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Research Article

Design of renewable energy based charging station for rotary wing UAVs

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Abstract: Unmanned Aerial Vehicles (UAVs) have emerged as remotely controlled aerial systems whose range of applications has expanded significantly in parallel with technological advancements. These vehicles, which do not carry human operators onboard, are widely utilized across various sectors due to their superior flight capabilities, low operational costs, and ease of development. However, their operational efficiency is often limited by short flight durations resulting from restricted battery capacities. To overcome this limitation, a renewable energy-supported charging station has been developed to enable rotary-wing UAVs to autonomously recharge during mission execution or standard flight operations. The proposed system integrates photovoltaic (PV) panels powered by solar energy as the primary energy source, alongside a battery storage unit. The conceptual design of the charging station is realized, simulation-based analyses are conducted, and hardware-testing procedures are implemented. The simulation studies include energy flow modeling between the PV panels, battery storage system, and the UAV battery. The autonomous charging of the battery and instantaneous charging status monitoring are performed via the charging pad in the developed system and the functionality is accomplished. According to the tests, the UAV has been charged in a balanced manner via the charging pad, regardless of the landing direction. The proposed system allows the autonomous charging of rotary wing UAV batteries without any human intervention and mission flight.

Keywords: *Charging station, Photovoltaic panel, Renewable energy, Rotary wing, UAV*

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1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have gained significant popularity due to rapid technological advancements and inherent advantages such as ease of procurement of hardware and software components, relatively low costs, and the capability for remote operation [1]. Initially introduced into the literature for military surveillance and combat missions, UAVs have evolved into widely utilized platforms across scientific research, commercial applications, and even personal use [2]. UAVs that are often called as drones are aerial vehicles that can be controlled remotely from the ground station without a pilot on it, or autonomously flying according to preprogrammed flight schedules [3]. In today's studies, UAV models are created in different ways in terms of parameters such as frame size, wing structure, the number of engines in order to perform certain tasks [4]. UAVs provide advantages such as high maneuverability, dependence on limited human capabilities and autonomous flying with software support compared with fully human-controlled helicopters and aircraft. UAVs have advantages over other aircraft as well as have disadvantages such as low payload and low flight time.

Energy consumption is a major challenge that significantly restricts the operational potential of UAVs, which primarily rely on batteries as their main source of electrical power. [5]. Studies indicate that current battery technologies typically support flight durations ranging between 10 to 30 minutes, as they are responsible for powering both the UAV’s propulsion system and onboard equipment [6,7]. This limitation significantly reduces the flight time and operational range of UAVs, necessitating frequent battery recharging to extend their flight duration. To address this challenge, various battery charging methods—both wired and wireless—have been developed that allow for autonomous energy replenishment without human intervention [7]. UAV charging stations are used for these operations.

In the present work, the design and implementation of a renewable energy-supported mobile charging station platform are addressed, aiming to autonomously recharge rotary-wing UAVs during mission or routine flights when their battery levels decrease, thereby extending their flight duration. Within the developed system, a UAV that lands on the charging station will initiate the charging process autonomously without requiring any human intervention. The charging process begins through the contact between the charging connectors located on the UAV’s landing gear and the conductive surface of the charging pad installed at the station. A battery management module integrated into the charging circuit ensures a balanced and safe charging process, thereby preventing potential issues such as overheating, structural degradation, or overcharging. This mechanism also contributes to the prolonged service life of the UAV battery by maintaining optimal charging conditions. The developed system enables the charging station’s energy requirement to be met without the need for a grid connection thanks to the renewable energy-supported autonomous charging technique; thereby, it enables UAVs to be charged autonomously, especially in scenarios where human intervention is limited or undesirable, such as military surveillance missions. In addition, a non-directional design charging track has been developed that allows the UAV to start the charging process on the charging station regardless of the landing direction. With the battery management module integrated into the system, the UAV battery is charged in a balanced and safe manner, and the charging process can be monitored instantly. The combination of these components provides technical contributions to the existing literature in terms of both energy sustainability and operational efficiency.

In Section 2, literature review section is presented. In Section 3, the method section including the simulation and design studies considered within the scope of the study is presented. In Section 4, the application tests and results performed within the scope of the study are presented. In Section 5, the scenario study related to the charging process to be carried out in the real environment and the charging station design are discussed. In Section 6, the results and recommendations section is discussed.

2. LITERATUR REVIEW

There are different charging station approaches in order to increase the flight time of UAVs [8]. There are two main approaches in the literature regarding the use of charging stations for charging or replacement the batteries of UAVs that are flying on a mission. In the first approach, the UAV is autonomously directed to a predetermined charging station location and energy is transferred via a charging pad by one of the methods such as direct contact [9,10,11] or wireless induction [12,13,14]. In addition to these studies, experimental studies have been carried out on remote charging methods using laser beams [15,16,17]. Thanks to the developed charging pads, it is possible for the UAV to start the charging process without the need for precise landing maneuvers. However, the most important limitation of this approach is that the charging process takes a relatively long time, which can shorten the mission duration and reduce operational efficiency. In the second approach, the battery of the UAV is automatically changed after it lands on the charging station [18,19,20]. This method completely eliminates the waiting time for charging, increases mission continuity and minimizes operational time losses. However, in order to implement this battery replacement mechanism, additional mechanical components must be present in the charging stations. This increases the initial installation cost of the system and significantly increases its structural complexity.

In Ref. [21], an innovative charging station system was developed by studying conceptual charging station designs. A docking station was built in accordance with the developed design and various tests were carried out to evaluate whether this system met the performance criteria. According to the tests, it was determined that the proposed system could successfully compensate for the deviations in the landing position of the UAV and safely connect the vehicle to the charger. It was observed that the selected charging unit was capable of safely charging the UAV battery. In addition, the developed user interface was able to provide instant and effective feedback to the user about the status of the station. In Ref. [22] a mobile hub concept is proposed, considering the requirements for precise landing under wind-induced drifts, environmental obstacles and unreliable global positioning conditions. The developed system enables standard commercial (unmodified) UAVs to perform continuous mission cycles. In Ref. [23], a shelter type autonomous wireless charging technology solution for rotary wing UAV cluster is proposed. Within the scope of the study, the scenarios where the system will be applied are analyzed and the general design, mobility planning, structural layout and basic component selection of the autonomous wireless charging shelter are discussed in detail. The shelter motion control and energy management system are designed and developed using the LabVIEW programming language. Thus, the design of the autonomous wireless charging shelter for the rotary wing UAV group is completed and performance verification tests are performed. In Ref. [24], a new foldable coil and charging station design is proposed for wireless charging of UAVs. The receiver and transmitter coils placed on the drone legs and the charging station provide inductive Power Transfer (IPT). The receiver coils are placed on both legs in a lightweight and balanced manner in order not to adversely affect the balance and weight of the UAV and are designed in the form of a vertical rectangular planar spiral. The transmitter coil consists of three rectangular planar spiral coils consisting of two movable side windings and a fixed middle winding. The foldable windings of the transmitter ensure the alignment of the UAV during landing and increase the magnetic coupling. The proposed foldable wireless charging system is designed for 138.1 kHz frequency and 100 W output power. The alignment tolerance of the design in the vertical axis is investigated and the magnetic flux density distribution is analyzed. In the experimental results, 97.66% efficiency is achieved in the case of full alignment. In addition, over 85.48% efficiency is achieved even in the case of alignment deviation up to 10 cm in the vertical. In addition to the fixed charging stations, there are also charging station studies supported by mobile platforms [25]. In these studies, the charging process of the UAV, which lands on a ground vehicle, is performed via the charging track via the mobile vehicle, and it is observed that the UAV continues its flight as a result of the charging process [26,27].

3. UAV CHARGE STATION DESIGN AND METHODOLOGY

This section presents a detailed explanation of the design processes and experimental studies related to the renewable energy-supported charging station developed for rotary-wing UAVs. Prior to the implementation of test procedures for the charging station, the intended hardware components to be integrated into the system were evaluated in terms of their functions and operational methods. Within the scope of the study, a prototype charging station was designed by integrating two different power sources (PV panels and battery packs). To ensure efficient system performance, Maximum Power Point Tracking (MPPT) algorithms were employed. The design process of the charging station was addressed in five main stages.

In the first stage, the general working structure of the charging station was revealed. In this context, the methods by which the power to be transmitted from energy sources to the charging track would be provided were determined. In the hybrid energy system, where PV panels and accumulator batteries are used together, the source activation is ascertained under different conditions and the energy flow is determined under these conditions. In the second stage, the simulations and results of the process of meeting the energy needs of the charging station from PV panels were discussed. As a result of the simulations, the current and voltage values to be used for charging LiPo batteries and accumulator batteries were obtained. In the third stage, a charging pad with an orientation-independent structure was designed to allow the UAV to initiate the charging process regardless of its landing position. This design enabled energy transfer to be performed autonomously, without dependence on the UAV's landing direction. In the fourth stage, the hardware system required to perform the charging process in a completely autonomous manner was designed. After the UAV lands on the charging pad, the developed mechanism initiates the charging process automatically, without requiring any human intervention, and ensures energy transfer from the station to the UAV’s battery. In the fifth and final stage, a monitoring system was developed to allow users to track both the cell-level and total voltage levels of the battery in real time during the charging process. Through a custom-designed user interface, battery data can be monitored live throughout the entire charging operation. Simulation studies and hardware tests conducted throughout this process were evaluated in terms of system stability and operational effectiveness, yielding positive results.

3.1. Design of UAV Charging Station

The block diagram of the renewable energy-supported charging station system developed within the scope of this study is presented in Fig. 1. During the design process, the charging station was conceptually divided into two main stages: Energy generation and energy utilization. In the first stage, electrical energy is generated from solar radiation through PV panels to meet the power requirements of the system. To maximize the efficiency of the harvested solar energy, a MPPT algorithm is used. This ensures optimal energy extraction from the PV panels under varying solar irradiance conditions. In the second stage, the system determines the appropriate energy destination and manages the charging/discharging processes. For this purpose, an intelligent charging control algorithm has been developed. According to the algorithm, if a UAV is present on the charging pad awaiting energy replenishment, the harvested energy is directed to the pad. Otherwise, the energy is stored in the battery storage units.

Before the energy obtained from the PV panels is delivered to either the batteries or the UAV, it is regulated using a DC/DC (direct current) buck converter to achieve a stable 12V output, which is required for compatibility with the charging pad and battery units. This voltage regulation ensures that both the battery storage units and the UAV charging pad receive energy at a level suitable for safe and efficient operation. During the simulation phase, a 100 W (17 V, 6 A) PV panel was simulated as part of the station. The energy harvested from this panel was regulated using a DC/DC buck converter to obtain a 12 V output compatible with both the battery pack and the charging pad. This configuration ensures that the system’s energy requirements are met reliably, allowing for autonomous operation without the need for human intervention, while supporting sustainability and system stability.

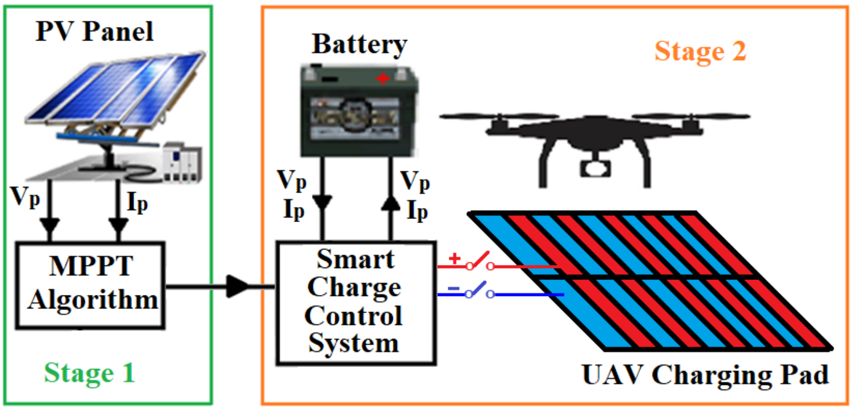


Figure 1. UAV charging station block diagram.

3.2. Simulation of Charging Station Energy System

In order to power the charging pad in the charging station, two different power sources are used: PV panels and battery packs. The electrical energy generated by the PV panels is directly transmitted to the charging pad under suitable conditions. At the same time, excess energy is stored in the battery packs. When sunlight is sufficient, energy is directly provided by the PV panels, while when there is no sunlight, the system meets the energy it needs from the power stored in the battery packs. This structure enables the charging station to operate continuously and uninterruptedly, regardless of environmental conditions. PV panels have a non-linear characteristic and are directly affected by atmospheric conditions (e.g., radiation intensity, temperature). Therefore, operating the panels directly with a load or battery can produce inefficient and unstable results [28]. MPPT methods come into play at this point. The MPPT technique is not physical hardware or mechanical structure, but an electronic device monitoring the voltage and current values of the PV system and controlling the output voltage with an algorithm structure. The MPPT technique is based on the principle of finding voltage and current values to obtain maximum power output from the PV panel under given solar radiation [29].

In the present work, the Perturb and Observe (P&O) algorithm, a widely used MPPT algorithm, was preferred in order to obtain maximum energy from PV panels. The P&O algorithm calculates the changes in power by periodically sampling the voltage and current values of the PV panel and aims to reach the maximum power point by adjusting the operating point of the system according to these changes. Before proceeding with the hardware tests, the general operation of the system was modeled and evaluated in a simulation environment. As a result of the simulations performed, the current and voltage values required for the energy obtained from the PV panel to charge the UAV battery in a safe and balanced manner were determined. In this context, a reference current of 3 A and a reference voltage of 12 V were defined for the charging process. These values were obtained in line with the simulation results of the P&O algorithm and represent the stable operating range of the system. These current and voltage values calculated by the algorithm are directly transferred to the charging pad during the charging process. Therefore, the stable production of the obtained reference values and their transmission to the charging unit are of great importance in terms of the reliability of the system and energy management. Simulation results show that the system successfully meets these requirements and provides a stable charging process. Fig. 2 shows the current (I_{lp}) and voltage (V_{lp}) values obtained from the charge simulation. In the figure, the results obtained appear to be stable throughout the simulation. The parameter’s used simulations have given in Table 1.

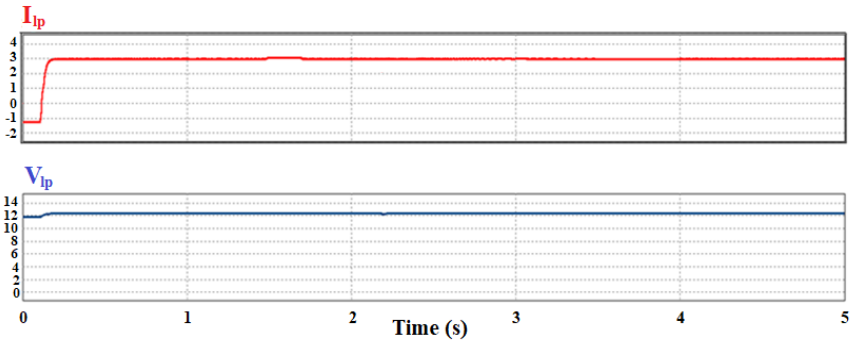


Figure 2. Simulation results of P&O algorithm.

Table 1. P&O simulation parameters

Parameters	Values
PV Panel Cell Number	36
PV Panel Temperature	25 ^{o}C
Irradiance	1000 W/m^2
Maximum Voltage	17 V
Short Circuit Current	3.8 A
Reference Voltage	12 V
Reference Current	3 a

3.3. Design of Charging Pad

The main purpose of the design studies performed regarding the charging runway is to ensure that the charging process is realized correctly and safely, regardless of the direction or position, where the UAV lands on the runway. In line with this goal, different prototype structures in the literature were examined and the final design model was developed in light of the information obtained. A visual of the designed charging runway is presented in Fig. 3. There are positive (+) and negative (−) power transmission lines placed on the runway, respectively. Insulated areas providing electrical isolation are positioned between these lines. Thanks to this structure, safe energy transfer is ensured by preventing short circuits on the surface that the UAV randomly touches during landing. One of the important features of the designed charging runway is that it has a modular and scalable structure. The runway dimensions are designed to be adaptable according to the physical dimensions of the UAV to be charged. This allows UAVs of different sizes to be charged via the same system and increases the flexibility of the system. During the application and testing phases, a 60 cm x 60 cm charging track prototype was used and successful results were obtained.

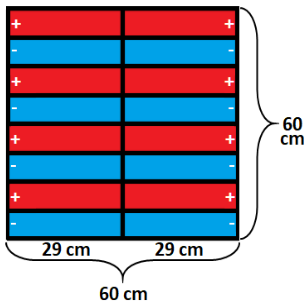


Figure 3. Design of charging pad.

3.4. Design of Battery Charging System

The block diagram of the charging system developed for the charging of the UAV battery is presented in Fig. 4. In this system, the DC power required for the charging process is supplied PV panels or the battery pack, depending on the decision made by the charge control unit, and is transmitted to a specially designed charging pad. This architecture enables flexible selection of the energy source based on environmental conditions, ensuring uninterrupted operation of the system. The charging system is designed to provide seamless energy transfer regardless of the UAVs landing orientation on the charging pad. This eliminates potential alignment issues during landing and minimizes the risk of short circuits. Once the UAV makes contact with the charging pad, the onboard Lithium-Polymer (LiPo) battery automatically begins charging. To ensure a safe and balanced charging process, the system incorporates a bridge diode network and a Battery Management System (BMS) module. These components regulate the voltage and current during charging, aiming to extend battery lifespan and enhance operational safety.

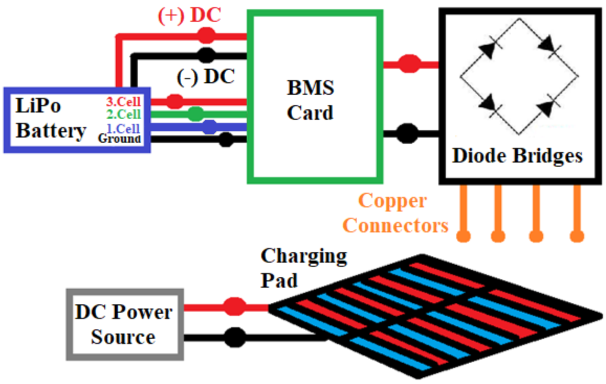


Figure 4. Block diagram of charging system.

The operating structure of the charging system is based on initiating energy transfer once the UAV lands on the charging pad and the four copper connectors, integrated into the UAV's landing gear, make contact with the conductive surface of the pad. These copper connectors are electrically connected to a bridge diode group located on the UAV. The energy supplied from the charging pad is first transmitted through the copper connectors to the bridge diodes, and subsequently to other components of the system. The electrical connection scheme of the bridge diodes and copper connectors is illustrated in Fig. 5. Each diode contains four pins: Two Alternating Current (AC) input terminals, one positive (+), and one negative (-) terminal. The positive and negative output lines of the two diodes are connected in parallel. The four AC input terminals (a, b, c, d) are connected to the corresponding four connectors located on the UAV's landing gear. Due to the non-polarized nature of AC input terminals, this connection configuration minimizes the risk of short circuits, even if the UAV lands on the pad with any orientation. This design enables omnidirectional operation of the system, thereby enhancing operational safety and flexibility.

Through this connection structure, the energy supplied via the charging pad is delivered to the Battery Management System (BMS) board along with the voltage and current parameters required for the balanced charging of the LiPo battery. BMS boards monitor and manage the condition of the individual cells within the battery throughout the charging and discharging processes, thereby optimizing both battery safety and overall performance. By equalizing voltage differences between cells, the BMS provides early detection of electrical and thermal abnormalities. This contributes to extending the battery's lifespan while also enhancing the overall efficiency and reliability of the system [30]. The block diagram presented in Fig. 4 illustrates the connection topology between a three-cell LiPo battery and the BMS board. These connections ensure controlled energy transfer, thereby enabling a precise and safe charging process

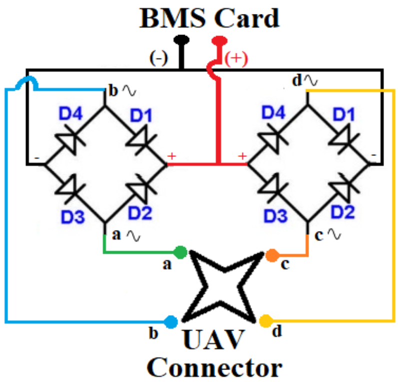


Figure 5. Connection diagram of diode bridges

3.5. Design of Battery Charging Monitoring System

The block diagram of the system developed to monitor the UAV battery status in real-time during the charging process is presented in Fig. 6. In this system, the cell voltage values of the LiPo battery are obtained through the BMS board during the charging operation. To ensure accurate and safe voltage measurement, voltage divider circuits have been implemented to resolve the mismatch between the analog input range of the Arduino Uno microcontroller (maximum 5V) and the cell voltages of the battery (up to 4.2V, 8.4V, and 12.6V). These circuits scale down the battery cell voltages to levels compatible with the Arduino's input limits, adjusting the maximum input to 4.2V. The raw analog data received from the Arduino is processed through custom-developed software, which accurately calculates the real-time voltage values of each battery cell. The processed data is then transmitted to the user interface via serial communication between the Arduino and the interface, enabling real-time monitoring of the battery's status.

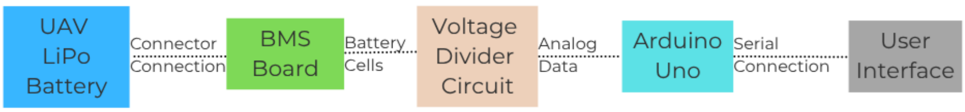


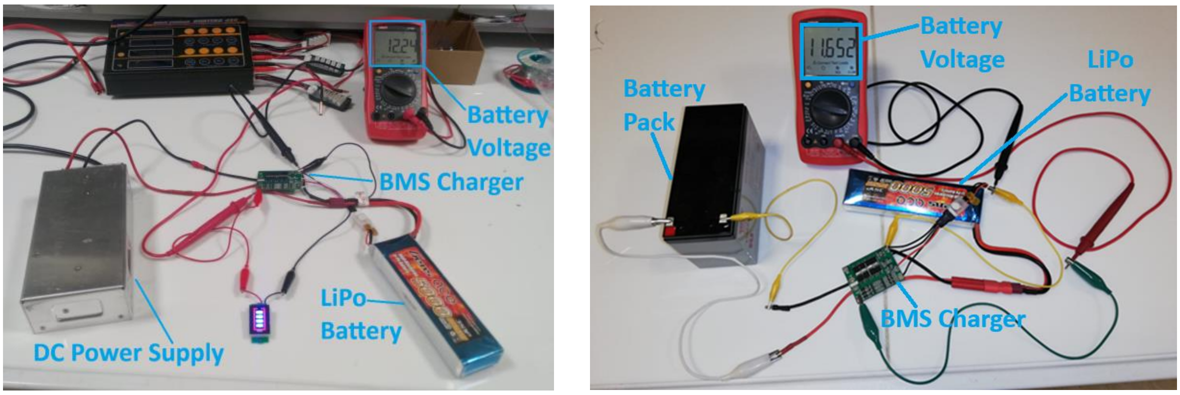
Figure 6. Charging monitoring system block diagram.

4. TEST STUDIES

After the completion of simulation and design studies, various hardware tests were conducted to evaluate the performance and functionality of the hardware components to be used within the charging station during the battery charging process. The testing process included several stages such as: Charging the LiPo battery via the BMS module using both a DC power supply and a battery pack, implementing UAV landing scenarios on the charging pad and verifying energy transfer during these operations, delivering energy from the DC source to the battery through the charging pad, real-time monitoring of cell voltage levels during LiPo battery charging, and charging the UAV battery using a PV panel simulator. Each test stage was initiated only after the successful completion of the preceding step, ensuring a systematic and controlled progression throughout the testing process. This approach enabled a comprehensive evaluation of both the reliability of the hardware components and the overall system performance.

4.1. LiPo Battery Charging using the BMS Module

LiPo batteries are charged in a balanced manner through BMS boards. This approach prevents potential voltage imbalances among the battery cells and contributes to extending the overall battery lifespan. In the initial phase of the study, charging tests were conducted using the BMS board to evaluate the charging process of the LiPo battery. During the testing process, the LiPo battery was charged using both a DC power supply and an external battery pack. Fig. 7(a) presents an image of the charging process performed with the DC power supply. At this stage, the instantaneous voltage of the LiPo battery was measured as 12.24 V. Fig. 7(b) presents an image of the charging process performed with the battery pack. At this stage, the instantaneous voltage of the LiPo battery was measured as 11.652 V. These tests demonstrated that the LiPo battery could be safely charged through different energy sources. The balanced charging method aims to ensure that each individual battery cell reaches equal voltage levels, thereby enhancing battery safety and preventing damage to the cells.



(a) DC power source *(b) Battery pack source*

Figure 7. LiPo battery charging with the BMS module

4.2. LiPo Battery Charging with Charge Pad

Test studies for the charging pad, designed to be used for charging the UAV battery within the charging station, are presented in Fig. 8. During the tests, energy was supplied to the charging pad via a DC power source. In the initial phase, an LED was used to control the correctness of the energy flow through the charging pad. It was observed whether the LED lit up when the connectors on the UAV's landing gear made contact with the aluminum foil strips arranged on the charging pad. The illumination of the LED indicated successful energy transfer, whereas no illumination signified a failure in energy transmission. To validate the accuracy of energy transfer, various landing tests were conducted. During these tests, the contact status between the "+" and "–" lines on the charging pad and the copper connectors (A, B, C, and D) was examined, and the success of energy transfer was assessed. The data obtained from the landing tests are summarized in Table 2. Analysis of these results revealed that the developed charging pad achieved a successful charging rate of 87.5%.

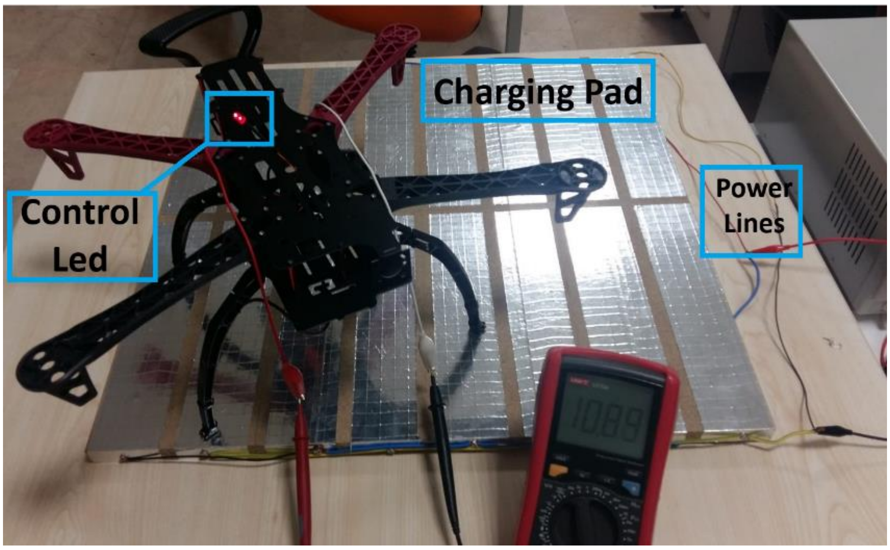


Figure 8. Charging pad test

Table 2. Detection of charge status on the charging pad ("-" => Negative line, "+" = Positive line)

TEST	A	B	C	D	CHARGE STATUS
1	-	-	-	-	×
2	-	-	-	+	√
3	-	-	+	-	√
4	-	-	+	+	√
5	-	+	-	-	√
6	-	+	-	+	√
7	-	+	+	-	√
8	-	+	+	+	√
9	+	-	-	-	√
10	+	-	-	+	√
11	+	-	+	-	√
12	+	-	+	+	√
13	+	+	-	-	√
14	+	+	-	+	√
15	+	+	+	-	√
16	+	+	+	+	×

Based on the results of the landing tests conducted on the charging pad, several improvements were made to the system in order to increase the success rate of the charging operations. Within this scope, the aim was to eliminate the unsuccessful charging scenarios presented in Table 2 by modifying the structural design of the charging pad through the integration of additional hardware components. With the implemented structural enhancement, the system is now capable of detecting whether energy transfer has occurred after the UAV lands on the charging pad. Depending on this detection, the power lines of the charging pad are automatically reconfigured, thereby preventing energy transmission failures caused by connection mismatches.

The updated charging pad design resulting from these structural modifications is presented in Fig. 9. In this process, two relays were connected to the power lines of the charging pad (+, -). The relays connected to the charging pad were used to switch the power lines during the charging process. In the process of changing the power lines, the lines on the left side were left fixed and the power lines on the right side were changed. The structural change in the charging pad was restored after the charging process was completed. In the charging pad connections, the left side was directly fed from the energy source, while the right side was fed from the energy source and relays.

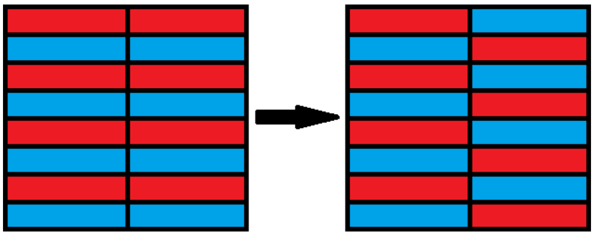


Figure 9. Structural Change of Charging Pad

In the test studies conducted on the charging pad, initially, the necessary installations are made for the charging process of the battery of the UAV that landed on the charging pad and the relays are closed. After the hardware installations, the charging process is started and the value of the LiPo battery cells is measured with the BMS card (V_{LiPo}). In the next step, after waiting for a minute, the voltage measurement of the cells (V_{LiPo+1}) is made again. The two measurements (V_{LiPo}, V_{LiPo+1}) are compared. If the second measurement is larger, it is determined that the charging process has started and no changes are made to the relays. This situation continues until the end of the charging process. If the second measurement is smaller, it is determined that the charging process has not been done and the relays are opened and the power lines on the right side of the charging track are changed. After the charging process is completed, the relays are closed and the power lines are returned to their previous states. As a result of this development, all charging operations performed via the pad were completed with a 100% success rate, significantly improving the overall reliability of the system.

4.3. LiPo Battery Charging over Charge Pad

Following the preliminary tests performed on charging the LiPo battery via the BMS card and ensuring energy transfer via the charging pad, an integrated test phase was initiated where both structures were brought together. In this phase, the aim was to directly charge the LiPo battery via the charging pad. During the test process, the prototype UAV frame was manually placed on the charging pad at different positions and it was observed whether the battery was charged instantly. The application regarding the successful charging process is presented in Figure 10. Aluminum foil conductive surfaces were used to create the positive ("+") and negative ("-") power lines on the charging pad. The charging pad was fed with a DC power source and the relevant connections were made via cables. The value (i.e., 12.531 V) seen on the voltmeter in the figure shows the instantaneous voltage level of the LiPo battery. During the charging process, the battery's cellular voltage information is obtained via the BMS control card and the system is continuously monitored to ensure a safe and balanced charging process.

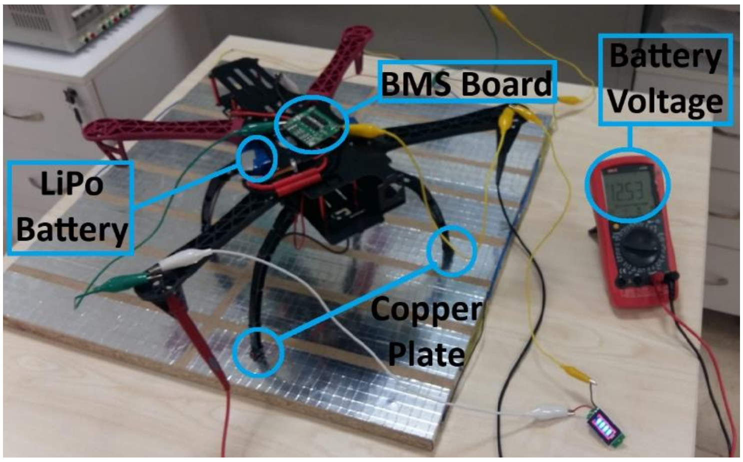


Figure 10. LiPo battery charging with charge pad.

4.4. Monitoring of LiPo Battery Voltage Values

Test studies were performed for an Arduino-based monitoring system in order to monitor the charging process of the LiPo battery and to follow the instantaneous voltage values. Within the scope of this test process, while the charging process was performed via the charging pad, the real-time data obtained from the LiPo battery was transferred to the user interface via the Arduino microcontroller. This data obtained during the charging process was analyzed graphically in order to visualize the cellular voltage behaviors of the battery. The visual of the Arduino-based monitoring system and the application of the charging process is presented in Fig. 11. Energy flow is provided via the power lines on the charging pad and the connectors connected to the UAV landing gear. The energy obtained is used to charge the LiPo battery connected to the BMS board. During the charging process via the BMS board, the voltage parameters of the battery cells are sent to the Arduino board in parallel via the voltage divider circuit.

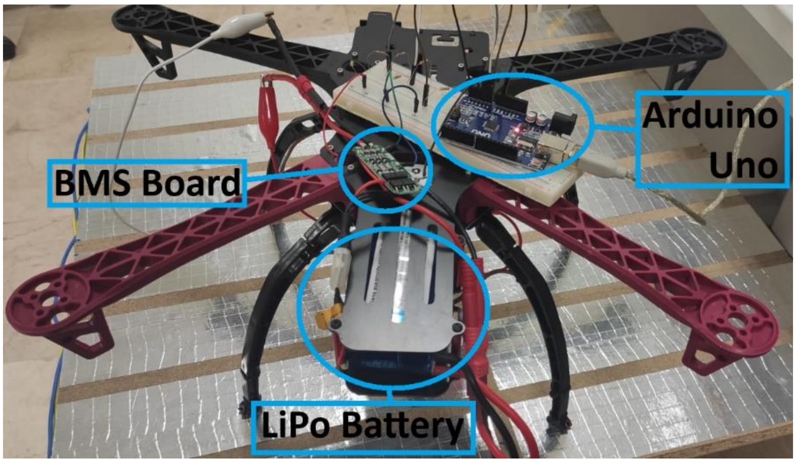


Figure11. Battery voltage monitoring hardware system.

In order to monitor the voltage values of the LiPo battery during charging, the cellular and total voltage values of the LiPo battery have displayed to the user instantly via the interface developed with the C# programming language. The visual for monitoring the LiPo battery voltage values via the interface is presented in Fig. 12. The battery voltage values sent to the Arduino card as analog via the BMS card are subjected to digital conversion processes within the Arduino. After the voltage values are obtained, these values are sent to the interface via the serial communication unit. The first cell, second cell, third cell and total voltage values are sent on the interface, respectively. For instant tracking, current date and time information is added to create data lines. The obtained voltage values and time parameters are added to the form on the screen and instant tracking is performed. The voltage amount of the LiPo battery is shown as a percentage on the interface.

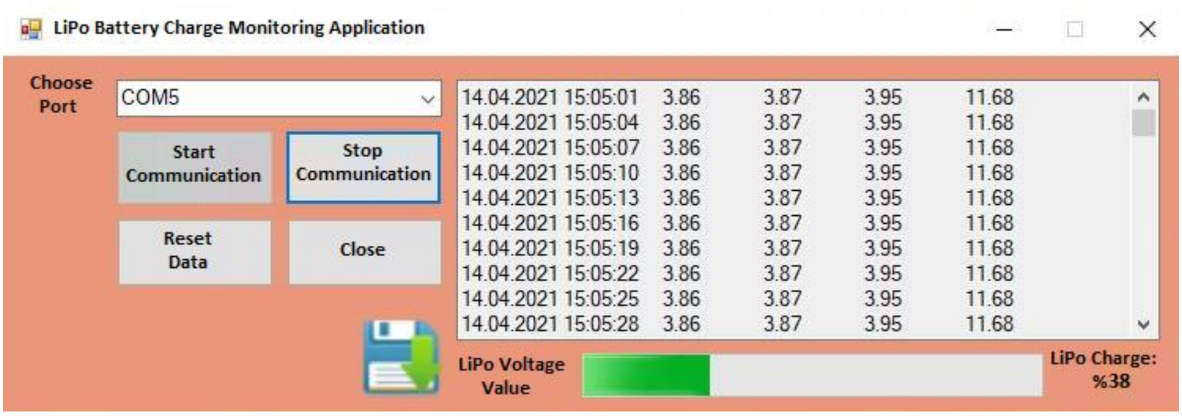


Figure12. Monitoring of battery cells with interface

When calculating the percentage value, the lower and upper levels where the LiPo battery works most efficiently, 11.1 V and 12.6 V, were selected. The percentage calculation formula is given in Eq. 1.

$$LiPo_{\%} = 100\left(\frac{V_{LiPo} - V_{LowerLevel}}{V_{UpperLevel} - V_{LowerLevel}}\right) \quad (1)$$

The cellular voltage information of the LiPo battery is transferred to the user interface during the charging process. All data obtained at the end of the charging process or as a result of the connection termination process made by the user are kept on the form. Voltage data and time parameters are saved to an Excel table via the Save button on the form. The recorded values are then visualized graphically and transferred to the users. The graphs for the cellular voltage values and total battery voltage value are presented in Fig. 13.

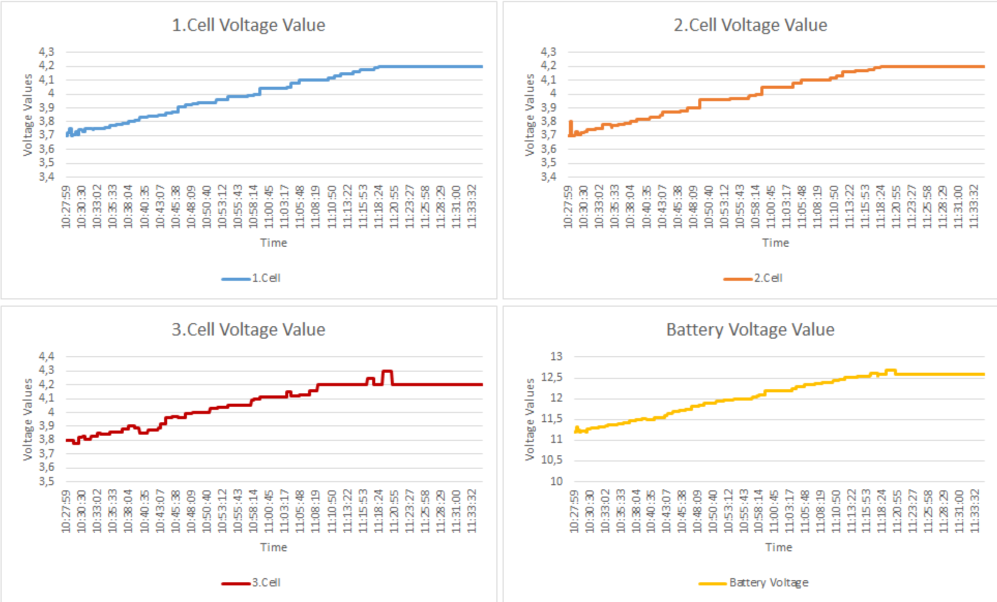


Figure 13. LiPo battery charging graphics

4.5. PV Panel Simulator and LiPo Battery Charging Test

After obtaining positive results from the simulation studies carried out with the PV panel, the hardware testing process of the system was started. In this context, the first test application aimed to obtain the targeted 24 Volt value in order to feed the DC bus line using the PV panel and to charge the LiPo battery using this voltage. In order to prevent instabilities during the test process and to make the measurement conditions controllable, a PV panel simulator called “Chroma Model 62000H-S” was used instead of physical PV panels. This simulator was preferred due to its high stability and fast transient response performance. With the PV panel simulator, the current and voltage values expected to be produced by a real PV panel were successfully simulated and the tests were carried out. The digital signal processing (DSP) based TMS320F28335 development card was used for the management and control of the system during the charging process of the LiPo battery using the PV panel simulator. Thanks to the embedded system cards integrated into this card, the current-voltage values obtained from the LiPo battery, battery pack and PV panel can be continuously monitored and the smart charge management algorithm is activated based on this data.

Fig. 14 shows a visual of the LiPo battery charging process using a PV panel simulator. The hardware test system includes a PV panel simulator, LiPo battery, BMS card and DSP-based control cards. During the test, the reference current value for the LiPo battery charge was determined as 2A and the charging process was carried out according to this current. The voltage value on the DC bus was measured using the voltmeter in the system and this value was observed as 23.86 V at the time of the test. The instantaneous voltage and current values obtained from the PV panel simulator were recorded as 17.2 V and 1.90 A, respectively. This test process is an application in which a real PV panel behavior is successfully imitated through the simulator and the system’s responses to this scenario are analyzed in detail. In this way, the performance of the designed charging system in real environment conditions was tested and verified in advance.

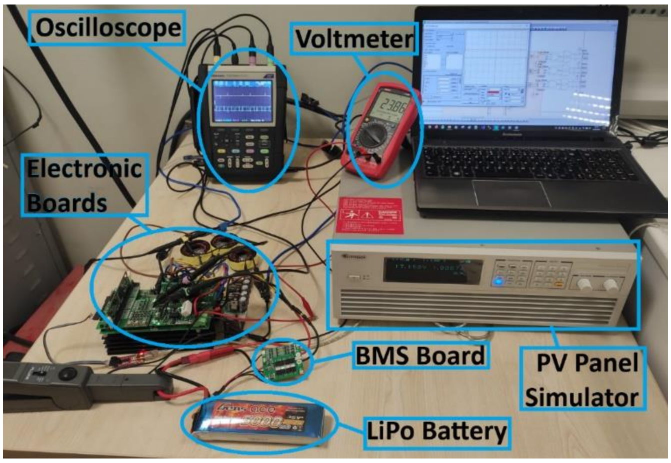


Figure 14. LiPo battery charging using PV panel simulator

5. A SCENARIO RELATED WITH ROTARY WING UAVs CHARGING

Within the scope of this study, a scenario was designed that allows the rotary wing UAV to be autonomously charged during flight missions and to continue its mission without interruption with the renewable energy supported charging station developed. The scenario includes steps such as sensing the energy status of the UAV during flight, directing to the charging station, performing autonomous landing and continuing its mission after recharging. The scenario was examined in three basic technical stages: In the first stage, when the battery charge status (State of Charge - SoC) of the UAV continuing its mission flight autonomously falls below the threshold voltage level defined by the users, the current mission flight is terminated and the UAV is directed to the nearest charging station. In the second stage, when the UAV reaches the location of the determined charging station, the landing process is performed using image processing algorithms and it is precisely positioned on the charging pad. Since the charging pad is designed as non-directional, it allows the UAV to land in different orientations and eliminates connector matching problems. After landing, energy transfer is initiated by the contact of the copper connectors with the conductive surface on the charging pad. In the third stage, the UAV battery is charged autonomously via the charging station; during this process, instant data about the battery can be monitored via the user interface. After the charging process is completed, the UAV switches back to flight mode and continues its mission from where it left off.

This autonomous scenario aims to contribute to the maintenance of UAV-based surveillance and monitoring systems in a fully autonomous manner without the need for human intervention. It offers a highly efficient solution that provides operational continuity, especially for UAV systems operating in large areas and in long-term missions such as environmental monitoring, agricultural applications or search and rescue. In the future, it is planned to scale this system to provide simultaneous charging support for multiple UAVs and to make it more advanced with network-based coordination and artificial intelligence-supported energy management modules.

5.1. Charging Scenario of Rotary Wing

The flow diagram of the scenario regarding the charging process is presented in Fig. 15. This diagram shows in detail how the process progresses based on the battery charge status of the UAV. In the first stage of the process, the SoC value is measured via the BMS card integrated on the UAV and the current voltage capacity of the battery is determined. This information is used as the basic parameter in deciding whether the UAV can continue its current mission. If the SoC value falls below 25% during the flight, the flight mission will be terminated by the system and the UAV will scan the pre-positioned charging stations via Global Positioning System (GPS) data. As a result of the location comparison performed, the nearest charging station will be determined and the UAV will be directed to that station. When the

UAV reaches the coordinates of the charging station, it performs the vertical landing maneuver. At this stage, the data obtained through the camera systems and sensors on the UAV are analyzed with image processing techniques and the landing is completed precisely. The landing process will be carried out synchronously with the communication and control systems. After the landing is completed, the UAV automatically switches from flight mode to charging mode and the charging process is started. The charging process continues until the battery reaches the desired charge level, and the data of the battery cells are monitored during this process. After the charging process is completed, the UAV switches back to flight mode and continues its mission from where it left off.

Within the scope of this scenario, the installation of two fixed charging stations is planned on the Bilecik Şeyh Edebali University campus. During the mission flight, the UAV will detect the closest station to its route, navigate and charge from this station. GPS-based sensor technology will be used to determine the distance between the UAV and the charging stations. This structure supports the autonomous structure of the system by providing energy continuity for the UAV to operate uninterruptedly.

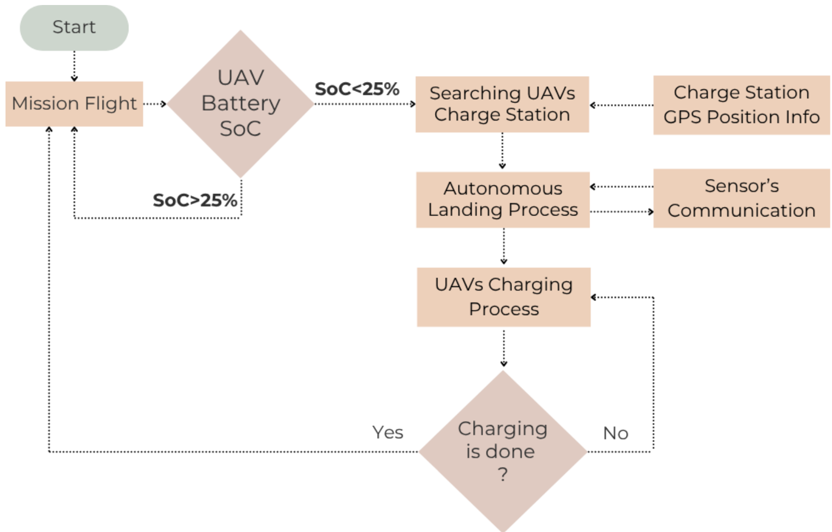


Figure 15. Flowchart of UAV charging process.

5.2. Design of UAV Charging Station

Within the framework of the developed scenario, a charging station design was made to be used in real application studies. Fig. 16 presents the conceptual drawing of the renewable energy-supported UAV charging station designed within the scope of this study. PV panels placed on the outer frame of the charging station meet the energy needs of the system. The energy obtained from the PV panels is either transferred directly to the charging pad or stored in battery packs under suitable conditions by means of a smart charging control system.

The main function of the smart charging control system is to reduce the voltage provided by the PV panels to 12V level with the help of DC-DC converters and make it suitable for charging. The system in question has three different operating modes: Charging the LiPo battery via PV panels, charging the battery packs via PV panels and charging the LiPo battery via battery packs. In the first mode, when the UAV is on the station, the energy obtained from the PV panels is converted and transmitted directly to the charging pad and the battery on the UAV is charged with this energy. In the second mode, when the UAV is not at the station, the energy generated from the PV panels is stored in the battery packs and used to ensure the continuity of the system when sunlight is insufficient. In the third mode, when there is insufficient sunlight or when the PV panels are not working, the energy in the battery packs is transferred to the system and used to charge the UAV battery. In Fig. 15, the red cable on the UAV landing pad indicates the positive (+) and the blue cable indicates the negative (-) power terminals. The charging process is automatically initiated when the connectors integrated into the UAV landing gear come into contact with the power transmission lines on the charging pad.

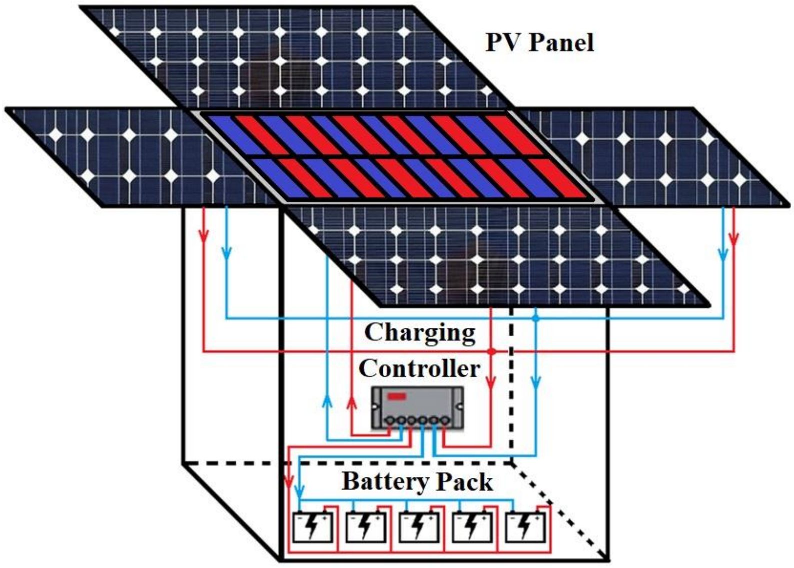


Figure 16. Overview of the proposed UAV charge station

6. CONCLUSION

In this study, the design and tests of a charging station that will allow autonomous charging of rotary wing type UAV battery with renewable energy supported charging station are presented. Within the scope of the study, initially the concept designs of the charging station were discussed and the hardware to be used in the station were determined. After the design studies, applications were made for the simulation of the hardware to be used in the station. In the simulation applications, studies were made for solar energy supported charging processes. As a result of the simulation studies, test studies were made regarding the hardware to be used in the charging station.

In the design studies, concept designs of the charging station and block diagrams of the energy and charging system were provided. Detailed modeling studies were carried out for the general operating principles of the UAV charging station. During this process, various design alternatives regarding the charging pad to be used in the station were examined and the design of the most suitable charging pad in terms of usage was determined. After the completion of the design of the charging pad, the charging system to be used for charging the UAV battery was modeled and developed. At this stage, a special charging system was designed to ensure a balanced charging of the battery and to eliminate possible short circuit risks. In addition, a tracking system design study was performed to instantly monitor the voltage values of the cells in the UAV battery during the charging process.

In the simulation studies, the energy transmission processes between the PV panel, battery pack and LiPo battery were modeled and analyzed in detail. In the system design, the PV panel was preferred as the primary energy source, and the battery pack was configured as the secondary energy source to be activated when sunlight was insufficient. In the energy management and distribution processes, a 24-volt DC bus was used to ensure that all energy components could operate over a common supply line. This value was determined as a common reference voltage level for the integrity of the system, considering the voltage requirements of the PV panel, battery pack and LiPo battery. In the first stage of the simulations, the 17-volt output voltage of the PV panel was increased to a level that could feed the DC bus. A DC/DC boost converter was used for this process and the voltage increase process was performed. The control strategy applied on the boost converter was configured as a proportional-integral (PI) controller-based in order to keep the output voltage of the system constant. In this way, a constant 24 volts was obtained on the DC bus despite the variable energy coming from the PV panel. In the second stage, energy was transferred from the DC bus to the LiPo battery and battery pack at appropriate voltage levels. In this direction, the 24-volt DC bus voltage was reduced to 12 volts by using a DC/DC buck converter to meet the charging requirements of the LiPo battery. Similarly, the PI control algorithm was applied in the buck converter circuit and the stability of the output voltage was ensured. In the simulation studies, charging tests were performed with three different current levels (1A, 2A and 3A) in order to evaluate the performance of the LiPo battery under different charging scenarios.

Hardware test studies were performed with a multi-stage and systematic approach in order to evaluate the performance and functionality of the developed charging system. In this context, initially, charging tests were performed using the BMS card over various energy sources to ensure the balanced and safe charging of the LiPo battery. In the second stage, direct energy transfer to the battery was provided via the surface where the UAV landed using the charging pad and the effectiveness of this method was tested. With this application, it was observed that the charging process could be started automatically regardless of the landing position of the UAV and that the energy transfer could be carried out safely. Thirdly, an Arduino-based tracking system was integrated to monitor the cell voltages of the battery instantly during the charging process. Thanks to this system, the voltage values of each cell of the battery were transferred to the user interface in real time during the charging process, thus protecting the battery against overcharging, imbalance or thermal problems. In another important test stage, 24 V DC power was generated to represent solar energy via the PV panel simulator and this energy was transferred to the DC bus system. With this energy provided via the DC bus, the LiPo battery was charged and it was confirmed that the system could work in an integrated manner with renewable energy sources. All these test procedures were carried out step by step and in a controlled manner, and when each test stage yielded successful results, the next step was moved on.

In the test studies performed with using PV panel and battery, the LiPo battery was charged via energy sources. In these test processes, it was checked whether the LiPo battery was charged in a controlled manner over the reference current values determined in the simulation studies. When the simulation results and the test results were compared, the fact that the given reference current and the current values drawn by the LiPo battery during charging were the same shows that the developed algorithm works in a controlled and correct manner. Thanks to this systematic approach, the reliability, energy management efficiency and operational stability of the charging system were comprehensively evaluated and important data were obtained for the usability of the system in the field.

A comprehensive scenario has been prepared to ensure the effective and safe use of the charging station to be implemented. This scenario provides a roadmap for how the charging station will operate under different operating conditions. As part of future work, the hardware prototype of the charging station will be developed in line with this prepared scenario, and then detailed simulation and testing procedures will be applied. These tests are of critical importance to evaluate the performance and durability of the system under real conditions. In particular, instead of the fixed DC power supply and PV panel simulator currently used in the test stages, it is planned to charge the UAV batteries using the charging station's PV panels and battery packs. In this way, the energy independence of the system will be increased and uninterrupted energy supply will be provided especially in the field. In addition, this approach will support the charging station to be more suitable for real-world applications by increasing its ability to adapt to different environmental and operational conditions.

Acknowledgement

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