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Modeling of Li-ion Battery Management System for Unmanned Aerial Vehicles

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Abstract: Nowadays, systems that use more electricity in aircraft are increasing due to harmful gas emissions. This increase has created the need to store electrical energy and accelerated the trend towards battery technologies. Since energy storage in batteries occurs as a result of chemical reactions, problems may occur that will damage the battery group or the entire system. These problems are caused by high current, voltage, and temperature, which affect the reaction rate during battery charging/discharging. A Battery Management System (BMS) is needed to prevent problems and to use the required electrical energy safely.

In this study, it is aimed to meet the energy needs of the system in a controlled manner by disabling only the damaged cell in case of problems that may occur in the cells in the battery. For this purpose, a model of an Unmanned Aerial Vehicle (UAV) system been created by adding a BMS block to each cell to control the battery cells. The BMS model is realized based on the cell temperature, the State of Charge (SoC) value of the cell, and the output voltage values of the cell. The UAV system is modeled using MATLAB/Simulink environment. Thanks to the proposed BMS, in case of a problem that may occur in any cell in the battery, that cell will be disabled and the required energy will be met through the remaining cells. It is observed from the results obtained that when the cell parameters become normal, it continues to feed the system again.

Key words: Li-ion, battery, battery management system, UAV.

İnsansız Hava Araçları için Li-iyon Batarya Yönetim Sisteminin Modellenmesi

Öz: Günümüzde zararlı gaz emisyonları nedeniyle uçaklarda daha fazla elektriğin kulanıldığı sistemler artmaktadır. Bu artış elektrik enerjisinin depolanması ihtiyacını doğurarak batarya teknolojilerine olan yönelimi hızlandırmıştır. Bataryalarda enerji depolanması kimyasal tepkimeler sonucu oluştuğundan batarya grubuna veya tüm sisteme zarar verecek problemler oluşabilir. Bu problemlere batarya şarj/deşarj esnasında tepkime hızını etkileyen yüksek akım, gerilim ve sıcaklık neden olmaktadır. Problemlerin oluşmaması ve ihtiyaç duyulan elektrik enerjisinin güvenli bir şekilde kullanılması için Batarya Yönetim Sistemine (BYS) ihtiyaç duyulmaktadır.

Bu çalışmada bataryada bulunan hücrelerde oluşabilecek problemlerde, sadece bozuk hücre devre dışı bırakılarak sistemin enerji ihtiyacının kontrollü bir şekilde karşılanması amaçlanmıştır. Bu amaçla, batarya hücrelerini kontrol etmek için her hücreye bir BYS bloğu eklenerek, İnsansız Hava Aracı (İHA) sisteminin modeli oluşturulmuştur. Hücre sıcaklığı, hücrenin şarj durumu ve hücrenin çıkış gerilim değerleri baz alınarak BYS modeli gerçekleştirilmiştir. İHA sistemi MATLAB/Simulink yazılımı kullanılarak modellenmiştir. Önerilen BYS sayesinde bataryadaki herhangi bir hücrede oluşan problem anında hücre devre dışı bırakılmış, ihtiyaç duyulan enerji ise kalan hücreler üzerinden karşılanmıştır. Batarya hücresinin parametreleri normal hale geldiğinde ise hücrenin tekrar sistemi beslemeye devam ettiği elde edilen sonuçlardan gözlemlenmiştir.

Anahtar kelimeler: Li-iyon, batarya, batarya yönetim sistemi, İHA.

1.Introduction

With the development of today's technology, human-induced harmful gas emissions are increasing. This increase causes climate changes and global warming and puts the lives of living things at risk. Fossil fuels used in transportation cause great harm to nature. Renewable energy sources are of great importance in reducing the damage caused by these fuels to the environment [1]. There is a need to use 'more electric' technologies to save fuel, reduce environmental damage, and costs [2]. Emissions created by aircraft propulsion systems at airports and during flight are one of the most important problems in the aviation industry. More electrical systems have begun to be used in aircraft to reduce emissions. Thus, the use of batteries to store electrical energy in the aviation field has become widespread [3].

Nowadays, Lithium Ion (Li-ion) batteries are more widely preferred because they have advantages such as energy-to-weight ratio and lower self-discharge rate when not working compared to other battery technologies, and they cause less harm to the environment than other battery types [4]. The most important disadvantage of Li-ion batteries is the aging problem that occurs due to capacity decrease, regardless of whether they are in use or

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not. It must contain a protection circuit, namely the Battery Management System (BMS), to prevent and control problems that may arise due to this aging problem. Thanks to the BMS, the battery group will be controlled and its damage will be prevented [3, 5].

A detailed literature review of some of the recent studies on Li-ion batteries and management systems is given below:

In a study conducted by Üçgün et al. [6], a system was created by designing a BMS module to control the charging process of Lithium polymer batteries used in UAVs with a charging pad. The basic way to find the State of Charge (SoC) is to determine the voltage of the battery. Battery voltage is used as an indicator to evaluate the health and performance of the battery. Therefore, in the mentioned study, the voltage values of the battery during charging were monitored. The study by Wang et al. [7] focused specifically on accurate SoC prediction for electric vehicles and hybrid electric vehicles. The impedance spectrum detection method was integrated into the battery management system. A new model update strategy for an electrochemical impedance spectroscopy-based SoC algorithm was proposed. In a study conducted by Yıldız [8], alternative architectural structures of batteries and BMS designs used in the aviation field were examined for different applications. It has been observed that the requirement-based parametric design of BMS is important for aviation battery management applications. In a study performed by Tarhan et al. [3], a hybrid BMS that can operate and control twelve serially connected Li-ion batteries and twelve serially connected Lithium iron phosphate batteries with two different features through separate ports was designed for electric aircraft. With this design, it was aimed to measure and control the voltage, temperature, current, SoC, and State of Health (SoH) of the battery. Altium program was used for design and LTC6804 microprocessor was used for cell measurements. The system was simulated by adding temperature, current, voltage, pressure and vibration sensors to the microprocessor. As a result of the tests, they concluded that 0.326 W thermal power was consumed to balance the cells by 90%. In a study conducted by Shibl et al. [9], a machine learning-based BMS was modeled for UAVs. For this purpose, they used deep neural networks and long short-term memory models for SoC prediction. For SoH prediction, they proposed an approach that includes four classes on the Random Forest model classification problem. Dündar et al. [10] were evaluated in terms of flight performance to find the required durability under each flight condition, and the selected battery model was modeled in MATLAB/Simulink. Tian et al [11] focused on the energy management system, which is important to ensure the effective operation of UAVs. The authors proposed the Adaptive Hierarchical Energy Management Strategy to increase energy management efficiency. They used the sequential convex optimization method to solve the battery SoC global reference orbit. The concept of electric aircraft and the development of electricity use in aircraft were examined in a study by Yıldız M. [12], and the basic functions and features of the battery and thermal management system were explained in line with the requirements for battery management. Battery types and parameters were examined and the batteries were analyzed in terms of thermodynamics, heat transfer and electrochemistry. It was presented analysis results for determining battery temperature. In the study by Li et al. [13], a smart digital twin model was proposed for BMS using battery data obtained from real driving cycles. The regression model between BMS variables was developed using a backpropagation artificial neural network. A threshold-based error detection method has been applied to diagnose errors in BMS. A one-year dataset collected from the electric vehicle was used to evaluate the performance of the proposed method. Experimental results have shown that faults in BMS can be effectively diagnosed. Khawaja et al [14] examined various methodologies and approaches to predict the SoC and SoH of Li-ion batteries using artificial intelligence methods. It showed that the condition of Li-ion batteries can be accurately predicted using six machine learning methods and can be combined with a BMS to improve electric vehicle performance. Son et al [15] proposed a system in which Li-ion batteries were the main energy source for UAVs and drones. A passive BMS was used for optimal performance. This BMS was designed considering that it operates in various ambient temperatures depending on the flight characteristics of the drone. The inputs for the design and sizing of the battery used in aircraft were examined in a study conducted by Yıldız and Karakoc [16] and design formulas were developed. It was concluded that with these formulas, it would be possible to make predictions for the weight of the battery and capacity iterations during the aircraft design phase.

In this study, the increasing electrical energy need in the aviation field has been met by Li-ion batteries. A BMS has been proposed in order to eliminate and control the security problems that may occur in the battery group of the UAV. The proposed BMS and UAV load are modeled in MATLAB/Simulink environment. SoC and voltage values are instantly monitored by the BMS with measuring instruments connected to the output of the battery. So, the damaged cell is detected based on the cell temperature of the BMS, the SoC value of the cell and the output voltage values of the cell. According to this data, the damaged cell is intervened and the cell is disabled. In this case, the energy need of the system is provided from other cells. The effect of BMS on the system can be seen from the graphics obtained as a result of the simulation. It has been observed that when the cell's values reach normal, it continues to feed the system by producing energy again.

2. Li-ion Battery

An electrochemical cell uses reduction and oxidation (redox) reactions to convert chemical energy into electrical energy. A separator plate is placed in the middle of the electrolyte to prevent a short circuit between the electrodes. As a result of the redox reaction that takes place during charging, Li-ions, which have the lowest weight, highest potential and energy among metals, are transferred from the cathode electrode to the anode electrode via the electrolyte and form a compound with the negative electrode. Electron transfer between electrodes is necessary to equalize polarization, but electrons cannot be transferred through the electrolyte due to the separator. Instead, they pass through the external circuit that connects the two electrodes. Since the reactions occurring in this process are two-way, the system can be discharged [17-19]. The chemical reactions occurring in Li-ion batteries, whose cathode and anode are composed of lithium cobalt oxide and carbon graphite, respectively, are given in Equations (1-3) [20].

Cathode Reaction;

$$Li_{1-x}CoO_2 + xLi^+ + xe^- \leftrightarrow LiCoO_2 \quad (1)$$

Anode Reaction;

$$CLi_x \leftrightarrow C + xLi^+ + xe^- \quad (2)$$

Overall Reaction;

$$Li_{1-x}CoO_2 + CLi_x \leftrightarrow LiCoO_2 + C \quad (3)$$

Li-ion batteries, which have a lightweight structure, have a cell voltage of approximately 4 V and an energy level of 100-150 Wh/kg [21]. In general, their cycle life is 2000 cycles, power density is 1800 W/m^2, operating temperature is between -20°C and +60°C, and energy efficiency is 80%. In addition, Li-ion batteries are widely preferred in electric vehicles due to their advantages such as having a very low self-discharge rate, being very stable in terms of thermal stability, having a low maintenance rate and no memory effect [5, 22]. The Li-ion batteries are used in electronic devices such as laptops, MP3 players, and mobile phones [21, 22].

Li-ion batteries selected according to the device to be used are determined by taking into account the chemistry of the battery's own cathode and the physical factors that play a role in its production, such as material density in the electrodes, composition and solid particle size, and cell geometry. The reason why these variables are taken into consideration is that they affect the performance, cost and safety features of the battery [23].

In this study, Li-ion batteries are preferred for use in UAVs. Because the positive characteristics mentioned above make the Li-ion battery stand out from other battery types.

3. Battery Management System

Batteries are composed of many cells coming together. The cells in the battery are connected in series to determine the required voltage, and in parallel to determine the current and capacity. BMSs are used to ensure compatibility, control, and operating range of these serial and parallel connections. BMS are electronic systems that prevent the battery from exceeding its operating conditions by controlling the temperature, current, voltage, and load values of the batteries during charging and discharging [20, 24]. One of the important duties of BMS is to protect the battery and prevent it from being damaged. Thus, if the operating conditions are exceeded, the system will be intervened [24].

Li-ion batteries have features such as higher energy and power density and lower self-propagation rate. Thanks to these features, choosing Li-ion batteries in electrical systems will increase the total efficiency of the system. Li-ion batteries can be cost-effective in many cases. These advantages include longer life, higher energy density, faster rechargeability and less maintenance. Their longer life requires them to be replaced less frequently, reducing costs in the long run. Additionally, having greater energy storage capacity per unit can deliver more energy than a battery of the same size or weight, making them more efficient and cost-effective for applications. Li-ion batteries can also generally be charged faster and require less maintenance than other battery types, reducing operating costs. However, determining the most suitable battery technology for a particular application requires consideration of economies of scale, manufacturing technologies, and other factors. Therefore, cost advantage is only one factor and other factors should be considered when making the decision [22]. However, Li-ion batteries are easily affected by the environment and operating conditions, causing safety problems, and a decrease in SoH. Inadequate monitoring and control of preferred Li-ion batteries can cause fires, gas emissions, and explosions when irreversible deterioration occurs. In order to prevent these negative situations from occurring, BMS is needed in Li-ion batteries. BMSs are of great importance for the industrialization and marketing of Li-ion batteries, whose development and use are increasing [24, 25]. BMSs have four types of topologies: centralized, decentralized, distributed type, and modular type. Figure 1 shows the decentralized BMS topology.

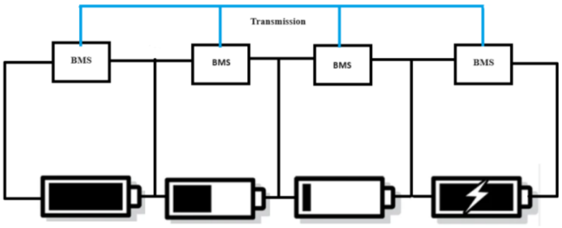

Figure 1. Decentralized BMS.

Decentralized BMS is often used to provide control and management of large amounts of battery packs or battery efficiencies. In the system, many small control units are distributed at different points of the battery pack. Each controller monitors, monitors, and controls several battery cells. These control units usually include a microcontroller and sensors. Sensors constantly monitor battery temperature, voltage, current and other parameters and transmit this data to the microcontroller, providing information about the state of the battery. It enables data sharing by communicating between control units. In this way, a problem observed by a control unit can be shared with other control units and necessary precautions can be taken. Some advantages of decentralized BMS are:

- Each control unit operates independently, ensuring that in the event of a system-wide failure, other control units are not affected.
- As the battery pack expands, new controllers can be easily added and integrated.
- Each control unit can quickly respond to changes in its area.
- Decentralization can increase data security. It does not compromise the entire system, such as an attack on a central control unit.

A decentralized BMS is preferred to control the problems that may occur in the four battery cells in this study according to the determined conditions. Because the control units work independently of each other.

4. UAV Load

UAVs can use various engine types depending on different application areas and performance requirements. Some of the motor types frequently used in the UAVs are Brushless Direct Current Motors (BLDC) motors, gas turbine motors, internal combustion motors, linear motors, ground effect motors.

One of the most common types of motors used in UAVs are BLDC motors. These motors provide high power density, low weight and high efficiency. They also require less maintenance and are long-lasting. BLDC motors are used in a wide range of applications, from multi-rotor drones to UAVs.

Gas turbines can be used to provide powerful thrust in large-sized and long-range UAVs. Gas turbines are engines that can operate at high speeds and usually use jet fuel. These are generally preferred in large UAVs for military or commercial purposes.

Some UAVs use internal combustion engines, especially for scale models or light commercial applications. These engines usually run on gasoline or other fuels and provide long range and payload capacity.

Linear motors can be used as a replacement for traditional rotary motors. Such engines provide linear thrust and can be used in some special applications.

Ground effect engines allow UAVs to take off and land vertically. These motors are often used in multi-propeller drones and allow each propeller to be controlled individually. Depending on the UAVs' design and application requirements, different engine types, and configurations may be preferred [26].

BLDC with permanent magnets is preferred for use in the power drive of UAVs and remotely piloted aircraft systems. BLDC motors transfer electrical power to mechanical power with very little power loss. The power coefficient, which remains in the range of 0.5-0.8 in brushed motors, can be higher than 0.9 in the BLDC motors. This low level of power loss of the BLDC motors allows them to be smaller and lighter [27]. Since BLDC motors are considered a three-phase system, they must be operated with a three-phase power supply. Then, the voltage induced in the stator winding and the voltage applied to the motor must be aligned so that the BLDC motor behaves like a three-phase motor and operates at its best operating point. For this, the position of the rotor must be known at certain angles. Equations (4-6) have been taken into account when creating the armature winding model for the BLDC motor.

$$V_a = Ri_a + L\frac{di_a}{dt} + e_a \tag{4}$$

$$V_b = Ri_b + L\frac{di_b}{dt} + e_b \tag{5}$$

$$V_c = Ri_c + L\frac{di_c}{dt} + e_c \tag{6}$$

L is the armature self inductance (H), R is the armature resistance (Ω), V_a, V_b, V_c is the terminal phase voltage (V), i_a, i_b, i_c is the motor input current (A), and e_a, e_b, e_c is the voltage induced in the stator windings (V). The induced voltage in the stator windings is a function of rotor position as it is induced due to rotor motion. The voltage induced in the stator winding of each phase has a phase difference of 120°. The voltage induced in the stator windings can be calculated with Equations (7-9).

$$e_a = K_w f(\theta_e) w \tag{7}$$

$$e_b = K_w f\left(\theta_e - {}^{2\pi}/_{3}\right) w \tag{8}$$

$$e_c = K_w f\left(\theta_e + {}^{2\pi}/_{3}\right) w \tag{9}$$

K_w is the constant of the voltage induced in the stator windings of a phase (V/rad.s^{-1}), θ_e is the electrical rotor angle, w is the rotor speed (rad. s^{-1}). The electrical rotor angle is obtained by multiplying the dipole number p by the mechanical rotor angle. It can be expressed by Equation (10).

$$\theta_e = \frac{p}{2}\theta_m \tag{10}$$

θ_m represents the mechanical rotor angle (rad). T_e is motor torque (N.m) and it can be calculated with the Equation (11).

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{w} \tag{11}$$

The torque of the mechanical part is as in Equation (12).

$$T_e - T_l = J\frac{dw}{dt} + Bw \tag{12}$$

Here; J represents the moment inertia of the engine (in Joule seconds), that is, the resistance of the engine's rotational motion to the speed change, and B represents the viscous friction coefficient (in Newton meters seconds), that is, the friction loss depending on the speed of the engine. This is the friction force that increases with increasing engine speed. This term describes the mechanical resistance of the motor [28].

5. Results and Discussions

The BMS of the UAV proposed in this study is modeled in the MATLAB/Simulink environment. In the system shown in Figure 2, there is a battery group containing four serial Li-ion battery cells. In order to manage the problems that may occur in these cells, a decentralized BMS block that can work independently of each other has been added. A capacitor block is used, which contains active or passive capacitors that disable the damaged battery cell according to the information they received from the BMS block. An inverter is used to convert the Direct Current (DC) voltage obtained from the battery output into Alternative Current (AC) voltage. The BLDC motor block, which represents the UAV load, is connected to the inverter output.

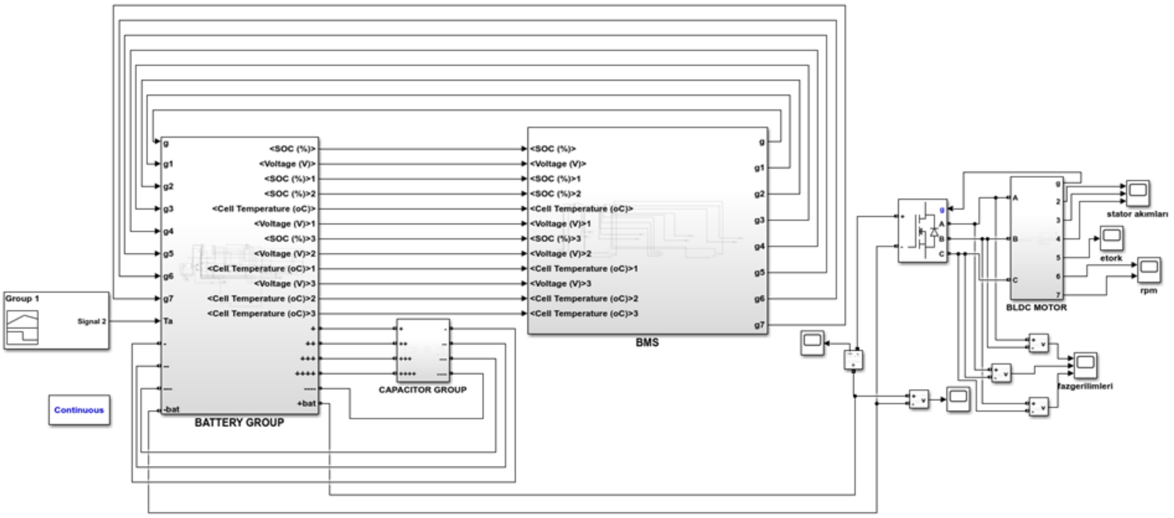

Figure 2. UAV system with BMS.

The battery group subsystem, which includes batteries and switches, is created in MATLAB/Simulink. This subsystem shown in Figure 3 includes four batteries. An ideal switch connected to the batteries is used to make each battery active or passive according to the specified conditions. Depending on whether these switches are on/off, the battery or the capacitor connected to the relevant battery is activated. The status of the switches in transmission is determined by four control mechanisms in the BMS subsystem. The outputs of the decision mechanisms here are connected to the inputs where the transmission conditions of the switches in the battery group subsystem are determined. Depending on whether the switches are in transmission, the battery or capacity will be active. The BMS subsystem used for control purposes can be seen in Figure 4.

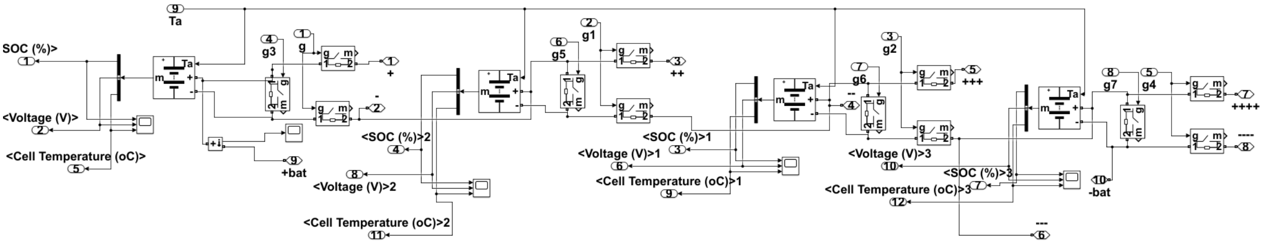

Figure 3. Battery group subsystem.

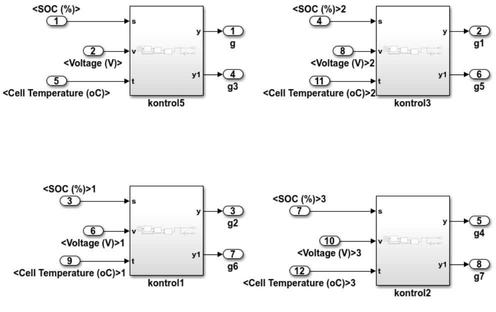

Figure 4. BMS subsystem.

In this study, the Battery Stack cell in MATLAB/Simulink is chosen to model the batteries used in the proposed system. Parameters of this battery; nominal voltage is 25 V, rated capacity is 5.4 Ah, initial state-of-charge is 50 %, 40 %, 75 %, 100 %, maximum capacity is 5.4 Ah, cut-off voltage is 18.75 V, fully charged voltage is 29.0997 V, internal resistance is 0.046296 ohm, capacity at nominal voltage is 4.8835 Ah.

If the batteries fail under specified conditions, the capacities will be activated. Serial RC branch cell in MATLAB/Simulink is used to represent capacities. The parameters determined for the capacities are as follows. Capacitor initial voltage is 25 V, resistance is $1e^{-9}$ ohm, capacitance is $1e^{-6}$ F.

Since temperature is one of the factors affecting the SoH of batteries during operation, the temperature of the battery is determined as the input value in this study. In order to measure the battery's response to temperature, an external ambient temperature change is created as shown in Figure 5. The damaged battery cell will be disabled by observing the change in battery temperature within this determined temperature range. Instead of the battery cell, the relevant capacitor from the capacitor group will be activated. The nominal operating temperature of the battery is determined as below 40^0C. If the cell temperature rises above 40^0C, BMS will activate and disable the cell.

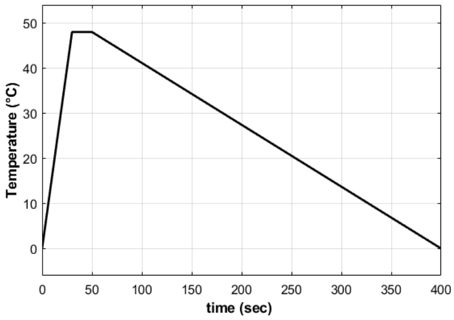

Figure 5. External ambient temperature change.

Figure 6 shows the SoC change graph of the three undamaged cells of the battery consisting of four cells. In undamaged battery cells, it is not possible for the temperature to exceed 40^0C or for the output voltage to drop below 24 V. However, if the damaged cell becomes disabled due to the SoC status, the undamaged cells feed this cell. For this reason, the shutdown of undamaged cells is observed only when the SoC change falls below 20%. In other words, at the end of the 350th second, the undamaged cells no longer feed the system. In this case, these cells are disabled by the BMS and the relevant capacities are activated.

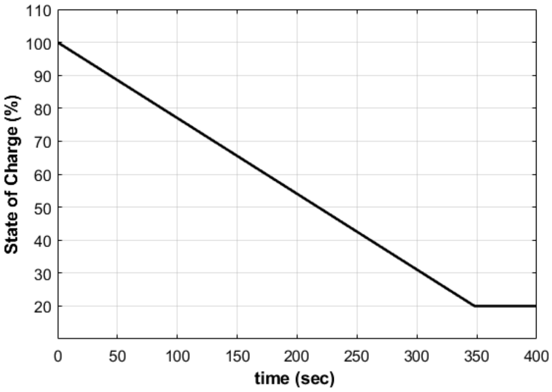

Figure 6. SoC change of undamaged battery cell.

The SoC change of the damaged cell is given in Figure 7. In the initial state, while the cell is active, its SoC decreases over time. SoC remained constant between approximately 35-60 seconds. Because the damaged cell has become disabled due to the increase in temperature. Afterwards, the cell comes into play again, feeding the system and its SoC decreases. However, when the SoC value of the battery cell is below the 20% value determined in the BMS, the BMS charges the cell by activating the relevant capacitor. It is seen that the cell comes into play again after a certain period of time and feeds the load.

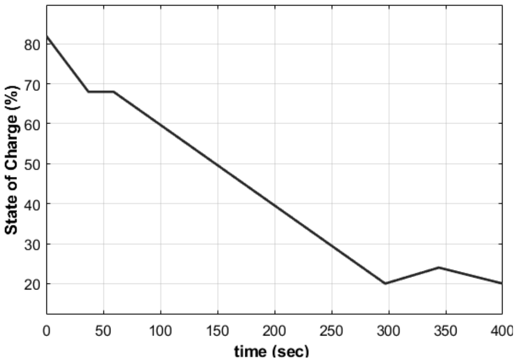

Figure 7. SoC change of damaged battery cell.

Figure 8 shows the output voltage of the battery. If the output voltage of any battery cell determined in the BMS block drops below 24 V, the capacitor group is activated to prevent the output voltage of the battery from decreasing. This will ensure that the voltage at the output of the four-cell battery never drops below 96 V. As can be seen from the figure, although the SoC of the battery cells dropped below 20%, the output voltage never dropped below 96 V. Figure 9 shows the output current change of the battery.

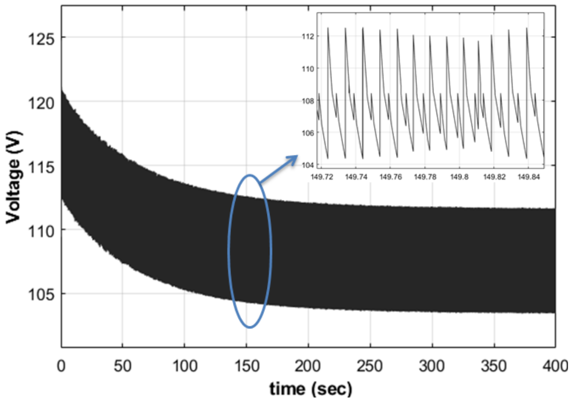

Figure 8. Output voltage of the battery.

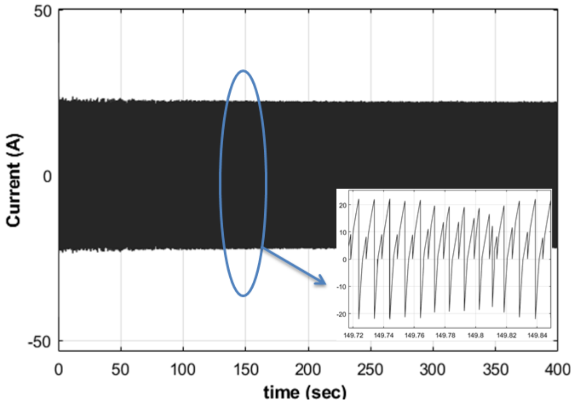

Figure 9. Current change of the battery.

Figure 10 shows the change in voltages between the phases of the three-phase inverter connected to the output of the batteries. Figure 11 indicates the change of stator currents of the BLDC Motor.

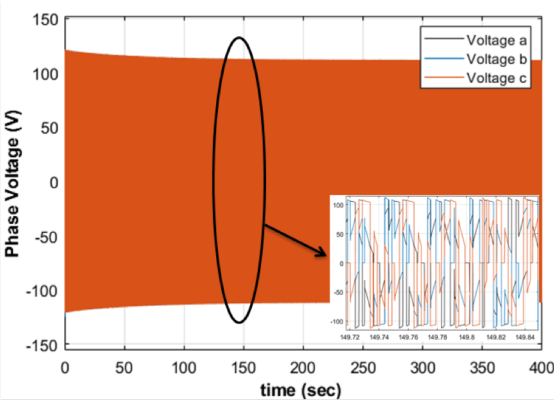

Figure 10. Inverter phase voltages.

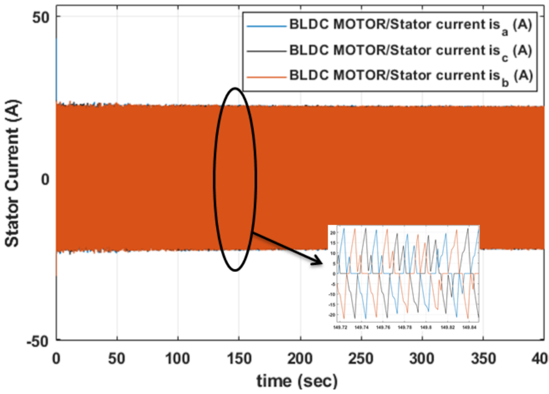

Figure 11. BLDC motor stator currents.

The change of electromagnetic torque depending on the UAV load is given in Figure 12. The rotor speed change graph of the BLDC motor is given in both rpm and rad/s in Figure 13. The rotor speed is desired to be kept at 500 rpm. It can be seen from the figure that it reaches 500 rpm in a short time as a result of the batteries being activated.

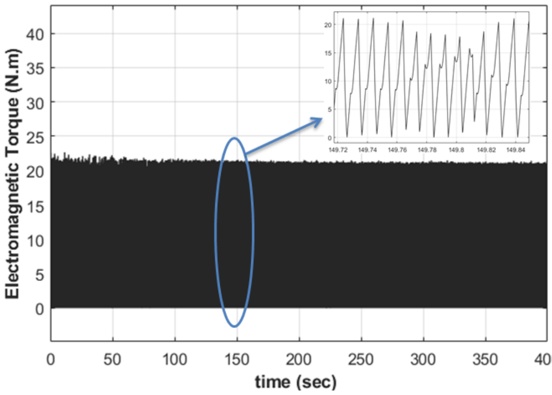

Figure 12. Electromagnetic torque change.

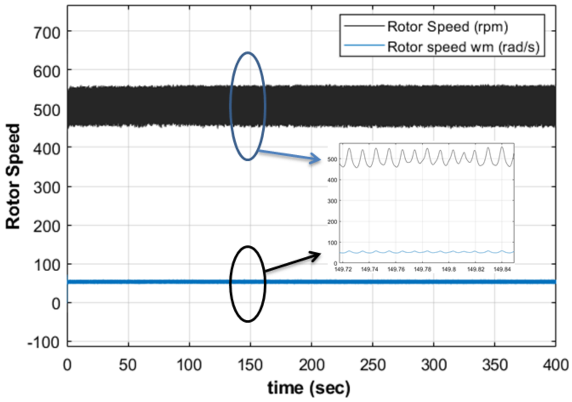

Figure 13. Rotor speed change.

According to these results, it is observed that in certain fault conditions, the BMS comes into play and meets the energy needs by ensuring the smooth operation of the system.

6. Conclusions

Li-ion batteries are used to meet the electrical energy needs of UAVs. During charging/discharging of Li-ion batteries, chemical reactions occur within the cells. While these reactions are taking place, optimum operating conditions must be provided by controlling the current, voltage and temperature values that affect the reaction speed. If the optimum operating conditions are exceeded, problems will occur because the reactions cannot occur as they should. Thus, it will prevent the battery group from working. BMSs are used to control problems that may occur in the battery. BMSs, which ensure the safe operation of batteries, receive high charge/discharge current, high/low output voltage, high/low temperature values from the battery through sensors. In case of possible problems, these problems will be prevented by taking the battery under control. In addition, BMSs provide us with information about battery life by estimating the current state of the battery with the information obtained from sensors.

In this study, a BMS system is modeled in order to disable the battery in case of any problem in a Li-ion battery containing four cells and use it more efficiently. Thanks to the capacitor block in the BMS module, the energy needs of the UAV are met even if the damaged cell is disabled. Thus, wide range of changes in the output current and voltage of the UAV system are prevented. In this way, the health of the battery cells is ensured. Thus, the efficiency of the system is increased by allowing it to be used for a longer period of time.

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