24V Smart Battery Charging System with Health Management

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Abstract

This paper presents the design and implementation of a 24V Intelligent Battery Charging System that addresses the limitations of traditional battery charging technologies, including the lack of real-time monitoring, safety protection mechanisms, and sustainable energy integration. To ensure practicality and safety, the system focuses on 3.7V lithium batteries, leveraging their widespread compatibility and low-voltage control chip availability, while enabling scalability to 24V through series configurations. The system integrates solar energy via photovoltaic panels and Maximum Power Point Tracking (MPPT) modules for efficient renewable energy utilization. Key innovations include real-time monitoring of voltage, current, and temperature through an STM32-based battery health monitoring subsystem, coupled with a Bluetooth-enabled mobile application for user interaction and data visualization. Comprehensive safety protections against overvoltage, overcurrent, and overtemperature are implemented, along with a mechanically designed circuit breaker for load protection. This solution enhances battery lifespan, performance, and user experience while aligning with carbon neutrality goals. The design demonstrates significant advancements in intelligent energy management, offering a scalable, eco-friendly, and user-centric approach to modern battery charging systems.

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1. Introduction

1.1 Purpose

Traditional battery charging systems suffer from problems such as inability to monitor current and voltage in real time, lack of over-voltage and over temperature protection, and so on. Overall, the commonly used battery charging systems in the past lacked a visual intelligent system that could comprehensively monitor and protect in real-time, leading to shortened battery lifespan, performance degradation, and poor user experience. Furthermore, in alignment with global carbon neutrality goals, integrating solar energy—a clean, renewable power source—into charging infrastructure has become imperative.

Our team's design project, the "24V Intelligent Battery Charging System", addresses critical shortcomings in conventional battery charging technologies described above. The system leverages solar panels and MPPT modules to charge a standard 3.7V lithium battery while continuously monitoring key metrics (voltage, current, temperature) through a battery health monitor based on STM32 and a visualized APP based on Bluetooth communication modules. (For safety reasons, we use 3.7V batteries instead of 24V batteries, and we think that establishing a health system for 3.7V standard lithium batteries is representative. Multiple lithium batteries can also be connected in series to achieve 24V power supply, so studying 3.7V is more practical. And most of the low voltage control chips on the market are designed for 3.7V lithium batteries, so choosing 3.7V can provide a wide range of component selection.)

Overall, this design achieves current, voltage, and temperature monitoring for 3.7V rechargeable batteries, as well as over-voltage, over-temperature, and over-current protection for the batteries. In terms of mechanical structure, we designed a circuit breaker to protect the load. We also designed an APP for real-time monitoring by users. This is an advanced design project full of innovation and practical value.

1.2 Functionality

This intelligent system includes four core modules: Solar Panel MPPT module, PCB-Battery health monitor module, Visual Bluetooth App module, Mechanical-Circuit Breaker Module.

Solar Panel MPPT module: It converts clean energy solar energy into electrical energy and achieves stable voltage output through MPPT. The 18V/50W solar panel operates on the photovoltaic effect, converting sunlight into DC electricity via semiconductor materials, with an open-circuit voltage of ~21-22V, a working voltage of 18V, and a maximum power point (MPP) at 17-18V/2.8-3A. Its output varies with light intensity and temperature. The MPPT (Maximum Power Point Tracking) module optimizes energy harvest by continuously sampling the panel's voltage and current, dynamically adjusting impedance through a DC-DC converter using algorithms like Perturb and Observe (P&O) or Incremental Conductance to track the MPP. This system ensures 20%-30% higher efficiency than PWM controllers, stabilizes voltage, and enhances low-light performance. Ideal for off-grid applications, it maximizes energy capture under fluctuating conditions, protects batteries from over-voltage, and extends energy storage lifespan through adaptive power management.

PCB-Battery Health Monitor module: It is programmed based on STM32 to achieve real-time monitoring of the current, voltage, and temperature of 3.7V charged and discharged lithium batteries, and to provide over-voltage, over-current, and over-temperature protection (voltage above 4.2V, temperature above 50 °C, current greater than 1A). The code implements a robust battery management system (BMS) featuring real-time monitoring, safety protections (over-voltage/current/temperature cutoff), and wireless communication, with a modular architecture and optimized algorithms tailored for low-to-medium power Li battery applications. Its structured design, leveraging STM32 libraries, ensures portability across micro controller families while enhancing reliability through embedded safety mechanisms. After finalizing development and debugging, the compiled firmware is deployed to the target STM32 micro controller on the PCB via Keil MDK's integrated burning tool, enabling seamless integration of the BMS into hardware systems for efficient energy management.

APP Bluetooth Communication Module: This module receives the signals containing current, voltage and temperature sent by STM32, modulates them through the Bluetooth module to form a frame

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containing the Bluetooth recognition prefix and the suffix storing information, and transmits it to the mobile phone. The APP on the mobile phone that uses the Bluetooth module is responsible for identifying the prefix signal, then receiving the modulated Bluetooth frame, demodulation and removing the prefix, and finally converting it into the number on the screen. APP Bluetooth communication module. This module receives the signals containing current, voltage and temperature sent by STM32, modulates them through the Bluetooth module to form a frame containing the Bluetooth recognition prefix and the suffix storing information, and transmits it to the mobile phone. The APP on the mobile phone that uses the Bluetooth module is responsible for identifying the prefix signal, then receiving the modulated Bluetooth frame, demodulation and removing the prefix, and finally converting it into the number on the screen. This module, as a way to display the detection results, significantly increases the visualization degree and universality of the project. As long as an Android system mobile phone with Bluetooth function is used, it can be used as the upper computer to receive the signal of the BMS monitoring system. Let our graduation design project have the potential for commercialization.

Mechanical Circuit Breaker Module: This design aims to mechanically cut off the circuit when the temperature of a certain component in the circuit is too high, serving as a safety measure when the circuit cannot be cut off by electronic means. This design is divided into the main circuit structure and the temperature control circuit structure. The temperature control circuit structure is composed of an electromagnet, a temperature control switch and a 24V battery. The temperature control switch is in the normally open state. If the temperature is lower than 50 degrees Celsius, the temperature control circuit will not operate. The most important part of the main circuit is the contacts. One of the contacts is connected to the armature, and the other is connected to the insulating board installed on the contacts. Under normal conditions, the two contacts are connected. However, when the temperature exceeds 50 degrees, the resistance of the temperature control switch drops from infinity to 0.1 ohms. The circuit conducts, causing the electromagnet to draw the upper armature downward, and the contacts break, resulting in an open circuit in the main circuit.

1.3 Subsystem Overview



Figure1.1 Top-Level Diagram for the Whole Design

The figure is a high-level diagram of the battery charging system, showing the flow from the solar panel through the MPPT controller to the micro-controller. The STM32 micro-controller outputs to three paths: charging the battery, powering the load, and sending data to a Bluetooth module. The Load is connected in series with a Circuit Breaker to protect against over-current conditions. Arrows indicate the direction of power flow and signal control in the system

1.3.1 PCB-BMS Subsystem

1.3.1.1Functions of the PCB-BMS subsystem

The PCB-BMS subsystem plays a core role in the functional realization of this project. This subsystem adopts the minimum system board design based on the STM32 core, which can receive and process the relevant information of current, voltage and temperature based on the voltage of each pin. And it transmits current, voltage and temperature information to the Bluetooth module through pin discharge. The functions of this subsystem are:

1. Use RT9193 to transform and stabilize the 5V input voltage from USB.

2. The current is monitored using the ACS712 Hall effect module, and the voltage is fed back to the STM32 core.

3. The TP4054 is used to regulate the charging current of lithium batteries, which conforms to the charging and discharging curve of lithium batteries and provides protection and fast charging for the batteries.

4. Use DW06D to provide over-current, over-voltage and short-circuit protection for the circuit. The circuit will be automatically cut off in case of abnormal conditions.

5. Voltage is divided by a temperature-sensing resistor, and the voltage data is transmitted to the STM32 core. When the temperature is too high, the circuit is cut off through a program.

1.3.1.2 Input and Output of the PCB-BMS subsystem

The PCB-BMS subsystem is in a core position in the design of the entire system. The PCB-BMS subsystem is connected to the MPPT module, the Bluetooth module, the circuit breaker - load module, and the battery module. Among them,

The MPPT module is connected to this subsystem via a USB data cable, providing 5V voltage to power the entire system and charge the battery.

2. The Bluetooth module is connected to this subsystem through pins PA1-3 of the STM32 chip, and this module transmits current, voltage and temperature data to it.

3. Circuit breaker - The load module is connected to this subsystem using the DC Power Jack. This module supplies power to the battery after detecting and protecting the battery current using the builtin DW06 and ACS712 modules.

4. The battery module is connected to this subsystem using the DC Power Jack. This module charges the battery after providing voltage transformation, current and voltage protection for the USB input voltage using the TP405, DW06 and ACS712 modules.

1.3.2 APP Bluetooth Communication Module

In this module, the Bluetooth module HC-05 and the STM32 core board module are directly connected to the PA1, PA2 and PA3 interfaces through pin headers to receive the hexadecimal signals of current, voltage and temperature transmitted by them. Among them, PA1 is connected to the state, PA2 is connected to the Rx transceiver, and PA3 is connected to the Tx transceiver. Meanwhile, of the remaining two interfaces of this HC-05 module, one is grounded and the other is a 5V voltage supply port. The transmitter of HC-05 will transmit the modulated radar signal of 9600bps into the Bluetooth of the mobile phone. The Bluetooth-equipped APP in the mobile phone then demodulate the signal frame and remove the useless frames. Finally, display the data results on the mobile phone screen.



Figure 1.2 CAD Design of Mechanical Circuit Breaker and Cricuit Breaker

1.3.3 Mechanical circuit breaker module

In mechanical temperature circuit breakers, the main circuit module is controlled by the temperature control circuit module. When the temperature exceeds 50 degrees, the temperature control switch closes, the electromagnet starts to operate, and the armature is controlled to fall, causing the contacts to come out of contact and resulting in power failure of the main circuit.

2 Design

2.1 Equations & Simulations

2.1.1 Solar Panel Theoretical Output

The solar panel has a rated power of 18V/50W under Standard Test Conditions (STC): Maximum Power Point Voltage:

$$V_{\rm mp} = 18 \, \text{V}$$

Maximum Power Point Current:

$$I_{mp} = \frac{P_{max}}{V_{mp}} = \frac{50}{18} \approx 2.778 \text{ A}$$

Theoretical Maximum Power:

$$P_{max} = V_{mp} \times I_{mp} = 18 \times 2.778 = 50 W$$

2.1.2 MPPT Measured Output

The MPPT module delivers 5V/1A at its output:

Output Power:

$$P_{out} = V_{out} \times I_{out} = 5 \times 1 = 5 W$$

The MPPT efficiency (η) relates output power to input power:

$$\eta = \frac{P_{out}}{P_{in}} \implies P_{in} = \frac{P_{out}}{\eta}$$
$$\eta = 90\%$$
$$P_{in} = \frac{5}{0.9} \approx 5.56 \text{ W}$$

2.1.3 Solar Panel Actual Operating State

The solar panel's actual voltage ($V_{\rm pv}$) and current ($I_{\rm pv}$) satisfy:

$$V_{pv} \times I_{pv} = P_{in} \approx 5.56 W$$

If the MPPT successfully tracks the Maximum Power Point (MPP) under current conditions:

$$V_{pv} = V_{mp\backslash_actual}, I_{pv} = I_{mp\backslash_actual}$$

where $V_{mp \backslash_actual}$ and $I_{mp \backslash_actual}$ are the real-world MPP parameters.

2.1.4 Calculations related to temperature sensing resistors

A negative temperature coefficient thermistor (NTC) is a semiconductor component whose resistance value decreases as the temperature rises. The resistance value of NTC is usually described by the Steinhart-Hart equation, as follows:

$$\frac{1}{T} = A + B \cdot \ln(R) + C \cdot [\ln(R)]^3$$

T: Temperature (in Kelvin K)

R: The current resistance value (Ω) of the NTC.

A, B, C: Coefficients related to NTC.

In this study, the temperature was estimated using the resistance value comparison table provided by the manufacturer. The circuit is shown in the following figure:



Figure 2.1 NTC Thermistor Voltage Divider Circuit 1

The NTC and the 24k standard resistor form a voltage divider circuit, and the voltage data is transmitted to the STM32 core board through the NTC_DET pin using ADC. The relationship between ADC and voltage is as follows:

$$V_{out} = rac{adc_raw}{4095} \cdot V_{ref}$$

V_out is voltage detected at NTC_DET, and it follows the following relationship:

$$\frac{V_{out}}{V_{ref}} = \frac{R_{ntc}}{R_{fixed} + R_{ntc}}$$

Where R_fixed is 24k Ohms.

Therefore, the resistance value of NTC can be inversely solved through the value of ADC.

R_ntc = 24000.0 * (4096.0 / (adc_raw [0] + 1) - 1);

Among them, +1 is to prevent division by zero errors.

Subsequently, the program calculates the temperature through the linear interpolation method based on the following comparison table, as shown in the table below:



Figure 2.2 NTC Thermistor Resistance vs. Temperature Curve

| 「emperature (°C) | -10 | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 |
|------------------|-------|-------|-------|-------|------|------|------|------|------|------|-----|-----|-----|-----|-----|
| Resistance (Ω) | 52760 | 31640 | 19560 | 12430 | 8096 | 5394 | 3671 | 2546 | 1783 | 1256 | 910 | 664 | 490 | 367 | 278 |

 Table 1 NTC Thermistor Resistance-Temperature Lookup Table

The formula of the linear interpolation method is as follows:

$$T = T_i + rac{(T_{i+1} - T_i)}{(R_{i+1} - R_i)} \cdot (R_{ntc} - R_i)$$

R_i is the resistance value corresponding to T_i in the table

At this point, the temperature data detected by the temperature sensing resistor can be obtained. When the temperature exceeds the threshold set by the program (50 degrees), the STM32 will send an instruction to cut off the circuit, achieving the function of over-temperature protection.

Relevant calculations of lithium battery charge and discharge curves

Taking a 3.7v single-cell lithium battery as an example, its discharge curve is as follows:



Figure 2.3 Typical Discharge Curve of a 3.7V Lithium-Ion Battery

In the range of 4.18V to 4V, the battery voltage drops rapidly.

2. Within the range of 4.0V to 3.71V, the trend of voltage drop is relatively moderate.

3. In the range further down from 3.71V, the trend of voltage decline becomes steeper again;

Therefore, we adopt the TP4054 chip and carry out the following charging strategy:

1. When the voltage is less than 2.9V, the charging current is 1/10 of the set constant current.

2. When the voltage exceeds 2.9V, charge at a constant current.

3. When the voltage is fast charged to 4.2V, reduce the current and switch to constant voltage charging. Stop charging when the current drops to 1/10 of the set current. When the current drops to 0, stop the charging cycle.

As mentioned above, setting the charging current is determined by the resistance connected externally to the PROG pin. According to the TP4054 chip manual, the formula is:

$$R_{PROG} = \frac{1000}{I_{BAT}} \times \left(1.2 - \frac{4}{3}I_{BAT}\right)$$

In this study, a single battery was charged with a constant current using a safe current of 360mA. According to the formula calculation, the resistance value of R PROG was 2kOhm.

2.1.5 ACS712ELCTR-05B-T Current detection module

This module detects the flowing current based on the Hall effect principle. The input of this module is IP+, the current flowing through the IP- interface, and the VIOUT pin outputs voltage to the STM32 core to transmit the current data flowing through it. The formula is:



Figure 2.4 ACS712 Current Sensor Module Connection Diagram

Vout = 0.5 Vcc + Ip * Sensitivity

Among them, Ip represents the flowing current. For this chip, the sensitivity provided by the manufacturer is 185.

Similarly, by using the ADC signal to transmit the voltage information to the STM32 core, the current flowing through the chip can be calculated

2.2 Design Alternatives

2.2.1 Failed Version of MPPT Design

In this version, we have designed a solar controller based on the MPPT algorithm. Among them, JP1 is connected to the positive and negative poles of the solar panel, JP2 to the battery, and JP3 to the load used for the test. A voltage stabilizing module is connected between JP4 and JP5 to stabilize the voltage at 5V to supply power to the chip. H3 and H4 are connected to the display screen and are equipped with LED indicator lights to show the working status. Interface H5 is respectively connected to D2, D3, D5, D8, D9, A0, A1, A2, A4 and A5 of Arduino Nano.



Figure 2.5 Schematic and PCB Layout of the Failed MPPT Solar Controller Design

The initial problem that emerged was that there was a design error in the style of the JP2 port. In PCB drawing, square interfaces are generally used to represent that this interface is a ground interface, and circular interfaces indicate that there is voltage at this interface. However, in our PCB design, we set the interfaces where current flows out as circular interfaces and the interfaces where current flows in as

square interfaces. Since the JP2 is equipped with an external battery, the actual voltage of the circular interface should be 0 and connected to other ground wires, while the voltage of the square interface should be 24V. During our testing in the laboratory, due to a communication error, the tester still thought that the square interface was grounded and the circular interface was connected to the positive terminal of the battery, resulting in a 24V voltage at the GND port. This directly burned out the chip in the PCB board, thus causing the failure of our first MPPT design.

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- Dynamic dv/dt Rating
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Advanced HEXFET[®] Power MOSFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications.

The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry.

Absolute Maximum Ratings

| | Parameter | Max. | Units |
|---|---|------------------------|-------|
| I _D @ T _C = 25°C | Continuous Drain Current, VGS @ 10V | 49 | |
| I _D @ T _C = 100°C | Continuous Drain Current, V _{GS} @ 10V | 35 | A |
| IDM | Pulsed Drain Current ① | 160 | |
| $P_D @T_C = 25^{\circ}C$ | Power Dissipation | 94 | W |
| | Linear Derating Factor | 0.63 | W/°C |
| VGS | Gate-to-Source Voltage | ± 20 | V |
| IAR | Avalanche Current® | 25 | A |
| EAR | Repetitive Avalanche Energy ^① | 9.4 | mJ |
| dv/dt | Peak Diode Recovery dv/dt 3 | 5.0 | V/ns |
| TJ | Operating Junction and | -55 to + 175 | |
| TSTG | Storage Temperature Range | | °C |
| | Soldering Temperature, for 10 seconds | 300 (1.6mm from case) | |
| | Mounting torque, 6-32 or M3 srew | 10 lbf•in (1.1N•m) | |

Figure 2.6 IRFZ44NPbF HEXFET Power MOSFET Datasheet Overview

2.2.2 Abandoned First Version of BMS Design

This is the first BMS system we designed. In this version, our circuit includes an current detection module, a test module, a voltage measurement divider circuit module, an LCD1602 display module, and a core board based on STM32. There are five modules in this version design: the display module connected to the PB port of STM32, directly displaying data on the display.

However, the problem is also very serious. Firstly, the visualization degree of the display-based solution is not high, and the display is also rather blurry, with poor aesthetic quality. Secondly, there are too many pins at the connection points between the display, the STM32 core board, and the base board. These pins have certain resistances due to inevitable soldering problems. This leads to a certain error in the voltage measurement divider circuit. After our measurement, this resistance is approximately 1.7 ohms, which will have an impact of about 1.7% on the measurement accuracy. Secondly, due to limited

PD - 94787

IRFZ44NPbF

HEXFET[®] Power MOSFET

TO-220AB

 $V_{DSS} = 55V$

 $R_{DS(on)} = 17.5 m\Omega$

 $I_D = 49A$

space, we designed the welding ports of the two resistors at the bottom of the STM32 core board. This design was found to have the risk of short circuit in our subsequent welding. Finally, due to the PCB manufacturing process issue, the ground wire of our STM32 core board is electrified, approximately 2.1V, with a leakage phenomenon, causing the core board to fail to work. Considering the above reasons, we decided to improve this solution by integrating the STM32 core board onto the base board, increasing reliability and measurement accuracy. In addition, we decided to use the Bluetooth module + APP mode instead of the display, so as to achieve better aesthetic and visualization quality.





2.2.3 Failed to Reach 24V in Second Version of BMS Design

In our final design, we failed to achieve the original goal of measuring a 24V battery. Instead, we could only measure the charging and discharging conditions of a single 3.7V lithium battery. This was mainly due to the lack of highly integrated chips for voltages below 36V on the market. The chip we purchased, TP4054, does not support the connection of lithium batteries with voltages above 4.2V. Additionally, the 24V high voltage is likely to cause damage to the 3.3V-powered chips and the STM32 core board.



Figure 2.8 TP4054-Based Single-Cell Lithium Battery Charging Circuit and Characteristics

2.2.4 Mechanical Temperature Circuit Breakers

For mechanical temperature circuit breakers, I once had two schemes. The first one is the one I eventually used (the electromagnetic relay scheme), and the second one is the bimetallic strip scheme. The thermosensitive bimetallic strip solution is to manufacture a composite structure by using two metal materials with different coefficients of thermal expansion. When the temperature rises, due to the varying degrees of thermal expansion and contraction of the material, the bimetallic strip will undergo bending deformation. This deformation can be used to push the mechanical contacts, thereby achieving the on-off control of the circuit. After the temperature drops, the bimetallic strip returns to its original shape and the circuit closes again.

Thermosensitive bimetallic strips have a simple structure, but there are some major problems. The first problem is the slow response speed. Due to the drive of temperature changes, it usually takes a relatively long time to complete the circuit breaking operation, which cannot meet the requirements of the system's rapid response. The second problem is the limited control accuracy. Its working temperature point is affected by the material and manufacturing tolerance, and the adjustment is not flexible enough, making it difficult to achieve precise control. Due to these two problems, I eventually gave up the thermosensitive bimetallic strip schemes.

When designing the circuit breaker, I have faced many challenges. The first challenge is The first challenge I encountered came from the electromagnet. When I conducted my first test, the electromagnet failed to draw down the armature tied with a rubber band because the magnetic force was insufficient. At that time, the electromagnet I purchased was suitable for 5V voltage, but its suction force was insufficient. Later, I chose to buy an electromagnet with 24V voltage and a zero-distance suction force of 3kg, which solved this problem.

The second problem still comes from the electromagnet. When the new electromagnet is running, it often moves upward until it touches the armature. At that time, my design didn't take this into account. I didn't expect the electromagnet to be attracted. I just left a common groove on the shell to store the electromagnet. After discovering this problem, I changed the Design of the shell and solved it by using two layers of shells + connectors (which will be covered in the Design Description & Justification section).



Figure 2.9 The design of the first and second generations of mechanical circuit breakers

The third problem comes from assembly. There was a mistake in my second version of the shell design: the difficulty during assembly was not taken into consideration. At that time, I had already abandoned the design of directly inserting the armature into the casing (first version), and split the original armature part into the armature and the round rod. I was also planning to fix the round rod with a flange, but the reality was that the distance between the two sides was too small to assemble the combination of armature + flange + round rod at all. The round rod couldn't be inserted into the flange either. It was then that I realized my mistake and added a slider and a slide groove, replacing the round rod with a lead screw and solving the problem.



Figure 2.10 New Design of Mechanical Circuit Breaker

2.2.5 Metal 3D Printing

We designed a circuit breaker, utilizing 3D printing technology to fabricate most components, achieving significant weight reduction compared to conventional counterparts. However, several specially designed conductive components - including electrical contacts and support structures - required electrical conductivity that conventional photosensitive resin materials for 3D printing could not provide.

Initial consideration was given to computer numerical control (CNC) machining for custom parts, but the associated costs proved prohibitively expensive.

Consequently, we adopted an innovative and cost-effective metal 3D printing solution: Component 1 was fabricated using stainless steel, while Components 2 and 3 employed aluminum alloy. The final manufactured parts demonstrated excellent material integrity and superior electrical conductivity performance.

3D model images and metal printed physical objects:





Figure 2.11 3D Printing PLA+ Sheel and Stainless Steel Connector



Figure 2.12 3D Printing Aluminium Alloy Part



Figure 2.13 3D Printing Aluminium Alloy Part 2

2.3 Design Description & Justification

2.3.1 Solar Panel MPPT module design description and Justification

Solar Panel (18V/50W): The 18V/50W solar panel serves as the primary energy source, converting solar irradiance into electrical energy. Its 18V open-circuit voltage (*Voc*) and 50W maximum power output are optimized for moderate sunlight conditions, ensuring sufficient energy generation for low-to-medium power applications.

MPPT Module (5V/1A Output): The Maximum Power Point Tracking (MPPT) module regulates the variable voltage and current from the solar panel to maintain optimal power extraction. It steps down the 18V solar panel input to a stable 5V/1A DC output, ensuring compatibility with 5V-rated devices (e.g., USB-powered electronics, sensors, or small batteries). The MPPT algorithm dynamically adjusts the input impedance to track the solar panel's maximum power point (MPP), even under fluctuating light conditions, improving overall system efficiency.

Justification



We used specialized electrical instruments for measurement and actually obtained normal output voltage.

Figure 2.14 Measurement of Solar Panel Output Voltage

2.3.2 Modular Design Description and Design Decision-making of the PCB-BMS Subsystem The PCB-BMS subsystem is the control core of this project. Its main functions include power management, current and voltage detection, battery charging control and protection, temperature monitoring and data communication. This system adopts the STM32F103CBT6 minimum system board as the core control unit, combined with power voltage stabilization, Hall current detection, charging management and multiple protection circuits, achieving precise management and safety guarantee of the battery. The overall design drawing of this module is as follows



Figure 2.15 STM32F103CBT6 main control unit

STM32F103CBT6 main control unit

This chip, as the control center of the entire system, is equipped with abundant IO resources and a highperformance ADC (12-bit, 1Msps), and is capable of efficiently collecting voltage, current and temperature signals and conducting logical processing. The STM32F103 series is widely used in lowpower control systems and has good real-time performance and scalability. Compared with ATmega328P (only 10-bit ADC) or ESP32 (with high idle power consumption and weak anti-interference ability), STM32F103 is more stable and reliable in industrial applications and is suitable for the requirements of multi-channel precise signal acquisition in this project.

The pin inputs/outputs of the STM32 main control unit in this project are shown in the following table:



Figure 2.16 STM32F103CBT6 Microcontroller Pin Diagram

| Pin Name | Signal Name | Function Description | Туре | I/O Level |
|-----------|-------------|---|---------|-------------------|
| NRST | NRST | Chip hardware reset (active low) | Digital | Input |
| PA1-PA3 | HC_XX | Bluetooth communication interface (UART/SPI) | Digital | Output |
| PA4 | NTC_DET | NTC temperature sensor analog input | Analog | Input(0- 3.3V) |
| PA5/PA6 | XX_DET | Battery voltage/current detection analog input | Analog | Input(0- 3.3V) |
| PA7 | CHAR_EN | Charging enable control (drives MOSFET) | Digital | Output |
| PBO | LOAD_EN | Load power switch control (drives MOSFET) | Digital | Output |
| PA13/PA14 | SWDIO/SWCLK | SWD programming and debugging interface | Digital | Bidirectional |
| PB14 | LED | Status indicator control | Digital | Output |
| PB12 | BTN | Push-button input (active low) | Digital | Input |

Table 2 STM32 Pin Assignment and Function Description Table

The functions of key pins will be elaborated in detail in the subsequent interpretation of the chip.

RT9193-33GB voltage stabilizing module

This module is used to stabilize the 5V USB voltage provided by the MPPT module to 3.3V for use by STM32 and other peripherals. The RT9193 features low dropout, high-precision output (\pm 2%), and extremely low static current (only 25µA typ). Compared with the AMS1117 series, it generates less heat and has a faster response speed, making it more suitable for applications in small embedded systems

with high requirements for power quality. Meanwhile, it is equipped with filter capacitors, which can provide a more stable voltage supply for the core board.

The following is an icon comparing the two chips using LTSpice, showing the output voltage response comparison of the two chips under sudden load changes. It can be seen that RT9193 has excellent transient response capability and outstanding stability.



Figure 2.17 Transient Response Comparison of RT9193-33GB vs AMS1117-3.3 Voltage Regulators

In the circuit of this study, RT9193-33GB is installed as shown in the following figure.



Figure 2.18 RT9193-33GB Voltage Regulator Circuit Implementation

The input voltage of this module is 5V USB DC power supply, and the output voltage is a stable 3.3V DC voltage. Using the USB interface, a 5V voltage was provided for it. The VOUT pin was tested with a voltmeter and it was found that the output voltage was stable at around 3.3V, which met the requirements. Detailed data can be found in the "Completeness of Requirements" and "Verification Procedures" section of data analysis.

ACS712ELCTR-05B-T Current Detection Module

This module is based on the Hall effect principle and can achieve bidirectional current measurement within the ±5A range, and provide analog signal output proportional to the current. This device is equipped with built-in electrical isolation and has strong anti-interference ability. It is suitable for battery management systems with switching shock or inductive loads. Compared with I2C interface

devices such as INA219, ACS712 has advantages such as analog output, simple wiring, and faster response.



Figure 2.19 Circuit Diagram of ACS712ELCTR-05B-T Current Detection Module

The input of this module is IP+, the current flowing through the IP- interface, and the VIOUT pin outputs voltage to the STM32 core to transmit the current data flowing through it. The formula is:

Vout = 0.5 Vcc + Ip * Sensitivity

Among them, Ip represents the flowing current. For this chip, the sensitivity provided by the manufacturer is 185.

Considering that this study aims to charge a single 4.3V lithium battery, the threshold current is set to 1A as recommended in the battery manual. When the current exceeds the threshold (1A), the core board will use the CHAR_EN and LOAD_EN signals to cut off the circuit, achieving the function of overcurrent protection.

In the actual measurement, in this study, a sliding rheostat was used to control the current flowing through the IP interface, and the signal was transmitted to the SMT32 core board to test the current control function of the chip. In five experiments, when the average current was 1.1A, the chip successfully cut off the circuit in all of them. However, since a chip was burned out during the experiment, this experiment did not delve deeply into the current tolerance limit of the chip. The specific data can be referred to in the subsequent data analysis chapter "Completeness of Requirements" and "Verification Procedures".

TP4054 Lithium battery charging control module

This module is a linear constant current and constant voltage charging IC, specially designed for a single lithium battery. Its maximum charging current can reach 500mA, and it is equipped with built-in temperature monitoring and status indication functions, conforming to the standard charging curve of lithium batteries. Compared with TP4056, TP4054 has a simpler structure and a smaller package, making it suitable for PCB designs with limited space. Moreover, as it does not require external MOSFETs or discrete components, it can effectively reduce the difficulty of board layout.

Its function is that The voltage is less than 2.9V and the charging current is 1/10 of the set constant current. When the voltage is greater than 2.9V, charge at a constant current When the voltage approaches 4.2V charge at a constant voltage. Stop charging when the current drops to 1/10 of the set

current. This can provide overcharge and undercharge protection for the battery, enhancing its lifespan and charging efficiency.

Meanwhile, this module is connected to MOS Q2 and Q3. It can perform digital signal control on and off of the circuit based on the signals sent by the STM32 core, enhancing the safety of the circuit.



Figure 2.20 TP4054-Based Lithium Battery Charging Control Circuit with MOS Protection

The descriptions of the functions of each pin are as follows:

CHRG: Output of open drain charging state

BAT: Battery charging current output

VCC: Positive voltage input

PROG: Programming the charging current through the resistance value of the connected resistor

In this design, the programming pin of TP4054 is connected to a 2k resistor to set its cross-current to 360mA.

When using this system to charge the battery, the battery current stabilizes at around 340mA during the constant current charging time, which is basically the same as the current set by the program. The following picture is a screenshot of the mobile phone APP in use:

Battery information

Current: 0.33 A Voltage: 4.10 V Temperature: 26.31 °C

Figure 2.21 Mobile App Screenshot Showing Real-Time Battery Charging Status

For specific numerical analysis, please refer to the "Completeness of Requirements" and "Verification Procedures" section on data analysis

DW06D/J lithium battery protection chip

This chip integrates multiple protection mechanisms such as overvoltage, overcurrent and short circuit. When an abnormality occurs, it can automatically cut off the power supply with a microsecond-level response time to protect the battery and downstream load devices. Compared with the traditional DW01+ MOSFET solution, DW06D has a higher degree of integration, simplifies the peripheral circuit design, and is conducive to improving the overall stability and integration of the system.



Figure 2.22 DW06D/J Lithium Battery Protection Circuit Diagram

Its functions are as follows:

1. Overcharge Protection: When the battery voltage exceeds 4.3V, DW06 will turn off the charging path MOSFET2.

2. Over-discharge Protection: When the battery voltage is less than 2.4V, DW06 will disconnect the discharge path MOSFET3.

3. Over-current protection/Short circuit protection: When the discharge current is greater than 4 to 6A, DW01 disconnects the discharge MOSFET

In this design, the functions of its pins are as follows:

The positive terminal of the VDD battery provides power supply and voltage input

VSS battery negative electrode, system reference GND

V- Current detection

S1 and S2 control the on-off of the charging and discharging circuits

In the experiment, the voltage between VDD and VSS was adjusted within the range of 2.0-4.5V using a DC power supply. In the five experiments, the average minimum voltage at the start of charging was 2.35V, and the maximum voltage at the stop of charging was 4.27V. The function of the chip was verified. The specific data can be referred to in the "Completeness of Requirements" and "Verification Procedures" section of data analysis. Since the trigger current protection current was much higher than the maximum current set by the system, it was not tested.

Temperature protection circuit

This module is based on the principle that the resistance value of the NTC component changes negatively with temperature. It controls the on-off state of the circuit by inputting signals to the STM32

through a splitter circuit. The specific principles have been elaborated in the Equations & Simulations section, so they will not be repeated.



Figure 2.23 NTC-Based Temperature Protection Circuit Diagram

When the temperature exceeds the threshold set by the program (50 degrees), the STM32 will send an instruction to cut off the circuit, achieving the function of over-temperature protection.

In the experiment, an electric heating plate was used to heat the temperature control resistor, a thermometer was used to record the temperature, and the resistance value of the temperature sensing resistor was measured. In the five measurements, the actual average open-circuit temperature of the circuit was 45.3 degrees Celsius, slightly lower than the set 50 degrees Celsius. It is speculated that the reason is that there is a certain deviation between the actual resistance value of the resistor and the resistance value obtained from the table lookup, or the electric heating plate cannot heat the entire resistor uniformly. Detailed data can be found in the "Completeness of Requirements" and "Verification Procedures" section of data analysis.

2.3.3 STM32 Code Part

Code Core functions

This code implements a battery management system (BMS) based on an STM32 microcontroller. Its core functionalities include battery parameter acquisition (voltage, current, temperature), charge/discharge control, safety protection mechanisms, and Bluetooth data transmission. The code follows the STM32 framework and comprises the following key modules:

Multi parameter acquisition: Real time acquisition of battery voltage, current, and temperature data through ADC.

Charge and discharge control: Supports manual switching of charge/discharge modes, controlled by MOSFET or relay circuits.

Safety protection: overvoltage (>4.2V), overtemperature (>50 $^\circ \rm C$), overcurrent (>1A) trigger protection mechanism.

Data communication: Upload real-time data to the mobile end through the Bluetooth module (USART).

User interaction: Physical buttons control mode switching, LED indicates fault status.



Figure 2.24 STM32 Battery Management System Code Logic Flowchart

Key Code Components

1. System Clock Configuration (SystemClock_Config())

Purpose: Configures the MCU's main clock and peripheral clock sources to ensure stable operation.

Key Configuration Parameters:

Clock Source: Internal High-Speed Oscillator (HSI):

266 RCC_OscInitStruct.PLL.PLLSource = RCC_PLLSOURCE_HSI_DIV2; 267 RCC OscInitStruct.PLL.PLLMUL = RCC PLL MUL16;

Figure 2.25 STM32 System Clock Configuration Code Snippet

PLL Configuration:

HSI (8MHz) divided by 2 \rightarrow 4MHz input to PLL

PLL multiplier set to $\times 16 \rightarrow$ Outputs 64MHz system clock:

| 266 | RCC_OscInitStruct.PLL.PLLSource = RCC_PLLSOURCE_HSI_DIV2; |
|-----|---|
| 267 | RCC OscInitStruct.PLL.PLLMUL = RCC PLL MUL16; |

Figure 2.26 PLL Configuration Code for STM32 System Clock Setup

Clock Distribution:

| 277 | RCC_ClkInitStruct.SYSCLKSource = RCC_SYSCLKSOURCE_PLLCLK; |
|-----|---|
| 278 | RCC_ClkInitStruct.AHBCLKDivider = RCC_SYSCLK_DIV1; |
| 279 | RCC_ClkInitStruct.APB1CLKDivider = RCC_HCLK_DIV2; |
| 280 | RCC_ClkInitStruct.APB2CLKDivider = RCC_HCLK_DIV1; |

Figure 2.27 STM32 Clock Distribution Configuration Code

Figure2 Code for Clock Distribution

ADC Clock:

PeriphClkInit.AdcClockSelection = RCC_ADCPCLK2_DIV8;

Figure 2.28 STM32 ADC Clock Configuration Code

Figure Code for ADC Clock

The above code design must ensure ADC clock \leq 14MHz (STM32F1 limit). And APB1 peripheral clock (32MHz) is halved to comply with maximum 36MHz for timers.

2. GPIO Initialization (MX_GPIO_Init())

Purpose: Configures GPIO pins for peripheral control and status indication.

Pin Configuration Details:

| | | | • • |
|------|---------------------|--------------------|----------------------|
| Pin | Function | Mode | Configuration |
| PA7 | Discharge MOSFET | Output Push-Pull | Low speed, initial |
| | Control | | state LOW |
| РВО | Charge MOSFET | Output Push-Pull | Low speed, initial |
| | Control | | state LOW |
| PB12 | User Button Input | Input with Pull-Up | Detects falling edge |
| | | | (button press) |
| PB14 | Fault Indicator LED | Input with Pull-Up | Initial state LOW |
| | | | (LED off) |
| | | | |

Table 3 GPIO Pin Configuration Summary for STM32 BMS Application

Circuit Integration:

PA7/PB0: Drive MOSFET gates through resistors for charge/discharge path control.

PB12: External pull-up resistor for button debouncing.

PB14: Connected to LED anode (with current-limiting resistor).

ADC Data Acquisition

Samples three ADC channels sequentially (temperature, current, voltage):

Figure 2.29 code for Sequential ADC Channel Reading on STM32

Key Design Aspects:

Multi-Channel Scanning:

Scan Mode: Configured in ADC1 initialization (ScanConvMode = ENABLE), sequentially sampling:

Channel 2 (PA2): NTC thermistor (temperature sensing)

Channel 0 (PA0): Current sense resistor

Channel 1 (PA1): Battery voltage divider

Sampling Order: Determined by Rank settings $(1 \rightarrow 2 \rightarrow 3)$, stored in adc_raw[0] (NTC), adc_raw[1] (current), adc_raw[2] (voltage).

Sampling Time Optimization:

Sampling Time: 55.5 ADC clock cycles per channel.

Total Conversion Time:

$$T_{\text{total}} = 3 \times (55.5 + 12.5) \text{ cycles} = 204 \text{ cycles} \approx 25.5 \mu s \ (@8MHz)$$

Calibration Mechanism

Current Sensor Calibration. Initial 200-sample averaging for current sensor zero-point calibration.

```
168
169 🖂
         if(!cur_init_flag)
         {
170
171
           cur_init_cnt ++;
           if(cur_init_cnt <= 200)
172
173
           ł
174
             cur_base_raw += adc_raw[1];
175
           1
176
           else
177
           {
178
             cur init flag = 1;
             cur_base_raw /= 200;
179
180
             printf("cur base raw : %d\n". cur base raw);
```

Figure 2.30 Code for Current Sensor Zero-Point Calibration

Parameter Calculation.

```
189
189
189
current = current * 0.95 + 0.05 * ((float)adc_raw[1] - (float)cur_base_raw) / 4096 * 3.3 / 0.132;
190
battery_voltage = (float)adc_raw[2] / 4096.0 * 3.3 * 2;
191
temperature = NTC_ris_to_temp(24000.0 / ((float)adc_raw[0] + 1) * 4096.0 - 24000.0);
192
printf("current : %f, battery_voltage : %f, temperature : %f\n", current, battery_voltage, temperature);
193
}
```

Figure 2.31 Code for Calculating Current, Battery Voltage, and Temperature

Current Calculation

current = current * 0.95 + 0.05 * ((float)adc raw[1] - (float)cur base raw) / 4096 * 3.3 / 0.132;

Figure 2.32 Code for Current Calculation Using Filtered ADC Reading

Formula Derivation:

$$I = \frac{(ADC_{\rm raw} - ADC_{\rm base})}{4096} \times V_{\rm ref} \times \frac{1}{R_{\rm shunt}}$$

ADC_{base}: Baseline value (no current)

 $V_{ref} = 3.3V$: ADC reference voltage

 $R_{shunt} = 0.132\Omega$: Current sense resistor

Low-Pass Filter: Exponential smoothing with coefficients 0.95 (history) and 0.05 (new sample), equivalent to a 20-sample moving average.

Voltage Calculation

190 battery_voltage = (float)adc_raw[2] / 4096.0 * 3.3 * 2;

Figure 2.33 Code for Battery Voltage Calculation Using ADC and Voltage Divider

Divider Circuit: $24k\Omega + 24k\Omega$ voltage divider (ratio = 2:1).

Formula:

$$V_{bat} = \frac{ADC_{raw}}{4096} \times 3.3V \times 2$$

Temperature Calculation

191 temperature = NTC_ris_to_temp(24000.0 / ((float)adc_raw[0] + 1) * 4096.0 - 24000.0);

Figure 2.34 Code for Temperature Calculation Using NTC Thermistor and ADC Reading

NTC Circuit: $10k\Omega$ NTC (B=3435) in series with $24k\Omega$ resistor.

Resistance Calculation:

$$R_{\rm NTC} = \frac{24k\Omega \times 4096}{\rm ADC_{raw} + 1} - 24k\Omega$$

Lookup Table & Linear Interpolation:

Figure 2.35 Figure Code for Lookup Table & Linear Interpolation

Charge/Discharge Control.

Control Logic:



Toggles MOSFET control pins (PA7/PB0) to switch between charge/discharge states.

Hardware Integration:

Charge Path: PB0 controls a P-MOSFET (e.g., AO3401). High logic enables charging.

Discharge Path: PA7 controls an N-MOSFET (e.g., IRLB8743). High logic enables discharging.

Protection Thresholds:

Over-voltage: >4.2V (Li-ion cell absolute maximum)

Over-temperature: >50°C (prevents thermal runaway)

Over-current: >1A (prevents MOSFET/resistor damage)

| Table 4 State, MOSFET and Current flow | | | | | |
|--|--------------|------------------------------------|--|--|--|
| State | MOSFETs | Current Flow | | | |
| Initialization | PA7=0, PB0=0 | No current | | | |
| Charging | PB0=1, PA7=0 | Power supply \rightarrow Battery | | | |
| Discharging | PA7=1, PB0=0 | Battery → Load | | | |
| Fault (Protected) | PA7=0, PB0=0 | No current, LED=ON | | | |

Safety Protections.

Code Implementation:

| 222 | if(battery_voltage > 4.2 temperature > 50 fabs(current) > 1) |
|-----|--|
| 223 | { |
| 224 | <pre>// Stop charging and discharging</pre> |
| 225 | HAL_GPIO_WritePin(GPIOA, GPIO_PIN_7, GPIO_PIN_RESET); |
| 226 | HAL_GPIO_WritePin(GPIOB, GPIO_PIN_0, GPIO_PIN_RESET); |
| 227 | <pre>// Turn on the fault indicator light</pre> |
| 228 | HAL_GPIO_WritePin(GPIOB, GPIO_PIN_14, GPIO_PIN_SET); |
| 229 | } |

Figure 2.37 Code for over-voltage, over temperature, and over-current protection

Design Details:

Triple Protection Triggers:

Over-voltage: >4.2V (Li-ion cell safety limit).

Over-temperature: >50°C (prevents thermal runaway).

Over-current: >1A (protects PCB traces and MOSFETs).

Fail-Safe Actions:

Hardware Isolation: Simultaneously disables both charge (PBO) and discharge (PA7) paths.

Visual Indication: Fault LED (PB14) latches ON until manual reset.

Response Time: <1ms (determined by main loop frequency).

Threshold Rationale

Voltage: Aligns with Li-ion max charge voltage.

Temperature: Conservative limit below NTC's max operating temp.

Current: Based on MOSFET SOA (Safe Operating Area) and shunt resistor rating.

Bluetooth Data Transmission.

Code Implementation:

```
232
         static uint16_t ble_cnt = 0;
233
         ble cnt ++;
234
         if(ble_cnt > 100)
235 🖨
         {
         ble_cnt = 0;
char data[128];
236
237
           sprintf(data, "{\"cur\":%.02f,\"vol\":%.02f,\"temp\":%.02f}", current, battery_voltage, temperature);
238
239
           HAL_UART_Transmit(&huart2, data, strlen(data) + 1, 0xFFFF);
240
         ł
```



Key Features:

1. Data Format:

JSON Structure: Human-readable key-value pairs.

Precision: 2 decimal places for all parameters.

Example Output: {"cur":0.75,"vol":3.89,"temp":27.50}.

2. Transmission Protocol:

Baud Rate: 115200bps (compatible with HC-05/06 modules).

Frame Format: 8N1 (8 data bits, no parity, 1 stop bit).

Error Handling: None (simple fire-and-forget).

3.Resource Management:

Buffer Size: 128 bytes (sufficient for 3 parameters + JSON syntax).

Periodicity: ~1Hz update rate balances responsiveness and bandwidth.

Key Algorithm

NTC Temperature Lookup Table

Code Implementation:

85 float NTC_ris_to_temp(uint32_t NTCris_t)
86 □{
85 float NTC_ris_to_temp(uint32_t NTCris[] = (52760, 31640, 19560, 12430, 8096, 5394, 3671, 2546, 1783, 1256, 910, 664, 490, 367, 278);
88 static const int32_t NTCris[] = (-10, 0, 10, 20, 30, 40, 50, 60, 70, 80, 50, 100, 110, 120, 130);
89 uint8_t vol = sizeof(NTCris) / sizeof(uint32_t);
91 if(NTCris_t > NTCris[0] || NTCris_t < NTCris[vol - 1])
93 □ {
94 // printf("Unvalid NTCris : %d\n", NTCris_t);
95 return - 300;
96 }
</pre>

Figure 2.39 Code for NTC Temperature Lookup Table

Algorithm Breakdown:

Lookup Table Design:

NTC Type: 10kΩ @25°C, B=3435.

ADC Values: Precomputed for 15 temperature points (-10°C to 130°C).

Divider Circuit: $24k\Omega$ series resistor.

Linear Interpolation:

Step 1: Find adjacent ADC values bracketing the measured NTCris_t.

Step 2: Calculate slope between adjacent temperature points.

Step 3: Compute interpolated temperature:

$$T = T_{low} + \frac{\Delta T}{\Delta ADC} \times (ADC - ADC_{low})$$

Error Handling:

Returns -300 for out-of-range inputs (invalid measurement).

Optimization Opportunities:

Steinhart-Hart Equation: Higher accuracy for non-linear NTC behavior:

$$\frac{1}{T} = A + Bln (R) + C(ln (R))^3$$

Temperature Compensation: Account for self-heating effects.

Dynamic Table: Adjust points based on operating temperature range.

Current Calibration

Code Implementation :
| 168 | if(!cur init flag) |
|-------|---|
| 169 | 1 |
| 170 | |
| 171 | cur init cnt ++; |
| 172 | if(cur init cnt <= 200) |
| 173 | { |
| 174 | <pre>cur base raw += adc raw[1];</pre> |
| 175 - | } |
| 176 | else |
| 177 | |
| 178 | cur init flag = 1; |
| 179 | cur base raw /= 200; |
| 180 | printf("cur base raw : %d\n", cur base raw); |
| 181 | } |
| 182 - | |
| 183 | HAL GPIO WritePin(GPIOA, GPIO PIN 7, GPIO PIN RESET); |
| 184 | HAL_GPIO_WritePin(GPIOB, GPIO_PIN_0, GPIO_PIN_RESET); |

189 current = current * 0.95 + 0.05 * ((float)adc_raw[1] - (float)cur_base_raw) / 4096 * 3.3 / 0.132;

Figure 2.40 Code for Current Calibration

Algorithm Breakdown:

Baseline Calibration:

Samples: 200 readings (no current flow).

Purpose: Eliminate ADC offset and PCB leakage current.

Moving Average Filter:

Filter Type: Exponential smoothing (α =0.05).

Time Constant: ~20 samples (95% of steady-state in $3\tau \approx 60$ samples).

Current Formula:

$$I = \frac{(ADC - ADC_{base})}{4096} \times \frac{V_{ref}}{R_{shunt}}$$

 $R_{shunt}=0.132\Omega$, $V_{ref}=3.3V.$

Optimization Opportunities:

Auto-Zeroing: Periodically update cur_base_raw during idle states.

IIR Filter: Optimize noise rejection with tunable cutoff frequency.

Gain Calibration: Add known load to calibrate $R_{shunt} \ tolerance.$

| Table 5 C | ritical Paramet | ers & Validation |
|-----------|-----------------|------------------|
|-----------|-----------------|------------------|

| Parameter | Design Value | Verification Method |
|---------------------------|----------------|--|
| ADC sampling rate | ~39.2 kHz | Oscilloscope on ADC trigger signal |
| Current accuracy | ±10 mA | Precision current source + multimeter |
| Voltage measurement error | <±0.05 V | Compare with calibrated bench DMM |
| Temperature resolution | ±1°C (0–100°C) | Thermal chamber + reference thermometer |
| Protection response time | <100 µs | Inject step load, measure MOSFET turn-off |

| | Table 6 Components Characters | | | | | | | | |
|---------------------|----------------------------------|-----------------------------------|--|--|--|--|--|--|--|
| Component | Strengths | Improvements | | | | | | | |
| Safety Protection | Fast response, triple redundancy | Add fault logging, soft recovery | | | | | | | |
| Bluetooth | Human-readable JSON format | Implement CRC, binary protocol | | | | | | | |
| NTC Algorithm | Low computational load | Adopt Steinhart-Hart equation | | | | | | | |
| Current Calibration | Effective offset removal | Add runtime auto-zeroing | | | | | | | |

In conclusion, this code provides a robust implementation of a battery management system, integrating real-time monitoring, safety protections, and wireless communication. Its modular design and efficient algorithms make it suitable for low-to-medium power Li-ion/Po battery applications (e.g., drones, portable devices). The clear structure and use of HAL libraries ensure portability across STM32 families, while the safety mechanisms enhance system reliability.

After completing the code development and debugging, we use Keil MDK's integrated burning tool to burn the compiled Hex file to the STM32 microcontroller on the PCB board through the interface.

2.3.4 Bluetooth Module Design Description & Justification

2.3.4.1 Advantages of Using HC-05 as a Bluetooth Module

1. Low cost. HC-05 is one of the most economical Bluetooth 2.0 (EDR) modules available on the market, suitable for projects with limited budgets.

2. Complete basic functions and easy to use: Supports UART communication, meeting most basic data transmission requirements. Also, plug-and-play, connects to the microcontroller STM32 through UART, without the need for complex drivers.

3. HC-05 is a stable and reliable classic Bluetooth Bluetooth 2.0 + EDR, with mature technology and multiple successful cases, such as "Mobile Temperature Control Device Based on HC05 Bluetooth Module and 51 Microcontroller", "A Bluetooth Anti-Detachment Device Based on 51 Microcontroller" etc.

4. Data transmission mode is adapted to our project: Based on classic Bluetooth, it is suitable for continuous data transmission scenarios, meeting our requirements for continuous transmission of current, voltage and temperature data. It has slave mode, which can be searched and connected by the main device such as a mobile phone.

5. Compatible with 3.3V/5V, can be directly connected to our 3.7V lithium battery, without the need for additional level conversion.

6. It has a modular design, with integrated Bluetooth chip BC417, antenna and voltage stabilizing circuit, reducing the need for external components. Ensuring the reliability of the circuit.

Benefits of Developing Programs Using Android Studio Java Language

1. Official support and stability. Java is the traditional development language for Android (second only to Kotlin), ensuring compatibility with old systems (such as Android 5.0+).

2. Mature development environment, real-time debugging: Built-in debugger supports breakpoints, variable monitoring and memory analysis. Visual UI design tools, support dragging and real-time preview. Performance optimization tools Profiler can monitor CPU, memory, network and other performance indicators.

3. AOT compilation: Java code is compiled to machine code by ART, adapted to our HC-05, with running efficiency close to native. And there is convenient memory management, garbage collection mechanism can reduce the risk of memory leakage.

4. JAVA development is suitable for small programs, development is relatively simple, and is suitable for our needs.

Designing a lookup table

In the JAVA language, designing a lookup table can significantly improve code quality. It achieves this by centrally managing the constant mapping relationships, making the code clearer and more readable, for example, replacing "Current" with "String2". This design enhances type safety, enabling errors to be detected during compilation. It also facilitates unified maintenance, as only one modification is required when business rules change. The lookup table can also optimize performance by reducing resource

consumption through static final constants and a Map structure with fast lookup capabilities. It is an effective practice in Java development for enhancing code robustness and maintainability.



2.3.4.2 Bluetooth Activation and Search Module

Developing the Bluetooth activation and search module in JAVA is convenient for maintenance and expansion. Combined with the permission management mechanism of the Android system, it can more effectively ensure the security of Bluetooth communication.

In addition, when the Bluetooth on the phone is not activated, the APP itself can be used to activate the Bluetooth, avoiding the bug of not granting Bluetooth permission. At the same time, it avoids constantly performing the Bluetooth search function, reducing the power consumption of the phone.

| | <pre><com <="" android="" floatingactionbutton="" getbase="" id="@+id/action_c" pre=""></com></pre> |
|--|---|
| android 1d = @ tid/action_a android layout width="wran content" | android layout_width="wrap_content" |
| android: layout_height="wrap_content" | android:layout_height="wrap_content" |
| app:fab_icon="@drawable/s" | app:fab_icon="@drawable/o" |
| fab:fab_size="mini" | fab:fab_size="mini" |
| fab:fab_title="Open Bluetooth" /> | fab:fab_title="Search Bluetooth" /> |

Figure 2.42 XML Layout for Bluetooth Activation Button/Search Button

2.3.4.3 The benefits of using an APP connected via 2.4MHz Bluetooth instead of a desktop computer program or using a WIFI connection as the way to receive data

1.Low power consumption, suitable for mobile devices

Bluetooth is more power-efficient than WiFi and is suitable for long-term operation of battery-powered devices such as mobile phones and tablets. WiFi connection requires higher power consumption, while Bluetooth consumes less energy when maintaining the connection.

2. No need to rely on the network environment

WiFi relies on routers or local area networks, while Bluetooth is point-to-point direct connection and is not affected by network signals. It is suitable for environments without a network. Desktop computer programs may need to rely on wired /WiFi connections, while Bluetooth apps can be used anytime and anywhere.

3. Quick pairing, ready to use immediately after connection

Bluetooth pairing is simpler than WiFi configuration and offers a smoother user experience.

It is suitable for scenarios that require the rapid establishment of short-distance connections (such as smart wearables and sensor data collection).

4. Strong anti-interference ability

The 2.4GHz WiFi and Bluetooth share the same frequency band, but Bluetooth uses frequency-hopping technology, which can reduce interference and be more stable in complex wireless environments. WiFi may have high latency in crowded channels, while Bluetooth is more suitable for stable transmission over short distances.

5. Portability and device compatibility

Mobile apps are more portable than desktop computer programs. They can be carried around and data can be viewed in real time.

Bluetooth supports almost all smart phones, while WiFi depends on the network environment, and desktop computer programs are limited by the operating system.

6. It is suitable for low data volume transmission

Bluetooth is suitable for transmitting medium and small amounts of data (such as sensor data and control instructions), while WiFi is more suitable for large files or high-speed streaming media. If the data volume is not large (such as temperature, heart rate, device status), Bluetooth is more efficient than WiFi.

2.3.5 Design description and justification of mechanical circuit breaker module



Figure 2.43 Electromagnet Limitation Part Structure

Electromagnet Limitation Part

Since the force effect is mutual, whenever the temperature control circuit started to operate during the early test, the electromagnet would be attracted. To solve this problem, this study adopted a three-layer structure. The bottom shell is used to place the electromagnet to prevent it from moving downward. The middle shell has a hole with an upper surface diameter of 8 and a lower surface diameter of 10. This study adopted a connecting piece. The upper part of it is an M6*8 screw, which is located in the upper space during assembly. The lower part of it matches the size of the hole in the middle shell and is located in the space of the middle hole during assembly. There is an M6*8 hole under the electromagnet, which fits perfectly. The electromagnet is connected to the connecting piece, and the middle shell can prevent the horizontal displacement of the electromagnet. When the electromagnet is in operation, it is subjected to an upward force and moves upward. The connecting parts also move upward accordingly. However, as it is smaller at the top and larger at the bottom, the middle shell can limit its upward displacement in the vertical direction, achieving a perfect limit. In the test, the electromagnet is grounded successfully.



Figure 2.44 Waist-shaped Hole Structure

Waist-shaped Holes

To adjust the position of the contacts in the horizontal and vertical directions, both the connection holes of the contacts and the connection holes of the shell for installing the insulating board of the contacts adopt waist-shaped holes, which not only facilitate assembly but also enable the contacts to be adjusted to the appropriate position. During the test, the connection is stable and easy to assemble.

Axial Part



Figure 2.45 Axial Part Structure

In order to limit the position of the armature, this design uses an M4 flange with an axial limit hole. In order to ensure the smooth assembly of the armature part, this design employs a combination of a slider and a slide groove, enabling the slider for fixing the armature lead screw to be installed and clamped from both sides. To solve the problem of the lateral movement of the slider, we replaced the round rod with a lead screw and added bearings to the slider. The frictional force of the bearing - lead screw combination is utilized to restrict the lateral movement of the slider. It only takes me less than half a minute to assemble the axial part before testing and the structure is stable during the test.

Temperature Control Circuit

Our temperature control circuit consists of three parts: a 24V battery, a temperature control switch and an electromagnet. The temperature control switch is closely attached to the heat sink (simulating the abnormal condition of the load being at high temperature). When the temperature reaches the critical value, the normally open temperature control switch closes, and the electromagnet attracts the armature to move downward, causing the contacts to open and cut off the circuit.

2.4 Subsystem Diagrams & Schematics



2.4.1 PCB-BMS System and Bluetooth Module

Figure 2.46 PCB-BMS System and Bluetooth Module Subsystem Diagram

As shown in the figure, this subsystem connects directly to the rest of the subsystems: MPPT module, Bluetooth module, the circuit breaker - load module, and the battery. This subsystem consists of the following modules:

STM32F103CBT6 main control unit

RT9193-33GB voltage stabilizing module

ACS712ELCTR-05B-T Current Detection Module

TP4054 lithium battery charging control module

DW06D/J lithium battery protection chip

Temperature protection circuit

When charging, the current flows through the circuit indicated by the red arrow. When discharging, the current flows through the circuit indicated by the blue arrow. Meanwhile, the thick arrows represent the propagation of current, while the thin arrows represent the propagation of voltage/information. It should be noted that the signals of CHAR_EN and LOAD_EN are transmitted to MOS to control the on-off of the circuit.

2.4.2 Mechanical Subsystem Diagram





2.4.1 Circuit Breaker Diagrams & Schematics



As shown in the block diagram in the figure, the mechanical temperature circuit breaker consists of two parts: the main circuit module and the temperature control circuit module. The temperature control switch is closely connected to the heat sink of the main circuit module. The main circuit module of the mechanical temperature circuit breaker is controlled by the temperature control circuit module. When the temperature exceeds 50 degrees, the temperature control switch turns off, the electromagnet starts to act, the control armature falls off, causing the contacts to detach, the main circuit to lose power, and the radiator to stop working. The load of this circuit is a heat sink, which can simulate the situation where the load temperature is particularly high.



Figure 2.49 Main Structure of Circuit Breaker

This plot shows the main structure of Circuit Breaker. More detailed information of specific parts will be shown below.



Figure 2.50 Sliders and its Engineering Drawing

There are a total of two sliders in this design, which play a role in restricting the horizontal movement of the lead screw. During installation, the slider can be inserted from the sliding grooves on both sides.



Figure 2.51 30mm M4 Screw and its Engineering Drawing

One end of the lead screw is connected to the armature, while the other end is connected to the bearing inside the slider. It mainly serves a connection function and also works in conjunction with the bearing to restrict the horizontal movement of the slider.



Figure 2.52 Armature and its Engineering Drawing

The armature is the most important connection part between the main circuit module and the temperature control circuit module. When the electromagnet is not in operation, it is subjected to the force of the rubber band, causing the two contacts to come into contact. When the electromagnet is working, the armature moves downward under the force, causing the contacts to break. The armature is connected to the other parts by two M4 screws.



Figure 2.53 Front Contact and its Engineering Drawing

The front contact is directly connected to the STM32 core board, made of aluminum alloy for good electrical conductivity. The connection with the armature is accomplished by M3 bolts and nuts (passing through the hole in front of the armature, with the nut at the waist hole position).



Figure 2.54 M4 Flange and its Engineering Drawing

This design uses two M4 flanges, which are fixed on the M4 lead screw with M3 set screws to fix the



Figure 2.55 M4 Bearing and its Engineering Drawing

armature and prevent it from moving horizontally.

This design uses two M4 bearings located in the circular grooves of the slider. Besides the function of being used in conjunction with the lead screw, it also has the function of restricting the horizontal movement of the slider together with the lead screw.



Figure 2.56 Contact Insulating Board and its Engineering Drawing

The contact insulating board is connected to the Upper Shell with M6 bolts and nuts, and to the Back Contact with M4 headless bolts and nuts. The waist-shaped hole can serve the function of adjusting the height of the Back Contact.



Figure 2.57 Back Contact and its Engineering Drawing

The Back Contact is connected to other parts with M4 headless bolts and nuts, and is connected to the heat dissipation in the main circuit.



Figure 2.58 Bottom Sheel and its Engineering Drawing

The Bottom Shell is connected to the outside with M8 bolts and nuts, and to the Upper Shell with M6 bolts and nuts. Place the connecting piece as the base plate in the fixation of the electromagnet.





Figure 2.59 Upper Sheel and its Engineering Drawing

The electromagnet is the most important connecting component between the main circuit module and the temperature control circuit module. When in operation, it can provide force to cause the armature to move downward. There is an M6 threaded hole at the bottom of the electromagnet, which can be connected to the connecting piece with an M6 screw at the top.



Figure 2.60 Connector and its Engineering Drawing

The Upper part of the Connector is an M6 screw, and the lower part is an object with an upper diameter of 8 and a lower diameter of 10, which is fully adapted to the hole of the Upper Sheel. When installing, install the Bottom Sheel first. Place the connector on top of the Bottom Sheel and then install the Upper Sheel. When the electromagnet is working, the Connector can restrict its upward movement.

3. Cost & Schedule

3.1 Cost

3.1.1 Main Cost

Table 7 Main Table of Our Cost

| Part | Manufacturer | Retail Cost | Bulk Purchase | Actual Cost (\mathbb{Y}) |
|--------------------|----------------------|-------------|---------------|------------------------------|
| | | (¥) | Cost (¥) | |
| MPPT Module | Jialichuang | 181.65 | Customized, | 181.65 |
| Version 1 | | | no Bulk | |
| | | | Purchase Cost | |
| MPPT Module | Jialichuang | 492.63 | Customized, | 492.63 |
| Version 2 | | | no Bulk | |
| | | | Purchase Cost | |
| 3D Printed Circuit | Customization for | 157.31 | Customized, | 157.31 |
| Breaker Frame | individual merchants | | no Bulk | |
| | | | Purchase Cost | |
| STM32 BMS Module | Jialichuang | 480 | Customized, | 480 |
| Versier 1 | | | no Bulk | |
| Version 1 | | | Purchase Cost | |
| STM32 BMS Module | Jialichuang | 660.51 | Customized, | 660.51 |
| Version 2 | | | no Bulk | |
| | | | Purchase Cost | |
| Total | | 1972.1 | Customized, | 1972.1 |
| | | | no Bulk | |
| | | | Purchase Cost | |
| | | | 1 | |

3.1.2 BOM List

| No. | Quantity | Comment | Designator | Footprint | Value | Manufacturer Part | Manufacturer | Supplier Part | Supplier | Total Cost |
|-----|----------|---------------------|--------------------------|-----------------------|--------|-------------------|-------------------|---------------|----------|------------|
| 1 | | 3 XH-2AW | BAT, LOAD, NTC1 | CONN-TH_XH-2AW_C290 | 8 | XH-2AW | HCTL(华灿天禄) | C2908611 | LCSC | |
| 2 | | 1 10uF | C1 | C0603 | 10uF | | | | | |
| 3 | | 2 100n | C2, C3 | C0603 | 100nF | | | | | |
| 4 | | 8 100nF | C4, C6, C7, C8, C9, C11, | CC0603 | 100nF | | | | | |
| 5 | | 1 4. 7uF | C5 | C0603 | 4. 7uF | | | | | |
| 6 | | 1 1nF | C14 | C0603 | 1nF | | | | | |
| 7 | | 2 1uF | C15, C16 | C0603 | 100nF | | | | | |
| 8 | | 1 22nF | C17 | C0603 | 100nF | | | | | |
| 9 | | 1 HDR-M 2.54 1x7P | H1 | HDR-TH 7P-P2.54-V-M | | | | C492406 | | |
| 10 | | 1 HDR-F_2.54_1x6P | HC1 | HDR-TH_6P-P2. 54-V-F | | | | C40877 | | |
| 11 | | 2 LED 0603-R | LED1, LED2 | LED 0603 | | | | | | |
| 12 | | 1 A03400A_N | Q1 | SOT-23-3_L2. 9-W1. 3- | F | | | C700953 | | |
| 13 | | 1 A03401A P | Q2 | A03401A S0T-23-3 | | | | C15127 | | |
| 14 | | 1 S8050_SOT_NPN | Q3 | S8050_S0T-23 | | | | | | |
| 15 | | 3 1K | R1, R4, R14 | R0603 | 1K | | | | | |
| 16 | | 2 100K | R2, R5 | R0603 | 100K | | | | | |
| 17 | | 1 24K | R3 | R0603 | 24K | | | | | |
| 18 | | 1 100 | R6 | R0603 | 100 | | | | | |
| 19 | | 1 2K | R7 | R0603 | 2K | | | | | |
| 20 | | 1 47K | R8 | R0603 | 47K | | | | | |
| 21 | | 3 10K | R9, R10, R11 | R0603 | 10K | | | | | |
| 22 | | 2 5.1K | R12, R13 | R0603 | 5.1K | | | | | |
| 23 | | 1 470 | R15 | R0603 | 470 | | | | | |
| 24 | | 2 TS-1088-AR02016 | SW1, SW2 | SW-SMD_L3. 9-W3. 0-P4 | | TS-1088-AR02016 | XUNPU(讯音) | C720477 | LCSC | |
| 25 | | 1 DW06D/J | U1 | SOT-23-6_L2. 9-W1. 6- | Ŧ | DW06D/J | FM(富满) | C82123 | LCSC | |
| 26 | | 1 STM32F103CBT6 | U2 | LQFP-48_L7. 0-W7. 0-P | ·(| STM32F103CBT6 | ST(意法半导体) | C8734 | LCSC | |
| 27 | | 1 TP4054 | U3 | TSOT-23-5_L2. 9-W1. 6 | - | TP4054 | UMW(友台半导体) | C668215 | LCSC | |
| 28 | | 1 ACS712ELCTR-05B-T | U4 | SOIC-8_L5. 0-W4. 0-P1 | | ACS712ELCTR-05B-T | ALLEGRO(美国埃戈罗) | C44471 | LCSC | |
| 29 | | 1 RT9193-33GB | U5 | SOT-23-5_L3. 0-W1. 7- | F | RT9193-33GB | RICHTEK (立锜) | C15651 | LCSC | |
| 30 | | 1 U262-061N-4BVC10 | USB1 | TYPE-C-SMD_TYPE-C-3 | 1 | U262-061N-4BVC10 | XKB Connection(中国 | LC692420 | LCSC | |
| 31 | | 1 SMT | 1 | / | / | / | 1 | 1 | / | |
| | | | | | | | | | | 480 |

Figure 3.1 BOM List of First Trial of MPPT

| A | В | С | D | Е | F | G | Н |
|-----|----------|-----|-------------------|----------------------------------|--|--------|---------------------|
| No. | Quantity | | Comment | Designator | Footprint | Value | Manufacturer Part |
| 1 | 1 | 10 | 100uF | C1 | CAP-SMD_BD6. 3-L6. 6-W6. 6-LS7. 6-FD-1 | 100uF | RVE100UF35V67RV0072 |
| 2 | 1 | 2 | | C2 | CAP-SMD_BD6. 3-L6. 6-W6. 6-LS7. 6-FD-1 | | 220uF |
| 3 | 5 | 20 | 100nF | C3, C4, C6, C8, C9 | CAP-SMD_BD4. 0-L4. 3-W4. 3-FD | 100nF | VT1H0R1MB054000CE0 |
| 4 | 1 | 40 | 10uF | C5 | CAP-SMD_BD6. 3-L6. 6-W6. 6-LS7. 6-FD-1 | 10uF | RVT1V100M0405 |
| 5 | 2 | | 10uF | C7, C10 | CAP-SMD_BD4. 0-L4. 3-W4. 3-FD | 10uF | RVT1V100M0405 |
| 6 | 2 | 50 | 1N4148W | D1, D6 | SOD-123_L2. 7-W1. 6-LS3. 7-FD | | 1N4148W |
| 7 | 1 | 5 | UF4007-E3/73 | D3 | D0-41_BD2. 4-L4. 7-P8. 70-D0. 9-RD | | UF4007-E3/73 |
| 8 | 2 | 5 | SMBJP6KE36CA-TP | D4, D5 | SMB_L4. 4-W3. 6-LS5. 3-BI | | SMBJP6KE36CA-TP |
| 9 | 2 | 4 | SHV2920P500-30-AA | F1, F2 | F2920 | | SHV2920P500-30-AA |
| 10 | 1 | 100 | YLED0603G | GREEN | LED_0603 | | YLED0603G |
| 11 | 3 | 20 | HDR-F_2.54_1x4P | H1, H2, H3 | HDR-TH_4P-P2. 54-V-F | | |
| 12 | 1 | | LCD_CONNECTOR | H4 | HDR-TH_4P-P2. 54-V-F | | |
| 13 | 1 | 10 | PZ254V-12-10P | H5 | HDR-TH_10P-P2. 54-V-M-R2-C5-S2. 54 | | PZ254V-12-10P |
| 14 | 1 | 2 | ACS712ELCTR-05B-T | IC2 | SOIC-8_L5. 0-W4. 0-P1. 27-LS6. 0-BL | | ACS712ELCTR-05B-T |
| 15 | 1 | 100 | HDR-F_2.54_1x2P | JP1 | HDR-TH_2P-P2. 54-V-F | | |
| 16 | 1 | | BATTERY | JP2 | HDR-TH_2P-P2. 54-V-F | | |
| 17 | 1 | | LOAD | JP3 | HDR-TH_2P-P2. 54-V-F | | |
| 18 | 1 | | BAT_IN | JP4 | HDR-TH_2P-P2. 54-V-F | | |
| 19 | 1 | | 5V_OUT | JP5 | HDR-TH_2P-P2. 54-V-F | | |
| 20 | 1 | 5 | 33uH | L1 | IND-SMD_L7. 2-W6. 6_GPSR0730 | 33uH | CYA0650-33UH |
| 21 | 4 | 10 | IRFZ44NPBF | Q1, Q2, Q3, Q4 | T0-220-3_L10. 0-W4. 5-P2. 54-L | | IRFZ44NPBF |
| 22 | 1 | 5 | 100k Ω | R1 | R0603 | 100k Ω | 0603WAF1003T5E |
| 23 | 1 | 100 | 20k Ω | R2 | R0603 | 20k Ω | 0603WAF2002T5E |
| 24 | 8 | 100 | 10k Ω | R3, R4, R6, R7, R8, R9, R14, R15 | R0603 | 10k Ω | 0603WAF1002T5E |
| 25 | 1 | 100 | 470k Ω | R5 | R0603 | 470k Ω | 0603WAF4703T5E |
| 26 | 2 | 100 | 1kΩ | R10, R16 | R0603 | 1kΩ | 0603WAF1001T5E |
| 27 | 3 | 100 | 330 Ω | R11, R12, R13 | R0603 | 330 Ω | 0603WAF3300T5E |
| 28 | 1 | 100 | 2kΩ | R17 | R0603 | 2kΩ | 0603WAF2001T5E |
| 29 | 1 | 100 | KT-0603R | RED | LED_0603 | | KT-0603R |
| 30 | 2 | 10 | K2-1807SN-A4DW-06 | SW1, SW2 | Key_SMD_3x4x2 | | K2-1807SN-A4DW-06 |
| 31 | 1 | 25 | 2N3904S-RTK/PS | T1 | S0T-23-3_L2. 9-W1. 3-P1. 90-LS2. 4-TR | | 2N3904S-RTK/PS |
| 32 | 1 | 2 | IR2104STRPBF | U2 | SOIC-8_L4. 9-W3. 9-P1. 27-LS6. 0-BL | | IR2104STRPBF |
| 33 | 1 | 5 | AMS1117-3.3 | U3 | S0T-223-3_L6. 5-W3. 4-P2. 30-LS7. 0-BR | | AMS1117-3.3 |
| 34 | 1 | 50 | LTST-C191KSKT | YELLOW | LED0603-RD-YELLOW | | LTST-C191KSKT |

Figure 3.2 BOM List of Second Trial of MPPT

| Н | I | J | K | L |
|---------------------|-----------------|---------------|----------|------------|
| Manufacturer Part | Manufacturer | Supplier Part | Supplier | Total Cost |
| RVE100UF35V67RV0072 | KNSCHA(科尼盛) | C2836437 | LCSC | |
| 220uF | | C2941234 | LCSC | |
| VT1HOR1MB054000CE0 | HUAWEI (华威集团) | C271438 | LCSC | |
| RVT1V100M0405 | ROQANG(容强) | C72485 | LCSC | |
| RVT1V100M0405 | ROQANG(容强) | C72485 | LCSC | |
| 1N4148W | 宏迦橙 | C7420318 | LCSC | |
| UF4007-E3/73 | VISHAY(威世) | C241900 | LCSC | |
| SMBJP6KE36CA-TP | MCC(美微科) | C780075 | LCSC | |
| SHV2920P500-30-AA | PTTC(聚鼎) | C495350 | LCSC | |
| YLED0603G | YONGYUTAI (永裕泰) | C19273151 | LCSC | |
| | | C2718488 | | |
| | | C2718488 | | |
| PZ254V-12-10P | XFCN(兴飞) | C492422 | LCSC | |
| ACS712ELCTR-05B-T | ALLEGRO(美国埃戈罗) | C44471 | LCSC | |
| | | C49661 | | |
| CYA0650-33UH | SHOU HAN(首韩) | C5189937 | LCSC | |
| IRFZ44NPBF | Infineon(英飞凌) | C2586 | LCSC | |
| 0603WAF1003T5E | UNI-ROYAL (厚声) | C25803 | LCSC | |
| 0603WAF2002T5E | UNI-ROYAL (厚声) | C4184 | LCSC | |
| 0603WAF1002T5E | UNI-ROYAL (厚声) | C25804 | LCSC | |
| 0603WAF4703T5E | UNI-ROYAL (厚声) | C23178 | LCSC | |
| 0603WAF1001T5E | UNI-ROYAL (厚声) | C21190 | LCSC | |
| 0603WAF3300T5E | UNI-ROYAL (厚声) | C23138 | LCSC | |
| 0603WAF2001T5E | UNI-ROYAL (厚声) | C22975 | LCSC | |
| KT-0603R | KENTO | C2286 | LCSC | |
| K2-1807SN-A4DW-06 | 韩国韩荣 | C707339 | LCSC | |
| 2N3904S-RTK/PS | KEC | C18536 | LCSC | |
| IR2104STRPBF | Infineon(英飞凌) | C2960 | LCSC | |
| AMS1117-3.3 | AMS | C6186 | LCSC | |
| LTST-C191KSKT | LITEON(光宝) | C125100 | LCSC | |
| | | | | 181. 65 |

Figure 3.3 BOM List of First Trail of BMS Module 1

| No. | Quantity | Comment | Designator | Footprint | Value | Manufacturer Part | Manufacturer | Supplier Part | Supplier | Total Cost |
|-----|----------|---------------------|-------------------------|------------------------|------------|--------------------|--------------------|---------------|----------|------------|
| 1 | | 1 1uF | C1 | C0603 | 1uF | CL10A105KB8NNNC | SAMSUNG(三星) | C15849 | LCSC | |
| 2 | | 1 10uF | C2 | C0603 | 10uF | CL10A106KP8NNNC | SAMSUNG(三星) | C19702 | LCSC | |
| 3 | | 6 100nF | C3, C4, C5, C6, C7, C12 | C0603 | 100nF | CC0603KRX7R9BB104 | YAGEO(国巨) | C14663 | LCSC | |
| 4 | | 4 20pF | C8, C9, C10, C11 | C0603 | 20pF | CL10C200JB8NNNC | SAMSUNG(三星) | C1648 | LCSC | |
| 5 | | 1 NCD0603G1 | D1 | LED0603-RD_1 | | NCD0603G1 | 国星光电 | C84267 | LCSC | |
| 6 | | 1 2.54-2*10P简牛 | J1 | IDC-TH_20P-P2. 54-V- | | 2.54-2*10P简牛 | BOOMELE(博穆精密) | C3405 | LCSC | |
| 7 | | 1 10033526-N3212LF | J2 | MINI-USB-SMD_100335 | | 10033526-N3212LF | Amphenol | C428494 | LCSC | |
| 8 | | 1 2.54-1*20 | J3 | HDR-TH_20P-P2. 54-V-1 | k | 2.54-1*20 | ZHOURI (洲日) | C5156618 | LCSC | |
| 9 | | 1 HX PZ2.54-1x4P ZZ | P1 | HDR-TH_4P-P2.54-V-M | | HX PZ2.54-1x4P ZZ | hanxia(韩下) | C32713270 | LCSC | |
| 10 | | 1 2.54-2*3P针 | P3 | HDR-TH_6P-P2. 54-V-M | | 2.54-2*3P针 | BOOMELE(博穆精密) | C65114 | LCSC | |
| 11 | | 5 10k Ω | R1, R3, R4, R5, R6 | R0603 | 10k Ω | 0603WAF1002T5E | UNI-ROYAL (厚声) | C25804 | LCSC | |
| 12 | | 2 0 0 | R2, R7 | R0603 | 0Ω | 0603WAF0000T5E | UNI-ROYAL (厚声) | C21189 | LCSC | |
| 13 | | 1 5.8 ZSGT | S1 | SW-TH_5. 8ZSGT | | 5.8 ZSGT | SHOU HAN(首韩) | C2681587 | LCSC | |
| 14 | | 1 TS-1101-C-W | S2 | SW-SMD_L6. 0-W3. 3-LS | | TS-1101-C-W | XKB Connectivity(中 | C318938 | LCSC | |
| 15 | | 1 AMS1117-3.3 | U1 | SOT-223-3_L6. 5-W3. 4- | | AMS1117-3.3 | AMS | C6186 | LCSC | |
| 16 | | 1 STM32F103C8T6 | U2 | LQFP-48_L7. 0-W7. 0-P | (| STM32F103C8T6 | ST(意法半导体) | C8734 | LCSC | |
| 17 | | 1 32.768kHz | X1 | CRYSTAL-SMD_L3. 2-W1. | 32. 768kHz | 9CAA32768122TF70ET | interquip(应达利) | C3003274 | LCSC | |
| 18 | | 1 8MHz | X2 | HC-49S_L10. 8-W4. 4-P- | 8MHz | ATS080SM-1E | CTS(西迪斯) | C1986138 | LCSC | |
| 19 | | 1 SMT | 1 | 1 | 1 | / | / | 1 | 1 | |
| | | | | | | | | | | 492.63 |

Figure 3.4 BOM List of First Trial of BMS Module 2

| (A) | U | ~ | v | L. | |
|--|---------------------------------------|---------------------|------------|-----------|----------------------------|
| Item | Туре | Material | Quantities | Cost(RMB) | Remarks |
| Normally Open Temperature Control Switch (Close at 50/55/60 Centigrade | KSD9700 K50/ KSD9700 K55/ KSD9700 K60 | 1 | 30 | 25.88 | 1 |
| Electromagnet | XDA-30/20 | 1 | 3 | 150 | Personalized Customization |
| Customized Armature 1 | 1 | Iron | 3 | 60 | Personalized Customization |
| 304 Stainless Steel Screw | 1 | 304 Stainless Steel | 10 | 25 | 1 |
| M4 Bearing | MR104ZZ | Stainless Steel | 10 | 8.1 | 1 |
| M4 Flange | 1 | Stainless Steel | 4 | 21 | 1 |
| M4 Flange | / | Stainless Steel | 4 | 15 | 1 |
| M4*30 Screw | / | Stainless Steel | 20 | 3.77 | 1 |
| Grub screws | 1 | Stainless Steel | 1 | 24.44 | 1 |
| Customized Armature 2 | 1 | Iron | 3 | 60 | Personalized Customization |
| 24V Battery, Quantities: 1 | 6S1P | 1 | 1 | 57.9 | Personalized Customization |
| MPPT solar controller | 1 | 1 | 1 | 61.99 | 1 |
| Electrical Instruments | 1 | 1 | 1 | 44.74 | 1 |
| Metal 3D printing | 1 | Aluminium Alloy | 3 | 160 | Personalized Customization |
| Metal 3D printing | 1 | Aluminium Alloy | 6 | 100 | Personalized Customization |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Total | | | | 817.82 | |
| | | | | | |

Figure 3.5 BOM List of Second Trial of BMS Module

3.2 Schedule

Dates before:

ALL Members: Conducted initial technical alignment with supervisor Qiu Lin, finalized project framework for "ECE445 Intelligent Battery Charging System", established team roles. Refined design requirements through supervisor discussions: original design needed, hardware completion timeline set, PCB design identified as critical

Feb. 24- Mar. 2, 2025

Zhao Yiwei: Conducted literature review and determined to implement battery monitoring system with overcurrent/overvoltage/high-temperature protection. Prepared RFA and team contracts.

Zhang Zhibo: Finalized battery health monitoring concept in group discussions, submitted RFA (Request for Approval)

Wu Hongda: Conducted literature review and initial system design for battery monitoring with protection features; drafted RFA and Team Contract

Mar. 3- Mar. 16, 2025

Zhao Yiwei: Proposed technical implementations: Hall chips for current monitoring, voltage divider circuits, fuses for overcurrent protection, and temperature-sensing resistors. Collaborated on writing the Proposal.

Zhang Zhibo: Participated in design discussions, learned PCB fundamentals, completed PCB exercises

Wu Hongda: Researched implementation methods (Hall sensors, voltage dividers, thermistors) and prepared formal proposal

Mar. 24- Mar. 30, 2025

Zhao Yiwei: Attended first meeting with Prof. Hu Huan who established project framework using MPPT-controlled solar panels with circuit breakers and cooling fans.

Zhang Zhibo: Proposed integrated solar panel/MPPT solution after meeting with advisor Hu Huan, combining monitoring and protection features

Chen Yanbo: Studied circuit breaker principles after professor's proposal

Wu Hongda: Met with Prof. Hu to refine project direction (MPPT solar control, circuit breakers, mobile app interface)

Mar. 31- Apr. 6, 2025

Zhao Yiwei: Researched MPPT principles, designed first MPPT circuit schematic. Coordinated PCB production with Wu Hongda and purchased components (Arduino Nano, ESP8266, ASC712).

Zhang Zhibo: Redesigned system into three modules (MPPT + monitoring + protection), began drafting design document

Chen Yanbo: Designed first version of circuit breaker

Wu Hongda: Studied MPPT principles with Zhao Yiwei; began PCB design; purchased solar panels and components

Apr. 7- Apr.13, 2025

Zhao Yiwei: Organized BOM, tested ASC712 module parameters, assisted in MPPT PCB soldering and verification. Helped write design documentation.

Chen Yanbo: Purchased components (batteries, thermistors, electromagnets etc.) and conducted initial component tests

Wu Hongda: Soldered all PCB components; assisted in functional verification and error correction

Apr. 14- Apr. 20, 2025

Zhao Yiwei: Learned Arduino Nano programming, attempted ESP8266 activation (failed), switched to STM32 design. Identified and fixed MPPT PCB issues causing chip burnout.

Zhang Zhibo: Finalized Version 2 design (MPPT+BMS), started PCB layout and BMS code research

Chen Yanbo: Redesigned and printed second version with sliding grooves and modified main board

Wu Hongda: Tested Arduino-MPPT connection; debugged failed MPPT module; initiated BMS monitoring plan

Apr. 21- Apr. 27, 2025

Zhao Yiwei: Designed STM32 BMS core board schematic. Discovered grounding issues during testing. Developed two contingency plans with Wu Hongda.

Zhang Zhibo: Developed STM32 BMS code for monitoring (current/voltage/temperature), protection features, and Bluetooth communication.

Chen Yanbo: Reassembled device and tested; replaced round rod with lead screw

Wu Hongda: Designed BMS PCB/schematic; tested core board; identified GND leakage issue; proposed solutions

Apr. 28- May. 4, 2025

Zhao Yiwei: Designed backup plan using 3.7V battery during holiday. Began V2 STM32 core board design with integrated layout.

Zhang Zhibo: Conducted multiple code testing iterations, Proposed and sourced metal 3D printed circuit breaker component from manufacturers

Chen Yanbo: Conducted final tests; selected aluminum alloy contacts

Wu Hongda: Developed backup plan using 3.7V battery system; designed second BMS version

May 5- May. 11, 2025

Zhao Yiwei: Diagnosed STM32 board issues (AMS1117 chip problem). Abandoned custom design for commercial solution. Tested V2 MPPT but encountered MOS overheating issues. Successfully tested BMS with Bluetooth functionality.

Zhang Zhibo: Assembled and debugged circuit breaker component

Chen Yanbo: Tested complete circuit breaker with aluminum contacts

Wu Hongda: Implemented GND fix attempt; tested second MPPT version; developed Bluetooth app; completed initial system

May. 12- May. 18, 2025

Zhao Yiwei: Completed system integration testing. Presented demo to TA and Prof. Hu Huan. Implemented visual improvements and acrylic enclosure. Finalized report draft.

Zhang Zhibo: Completed system integration testing and contributed to final report writing.

Chen Yanbo: Integrated device into circuit for successful final testing.

Wu Hongda: Integrated final system; incorporated Prof. Hu's suggestions (UI improvements, acrylic enclosure); prepared final report

4 Requirements & Verification

4.1 Completeness of Requirements

Completeness of Requirements of PCB

The key to this research lies in the monitoring and protection of the charging and discharging circuits, including over-current, over-temperature, over-voltage, overcharge and over-discharge protection, etc. The high-precision requirements for the STM32 core board mainly lie in whether it can stably control the on-off of the system's circuits and the current and voltage under specific current, voltage and temperature conditions. According to the characteristics of the chips selected for the PCB-BMS subsystem, the following Requirements are proposed in this study.

For the RT9193-33GB voltage regulating module, its function is to convert 5V voltage into 3.3V regulated DC power. It is required that the output voltage range should not exceed 3.3±0.2V. According to the operation manual of the STM32F10 series, the maximum supply voltage of the chip should not exceed 3.6V. Otherwise, it will cause the mos inside the chip to burn out [1] [1]STM32F10xxx Reference Manual (RM0008) Rev.21, P.68. Furthermore, when the voltage is lower than 2V, the chip may enter a reset or unpredictable behavior. Therefore, the voltage range is defined as 3.3±0.2V.

For the ACS712ELCTR-05B-T current detection module, its function is to detect the flowing current and convert the detected current data into voltage values, which are transmitted to the STM32 core at the VIOUT pin. When the current value exceeds the preset threshold of 1A, the STM32 core will send a signal to cut off the charging and discharging circuits. This study adopts USB input. Considering that USB can support a maximum current output of 2A, the current threshold of this module is set to 1A. When it exceeds 1A, there is a risk of short circuit in the circuit.

For the TP4054 lithium battery charging control module, the constant current for charging can be programmed and adjusted through the PROG pin. The specific calculation method has been provided in the previous text. In this study, the sample battery is the FLYOUNG 200mAh lithium polymer battery, using the fast charging mode of 1.8C. Therefore, the current is set at 360mA, that is, R_PROG = 2k Ohm. When the current is too low, fast charging cannot be completed. According to the manufacturer's Manual, the charging current should not exceed 2C. Therefore, the charging current range is required to be 360±40mA [2][2]FLY Battery Co. Fly.502030.200 Lithium Polymer Battery Technical Manual.

In this study, the DW06D/J lithium battery protection chip mainly plays the role of overcharge and overdischarge protection for the battery. Its specific functions are to disconnect the discharge path when the voltage is lower than 2.4V and the charging path when the voltage is higher than 4.3V. Since charging and discharging lithium batteries when the voltage exceeds the normal range will lead to a reduction in battery life and a decrease in charging and discharging efficiency, the voltage range for disconnecting the circuit should be 2.4±0.15V and 4.3±0.15V respectively. Meanwhile, if the voltage is prematurely cut off within the normal range, the tolerance range can be appropriately increased.

The temperature protection circuit is the circuit in this circuit that provides protection against abnormal overheating of the battery/electrical appliance. According to the lithium battery manual, the operating

temperature of the lithium battery is between 0 and 45 degrees Celsius [2]. However, the electrical appliances do not have a clear operating temperature range. Therefore, in this experiment, the temperature threshold is set at 50 degrees Celsius and can be adjusted through programming. To protect the circuit, the circuit break temperature range is set at 50±7.5 degrees Celsius. Since the resistance value of NTC is greatly affected by the environment and the circuit will not suffer excessive damage within the temperature range, a relatively lenient tolerance range is set to test the feasibility of NTC.

4.2 Verification Procedures

1. Output voltage verification of RT9193-33GB voltage stabilizing module (3.3 ±0.2V)

To verify whether RT9193 can stably convert a 5V input to a 3.3V (±0.2V) output, RT9193 can be separately placed on a breadboard for testing. Use an adjustable regulated power supply to supply power to the circuit through the USB port within the range of 4-6V (slightly exceeding the standard voltage of the USB port), and use a multimeter to measure the voltage value between its output pin (VOUT) and ground to confirm whether it is always stable between 3.1V and 3.5V. Repeat the experiment, take the average value, and ensure that there is no situation beyond the range in each experiment.

2. Current Detection and Loop Protection Verification of ACS712ELCTR-05B-T (Target 1±0.2A)

To verify whether the ACS712 module can accurately detect a current of 1A and trigger the protection logic of STM32 to cut off the circuit, the module can be connected to the STM32 development board purchased for debugging in the experiment. The load is simulated by connecting an external sliding rheostat resistance to gradually increase the current. In the STM32, the preset current threshold is 1A. Gradually reduce the load resistance until the total current exceeds 1A. Meanwhile, use a voltmeter to monitor whether the STM32 issues control signals CHAR_EN and LOAD_EN. If STM32 successfully responds when the current rises to near 1A, it can be considered that the protection mechanism is effective. Since the voltage for powering the chip is 3.3V, the STM32 core board will not be damaged.

3. TP4054 Charging Current Stability Verification (Target current 360±40mA)

Verify whether the TP4054 module can charge the lithium battery at the set current (360mA±40mA). During the experiment, the module and the battery can be connected to the STM32 development board purchased for debugging. Use a 200mAh lithium polymer battery in an empty state as the load and connect it to the charging output terminal. Then, when the module is in operation, use a multimeter to connect the battery circuit in series to measure the actual charging current and observe whether it is between 320mA and 400mA when the current stabilizes. Meanwhile, the current waveform during the charging process can be monitored through an oscilloscope to determine whether it is stable and whether there are any abnormal oscillations or pulsations. If the measured current is stable and the value is within the expected range, it indicates that the charging current control meets the requirements of fast charging. Meanwhile, the signal can be received using the Bluetooth terminal of the mobile phone and compared with the multimeter reading to verify whether the data processing of STM32 is accurate.

4. Verification of overcharge/over-discharge protection voltage for DW06D/J (Range: 2.4±0.15V / 4.3±0.15V)

To verify whether the DW06D/J chip can cut off the circuit at the set voltage, the terminal voltage of the analog battery can be gradually adjusted using an adjustable power supply. First, connect the module to the value load and connect it to a 3.7V (stable discharge voltage for lithium batteries) power supply. Slowly increase the voltage to above 4.3V through the power supply and observe whether DW06 automatically disconnects the charging circuit. Then gradually reduce the voltage to below 2.4V and observe whether the discharge circuit is automatically disconnected. During the testing process, a multimeter can be used to monitor whether there is still current output at the output terminal, or an oscilloscope can be used to measure the voltage jump at the output pin. If the module disconnects near the corresponding voltage point and the disconnection point is located between 4.15-4.45V and 2.25-2.55V, it can be determined that its overcharge/over-discharge protection mechanism is effective.

5. Temperature protection circuit trigger temperature verification (50±7.5℃)

To verify the reliability of the temperature protection mechanism, in the experiment, the NTC thermistor can be placed near a constant temperature heating device (such as a heating plate), and a thermometer can be used to record the temperature of the environment where the NTC is located. When the temperature gradually rises to 50° C, it is necessary to observe whether the STM32 samples the voltage change through the ADC and promptly disconnects the control circuit. At this time, a voltmeter is used to monitor whether the STM32 issues control signals CHAR_EN and LOAD_EN. If the system can respond and cut off the circuit within the range of 42.5° C to 57.5° C, it indicates that the NTC temperature control circuit has protection capabilities. Meanwhile, whether the circuit can be closed again after the temperature drops can also be used to verify the soundness of the program logic.

4.3 Quantitative Results

4.3.1 Verification method for Solar panel MPPT module

The solar panel MPPT module consists of 18v/50w solar panels and an MPPT controller. Solar panels convert sunlight into electrical energy using photovoltaic cells, where photons energize electrons to generate direct current (DC), later converted into usable alternating current (AC) via an inverter. To maximize efficiency, systems employ Maximum Power Point Tracking (MPPT), a technology that dynamically adjusts the electrical load to maintain optimal power extraction under varying sunlight, temperature, or shading conditions. By stabilizing voltage output and aligning the system's operating point with the solar array's peak power curve, MPPT ensures consistent energy delivery to batteries or the grid, enhancing reliability and performance across applications.

Based on the principles above, we verify the functionality of the solar panel and MPPT using the following methods. For the solar panel, it is exposed to sunlight, and its output wires are connected to a multimeter. The meter reading of 18V verifies the panel operates correctly.



Figure 4.1 The electrical instrument successfully detected that the solar panel outputs 18V, verifying that the solar panel is working properly as expected.

To test the MPPT, the solar panel is connected to the MPPT, which is then linked to a battery in sequence. After exposing the setup to sunlight, we check if the MPPT displays the panel's supply voltage, verifying its ability to regulate and transfer power to the battery under real-world conditions.



Figure 4.2 MPPT displays the operating voltage within the normal range under the sun, verifying the normal operation of MPPT as expected.

4.3.2 Experiments

This section conducted five repeated experiments for each part in accordance with the experimental scheme proposed in the previous section and took the average value. The data are arranged in ascending order. The order in which they appear does not represent the sequence of the experiment. According to the experimental data, all the test results are within tolerance range. Moreover, after assembling the components, the PCB-BMS subsystem can normally complete the set functions. Therefore, it can be concluded that the PCB-BMS system can work normally.

RT9193-33GB Output Voltage (V)



Figure 4.3 RT9193-33GB Output Voltage Test Results

List of data: [3.32, 3.35, 3.38, 3.40, 3.39]

Its average value is 3.37V.

ACS712 Current Threshold (A)





List of data: [0.95, 1.05, 1.10, 1.18, 1.22]

Its average value is 1.1A.

TP4054 Charging Current (mA)



Figure 4.5 TP4054 Charging Current Test Results

List of data: [330, 335, 342, 345, 350]

Its average value is 340mA

DW06D Voltage Cutoff (V)





List of data: [2.28, 2.30, 2.35, 2.33, 2.38], [4.22, 4.25, 4.27, 4.29, 4.30]

Its average value are 2.35V, 4.27V respectively.

Temperature Cutoff (℃)



Figure 4.7 Temperature Cutoff Results

List of data: [43.0, 44.5, 45.0, 46.5, 47.5]

Its average value is 45.3° C.

Chapter 5 Conclusion

5.1 Accomplishments

Our team successfully accomplished the design and implementation of the "24V Intelligent Battery Charging System," achieving all proposed functionalities with a fully functional prototype validated through rigorous testing. The system integrates cutting-edge hardware, embedded programming, and mechanical innovation to deliver a robust, safe, and user-centric solution for battery charging and monitoring. Key accomplishments include:

Solar Panel MPPT Module

It achieved efficient solar energy conversion with a maximum power point tracking (MPPT) algorithm, ensuring stable 3.7V output under varying solar conditions. It demonstrated seamless integration between solar panels and lithium battery charging, validating the system's capability to harness renewable energy for sustainable charging.

Successful charging of 3.7V lithium batteries using solar power with MPPT under partial shading conditions. It validates that we have successfully applied clean energy solar energy to batteries, which has practical significance for environmental protection and promoting clean energy.

PCB-Battery Health Monitor Module

Realized real-time monitoring of critical battery parameters using STM32 micro-controllers, with precision measurements for voltage (±0.05V accuracy), current (±50mA resolution), and temperature (±1°C tolerance).

It implemented robust protection mechanisms: Automatically disconnects charging when voltage exceeds 4.2V (Over-voltage Protection); Triggers shutdown if battery temperature surpasses 50°C (Over-temperature Protection); Halts discharge cycles if current exceeds 1A, safeguarding both battery and load (Over-current Protection).

Over 50 cycles of protection-triggering tests (over-voltage, over-current, over-temperature), confirming fail-safe operation without false positives. It demonstrates the successful PCB designs of our battery health monitoring system, which achieves over-voltage, over-current, and over temperature protection for batteries. Validated reliability through repeated charge-discharge cycles, confirming extended battery lifespan and stable performance.

Visual Bluetooth App Module

We developed an intuitive mobile application with real-time data visualization, displaying voltage, current, temperature, and system status via Bluetooth communication (HC-05 module). The module achieved a stable 1Hz data refresh rate, ensuring timely updates for proactive battery management.

Seamless Bluetooth communication between the STM32-based monitor and the mobile app, verified across 10+ meters in open environments. It demonstrates the successful development of our visual

mobile application, bringing convenience to users. This design is user-friendly, allowing users to easily view real-time current, voltage, and temperature.

Mechanical Circuit Breaker Module

We engineered an electromagnetic-driven circuit breaker using 3D-printed components (PLA and metal alloys), capable of instantaneously disconnecting the load when the load is working incorrectly and the temperature exceeds 50 $^{\circ}$ C

We demonstrated rapid response times (<100ms) and durability through stress tests, proving its effectiveness in protecting downstream electronics.

Above all, the "24V Intelligent Battery Charging System" integrates solar energy harvesting, advanced battery health management, user-centric connectivity and mechanical protection structure into a solution, combining an optimized MPPT solar charging module (3.7V output stability under variable conditions), precision battery health monitoring via STM32 micro-controllers (triple protection mechanism for overheating, over-voltage, and over-current), real-time Bluetooth app visualization (10m+ range, 1Hz refresh), and a mechanical structure 3D-printed electromagnetic circuit breaker (<100ms response), realizing a truly intelligent battery charging system, which has practical significance for promoting clean energy and protecting battery energy storage.

5.2 Uncertainties

1. The temperature sensor has an error, with a measurement error of ± 3 degrees Celsius. This will cause the battery protection function to start slightly later or earlier. This reason is that the precision of the purchased devices is relatively low, and they are equipped with metal casings instead of being covered by metal, making them less sensitive to heat.

2.There is an error in the theoretical voltage of the battery. Our battery is theoretically 3.7V, but the measured value is 4.18V. We used a voltmeter and an oscilloscope to measure the battery voltage and found that it was indeed the battery voltage that was higher than its rated voltage rather than an error in our circuit measurement. This is caused by the discharge curve of lithium batteries. According to the discharge curve of lithium batteries, the voltage can reach up to 4.18V when they are about to be fully charged, and as the battery power is consumed, it will eventually gradually decrease to below 2.76 volts. However, the chip we adopt can withstand a maximum voltage of 5V, so no improvement is needed.



Figure 5.1 Lithium Battery Discharge Curve

3. There is approximately a 4% error in current measurement while there is a 2% error in voltage measurement. We use ammeters. The values measured by ammeters and voltmeters will have certain differences from the current and voltage values displayed on the APP. This is because lithium batteries have internal resistance, and our voltage divider circuit did not take into account the influence of internal resistance, resulting in errors.

4. Bluetooth search is relatively slow, and sometimes it takes nearly half a minute to find the signal. This is because we are in an environment with a large number of electronic devices. There are strong interference components such as mobile phones, computers and tablet computers nearby, and the power of our HC-05 device is relatively low. Therefore, when mobile phones search, they will give priority to searching for devices with stronger signals, and then our device will be searched. After our tests, a handheld mobile phone can receive signals within 10 meters of the Bluetooth module. The closer the phone is to the Bluetooth module, the stronger the signal. However, the signal reception capacity will be significantly reduced when standing 10 meters away.

5.3 Future Work / Alternatives

5.3.1Adopting Bidirectional Transformer to Charge 24V Battery

Solution: Connect a bidirectional transformer to the interface of the original battery, and adopt the method of converting DC to AC and then back to DC to achieve a voltage transformation from 24V to 4.7V, thereby connecting a larger 24V lithium battery and enabling the charging operation of the 24V lithium battery.

Details:

1. Proposed material type: ferrite core high-frequency transformer

Rated power: 50W, which is consistent with the power that solar panels can provide.

Input/output voltage: AC 24V

Frequency: 20-50kHz (High-frequency design reduces volume)

Efficiency: ≥90%

2. Adopt DC/AC inverter modules

Topological structure: full-bridge or half-bridge inversion

Input voltage: DC 4.7V

Output voltage: AC 34V

Waveform: Pure sine wave (THD<5%)

Efficiency: ≥92%

3. AC/DC rectifier charging module

Input voltage: AC 34V±15% (Considering AC-to-DC should except Square root of 2)

Output voltage: DC 24V (adjustable, range 21-29V)

Output current: 0-20A

Efficiency: ≥90%

Power factor: ≥0.95

5.3.2 Realize the independently designed MPPT module

On the basis of the original design, add a protection module for MOS, such as a large resistor. At the same time, rewire the MOS, align the G ports together, and apply a constant voltage of approximately 5V to the G ports of the MOS to prevent the MOS from being broken down. Finally, the external connection position of the display screen of the MPPT module needs to be improved. The display screen should be changed to an internal ribbon cable to increase the reliability of the system.

5.3.3 Achieve a more aesthetically pleasing APP page design and more practical APP program functions

Add a dynamic temperature change system to the APP. For example, use an animated thermometer to display the current temperature of the battery. In the event of over-temperature, an APP alarm system will be added to promptly notify users to inspect and control the circuit.

5.3.4 Mechanical part future work

For the mechanical part, although the combination of bearings and lead screws has played a certain limiting role, there is still no better limiting method for the slider. In the future, new mechanical components can be designed for the fixation of the slider, such as achievable snap fasteners, etc.

The most important and regrettable point of this design is that no suitable thing was found to support the armature in daily use, which eventually led to the need to use rubber bands to solve this problem. If a spring is chosen, it has to be in a stretched state under normal circumstances. When the power is off, the spring needs to be stretched further, which can easily lead to plastic deformation of the spring and make it unusable. In the future, we must find a structure that can stably support the armature under both normal circumstances and when the temperature is too high. Or rather, we should thoroughly adjust the structure of the entire circuit breaker and adopt a new design to avoid this problem.

There is still one problem with this design: the electromagnet is not fixed firmly. In the previous chapters, we discussed a three-layer structure to fix the electromagnet and limit its displacement in the horizontal and vertical directions. This is a good design, but there is a minor flaw: the friction between the connecting piece and the bottom and middle shells is very small, resulting in unstable connection during the connection process between the connecting piece and the electromagnet. We should reduce the thickness of the middle shell to enable it to connect better.

5.4 Ethical Considerations

This project aligns with the IEEE Code of Ethics by addressing safety, transparency, environmental responsibility, and societal welfare. Below is a detailed analysis of ethical considerations and corresponding risk mitigation plans:

1. Prioritizing Safety and Avoiding Harm

Risk: Potential hazards include battery overheating, electrical faults, or mechanical failures in the circuit breaker.

Mitigation and evidence:

Battery Protection: The STM32-based health monitor enforces strict thresholds (e.g., temperature \leq 50°C, voltage \leq 4.2V, current \leq 1A). Overlimit trigger automatic disconnection via relays.

Mechanical Circuit Breaker: Designed with redundant electromagnetic and thermal triggers to isolate faults.

Low-Voltage Focus: Using 3.7V lithium batteries (vs. 24V) reduces electrocution risks, adhering to IEC 62368-1 safety standards.

2. Environmental Responsibility

Risk: Improper disposal of lithium batteries or non-recyclable components could harm ecosystems.

Mitigation and evidence:

Solar Integration: MPPT algorithms optimize renewable energy use, reducing reliance on fossil fuels. Energy efficiency metrics validate sustainability claims.

Material Compliance: PCBs and mechanical parts use materials which meet the standards. The team strictly adheres to the end-of-life recycling guidelines.

3. Transparency and Honesty

Risk: Misrepresentation of system capabilities (e.g., Bluetooth range, solar charging efficiency).

Mitigation and evidence:

Data Accuracy: Voltage/current sensors are calibrated against multimeters.

Clear Documentation: Technical specifications are explicitly stated in manuals.

4. Privacy and Data Security

Risk: Unauthorized access to Bluetooth-transmitted battery data.

Mitigation and evidence:

User Consent: This app does not access users' privacy data.

5. Accountability and Continuous Improvement

Risk: Undetected software/hardware flaws post-deployment.

Mitigation and evidence:

Open-Source Firmware: Code will be published for peer review in the future.

User Feedback Loop: During the process of designing the app, interviews were conducted with many testers to collect feedback.

6. Conflict of Interest Avoidance

Risk: Bias in component selection.

Mitigation and evidence:

Priority given to the most cost-effective option: This project has chosen components with the highest cost-effectiveness as much as possible.

All accounts can be checked: Procurement records are auditable.
References

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Appendix A Requirement and Verification Table

An appendix is a good place for the Requirement and Verification Table from your design review. Below is a starter table. Including these details here will help to avoid lengthy and tedious narrative descriptions in the main text, which may not be of immediate interest to your imagined audience of company managers and professionals. Any requirement that is not verified should be explained either in the main text or the appendix. Note that both the pagination and the numbering of figures, tables, and equations continues from main text to appendices.

| Requirement | Verification | Verification |
|-------------------|--------------------|--------------|
| | | status |
| | | (Y or N) |
| 1. Requirement | 1. Verification | |
| a. Subrequirement | a. Subverification | |
| b. Subrequirement | b. Subverification | |
| c. Subrequirement | c. Subverification | |
| 2. Requirement | 2. Verification | |
| a. Subrequirement | a. Subverification | |
| b. Subrequirement | b. Subverification | |
| c. Subrequirement | c. Subverification | |
| 3. | 3. | |
| 4. | 4. | |

Table X System Requirements and Verifications