Design of battery charging system update for glider launcher

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Abstract: This paper presents an innovative solution for increasing life of lead-acid batteries used in a glider launcher. The study is focused on upgrading a charging system instead of a costly full replacement of it. Based on literature review, the advanced three-stage charging profile was indicated. The new topology of the power converter was proposed and a simulation model was developed. A simulation study was performed which leads to a conclusion that the suggested solution can be successfully applied to the studied device. As a result, the conclusion of this work is the recommendation for modification of the launching system with an additional converter enabling 3 stage charging.

Key words: alternative power supply, battery modelling, lead-acid batteries

1. Introduction

Toulouse Aviation and Aeronautics Association (AVAT) was funded by glider enthusiasts. Gliders are aircraft without propulsion systems incapable of autonomous ascension. The association launches its gliders using a small aeroplane or a special hybrid glider launcher. On account of the air-fuel cost and environmental pollution associated with using an aeroplane, the hybrid launcher is the preferred method of propelling the gliders up into the air. The launcher Fig. 1(a) consists of a stack of lead-acid batteries, an electrical motor and power-electronic devices that control charging of the battery stack and work of motor. The launcher is situated on a diesel truck. Due to the large temperature fluctuations ($0°C – 40°C$) in the Toulouse area where the launcher is located, AVAT is interested in extending the life of lead-acid batteries in such unfavourable conditions. It is worth noting that currently better alternatives to this battery technology are available such as lithium-ion batteries. Despite this, due to budget reasons, the possibility of replacement

of the full battery stack was excluded and a search for an alternative solution commenced. For this purpose, an analysis of a battery charging method using models and PLECS software simulations was carried out. Conclusions drawn from this analysis and from the literature review have led to the proposal of applying the 3-stage charging method.

(a) (b)

Fig. 1. View of the studied launcher Electronic circuits: (a) Mercedes-Benz model 914; (b) all power electronic components of the launcher (1. inverter with control driver, 2. contractors and relays, 3. fuses, 4. battery charger with driver)

2. Survey of related works

The goal of the project was to improve the exciting power supply system of the glider launcher to extend a lead-acid battery's life cycle. The first stage was to developed the simulation model of the launcher system. For this purpose, the critical review of the launcher documentation [1] was carried out, which was confronted with the whole electrical system at AVAT. During the launcher system inspection, particular attention was paid to the power supply system of the glider launcher. Using this information, the simulation model was designed (Fig. 2). It described this system in the form of a model which next could be modified and improved.
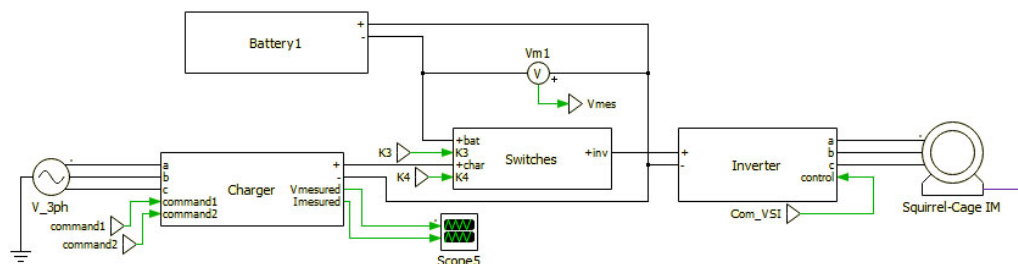

Fig. 2. Simulation model of the AVAT glider launcher electrical system

The main focus was put on the stack of lead-acid batteries used as energy storage and the converter used to charge them. Sufficient literature enabling authors to model batteries was found

[2, 3]. Due to a lack of producer mark or model on the device, a description of the converter provided by the producer was not found. In its place, a prototype structure was created based on the analysis of documentation and on-site observation of the device. The topology of this device as recreated in PLECS software is shown in Fig. 3.
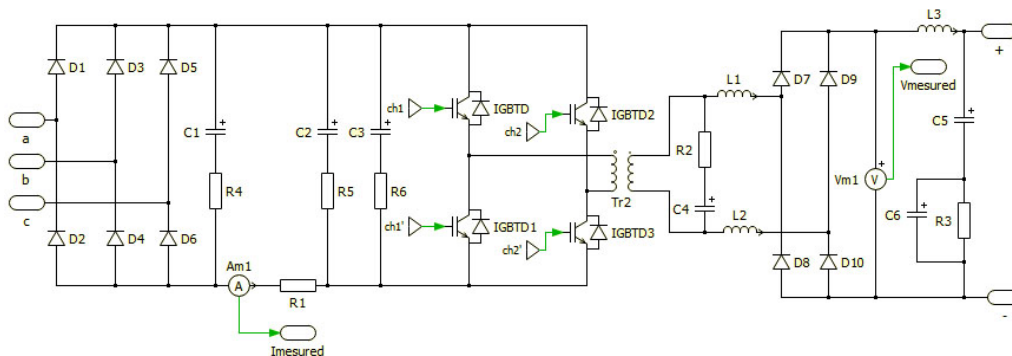

Fig. 3. Charger architecture realized in PLECS

While all of the components of converters such as transistors and diodes age, it was batteries that were found to be the costliest element of the system to replace. Every charge-discharge cycle leads to deterioration of its health due to chemical changes happening to electrolyte and electrodes. Because of that, it was deemed necessary to minimize this process using the least expensive way. An advanced three-stage charging profile, to be realized by the converter, was chosen due to promising results presented in [4]. The proposed three-stage battery charging profile constitutes of charging with constant current followed by charging with constant voltage. During the later part, when the charging current reaches stability the applied voltage is lowered to enable ao deeper charge. A profile of the charging current and voltage is shown in Fig. 4 [4].

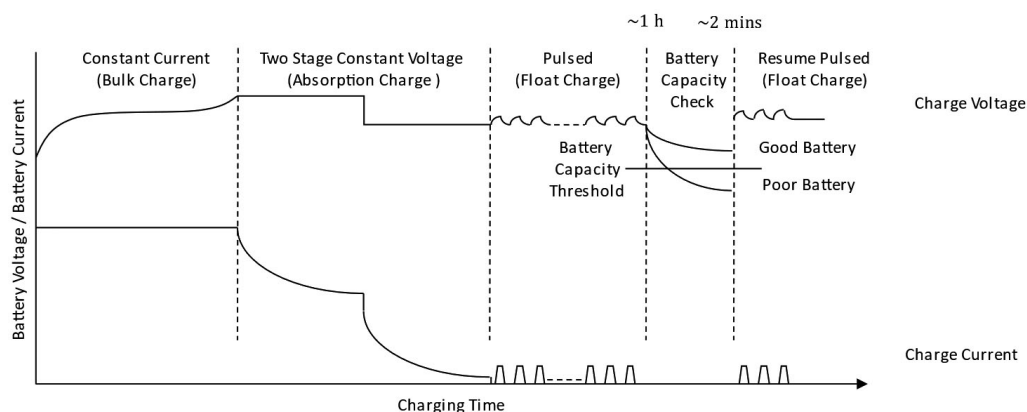Fig. 4. The proposed three-stage charging battery profile used in modern lead-acid batteries [4]

3. Objective and scope

The main objective of this paper is to analyze the charging chain of the lead-acid battery stack, analyze its influence on the lifetime of the system and propose means that could lead to increasing this lifetime. Because of the problems nature, a solution least invasive for the currently used system was researched.

Literature research, described in part 2 of this paper, lead to the conclusion, that the most promising way of increasing longevity of the system was through the application of a modern charging method. Based on the system assumption, provided by the AVAT association, it was concluded, that the chosen charging method could not be realized by modification of controls for a currently used converter.

These conclusions lead to the decision that the research should focus on the design of an additional converter that could be inserted in the current system that could realize the new charging method. All modelling and simulation processes, necessary for designing such a converter and its control system, are included in this paper.

4. Solution

As previously stated, solving the problem described in this article required extensive modelling and simulation work to be performed. The equivalent circuit model of the battery stack was based on literature research, electrochemical properties of the lead-acid batteries and the study of the glider launcher system [2–6]. The circuit model of the charger was based on a technical description of the elements and on-site study of converters' topology. The simulations were based on the work profile of the system provided by the AVAT association and the battery charge and discharge cycle were studied on-site.

The topology of the supplementary converter, enabling three-stage battery charging, was designed using the buck converter operation principle and control engineering theory. It was designed with the lowest possible invasiveness to the already existing architecture and simplicity of operation in mind [5].

Main contributions of the presented research are:
– an equivalent circuit model of the lead-acid battery stack used as a power source for the glider launcher;
– an equivalent circuit model of the charging chain used to charge a battery stack;
– the proposed architecture of a supplementary buck converter;
– simulation proof for the correctness of the upgraded charging chain operation.

5. Modelling and simulation

5.1. Battery model

In order to evaluate the reason for inefficient battery charging, in the current state of the launcher, simulation study of the lead-acid battery was conducted. The chosen base for the

preparation battery model used later for a simulation purpose and theoretical analysis, was a dynamic model for photovoltaic purposes given by [7] (Fig. 5).
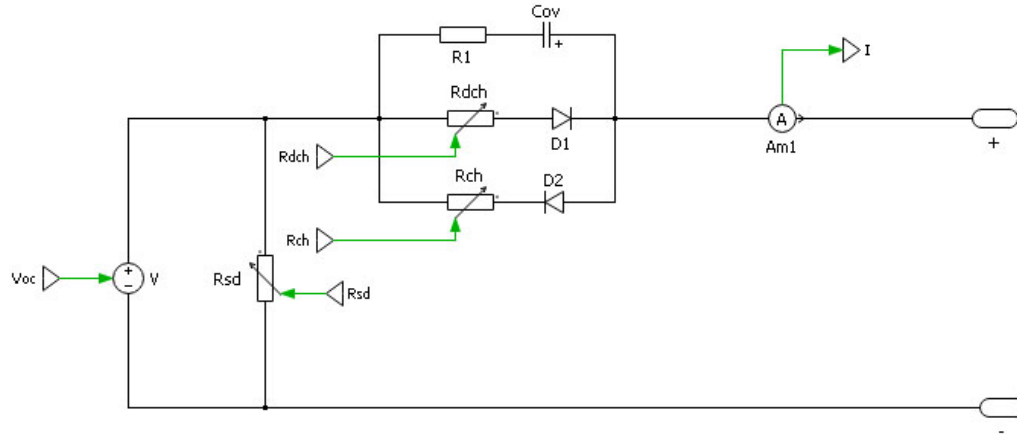

Fig. 5. The equivalent circuit model of lead-acid battery developed in PLECS environment

This model was a good starting point as it takes into account and represents most of the physical phenomena occurring in the charge/discharge cycle of a lead-acid battery. It was adapted to fit the requirements of simulation software used. Values of all elements depend on State of Charge (SoC) value which is calculated by Formula (1) [2, 8–10]:

$$\text{SoC} = \frac{Q_e}{C \cdot 100} = \text{SoC}_0 - \frac{\int_{t_{\text{SoC}_0}}^{t_{\text{SoC}_{final}}} i \, \mathrm{d}t}{C}, \tag{1}$$

where: Q_e is the charge stored in a battery, C is the maximal capacity of a battery.

The Q_e parameter is calculated as shown by Formula (2):

$$Q_e = Q_0 + \int I_{ch} \, \mathrm{d}t - \int I_{dch} \, \mathrm{d}t, \tag{2}$$

where: I_{dch} is the discharge current, I_{ch} is the charging current and Q_0 is the charge accumulated.

The voltage source in the model represents open-circuit voltage V_{oc} [11]. Resistor R_{sd}, connected in parallel to it, represents the self-discharge process occurring inside the battery at all times. Its value in kΩ is dependent on SoC. This can be used to model the deterioration of its health due to chemical changes happening to electrolyte and electrodes.

Resistors R_{dch} and R_{ch} both represent inner resistances of the battery for respectively discharging and charging processes [12]. They can, however, be also approximated using Formula (3) and Formula (4):

$$R_{dch} = \frac{\Delta V_{dch}}{I_{dch}}, \tag{3}$$

$$R_{ch} = \frac{\Delta V_{ch}}{I_{ch}}, \tag{4}$$

where: ΔV_{dch} is the voltage drop during discharge, ΔV_{ch} is the voltage drop during charge, I_{dch} is the discharge current, I_{ch} is the charging current.

The last element of the model is capacitor C_{ov} which represents overvoltage that can occur in the battery and is the sole component with a constant value of 40 F. The resistor, connected in series with it, has negligible value and is there solely to ensure the stability of the numerical calculations during the simulation [3].

A simple charge/discharge simulation was performed in order to verify the proper functioning of this model and its results are shown in Fig. 6.
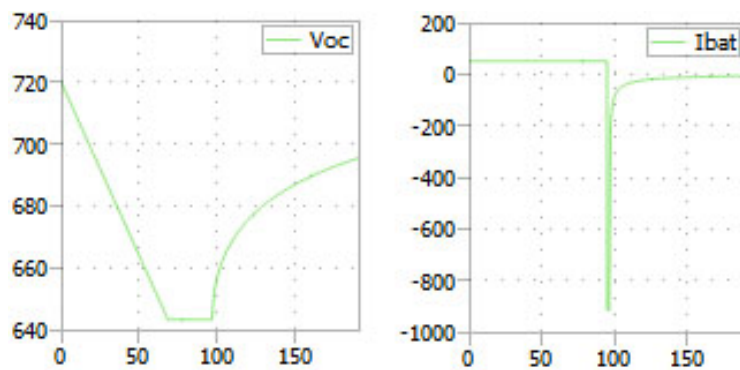

Fig. 6. Battery open-circuit voltage and current during discharge and charging

The simulation results have proved the model to be a realistic representation of batteries' behaviour during charge and discharge processes as shown by the voltage and current. The very high value of current during charging is simply due to minimal R_{ch} which was decreased in order to shorten the simulation time.

5.2. Architecture of supplementary buck converter

The goal behind changing the charging system was to lower the battery chargers' current when the battery is fully loaded. In order to do that, an understanding of the reason behind the heightened currents was needed. Through analysis of the simplified battery model, Formula (5) for battery current dependent on charging voltage V_{ch} was obtained:

$$I_B \approx \frac{V_{ch} - V_{oc}}{R_{ch}} \,.$$ (5)

As both V_{oc} and R_{ch} are dependent on SoC, when SoC saturates, I_B will reach a certain minimal value. This leads to the conclusion that the only way to further lower I_B in this situation is to lower V_{ch}. Papers [4, 10] give a good insight into modern methods for charging lead-acid batteries. A multiple-stage charging method shown in Fig. 7 allows one to reach a very low charging current during float charge as well as to optimize energy stored inside the battery. This information is in agreement with conclusions to which the authors came earlier through simplified model analysis.

It was decided, that to reach a satisfactory charge profile of the battery, the charging process should be divided into three steps, charging with a constant current of 23.75 A, a constant voltage of 720 V and a constant voltage of 682.5 V. A buck converter, connected in-between a battery charger and battery stack, was chosen to realize this charging method. It imposes the need for smallest possible modification of an already existing charger. In order to realize the control of the three-stage charging method, an additional component called capacity check needs to be added. At the same time a current control loop in the already existing charger needs to be disconnected. The concept of the modified charging chain is shown in Fig. 7.
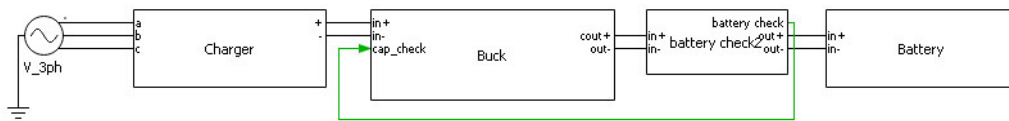

Fig. 7. Concept of battery charging chain with proposed components

The buck converter operating at 10 kHz frequency was chosen because it allows lowering the input voltage of the battery and as a result, controlling current. Values of filters' capacity and inductance were calculated taking into account the operating frequency of the converter and were accordingly 30 mH for L1 and 84.43 μF for C1. The buck converter's topology realized for simulation purposes in PLECS is shown in Fig. 8.
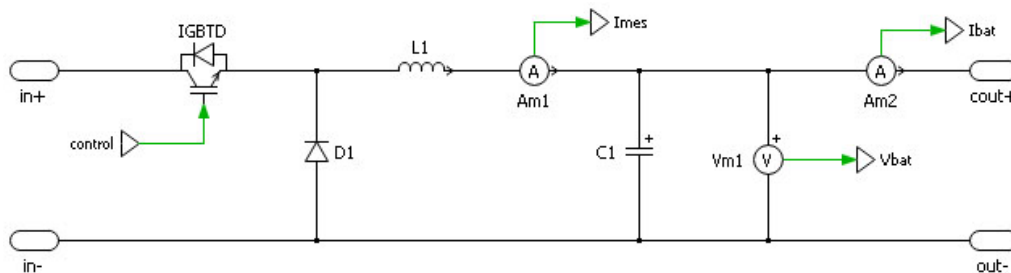

Fig. 8. Buck converter structure as realized in PLECS

The other element, that should be added to realize the three-stage charging method, was given the name of "battery check". Its purpose is to periodically check if the battery is at a satisfactory level of charge and if not, to initiate the charging process. It works by disconnecting the battery from the system and connecting it to a resistor for a very short period of time. Values of current and voltage drops on the resistor are then measured and used to calculate the power of the battery. If the power is below a certain value depending on the resistance of the resistor, the element sends a positive signal. In any other state, the output of the element is negative [11].

Control of the buck converter consists of current and voltage loops. For the purpose of calculating regulators' parameters, the system working with a current control loop was presumed to be as shown in Fig. 9. The output voltage was treated as perturbation and considered to be almost constant. Because of that, it was neglected as it will be compensated by the integrator in the current control loop.
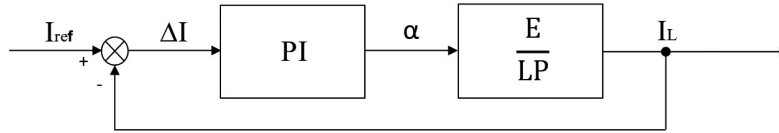
Fig. 9. System in the current control mode

For the system working in voltage control mode, the output current was treated as perturbation and considered almost constant and neglected for the same reason as the output voltage in the previous example. The result was the system form as shown in Fig. 10.
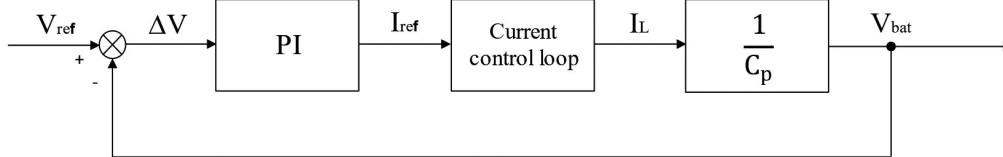

Fig. 10. System in voltage control mode

Because of the fact, that the current control loop is faster, it was treated as gain with a value of 1 which allowed one to separate the two modes.

In order to realize three-stage charging, switching between two control modes and two voltage references was needed. The state machine is a method which allows achieving such functionality with ease. Its three states represent respectively constant current charging, constant voltage charging for $V_{ch} = 720$ V and constant voltage charging for $V_{ch} = 682.5$ V. The state machine has 3 inputs, battery voltage V_{bat}, battery current I_{bat} and batteries state of charge (*Cap_check*) which are used as triggers for switching between states. Its outputs are numerical variable *voltage_reference* and Boolean variable *control_loop*. The *control_loop* variable takes a value of 0 for charging with constant current and 1 for charging with constant voltage.
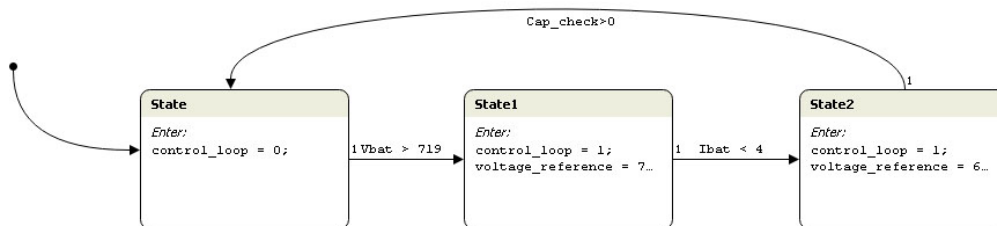

Fig. 11. State machine used to switch between charging modes

5.3. Simulation

The simulations' goal was to study if the new charging method will eliminate too high charging current after the battery has been fully charged. All the simulations were performed in PLECS software using models mentioned in the previous paragraphs. PLECS was chosen as software

created especially for simulations of power electronic systems. It is a software package enabling to simulate both electrical circuits (battery, power electronic elements) as well as their controls (state machine, regulators). The software includes a rich library of ready to use models and is able to simulate both non-stiff and stiff systems. All of the simulations were performed using a non-stiff solver with a variable time step.

The first step was to simulate the charging chain consisting of the charger currently used in the AVAT launcher, powered by a 3-phase voltage source connected to a battery model. This charging chain, as realized in PLECS, is shown in Fig. 12. The inner command of the inverter within the charger is not known. Because of that, for the simulation purpose, a simple control was assumed as shown in Fig. 12.
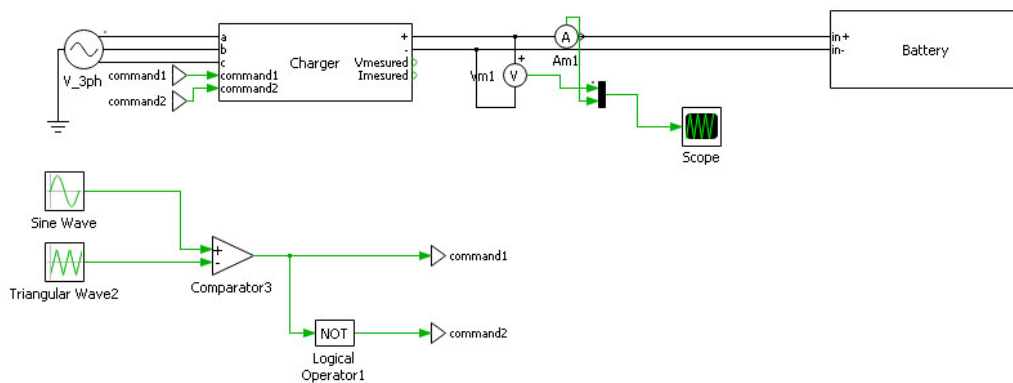
Fig. 12. Simulation model of the existing charging chain

The next simulation was performed in order to check the work of the proposed three-stage charging method utilizing a buck converter. For the purpose of the simulation, an assumption was made, that the currently used charger control would be modified so that it functions as a voltage source with an output voltage of 720 V. Based on this assumption, the model of the buck converter used during the third simulation was connected to the voltage source. Due to the already proven proper work of the battery check element and because the discharging battery was not of interest for this part of the project, a one-time charging process was simulated using the charging chain model shown in Fig. 13.
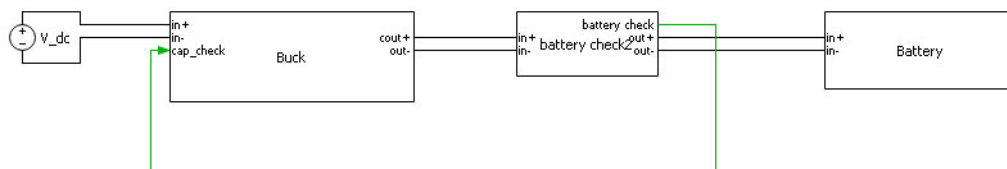
Fig. 13. PLECS model of charging chain with buck converter and battery check element

As seen in Fig. 14, the results of the simulation show that the three-stage charging method allowed one to lower the current in a fully charged battery to a mean value of 0.4 A. This value

can be kept thanks to voltage control in the third stage which forces negative current reference. All this was done while maintaining the maximum voltage of the battery.
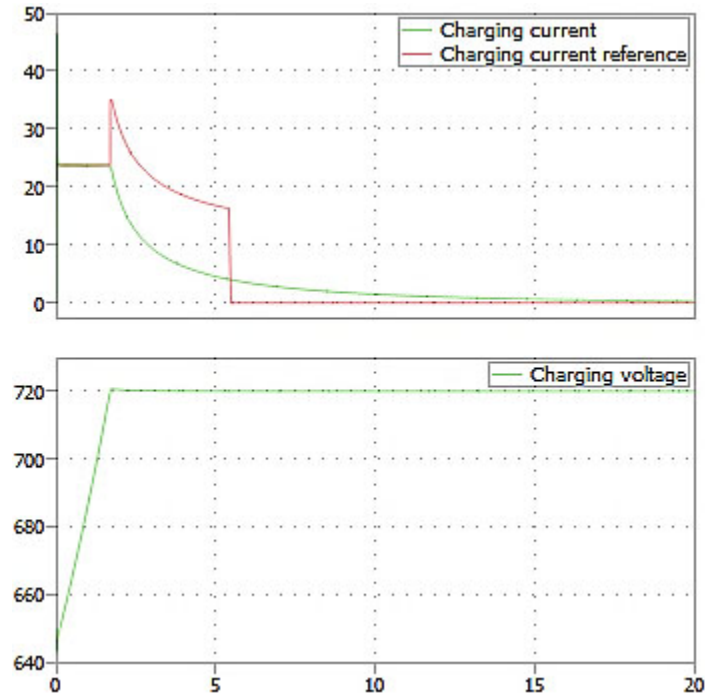

Fig. 14. Charging current and current reference [A] (on top) and voltage [V] (on bottom)
for the charging chain with buck converter and battery check element

Fig. 15 shows battery voltage V_{oc} which reached a satisfactory level during the charging process. The maximal capacity of the battery model was accordingly lowered in the simulation for the same reasons as in the first simulation.
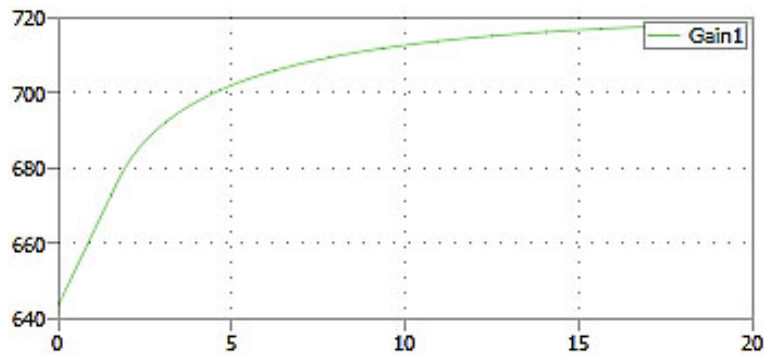

Fig. 15. Open circuit voltage of the battery during for the charging chain with buck converter
and battery check element

6. Conclusions

In order to increase the efficiency of charging and storing electrical energy in the lead-acid battery stack used by the AVAT launcher, modifications of the current system have to be made. The three-stage charging method is a promising solution that can help achieve this with relatively small changes to the architecture of the whole system. A new architecture was proposed and successfully simulated in PLECS software. The results are promising and suggest the viability of this solution.

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