Development of low earth orbit spacecraft battery management environment with battery management control algorithm

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Abstract.

Electrical power system is a main system for a Spacecraft. This system is responsible to provide the required power to all SC loads successfully until SC End-of-Life (EOL). Solar array (SA) is the primary power supply while the storage battery is the secondary one. A spacecraft Charging Analysis Tool with Battery Management Control Algorithm software program to examine spacecraft charging, has been developed. This paper has two objectives. The first objective is to develop a battery management control algorithm. The developed algorithm is to control the battery charging and discharging process during all modes of SC operation. The second objective is to develop a battery management environment to simulate the dynamic behaviour of the SC battery with the aid of the developed control algorithm to ensure the battery health. Also, the battery simulation with the developed control algorithm shall adequate the behaviour of the SC battery during the worst-case scenario and nominal operation of SC. The state of charge (SOC) of the battery, the thermal emission, voltage and pressure of the battery are calculated during worst-case scenario to prove that the battery operates well under the developed control algorithm. The dynamic behaviour of the battery together with the developed algorithms will be validated by ground tests and real telemetry.

1. Introduction

In the past decades, the demands of electrical power levels of SC in low Earth orbit (LEO) have increased dramatically to respond for more functionality. As The power levels increase, the risk of catastrophic failure in the power supply and distribution system will increase. It was unfortunately demonstrated by the loss of many satellites due to the failures in the battery management. Therefore, the development of a battery management environment is essential. The charging and discharging control of the SC battery system is considered one of the major tasks of the power supply system (PSS) to ensure the well operation of the SC mission.

This paper presents the development of a master charging and discharging control algorithm for SC battery in orbit. The developed battery management environment is built based on the battery experimental model simulation which is given in [1]. This paper also presents the integration of this experimental model simulation with the developed charging and discharging control algorithm in a single battery management environment. The master algorithm is developed to control the SC battery charging and discharging process during different modes of SC operation. Also, the control algorithm is developed in order to control and calculate the battery performance parameters during the worst-case scenario. The ability of the battery will be verified to execute the SC mission operation. The battery management environment is verified by simulation. Also, the validation is done by using a real telemetry of the chosen SC power supply system (PSS) parameters in orbit [2-8].

2. Space Mission Specifications and System Description

In this paper a remote sensing satellite in a circular low-earth orbit (LEO) is chosen. The orbit average altitude is of 600-800 km, orbit inclination angle is 63◦, and orbit period is about 90 min. The eclipse period is about 35 min. The satellite life time is about 7 years. The primary power source is a solar array (SA), which consists of three solar panels. The generated SA power provides the SC loads with the required power in addition to charging of a storage battery [2-6] during the illuminated part of the orbit till the EOL. The selected SC battery is a Nickel-Hydrogen Storage Battery (NHSB) type 17HB-140 described in [1, 3, 7, 8, 9, 10].

3. Developed Algorithm

The master algorithm is for battery charging and discharging control and protection:

This algorithm controls battery charge when permission commands are received from power control unit (PCU) (Chr_ON and Chr_OFF). To provide the battery operation three pressure settings are used (Pset1, Pset2, Pset3) corresponding to battery upper level of charge (ULC). During normal operation the battery charges up to the setting Pset1. Algorithm monitors the battery cells change of pressure and voltage. If change of pressure and voltage values at the battery cells is higher than maximum pressure variation (ΔP), (in the measured cells) or maximum voltage variation (ΔU) the first algorithm changes to the setting Pset2 automatically. Reverse change to the setting Pset1 is possible if there is no ΔP or ΔU value excess. In this algorithm the battery average temperature is monitored by battery temperature sensors. If during charge the temperature value is higher than temperature setting Tset1 the algorithm changes to the setting Pset3 automatically. The change from setting Pset3 to setting Pset1 is happened if the values ΔP or ΔU are high, and if temperature conditions are restored. The procedure of voltage analysis includes calculation of maximum and minimum voltage at measured cells (№ 1, 2, 16, 17), as well as maximum and minimum voltage at unmeasured cells (№ 3-15). In the first algorithm the calculated value ΔUstp is compared with setting ΔU and ΔP to ensure the change from setting Pset3 to setting Pset1. The first algorithm function is shown in the flow chart of figure 1.

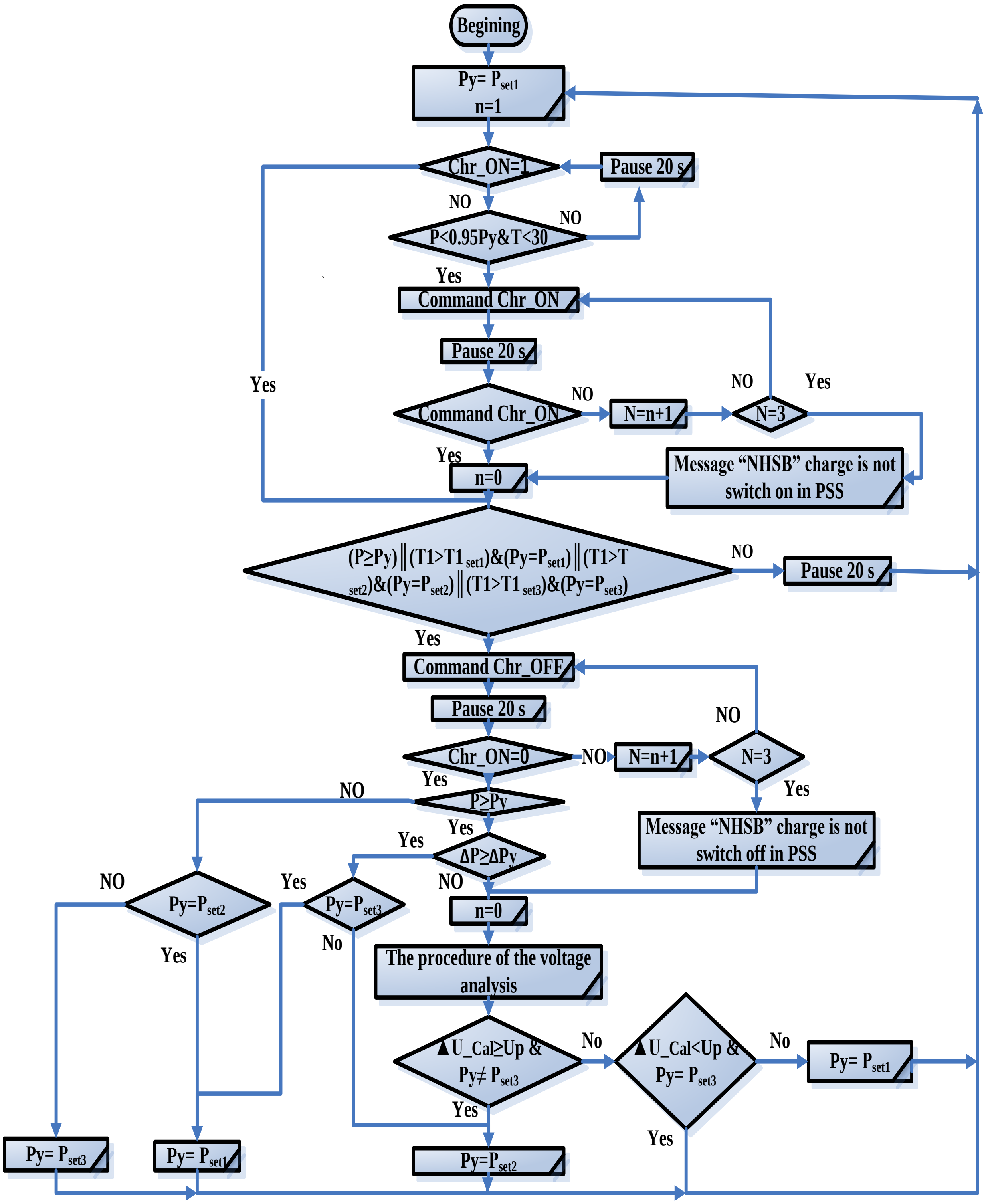

Figure 1: Master charging and discharging algorithm flow chart.

3.1. Calculation of battery average pressure value

The cells average pressure value is calculated and then compared with the proved value (stored in onboard computer). The error variation (ΔP) is initially taken as 5% of calculated average pressure range which can be varied during the battery operation. If deviation of pressure values is more than ΔP, the parameter with maximum deviation from average pressure is rejected. The rest values are averaged. If the cell is failed due to results of onboard and ground analysis, the cell voltage and pressure values is given invalidation sign (negative sign). In the case if failed cell is measured one (№ 1, 2, 16, 17), then the values of the pressure sensors which installed on these cells (P11, P12, P13, P14, respectively) must be excluded from the processing by giving them the negative sign of invalidation.

3.2. Parameters used in the algorithm

Table 1: list of parameters, used in the developed algorithm.

Parameter name	**Designation**	**setting value at the beginning of operation**	**Parameter variation range**
1. Upper charge level of the battery (default), kgf/cm2	Pset1	42	40: 50
2. Upper charge level of the battery restoration, kgf/ cm2	Pset2	48	46: 50
3. Upper charge level of the battery at high temperature conditions, kgf/ cm2	Pset3	38	38: 46
4. The maximum variation of measurable cells of the battery pressure, kgf/ cm2	ΔP	4	3.5: 5
5. The maximum variation of battery cells voltage, V	ΔU	0.07	0.07: 0.1
6. Battery Cell average pressure when battery voltage (U≤ (17±0.2V), kgf/ cm2	P10	1	0: 3
7. Coefficient used for current capacity calculation, charge value, Wh	W1test	2900	2500: 2900
8. Maximum allowable battery temperature at charge level P set1	T1(2) set1	25	23: 26
9. Maximum allowable battery temperature at charge level P set2	T1(2) set2	25	23: 26
10. Maximum allowable battery temperature at charge level P set3	T1(2) set3	20	15: 21

Table 2**:** List of parameters, calculated by developed algorithm.

Number	Parameter name	Designation	Range of values
1	Minimum voltage of the battery cells, V	U_{min}	-0,7: 2,0
2	Maximum voltage of the battery cells, V	U_{max}	-0,7: 2,0
3	Current value of average pressure in the battery cells, kgf/cm^2	P1	0: 50
4	Current value of the battery average temperature, °C	T1	10: 45
5	Current charge level of battery, Wh	W1	0: 2900
6	Voltage difference between battery cells measured and unmeasured cells, V	ΔU1	0: 0,14
7	Power capacity received during test discharge, Wh	$W1_{test}$	2500: 2900

Table 3: List of control commands used in the developed algorithm.

Number	Command name	Command designation
1	Allowance of battery charge	Chr_ON
2	Switching on of discharge resistance	PC_ON
3	Prohibition of battery charge	Chr_OFF
4	Switching off of discharge resistance	PC_OFF
5	Switching on of compensative charge	compens. Charge_ON
6	Switching off of compensative charge	compens. Charge_OFF

Table 4: Parameters calculated by the developed algorithm to be sent to the ground.

Number	Parameter name	Designation
1	Present level of charge of the battery, Wh	W1
2	Minimum voltage of the 17 battery cells, V	U1min
3	Maximum voltage of the 17 battery cells, V	U1max
4	Average pressure of the 4 measured battery cells, kgf/cm2	P1
5	Maximum pressure of the 4 measured battery cells, kgf/cm 2	Pmax1
6	Minimum pressure of the 4 measured battery cells, kgf/cm 2	Pmin1
7	Difference between voltage values of measured and unmeasured battery cells, V	ΔU1

Table 5: List of messages, generated by the developed algorithm to be sent to the ground.

Message text	Message type
Battery charge is not switched on in PSS	Emergency
Battery charge is not switched off in PSS	Emergency
Temperature rises in PSS during testing	Emergency
Testing is finished in PSS	Command
Discharge current is not switched on in PSS	Command
Discharge current is not switched off in PSS	Emergency

4. Program Model description

4.1. The assumptions of program model

- Battery Modeling flow chart [1]
- Methodology and Initial data for program model [1]
- The values and definitions of the developed program [12].
- EOL worst case solar array degradation
- Summer solstice intensity
- Battery has one shorted cell
- Solar array high temperature
- Spacecraft load profile with payload operation
- Solar array off-point angle variation
- Solar array clamped to battery voltage after eclipse

In this paper, all environmental conditions which can affect the SA power are considered. All factors that affect the power including the load profile, SA temperature, SA off-point angle, and SA shadowing effect are taken into consideration. Also, margin factors are included in the energy budget analysis program for worst case conditions [2, 4, 7, 9].

4.2. program mathematical model [1]

The following system of equations are the estimated polynomials (pressure, temperature and the voltage) equations from the experimental model.

$$P0{=}Vb(DOD) = p1 * DOD^5 + p2 * DOD^4 + p3 * DOD^3 + p4 * DOD^2 + p5 * DOD + p6 \quad (1)$$

$$DOD = 1 - SOC \quad (2)$$

$p1\ , p2, p3, p4, p5 \& p6$ are polynomial coefficients which are

$$(0{,}2791.\ -7{,}3433.\ 9{,}1970.\ -3{,}4611.\ -0{,}3647 and\ 4{,}0937)$$

$$P1{=}Vch(t) = p1 * t^4 + p2 * t^3 + p3 * t^2 + p4 * t + p5 \quad (3)$$

$p1\ , p2, p3, p4, p5$ *are polynomial coefficients which are*

$$(-0{,}0822\ .\ 0{,}6925\ . -2{,}1478\ .\ 2{,}9177\ .\ 2{,}8331),$$

$$P2{=}SOC(t) = p1 * t^5 + p2 * t^4 + p3 * t^3 + p4 * t^2 + p5 * t + p6 \quad (4)$$

$p1. p2. p3. p4. p5 \& p6\ are$

$$0{,}016.0{,}0267. -0{,}2080.0{,}2678.0{,}5567 and - 0{,}0084\ respectively$$

$$P3{=}Ich(t) = p1 * t^7 + p2 * t^6 + p3 * t^5 + p4 * t^4 + p5 * t^3 + p6 * t^2 + p7 * t + p8 \quad (5)$$

$p1\ . p2. p3. p4. p5. p6. p7. p8\ are$

$$(0{,}0636. -0{,}7004.2{,}9053. -5{,}5249.4{,}6879. -1{,}675.0{,}2012.0{,}9956. respectively)$$

$$P4{=}T(t) = p1 * t^3 + p2 * t^2 + p3 * t + p4 \quad (6)$$

$$p1. p2. p3 \& p4\ equal\ 2{,}5127. -12{,}6206.36{,}3938.\ \&\ 22{,}1207\ respectively$$

$$P5{=}Vdis(t) = p1 * t^5 + p2 * t^4 + p2 * t^3 + p2 * t^3 + p3 * t + p4 \quad (7)$$

$p1, p2, p3, p4\ \& p5\ equal$

$$12.7384, -34.029, 28.7928, -8.8753, 0.3011\ \& 3.9769\ respectively$$

4.3. Program Methodology

The SC flight time is divided into time intervals with specific electric consumption of SC equipment and solar array power generation. In each time interval the battery charge level is defined as at the end of (i-interval).

It is defined as:

$$W_i = W_{i-1} + \Delta W \tag{8}$$

where W_{i-1} – charge level at the beginning of i-interval, corresponding to charge level at the end of preceding interval, ΔW_i – NHSB energy changing of the current interval.

If SA power of the current interval is lower than SC equipment total power consumption or power supply from SA is eliminated, so that NHSB is being discharged. Energy received from NHSB during the battery discharge for i-interval is calculated by equation:

$$\Delta W_i(\text{discharge}) = ((P_i - P_{i(SA))}/\eta_{disch})\times (t_i - t_{i-1}) \tag{9}$$

Where:

P_i– total electrical power of equipment including harness and switches losses, consumed during i-interval,

$P_{i(SA)}$ – SA power, taken to the PSS bus, for the i-interval;

η_{disch} – discharge device efficiency

t_i – interval ending time

t_{i-1} – interval beginning time

If the SA power during the current interval is higher than total load consumed power, then NHSB is being charged. The maximum total charging current of the two NHSB is limited by value 60 A. If SA power increases with respect to load power and increases than the charging limit of the NHSB, then the following condition is satisfied:

$$(P_{i(SA)} - P_i) \times \eta_{charge} \geq I_{charge\ max} \times U \tag{10}$$

Where:

$P_{i(SA)}$ –SA power, taken to the PSS bus, for the i-interval;

P_i – total electrical power of loads including harness and switches losses, consumed during i-interval;

η_{charge} – charging unit efficiency

$I_{charge\ max}$ – maximum total charging current of the two NHSB;

U – PSS buses nominal voltage.

The energy supplied to the NHSB during charging in i-interval is calculated by the following equation:

$$\Delta W_{i(charge)} = I_{charge\ max} \times U \times \eta_{аб} \times (t_{i\_end} - t_{i\_begin}) \tag{11}$$

where

$\eta_{аб}$ – storage battery efficiency for charge-discharge cycle.

t_i – interval ending time.

t_{i-1} – interval beginning time.

$$\text{If condition } (P_{i(SA)} - P_i) \times \eta_{charge} \geq I_{charge\ max} \times U \tag{12}$$

is not satisfied, then the energy, supplied to the NHSB during charging in i-interval is calculated by equation.

$$\Delta W_{i(charge)} = (P_{i(SA)} - P_i) \times \eta_{charge} \times \eta_{аб} \times (t_{i\_end} - t_{i\_begin}) \tag{13}$$

As a result of the calculation of different charge levels by intervals, the graph of charge level vs. time is developed during real examined flight stage. As the NHSB initial charge level the firm energy capacity of NHSB will be confirmed during the examined flight stage [2, 4, 6, 9].

5. Battery Management Environment Verification Results

The estimated battery behaviour through the worst-case scenario (WCS) can be achieved through the software modules described in this section where the load profile of the designed WCS is shown in figure (2).

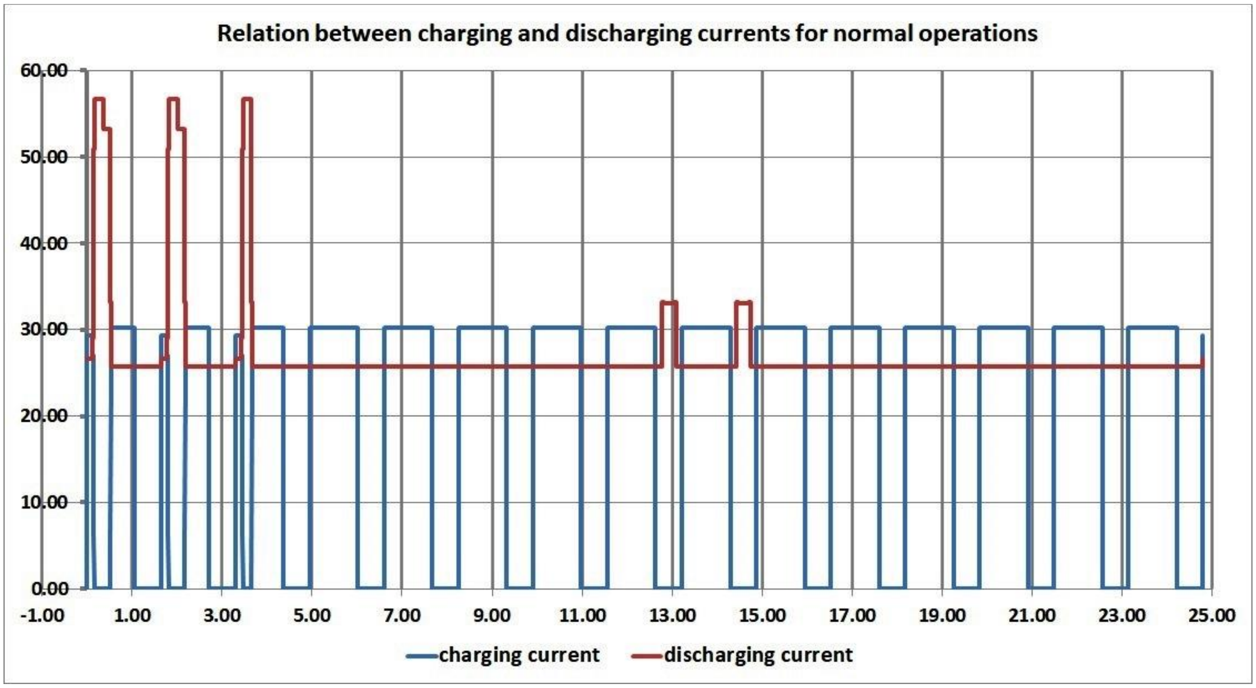

Figure 2**:** The load profile of the designed worst case scenario.

The environment software includes three main modules as follows:

- Module of simulation of the worst-case scenario. This module is used to classify the charge & discharge period during the whole WCS day. Also, it estimates the current of charge and discharge for each time step in order to calculate the capacity of the battery during the WCS at each time step.
- Module for distinguishes of each period of charge for different charging current. It also distinguishes for each period of discharge for different discharging current. This is done according to the charging and discharging setting (P_{set1}, P_{set2}, P_{set3}) of the master charging algorithm. Also, it determines the time interval of charge or discharge for calculation of battery capacity.
- Module for calculation of the battery capacity at each time step during the whole WCS

Figure 4 shows battery capacity - time during WCS.

The results of the previous modules depend on the real behaviour of the given battery with the designed WCS. Also, these results are considered as judgment of the designed WCS if the battery will be able to execute this scenario in a good performance condition or not.

The developed battery management environment and the developed control algorithm are implemented on the experimental battery model [1]. The results of the implementation are given in figure (3).

These results show that the battery capacity capabilities are enhanced in terms of battery capacity excess starting from orbit number six to orbit number 15. Therefore, the excess battery charged capacity is shunted. This excess of the battery charged capacity represents about 60% over the battery capacity capabilities (hardware capabilities).

From the analysis of figure (3), this curve verified that the behaviour of the battery is compatible with the designed worst case scenario.

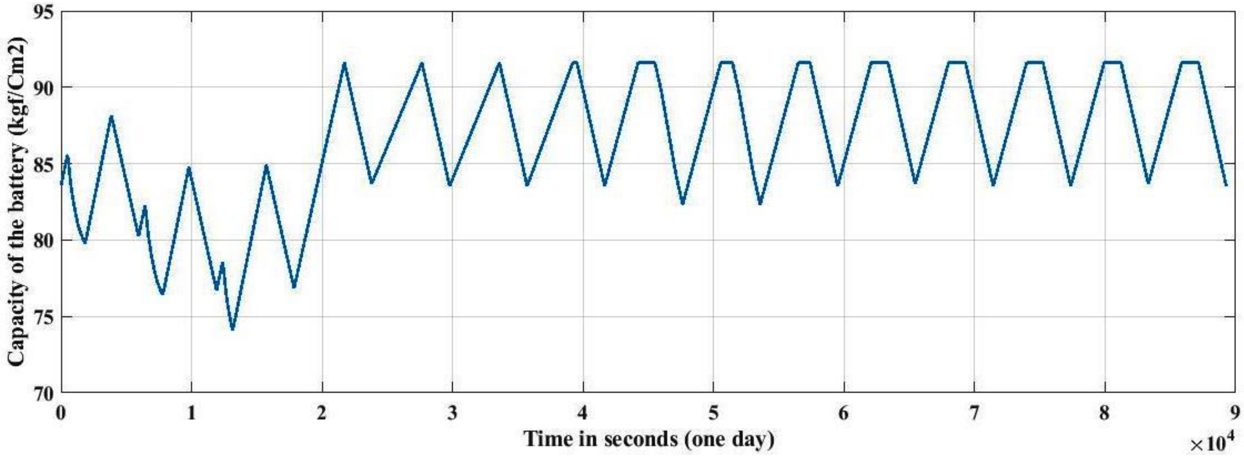

Figure 3: Battery capacity – time during designed WCS.

Another submodule is developed for estimation of the battery voltage behaviour during WCS. It is based on the comparison of the state of battery charge (capacity) at each time step in WCS with the real behaviour of the battery (from real battery ground test) figure (4). Figure (5) shows the cell battery voltages against time.

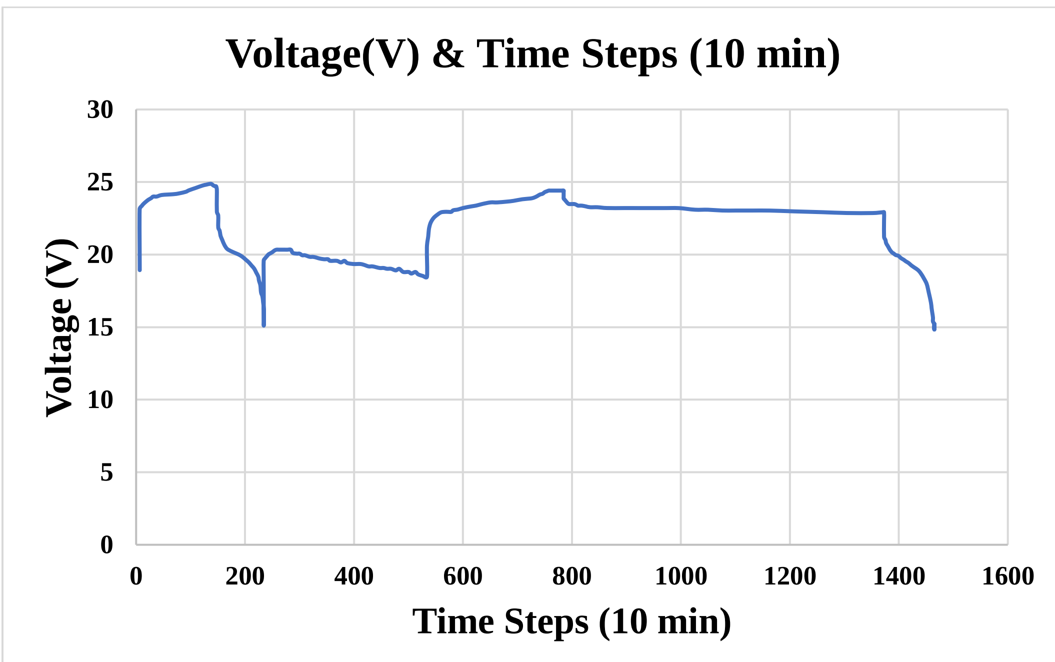

Figure 4: Battery total (voltage – time) during battery ground test [1, 9, 10].

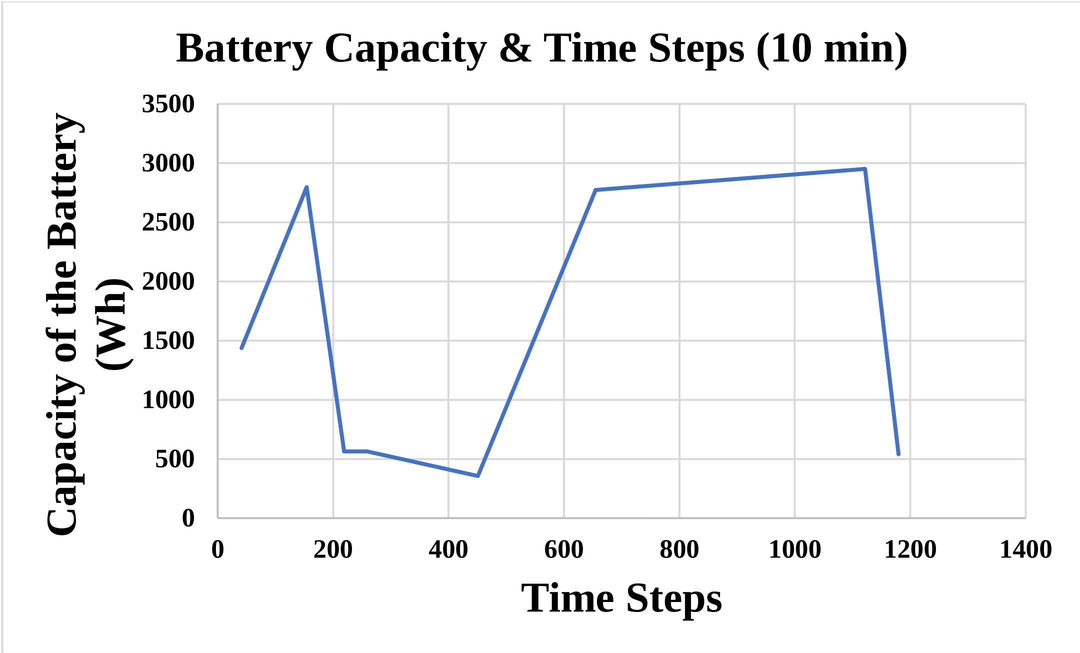

Figure 5: (Battery capacity– time) during battery ground test [1, 9, 10].

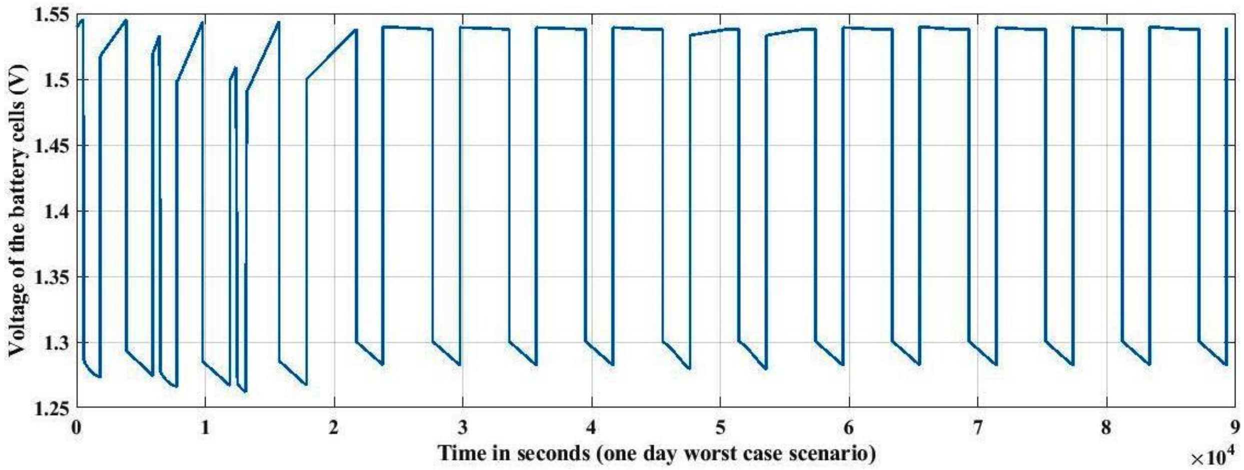

Figure 6: Battery Cells voltage – time.

Another module in the battery management environment is developed to calculated the heat emission [W] of the battery during charging and discharging. The calculation results are given in figure (7) and figure (8). These figures reflect the proper operation of the battery under the developed control algorithm. Also, it illustrates that the maximum heat emission of the battery during charging is about (35-38) W, and during discharging is about 120 W which are less than the technical specification of the battery which is 140 W [9].

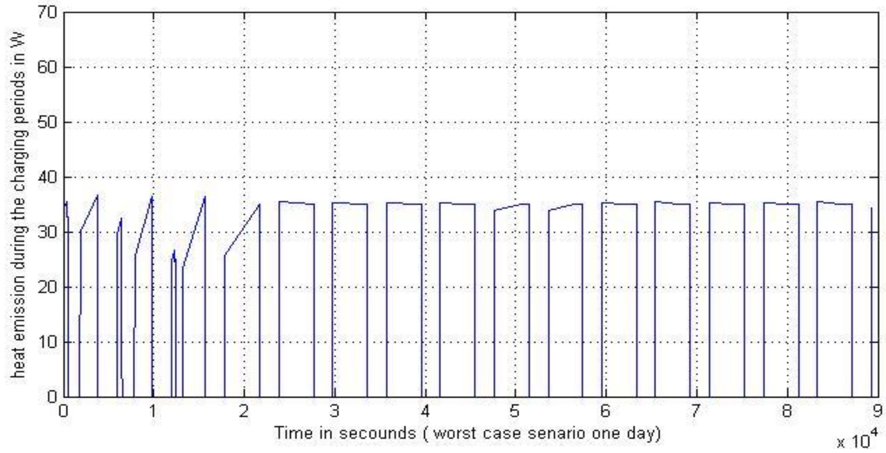

Figure 7**:** Battery heat emission power during charging periods.

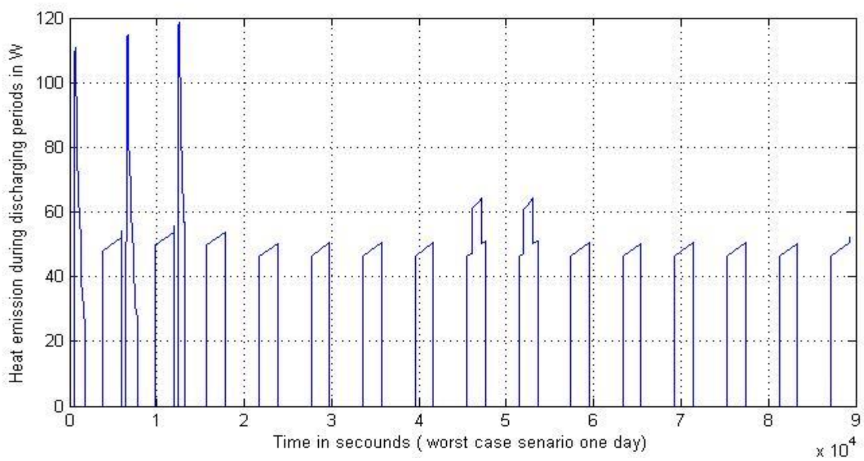

Figure 8**:** Battery heat emission power during discharging periods.

From the previous results of the battery behaviour under the conditions of the designed WCS is in the permissible limits. The selected battery will be able to satisfy the requirements of the designed WCS. This battery management environment reflects the real behaviour of the battery under the developed control algorithm. Also, it can predict the battery behaviour at any other scenarios specially if the SC faced off-nominal situation which considered the main goal of constructing such the developed battery management environment.

6. Battery Management Environment Validation Results

The Battery management environment validation results is performed by comparing of our simulation results with the proposed SC telemetry which indicate the same results of our simulation results as following [2, 11]:

1. The average current of the solar array generator is 63A, as shown in figure (9).
2. The two NHSB capacity profile during executing the designed WCS is as the planed power budget and our simulation. as shown in figure (10).
3. Battery total voltage – time during executing the worst case designed scenario figure (11).
4. Battery temperature – time during executing the worst case designed scenario figure (12).

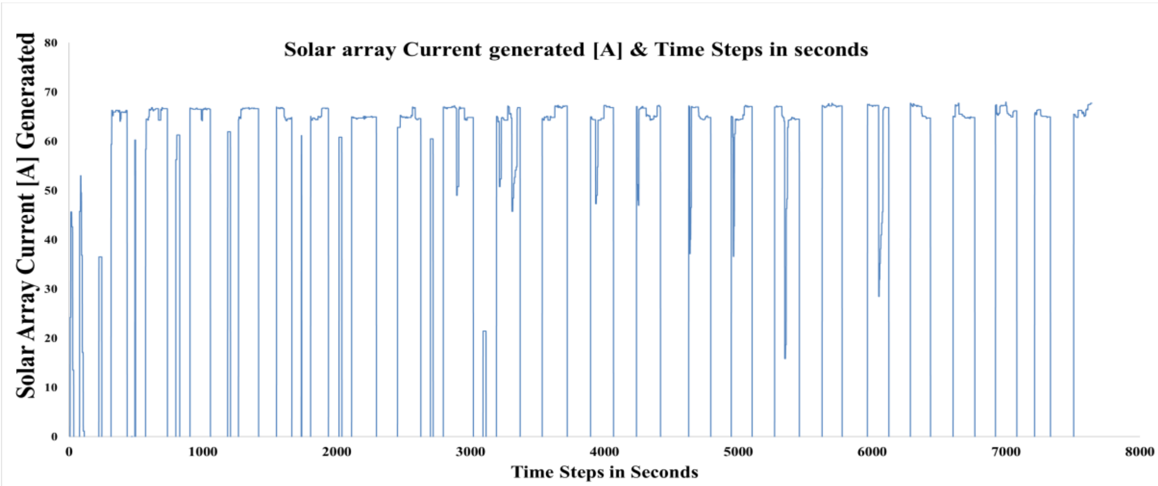

Figure 9: SA current-time [1, 12].

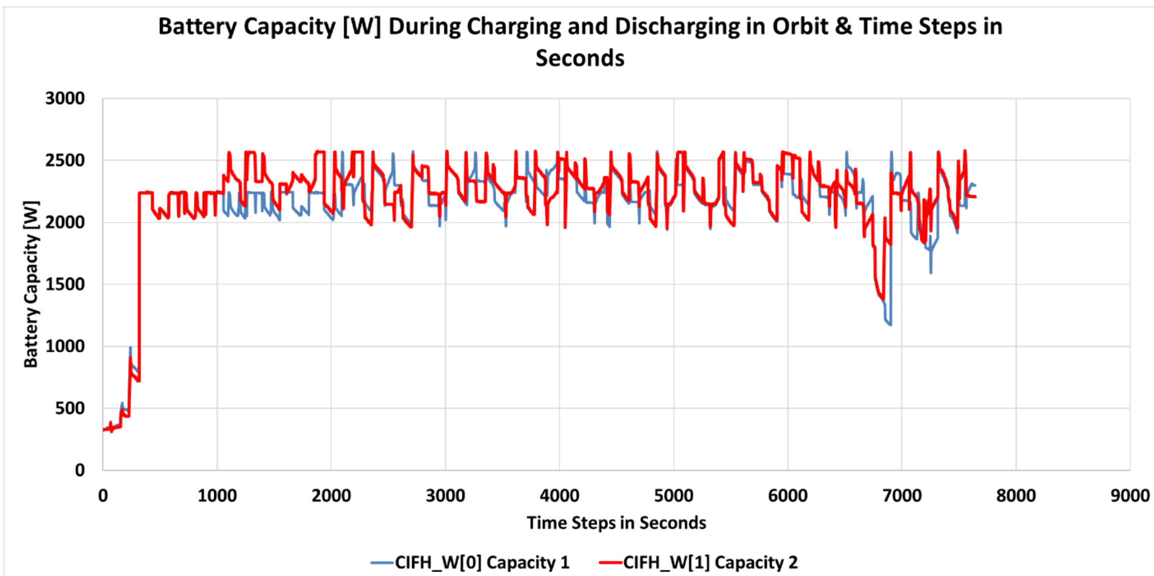

Figure 10: The two NHSB capacity profile during the designed WCS [2, 12].

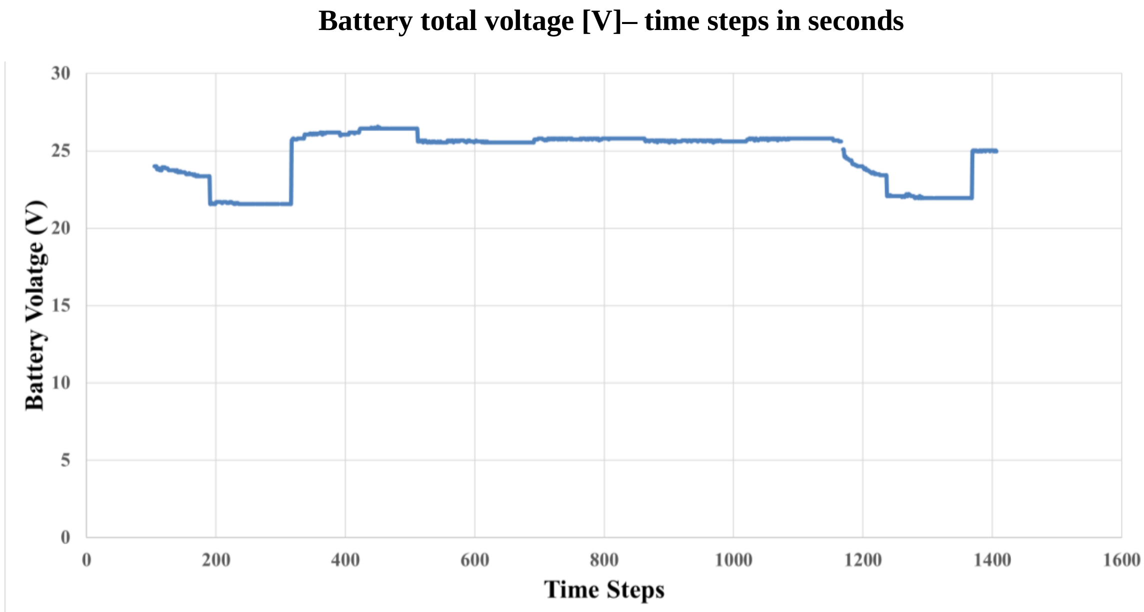

Figure 11: Battery total voltage [V] – time during executing the worst case designed scenario [2,12].

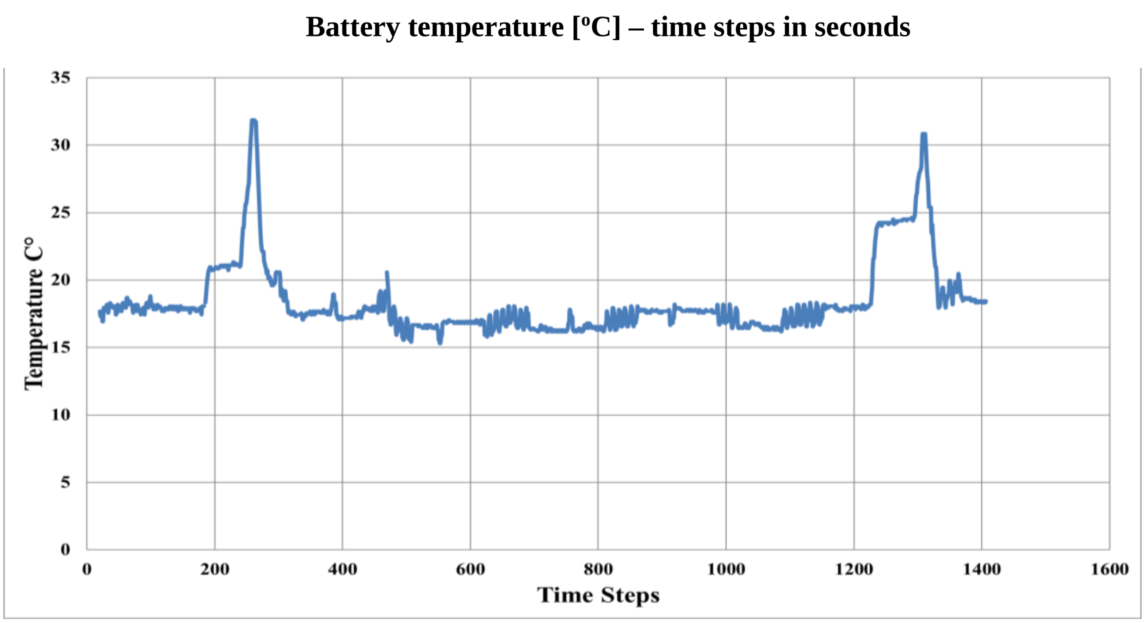

Figure 12: Battery temperature [ºC] – time during executing the worst case designed scenario [2,12].

7. CONCLUSION

This paper presents the development of a complete environment of the SC battery control and management. This environment ensures the SC power budget calculations and the well performance of the battery in orbit. Within the developed environment a battery charging and discharging control algorithm is developed to prove the capability of the battery control and management during the operating scenarios in orbit. The novelty of this environment is to validate the battery design as secondary power generation subsystem of (LEO) SC under the real operating conditions. Also, it ensures the battery output before starting the battery manufacturing process. By this environment, the battery design and battery output verification will satisfy the required battery specifications under the operating conditions. Also, the main output of this developed environment including the developed charging and discharging control algorithm and its implementation is to ensure that the behaviour of the battery under the developed control algorithm during the WCS is in the permissible limits. The battery behaviour during any other scenario can be predicted by the developed environment, especially if the SC faced off-nominal situation which considered one of the main goals of the developed environment.

References

[1] Mohamed A M, Amer F E H, Mostafa R M, and Sarhan A 2022 *13th Int. Conf. on Electrical Engineering (ICEENG)* 42-46
[2] (2023) Pleiades-HR (*high-resolution optical imaging constellation of CNES*). Available at: https://directory.eoportal.org/web/eoportal/satellite-missions/p/pleiades (Accessed: 07 June 2023)
[3] Patel and M R 2004 *Spacecraft Power Systems* (CRC press)
[4] Larson W J and Wertz J R 1992 Space *Mission Analysis and Design* United States
[5] Gurnett and D A 1998 *Principles of Space Plasma Wave Instrument Design Measurement Techniques in Space Plasmas Fields* **103** 121-136
[6] Fortescue P and Stark 2011 *Spacecraft System Engineering* (John Wiley & Sons, Ltd)
[7] Dahbi S, Aziz A, Zouggar S, El Hafyani M, Morocco Hanafi, A Karim, M Latachi I and Rachidi T 2017 *Int. Conf. on Advanced Technologies for Signal and Image Processing (ATSIP)* 1-6
[8] Kharsanky and A 2017 *small satellite. Conf. ALL2017* 143
[9] (2023) News - en.saturn-kuban.ru. Available at: https://en.saturn-kuban.ru/about/press-center/news/ (Accessed: 07 June 2023)
[10] Ahmed Mokhtar M, Fawzy ElTohamy, R M Mostafa and Walid A. Wahballah 2018 *IEEE Aerospace Conf.* pp 1-11
[11] Thaller L H, Zimmerman and A H 2003 National Aeronautics and Space Administration Glenn Research Center
[12] (2023) db.satnogs.org/. Available at: https://db.satnogs.org/ (Accessed: 07 June 2023)