1 unit (1U) LEO cube sate that was designed by students from the American University of Sharjah (AUS) with the support and assistance from Sheikh Mohammed Bin Rashid Space Center (MBRSC) and Innovative Solutions in Space . The satellite was a passenger in the ISL 17 launch. The main objective of the satellite is to promote space science and technology in the UAE through the MBRSC outreach programs [40]. The Nayif-1 architecture of the satellite is shown in Figure 8. As stated in [40], the components of the satellite consist of the satellite structure and the antenna system as mechanical and communication systems. At the top panel of the satellite shown in Figure 8 is the generic interface system (IGIS). In addition, the three panels below the IGIS are the payload system which are the onboard computer payload interface board (CCT + ASIB), the radio frequency board (RF) and the power amplifier board (PA). For the power system of the satellite it contains the EPS which is the Gomspace nano power P31u and the iSPA set which is the solar panel set including the temperature sensor. Finally, the last panel contains magnetorquer board (iMTQ).

Moreover, Nayif-1 has mainly three modes of operations [40]:

1. Educational mode: this mode is when the satellite detects that it is in daylight, meaning that is receiving power from at least one of the solar panels. In this mode, the satellite is operating at maximum power.
2. Amateur mode: this mode is when the satellite detects that is in eclipse, in other words when it is receiving no current at all from the solar panels. In this mode, the amateur transponder is activated and the telemetry transmission is at lower output to allow enough power for the transponder.
3. Safe mode: when the satellite detects a battery voltage irregularity, it switches to this mode and operates at very low power. In this mode, the iMTQ is off; and the satellite transmits only the low power telemetry signals.

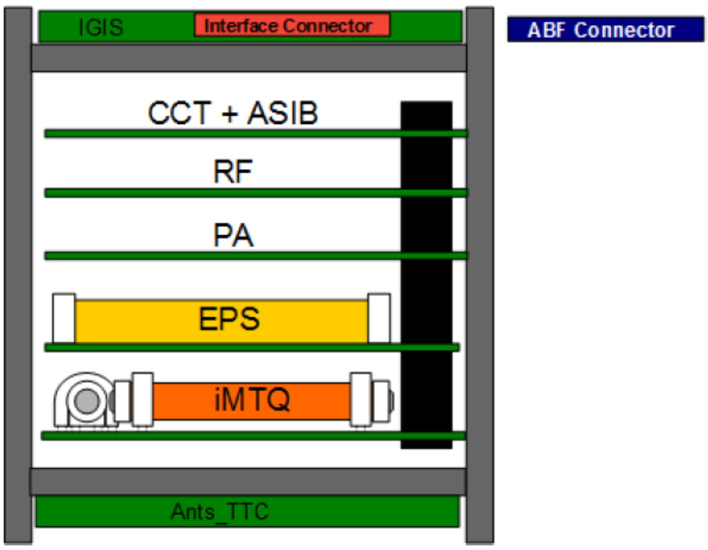

Figure 8: Nayif-1 architecture layout [40]

Furthermore, Nayif-1 is tracked from the ground station located at AUS which consists of a terminal, a computer for running the commanding software and the Nayif-1 dashboard. The Nayif-1 dashboard software which is written by AMSAT-UK is used to connect to the satellite to decode and display the telemetry data sent by the satellite [40].

The overall system of the satellite more specifically for the downlink system, the satellite transmits the telemetry through very high frequency (VHF) range which is received by the AUS ground station and is transmitted to the satellite control unit that is accessed by the Nayif-1 operators [41]. While for the uplink system, the telecommand is sent from the satellite control unit and the ground station command unit by the Nayif-1 operators to the AUS ground station and the telecommand is transmitted through ultra-high frequency (UHF) range to the satellite [41].

In addition to that, it was stated that the satellite health should be constantly monitored; the four main parameters that are critical are [40]:

1. Power balance: the balance between the power consumed and the power produced by the satellite.
2. Battery voltage: the maximum voltage of the battery should be 8.4 V and the minimum voltage is 6 V.
3. Spin rate: since a high spin rate can affect the quality of the communication with the satellite. The nominal spin rate is 20º/s and the critical spin rate is 100 º/s.
4. Temperature: it is important to have the temperature of the satellite in the range that it has been qualified. The temperature range qualification for the satellite is from -10℃ to 40℃.

Finally, it is important to mention the downlink structure of the Nayif1 without going into deep details about it. The satellite continually transmits telemetry data with 4 main telemetry types [42]:

1. Real time telemetry (RIT).
2. Whole orbit data (WOB).
3. High resolution data (HiRes).
4. Fitter messages.

From these four different downlink data, and for research purposes, the most important one is the WOB since it is the only one that conveys the satellite power system behavior throughout the whole 97 minutes orbital period while the others are only for certain time periods. Therefore, the focus will be on the WOB telemetry, the data for the WOB is comprised the following parameters [42]:

1. CCT microcontroller temperature.
2. RF board crystal temperature.

3. Solar panel temperatures.
4. Sun sensors.
5. Battery temperature.
6. Total solar panel current.
7. Total system current.

WOB data will be used in this thesis in order to be able to present a scheduling model based on the behavior of the satellite.

Chapter 3. Mathematical Model

This chapter, starts by introducing the type of battery currently used by Nayif-1 through specifying the important parameters and manufacturer recommendations. The chapter then tackles the model assumptions, model parameters, model decision variables and the model objective function along with the model constraints.

3.1. Nayif-1 Specifications

It is important to start this chapter by specifying the battery being currently used by Nayif-1 satellite. The battery used is a Nano power p31u manufactured by GOM space [30]. The p31u is designed for small, low cost satellites that have a power demands between 1-30W [30]. In addition to that, the p31u consists of two battery cells that deliver a total voltage of 6 -8.4V, giving a capacity of 5200 mAH along with three photovoltaic input converters [30]. Further information on the p31u can be found in [30]. Moreover, for each battery cell, it offers a capacity of 2600 mAH [14], Table 5 summarizes the main specifications for it:

Table 5: 1 Battery cell specification as per GOMspace [14]

Parameter	Condition	Minimum	Typical	Maximum	Unit
Voltage		3.0	3.7	4.2	V
Current - charge	0 - +45 °C		1000	2500	mA
Current - discharge	-20 - +5 °C +5 - +60 °C		1000	1250 3750	mA mA

Since the p31u contains two battery cells, some of the values in Table 5 are doubled in order to have the specifications of the p31u battery used in Nayif-1. Therefore, Table 6 shows the p31u battery specifications.

It is also important to know the different amounts of power demands the Nayif-1 satellite needs in order to be able to provide its activities. Based on the Nayif-1 operation manual [41] and the Nayif-1 commissioning plan document [40] Table 7 provides all the possible power demands for the satellite given the different modes of the satellite that were discussed in chapter 2.

Table 6: p31u battery specification [14, 30]

Parameter	Condition	Minimum	Typical	Maximum	Unit
Voltage		3.0	7.4	8.4	V
Current - charge	0 - +45 °C		1000	2500	mA
Current - discharge	-20 - +5 °C +5 - +60 °C		1000	1250 3750	mA mA

Table 7: Nayif-1 power consumptions [40, 41]

Nominal modes	Current consumption	Voltage	Power consumption
Safe Mode			
	183 mA @	6.8 V	1169 mW
	180 mA @	7 V	1185 mW
	177.3 mA @	7.2 V	1202 mW
	173 mA @	7.49 V	1221 mW
	169 mA @	7.8 V	1243 mW
Educational mode (sunlight)			
iMTQ off	244 mA @	7.5 V	1755 mW
iMTQ idle	270 mA @	7.5 V	1875 mW
iMTQ torque 50%	305 mA @	7.49 V	2134 mW
iMTQ torque 100%	410 mA @	7.5 V	2925 mW
Amateur mode (eclipse) transponder not used			
iMTQ off	208 mA @	7.51 V	1487 mW
iMTQ idle	233 mA @	7.5 V	1598 mW
iMTQ torque 50%	270 mA @	7.49 V	1872 mW
iMTQ torque 100%	373 mA @	7.47 V	2636 mW
Amateur mode (eclipse) transponder used			
iMTQ off	225 mA @	7.5 V	1613 mW
iMTQ idle	252 mA @	7.49 V	1737 mW
iMTQ torque 50%	288 mA @	7.49 V	2007 mW
iMTQ torque 100%	390 mA @	7.48 V	2767 mW

Based on Table 7, we can conclude that the satellite has a maximum power demand of 2.925 Watts and a minimum power demand of 1.169 Watts.

3.2. Model Setup

The objective of the thesis is to develop and solve a mathematical model that provides an optimal switching of the battery and amount of current for charging/discharging states. Consequently, the solution of this mathematical model will minimize the SOH degradation of the battery and as result augment the battery lifetime and cycle lifetime of LEO satellite.

3.2.1. Model assumptions

The proposed model assumes the following:

1. The initial state of charge of the battery is 99%.
2. The battery is operating at an average temperature of 23ºC.
3. The depth of discharge of the battery remains constant for determining the expected lifetime enhancement of the battery.

3.2.2. Model parameters and indices

k Time step.

Δt Step size.

$Ps_{k\Delta t}$ Power supplied by solar panels at time kΔt (Watts).

$P_{k\Delta t}$ Demanded power at time kΔt (Watts).

C_{rated} Rated capacity of the battery (Ah).

3.2.3. Decision variables

The following are the decision variables of the model:

$SP_{k\Delta t}$ A binary variable that represents the solar panel switch state and is equal to 1, if the solar panels are supplying the demand of the system at time step t, 0 otherwise.

$CH_{k\Delta t}$ A binary variable that represents the battery charging state switch and is equal to 1, if the battery is charging from the solar panels at time step t, 0 otherwise.

$DCH_{k\Delta t}$ A binary variable that represents the battery discharging state switch and is equal to 1, if the battery is discharging and supplying the demand of the system at time step t, 0 otherwise.

It is important to have specific state switches for the charging and discharging states of the battery since the switch states are not complimentary. Although the battery cannot charge and discharge simultaneously, the battery can be kept at rest and thus both the charging and discharging switch states can be zero.

$C_{k\Delta t}$	A non-integer variable that represents the charging current of the battery and is greater than 0, if the battery is charging from the solar panels at time step t, 0 otherwise (Amps).
$D_{k\Delta t}$	A non-integer variable that represents the discharging current of the battery and is greater than 0, if the battery is discharging and supplying the demand of the system at time step t, 0 otherwise (Amps).

The following are variables that are calculated based on the decision variables:

$SOC_{k\Delta t}$	State of charge of the battery at time kΔt.
$DOD_{k\Delta t}$	Depth of discharge of the battery at time kΔt.
$V_{k\Delta t}$	Battery voltage at time kΔt (Volts).
$Cmax_{Cycle\#}$	Maximum capacity per cycle number (Ah).
$Cretained_{cycle\#}$	Percent of capacity retained per cycle number.
$SOHdeg_{k\Delta t}$	State of health degradation at time kΔt.
$Vst_{k\Delta t}$	Short transient voltage of the battery at time kΔt (Volts).
$Vlt_{k\Delta t}$	Long transient voltage of the battery at time kΔt (Volts).
$Eo_{SOC_{k\Delta t}}$	Open circuit voltage at SOC (kΔt) (Volts).
$Rst_{SOC_{k\Delta t}}$	Short transient resistor at SOC (kΔt) (Ohms).
$Rlt_{SOC_{k\Delta t}}$	Long transient resistor at SOC (kΔt) (Ohms).
$Cst_{SOC_{k\Delta t}}$	Short transient capacitor at SOC (kΔt) (Farads).
$Clt_{SOC_{k\Delta t}}$	Long transient capacitor at SOC (kΔt) (Farads).
$Rs_{SOC_{k\Delta t}}$	Series resistor at SOC (kΔt) (Ohms).

3.2.4. Objective function

This thesis focuses on minimizing the degradation of the battery for the LEO satellites. Three objective functions will be implemented, solved and compared. The formulations are given by equation 3 to 5.

$$Minimizing\ battery\ switch\ states\ = \sum_{k=1}^{N} (CH_{k\Delta t} + \ DCH_{k\Delta t}) \tag{3}$$

$$Minimizing\ sum\ product\ of\ battery\ switch\ states\ and\ battery\ current \tag{4}$$
$$= \sum_{k=1}^{N} (CH_{k\Delta t} \times C_{k\Delta t} + \ DCH_{k\Delta t} \times D_{k\Delta t})$$

$$Minimizing\ DOD\ = \sum_{k=1}^{N} (DOD_{k\Delta t}) \tag{5}$$

The objective function (3) will minimize the battery state switches since it will result in reducing the SOC swing of the battery, and as mentioned earlier in chapter 2, reducing the SOC swing will result in increasing the lifetime of the battery. As for objective function (4), it will minimize the sum product of the battery state switches and the battery current; the reason for having this objective function is simply because that as the battery current is reduced the life time of the battery will be enhanced as stated earlier in chapter 2. Finally, the objective function (5) will minimize the overall DOD of the battery since the DOD has a direct effect on the maximum capacity of the battery after every cycle, and the maximum capacity of the battery is linked to the SOH degradation estimation of the battery. All the objective functions will result in minimizing the SOH degradation by the end of one orbital period of the Nayif-1 satellite (97 minutes); therefore the SOH degradation for each objective will be compared.

3.2.5. Constraints

The objective functions are subject to the following constraints:

1. Battery charge and discharge switch states are not simultaneous:

$$CH_{k\Delta t} \times DCH_{k\Delta t} = 0 \tag{6}$$

2. Battery charge switch can be on only when the solar panel switch is on:

$$CH_{k\Delta t} \leq SP_{k\Delta t} + DCH_{k\Delta t} \quad (7)$$

3. Limits of the SOC of the battery:

$$0.3 \leq SOC_{k\Delta t} \leq 1 \quad (8)$$

This constraint protects from overcharging and deep discharging the battery since they affect the battery lifetime as previously mentioned in chapter 1 and 2.

4. Charge and discharge limits:

$$0 \leq C_{k\Delta t} \leq 2.5 \quad (9)$$

$$0 \leq D_{k\Delta t} \leq 3.75 \quad (10)$$

These constraints are for the charge and discharge current limits of the battery that are specified by the manufacturer respectively. NASA guidelines for Li-ion use in space clearly specified that no battery cell should be discharged or charged at currents higher than the specified ratings by the manufacturer [14].

5. Limits of the DOD of the battery:

$$DOD_{k\Delta t} \leq 0.2 \quad (11)$$

The maximum allowable depth of discharge for the battery is specified by the manufacturer is 0.2. This constraint is important because as previously mentioned in chapter 2 that higher DOD results in reducing the battery lifetime.

6. Satisfying the required power demand:

$$SP_{k\Delta t} \times (Ps_{k\Delta t}) + DCH_{k\Delta t} \times (D_{k\Delta t} \times V_{k\Delta t}) - CH_{k\Delta t} \times (C_{k\Delta t} \times V_{k\Delta t}) \geq P_{k\Delta t} \quad (12)$$

$P_{k\Delta t}$ includes the power for altitude control of battery, the power for transmitting and receiving and finally the power for heating the battery when necessary. The data for $P_{k\Delta t}$ *and* $Ps_{k\Delta t}$ are going to be provided from the power budget estimation data retrieved for the Nayif-1 satellite which is shown in Appendix A. This constraint is important since it makes sure that the power equation is balanced, and that the battery is not charged more than required. At the same time, it ensures having the power demand satisfied in all cases.

7. Limits of battery terminal voltage:

$$6 \leq V_{k\Delta t} \leq 8.4 \quad (13)$$

According to manufacturer's specifications, the minimum voltage should not go below 6 volts and above the maximum volts of 8.4 [40]. As per NASA guidelines for Li-ion use in space, no battery should be allowed to discharge below or charge above the specified voltage by the manufacturer [14].

8. Battery state of charge:

$$SOC_{k\Delta t} = SOC_{(k-1)\Delta t} - DCH_{k\Delta t} \frac{\Delta t \times D_{k\Delta t}}{Cmax_{Cycle\#}} + CH_{k\Delta t} \frac{\Delta t \times C_{k\Delta t}}{Cmax_{Cycle\#}} \quad (14)$$

The SOC of the battery will be updated after each Δt through equation 14 which is based on Coulomb counting estimation technique in [15] discussed earlier in chapter 2.

9. Maximum capacity change through time:

$$Cmax_{cycle\#} = Cretained_{cycle\#} \times C_{rated}, \quad Cretained_{cycle\#} \in [0,1] \quad (15)$$

Where $Cmax_0 = C_{rated}$

The maximum capacity of the battery after every cycle is the result of capacity fading as previously illustrated in chapter 1 and 2. Since, the capacity of the battery is affected by number of cycles and depth of discharge for each cycle the battery goes through, as stated in [27]. It is also stated in [12] that the rate of the SOH degradation is affected by the SOC swing of the battery. C_{rated} is given by the manufacturer as stated in [30] which is 5200 mAH equivalent to 312 Amin.

The values for $Cretained_{cycle\#}$ had to be calculated based on Figure 9 and Figure 10. Based on Figure 9 and Figure 10 it was concluded that for the two batteries after 300 cycles, the maximum capacity they can deliver is 87% of the rated capacity. Thus, they lost 13% of its capacity by cycle number 300 [11]. However, this is for the case when the battery goes from 100% SOC to 0% SOC, in the current case of Nayif-1 that does not happen in the 97 minutes orbital period. Therefore, the model will multiply this value by the decrease in the SOC for the first cycle. In other words $Cretained_{cycle\#}$ are calculated as per equation (16).

$$Cretained_{cycle\#} = 1 - \frac{0.13}{300} \times \sum_{k=1}^{N} (DOD_{k\Delta t}) \quad (16)$$

Based on this calculation for the maximum capacity, the SOH degradation is calculated as per equation (17)

$$SOHdeg_{k\Delta t} = \left(1 - \frac{Cmax_{cycle\#}}{C_{rated}}\right) \quad (17)$$

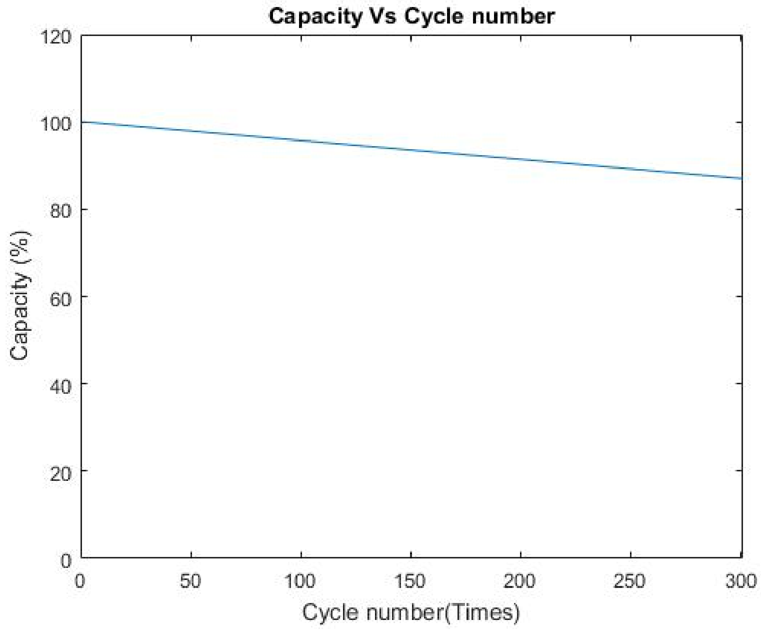

Figure 9: Percent capacity vs cycle number for 2.2AH battery at 23ºC [11]

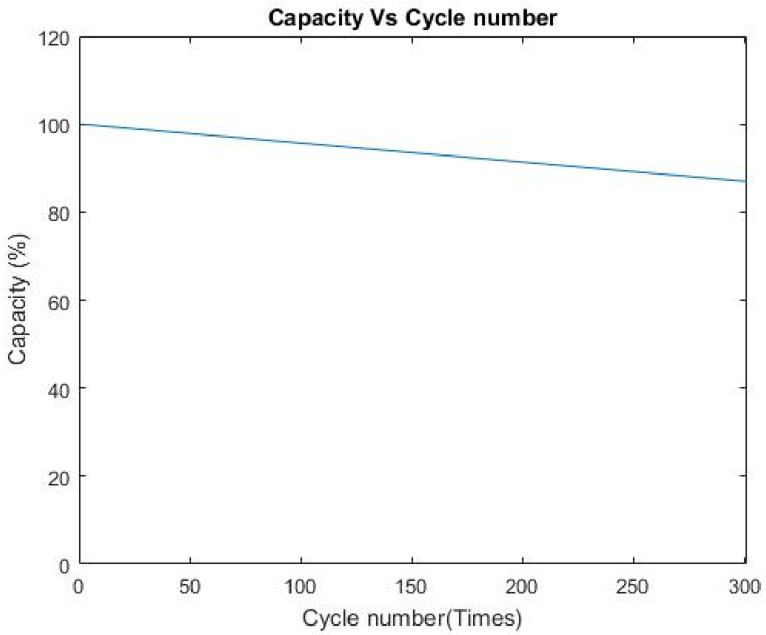

Figure 10: Percent capacity vs cycle number for 2.2AH battery (NMC electrode) [11]

10. Battery voltage estimation:

$$Vst_{k\Delta t} = Vst_{(k-1)\Delta t} - \frac{\Delta t \times Vst_{(k-1)\Delta t}}{Rst_{SOC_{k\Delta t}} \times Cst_{SOC_{k\Delta t}}} + DCH_{k\Delta t} \frac{\Delta t \times D_{k\Delta t}}{Cst_{SOC_{k\Delta t}}} - CH_{k\Delta t} \frac{\Delta t \times C_{k\Delta t}}{Cst_{SOC_{k\Delta t}}} \quad (18)$$

$$Vlt_{k\Delta t} = Vlt_{(k-1)\Delta t} - \frac{\Delta t \times Vlt_{(k-1)\Delta t}}{Rtl_{SOC_{k\Delta t}} \times Ctl_{SOC_{k\Delta t}}} + DCH_{k\Delta t} \frac{\Delta t \times D_{k\Delta t}}{Ctl_{SOC_{k\Delta t}}} - CH_{k\Delta t} \frac{\Delta t \times C_{k\Delta t}}{Csl_{SOC_{k\Delta t}}} \quad (19)$$

$$Eo_{SOC_{k\Delta t}} = -a_1 e^{-a_2 SOC_{k\Delta t}} + a_3 + a_4 SOC_{k\Delta t} - a_5 {SOC_{k\Delta t}}^2 + a_6 {SOC_{k\Delta t}}^3 \quad (20)$$

$$Rst_{SOC_{k\Delta t}} = -a_7 e^{-a_8 SOC_{k\Delta t}} + a_9 \quad (21)$$

$$Rlt_{SOC_{k\Delta t}} = a_{10} e^{-a_{11} SOC_{k\Delta t}} + a_{12} \quad (22)$$

$$Cst_{SOC_{k\Delta t}} = -a_{13} e^{-a_{14} SOC_{k\Delta t}} + a_{15} \quad (23)$$

$$Clt_{SOC_{k\Delta t}} = -a_{16} e^{-a_{17} SOC_{k\Delta t}} + a_{18} \quad (24)$$

$$Rs_{SOC_{k\Delta t}} = a_{19} e^{-a_{20} SOC_{k\Delta t}} + a_{21} \quad (25)$$

$$V_{k\Delta t} = Eo_{SOC_{k\Delta t}} - Vst_{k\Delta t} - Vlt_{k\Delta t} - DCH_{k\Delta t}(D_{k\Delta t} \times Rs_{soc}) + CH_{k\Delta t}(C_{k\Delta t} \times Rs_{SOC_{k\Delta t}}) \quad (26)$$

Equations (17) to (26) are based on the Chen and Mora circuit model representation for the Li-ion battery [7, 15] shown in Figure 7. The parameters a_1 to a_{21} are retrieved from [7] and multiplied by 2 since they represent one battery cell of 3.6-4.1 voltage while the Nayif-1 battery is a two cells batter of 6-8.4 voltage. For the parameters $Vst_{k\Delta t}$ and $Vlt_{k\Delta t}$ they had to be estimated based on the Chen and Mora model [7] in order to reduce the computation complexity in LINGO. Thus, the researcher implemented the Chen and Mora model simulation on MATLAB and graphed the parameters as per Figure 11 and Figure 12.

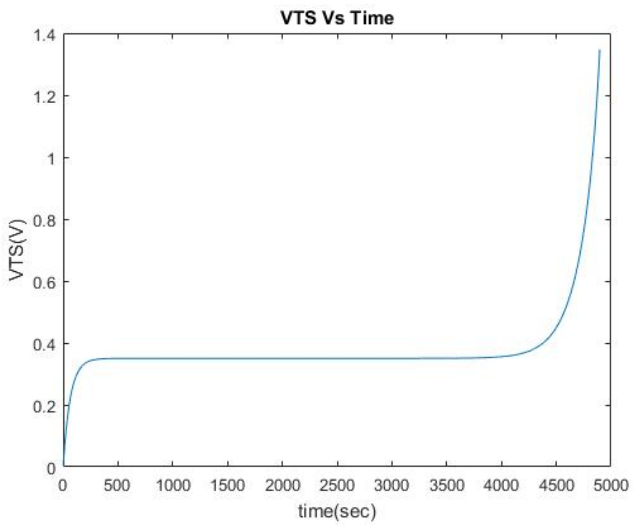

Figure 11: VTS Vs Time

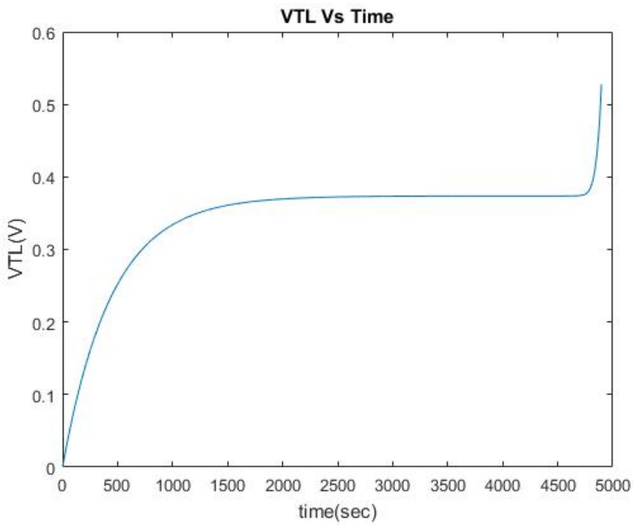

Figure 12: VTL Vs Time

An estimate value for the parameters was determined by taking the average of all values for the VTS and VTL until the values start shooting. As per the results from the MATLAB simulation, the shooting starts at period 4102 for VTS and 4674 for the VTL. Thus, the estimated value for VTS and VTL are 0.344975 Volts and 0.338128 Volts respectively. The MATLAB code can be referred to in Appendix C.

11. Depth of discharge estimation for each time period:

$$DOD_{k\Delta t} = SOC_{(k-1)\Delta t} - SOC_{k\Delta t} \tag{27}$$

The DOD of the battery will be calculated continuously as the battery is discharging using equation (27) which is simply the difference between the previous SOC of the battery and the current SOC of the battery after satisfying the power demand.

This mathematical setup will be the model which will be simulated on LINGO solver in order to solve the mixed integer nonlinear model and provide optimal solutions for each objective function. This means that the application will be implemented offline; however, in order to have it online, there is need for programming the model into a microcontroller that will be attached to the satellite.

Chapter 4. Heuristic Approach

As an alternative to our model in chapter 3 to provide wider scope of comparison; a heuristic approach was developed to solve the problem under study with the objective of diminishing the SOH degradation of the LEO satellite battery. A flow chart representing the heuristic algorithm is shown in Figure 13.

The heuristic starts with checking if the power supplied by the solar panel is greater than the demanded of power. If the solar panel power is more than the demanded power, the solar panel switch state will be on and will supply the demanded power, the model will simultaneously check if the SOC of the battery is less than 100%. If the SOC is less than 100% the battery charge switch and solar panel switch state will be on and the solar panel will charge the battery with a current of 0.0400 Amps which is four hundredth of the typical charging current specified by the manufacturer specifications of the battery [14]. Moving on, if the demanded power is greater than the power supplied by solar panels, and the solar panel power is greater than 0, entails that it is a peak power demand period. The model will check if the SOC of the battery is more than 30%, if yes the battery discharge switch and solar panel switch state will be on, and the battery will be discharging the satellite with exactly the remaining power needed to aid the solar panels. If the power of the solar panels is 0, then the battery discharge switch will be on and will be providing the system with the demanded power through the battery. Finally, if the demanded power of the system is 0 and the solar panel power is greater than 0, the model will check if the SOC of the battery is below than 100%. If yes, the solar panel switch state and the battery charging switch will be on and the solar panels will be charging the battery. The algorithm for this loop for the whole orbital period is shown below:

for i=1:97
    if $(P_{demand}(i) \leq P_{solar}(i))$
        $S_{PV}(i) = 1;$
        if $(SOC_B(i-1) < 1)$
            $CH_B(i) = 1;$
        end
      elseif $(P_{demand}(i) > P_{solar}(i))$ && $(P_{solar}(i) > 0)$
            if $(SOC_B(i-1) > 0.3)$
            $DCH_B(i) = 1;$
            $S_{PV}(i) = 1;$
            end
        elseif $(P_{solar}(i) == 0)$

if $(SOC_B(i-1) > 0.3)$
$DCH_B(i) = 1;$
$S_{PV}(i) = 0;$
end
elseif $(P_{demand}(i) == 0)$
if $(SOC_B(i-1) < 1)$
$S_{PV}(i) = 1;$
$CH_B(i) = 1;$
end
end
end for

The heuristic was coded and solved using MATLAB and the computation time was in seconds. The results generated for the heuristic are discussed in chapter 5.

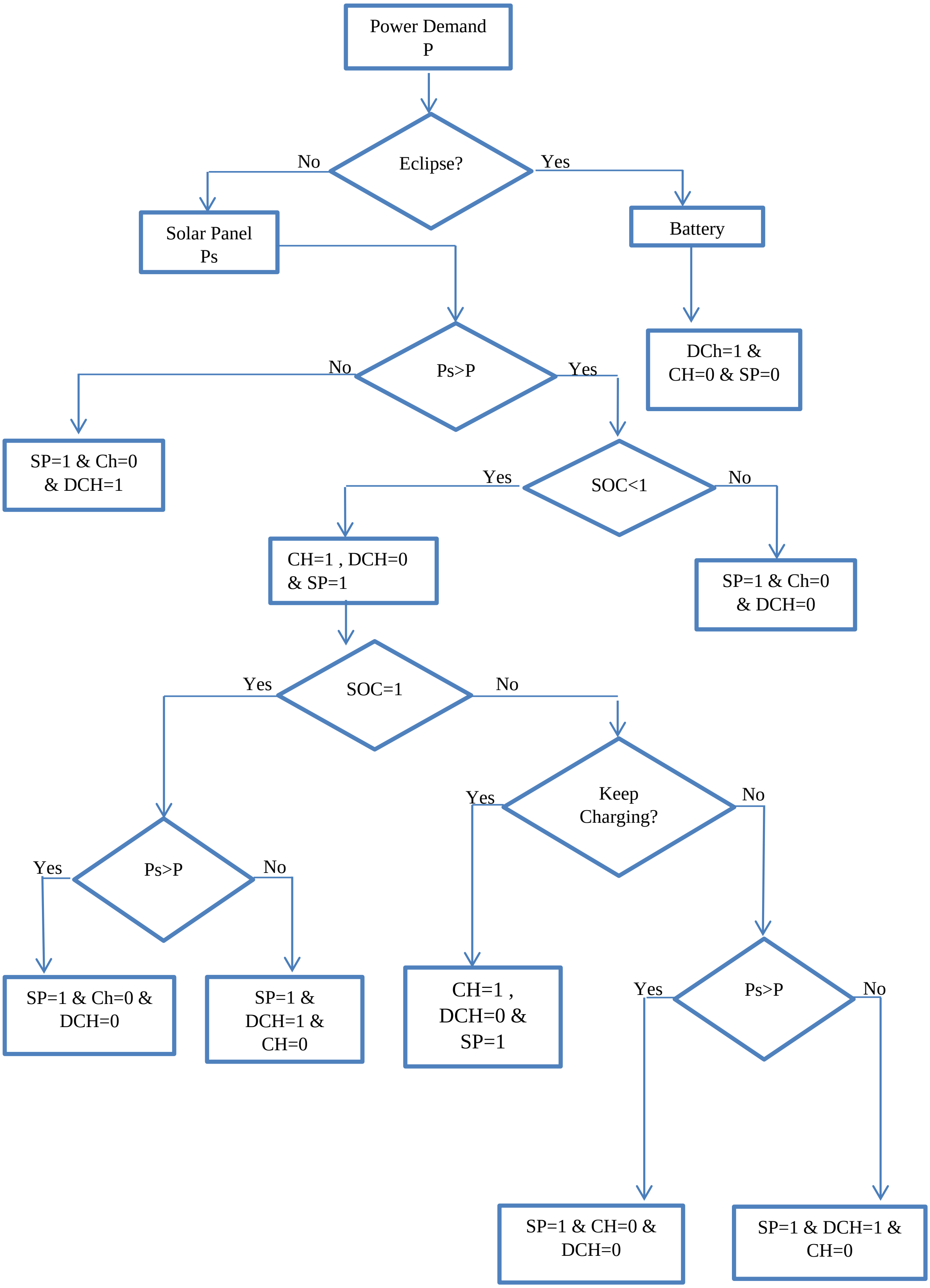

Figure 13: Model flow chart

Chapter 5. Results and Analysis

In this chapter, the current case of Nayif-1 will be presented as well as the results for the three objective functions together with the heuristic results. The code for each case can be referred to in Appendix D.

5.1. Simulation Results

5.1.1. Nayif-1 current case

A real time data from Nayif-1 was collected and analyzed in order to study the satellite power system behavior during a real whole orbit equivalent to 97 minutes. The data was collected with the aid of Mr. Ibrahim Abu Saif from the Nayif-1 AUS control center. The data under study can be referred to in Appendix A. It is important to mention that the Nayif-1 power system behaves as the following manner. Whenever the sunlight is hitting the satellite, the solar panels would be supplying and charging the battery if and only if the power generated from the solar panels is more than the demanded power and the charging is needed to keep the voltage limit high; however, if the power supplied by the solar panels is not sufficient, the battery kicks in to aid the solar panels to satisfy the demanded power. On the other hand, during every orbit, the satellite faces eclipse for around 31 minutes, and it is usually from period 41 to 71 from the total 97 minutes whole orbital period. During this eclipse period, the solar panels generate no power and the battery supplies the whole demanded power during this period.

Based on such information and the data gathered, the charging and discharging switches of the battery are determined as shown in Appendix A. Consequently, current scenario have been implemented on LINGO in order to have a better understanding of the battery behavior, then the battery SOH degradation is calculated accordingly. The most important results obtained from this current case are summarized in Table 8 and the behavior of the battery is summarized in Figure 14 to Figure 18. The LINGO code is found in Appendix B. Based on the results, the battery goes through a DOD of 0.021186 which yield a SOH degradation value of 9.1806E-06 and maximum capacity of 311.9971357 Amin at the end of the orbital period. Those are the main critical values which will be compared with the model results in order to determine the improvement it provides.

Table 8: Current Case results

Charge time usage	22 minutes
Discharge time usage	32 minutes
Solar panel time usage	66 minutes
Average discharge current	0.207 Amps
Average charge current	0.123 Amps
Average discharge power	1.540 Watts
Average charge power	0.926 Watts
Cycle number	1
Maximum capacity/cycle	311.9971357 Amps minutes
DOD/cycle	0.021186
SOH degradation/cycle	9.1806E-06

It is important to note that based on Figure 14, the charging switch is on and the solar panels charge the battery for a period of 10 minutes in total from the 39 minutes available before the discharging switch kicks in and discharge the battery for a period of 32 minutes. The solar panels then charge the battery for a period of 12 minutes in total from the available time of 26 minutes until the first orbital period ends, yielding a final SOC of 97.8% at the end of the first orbital period based on Figure 15. In addition, Figure 16 shows that the average voltage of the battery is 7.4871 Volts throughout the first orbital period and an end voltage of 7.5058 Volts at the end of the orbital period.

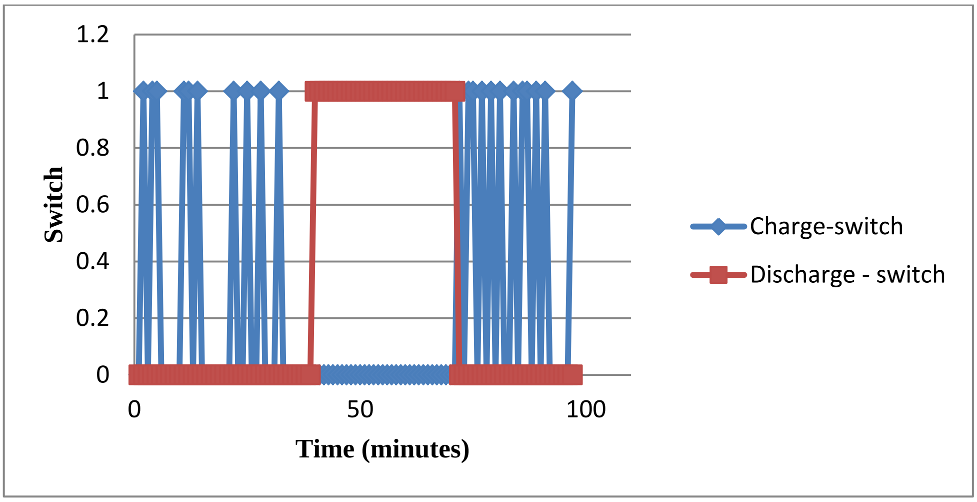

Figure 14: Current case battery switch states vs Time graph

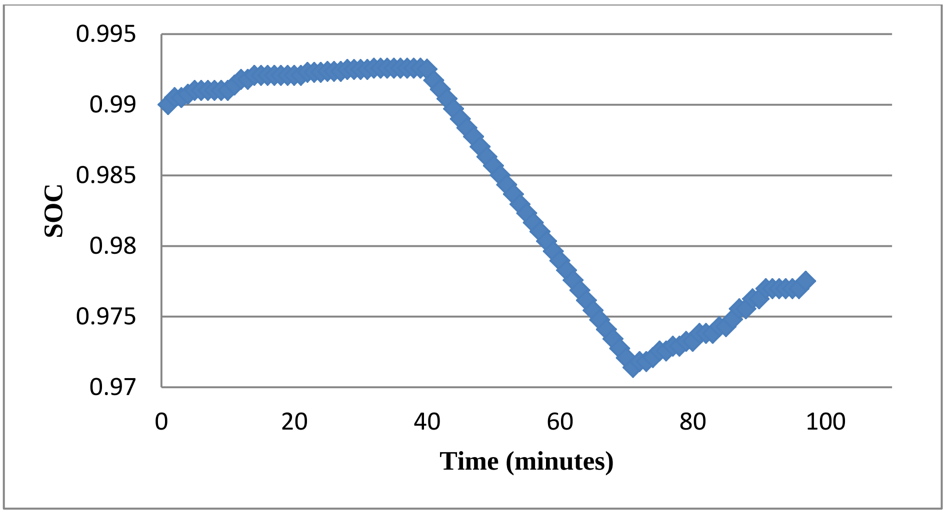

Figure 15: Current case SOC vs Time graph

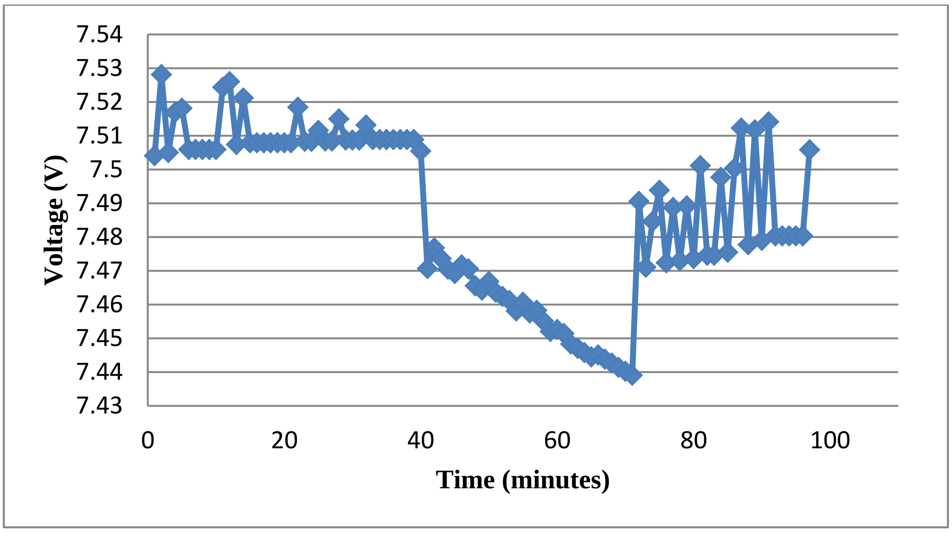

Figure 16: Current case voltage vs Time graph

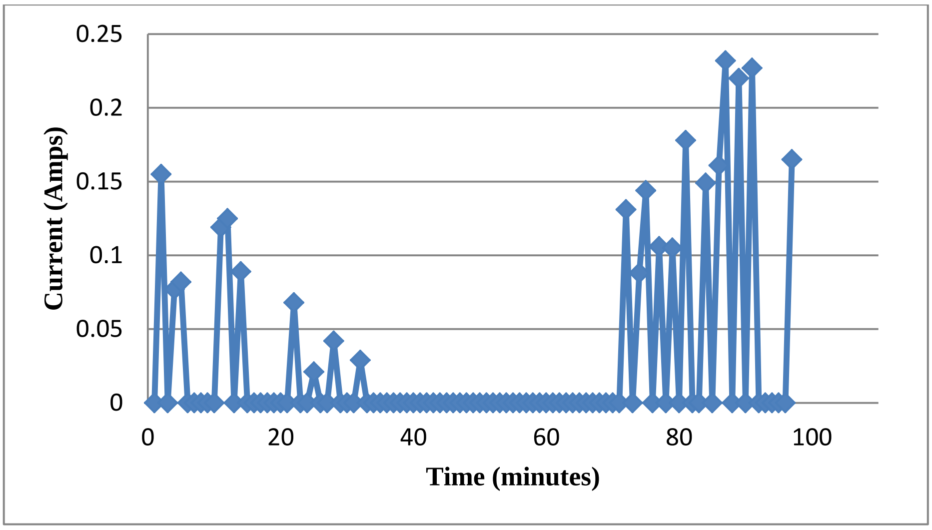

Figure 17: Current case charge current vs Time graph

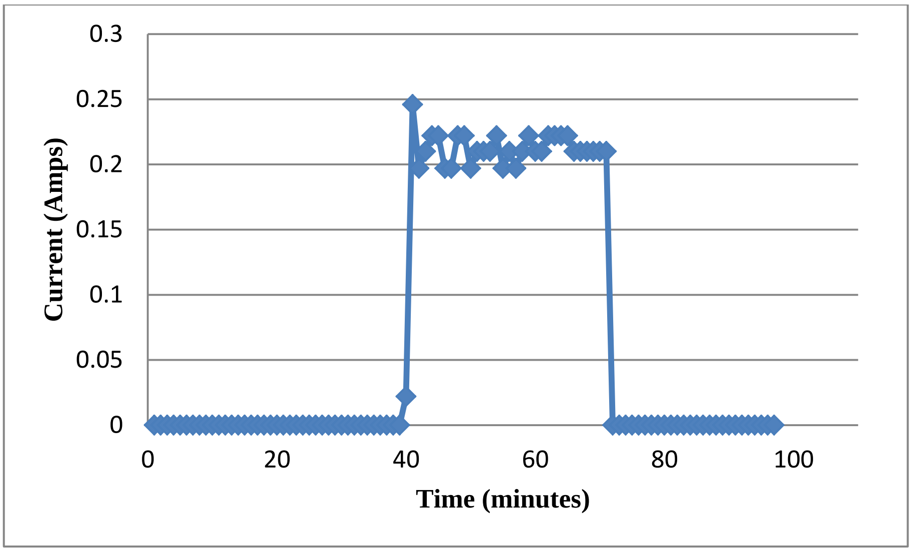

Figure 18: Current case discharge current vs Time graph

5.1.2. Results for objective function I

For the first objective function (equation 3, Chapter 3) which is minimizing the battery charging and discharging switches, the results are summarized in the Table 9 and Figure 19 to Figure 23.

The results show that battery goes through a DOD of 0.021173 which is less than the current case illustrated earlier which was 0.021186. This yields a SOH degradation value of 9.1750E-06 which is also less than the current case which was 9.1806E-06.

Table 9: Objective function I results

Charge time usage	41 minutes
Discharge time usage	32 minutes
Solar panel time usage	66 minutes
Average discharge current	0.206 Amps
Average charge current	0123 Amps
Average discharge power	1.540 Watts
Average charge power	0.925 Watts
Cycle number	1
Maximum capacity/cycle	311.9971374 Amps minutes
DOD/cycle	0.021173
SOH degradation/cycle	9.1750E-06

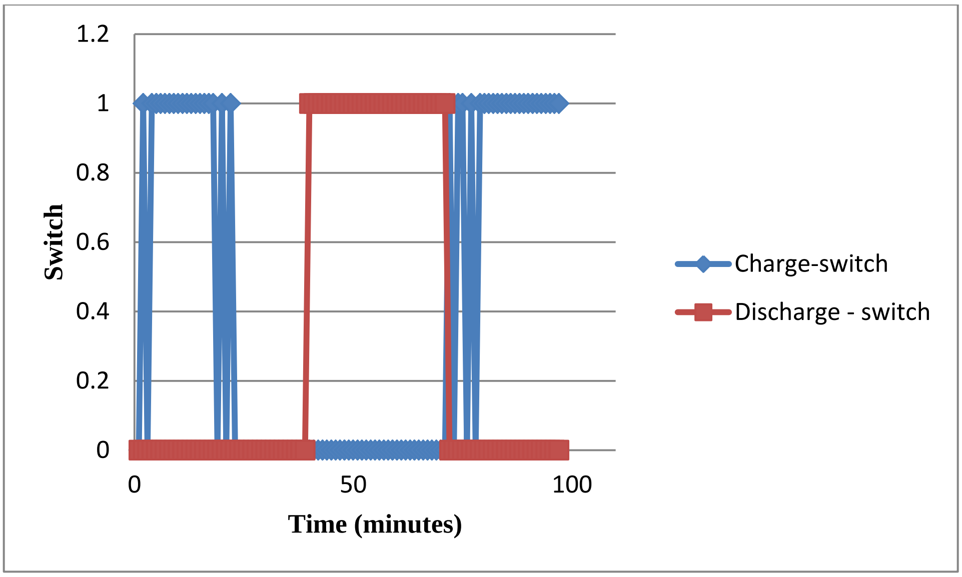

Figure 19: Objective function I battery switch states vs Time graph

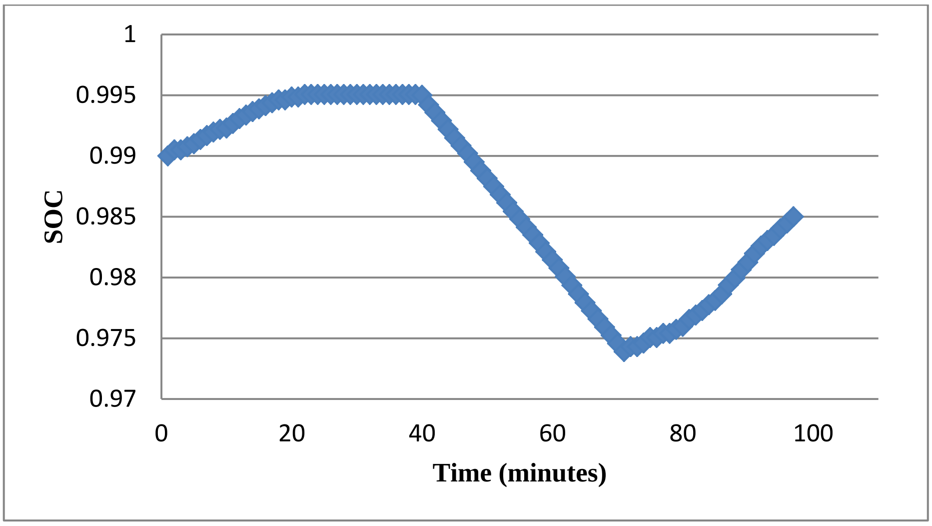

Figure 20: Objective function I SOC vs Time graph

It is important to note that based on Figure 19, the charging switch state is on and the solar panels charge the battery for a period of 18 minutes in total from the 39 minutes available before the discharging switch kicks in and discharge the battery for a period of 32 minutes. The solar panels then charge the battery for a period of 23 minutes in total from the available time of 26 minutes until the first orbital period ends, yielding a final SOC of 98.5% as shown in Figure 20. Based on Figure 21 the average voltage of the battery is 7.4956 Volts throughout the first orbital period, and an end voltage of 7.5194 Volts, which is better than the current case of Nayif-1 data which had a value of 7.5058 Volts. In addition, based on Figure 22 and Figure 23, the solar panels charge the battery for the period at which the battery charging switch is on by an average current of 0.123 Amps, at the period when the discharging switch is on which starts at period 40 which has the least value. The reason for that is because it is a period of peak demand for the system, and solar panels are not providing enough power, while at the later periods, the battery solely provides power to the satellite with average discharge current of 0.206 Amps. Moreover, since the SOC at the end of the first orbital period is higher than the current case, this means that in the next orbit the satellite battery will have a higher SOC to start. As result the battery will need less current to satisfy the required demand which will lead for the SOH degradation to be less than the current case of Nayif-1 at the second orbital period in specific and future orbits in general. Thus, the model can be generalized for all orbits of the satellite to improve the SOH degradation of the battery.

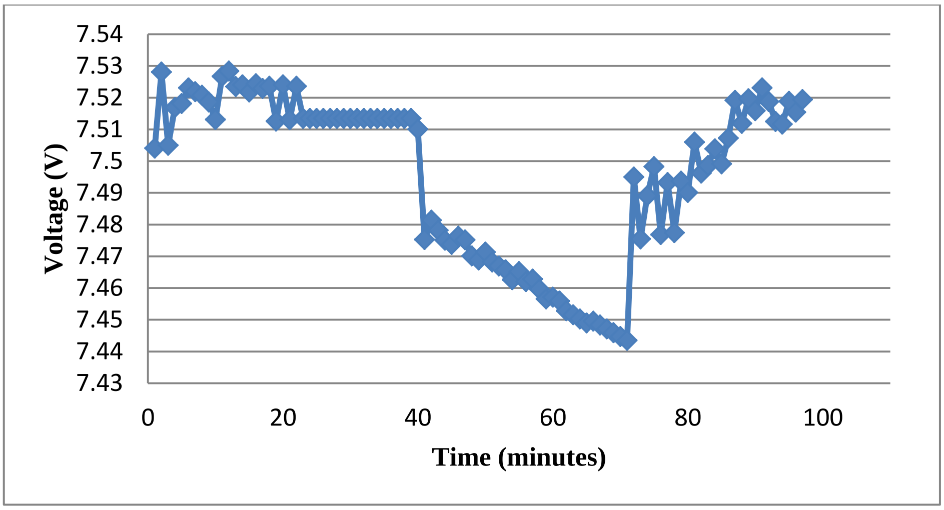

Figure 21: Objective function I voltage vs Time graph

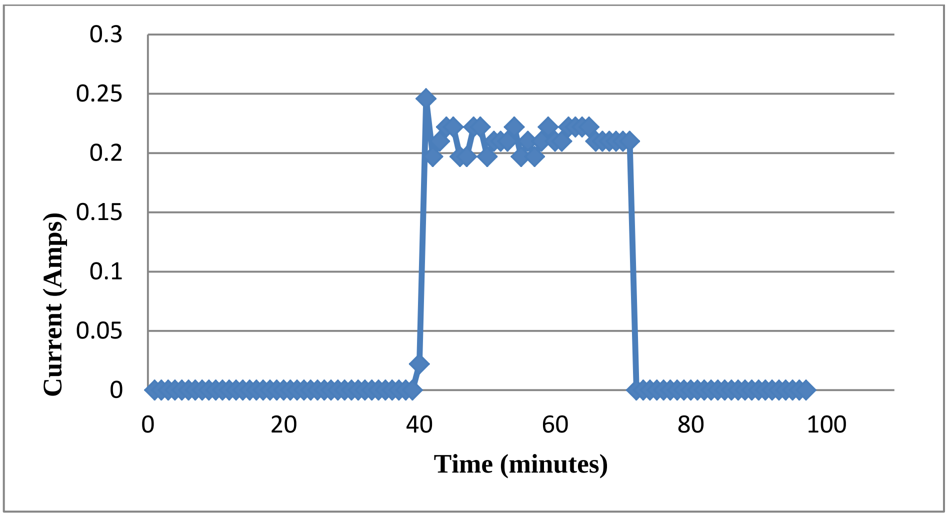

Figure 22: Objective function I Discharge current vs Time graph

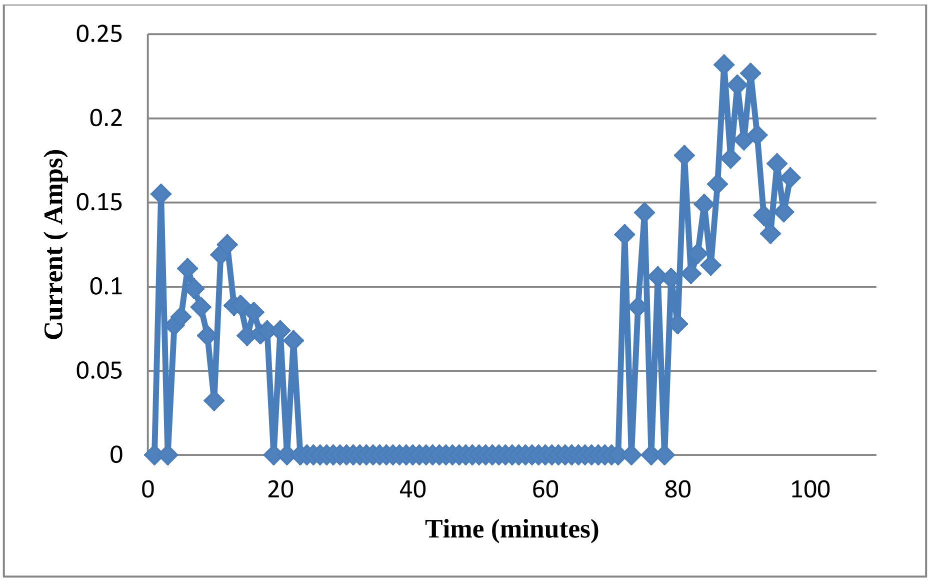

Figure 23: Objective function I charge current vs Time graph

5.1.3. Results for objective function II

As previously presented in chapter 4, the second objective function is shown in equation 4 which is the sum product of the battery current and the battery switch states. The results of this model are summarized in the Table 10 and Figure 24 to Figure 28.

Table 10: Objective function II results

Charge time usage	62 minutes
Discharge time usage	32 minutes
Solar panel time usage	66 minutes
Average discharge current	0.206 Amps
Average charge current	0.088 Amps
Average discharge power	1.540 Watts
Average charge power	0.665 Watts
Cycle Number	1
Maximum Capacity	311.9971389 Amps minutes
DOD	0.021162
SOH degradation	9.17021E-06

Based on the results in Table 10, the battery goes through a DOD of 0.021162 which is less than the current case of Nayif-1 illustrated earlier which was 0.021186.

This yields a SOH degradation value of 9.1702E-06 which is also less than the current case of Nayif-1 which was 9.1806E-06.

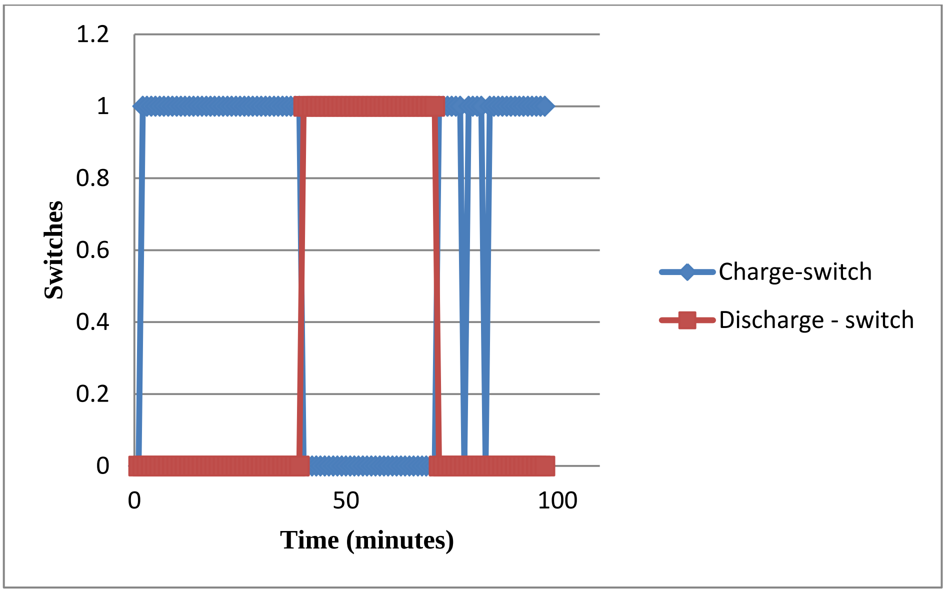

Figure 24: Objective function II battery switch states vs Time graph

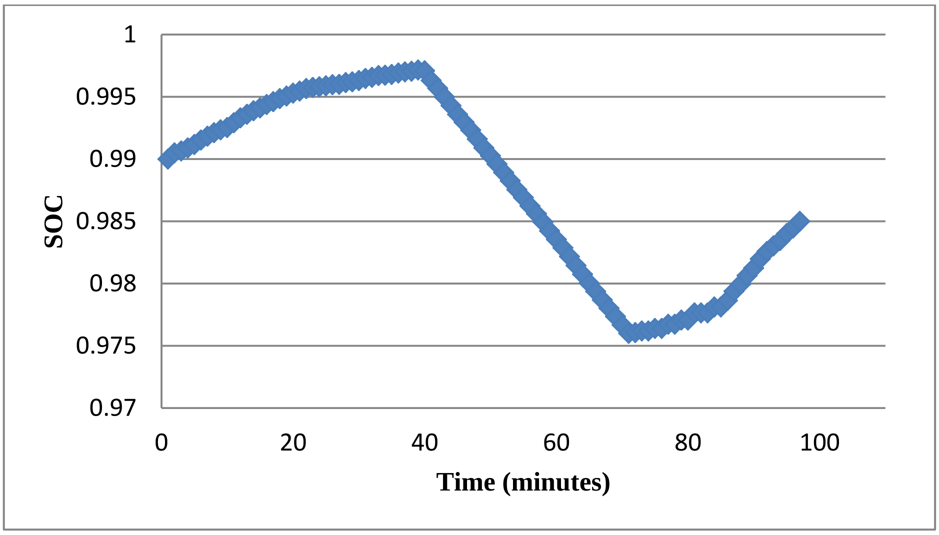

Figure 25: Objective function II SOC vs Time graph

Based on the results from Figure 24, the charging switch state is on and the solar panels charge the battery for a period of 38 minutes in total from the 39 minutes available before the discharging switch kicks in and discharge the battery for a period of 32 minutes. The solar panels then charge the battery for a period of 24 minutes in total from the available time of 26 minutes until the first orbital period ends, yielding a final SOC 98.5% as shown in Figure 25 which is also higher than the current case of Nayif-1.

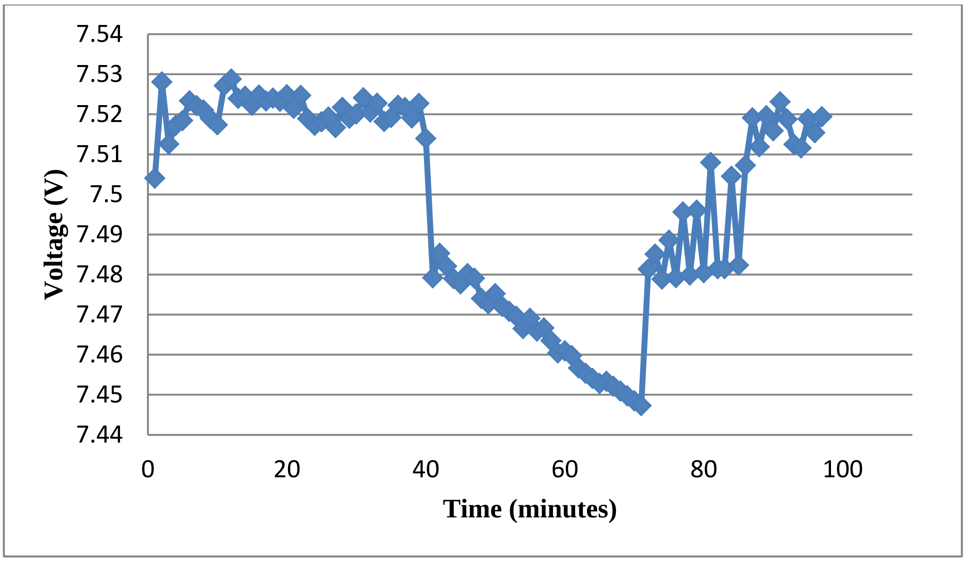

Figure 26: Objective function II voltage vs Time graph

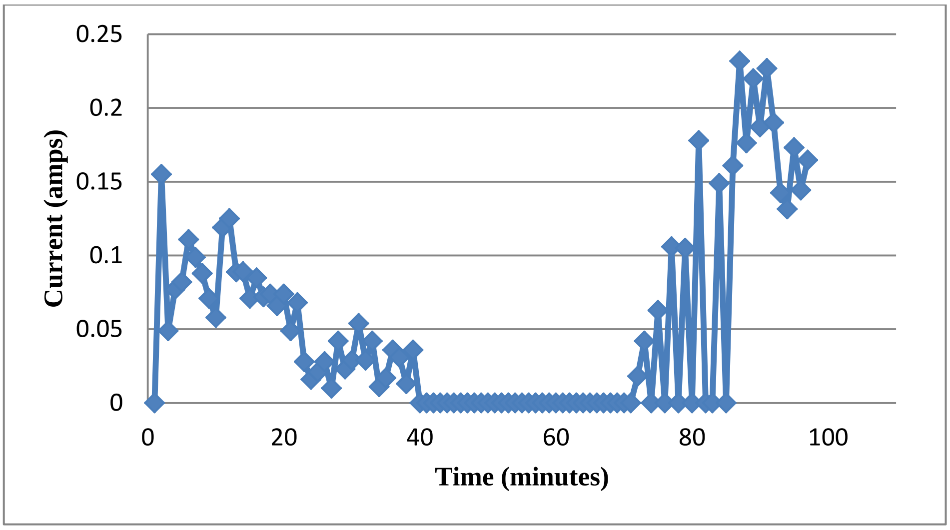

Figure 27: Objective function II charge current vs Time graph

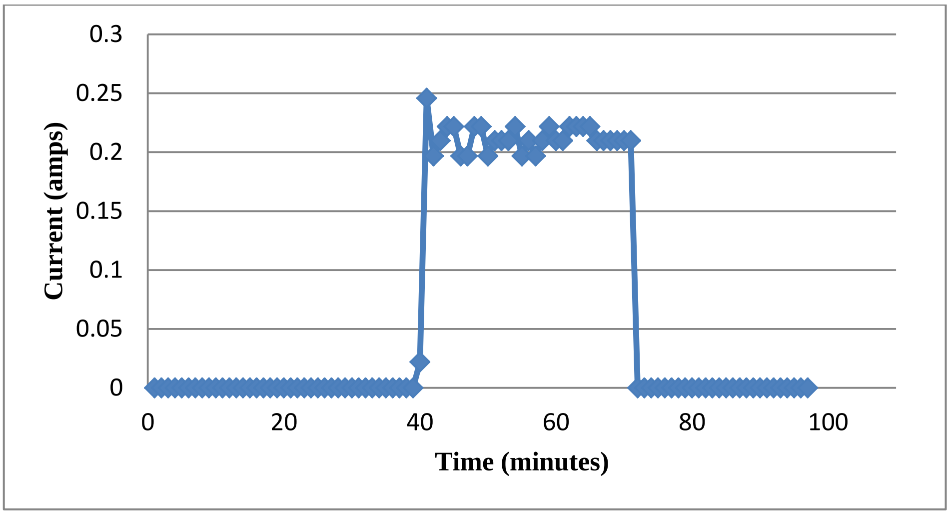

Figure 28: Objective function II discharge current vs Time graph

Based on Figure 26, the average voltage of the battery is 7.4977 Volts throughout the first orbital period and an end voltage of 7.5194 Volts which is also better than the current case of Nayif-1 data which had a value of 7.5058 Volts. In addition, based on Figure 27 and Figure 28, the solar panels charges the battery for the period at which the battery charging switch is on by an average current of 0.088 Amps which is less than the Nayif-1 current case and first objective function, at the period when the discharging switch is on which starts at period 40 which has the least value. The reason for that is because it is a period of peak demand for the system and solar panels are not providing enough power, while at the later periods the battery solely providing power to the satellite with average discharge current of 0.206 Amps. Finally, the same conclusion can be made from the first objective function on the final SOC to the second objective function. Thus, in this objective function the model can also be generalized for all orbits of the satellite to improve the SOH degradation of the LEO satellite battery.

5.1.4. Results for objective function III

As previously presented in chapter 4, the second objective function is shown in equation 5 which is minimizing the overall DOD of the battery. The results of this model are summarized in the Table 11 and Figure 29 to Figure 33.

Table 11: Objective function III function results

Charge time usage	60 minutes
Discharge time usage	32 minutes
Solar panel time usage	66 minutes
Average discharge current	0.206 Amps
Average charge current	0.093 Amps
Average discharge power	1.540 Watts
Average charge power	0.696 Watts
Cycle number	1
Maximum capacity/cycle	311.9971389 Amps minutes
DOD/cycle	0.021162
SOH degradation/cycle	9.1702E-06

Based on the results, the battery goes through a DOD of 0.021162 which is less than the current case illustrated earlier which was 0.021186. This yields a SOH degradation value of 9.1702E-06 which is also less than the current case which was 9.1806E-06.

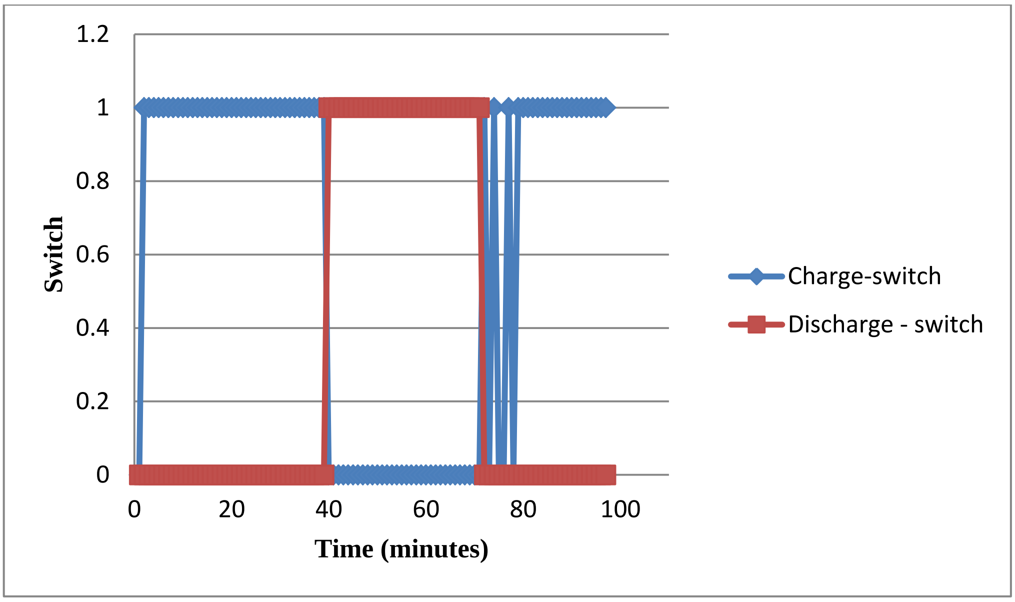

Figure 29: Objective function III battery switches vs Time graph

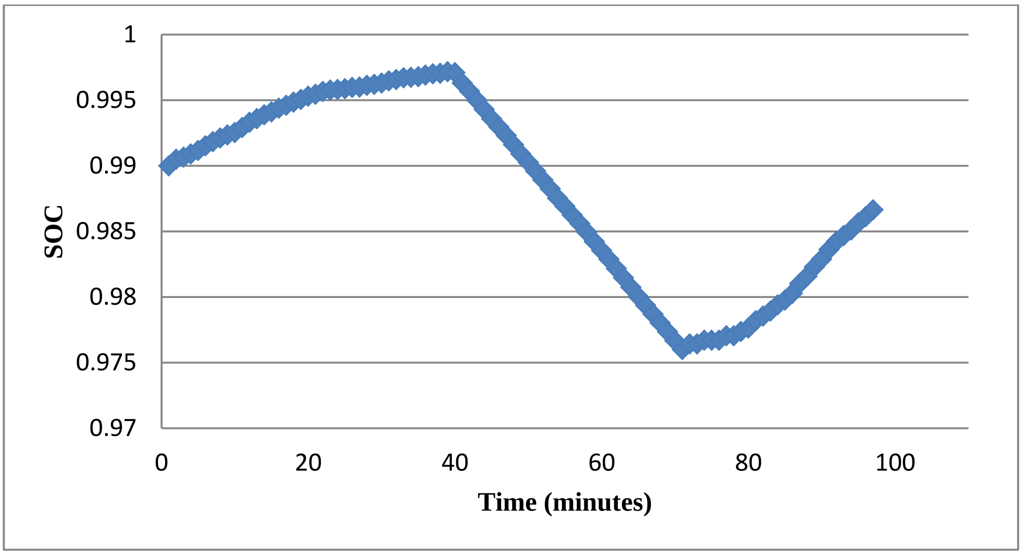

Figure 30: Objective function III SOC vs Time graph

It can be noted from Figure 29 that the charging switch is on, and the solar panels charge the battery for a period of 38 minutes in total from the 39 minutes available before the discharging switch kicks in and discharge the battery for a period of 32 minutes. The solar panels then charge the battery for a period of 22 minutes in total from the available time of 26 minutes until the first orbital period ends, yielding a final SOC of 98.7% as noted in Figure 30 which is also higher than the current case of Nayif-1.

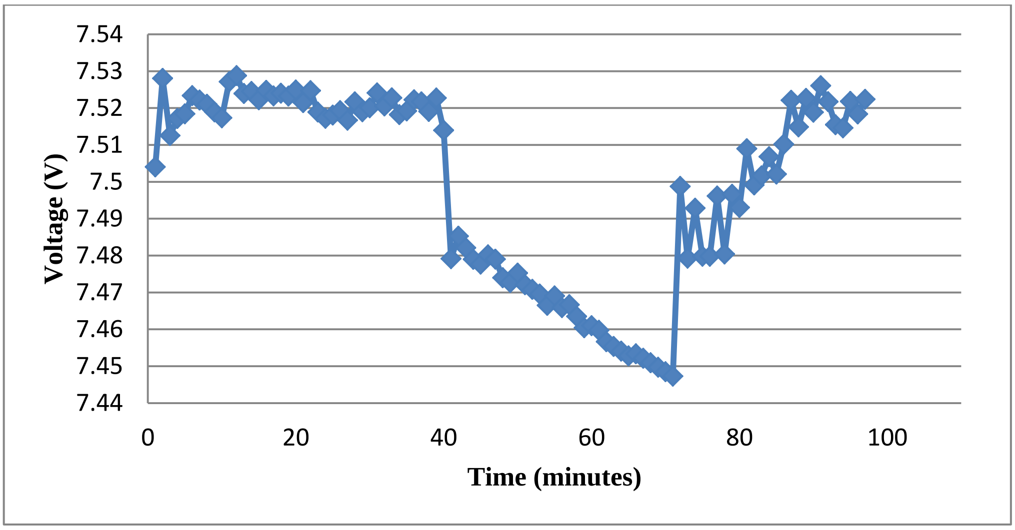

Figure 31: Objective function III voltage vs Time graph

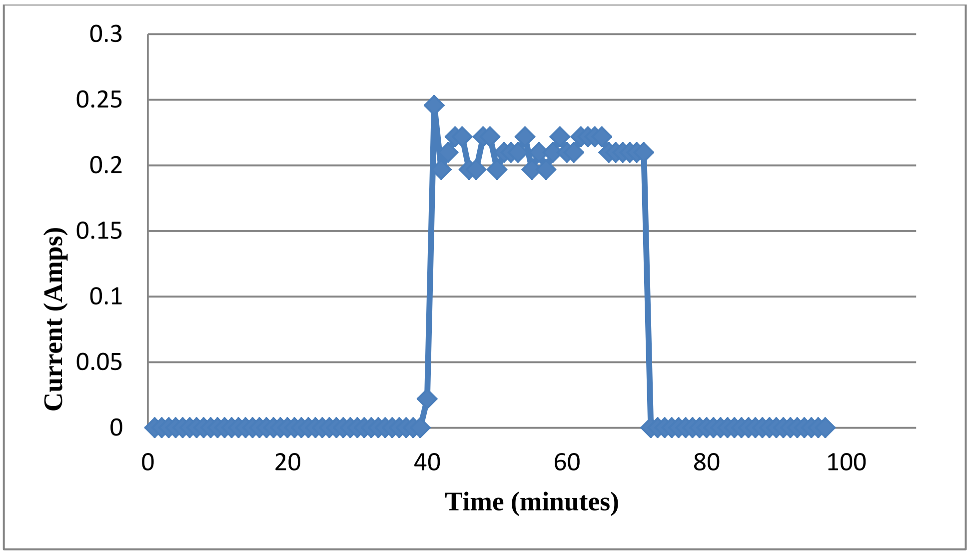

Figure 32: Objective function III discharge current vs Time graph

Finally, Based on Figure 31, the average voltage of the battery is 7.4991 Volts throughout the first orbital period and an end voltage of 7.5224 Volts which is also better than the current case of Nayif-1 data which had a value of 7.5058 Volts. In addition, we can note from Figure 32 and Figure 33 that the solar panels charge the battery for the period at which the battery charging switch is on by an average current of 0.093 Amps which is less than the Nayif-1 current case and first objective function, but higher than the second objective function, at the period when the discharging switch is on, which starts at period 40 which has the least value. The reason of that is because it is a period of peak demand for the system and solar panels are not providing enough power, while at later periods the battery solely provides power to the satellite with average discharge current of 0.206 Amps.

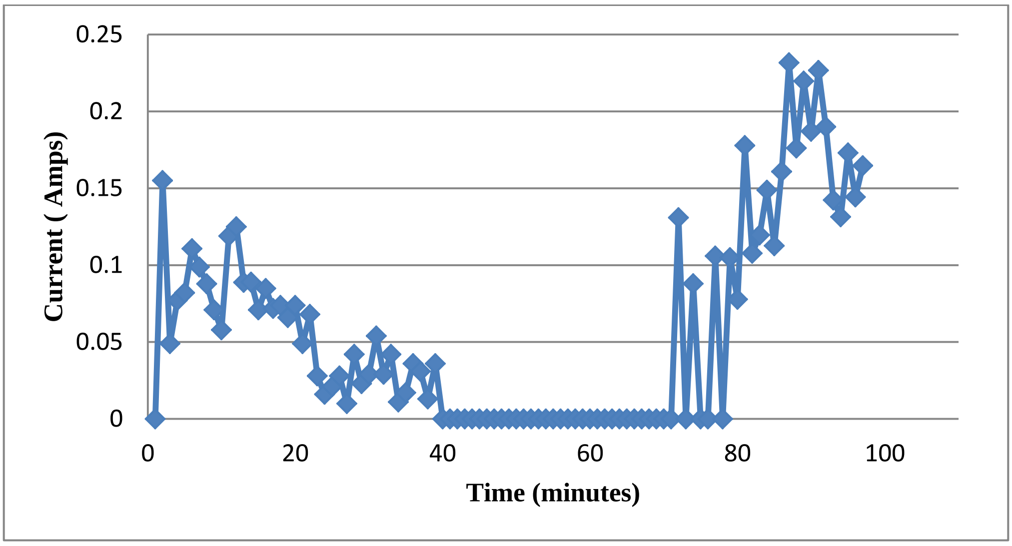

Figure 33: Objective function III charge current vs Time graph

Since, in this objective function the final SOC is also higher than the current case of Nayif-1, the model can be generalized for all orbits of the satellite to improve the SOH degradation of the battery.

5.1.5. Heuristic results

In this heuristic approach, which is based on the flow chart presented in chapter 4, the MATLAB code for it can be referred to in Appendix E. The results of this approach are summarized in the Table 12 and Figure 34 to Figure 38.

Based on the results from Table 12, the battery goes through a DOD of 0.021167 which is less than the current case of Nayif-1 illustrated earlier which was 0.021186, but higher than all the previous objective functions. This yields a SOH degradation value of 9.1724E-06 which is also less than the current case Nayif-1 which was 9.1806E-06 and the first objective function, but more than the second and third objective functions. It is important to note that based on Figure 34 the charging switch is on and the solar panels charge the battery for a period of 38 minutes in total from the 39 minutes available before the discharging switch kicks in and discharge the battery for a period of 32 minutes. The solar panels then charge the battery for a period of 26 minutes in total from the available time of 26 minutes until the first orbital period ends, yielding a final SOC of 97.7% as noted in Figure 35 which is as well higher than the current case of Nayif-1.

Table 12: Heuristic results

Charge time usage	64 minutes
Discharge time usage	32 minutes
Solar panel time usage	66 minutes
Average discharge current	0.206 Amps
Average charge current	0.040 Amps
Average discharge power	1.540 Watts
Average charge power	0.300 Watts
Cycle number	1
Maximum capacity/cycle	311.9971382 Amps minutes
DOD/cycle	0.02116713
SOH degradation/cycle	9.17242E-06

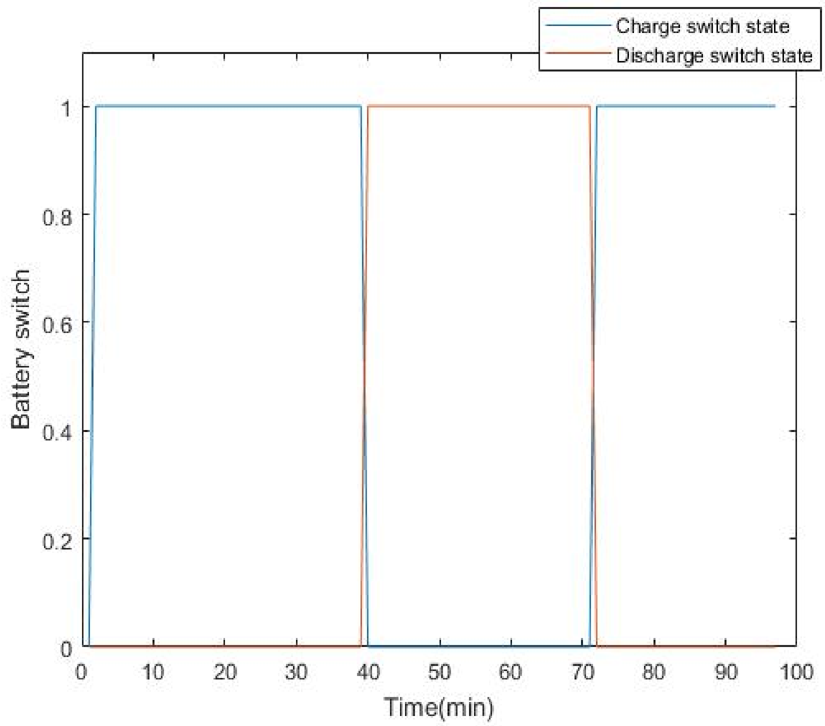

Figure 34: Heuristic Battery switch states vs Time Graph

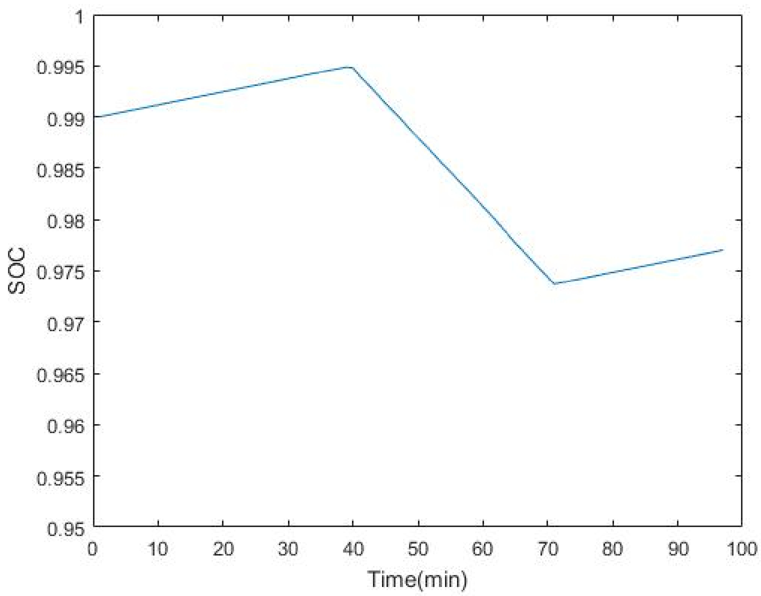

Figure 35: Heuristic SOC vs Time Graph

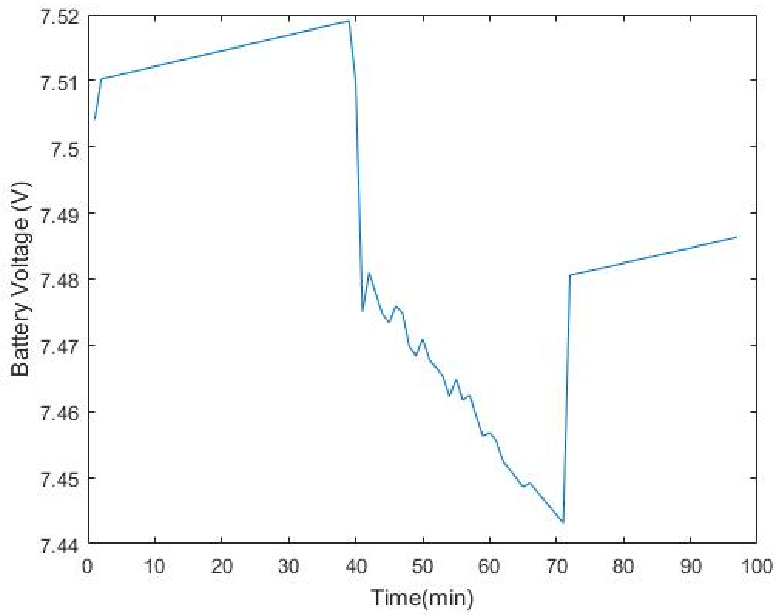

Figure 36: Heuristic Battery voltages vs Time Graph

Finally, Based on Figure 36 the average voltage of the battery is 7.4891 Volts throughout the first orbital period and an end voltage of 7.4864 Volts. In addition, one can note from Figure 37 and Figure 38 that the solar panels charge the battery for the period at which the battery charging switch is on by an average current of 0.04 Amps. At the period when the discharging switch is on which starts at period 40 which has the least value. The reason for that is because it is a period of peak demand for the system and solar panels are not providing enough power, while at later periods the battery solely provides power to the satellite with average discharge current of 0.206 Amps.

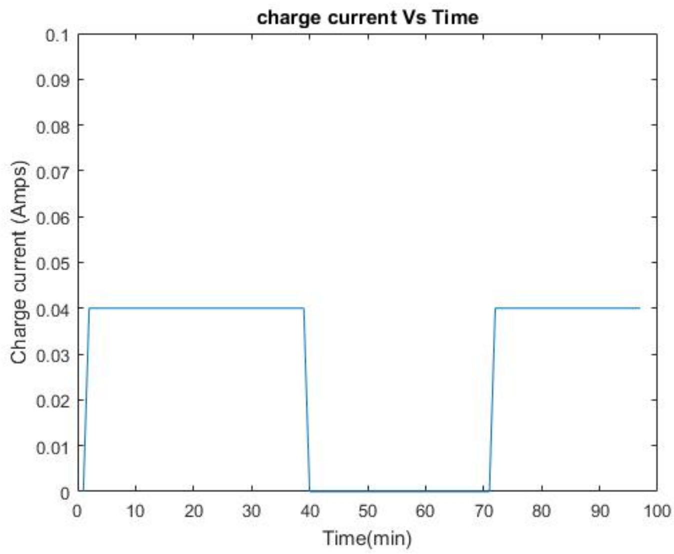

Figure 37: Heuristic battery charge current vs Time Graph

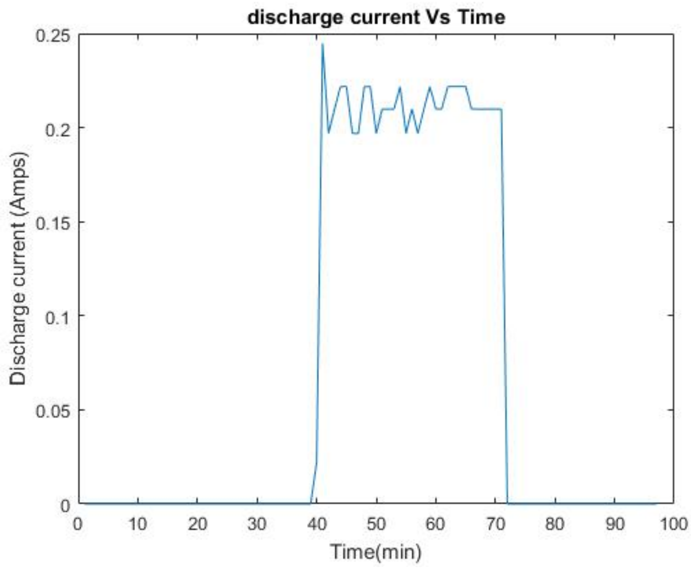

Figure 38: Heuristic battery discharge current vs time Graph

5.2. Performance Evaluation and Comparison

This section will present an evaluation of the results shown in section 5.1 which will be compared with each other and with the current case of Nayif-1 battery behavior. Table 13 summarizes all the important parameters of the three objective functions, the heuristic and the current case of Nayif-1. In addition, based on Table 13, Table 14 will show a direct comparison for each objective function with the current case of Nayif-1.

Table 13: Important parameters summary for all objective functions and current case

	Objective function I	Objective function II	Objective function III	Heuristic	Current Case of Nayif-1
Cycle Number	1	1	1	1	1
Maximum capacity /cycle	311.997137	311.997139	311.997139	311.997138	311.997136
Depth of discharge /cycle	0.02117299	0.02116202	0.02116202	0.02116713	0.02118590
SOH degradation /cycle	9.17496E-06	9.17021E-06	9.17021E-06	9.17242E-06	9.18056E-06
Average charge current	0.12307	0.08847	0.09259	0.04000	0.12332
Average discharge current	0.20644	0.20633	0.20633	0.20638	0.20656

Table 14: Direct parameters comparison

	Difference between current case of Nayif-1 and objective function I	Difference between current case of Nayif-1 and objective function II	Difference between current case of Nayif-1 and objective function III	Difference between current case of Nayif-1 and heuristic
Cycle Number	0	0	0	0
Maximum capacity/cycle	0.0000017	0.0000032	0.0000032	0.0000025
Depth of discharge/cycle	1.291E-05	2.388E-05	2.388E-05	1.877E-05
SOH Degradation/cycle	5.593E-09	1.035E-08	1.035E-08	8.132E-09
Average charge current	0.00025	0.03485	0.03073	0.08332
average discharge current	0.00013	0.00023	0.00023	0.00018

Since the main focus of this thesis is to depict the enhancement of the LEO satellite battery SOH degradation the model provides, in order to easily depict the clear improvement of the model, Figure 39 shows a direct SOH degradation comparison between the current case and all scenarios based on Table 13.

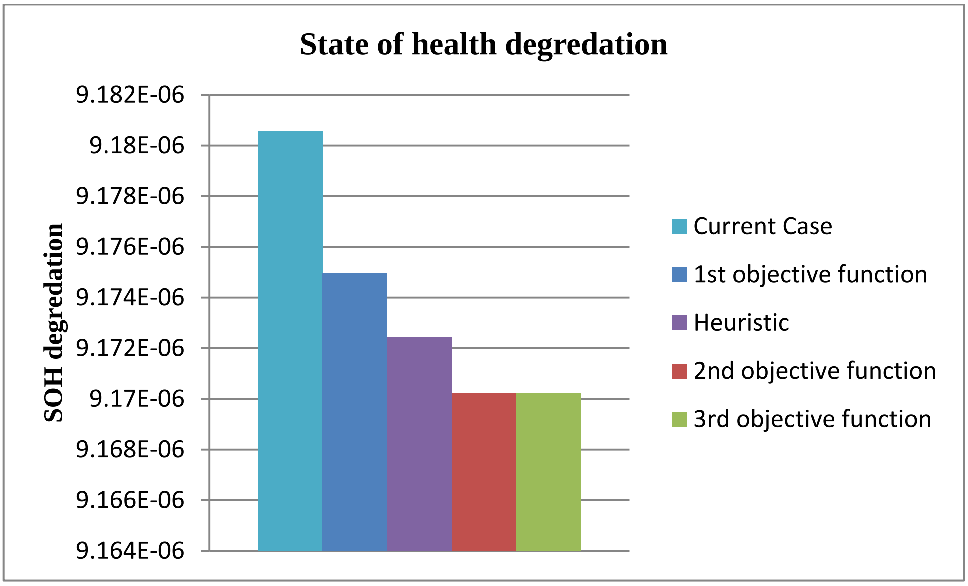

Figure 39: Battery SOH degradation comparison

Based on the results from Table 13 and Figure 39 it can be concluded that the second and third objective functions enhance the battery by reducing the SOH degradation by 2.388E-05 from the current case which results in higher capacity being retained by 0.0000032 compared by the current case of Nayif-1. Consequently, this will result in augmenting the battery lifetime and cycle lifetime. In addition to that, it is important to depict how this one orbital period enhancement will function in the long term, and how much more lifetime in terms of days and cycle life it will ensure. Assuming that the DOD of the battery is going to stay constant throughout each orbit of the satellite, the expected lifetime of battery is calculated and showed in Table 15 for each case. Based on Table 15, in order to easily depict the enhancement in term of battery cycle life, Figure 40 shows a direct comparison for all the cases. In addition, based on Table 15 and Figure 40, the exact difference between each scenario and the current case are shown in Table 16. It is important to mention that based on Table 15 the lifetime of the satellite is shown to be 20 years, this estimate is based only on the battery power factor. However, in real case scenario the Cubesat will be losing orbit eventually which will result to a lifetime of the satellite to be between 3 to 5 years.

Table 15: lifetime summary for every scenario

	Objective function I	Objective function II	Objective function III	Heuristic	Current Case of Nayif-1
expected lifetime (minutes)	10,572,249	10,577,730	10,577,731	10,575,176	10,565,809
expected lifetime (hours)	176,204.16	176,295.50	176,295.52	176,252.95	176,096.82
expected lifetime (days)	7,341.84	7,345.65	7,345.65	7,343.87	7,337.37
expected lifetime (years)	20.11	20.13	20.13	20.12	20.10
expected cycle life (orbits)	108,992.27	109,048.77	109,048.78	109,022.44	108,925.87

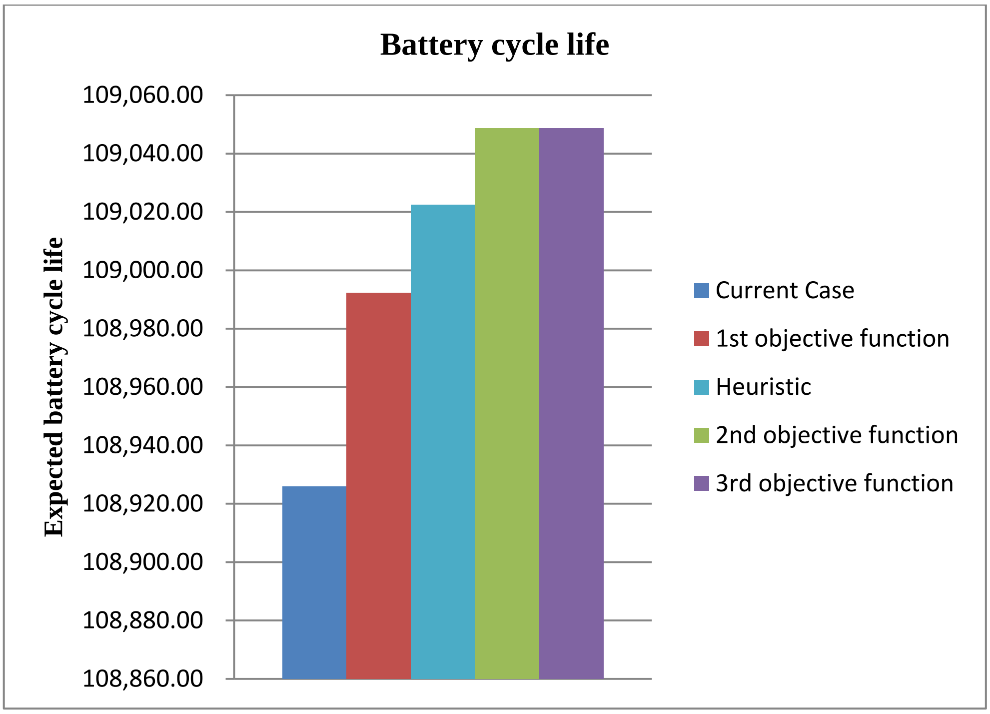

Figure 40: Battery cycle life comparison

Table 16: lifetime improvement comparison summary

	Difference between current case of Nayif-1 and objective function I	Difference between current case of Nayif-1 and objective function II	Difference between current case of Nayif-1 and objective function III	Difference between current case of Nayif-1 and heuristic
expected lifetime (minutes)	6,440.44	11,920.91	11,922.08	9,367.42
expected lifetime (hours)	107.34	198.68	198.70	156.12
expected lifetime (days)	4.47	8.28	8.28	6.51
expected lifetime (years)	0.01	0.02	0.02	0.02
expected cycle life (orbits)	66.40	122.90	122.91	96.57

In conclusion for this section, it can be seen that the second and third objective functions increase the lifetime and the cycle life of the battery the most by 8 days and 122 cycles respectively.

Chapter 6. Sensitivity analysis

In this chapter, the results of the sensitivity analysis will be presented. The analysis was performed for the cases in which the battery starts at lower initial SOC. The section will then present the behavior of the model for a different demand profile that was retrieved from AMSAT-UK data warehouse for Nayif-1 website; the link for this website can be found in the Appendix F.

6.1 Analysis on Different Initial SOC

Although a current data for Nayif-1 showing that the battery started at lower initial SOC is not available, as time goes by through the satellite, the initial SOC for every new orbit will be less by a very small amount than the previous one. Therefore, it is a must to see the behavior of the battery at different initial SOC for every orbit. Table 17 to Table 19 present a summary for each SOC that has been implemented on the model for each objective function. For size limitation of the report the graphs for each one can be referred to in Appendix G.

Table 17: Different initial SOC summary parameters for objective function I

	Objective function I	
Initial SOC	0.7	0.5
Cycle Number	1	1
Maximum capacity/cycle	311.996972	311.996898
DOD/cycle	0.02239944	0.02294545
SOH degradation/cycle	9.706425E-06	9.943026E-06
Average charge current	0.086134	0.130208
Average discharge current	0.218327	0.223718
Average charge power	0.612244	0.903866

It can be seen from Table 17 to Table 19 that as the SOC of the battery decreases the DOD increases and the SOH degradation increases. In all cases the second and third objective functions produced the lowest DOD and SOH degradation of the battery, however it can be noticed that the second objective function results in better improvement in terms of the DOD and SOH degradation than the third objective function as the SOC decreases. Thus, it can be concluded that the second objective function is the optimal case for reducing the SOH degradation of the battery in order to increase the lifetime and cycle life of the battery. In order to depict better the effect of initial SOC on the SOH degradation, Figure 41 will show how the SOH degradation increases as the initial SOC decreases specifically for the second objective function.

Table 18: Different initial SOC summary parameters for objective function II

	Objective function II	
Initial SOC	0.7	0.5
Cycle Number	1	1
Maximum capacity/cycle	311.996973	311.996898
DOD/cycle	0.02239250	0.02294146
SOH degradation/cycle	9.703416E-06	9.941301E-06
Average charge current	0.096990	0.096512
Average discharge current	0.218366	0.223679
Average charge power	0.689389	0.669923
Average discharge power	1.540375	1.540375

Table 19: Different initial SOC summary parameters for objective function III

	3rd objective function	
Initial SOC	0.7	0.5
Cycle Number	1	1
Maximum capacity/cycle	311.996972	311.996898
DOD/cycle	0.02239655	0.02294645
SOH degradation/cycle	9.705173E-06	9.943461E-06
Average charge current	0.096990	0.101854
Average discharge current	0.218366	0.223728
Average charge power	0.689389	0.706887
Average discharge power	1.540375	1.540375

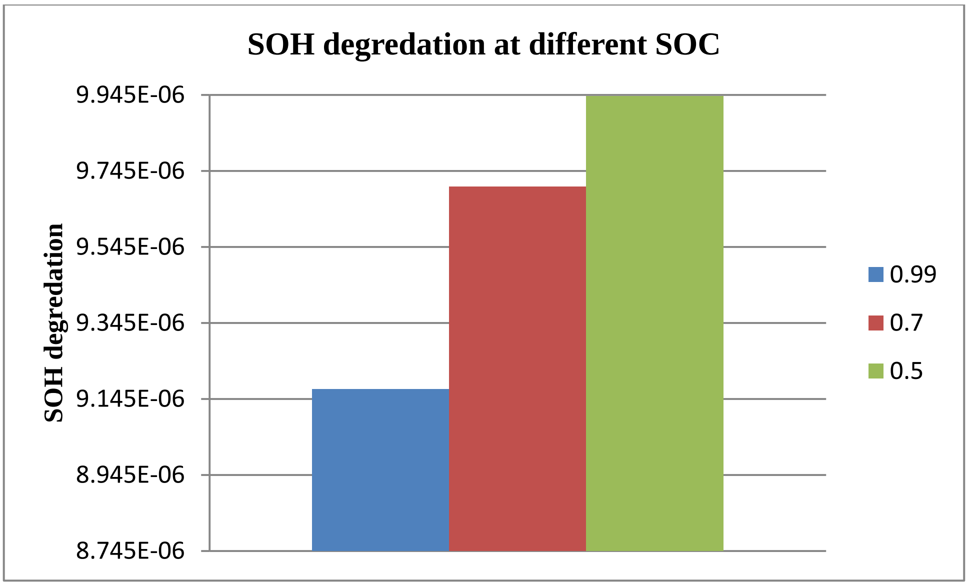

Figure 41: Effect of initial SOC on SOH degradation

6.2 Analysis on Different Demand Profiles

This section provides a comparison for a different demand profile that was retrieved from AMSAT-UK data warehouse for Nayif-1 website. In this new demand profile the only major difference is that the eclipse happens earlier than the original case and the duration of the eclipse. In this data, the eclipse happens from periods 25 to 58 rather than 41 to 71, giving duration of 32 rather than 31. The results for each objective function are compared at an initial SOC of 99% with the new current profile in order to provide a more concrete conclusion to the results. The results and comparison are shown in Table 20 and Table 21 respectively. The code and graphs can be referred to in Appendix G. Based on Table 20 it is clear that the second objective function results in better improvements in terms of diminishing the SOH degradation of the battery which approves the previous conclusions. Therefore in order to further depict the difference between each scenario, Figure 42 shows a direct comparison in terms of the SOH degradation between each scenario. Furthermore, the differences between each scenario for each important parameter are shown in Table 21.

Based on the main results and the sensitivity analysis conducted, we can firmly conclude the second objective function yields the best results in terms of diminishing the SOH degradation by 2.0355E-08 from the current case and reducing the DOD of the battery by 4.6974E-05. As a result, it will augment the battery cycle life and lifetime of the battery the most.

Table 20: New demand profile parameters summary

	Objective function I	Objective function II	Objective function III	New current case of Nayif-1
Cycle Number	1	1	1	1
Maximum capacity/cycle	311.9968399	311.9968400	311.9968400	311.9968336
depth of discharge/cycle	0.0233735	0.0233728	0.0233730	0.0234198
SOH degradation/cycle	1.01285E-05	1.01283E-05	1.01283E-05	1.01486E-05
Average charge current	0.14331	0.11024	0.11904	0.10761
Average discharge current	0.21449	0.21448	0.21448	0.21491

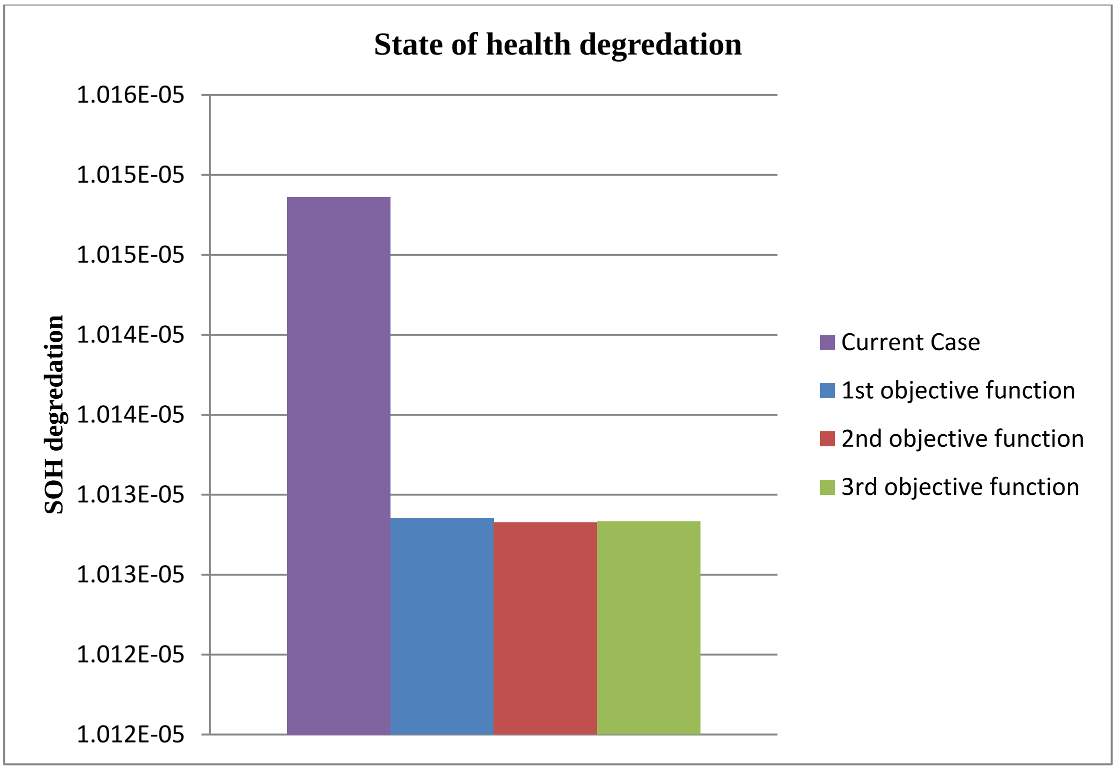

Figure 42: SOH degradation comparison for new demand profile

Table 21: New demand profile direct parameters comparison

	Difference between new current case of Nayif-1 and objective function I	Difference between new current case of Nayif-1 and objective function II	Difference between new current case of Nayif-1 and objective function III
Cycle Number	0	0	0
Maximum capacity/cycle	0.0000063	0.0000064	0.0000032
Depth of discharge/cycle	4.6330E-05	4.6974E-05	4.6839E-05
SOH Degradation/cycle	2.0076E-08	2.0355E-08	2.0297E-08
Average charge current	0.03570	0.00263	0.011432
Average discharge current	0.00043	0.00043	0.000430

Chapter 7. Conclusion and Future Work

This research addressed the satellite power management with a focus on the satellite batteries to improve the battery lifetime. A mixed integer nonlinear model for LEO satellite battery has been developed. The developed model is solved separately for three different objectives, which are minimizing the number of battery switches between charging and discharging, minimizing the sum product of battery state switches and battery current, and minimizing the total depth of discharge (DOD). The model was developed in order to provide a better battery management system for LEO satellites in order to enhance the lifetime and cycle lifetime of the LEO satellite battery. In addition to this, a heuristic model was developed and simulated through MATLAB to provide a wider scope of comparison and evaluation for the results. The current thesis uses the Chen and Mora circuit model to represent a Li-ion battery. In addition to that, the Coulomb counting method is considered for the SOC estimation in the model. Starting with the first objective function, the results showed that it enhances the lifetime and the cycle lifetime of the battery by 4 days and 66 cycles. The second and third objective functions result in equal enhancement by 8 days and 122 more cycles. The heuristic also enhances the battery lifetime by 6 days and 96 cycles. Moreover, a sensitivity analysis was performed on the models; the first analysis was done by running the model at different lower initial SOC than the current Nayif-1 data. The second analysis was performed on a different demand profile in which the eclipse happens earlier and lasts longer than the current Nayif-1 data. The results from the sensitivity analysis have verified the conclusion that the second objective function provides the best enhancement of the battery lifetime.

Moreover, the proposed model has some limitations that include:

1. Budget limitation, performing an experimental study on the proposed model is extremely expensive since launching satellites into outer space will require significant amount of money to be invested.
2. Computational time limitation, the computation of the proposed model requires hours of computation and significant amount of iteration to be performed in order to for the model to provide the optimal answer.

Finally, based on the results and conclusions, the following points are left for future research.

1. Accounting for the battery temperature in the scheduling model.
2. Performing the scheduling model on GEO and MEO satellites which are larger and their orbital periods for the respective cases are longer. This would result in more significant results in terms of battery lifetime enhancement.

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Appendix A

In this Appendix, the original data for Nayif-1 Cubesate retrieved by Mr. Ibrahim Abu Saif through the AUS control center using the dashboard software. This data is more accurate than the data collected online from AMSAT data warehouse for Nayif-1 which was used in the sensitivity analysis. This collected data is the main data used in the results comparison that are presented in chapter 5. The data is shown in the following page due to the size limitation:

	Current panel	Battery voltage	Current sys	Power supplied by panels mW	W	Power sys mW Demand	W	discharging Switch	Battery Current	in Amps	Charging Switch
1	403	8.2	283	3344.5	3.3	2348.6	2.3	0.0	0.0	0.000	0.0
2	426	8.3	271	3539.6	3.5	2251.7	2.3	0.0	155.0	0.155	1.0
3	320	8.2	271	2649.6	2.6	2243.9	2.2	0.0	0.0	0.000	0.0
4	360	8.2	283	2984.4	3.0	2346.1	2.3	0.0	77.0	0.077	1.0
5	377	8.2	295	3128.7	3.1	2448.2	2.4	0.0	82.0	0.082	1.0
6	394	8.2	283	3269.8	3.3	2348.6	2.3	0.0	0.0	0.000	0.0
7	394	8.2	295	3269.8	3.3	2448.2	2.4	0.0	0.0	0.000	0.0
8	383	8.2	295	3178.5	3.2	2448.2	2.4	0.0	0.0	0.000	0.0
9	354	8.2	283	2937.8	2.9	2348.6	2.3	0.0	0.0	0.000	0.0
10	316	8.2	258	2619.6	2.6	2138.8	2.1	0.0	0.0	0.000	0.0
11	377	8.2	258	3128.7	3.1	2141.1	2.1	0.0	119.0	0.119	1.0
12	383	8.3	258	3182.3	3.2	2143.7	2.1	0.0	125.0	0.125	1.0
13	360	8.2	271	2987.6	3.0	2249.0	2.2	0.0	0.0	0.000	0.0
14	360	8.3	271	2991.2	3.0	2251.7	2.3	0.0	89.0	0.089	1.0
15	354	8309	283	2941.4	2.9	2351.4	2.4	0.0	0.0	0.000	0.0
16	343	8309	258	2850.0	2.8	2143.7	2.1	0.0	0.0	0.000	0.0
17	343	8309	271	2850.0	2.8	2251.7	2.3	0.0	0.0	0.000	0.0
18	332	8309	258	2758.6	2.8	2143.7	2.1	0.0	0.0	0.000	0.0
19	337	8309	271	2800.1	2.8	2251.7	2.3	0.0	0.0	0.000	0.0
20	332	8299	258	2755.3	2.8	2141.1	2.1	0.0	0.0	0.000	0.0
21	320	8299	271	2655.7	2.7	2249.0	2.2	0.0	0.0	0.000	0.0
22	326	8309	258	2708.7	2.7	2143.7	2.1	0.0	68.0	0.068	1.0
23	311	8299	283	2581.0	2.6	2348.6	2.3	0.0	0.0	0.000	0.0
24	311	8299	295	2581.0	2.6	2448.2	2.4	0.0	0.0	0.000	0.0
25	316	8309	295	2625.6	2.6	2451.2	2.5	0.0	21.0	0.021	1.0
26	311	8299	283	2581.0	2.6	2348.6	2.3	0.0	0.0	0.000	0.0
27	305	8299	295	2531.2	2.5	2448.2	2.4	0.0	0.0	0.000	0.0
28	300	8309	258	2492.7	2.5	2143.7	2.1	0.0	42.0	0.042	1.0
29	294	8299	271	2439.9	2.4	2249.0	2.2	0.0	0.0	0.000	0.0
30	300	8299	271	2489.7	2.5	2249.0	2.2	0.0	0.0	0.000	0.0
31	300	8299	246	2489.7	2.5	2041.6	2.0	0.0	0.0	0.000	0.0
32	300	8309	271	2492.7	2.5	2251.7	2.3	0.0	29.0	0.029	1.0
33	300	8309	258	2492.7	2.5	2143.7	2.1	0.0	0.0	0.000	0.0
34	294	8309	283	2442.8	2.4	2351.447	2.4	0.0	0.0	0.000	0.0
35	288	8309	271	2393.0	2.4	2251.739	2.3	0.0	0.0	0.000	0.0
36	294	8309	258	2442.8	2.4	2143.722	2.1	0.0	0.0	0.000	0.0
37	277	8299	246	2298.8	2.3	2041.554	2.0	0.0	0.0	0.000	0.0
38	271	8299	258	2249.0	2.2	2141.142	2.1	0.0	0.0	0.000	0.0
39	294	8299	258	2439.9	2.4	2141.142	2.1	0.0	0.0	0.000	0.0
40	249	8299	271	2066.5	2.1	2249.029	2.2	1.0	22.0	0.022	0.0
41	7	8233	246	57.6	0.1	2025.318	2.0	1.0	246.0	0.246	0.0
42	7	8233	197	57.6	0.1	1621.901	1.6	1.0	197.0	0.197	0.0
43	7	8233	210	57.6	0.1	1728.930	1.7	1.0	210.0	0.210	0.0
44	7	8223	222	57.6	0.1	1825.506	1.8	1.0	222.0	0.222	0.0
45	7	8223	222	57.6	0.1	1825.506	1.8	1.0	222.0	0.222	0.0
46	7	8214	197	57.5	0.1	1618.158	1.6	1.0	197.0	0.197	0.0
47	7	8214	197	57.5	0.1	1618.158	1.6	1.0	197.0	0.197	0.0
48	7	8204	222	57.4	0.1	1821.288	1.8	1.0	222.0	0.222	0.0
49	7	8204	222	57.4	0.1	1821.288	1.8	1.0	222.0	0.222	0.0
50	7	8195	197	57.4	0.1	1614.415	1.6	1.0	197.0	0.197	0.0
51	7	8195	210	57.4	0.1	1720.950	1.7	1.0	210.0	0.210	0.0
52	7	8185	210	57.3	0.1	1718.850	1.7	1.0	210.0	0.210	0.0
53	7	8185	210	57.3	0.1	1718.850	1.7	1.0	210.0	0.210	0.0
54	7	8176	222	57.2	0.1	1815.072	1.8	1.0	222.0	0.222	0.0
55	7	8176	197	57.2	0.1	1610.672	1.6	1.0	197.0	0.197	0.0
56	7	8169	210	57.2	0.1	1715.490	1.7	1.0	210.0	0.210	0.0
57	7	8169	197	57.2	0.1	1609.293	1.6	1.0	197.0	0.197	0.0
58	7	8160	210	57.1	0.1	1713.600	1.7	1.0	210.0	0.210	0.0
59	7	8160	222	57.1	0.1	1811.520	1.8	1.0	222.0	0.222	0.0
60	7	8150	210	57.1	0.1	1711.500	1.7	1.0	210.0	0.210	0.0
61	7	8150	210	57.1	0.1	1711.500	1.7	1.0	210.0	0.210	0.0
62	7	8141	222	57.0	0.1	1807.302	1.8	1.0	222.0	0.222	0.0
63	7	8141	222	57.0	0.1	1807.302	1.8	1.0	222.0	0.222	0.0
64	7	8131	222	56.9	0.1	1805.082	1.8	1.0	222.0	0.222	0.0
65	7	8131	222	56.9	0.1	1805.082	1.8	1.0	222.0	0.222	0.0
66	7	8122	210	56.9	0.1	1705.620	1.7	1.0	210.0	0.210	0.0
67	7	8122	210	56.9	0.1	1705.620	1.7	1.0	210.0	0.210	0.0
68	7	8112	210	56.8	0.1	1703.520	1.7	1.0	210.0	0.210	0.0
69	7	8112	210	56.8	0.1	1703.520	1.7	1.0	210.0	0.210	0.0
70	7	8103	210	56.7	0.1	1701.630	1.7	1.0	210.0	0.210	0.0
71	7	8103	210	56.7	0.1	1701.630	1.7	1.0	210.0	0.210	0.0
72	377	8185	246	3085.7	3.1	2013.510	2.0	0.0	131.0	0.131	1.0
73	300	8176	258	2452.8	2.5	2109.408	2.1	0.0	0.0	0.000	0.0
74	383	8204	295	3142.1	3.1	2420.180	2.4	0.0	88.0	0.088	1.0
75	415	8214	271	3408.8	3.4	2225.994	2.2	0.0	144.0	0.144	1.0
76	360	8204	295	2953.4	3.0	2420.180	2.4	0.0	0.0	0.000	0.0
77	377	8214	271	3096.7	3.1	2225.994	2.2	0.0	106.0	0.106	1.0
78	332	8204	271	2723.7	2.7	2223.284	2.2	0.0	0.0	0.000	0.0
79	400	8223	295	3289.2	3.3	2425.785	2.4	0.0	105.0	0.105	1.0
80	349	8223	271	2869.8	2.9	2228.433	2.2	0.0	0.0	0.000	0.0
81	449	8252	271	3705.1	3.7	2236.292	2.2	0.0	178.0	0.178	1.0
82	403	8242	295	3321.5	3.3	2431.390	2.4	0.0	0.0	0.000	0.0
83	415	8242	295	3420.4	3.4	2431.390	2.4	0.0	0.0	0.000	0.0
84	420	8252	271	3465.8	3.5	2236.292	2.2	0.0	149.0	0.149	1.0
85	420	8252	307	3465.8	3.5	2533.364	2.5	0.0	0.0	0.000	0.0
86	432	8271	271	3573.1	3.6	2241.441	2.2	0.0	161.0	0.161	1.0
87	503	8290	271	4169.9	4.2	2246.590	2.2	0.0	232.0	0.232	1.0
88	460	8280	283	3808.8	3.8	2343.240	2.3	0.0	0.0	0.000	0.0
89	503	8299	283	4174.4	4.2	2348.617	2.3	0.0	220.0	0.220	1.0
90	471	8290	283	3904.6	3.9	2346.070	2.3	0.0	0.0	0.000	0.0
91	498	8309	271	4137.9	4.1	2251.739	2.3	0.0	227.0	0.227	1.0
92	486	8309	295	4038.2	4.0	2451.155	2.5	0.0	0.0	0.000	0.0
93	426	8299	283	3535.4	3.5	2348.617	2.3	0.0	0.0	0.000	0.0
94	415	8299	283	3444.1	3.4	2348.617	2.3	0.0	0.0	0.000	0.0
95	432	8299	258	3585.2	3.6	2141.142	2.1	0.0	0.0	0.000	0.0
96	403	8290	258	3340.9	3.3	2138.820	2.1	0.0	0.0	0.000	0.0
97	460	8299	295	3817.5	3.8	2448.205	2.4	0.0	165.0	0.165	1.0

Appendix B

In this Appendix, the lingo code for the current case of Nayif-1 based on the data retrieved from Appendix A is shown, the results of this code is presented in chatper 5:

```
Model:
! real case scenario for Nayif1;
Sets:
states
/1..97/:ch,dch,sp,ps,VBATT,IBATT,soc,dod,p,pd,pc,cycleN,cmax,sohd,CHCUM,CHSIGN,ID,IC,eo,rs
;

Endsets
Data:
crated=312;  !rated capacity of 5.2 Ah * 60 min/hour = 312 Amin;
p=2.123648657   2.040104124   2.033848739   2.127282728   2.217848621   2.124175213
        2.214246247   2.214246247   2.124175213   1.936527226   1.941281521
        1.941703522   2.034496632   2.03823172    2.124734675   1.937037265
        2.034639918   1.937037265   2.034639918   1.937037265   2.034639918
        1.939754191   2.124849051   2.214948658   2.215908047   2.124884383
        2.214985487   1.938851877   2.034850957   2.034850957   1.847134079
        2.036068059   1.937282678   2.125003868   2.034897697   1.937282678
        1.847176507   1.937282678   1.937282678   2.033974377   1.837772639
        1.472919419   1.569449158   1.658443439   1.658152009   1.471927399
        1.471698449   1.657345312   1.657055292   1.470955296   1.567357967
        1.567099388   1.566841124   1.655689919   1.469745065   1.566069445
        1.469277491   1.565571624   1.654349606   1.565044512   1.564788756
        1.653523072   1.653237979   1.652953256   1.6526689     1.5634566
        1.563202788   1.562949286   1.562696095   1.562443215   1.562190645
        1.842671583   1.927524803   2.207967482   2.030819983   2.204345078
        2.029451226   2.02517335    2.209315127   2.025336717   2.032797494
        2.205004051   2.205004051   2.03185937    2.29496222    2.032594827
        2.035822546   2.116192179   2.125823233   2.116551474   2.036320291
        2.206686191   2.116922685   2.116922685   1.929915381   1.929915381
        2.214216458;

IBATT=0   0.155  0      0.077  0.082  0      0      0      0      0
      0.119  0.125  0      0.089  0      0      0      0      0      0      0
      0.068  0      0      0.021  0      0      0.042  0      0      0
      0.029  0      0      0      0      0      0      0      0.022  0.246
      0.197  0.21   0.222  0.222  0.197  0.197  0.222  0.222  0.197  0.21   0.21
      0.21   0.222  0.197  0.21   0.197  0.21   0.222  0.21   0.21   0.222
      0.222  0.222  0.222  0.21   0.21   0.21   0.21   0.21   0.21   0.131  0
      0.088  0.144  0      0.106  0      0.105  0      0.178  0      0
      0.149  0      0.161  0.232  0      0.22   0      0.227  0      0      0
      0      0      0.165;
dch = 0 0   0   0   0   0   0   0   0   0   0   0
        0   0   0   0   0   0   0   0   0   0   0
        0   0   0   0   0   0   0   0   0   0   0
        0   0   0   0   0   1   1   1   1   1   1
        1   1   1   1   1   1   1   1   1   1   1
        1   1   1   1   1   1   1   1   1   1   1
        1   1   1   1   0   0   0   0   0   0   0
```

```
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0;
ch= 0   1       0       1       1       0       0       0       0       0       1       1
        0       1       0       0       0       0       0       0       0       1       0
        0       1       0       0       1       0       0       0       1       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       1       0       1       1       0       1       0
        1       0       1       0       0       1       0       1       1       0       1
        0       1       0       0       0       0       0       1;

ps= 3.024135723.206953346   2.401592607     2.706084036     2.834335357
        2.957332275     2.957332275     2.874767161     2.657095496     2.371870556
        2.836678812     2.882451353     2.702652352     2.707614092     2.657795317
        2.575208457     2.575208457     2.492621597     2.530161079     2.492621597
        2.402526841     2.451007233     2.335081466     2.335081466     2.373650653
        2.335120293     2.290069741     2.254478927     2.207550485     2.252602535
        2.252602535     2.253949881     2.252654277     2.207601191     2.162548106
        2.207601191     2.079950782     2.034897697     2.207601191     1.868854686     0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       2.823931653
        2.24130791      2.866615409     3.109927281     2.690048231     2.823258717
        2.481024178     2.995681528     2.60827496      3.367992896     3.012259771
        3.101954851     3.149007142     3.139687728     3.240151164     3.77866694
        3.439747004     3.778406665     3.522599803     3.742020313     3.635421997
        3.186604466     3.104321252     3.231486219     3.014557746     3.452676512;


a1=1.031;
a2=35;
a3=3.685;
a4=0.2156;
a5=0.1178;
a6=0.3201;
a7=0.3208;
a8=29.14;
a9=0.04669;
a10=6.603;
a11=155.2;
a12=0.04984;
a13=752.9;
a14=13.51;
a15=703.6;
a16=6056;
a17=27.12;
a18=4475;
a19=0.1562;
a20=24.37;
a21=0.07446;
```

```
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','A2:A98') = p;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','B2:B98') = ps;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','C2:C98') = ch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','D2:D98') = dch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','E2:E98') = sp;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','F2:F98') = ID;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','G2:G98') = IC;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','H2:H98') = pd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','I2:I98') = pc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','J2:J98') = cyclen;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','K2:K98') = cmax;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','L2:L98') = sohd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','M2:M98') = soc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','N2:N98') = VBATT;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','O2:O98') = dod;
enddata


!solar panels are off during eclipse;
@for(states(i)| i #GE# 41 #and# i #LE# 71:sp(i)=0);
@for(states(i)| i #GE# 1 #and# i #LE# 40:sp(i)=1);
@for(states(i)| i #GE# 72 #and# i #LE# 97:sp(i)=1);



!intialising the state of charge of the battery;
@for(states(i)| i #EQ# 1:soc(i)=0.99);
@for(states(i)| i #EQ# 1:cycleN(i)=0);
@for(states(i)| i #EQ# 1: dod(i)=0);
@for(states(i)| i #EQ# 1: CHCUM(i) =0);
@for(states(i)| i #EQ# 1: CHSIGN(i) =0);


!final cycle number & cycle number calculation;
@for(states(i)| i #EQ# 97: fcycleN = cycleN);
@for(states(i)| i #EQ# 39:soc39 = soc(i));
@for(states(i)| i #EQ# 71:soc71 = soc(i));
deltasoc=soc39-soc71;
losscycle=(0.13/300)*deltasoc;
retainedc=1-losscycle;


DCHTIME=  @sum(states(i):dch(i)) ;
CHTIME=  @sum(states(i):ch(i)) ;
@for(states(i)| i #GT# 1:CHCUM(i)=ch(i)+CHCUM(i-1) );
@for(states(i)| i #GT# 1:CHSIGN(i)= @if(CHCUM(i)#GT# 0,1,0) );
@for(states(i)| i #GT# 1: cycleN(i) = @if( (cycleN(i-1)  #EQ# 1) #or# ((dch(i)-CHSIGN(i-1) #EQ# -1)
#and# (dch(i)+CHSIGN(i-1) #EQ# 1) #and# (dch(i-1) #EQ# 1)),1,0));


@for(states(i):cmax(i)=
@if(CycleN(i) #EQ# 1,retainedc*crated,crated));




! state of charge & Depth of discharge estimation;
@for(states(i)| i #GT# 1:
```

```
soc(i)=soc(i-1)-(dch(i)*((1*IBATT)/cmax(i)))+(ch(i)*((1*IBATT)/cmax(i)));
dod(i)=@if(dch(i) #EQ# 1, soc(i-1)-soc(i),0);
);

! battery terminal voltage estimation;
@for(states(i):
eo(i) = (-a1*@exp(-a2*soc(i))+a3+a4*soc(i)-a5*(soc(i)^2)+a6*(soc^3))*2; !open circuit emf voltage;
rs(i)= (a19*@exp(-a20*soc(i))+a21)*2; !series resistance value;
VBATT(i)= eo(i)-0.344975-0.338128-(dch(i)*(IBATT(i)*rs(i)))+(ch(i)*(IBATT(i)*rs(i)));
);

!limits of the SOC & DOD of the battery;
@for(states(i):
socmin <= soc(i);
soc(i) <= socmax;
dod(i) <= dodmax;
);

!soh degredation calculation;
@for(states(i):sohd(i)=(1-(cmax(i)/crated)));


! satisfying the required power demand;
@for(states(i):
ID(i)=IBATT(i)*dch(i);
IC(i)=IBATT(i)*ch(i);
sp(i)*ps(i)+(dch(i)*(VBATT*IBATT))-(ch(i)*(VBATT*IBATT)) >= p(i);
pd(i)=dch(i)*(VBATT*IBATT);
pc(i)= ch(i)*(VBATT*IBATT);
);



!standard deviation calculation;
socavg= @sum(states(i):soc(i))/97;
sd=@sqrt(@sum(states(i):(soc(i)-socavg)^2)/97);
```

Appendix C

In this Appendix, the long transient and short transient voltages MATLAB estimation code is shown. As previously illustrated in chapter 3, the reason of this estimation is to reduce the complexity code of the LINGO optimization solver.

```
clc;clear;close all
C=18720; %Amp second
t=0;
i=1;
DischI(i)=7.5;   %discharge Current
x1(i)=1;
x2(i)=0;
x3(i)=0;
Rseries_x1(i)=0.1562*exp(-24.37*x1(i))+0.07446;
Rtransients_x1(i)=0.3208*exp(-29.14*x1(i))+0.04669;
Ctransients_x1(i)=-752.9*exp(-13.51*x1(i))+703.6;
Rtransientl_x1(i)=6.603*exp(-155.2*x1(i))+0.04984;
Ctransientl_x1(i)=-6056*exp(-27.12*x1(i))+4475;
E0_x1(i)=-1.031*exp(-35*x1(i))+3.685+0.2156*x1(i)-0.1178*x1(i)^2+0.3201*x1(i)^3;
y(i)=E0_x1(i)-x2(i)-x3(i)-DischI(i)*Rseries_x1(i);
deltat=0.5;
i=i+1;
x1(i) =1; %dummy
DischI(i)=7.5;
while (x1(i-1) >= 0) && (y(i-1)>=0)
x1(i)=((-deltat*DischI(i-1))/C)+x1(i-1);
fprintf('the time =  %4.0f s\n',t);
fprintf('the SOC =  %4.6f \n',x1(i));
DischI(i)=7.5;
Rseries_x1(i)=0.1562*exp(-24.37*x1(i))+0.07446;
Rtransients_x1(i)=0.3208*exp(-29.14*x1(i))+0.04669;
Ctransients_x1(i)=-752.9*exp(-13.51*x1(i))+703.6;
Rtransientl_x1(i)=6.603*exp(-155.2*x1(i))+0.04984;
Ctransientl_x1(i)=-6056*exp(-27.12*x1(i))+4475;

E0_x1(i)=-1.031*exp(-35*x1(i))+3.685+0.2156*x1(i)-0.1178*(x1(i)^2)+0.3201*(x1(i)^3);
fprintf('the OC EMF =  %4.6f \n',E0_x1(i));
x2(i)=x2(i-1)-(deltat*x2(i-1))/(Rtransients_x1(i)*Ctransients_x1(i))+deltat*DischI(i-
1)/Ctransients_x1(i);
fprintf('the VTS =  %4.6f \n',x2(i));
x3(i)=x3(i-1)-(deltat*x3(i-1))/(Rtransientl_x1(i)*Ctransientl_x1(i))+deltat*DischI(i-
1)/Ctransientl_x1(i);
fprintf('the VTL =  %4.6f \n',x3(i));
y(i)=E0_x1(i)-x2(i)-x3(i)-DischI(i)*Rseries_x1(i);

fprintf('the terminal voltage =  %4.6f V\n',y(i));
t=t+deltat;
i=i+1;
disp('******************');
end
figure(1)
plot(1:length(x1)-1,x2(2:end)),xlabel('time(sec)'),ylabel('VTS(V)'),title('VTS Vs Time');
figure(2)
plot(1:length(x1)-1,x3(2:end)),xlabel('time(sec)'),ylabel('VTL(V)'),title('VTL Vs Time');
figure(3)
```

```
plot(1:length(x1)-1,y(2:end)),xlabel('time(sec)'),ylabel('Terminal Voltage(V)'),title('Terminal Voltage Vs Time'),ylim([2 4.5]);
figure(4)
plot(1:length(x1)-1,DischI(2:end)),xlabel('time(sec)'),ylabel('Discharge Current Amps'),title('Discharge Current Vs Time');
```

Appendix D

In this Appendix, the LINGO code for the three objective functions previously presented in chapter 3 are illustrated, starting with the first objective function, the second and finally the third. The results of these codes are presented in chapter 5.

1st objective function:

```
Model:
!1st function Code;
Sets:
states /1..97/:ch,dch,sp,ps,c,d,soc,dod,v,eo,p,rs,pd,pc,cycleN,cmax,sohd,IC,ID,CHCUM,CHSIGN;

Endsets
Data:
crated=312;  !rated capacity of 5.2 Ah * 60 min/hour = 312 Amin;
p= 2.123648657  2.040104124   2.033848739   2.127282728   2.217848621   2.124175213
    2.214246247   2.214246247   2.124175213   1.936527226   1.941281521
    1.941703522   2.034496632   2.03823172    2.124734675   1.937037265
    2.034639918   1.937037265   2.034639918   1.937037265   2.034639918
    1.939754191   2.124849051   2.214948658   2.215908047   2.124884383
    2.214985487   1.938851877   2.034850957   2.034850957   1.847134079
    2.036068059   1.937282678   2.125003868   2.034897697   1.937282678
    1.847176507   1.937282678   1.937282678   2.033974377   1.837772639
    1.472919419   1.569449158   1.658443439   1.658152009   1.471927399
    1.471698449   1.657345312   1.657055292   1.470955296   1.567357967
    1.567099388   1.566841124   1.655689919   1.469745065   1.566069445
    1.469277491   1.565571624   1.654349606   1.565044512   1.564788756
    1.653523072   1.653237979   1.652953256   1.6526689     1.5634566
    1.563202788   1.562949286   1.562696095   1.562443215   1.562190645
    1.842671583   1.927524803   2.207967482   2.030819983   2.204345078
    2.029451226   2.02517335    2.209315127   2.025336717   2.032797494
    2.205004051   2.205004051   2.03185937    2.29496222    2.032594827
    2.035822546   2.116192179   2.125823233   2.116551474   2.036320291
    2.206686191   2.116922685   2.116922685   1.929915381   1.929915381
    2.214216458;


ps = 3.02413572     3.206953346   2.401592607   2.706084036   2.834335357
    2.957332275   2.957332275   2.874767161   2.657095496   2.371870556
    2.836678812   2.882451353   2.702652352   2.707614092   2.657795317
    2.575208457   2.575208457   2.492621597   2.530161079   2.492621597
    2.402526841   2.451007233   2.335081466   2.335081466   2.373650653
    2.335120293   2.290069741   2.254478927   2.207550485   2.252602535
    2.252602535   2.253949881   2.252654277   2.207601191   2.162548106
    2.207601191   2.079950782   2.034897697   2.207601191   1.868854686   0
    0       0       0       0       0       0       0       0       0       0       0
    0       0       0       0       0       0       0       0       0       0       0
    0       0       0       0       0       0       0       0       2.823931653
    2.24130791    2.866615409   3.109927281   2.690048231   2.823258717
    2.481024178   2.995681528   2.60827496    3.367992896   3.012259771
    3.101954851   3.149007142   3.139687728   3.240151164   3.77866694
    3.439747004   3.778406665   3.522599803   3.742020313   3.635421997
    3.186604466   3.104321252   3.231486219   3.014557746   3.452676512;
```

```
socmin=0.3;
socmax=1;
dodmax=0.2;

a1=1.031;
a2=35;
a3=3.685;
a4=0.2156;
a5=0.1178;
a6=0.3201;
a7=0.3208;
a8=29.14;
a9=0.04669;
a10=6.603;
a11=155.2;
a12=0.04984;
a13=752.9;
a14=13.51;
a15=703.6;
a16=6056;
a17=27.12;
a18=4475;
a19=0.1562;
a20=24.37;
a21=0.07446;

@OLE('C:\Users\User\Desktop\RESULTS.xlsx','A2:A98') = p;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','B2:B98') = ps;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','C2:C98') = ch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','D2:D98') = dch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','E2:E98') = sp;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','F2:F98') = IC;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','G2:G98') = ID;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','H2:H98') = pd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','I2:I98') = pc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','J2:J98') = cyclen;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','K2:K98') = cmax;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','L2:L98') = sohd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','M2:M98') = soc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','N2:N98') = v;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','O2:O98') = dod;

enddata


!solar panels are off during eclipse;
@for(states(i)| i #GE# 41 #and# i #LE# 71:sp(i)=0);




!intialising the state of charge of the battery;
@for(states(i)| i #EQ# 1:soc(i)=0.99);
@for(states(i)| i #EQ# 1: dch(i)=0);
@for(states(i)| i #EQ# 1: ch(i)=0);
@for(states(i)| i #EQ# 1:cycleN(i)=0);
@for(states(i)| i #EQ# 1: dod(i)=0);
@for(states(i)| i #EQ# 1: v(i)= eo(i)-0.344975-0.338128);
```

```
@for(states(i)| i #EQ# 1: CHCUM(i) =0);
@for(states(i)| i #EQ# 1: CHSIGN(i) =0);

!final cycle number & cycle number calculation;
@for(states(i)| i #EQ# 97:fcycleN = cyclen(i));
@for(states(i)| i #EQ# 39:soc39 = soc(i));
@for(states(i)| i #EQ# 71:soc71 = soc(i));
deltasoc=soc39-soc71;
losscycle=(0.13/300)*deltasoc;
retainedc=1-losscycle;
X=8.4/4.1029;

DCHTIME=  @sum(states(i):dch(i)) ;
CHTIME=  @sum(states(i):ch(i)) ;
@for(states(i)| i #GT# 1:CHCUM(i)=ch(i)+CHCUM(i-1) );
@for(states(i)| i #GT# 1:CHSIGN(i)= @if(CHCUM(i)#GT# 0,1,0) );
@for(states(i)| i #GT# 1: cycleN(i) = @if( (cycleN(i-1)  #EQ# 1) #or# ((dch(i)-CHSIGN(i-1) #EQ# -1)
#and# (dch(i-1) #EQ# 1)),1,0));


@for(states(i):cmax(i)=
@if(CycleN(i) #EQ# 1,retainedc*crated,crated));



! state of charge & Depth of discharge estimation;
@for(states(i)| i #GT# 1:
soc(i)=soc(i-1)-(dch(i)*((1*ID(i))/cmax(i)))+(ch(i)*((1*IC(i))/cmax(i)));
dod(i)=@if(dch(i) #EQ# 1, soc(i-1)-soc(i),0);
);

! battery terminal voltage estimation;
@for(states(i):
eo(i) = (-a1*@exp(-a2*soc(i))+a3+a4*soc(i)-a5*(soc(i)^2)+a6*(soc^3))*2; !open circuit emf voltage;
rs(i)= (a19*@exp(-a20*soc(i))+a21)*2; !series resistance value;
);


@for(states(i)| i #GT# 1: v(i)= eo(i)-0.344975-0.338128-(dch(i)*(ID(i)*rs(i)))+(ch(i)*(IC(i)*rs(i))));



!limits of the SOC & DOD of the battery;
@for(states(i):
socmin <= soc(i);
soc(i) <= socmax;
dod(i) <= dodmax;
);

!soh degredation calculation;
@for(states(i):sohd(i)=(1-(cmax(i)/crated)));


!rates are positive values;
@for(states(i):@bnd(0,d(i),3.75));
@for(states(i):@bnd(0,c(i),2.5));
@for(states(i):@bnd(6,v(i),8.4));
@for(states(i):IC(i)=c(i)*ch(i));
@for(states(i):ID(i)=d(i)*dch(i));
```

```
@for(states(i)| i #EQ# 97:soc(i)>=0.985);
@for(states(i)| i #EQ# 39:soc(i)>=0.995);

!objective Function;
min=@sum(states(i):dch(i)+ch(i));                                   !first objective
function;
!min=@sum(states(i):dch(i)*ID(i)+ch(i)*IC(i)) ;          !Second objective function;


! Constraints;
!solar panel usage,battery charge and discharge are not simultaneous;
@for(states(i):
@BIN(dch(i));
@BIN(sp(i));
@BIN(ch(i));
ch(i)<=dch(i)+sp(i);
ch(i)*dch(i)=0;
);


! satisfying the required power demand;
@for(states(i):
sp(i)*ps(i)+(dch(i)*(v(i)*ID(i)))-(ch(i)*(v(i)*IC(i))) >= p(i);
pd(i)=dch(i)*(v(i)*ID(i));
pc(i)= ch(i)*(v(i)*IC(i));
);



!standard deviation calculation;
socavg= @sum(states(i):soc(i))/97;
sd=@sqrt(@sum(states(i):(soc(i)-socavg)^2)/97);
```

2nd objective function:

```
Model:
! 2nd objective function Code;
Sets:
states /1..97/:ch,dch,sp,ps,c,d,soc,dod,v,eo,p,rs,pd,pc,cycleN,cmax,sohd,IC,ID,CHCUM,CHSIGN;

Endsets
Data:
crated=312;  !rated capacity of 5.2 Ah * 60 min/hour = 312 Amin;
p= 2.123648657  2.040104124   2.033848739   2.127282728   2.217848621   2.124175213
    2.214246247   2.214246247   2.124175213   1.936527226   1.941281521
    1.941703522   2.034496632   2.03823172    2.124734675   1.937037265
    2.034639918   1.937037265   2.034639918   1.937037265   2.034639918
    1.939754191   2.124849051   2.214948658   2.215908047   2.124884383
    2.214985487   1.938851877   2.034850957   2.034850957   1.847134079
    2.036068059   1.937282678   2.125003868   2.034897697   1.937282678
    1.847176507   1.937282678   1.937282678   2.033974377   1.837772639
    1.472919419   1.569449158   1.658443439   1.658152009   1.471927399
    1.471698449   1.657345312   1.657055292   1.470955296   1.567357967
    1.567099388   1.566841124   1.655689919   1.469745065   1.566069445
    1.469277491   1.565571624   1.654349606   1.565044512   1.564788756
    1.653523072   1.653237979   1.652953256   1.6526689     1.5634566
    1.563202788   1.562949286   1.562696095   1.562443215   1.562190645
    1.842671583   1.927524803   2.207967482   2.030819983   2.204345078
```

```
            2.029451226   2.02517335    2.209315127   2.025336717   2.032797494
            2.205004051   2.205004051   2.03185937    2.29496222    2.032594827
            2.035822546   2.116192179   2.125823233   2.116551474   2.036320291
            2.206686191   2.116922685   2.116922685   1.929915381   1.929915381
            2.214216458;


ps = 3.02413572           3.206953346   2.401592607   2.706084036   2.834335357
            2.957332275   2.957332275   2.874767161   2.657095496   2.371870556
            2.836678812   2.882451353   2.702652352   2.707614092   2.657795317
            2.575208457   2.575208457   2.492621597   2.530161079   2.492621597
            2.402526841   2.451007233   2.335081466   2.335081466   2.373650653
            2.335120293   2.290069741   2.254478927   2.207550485   2.252602535
            2.252602535   2.253949881   2.252654277   2.207601191   2.162548106
            2.207601191   2.079950782   2.034897697   2.207601191   1.868854686   0
            0      0      0      0      0      0      0      0      0      0      0
            0      0      0      0      0      0      0      0      0      0      0
            0      0      0      0      0      0      0      0      2.823931653
            2.24130791    2.866615409   3.109927281   2.690048231   2.823258717
            2.481024178   2.995681528   2.60827496    3.367992896   3.012259771
            3.101954851   3.149007142   3.139687728   3.240151164   3.77866694
            3.439747004   3.778406665   3.522599803   3.742020313   3.635421997
            3.186604466   3.104321252   3.231486219   3.014557746   3.452676512;


socmin=0.3;
socmax=1;
dodmax=0.2;

a1=1.031;
a2=35;
a3=3.685;
a4=0.2156;
a5=0.1178;
a6=0.3201;
a7=0.3208;
a8=29.14;
a9=0.04669;
a10=6.603;
a11=155.2;
a12=0.04984;
a13=752.9;
a14=13.51;
a15=703.6;
a16=6056;
a17=27.12;
a18=4475;
a19=0.1562;
a20=24.37;
a21=0.07446;

@OLE('C:\Users\User\Desktop\RESULTS.xlsx','A2:A98') = p;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','B2:B98') = ps;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','C2:C98') = ch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','D2:D98') = dch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','E2:E98') = sp;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','F2:F98') = IC;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','G2:G98') = ID;
```

```
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','H2:H98') = pd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','I2:I98') = pc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','J2:J98') = cyclen;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','K2:K98') = cmax;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','L2:L98') = sohd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','M2:M98') = soc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','N2:N98') = v;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','O2:O98') = dod;

enddata


!solar panels are off during eclipse;
@for(states(i)| i #GE# 41 #and# i #LE# 71:sp(i)=0);




!intialising the state of charge of the battery;
@for(states(i)| i #EQ# 1:soc(i)=0.99);
@for(states(i)| i #EQ# 1: dch(i)=0);
@for(states(i)| i #EQ# 1: ch(i)=0);
@for(states(i)| i #EQ# 1:cycleN(i)=0);
@for(states(i)| i #EQ# 1: dod(i)=0);
@for(states(i)| i #EQ# 1: v(i)= eo(i)-0.344975-0.338128);
@for(states(i)| i #EQ# 1: CHCUM(i) =0);
@for(states(i)| i #EQ# 1: CHSIGN(i) =0);

!final cycle number & cycle number calculation;
@for(states(i)| i #EQ# 97:fcycleN = cyclen(i));
@for(states(i)| i #EQ# 39:soc39 = soc(i));
@for(states(i)| i #EQ# 71:soc71 = soc(i));
deltasoc=soc39-soc71;
losscycle=(0.13/300)*deltasoc;
retainedc=1-losscycle;
X=8.4/4.1029;

DCHTIME=  @sum(states(i):dch(i)) ;
CHTIME=  @sum(states(i):ch(i)) ;
@for(states(i)| i #GT# 1:CHCUM(i)=ch(i)+CHCUM(i-1) );
@for(states(i)| i #GT# 1:CHSIGN(i)= @if(CHCUM(i)#GT# 0,1,0) );
@for(states(i)| i #GT# 1: cycleN(i) = @if( (cycleN(i-1)  #EQ# 1) #or# ((dch(i)-CHSIGN(i-1) #EQ# -1)
#and# (dch(i-1) #EQ# 1)),1,0));


@for(states(i):cmax(i)=
@if(CycleN(i) #EQ# 1,retainedc*crated,crated));



! state of charge & Depth of discharge estimation;
@for(states(i)| i #GT# 1:
soc(i)=soc(i-1)-(dch(i)*((1*ID(i))/cmax(i)))+(ch(i)*((1*IC(i))/cmax(i)));
dod(i)=@if(dch(i) #EQ# 1, soc(i-1)-soc(i),0);
);

! battery terminal voltage estimation;
@for(states(i):
eo(i) = (-a1*@exp(-a2*soc(i))+a3+a4*soc(i)-a5*(soc(i)^2)+a6*(soc^3))*2; !open circuit emf voltage;
```

```
rs(i)= (a19*@exp(-a20*soc(i))+a21)*2; !series resistance value;
);


@for(states(i)| i #GT# 1: v(i)= eo(i)-0.344975-0.338128-(dch(i)*(ID(i)*rs(i)))+(ch(i)*(IC(i)*rs(i))));



!limits of the SOC & DOD of the battery;
@for(states(i):
socmin <= soc(i);
soc(i) <= socmax;
dod(i) <= dodmax;
);

!soh degredation calculation;
@for(states(i):sohd(i)=(1-(cmax(i)/crated)));


!rates are positive values;
@for(states(i):@bnd(0,d(i),3.75));
@for(states(i):@bnd(0,c(i),2.5));
@for(states(i):@bnd(6,v(i),8.4));
@for(states(i):IC(i)=c(i)*ch(i));
@for(states(i):ID(i)=d(i)*dch(i));
@for(states(i)| i #EQ# 97:soc(i)>=0.985);
@for(states(i)| i #EQ# 39:soc(i)>=0.995);

!objective Function;
!min=@sum(states(i):dch(i)+ch(i));                                              !first
objective function;
min=@sum(states(i):dch(i)*ID(i)+ch(i)*IC(i)) ;                  !Second objective function;


! Constraints;
!solar panel usage,battery charge and discharge are not simultaneous;
@for(states(i):
@BIN(dch(i));
@BIN(sp(i));
@BIN(ch(i));
ch(i)<=dch(i)+sp(i);
ch(i)*dch(i)=0;
);


! satisfying the required power demand;
@for(states(i):
sp(i)*ps(i)+(dch(i)*(v(i)*ID(i)))-(ch(i)*(v(i)*IC(i))) >= p(i);
pd(i)=dch(i)*(v(i)*ID(i));
pc(i)= ch(i)*(v(i)*IC(i));
);



!standard deviation calculation;
socavg= @sum(states(i):soc(i))/97;
sd=@sqrt(@sum(states(i):(soc(i)-socavg)^2)/97);
```

3rd objective function:

```
Model:
!third objective function code;

Sets:
states /1..97/:ch,dch,sp,ps,c,d,soc,dod,v,eo,p,rs,pd,pc,cycleN,cmax,sohd,IC,ID,CHCUM,CHSIGN;

Endsets
Data:
crated=312;  !rated capacity of 5.2 Ah * 60 min/hour = 312 Amin;
p= 2.123648657  2.040104124       2.033848739       2.127282728       2.217848621       2.124175213
            2.214246247       2.214246247       2.124175213       1.936527226       1.941281521
            1.941703522       2.034496632       2.03823172        2.124734675       1.937037265
            2.034639918       1.937037265       2.034639918       1.937037265       2.034639918
            1.939754191       2.124849051       2.214948658       2.215908047       2.124884383
            2.214985487       1.938851877       2.034850957       2.034850957       1.847134079
            2.036068059       1.937282678       2.125003868       2.034897697       1.937282678
            1.847176507       1.937282678       1.937282678       2.033974377       1.837772639
            1.472919419       1.569449158       1.658443439       1.658152009       1.471927399
            1.471698449       1.657345312       1.657055292       1.470955296       1.567357967
            1.567099388       1.566841124       1.655689919       1.469745065       1.566069445
            1.469277491       1.565571624       1.654349606       1.565044512       1.564788756
            1.653523072       1.653237979       1.652953256       1.6526689         1.5634566
            1.563202788       1.562949286       1.562696095       1.562443215       1.562190645
            1.842671583       1.927524803       2.207967482       2.030819983       2.204345078
            2.029451226       2.02517335        2.209315127       2.025336717       2.032797494
            2.205004051       2.205004051       2.03185937        2.29496222        2.032594827
            2.035822546       2.116192179       2.125823233       2.116551474       2.036320291
            2.206686191       2.116922685       2.116922685       1.929915381       1.929915381
            2.214216458;


ps = 3.02413572           3.206953346       2.401592607       2.706084036       2.834335357
            2.957332275       2.957332275       2.874767161       2.657095496       2.371870556
            2.836678812       2.882451353       2.702652352       2.707614092       2.657795317
            2.575208457       2.575208457       2.492621597       2.530161079       2.492621597
            2.402526841       2.451007233       2.335081466       2.335081466       2.373650653
            2.335120293       2.290069741       2.254478927       2.207550485       2.252602535
            2.252602535       2.253949881       2.252654277       2.207601191       2.162548106
            2.207601191       2.079950782       2.034897697       2.207601191       1.868854686     0
            0         0         0         0         0         0         0         0         0         0         0
            0         0         0         0         0         0         0         0         0         0         0
            0         0         0         0         0         0         0         0         2.823931653
            2.24130791        2.866615409       3.109927281       2.690048231       2.823258717
            2.481024178       2.995681528       2.60827496        3.367992896       3.012259771
            3.101954851       3.149007142       3.139687728       3.240151164       3.77866694
            3.439747004       3.778406665       3.522599803       3.742020313       3.635421997
            3.186604466       3.104321252       3.231486219       3.014557746       3.452676512;

socmin=0.3;
socmax=1;
dodmax=0.2;

a1=1.031;
a2=35;
a3=3.685;
```

```
a4=0.2156;
a5=0.1178;
a6=0.3201;
a7=0.3208;
a8=29.14;
a9=0.04669;
a10=6.603;
a11=155.2;
a12=0.04984;
a13=752.9;
a14=13.51;
a15=703.6;
a16=6056;
a17=27.12;
a18=4475;
a19=0.1562;
a20=24.37;
a21=0.07446;

@OLE('C:\Users\User\Desktop\RESULTS.xlsx','A2:A98') = p;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','B2:B98') = ps;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','C2:C98') = ch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','D2:D98') = dch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','E2:E98') = sp;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','F2:F98') = IC;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','G2:G98') = ID;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','H2:H98') = pd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','I2:I98') = pc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','J2:J98') = cyclen;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','K2:K98') = cmax;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','L2:L98') = sohd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','M2:M98') = soc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','N2:N98') = v;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','O2:O98') = dod;

enddata


!solar panels are off during eclipse;
@for(states(i)| i #GE# 41 #and# i #LE# 71:sp(i)=0);




!intialising the state of charge of the battery;
@for(states(i)| i #EQ# 1:soc(i)=0.5);
@for(states(i)| i #EQ# 1: dch(i)=0);
@for(states(i)| i #EQ# 1: ch(i)=0);
@for(states(i)| i #EQ# 1:cycleN(i)=0);
@for(states(i)| i #EQ# 1: dod(i)=0);
@for(states(i)| i #EQ# 1: v(i)= eo(i)-0.344975-0.338128);
@for(states(i)| i #EQ# 1: CHCUM(i) =0);
@for(states(i)| i #EQ# 1: CHSIGN(i) =0);

!final cycle number & cycle number calculation;
@for(states(i)| i #EQ# 97:fcycleN = cyclen(i));
@for(states(i)| i #EQ# 39:soc39 = soc(i));
@for(states(i)| i #EQ# 71:soc71 = soc(i));
deltasoc=soc39-soc71;
```

```
losscycle=(0.13/300)*deltasoc;
retainedc=1-losscycle;
X=8.4/4.1029;

DCHTIME=  @sum(states(i):dch(i)) ;
CHTIME=  @sum(states(i):ch(i)) ;
@for(states(i)| i #GT# 1:CHCUM(i)=ch(i)+CHCUM(i-1) );
@for(states(i)| i #GT# 1:CHSIGN(i)= @if(CHCUM(i)#GT# 0,1,0) );
@for(states(i)| i #GT# 1: cycleN(i) = @if( (cycleN(i-1)  #EQ# 1) #or# ((dch(i)-CHSIGN(i-1) #EQ# -1)
#and# (dch(i-1) #EQ# 1)),1,0));


@for(states(i):cmax(i)=
@if(CycleN(i) #EQ# 1,retainedc*crated,crated));



! state of charge & Depth of discharge estimation;
@for(states(i)| i #GT# 1:
soc(i)=soc(i-1)-(dch(i)*((1*ID(i))/cmax(i)))+(ch(i)*((1*IC(i))/cmax(i)));
dod(i)=@if(dch(i) #EQ# 1, soc(i-1)-soc(i),0);
);

! battery terminal voltage estimation;
@for(states(i):
eo(i) = (-a1*@exp(-a2*soc(i))+a3+a4*soc(i)-a5*(soc(i)^2)+a6*(soc^3))*2; !open circuit emf voltage;
rs(i)= (a19*@exp(-a20*soc(i))+a21)*2; !series resistance value;
);


@for(states(i)| i #GT# 1: v(i)= eo(i)-0.344975-0.338128-(dch(i)*(ID(i)*rs(i)))+(ch(i)*(IC(i)*rs(i))));



!limits of the SOC & DOD of the battery;
@for(states(i):
socmin <= soc(i);
soc(i) <= socmax;
dod(i) <= dodmax;
);

!soh degredation calculation;
@for(states(i):sohd(i)=(1-(cmax(i)/crated)));


!rates are positive values;
@for(states(i):@bnd(0,d(i),3.75));
@for(states(i):@bnd(0,c(i),2.5));
@for(states(i):@bnd(6,v(i),8.4));
@for(states(i):IC(i)=c(i)*ch(i));
@for(states(i):ID(i)=d(i)*dch(i));
@for(states(i)| i #EQ# 97:soc(i)>=0.495);
@for(states(i)| i #EQ# 39:soc(i)>=0.505);


!objective Function;
!min= soc39-soc71;
min=@sum(states(i):dod(i));
```

```
! Constraints;
!solar panel usage,battery charge and discharge are not simultaneous;
@for(states(i):
@BIN(dch(i));
@BIN(sp(i));
@BIN(ch(i));
ch(i)<=dch(i)+sp(i);
ch(i)*dch(i)=0;
);


! satisfying the required power demand;
@for(states(i):
sp(i)*ps(i)+(dch(i)*(v(i)*ID(i)))-(ch(i)*(v(i)*IC(i))) >= p(i);
pd(i)=dch(i)*(v(i)*ID(i));
pc(i)= ch(i)*(v(i)*IC(i));
);



!standard deviation calculation;
socavg= @sum(states(i):soc(i))/97;
sd=@sqrt(@sum(states(i):(soc(i)-socavg)^2)/97);
```

Appendix E

In this Appendix, as previously illustrated in chapter 4, the heuristic approach MATLAB code is presented, the results of this code is presented in chapter 5.

```
%Data;
PS= [3.02413572,    3.206953346,    2.401592607,    2.706084036,    2.834335357,    2.957332275,
2.957332275,    2.874767161,    2.657095496,    2.371870556,    2.836678812,    2.882451353,
2.702652352,    2.707614092,    2.657795317,    2.575208457,    2.575208457,    2.492621597,
2.530161079,    2.492621597,    2.402526841,    2.451007233,    2.335081466,    2.335081466,
2.373650653,    2.335120293,    2.290069741,    2.254478927,    2.207550485,    2.252602535,
2.252602535,    2.253949881,    2.252654277,    2.207601191,    2.162548106,    2.207601191,
2.079950782,    2.034897697,    2.207601191,    1.868854686,    0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,
0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  2.823931653,    2.24130791, 2.866615409,
3.109927281,    2.690048231,    2.823258717,    2.481024178,    2.995681528,    2.60827496,
3.367992896,    3.012259771,    3.101954851,    3.149007142,    3.139687728,    3.240151164,
3.77866694, 3.439747004,    3.778406665,    3.522599803,    3.742020313,    3.635421997,
3.186604466,    3.104321252,    3.231486219,    3.014557746,    3.452676512];

Pdemand=[2.123648657, 2.040104124, 2.033848739, 2.127282728, 2.217848621, 2.124175213,
2.214246247, 2.214246247, 2.124175213, 1.936527226, 1.941281521, 1.941703522,    2.034496632,
2.03823172, 2.124734675,    1.937037265,    2.034639918,    1.937037265,    2.034639918,
1.937037265,    2.034639918,    1.939754191,    2.124849051,    2.214948658,    2.215908047,
2.124884383,    2.214985487,    1.938851877,    2.034850957,    2.034850957,    1.847134079,
2.036068059,    1.937282678,    2.125003868,    2.034897697,    1.937282678,    1.847176507,
1.937282678,    1.937282678,    2.033974377,    1.837772639,    1.472919419,    1.569449158,
1.658443439,    1.658152009,    1.471927399,    1.471698449,    1.657345312,    1.657055292,
1.470955296,    1.567357967,    1.567099388,    1.566841124,    1.655689919,    1.469745065,
1.566069445,    1.469277491,    1.565571624,    1.654349606,    1.565044512,    1.564788756,
1.653523072,    1.653237979,    1.652953256,    1.6526689,  1.5634566,  1.563202788,    1.562949286,
1.562696095,    1.562443215,    1.562190645,    1.842671583,    1.927524803,    2.207967482,
2.030819983,    2.204345078,    2.029451226,    2.02517335, 2.209315127,    2.025336717,
2.032797494,    2.205004051,    2.205004051,    2.03185937, 2.29496222, 2.032594827,
2.035822546,    2.116192179,    2.125823233,    2.116551474,    2.036320291,    2.206686191,
2.116922685,    2.116922685,    1.929915381,    1.929915381,    2.214216458];



Cc= 312;
%intialization of matrices;
DCHB=zeros(1,97);
CMAX=zeros(1,97);
IDB=zeros(1,97);
ICB=zeros(1,97);
CHB=zeros(1,97);
SPV=zeros(1,97);
PBD=zeros(1,97);
PBC=zeros(1,97);
VB=zeros(1,97);
PPV=zeros(1,97);
E0=zeros(1,97);
Rs=zeros(1,97);
CHCUM=zeros(1,97);
CHSIGN=zeros(1,97);
SOCB=[0.99,0 , 0, 0, 0, 0, 0, 0, 0,0,0
,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0];
```

```
cyclen=zeros(1,97);



if (Pdemand(1)>0)

               if (Pdemand(1) < PS(1))
                   SPV(1)=1;
               end

               elseif (SOCB(1) >0.3)
                if (Pdemand(1) > PS(1))
                       DCHB(1)=1;
                        SPV(1)=1;

                end
end

%Batteries;
ICB(1)=CHB(1)*0.04;



CMAX(1)=Cc;
Rs(1)=0;
%PV;
PPV(1)= SPV(1)*PS(1);
%Cycle Number
if (DCHB(1)>=1) || (CHB(1)>=1)
    cyclen(1)=1;
else
    cyclen(1)=0;
end
%State of charge
SOCB(1) = (((-1/CMAX(1))*IDB(1))*DCHB(1))+(((1/CMAX(1))*ICB(1))*CHB(1))+0.99;

E0(1)=(-1.031*exp(-35*SOCB(1))+3.685+0.2156*SOCB(1)-
0.1178*(SOCB(1)^2)+0.3201*(SOCB(1)^3))*2;
VB(1)= E0(1)-0.344975-0.338128;
PBD(1) = VB(1)*IDB(1)*DCHB(1);
PBC(1)=VB(1)*CHB(1)*ICB(1);

for i=2:97



               if (Pdemand(i)<=PS(i))
                   SPV(i)=1;
                   if(SOCB(i-1)<1)
                       SPV(i)=1;
                       CHB(i)=1;

                   end
```

```
            elseif (Pdemand(i)>PS(i))&&(PS(i)>0)
                if (SOCB(i-1)> 0.3)
                    DCHB(i)=1;
                    SPV(i)=1;
                    IDB(i)=DCHB(i)*((Pdemand(i)-PS(i))/VB(i-1));

               end
            elseif (PS(i)==0)
               if(SOCB(i-1)>0.3)
                   DCHB(i)=1;
                   SPV(i)=0;
                   IDB(i)=DCHB(i)*Pdemand(i)/VB(i-1);
               end


            elseif (Pdemand(i)== 0)

                  if (SOCB(i-1)<1)
                           SPV(i)=1;
                           CHB(i)=1;

                  end
            end




%PV;
PPV(i)= SPV(i)*PS(i);

%cycle number and CMax calculation;

 CHCUM(i)=CHB(i)+CHCUM(i-1);
   if (CHCUM(i)>=0)
       CHSIGN(i)=1;
   else
       CHSIGN(i)=0;
   end

   if  (cyclen(i-1)>=1) || ((DCHB(i)-CHSIGN(i-1)<=-1) && (DCHB(i-1)>=1))
   cyclen(i)=1;
   else
   cyclen(i)=0;
   end



   if (cyclen(i) >= 1)
       deltasoc=SOCB(39)-SOCB(71);
          losscycle=(0.13/300)*deltasoc;
          retainedc=1-losscycle;
   CMAX(i)=retainedc*Cc;
   else
  CMAX(i)=Cc;
   end
```

```
%State of charge
 ICB(i)=CHB(i)*0.04;

    SOCB(i) = ((-1/CMAX(i))*IDB(i))*DCHB(i)+((1/CMAX(i))*ICB(i))*CHB(i)+SOCB(i-1);
    E0(i)=(-1.031*exp(-35*SOCB(i))+3.685+0.2156*SOCB(i)-
0.1178*(SOCB(i)^2)+0.3201*(SOCB(i)^3))*2;
    Rs(i)=(0.1562*exp(-24.37*SOCB(i))+0.07446)*2;
    VB(i)=E0(i)-0.344975-0.338128-DCHB(i)*(IDB(i)*Rs(i))+CHB(i)*(ICB(i)*Rs(i));

%Batteries;
PBD(i) = VB(i)*IDB(i)*DCHB(i);
PBC(i)=VB(i)*CHB(i)*ICB(i);


end
 SOHBdeg=1-(CMAX(97)/Cc);

figure(1)
plot(1:97,SOCB(1:end)),xlabel('Time(min)'),ylabel('SOC'),ylim([0.95 1]);
figure(2)
plot(1:97,VB(1:end)),xlabel('Time(min)'),ylabel('Battery Voltage (V)');
figure(3)
plot(1:97,IDB),xlabel('Time(min)'),ylabel('Discharge current (Amps)'),title('discharge current Vs
Time');
figure(4)
plot(1:97,ICB),xlabel('Time(min)'),ylabel('Charge current (Amps)'),title('charge current Vs
Time'),ylim([0 0.1]);
figure(5)
plot(1:97,CHB(1:end)),xlabel('Time(min)'),ylabel('Battery switch'),ylim([0 1.1]);
hold on
plot(1:97,DCHB(1:end)),xlabel('Time(min)'),ylabel('Battery switch'),ylim([0 1.1]);
legend('Charge switch state','Discharge switch state');
hold off
```

Appendix F

In this Appendix, the AMSAT data warehouse for Nayif-1 website that has been used to collected the second sample of data in order to provide the sensitivity analysis to the results in chapter 5 is shown:

http://data.amsat-uk.org/nayif1/wod.html

Appendix G

In this Appendix, the sensitivity analysis conducted for the different initial SOC graphs are presented, beginning with the SOC of 0.7 followed by 0.5 as previously shown in chapter 5, for each of the three objective functions. The Appendix will then introduce the new data retrieved from the AMSAT data warehouse and the codes for the current case of the new data of Nayif-1, followed by the codes for the three objective functions based on the new data respectively.

1st objective function graphs:

SOC=0.7

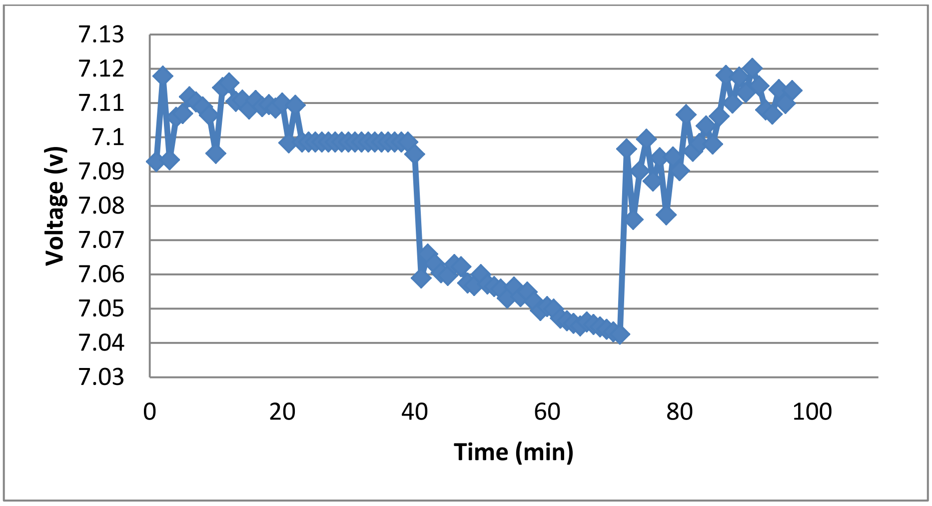

Figure 43: Voltage Vs time for 1st objective function at initial SOC of 0.7

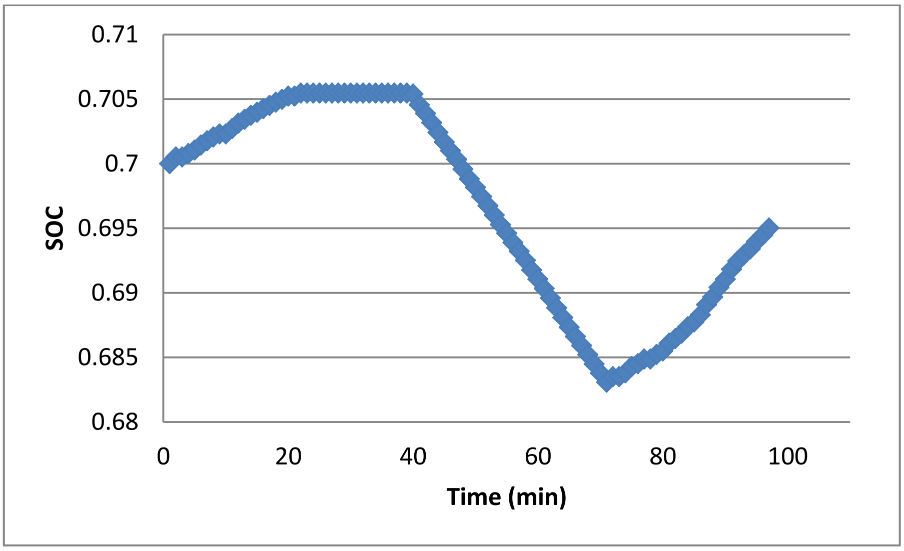

Figure 44: SOC Vs time for 1st objective function at initial SOC of 0.7

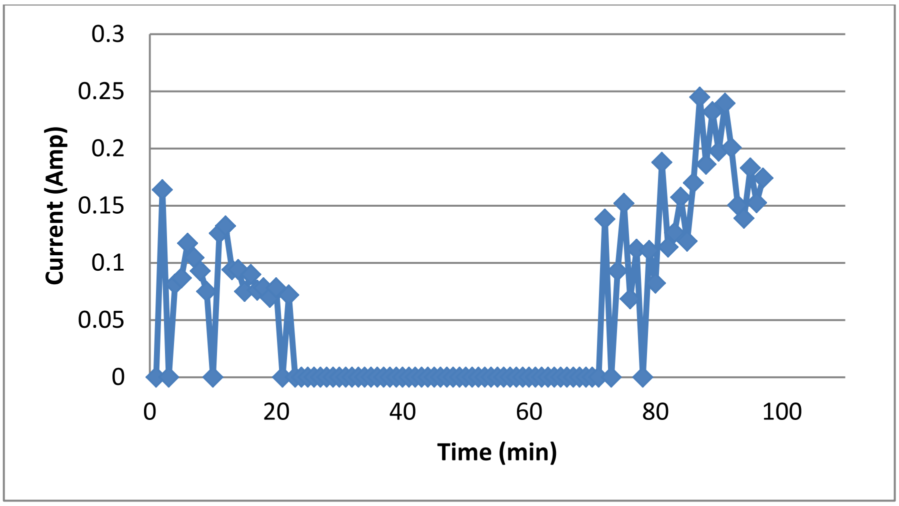

Figure 45: Charge current Vs time for 1st objective function at initial SOC of 0.7

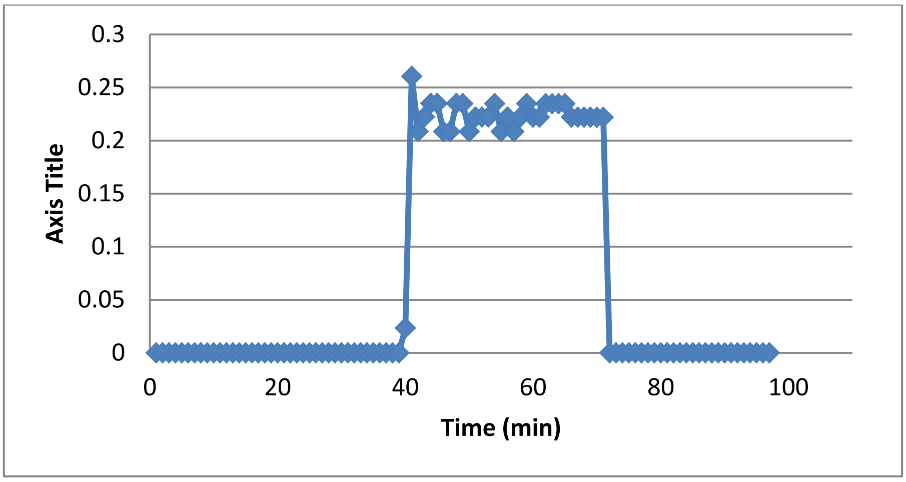

Figure 46: Discharge current Vs time for 1st objective function at initial SOC of 0.7

SOC=0.5

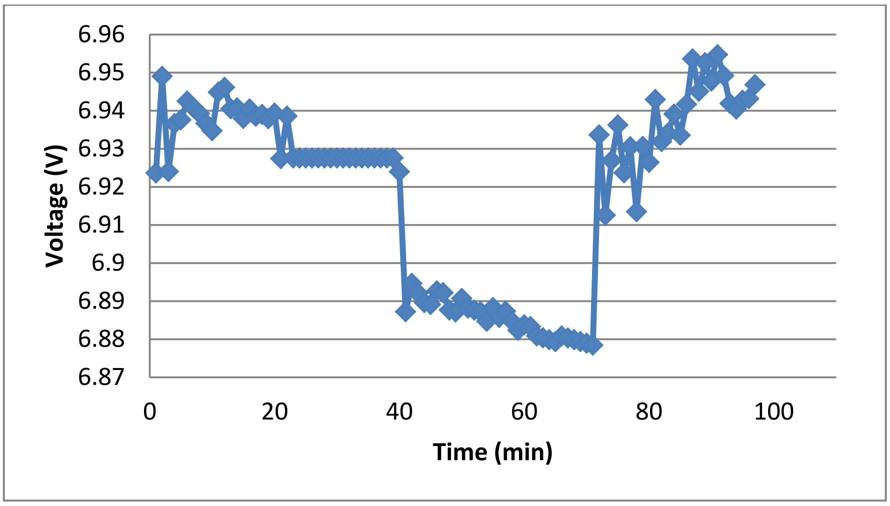

Figure 47: Voltage Vs time for 1st objective function at initial SOC of 0.5

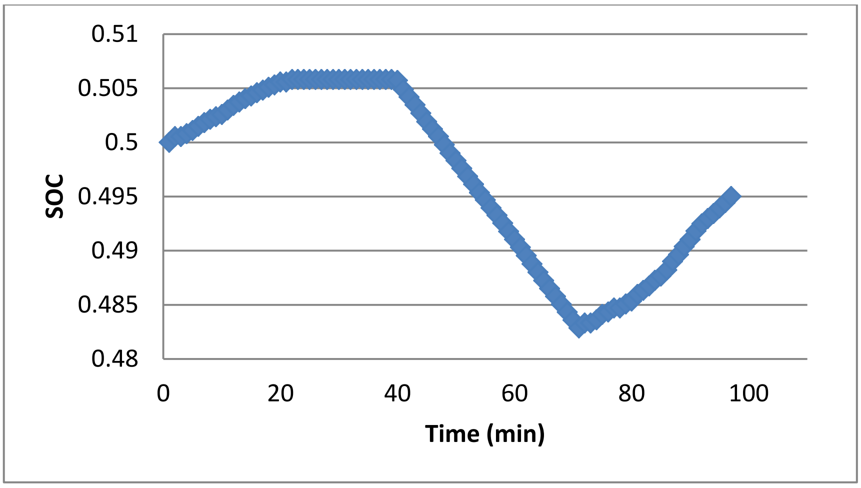

Figure 48: SOC Vs time for 1st objective function at initial SOC of 0.5

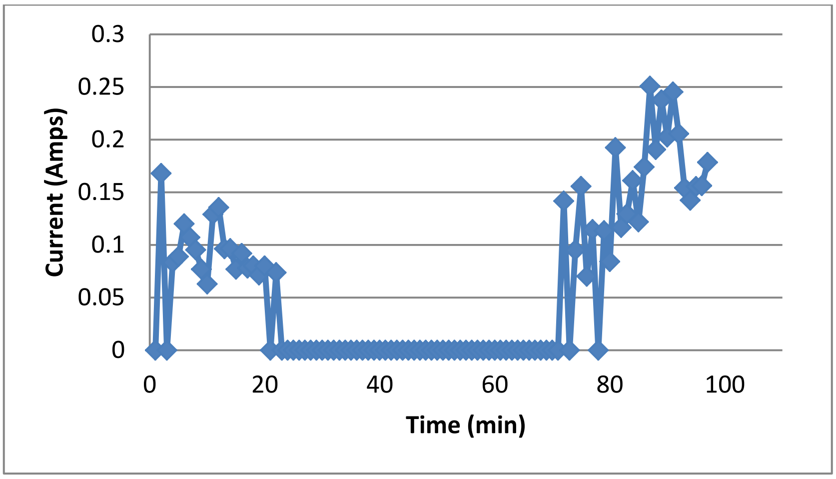

Figure 49: Charge current Vs time for 1st objective function at initial SOC of 0.5

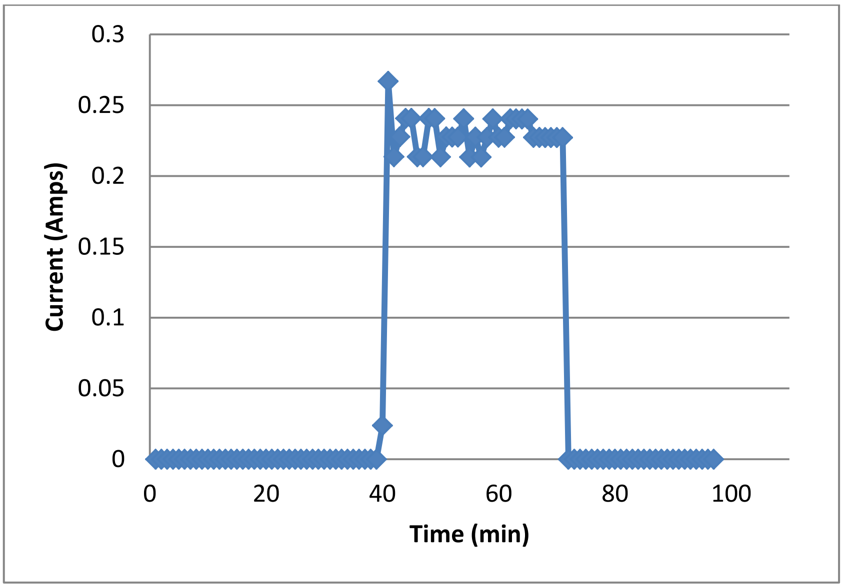

Figure 50: Discharge current Vs time for 1st objective function at initial SOC of 0.5

2nd objective function graphs:

SOC=0.7

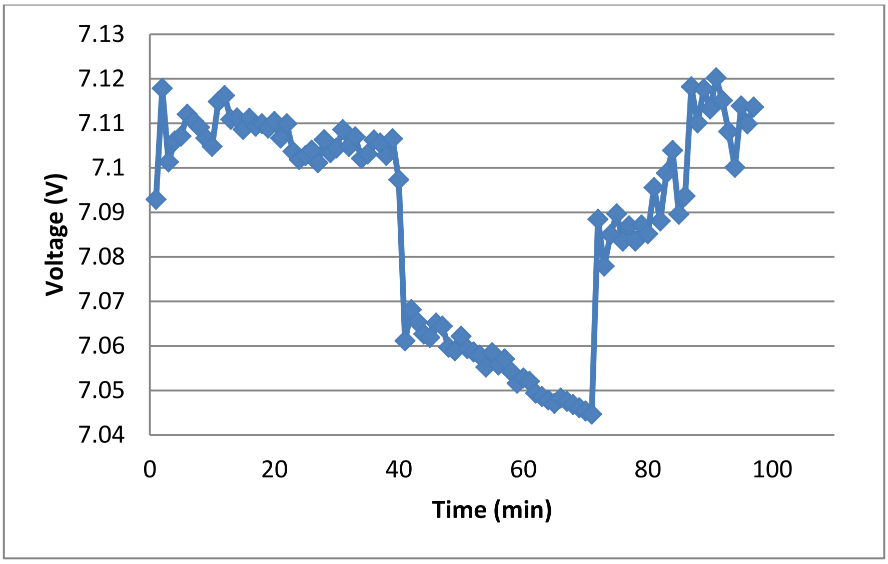

Figure 51: Voltage Vs time for 2nd objective function at initial SOC of 0.7

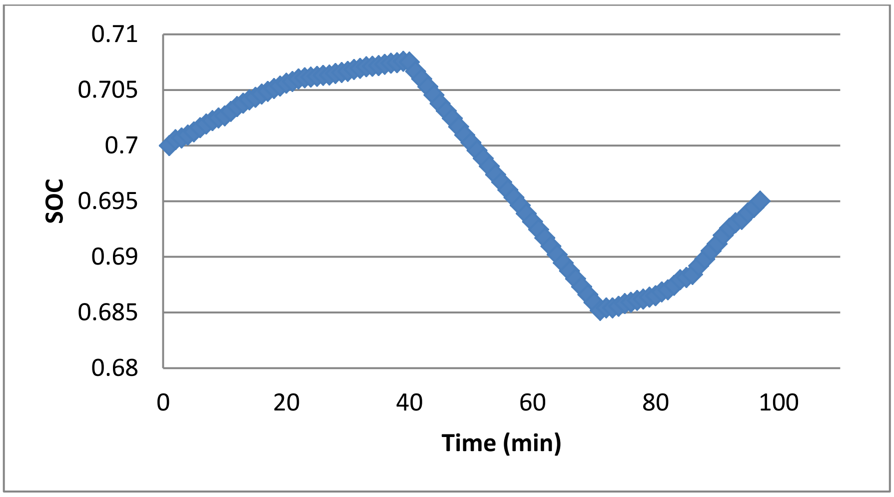

Figure 52: SOC Vs time for 2nd objective function at initial SOC of 0.7

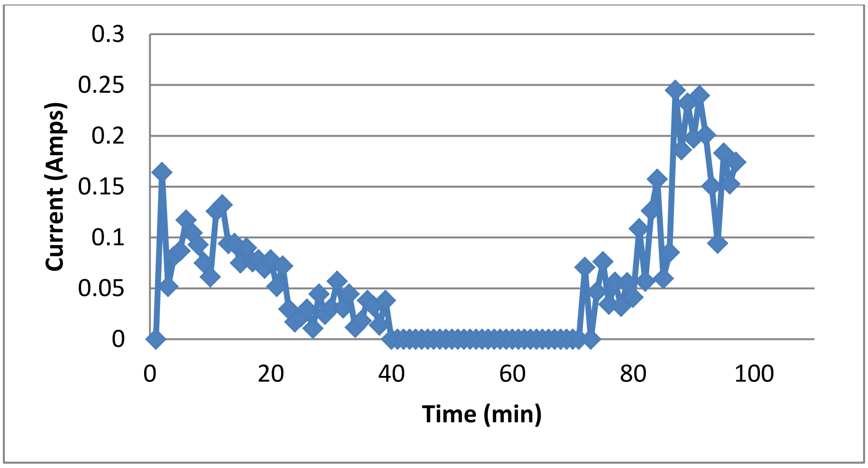

Figure 53: Charge current Vs time for 2nd objective function at initial SOC of 0.7

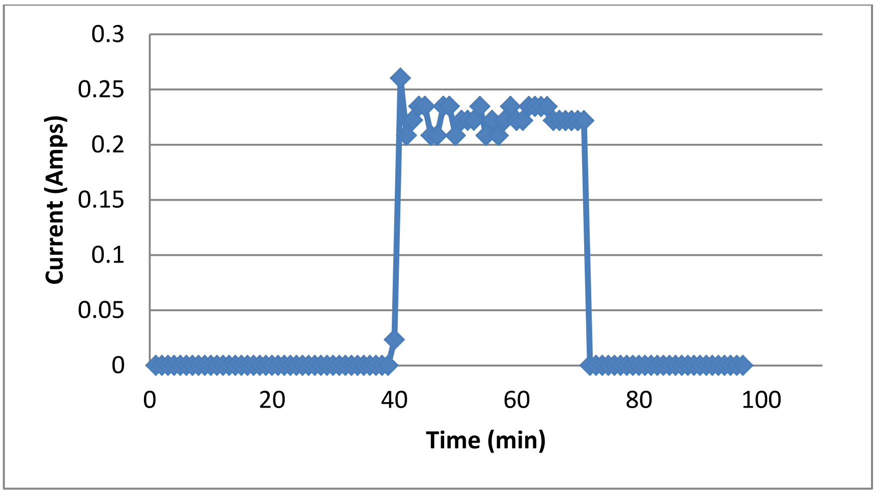

Figure 54: Discharge current Vs time for 2nd objective function at initial SOC of 0.7

SOC=0.5

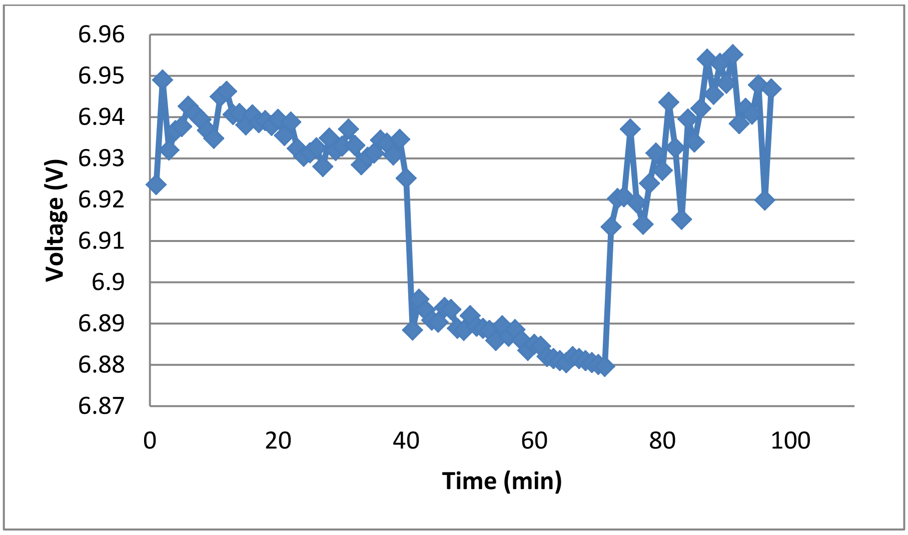

Figure 55: Voltage Vs time for 2nd objective function at initial SOC of 0.5

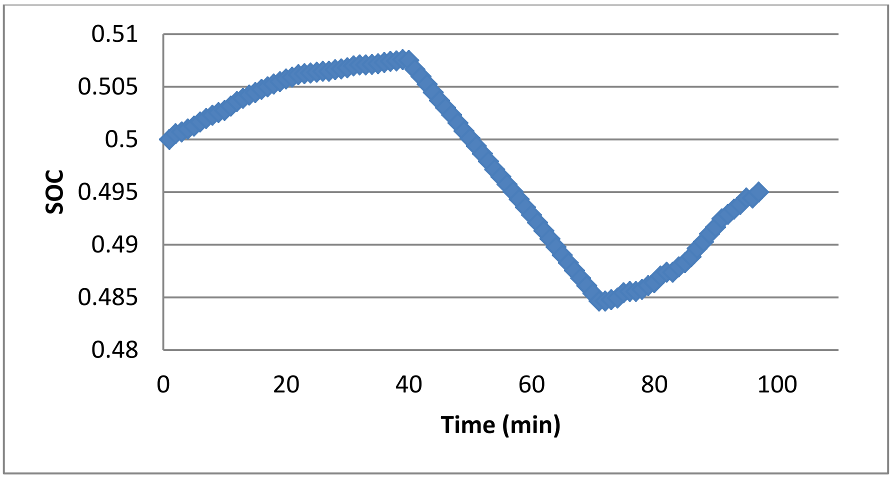

Figure 56: SOC Vs time for 2nd objective function at initial SOC of 0.5

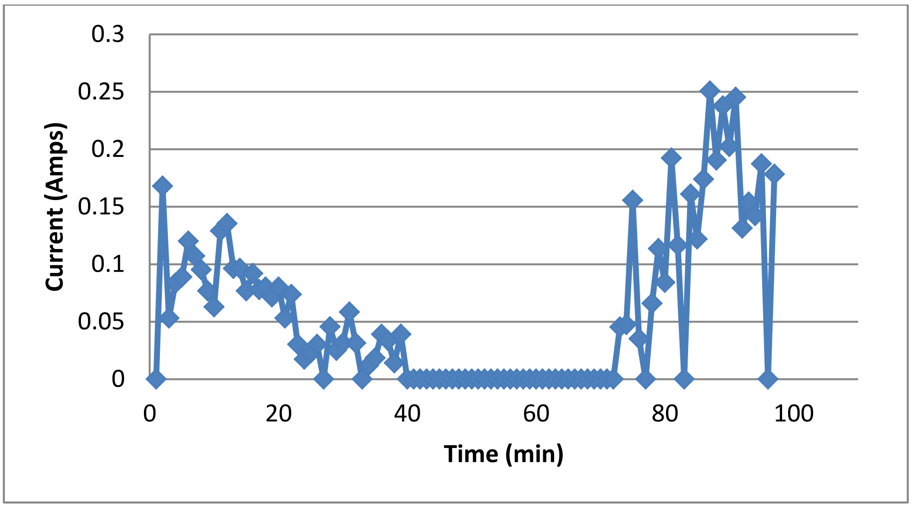

Figure 57: Charge current Vs time for 2nd objective function at initial SOC of 0.5

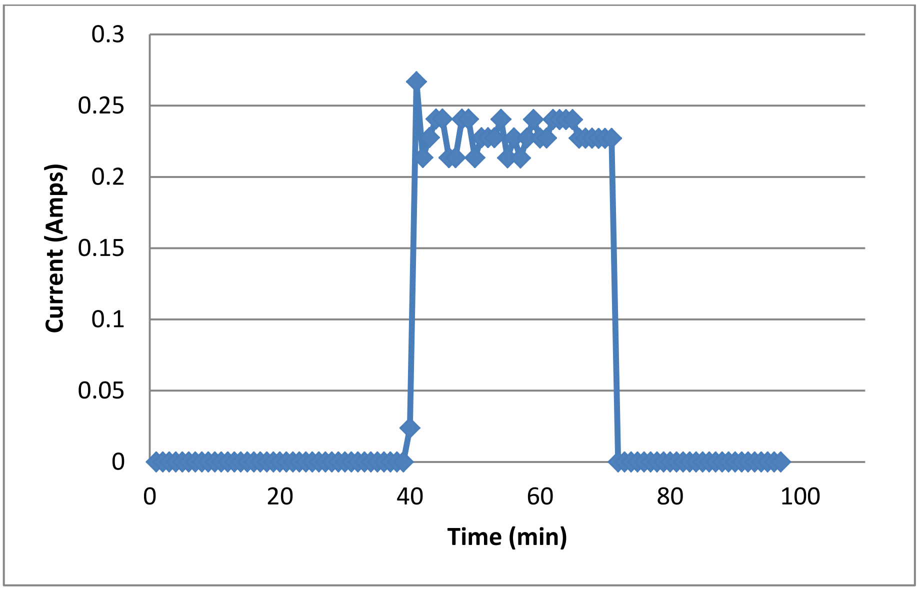

Figure 58: Discharge current Vs time for 2nd objective function at initial SOC of 0.5

3rd objective function graphs:

SOC=0.7

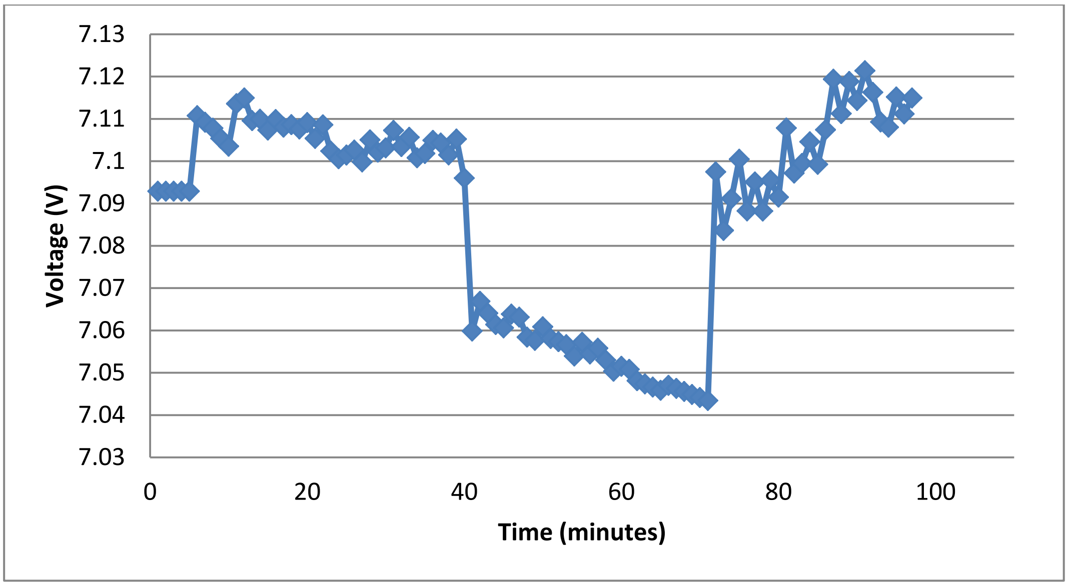

Figure 59: Voltage Vs time for 3rd objective function at initial SOC of 0.7

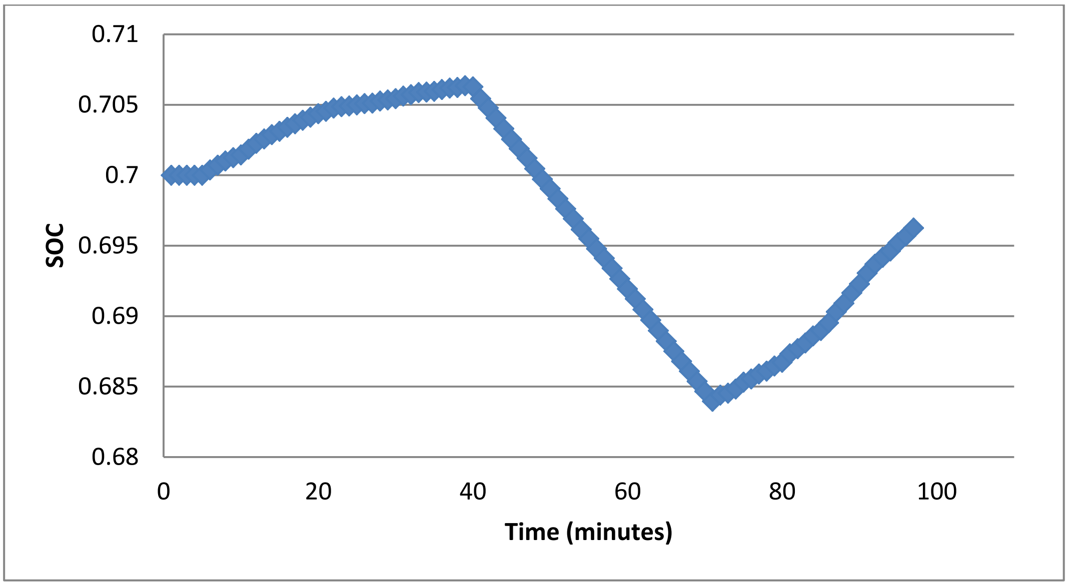

Figure 60: SOC Vs time for 3rd objective function at initial SOC of 0.7

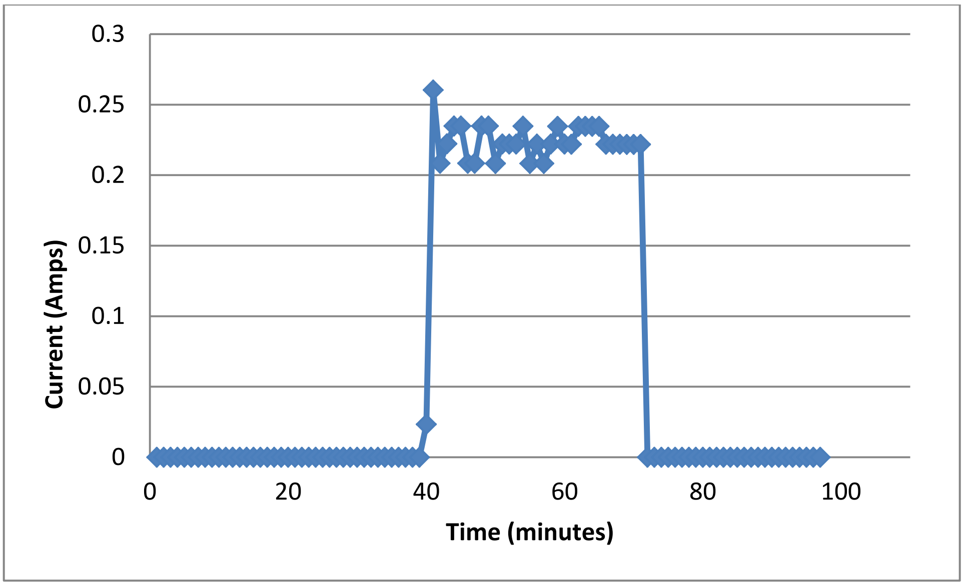

Figure 61: Discharge current Vs time for 3rd objective function at initial SOC of 0.7

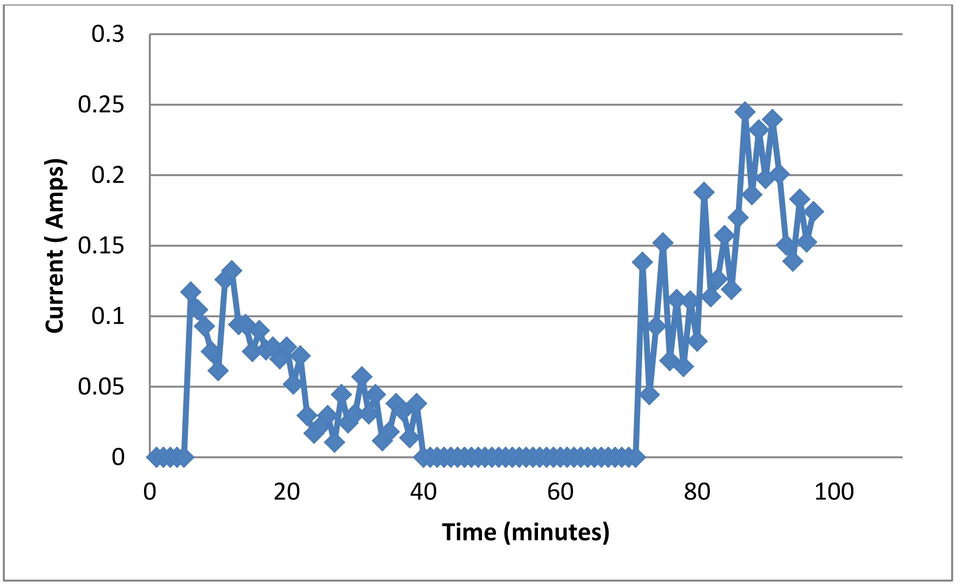

Figure 62: Charge current Vs time for 3rd objective function at initial SOC of 0.7

SOC=0.5

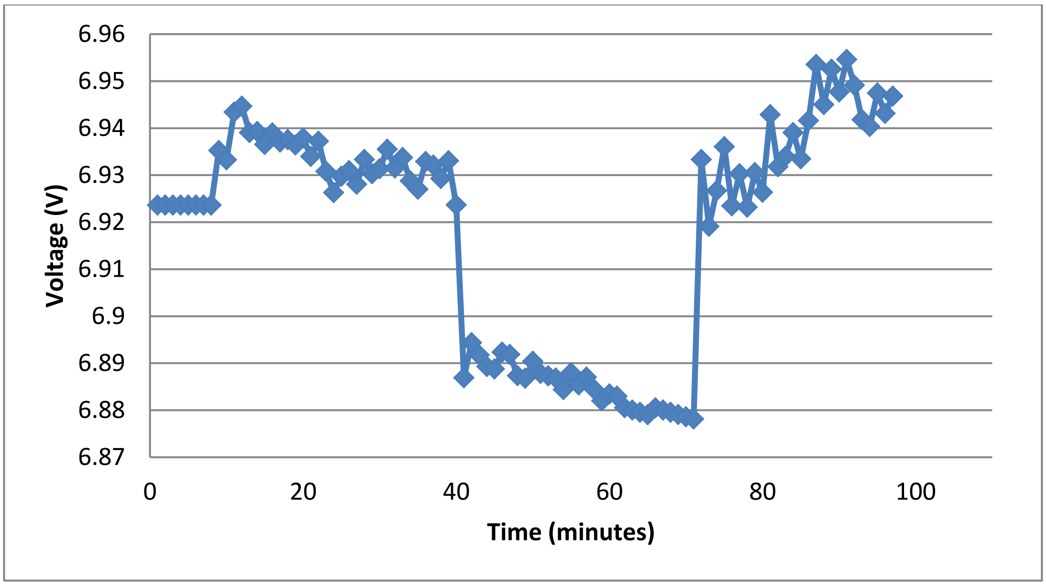

Figure 63: Voltage Vs time for 3rd objective function at initial SOC of 0.5

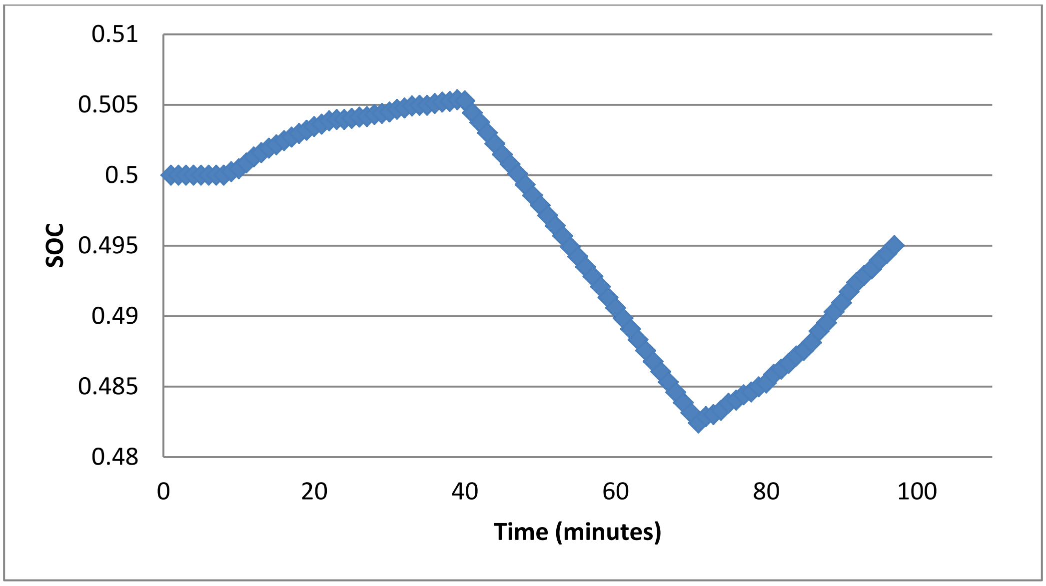

Figure 64: SOC Vs time for 3rd objective function at initial SOC of 0.5

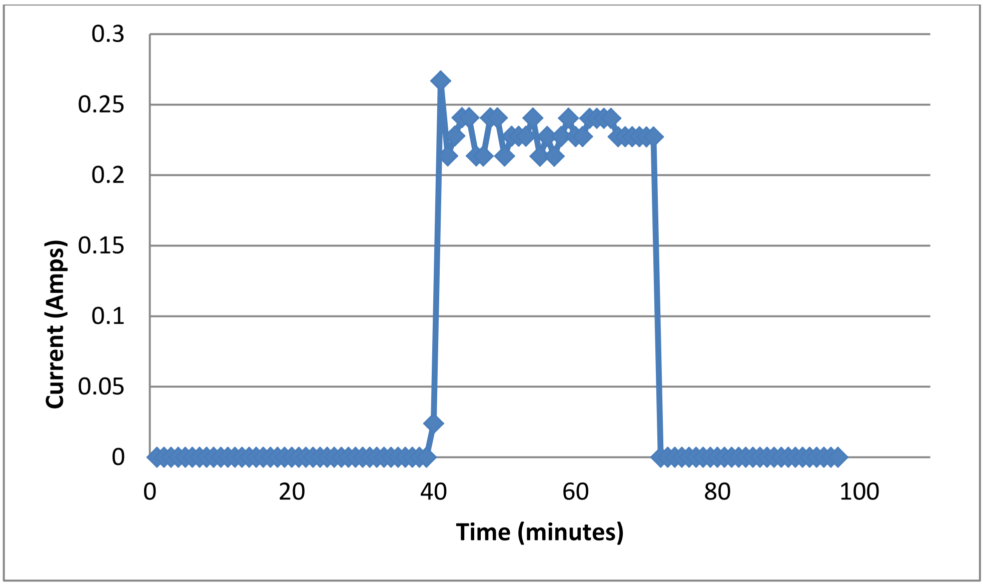

Figure 65: Discharge current Vs time for 3rd objective function at initial SOC of 0.5

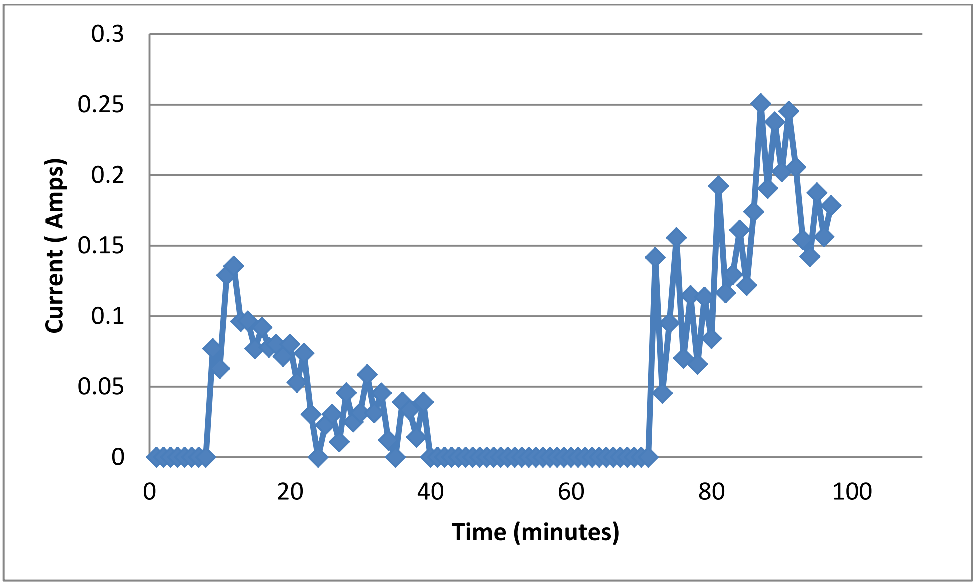

Figure 66: Charge current Vs time for 3rd objective function at initial SOC of 0.5

Data retrieved for different demand profile:

Time	Voltage	Current panel	Current sys	Battery Current mA	Amps	Power supplied by panels	Demand	Battery Charging	Battery dishch
1	7.504059	492	283	0.0	0.000	3.692	2.124	0.0	0.0
2	7.504059	492	283	0.0	0.000	3.692	2.124	0.0	0.0
3	7.540912	509	271	238.0	0.238	3.838	2.044	1.0	0.0
4	7.505469	503	271	0.0	0.000	3.775	2.034	0.0	0.0
5	7.505469	515	295	0.0	0.000	3.865	2.214	0.0	0.0
6	7.54666	537	271	266.0	0.266	4.053	2.045	1.0	0.0
7	7.507047	549	283	0.0	0.000	4.121	2.124	0.0	0.0
8	7.507047	549	307	0.0	0.000	4.121	2.305	0.0	0.0
9	7.507047	532	283	0.0	0.000	3.994	2.124	0.0	0.0
10	7.507047	526	307	0.0	0.000	3.949	2.305	0.0	0.0
11	7.507047	498	295	0.0	0.000	3.739	2.215	0.0	0.0
12	7.507047	471	283	0.0	0.000	3.536	2.124	0.0	0.0
13	7.507047	454	307	0.0	0.000	3.408	2.305	0.0	0.0
14	7.507047	409	283	0.0	0.000	3.070	2.124	0.0	0.0
15	7.507047	383	295	0.0	0.000	2.875	2.215	0.0	0.0
16	7.507047	366	307	0.0	0.000	2.748	2.305	0.0	0.0
17	7.507047	354	307	0.0	0.000	2.657	2.305	0.0	0.0
18	7.507047	349	271	0.0	0.000	2.620	2.034	0.0	0.0
19	7.507047	360	295	0.0	0.000	2.703	2.215	0.0	0.0
20	7.518816	383	307	76.0	0.076	2.880	2.308	1.0	0.0
21	7.507498	383	283	0.0	0.000	2.875	2.125	0.0	0.0
22	7.507498	403	271	0.0	0.000	3.026	2.035	0.0	0.0
23	7.507498	415	283	0.0	0.000	3.116	2.125	0.0	0.0
24	7.507498	420	258	0.0	0.000	3.153	1.937	0.0	0.0
25	7.474978	0	210	210.0	0.210	0.000	1.570	0.0	1.0
26	7.471875	0	222	222.0	0.222	0.000	1.659	0.0	1.0
27	7.464986	0	258	258.0	0.258	0.000	1.926	0.0	1.0
28	7.469035	0	222	222.0	0.222	0.000	1.658	0.0	1.0
29	7.469582	0	210	210.0	0.210	0.000	1.569	0.0	1.0
30	7.466486	0	222	222.0	0.222	0.000	1.658	0.0	1.0
31	7.465178	0	222	222.0	0.222	0.000	1.657	0.0	1.0
32	7.46573	0	210	210.0	0.210	0.000	1.568	0.0	1.0
33	7.464496	0	210	210.0	0.210	0.000	1.568	0.0	1.0
34	7.461406	0	222	222.0	0.222	0.000	1.656	0.0	1.0
35	7.461962	0	210	210.0	0.210	0.000	1.567	0.0	1.0
36	7.458876	0	222	222.0	0.222	0.000	1.656	0.0	1.0
37	7.459435	0	210	210.0	0.210	0.000	1.566	0.0	1.0
38	7.456352	0	222	222.0	0.222	0.000	1.655	0.0	1.0
39	7.456914	0	210	210.0	0.210	0.000	1.566	0.0	1.0
40	7.453834	0	222	222.0	0.222	0.000	1.655	0.0	1.0
41	7.454399	0	210	210.0	0.210	0.000	1.565	0.0	1.0
42	7.453179	0	210	210.0	0.210	0.000	1.565	0.0	1.0
43	7.451961	0	210	210.0	0.210	0.000	1.565	0.0	1.0
44	7.450743	0	210	210.0	0.210	0.000	1.565	0.0	1.0
45	7.449528	0	210	210.0	0.210	0.000	1.564	0.0	1.0
46	7.448314	0	210	210.0	0.210	0.000	1.564	0.0	1.0
47	7.447101	0	210	210.0	0.210	0.000	1.564	0.0	1.0
48	7.447901	0	197	197.0	0.197	0.000	1.467	0.0	1.0
49	7.444755	0	210	210.0	0.210	0.000	1.563	0.0	1.0
50	7.443547	0	210	210.0	0.210	0.000	1.563	0.0	1.0
51	7.44234	0	210	210.0	0.210	0.000	1.563	0.0	1.0
52	7.441135	0	210	210.0	0.210	0.000	1.563	0.0	1.0
53	7.439931	0	210	210.0	0.210	0.000	1.562	0.0	1.0
54	7.438728	0	210	210.0	0.210	0.000	1.562	0.0	1.0
55	7.437527	0	210	210.0	0.210	0.000	1.562	0.0	1.0
56	7.436328	0	210	210.0	0.210	0.000	1.562	0.0	1.0
57	7.43513	0	210	210.0	0.210	0.000	1.561	0.0	1.0
58	7.428368	0	246	246.0	0.246	0.000	1.827	0.0	1.0
59	7.506903	288	271	17.0	0.017	2.162	2.034	1.0	0.0
60	7.466546	288	258	0.0	0.000	2.150	1.926	0.0	0.0
61	7.466546	288	283	0.0	0.000	2.150	2.113	0.0	0.0
62	7.466546	300	258	0.0	0.000	2.240	1.926	0.0	0.0
63	7.512161	316	295	21.0	0.021	2.374	2.216	1.0	0.0
64	7.468229	337	283	0.0	0.000	2.517	2.114	0.0	0.0
65	7.511991	354	283	71.0	0.071	2.659	2.126	1.0	0.0
66	7.469847	366	283	0.0	0.000	2.734	2.114	0.0	0.0
67	7.513612	388	283	105.0	0.105	2.915	2.126	1.0	0.0
68	7.471468	383	283	0.0	0.000	2.862	2.114	0.0	0.0
69	7.517091	388	295	93.0	0.093	2.917	2.218	1.0	0.0
70	7.47316	400	295	0.0	0.000	2.989	2.205	0.0	0.0
71	7.47316	377	283	0.0	0.000	2.817	2.115	0.0	0.0
72	7.47316	366	283	0.0	0.000	2.735	2.115	0.0	0.0
73	7.47316	349	258	0.0	0.000	2.608	1.928	0.0	0.0
74	7.47316	343	295	0.0	0.000	2.563	2.205	0.0	0.0
75	7.492183	394	271	123.0	0.123	2.952	2.030	1.0	0.0
76	7.473866	377	283	0.0	0.000	2.818	2.115	0.0	0.0
77	7.473866	326	295	0.0	0.000	2.436	2.205	0.0	0.0
78	7.485002	343	271	72.0	0.072	2.567	2.028	1.0	0.0
79	7.47428	366	283	0.0	0.000	2.736	2.115	0.0	0.0
80	7.47428	383	271	0.0	0.000	2.863	2.026	0.0	0.0
81	7.494696	403	271	132.0	0.132	3.020	2.031	1.0	0.0
82	7.475039	371	295	0.0	0.000	2.773	2.205	0.0	0.0
83	7.475039	300	295	0.0	0.000	2.243	2.205	0.0	0.0
84	7.475039	271	271	0.0	0.000	2.026	2.026	0.0	0.0
85	7.475039	266	258	0.0	0.000	1.988	1.929	0.0	0.0
86	7.475812	300	295	5.0	0.005	2.243	2.205	1.0	0.0
87	7.485121	360	295	65.0	0.065	2.695	2.208	1.0	0.0
88	7.48797	388	307	81.0	0.081	2.905	2.299	1.0	0.0
89	7.475907	377	307	0.0	0.000	2.818	2.295	0.0	0.0
90	7.475907	383	295	0.0	0.000	2.863	2.205	0.0	0.0
91	7.495242	383	258	125.0	0.125	2.871	1.934	1.0	0.0
92	7.497045	403	271	132.0	0.132	3.021	2.032	1.0	0.0
93	7.477388	394	271	0.0	0.000	2.946	2.026	0.0	0.0
94	7.477388	377	258	0.0	0.000	2.819	1.929	0.0	0.0
95	7.497807	415	283	132.0	0.132	3.112	2.122	1.0	0.0
96	7.478149	426	271	0.0	0.000	3.186	2.027	0.0	0.0
97	7.506458	466	283	183.0	0.183	3.498	2.124	1.0	0.0

Current Case Lingo Code for new demand profile data:

```
Model:
! Second Data real case scenario for Nayif1;
Sets:
states
/1..97/:ch,dch,sp,ps,VBATT,IBATT,soc,dod,p,pd,pc,cycleN,cmax,sohd,CHCUM,CHSIGN,ID,IC,eo,rs
;

Endsets
Data:
crated=312;  !rated capacity of 5.2 Ah * 60 min/hour = 312 Amin;
p=2.12364865732340       2.12364865732340         2.04358709485056         2.0339820526899
       2.21411330458864         2.04514477692046         2.12449429348091
       2.30466342084325         2.12449429348091         2.30466342084325
       2.21457885716208         2.12449429348091         2.30466342084325
       2.12449429348091         2.21457885716208         2.30466342084325
       2.30466342084325         2.03440972979974         2.21457885716208
       2.30827658485686         2.124622023801  2.03453204399318         2.124622023801
       1.93693456586805         1.56974547771244         1.65875628982507
       1.92596651402664         1.65812577218257         1.56861221013519
       1.65755980128721         1.65726950528197         1.5678032122389
       1.56754409177234         1.65643209908916         1.56701203517168
       1.6558703632592          1.56648131076982         1.65531003459042
       1.56595191642548         1.65475111081918         1.56542384999737
       1.56516763005169         1.56491172314598         1.56465612903427
       1.5644008474706          1.564145878209  1.56389122100349         1.46723645323795
       1.56339855863867         1.56314481686071         1.56289138617018
       1.56263826632114         1.56238545706761         1.56213295816361
       1.56188076936319         1.56162889042037         1.56137732108919
       1.82737841534553         2.0343707568304 1.92636882716663         2.11303247320991
       1.92636882716663         2.21608742031128         2.11350890514806
       2.12589358480373         2.11396673092241         2.12635216944751
       2.11442531556622         2.21754183185674         2.20458206885537
       2.11490415419007         2.11490415419007         1.92807516530402
       2.20458206885537         2.03038160917414         2.1151040496098
       2.20479044040597         2.02843550003023         2.11522112825147
       2.02552977298992         2.03106260441921         2.205136362593  2.205136362593
       2.02573543817866         1.92855993745422         2.20536450325514
       2.20811069741226         2.29880676071342         2.295103567073040
       2.205392678457810        1.933772494176670        2.03169930012701
       2.02637213388648         1.92916609056351         2.12187929514714
       2.02657844854702         2.12432762466978;


IBATT= 0.000  0.000   0.238   0.000   0.000   0.266   0.000   0.000   0.000   0.000
       0.000  0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.076
       0.000  0.000   0.000   0.000   0.210   0.222   0.258   0.222   0.210   0.222
       0.222  0.210   0.210   0.222   0.210   0.222   0.210   0.222   0.210   0.222
       0.210  0.210   0.210   0.210   0.210   0.210   0.210   0.197   0.210   0.210
       0.210  0.210   0.210   0.210   0.210   0.210   0.210   0.246   0.017   0.000
       0.000  0.000   0.021   0.000   0.071   0.000   0.105   0.000   0.093   0.000
       0.000  0.000   0.000   0.000   0.123   0.000   0.000   0.072   0.000   0.000
       0.132  0.000   0.000   0.000   0.000   0.005   0.065   0.081   0.000   0.000
       0.125  0.132   0.000   0.000   0.132   0.000   0.183;
dch =0 0      0       0       0       0       0       0       0       0       0       0
       0      0       0       0       0       0       0       0       0       0       0
       0      1       1       1       1       1       1       1       1       1       1
```

```
        1       1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1       1       1       1       1       1       1
        1       1       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0;

ch= 0   0       1       0       0       1       0       0       0       0       0       0
        0       0       0       0       0       0       0       1       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       1       0       0       0       1       0       1       0       1
        0       1       0       0       0       0       0       1       0       0       1
        0       0       1       0       0       0       0       1       1       1       0
        0       1       1       0       0       1       0       1;
ps= 3.69199695902160 3.69199695902160    3.83832410066028    3.77525082104436
        3.86531644699373    4.05255625537376    4.12136878841350
        4.12136878841350    3.99374898986518    3.94870670802459
        3.73850939276853    3.53581912448590    3.40819932593758
        3.07038221213319    2.87519899082399    2.74757919227567
        2.65749462859450    2.61995939372734    2.70253691043508
        2.87970661889309    2.87537185553280    3.02552182187916
        3.11561180168698    3.15314929327357    0       0       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       0       0       0       0
        0       0       0       0       0       0       0       2.16198811057990
        2.15036520241856    2.15036520241856    2.23996375251933
        2.37384279599446    2.51679328987596    2.65924497887109
        2.73396404069824    2.91528141959588    2.86157207018326
        2.91663129071327    2.98926382217678    2.81738115240161
        2.73517639729175    2.60813268484924    2.56329372751659
        2.95192012551517    2.81764744417984    2.43648028329609
        2.56735563287959    2.73558633547717    2.86264908876436
        3.02036247077838    2.77323928990510    2.24251155517933
        2.02573543817866    1.98836024559234    2.24274356263235
        2.69464356294378    2.90533232298634    2.81841708399524
        2.86327252830285    2.87067777236303    3.02130929133278
        2.94609085148071    2.81897525636606    3.11158977910270
        3.18569158332483    3.49800944556931;


a1=1.031;
a2=35;
a3=3.685;
a4=0.2156;
a5=0.1178;
a6=0.3201;
a7=0.3208;
a8=29.14;
a9=0.04669;
a10=6.603;
a11=155.2;
a12=0.04984;
a13=752.9;
```

```
a14=13.51;
a15=703.6;
a16=6056;
a17=27.12;
a18=4475;
a19=0.1562;
a20=24.37;
a21=0.07446;

@OLE('C:\Users\User\Desktop\RESULTS.xlsx','A2:A98') = p;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','B2:B98') = ps;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','C2:C98') = ch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','D2:D98') = dch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','E2:E98') = sp;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','F2:F98') = ID;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','G2:G98') = IC;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','H2:H98') = pd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','I2:I98') = pc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','J2:J98') = cyclen;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','K2:K98') = cmax;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','L2:L98') = sohd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','M2:M98') = soc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','N2:N98') = VBATT;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','O2:O98') = dod;
enddata


!solar panels are off during eclipse;
@for(states(i)| i #GE# 25 #and# i #LE# 58:sp(i)=0);
@for(states(i)| i #GE# 1 #and# i #LE# 24:sp(i)=1);
@for(states(i)| i #GE# 59 #and# i #LE# 97:sp(i)=1);



!intialising the state of charge of the battery;
@for(states(i)| i #EQ# 1:soc(i)=0.99);
@for(states(i)| i #EQ# 1:cycleN(i)=0);
@for(states(i)| i #EQ# 1: dod(i)=0);
@for(states(i)| i #EQ# 1: CHCUM(i) =0);
@for(states(i)| i #EQ# 1: CHSIGN(i) =0);


!final cycle number & cycle number calculation;
@for(states(i)| i #EQ# 97: fcycleN = cycleN);
@for(states(i)| i #EQ# 24:soc24 = soc(i));
@for(states(i)| i #EQ# 58:soc58 = soc(i));
deltasoc=soc24-soc58;
losscycle=(0.13/300)*deltasoc;
retainedc=1-losscycle;


DCHTIME=  @sum(states(i):dch(i)) ;
CHTIME=  @sum(states(i):ch(i)) ;
@for(states(i)| i #GT# 1:CHCUM(i)=ch(i)+CHCUM(i-1) );
@for(states(i)| i #GT# 1:CHSIGN(i)= @if(CHCUM(i)#GT# 0,1,0) );
@for(states(i)| i #GT# 1: cycleN(i) = @if( (cycleN(i-1)  #EQ# 1) #or# ((dch(i)-CHSIGN(i-1) #EQ# -1)
#and# (dch(i)+CHSIGN(i-1) #EQ# 1) #and# (dch(i-1) #EQ# 1)),1,0));
```

```
@for(states(i):cmax(i)=
@if(CycleN(i) #EQ# 1,retainedc*crated,crated));



! state of charge & Depth of discharge estimation;
@for(states(i)| i #GT# 1:
soc(i)=soc(i-1)-(dch(i)*((1*IBATT)/cmax(i)))+(ch(i)*((1*IBATT)/cmax(i)));
dod(i)=@if(dch(i) #EQ# 1, soc(i-1)-soc(i),0);
);

! battery terminal voltage estimation;
@for(states(i):
eo(i) = (-a1*@exp(-a2*soc(i))+a3+a4*soc(i)-a5*(soc(i)^2)+a6*(soc^3))*2; !open circuit emf voltage;
rs(i)= (a19*@exp(-a20*soc(i))+a21)*2; !series resistance value;
VBATT(i)= eo(i)-0.344975-0.338128-(dch(i)*(IBATT(i)*rs(i)))+(ch(i)*(IBATT(i)*rs(i)));
);

!limits of the SOC & DOD of the battery;
@for(states(i):
socmin <= soc(i);
soc(i) <= socmax;
dod(i) <= dodmax;
);

!soh degredation calculation;
@for(states(i):sohd(i)=(1-(cmax(i)/crated)));


! satisfying the required power demand;
@for(states(i):
ID(i)=IBATT(i)*dch(i);
IC(i)=IBATT(i)*ch(i);
sp(i)*ps(i)+(dch(i)*(VBATT*IBATT))-(ch(i)*(VBATT*IBATT)) >= p(i);
pd(i)=dch(i)*(VBATT*IBATT);
pc(i)= ch(i)*(VBATT*IBATT);
);



!standard deviation calculation;
socavg= @sum(states(i):soc(i))/97;
sd=@sqrt(@sum(states(i):(soc(i)-socavg)^2)/97);
```

1st objective function Lingo Code for new demand profile data:

```
Model:
!second data 1st and 2nd objective function code;
Sets:
states /1..97/:ch,dch,sp,ps,c,d,soc,dod,v,eo,p,rs,pd,pc,cycleN,cmax,sohd,IC,ID,CHCUM,CHSIGN;

Endsets
Data:
crated=312;  !rated capacity of 5.2 Ah * 60 min/hour = 312 Amin;
```

p= 2.12364865732340 2.12364865732340 2.04358709485056 2.0339820526899
2.21411330458864 2.04514477692046 2.12449429348091
2.30466342084325 2.12449429348091 2.30466342084325
2.21457885716208 2.12449429348091 2.30466342084325
2.12449429348091 2.21457885716208 2.30466342084325
2.30466342084325 2.03440972979974 2.21457885716208
2.30827658485686 2.124622023801 2.03453204399318 2.124622023801
1.93693456586805 1.56974547771244 1.65875628982507
1.92596651402664 1.65812577218257 1.56861221013519
1.65755980128721 1.65726950528197 1.5678032122389
1.56754409177234 1.65643209908916 1.56701203517168
1.6558703632592 1.56648131076982 1.65531003459042
1.56595191642548 1.65475111081918 1.56542384999737
1.56516763005169 1.56491172314598 1.56465612903427
1.5644008474706 1.564145878209 1.56389122100349 1.46723645323795
1.56339855863867 1.56314481686071 1.56289138617018
1.56263826632114 1.56238545706761 1.56213295816361
1.56188076936319 1.56162889042037 1.56137732108919
1.82737841534553 2.0343707568304 1.92636882716663 2.11303247320991
1.92636882716663 2.21608742031128 2.11350890514806
2.12589358480373 2.11396673092241 2.12635216944751
2.11442531556622 2.21754183185674 2.20458206885537
2.11490415419007 2.11490415419007 1.92807516530402
2.20458206885537 2.03038160917414 2.1151040496098
2.20479044040597 2.02843550003023 2.11522112825147
2.02552977298992 2.03106260441921 2.205136362593 2.205136362593
2.02573543817866 1.92855993745422 2.20536450325514
2.20811069741226 2.29880676071342 2.295103567073040
2.205392678457810 1.933772494176670 2.03169930012701
2.02637213388648 1.92916609056351 2.12187929514714
2.02657844854702 2.12432762466978;

ps = 3.69199695902160 3.69199695902160 3.83832410066028 3.77525082104436
3.86531644699373 4.05255625537376 4.12136878841350
4.12136878841350 3.99374898986518 3.94870670802459
3.73850939276853 3.53581912448590 3.40819932593758
3.07038221213319 2.87519899082399 2.74757919227567
2.65749462859450 2.61995939372734 2.70253691043508
2.87970661889309 2.87537185553280 3.02552182187916
3.11561180168698 3.15314929327357 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 2.16198811057990
2.15036520241856 2.15036520241856 2.23996375251933
2.37384279599446 2.51679328987596 2.65924497887109
2.73396404069824 2.91528141959588 2.86157207018326
2.91663129071327 2.98926382217678 2.81738115240161
2.73517639729175 2.60813268484924 2.56329372751659
2.95192012551517 2.81764744417984 2.43648028329609
2.56735563287959 2.73558633547717 2.86264908876436
3.02036247077838 2.77323928990510 2.24251155517933
2.02573543817866 1.98836024559234 2.24274356263235
2.69464356294378 2.90533232298634 2.81841708399524
2.86327252830285 2.87067777236303 3.02130929133278

```
        2.94609085148071     2.81897525636606     3.11158977910270
        3.18569158332483     3.49800944556931;


socmin=0.3;
socmax=1;
dodmax=0.2;

a1=1.031;
a2=35;
a3=3.685;
a4=0.2156;
a5=0.1178;
a6=0.3201;
a7=0.3208;
a8=29.14;
a9=0.04669;
a10=6.603;
a11=155.2;
a12=0.04984;
a13=752.9;
a14=13.51;
a15=703.6;
a16=6056;
a17=27.12;
a18=4475;
a19=0.1562;
a20=24.37;
a21=0.07446;

@OLE('C:\Users\User\Desktop\RESULTS.xlsx','A2:A98') = p;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','B2:B98') = ps;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','C2:C98') = ch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','D2:D98') = dch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','E2:E98') = sp;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','F2:F98') = IC;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','G2:G98') = ID;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','H2:H98') = pd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','I2:I98') = pc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','J2:J98') = cyclen;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','K2:K98') = cmax;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','L2:L98') = sohd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','M2:M98') = soc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','N2:N98') = v;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','O2:O98') = dod;

enddata


!solar panels are off during eclipse;
@for(states(i)| i #GE# 25 #and# i #LE# 58:sp(i)=0);




!intialising the state of charge of the battery;
@for(states(i)| i #EQ# 1:soc(i)=0.99);
@for(states(i)| i #EQ# 1: dch(i)=0);
```

```
@for(states(i)| i #EQ# 1: ch(i)=0);
@for(states(i)| i #EQ# 1:cycleN(i)=0);
@for(states(i)| i #EQ# 1: dod(i)=0);
@for(states(i)| i #EQ# 1: v(i)= eo(i)-0.344975-0.338128);
@for(states(i)| i #EQ# 1: CHCUM(i) =0);
@for(states(i)| i #EQ# 1: CHSIGN(i) =0);

!final cycle number & cycle number calculation;
@for(states(i)| i #EQ# 97:fcycleN = cyclen(i));
@for(states(i)| i #EQ# 24:soc24 = soc(i));
@for(states(i)| i #EQ# 58:soc58 = soc(i));
deltasoc=soc24-soc58;
losscycle=(0.13/300)*deltasoc;
retainedc=1-losscycle;
X=8.4/4.1029;

DCHTIME=  @sum(states(i):dch(i)) ;
CHTIME=  @sum(states(i):ch(i)) ;
@for(states(i)| i #GT# 1:CHCUM(i)=ch(i)+CHCUM(i-1) );
@for(states(i)| i #GT# 1:CHSIGN(i)= @if(CHCUM(i)#GT# 0,1,0) );
@for(states(i)| i #GT# 1: cycleN(i) = @if( (cycleN(i-1)  #EQ# 1) #or# ((dch(i)-CHSIGN(i-1) #EQ# -1)
#and# (dch(i-1) #EQ# 1)),1,0));


@for(states(i):cmax(i)=
@if(CycleN(i) #EQ# 1,retainedc*crated,crated));



! state of charge & Depth of discharge estimation;
@for(states(i)| i #GT# 1:
soc(i)=soc(i-1)-(dch(i)*((1*ID(i))/cmax(i)))+(ch(i)*((1*IC(i))/cmax(i)));
dod(i)=@if(dch(i) #EQ# 1, soc(i-1)-soc(i),0);
);

! battery terminal voltage estimation;
@for(states(i):
eo(i) = (-a1*@exp(-a2*soc(i))+a3+a4*soc(i)-a5*(soc(i)^2)+a6*(soc^3))*2; !open circuit emf voltage;
rs(i)= (a19*@exp(-a20*soc(i))+a21)*2; !series resistance value;
);


@for(states(i)| i #GT# 1: v(i)= eo(i)-0.344975-0.338128-(dch(i)*(ID(i)*rs(i)))+(ch(i)*(IC(i)*rs(i))));


!limits of the SOC & DOD of the battery;
@for(states(i):
socmin <= soc(i);
soc(i) <= socmax;
dod(i) <= dodmax;
);

!soh degredation calculation;
@for(states(i):sohd(i)=(1-(cmax(i)/crated)));


!rates are positive values;
@for(states(i):@bnd(0,d(i),3.75));
@for(states(i):@bnd(0,c(i),2.5));
```

```
@for(states(i):@bnd(6,v(i),8.4));
@for(states(i):IC(i)=c(i)*ch(i));
@for(states(i):ID(i)=d(i)*dch(i));
@for(states(i)| i #EQ# 97:soc(i)>=0.985);
@for(states(i)| i #EQ# 24:soc(i)>=0.995);

!objective Function;
min=@sum(states(i):dch(i)+ch(i));                                    !first objective
function ;
!min=@sum(states(i):dch(i)*ID(i)+ch(i)*IC(i)) ;                      !Second objective function ;


! Constraints;
!solar panel usage,battery charge and discharge are not simultaneous;
@for(states(i):
@BIN(dch(i));
@BIN(sp(i));
@BIN(ch(i));
ch(i)<=dch(i)+sp(i);
ch(i)*dch(i)=0;
);


! satisfying the required power demand;
@for(states(i):
sp(i)*ps(i)+(dch(i)*(v(i)*ID(i)))-(ch(i)*(v(i)*IC(i))) >= p(i);
pd(i)=dch(i)*(v(i)*ID(i));
pc(i)= ch(i)*(v(i)*IC(i));
);



!standard deviation calculation;
socavg= @sum(states(i):soc(i))/97;
sd=@sqrt(@sum(states(i):(soc(i)-socavg)^2)/97);
```

2nd objective function Lingo Code for new demand profile data:

```
Model:
!second data 1st and 2nd objective function code;
Sets:
states /1..97/:ch,dch,sp,ps,c,d,soc,dod,v,eo,p,rs,pd,pc,cycleN,cmax,sohd,IC,ID,CHCUM,CHSIGN;

Endsets
Data:
crated=312;  !rated capacity of 5.2 Ah * 60 min/hour = 312 Amin;
p= 2.12364865732340     2.12364865732340        2.04358709485056        2.0339820526899
        2.21411330458864        2.04514477692046        2.12449429348091
        2.30466342084325        2.12449429348091        2.30466342084325
        2.21457885716208        2.12449429348091        2.30466342084325
        2.12449429348091        2.21457885716208        2.30466342084325
        2.30466342084325        2.03440972979974        2.21457885716208
        2.30827658485686        2.124622023801  2.03453204399318        2.124622023801
        1.93693456586805        1.56974547771244        1.65875628982507
        1.92596651402664        1.65812577218257        1.56861221013519
        1.65755980128721        1.65726950528197        1.5678032122389
        1.56754409177234        1.65643209908916        1.56701203517168
```

```
1.6558703632592         1.56648131076982        1.65531003459042
1.56595191642548        1.65475111081918        1.56542384999737
1.56516763005169        1.56491172314598        1.56465612903427
1.5644008474706         1.564145878209  1.56389122100349        1.46723645323795
1.56339855863867        1.56314481686071        1.56289138617018
1.56263826632114        1.56238545706761        1.56213295816361
1.56188076936319        1.56162889042037        1.56137732108919
1.82737841534553        2.0343707568304 1.92636882716663        2.11303247320991
1.92636882716663        2.21608742031128        2.11350890514806
2.12589358480373        2.11396673092241        2.12635216944751
2.11442531556622        2.21754183185674        2.20458206885537
2.11490415419007        2.11490415419007        1.92807516530402
2.20458206885537        2.03038160917414        2.1151040496098
2.20479044040597        2.02843550003023        2.11522112825147
2.02552977298992        2.03106260441921        2.205136362593  2.205136362593
2.02573543817866        1.92855993745422        2.20536450325514
2.20811069741226        2.29880676071342        2.295103567073040
2.205392678457810       1.933772494176670       2.03169930012701
2.02637213388648        1.92916609056351        2.12187929514714
2.02657844854702        2.12432762466978;


ps = 3.69199695902160 3.69199695902160  3.83832410066028        3.77525082104436
3.86531644699373        4.05255625537376        4.12136878841350
4.12136878841350        3.99374898986518        3.94870670802459
3.73850939276853        3.53581912448590        3.40819932593758
3.07038221213319        2.87519899082399        2.74757919227567
2.65749462859450        2.61995939372734        2.70253691043508
2.87970661889309        2.87537185553280        3.02552182187916
3.11561180168698        3.15314929327357        0       0       0       0       0
0       0       0       0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       2.16198811057990
2.15036520241856        2.15036520241856        2.23996375251933
2.37384279599446        2.51679328987596        2.65924497887109
2.73396404069824        2.91528141959588        2.86157207018326
2.91663129071327        2.98926382217678        2.81738115240161
2.73517639729175        2.60813268484924        2.56329372751659
2.95192012551517        2.81764744417984        2.43648028329609
2.56735563287959        2.73558633547717        2.86264908876436
3.02036247077838        2.77323928990510        2.24251155517933
2.02573543817866        1.98836024559234        2.24274356263235
2.69464356294378        2.90533232298634        2.81841708399524
2.86327252830285        2.87067777236303        3.02130929133278
2.94609085148071        2.81897525636606        3.11158977910270
3.18569158332483        3.49800944556931;


socmin=0.3;
socmax=1;
dodmax=0.2;

a1=1.031;
a2=35;
```

```
a3=3.685;
a4=0.2156;
a5=0.1178;
a6=0.3201;
a7=0.3208;
a8=29.14;
a9=0.04669;
a10=6.603;
a11=155.2;
a12=0.04984;
a13=752.9;
a14=13.51;
a15=703.6;
a16=6056;
a17=27.12;
a18=4475;
a19=0.1562;
a20=24.37;
a21=0.07446;

@OLE('C:\Users\User\Desktop\RESULTS.xlsx','A2:A98') = p;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','B2:B98') = ps;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','C2:C98') = ch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','D2:D98') = dch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','E2:E98') = sp;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','F2:F98') = IC;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','G2:G98') = ID;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','H2:H98') = pd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','I2:I98') = pc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','J2:J98') = cyclen;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','K2:K98') = cmax;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','L2:L98') = sohd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','M2:M98') = soc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','N2:N98') = v;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','O2:O98') = dod;

enddata


!solar panels are off during eclipse;
@for(states(i)| i #GE# 25 #and# i #LE# 58:sp(i)=0);




!intialising the state of charge of the battery;
@for(states(i)| i #EQ# 1:soc(i)=0.99);
@for(states(i)| i #EQ# 1: dch(i)=0);
@for(states(i)| i #EQ# 1: ch(i)=0);
@for(states(i)| i #EQ# 1:cycleN(i)=0);
@for(states(i)| i #EQ# 1: dod(i)=0);
@for(states(i)| i #EQ# 1: v(i)= eo(i)-0.344975-0.338128);
@for(states(i)| i #EQ# 1: CHCUM(i) =0);
@for(states(i)| i #EQ# 1: CHSIGN(i) =0);

!final cycle number & cycle number calculation;
@for(states(i)| i #EQ# 97:fcycleN = cyclen(i));
@for(states(i)| i #EQ# 24:soc24 = soc(i));
@for(states(i)| i #EQ# 58:soc58 = soc(i));
```

```
deltasoc=soc24-soc58;
losscycle=(0.13/300)*deltasoc;
retainedc=1-losscycle;
X=8.4/4.1029;

DCHTIME=  @sum(states(i):dch(i)) ;
CHTIME=  @sum(states(i):ch(i)) ;
@for(states(i)| i #GT# 1:CHCUM(i)=ch(i)+CHCUM(i-1) );
@for(states(i)| i #GT# 1:CHSIGN(i)= @if(CHCUM(i)#GT# 0,1,0) );
@for(states(i)| i #GT# 1: cycleN(i) = @if( (cycleN(i-1)  #EQ# 1) #or# ((dch(i)-CHSIGN(i-1) #EQ# -1)
#and# (dch(i-1) #EQ# 1)),1,0));


@for(states(i):cmax(i)=
@if(CycleN(i) #EQ# 1,retainedc*crated,crated));



! state of charge & Depth of discharge estimation;
@for(states(i)| i #GT# 1:
soc(i)=soc(i-1)-(dch(i)*((1*ID(i))/cmax(i)))+(ch(i)*((1*IC(i))/cmax(i)));
dod(i)=@if(dch(i) #EQ# 1, soc(i-1)-soc(i),0);
);

! battery terminal voltage estimation;
@for(states(i):
eo(i) = (-a1*@exp(-a2*soc(i))+a3+a4*soc(i)-a5*(soc(i)^2)+a6*(soc^3))*2; !open circuit emf voltage;
rs(i)= (a19*@exp(-a20*soc(i))+a21)*2; !series resistance value;
);


@for(states(i)| i #GT# 1: v(i)= eo(i)-0.344975-0.338128-(dch(i)*(ID(i)*rs(i)))+(ch(i)*(IC(i)*rs(i))));


!limits of the SOC & DOD of the battery;
@for(states(i):
socmin <= soc(i);
soc(i) <= socmax;
dod(i) <= dodmax;
);

!soh degredation calculation;
@for(states(i):sohd(i)=(1-(cmax(i)/crated)));


!rates are positive values;
@for(states(i):@bnd(0,d(i),3.75));
@for(states(i):@bnd(0,c(i),2.5));
@for(states(i):@bnd(6,v(i),8.4));
@for(states(i):IC(i)=c(i)*ch(i));
@for(states(i):ID(i)=d(i)*dch(i));
@for(states(i)| i #EQ# 97:soc(i)>=0.985);
@for(states(i)| i #EQ# 24:soc(i)>=0.995);

!objective Function;
!min=@sum(states(i):dch(i)+ch(i));                                          !first
objective function ;
min=@sum(states(i):dch(i)*ID(i)+ch(i)*IC(i)) ;                    !Second objective function ;
```

```
! Constraints;
!solar panel usage,battery charge and discharge are not simultaneous;
@for(states(i):
@BIN(dch(i));
@BIN(sp(i));
@BIN(ch(i));
ch(i)<=dch(i)+sp(i);
ch(i)*dch(i)=0;
);


! satisfying the required power demand;
@for(states(i):
sp(i)*ps(i)+(dch(i)*(v(i)*ID(i)))-(ch(i)*(v(i)*IC(i))) >= p(i);
pd(i)=dch(i)*(v(i)*ID(i));
pc(i)= ch(i)*(v(i)*IC(i));
);



!standard deviation calculation;
socavg= @sum(states(i):soc(i))/97;
sd=@sqrt(@sum(states(i):(soc(i)-socavg)^2)/97);
```

3rd objective function Lingo Code for new demand profile data:

```
Model:
!Third objective function code for new data;
Sets:
states /1..97/:ch,dch,sp,ps,c,d,soc,dod,v,eo,p,rs,pd,pc,cycleN,cmax,sohd,IC,ID,CHCUM,CHSIGN;

Endsets
Data:
crated=312;  !rated capacity of 5.2 Ah * 60 min/hour = 312 Amin;
p= 2.12364865732340      2.12364865732340         2.04358709485056         2.0339820526899
        2.21411330458864         2.04514477692046         2.12449429348091
        2.30466342084325         2.12449429348091         2.30466342084325
        2.21457885716208         2.12449429348091         2.30466342084325
        2.12449429348091         2.21457885716208         2.30466342084325
        2.30466342084325         2.03440972979974         2.21457885716208
        2.30827658485686         2.124622023801  2.03453204399318         2.124622023801
        1.93693456586805         1.56974547771244         1.65875628982507
        1.92596651402664         1.65812577218257         1.56861221013519
        1.65755980128721         1.65726950528197         1.5678032122389
        1.56754409177234         1.65643209908916         1.56701203517168
        1.6558703632592          1.56648131076982         1.65531003459042
        1.56595191642548         1.65475111081918         1.56542384999737
        1.56516763005169         1.56491172314598         1.56465612903427
        1.5644008474706          1.564145878209  1.56389122100349         1.46723645323795
        1.56339855863867         1.56314481686071         1.56289138617018
        1.56263826632114         1.56238545706761         1.56213295816361
        1.56188076936319         1.56162889042037         1.56137732108919
        1.82737841534553         2.0343707568304 1.92636882716663         2.11303247320991
        1.92636882716663         2.21608742031128         2.11350890514806
        2.12589358480373         2.11396673092241         2.12635216944751
        2.11442531556622         2.21754183185674         2.20458206885537
```

```
2.11490415419007        2.11490415419007        1.92807516530402
2.20458206885537        2.03038160917414        2.1151040496098
2.20479044040597        2.02843550003023        2.11522112825147
2.02552977298992        2.03106260441921        2.205136362593  2.205136362593
2.02573543817866        1.92855993745422        2.20536450325514
2.20811069741226        2.29880676071342        2.295103567073040
2.205392678457810       1.933772494176670       2.03169930012701
2.02637213388648        1.92916609056351        2.12187929514714
2.02657844854702        2.12432762466978;


ps = 3.69199695902160 3.69199695902160  3.83832410066028  3.77525082104436
        3.86531644699373        4.05255625537376        4.12136878841350
        4.12136878841350        3.99374898986518        3.94870670802459
        3.73850939276853        3.53581912448590        3.40819932593758
        3.07038221213319        2.87519899082399        2.74757919227567
        2.65749462859450        2.61995939372734        2.70253691043508
        2.87970661889309        2.87537185553280        3.02552182187916
        3.11561180168698        3.15314929327357        0    0    0    0    0
        0    0    0    0    0    0    0    0    0    0    0
        0    0    0    0    0    0    0    0    0    0    0
        0    0    0    0    0    0    0    2.16198811057990
        2.15036520241856        2.15036520241856        2.23996375251933
        2.37384279599446        2.51679328987596        2.65924497887109
        2.73396404069824        2.91528141959588        2.86157207018326
        2.91663129071327        2.98926382217678        2.81738115240161
        2.73517639729175        2.60813268484924        2.56329372751659
        2.95192012551517        2.81764744417984        2.43648028329609
        2.56735563287959        2.73558633547717        2.86264908876436
        3.02036247077838        2.77323928990510        2.24251155517933
        2.02573543817866        1.98836024559234        2.24274356263235
        2.69464356294378        2.90533232298634        2.81841708399524
        2.86327252830285        2.87067777236303        3.02130929133278
        2.94609085148071        2.81897525636606        3.11158977910270
        3.18569158332483        3.49800944556931;

socmin=0.3;
socmax=1;
dodmax=0.2;

a1=1.031;
a2=35;
a3=3.685;
a4=0.2156;
a5=0.1178;
a6=0.3201;
a7=0.3208;
a8=29.14;
a9=0.04669;
a10=6.603;
a11=155.2;
a12=0.04984;
a13=752.9;
a14=13.51;
a15=703.6;
```

```
a16=6056;
a17=27.12;
a18=4475;
a19=0.1562;
a20=24.37;
a21=0.07446;

@OLE('C:\Users\User\Desktop\RESULTS.xlsx','A2:A98') = p;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','B2:B98') = ps;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','C2:C98') = ch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','D2:D98') = dch;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','E2:E98') = sp;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','F2:F98') = IC;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','G2:G98') = ID;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','H2:H98') = pd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','I2:I98') = pc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','J2:J98') = cyclen;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','K2:K98') = cmax;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','L2:L98') = sohd;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','M2:M98') = soc;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','N2:N98') = v;
@OLE('C:\Users\User\Desktop\RESULTS.xlsx','O2:O98') = dod;

enddata


!solar panels are off during eclipse;
@for(states(i)| i #GE# 25 #and# i #LE# 58:sp(i)=0);




!intialising the state of charge of the battery;
@for(states(i)| i #EQ# 1:soc(i)=0.99);
@for(states(i)| i #EQ# 1: dch(i)=0);
@for(states(i)| i #EQ# 1: ch(i)=0);
@for(states(i)| i #EQ# 1:cycleN(i)=0);
@for(states(i)| i #EQ# 1: dod(i)=0);
@for(states(i)| i #EQ# 1: v(i)= eo(i)-0.344975-0.338128);
@for(states(i)| i #EQ# 1: CHCUM(i) =0);
@for(states(i)| i #EQ# 1: CHSIGN(i) =0);

!final cycle number & cycle number calculation;
@for(states(i)| i #EQ# 97:fcycleN = cyclen(i));
@for(states(i)| i #EQ# 24:soc24 = soc(i));
@for(states(i)| i #EQ# 58:soc58 = soc(i));
deltasoc=soc24-soc58;
losscycle=(0.13/300)*deltasoc;
retainedc=1-losscycle;
X=8.4/4.1029;

DCHTIME=  @sum(states(i):dch(i)) ;
CHTIME=  @sum(states(i):ch(i)) ;
@for(states(i)| i #GT# 1:CHCUM(i)=ch(i)+CHCUM(i-1) );
@for(states(i)| i #GT# 1:CHSIGN(i)= @if(CHCUM(i)#GT# 0,1,0) );
@for(states(i)| i #GT# 1: cycleN(i) = @if( (cycleN(i-1)  #EQ# 1) #or# ((dch(i)-CHSIGN(i-1) #EQ# -1)
#and# (dch(i-1) #EQ# 1)),1,0));
```

```
@for(states(i):cmax(i)=
@if(CycleN(i) #EQ# 1,retainedc*crated,crated));



! state of charge & Depth of discharge estimation;
@for(states(i)| i #GT# 1:
soc(i)=soc(i-1)-(dch(i)*((1*ID(i))/cmax(i)))+(ch(i)*((1*IC(i))/cmax(i)));
dod(i)=@if(dch(i) #EQ# 1, soc(i-1)-soc(i),0);
);

! battery terminal voltage estimation;
@for(states(i):
eo(i) = (-a1*@exp(-a2*soc(i))+a3+a4*soc(i)-a5*(soc(i)^2)+a6*(soc^3))*2; !open circuit emf voltage;
rs(i)= (a19*@exp(-a20*soc(i))+a21)*2; !series resistance value;
);


@for(states(i)| i #GT# 1: v(i)= eo(i)-0.344975-0.338128-(dch(i)*(ID(i)*rs(i)))+(ch(i)*(IC(i)*rs(i))));



!limits of the SOC & DOD of the battery;
@for(states(i):
socmin <= soc(i);
soc(i) <= socmax;
dod(i) <= dodmax;
);

!soh degredation calculation;
@for(states(i):sohd(i)=(1-(cmax(i)/crated)));


!rates are positive values;
@for(states(i):@bnd(0,d(i),3.75));
@for(states(i):@bnd(0,c(i),2.5));
@for(states(i):@bnd(6,v(i),8.4));
@for(states(i):IC(i)=c(i)*ch(i));
@for(states(i):ID(i)=d(i)*dch(i));
@for(states(i)| i #EQ# 97:soc(i)>=0.985);
@for(states(i)| i #EQ# 24:soc(i)>=0.995);


!objective Function;
!min= soc24-soc58;
min=@sum(states(i):dod(i));

! Constraints;
!solar panel usage,battery charge and discharge are not simultaneous;
@for(states(i):
@BIN(dch(i));
@BIN(sp(i));
@BIN(ch(i));
ch(i)<=dch(i)+sp(i);
ch(i)*dch(i)=0;
);


! satisfying the required power demand;
```

```
@for(states(i):
sp(i)*ps(i)+(dch(i)*(v(i)*ID(i)))-(ch(i)*(v(i)*IC(i))) >= p(i);
pd(i)=dch(i)*(v(i)*ID(i));
pc(i)= ch(i)*(v(i)*IC(i));
);



!standard deviation calculation;
socavg= @sum(states(i):soc(i))/97;
sd=@sqrt(@sum(states(i):(soc(i)-socavg)^2)/97);
```

Vita

Mahmoud Shareef Lami was born in 1994, in Abu Dhabi, United Arab Emirates. He received his primary and secondary education in Abu Dhabi, UAE. He received his B.Sc. degree in Electrical Engineering from the American University of Sharjah in 2015. From 2015 to 2016, he worked as a Site Engineer in Bin Hafeez General Contracting Establishment and from 2016 to 2018; he worked as a project engineer in Al Fahim Group.

In September 2015, he joined the Engineering Systems Management master's program in the American University of Sharjah. His research interests are in battery management, systems operations management and space applications.