iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** IV **Month of publication:** April 2026

DOI: https://doi.org/10.22214/ijraset.2026.79798

www.ijraset.com

Call: 08813907089 | E-mail ID: ijraset@gmail.com

Adaptive Duty Cycle Control for Safe and Efficient EV Fast Charging

Adikrishna S[1], Basil Baby[2], Caren Viji Mathew[3], Sooraj R[4], Neethu Salim[5], Jeena Joy[6]
[1, 2, 3, 4]*Dept. of EEE, Mar Athanasius College of Engineering, Kothamangalam, India*
[5]*Asst. Professor, Dept. of EEE, Mar Athanasius College of Engineering, Kothamangalam, India*
[6]*Assoc. Professor, Dept. of EEE, Mar Athanasius College of Engineering, Kothamangalam, India*

Abstract: Electric Vehicle (EV) charging technology currently faces critical challenges related to slow charging speeds and safety risks associated with overheating. Traditional Battery Management Systems (BMS) often lack the real-time adaptability required to handle rapid temperature fluctuations during high-current charging scenarios. This paper proposes an intelligent external control system designed to ensure fast, safe, and efficient battery charging by integrating a Dynamic Duty Cycle (DDC) control circuit with the existing BMS infrastructure. Utilizing an ESP32 microcontroller as the central processing unit, the system monitors the rate of temperature change (dT/dt) in real-time and employs automatic relay switching to manage thermal loads effectively. Theoretical analysis using the Arrhenius aging law validates that this approach significantly reduces battery degradation mechanisms. Furthermore, the hardware implementation demonstrates effective thermal peak clipping, ensuring the battery operates within safe thermal limits while optimizing the overall charging duration.

Index Terms: Dynamic Duty Cycle, Thermal Management, ESP32, Arrhenius Law, Fast Charging, EV Battery Safety, Lithium-Ion.

I. INTRODUCTION

The global transition to electric mobility is often hindered by the physical and technical limitations of the current charg-ing infrastructure. While improvements in battery chemistry have increased energy density, the ”thermal bottleneck” re-mains a persistent issue. This phenomenon occurs when high charging currents lead to rapid and dangerous internal heat buildup within the battery cells due to Joule heating and electrochemical entropy changes. As noted in recent studies and documented incidents, uncontrolled heat generation during the fast-charging process can lead to catastrophic failures, including thermal runaway and fire hazards.

Conventional Battery Management System (BMS) architec-tures typically rely on static charging protocols, such as the standard Constant Current-Constant Voltage (CC-CV) method. While effective for low-power applications or slow overnight charging, these static protocols do not account for the in-stantaneous thermal state of the battery cells during high-stress operations (1C to 3C charging rates). They often fail to react quickly enough to sudden temperature spikes, leading to cumulative thermal damage that degrades the Solid Electrolyte Interphase (SEI) layer.

This project aims to bridge this gap by developing an intel-ligent external control system that integrates seamlessly with the vehicle’s existing BMS to provide active, real-time thermal and current management. The primary objectives of this work are to develop a system that utilizes the high-performance ESP32 microcontroller for real-time monitoring, implements automatic relay switching between the vehicle’s internal BMS and an external DDC control circuit, and achieves optimal thermal management. By preventing overheating, the system aims to significantly extend the operational life of the battery pack. The proposed solution dynamically modulates the charg-ing duty cycle based on the computed rate of temperature rise (*dT/dt*), effectively balancing the critical trade-off between charging speed and thermal safety.

II. LITERATURE REVIEW

Current research in the field highlights the absolute neces-sity of active thermal control in modern EV battery systems to ensure both safety and longevity.

Zehui Lu et al. [1] proposed a control-oriented thermal-electrical model in their work titled ”Integrated Optimal Fast Charging and Active Thermal Management.” Their research demonstrated that combining fast charging algorithms with active thermal control significantly enhances safety, particularly in extreme ambient temperatures. Their method reduces thermal stress using predictive model-based control strategies that anticipate temperature rises before they become critical.

However, a significant disadvantage of their model is the high computational complexity required to solve the optimization problems in real-time, which makes it difficult to deploy on low-cost, low-power embedded hardware typically found in consumer charging equipment.

Dominic Karnehm et al. [2] introduced advanced machine learning approaches, specifically utilizing Long Short-Term Memory (LSTM) networks and Kolmogorov-Arnold Networks (KAN), for core temperature estimation. While their method provides highly accurate core temperature readings without the need for invasive sensors inside the cell—thus enhancing safety—it requires large datasets for training and substantial computational resources for inference. This limits its portabil-ity and increases the cost of implementation for mass-market applications.

Bibin et al. [3] provided a comprehensive review on ther-mal issues in Li-ion batteries, categorizing the various heat generation sources including ohmic, reaction, and polarization heat. Their work emphasizes the need for robust thermal management systems (TMS) but notes that passive cooling techniques often fall short during fast charging.

Leng et al. [4] experimentally quantified the relationship between operating temperature and electrochemical aging. They determined that operating Li-ion batteries above room temperature drastically accelerates aging rates due to side reactions at the electrode-electrolyte interface. Specifically, every 10◦C rise can halve the calendar life of the cell. Chen et al. [5] highlighted the critical issue of temperature gradients. During fast charging, the core of the battery can be significantly hotter than the surface. Standard surface-mounted sensors may delay the response of the BMS. Jaguemont et al. [6] focused on thermal modeling, pro-viding the foundational heat transfer equations that underpin modern BMS logic. This project addresses the gaps identified in these literature sources by proposing a hardware-based, computationally efficient DDC solution that runs on a standard ESP32 microcontroller, avoiding the need for expensive computational hardware while still providing robust thermal protection.

III. THEORETICAL FRAMEWORK AND ANALYSIS

The DDC control strategy is strictly grounded in fundamen-tal electrochemical and thermal principles. This section details the mathematical models governing the system's operation.

A. Thermodynamics of Battery Heating

The core principle of the DDC system is the management of the battery's internal thermal balance. The temperature rise in a lithium-ion cell is not instantaneous; it is governed by the thermal mass of the cell and the balance between heat generation and heat dissipation. The thermal behavior is described by the first-order differential thermal balance equation:

$$C_{th} \frac{dT}{dt} = \dot{Q}_{gen} - \dot{Q}_{diss} \tag{1}$$

Expanding the generation and dissipation terms:

$$C_{th} \frac{dT}{dt} = I^2 R_{int} - \frac{T_{cell} - T_{amb}}{R_{th}} \tag{2}$$

Where:

- C_{th} is the thermal heat capacity of the cell (J/K).
- R_{int} is the internal ohmic resistance (Ω).
- R_{th} is the thermal resistance to the ambient environment (K/W).
- I is the charging current (A).

During the "ON" phase of the duty cycle, the term I^2R_{int} is dominant, causing $\frac{dT}{dt}$ to be positive (heating). During the "OFF" phase of the DDC cycle, the current I becomes zero. Consequently, the heat generation term vanishes:

$$C_{th} \frac{dT}{dt} = 0 - \frac{T_{cell} - T_{amb}}{R_{th}} \tag{3}$$

This forces the rate of change $\frac{dT}{dt}$ to become negative, initiating active cooling. The DDC system exploits this physics by dynamically inserting these "OFF" periods exactly when the thermal inertia (C_{th}) can no longer absorb the generated heat, effectively clipping thermal peaks.

B. Electrochemical Aging Kinetics (Arrhenius Law)

Battery degradation is not linearly related to temperature; it is an exponential relationship. The growth of the Solid Electrolyte Interphase (SEI) layer, which is the primary cause of capacity fade, follows the Arrhenius equation for chemical reaction rates:

$$k = A \exp \frac{-E_a}{R_g T} \qquad (4)$$

Applying this to battery aging ($A^{\cdot}$):

$$A^{\cdot}(t) \propto \exp -\frac{E_a}{R_g T(t)} \qquad (5)$$

Where:

- E_a is the activation energy of the side reactions.
- R_g is the universal gas constant.
- $T(t)$ is the instantaneous temperature in Kelvin.

The exponential nature of this equation implies that even a small reduction in peak temperature (T) yields a dispropor-tionately large reduction in the aging rate ($A^{\cdot}$). By keeping the battery temperature below the critical 45°C threshold via DDC, the system maintains the reaction rate of SEI decom-position at a minimal level, significantly extending cycle life compared to standard charging methods where temperatures often exceed 50°C.

C. Concentration Polarization and Lithium Plating

Beyond thermal management, the DDC approach addresses electrochemical safety. During high-current charging, lithium ions (Li^+) move from the cathode to the anode.

$Li^+ + e^- + C6 \rightarrow LiC6$ (6)

However, diffusion within the graphite anode is slower than the ion transport through the electrolyte. This leads to a concentration gradient, or "Concentration Polarization." If the concentration of ions at the anode surface becomes too high, the potential drops, and metallic lithium plates onto the surface instead of intercalating.

$Li^+ + e^- \rightarrow Li(metal)$ (7)

The "Relaxation" periods introduced by the DDC logic allow time for the ions on the surface to diffuse into the bulk of the anode material. This effectively reduces the concentration gradient and surface overpotential, mitigating the risk of lithium plating and dendrite formation.

IV. SYSTEM CALIBRATION AND MATHEMATICAL MODELING

To ensuring precise control, the DDC logic parameters were not chosen arbitrarily. They were derived through a rigorous mathematical modeling of the specific battery cells used in the prototype.

A. System Identification Parameters

The physical properties of the 3S Li-ion battery pack were identified for calibration:

- Cell Mass (M): 0.045 Kg
- Specific Heat Capacity (Cp): 900 J/KgK
- Internal Resistance ($Rint$): 0.05 Ω
- Target Charging Current (Ich): 2.6 A

B. Heat Generation Calculation

First, the rate of internal heat generation ($Pheat$) during the continuous conduction phase was calculated using Joule's Law:

$$P_{heat} = I_{ch}^2 \times R_{int} \qquad (8)$$

Substituting the values:

$$P_{heat} = (2.6)^2 \times 0.05 = 6.76 \times 0.05 = 0.338 \text{ W} \qquad (9)$$

This represents the steady-state power dissipated as heat inside the cell.

C. Thermal Mass Capacity Determination

The thermal mass (MC) represents the energy required to raise the cell's temperature by one degree Kelvin. It determines the thermal inertia of the system:

$$MC = M \times C_p \quad (10)$$

$$MC = 0.045 \text{ Kg} \times 900 \text{ J/KgK} = 40.5 \text{ J/K} \quad (11)$$

D. Standard Rate of Rise Derivation

Using the relationship between power, thermal mass, and temperature change, we derived the theoretical rate of temper-ature rise (dT/dt) expected under normal conditions:

$$P_{heat} = MC \times \frac{dT}{dt} \Longrightarrow \frac{dT}{dt} = \frac{P_{heat}}{MC} \quad (12)$$

$$\frac{dT}{dt} = \frac{0.338}{40.5} \approx 0.008345\,^{\circ}\text{C/s} \quad (13)$$

To make this value usable for the microcontroller's logic loop (which runs in seconds/minutes), it was converted to a per-minute scale:

$$\frac{dT}{dt}_{minute} = 0.008345 \times 60 \approx 0.5\,^{\circ}\text{C/min} \quad (14)$$

E. Adaptive Control Logic Implementation

This calculated value of 0.5°C/min serves as the fundamen-tal baseline for the adaptive control algorithm. The firmware compares the real-time measured slope against this derived constant to determine the necessary cooling duration:

- Baseline (Standard Heating): If the measured $dT/dt \approx 0.5$°C/min, the system sets the DDC "OFF" time to 60 seconds. This matches the natural thermal time constant derived from the model.
- Optimization (Low Heating): If $dT/dt < 0.5$°C/min, indicating efficient heat dissipation, the "OFF" time is reduced to 30 seconds. This increases the effective duty cycle to speed up charging.
- Protection (High Heating): If $dT/dt > 1.0$°C/min, indicating thermal stress, the "OFF" time is extended to **90 seconds** to force deep cooling.

V. SYSTEM METHODOLOGY

The proposed methodology focuses on the seamless integra-tion of sensing, logic, and power control to achieve dynamic thermal regulation.

A. System Architecture and Signal Flow

The system architecture consists of five main stages:

- Input Stage: Ensures a stable power supply for the DDC circuit using a DC-DC converter.
- Sensing & Monitoring: Voltage, current, and temperature sensors continuously feed data to the ESP32
- Control & Logic: The ESP32 generates PWM signals to modulate the charging current based on thermal feedback.
- Charge Control: MOSFETs act as electronic switches, regulating the power flow to the battery pack.
- Output & Safety: An LCD display provides real-time status updates, while a cooling fan and buzzer are acti-vated during thermal events to prevent runaway.

In Fig. 1, the block diagram illustrates the closed-loop feedback mechanism where the ESP32 acts as the central coordinator between the sensor inputs (left) and the power stage outputs (right), isolating the BMS logic.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

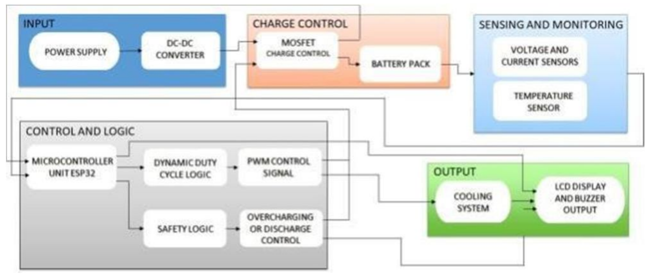


Fig. 1. Block diagram of Integrated Fast charging with DDC Control for EV Battery Charging & Thermal Management.

B. Circuit Implementation

The detailed circuit implementation centers around an ESP32 microcontroller interfacing with a high-current MOS-FET driver stage. *In Fig. 2, the circuit diagram reveals the*

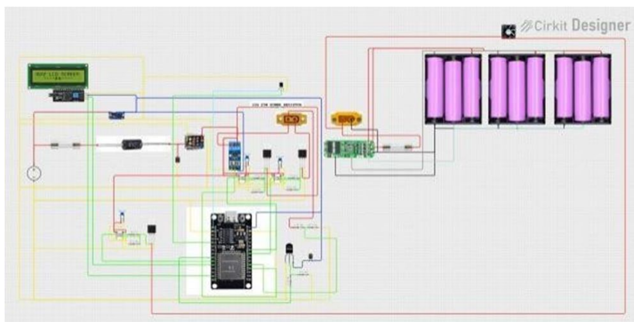


Fig. 2. Circuit diagram of ESP32-based Dynamic Duty Cycle Controlled Fast-Charging System.

specific wiring of the IRF540N MOSFET, the ACS712 current sensor, and the NTC thermistor to the ESP32 GPIO pins, which facilitates the DDC logic execution.

C. Algorithm Implementation and State Machine

The reliability of the system depends on the robust imple-mentation of the control firmware on the ESP32. The algorithm is structured as a Finite State Machine (FSM) to handle the transitions between standard charging and DDC thermal protection modes effectively.

1) State Definitions: The FSM consists of four primary states:

- IDLE / MONITORING: The system is in a passive state where it continuously reads data from the voltage, current, and temperature sensors. In this state, the ve-hicle's standard BMS controls the charging. The ESP32 calculates the rolling average of temperature to filter out sensor noise.
- ACTIVE DDC CHARGING: This state is triggered when the battery temperature (Tbat) exceeds the 45◦C threshold. The relay activates to bypass the BMS and engage the external DDC circuit. The MOSFET begins switching at the base duty cycle (D0).
- COOLING / RELAXATION: This state is entered periodically based on the adaptive timing logic derived In Section V. The MOSFET is turned OFF (D = 0), and the active cooling fan is engaged. The system remains in this state for 30, 60, or 90 seconds depending on the computed dT/dt.
- FAULT / SHUTDOWN: If any critical safety limits are breached (e.g., Vbat > 4.2V or Tbat > 60◦C), the system enters this latching state. All charging is disabled, the buzzer sounds a continuous alarm, and the system requires a manual reset.

2) Fault Detection and Safety Interlocks: Robust fault handling is a primary objective. The firmware includes specific checks:

- Over-Voltage Cutoff: Software interrupt triggers at 4.25V to prevent electrolyte breakdown.
- Sensor Continuity: The system checks for open-circuit faults on the NTC thermistor line. If the resistance reads infinity (broken wire), the system defaults to FAULT mode.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

VI. RESULTS AND SIMULATION

The system's performance was validated through both soft-ware simulation and hardware testing to ensure the control logic operates as intended.

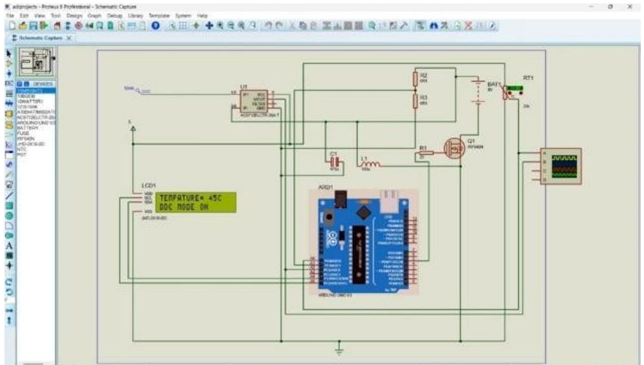


Fig. 3. Simulation Environment for DDC Control of EV's battery.

In Fig. 3, the Simulink model layout includes the battery plant, thermal model, and the switching logic blocks used to verify the DDC algorithm before hardware deployment.

A. Simulation Analysis

The simulation results illustrate the Temperature vs. Time profile with Exponential Cooling enabled. The graph clearly shows the temperature rising during the "ON" charge cycles and effectively decreasing during the DDC "OFF" cycles. This results in a "sawtooth" thermal profile that confirms that the DDC logic successfully clips thermal peaks, keeping the battery temperature below the critical safety limits.

In Fig. 4, the thermal trajectory shows the 'clipping' effect of the DDC logic, preventing the exponential runaway typi-cally seen in unmanaged CC-CV charging.

The accompanying Current vs. Time waveform confirms the PWM operation, cleanly toggling between the set charging current and zero amps during relaxation periods. This confirms

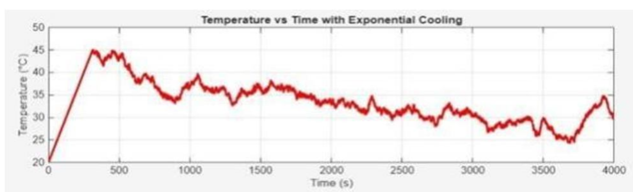


Fig. 4. Simulation Results: Temperature vs Time for DDC Control.

the logic correctly modulates the power stage based on the thermal feedback loop

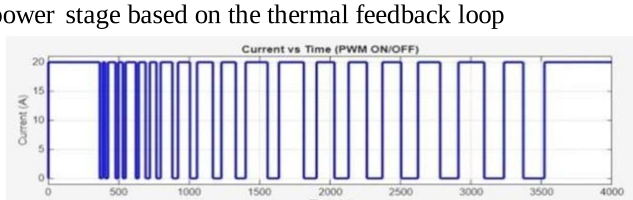


Fig. 5. Simulation Results: Current vs Time for DDC Control.

In Fig. 5, the current pulses demonstrate the duty cycle modulation, with clear relaxation periods where current drops to zero, allowing ion diffusion.

VII. HARDWARE ARCHITECTURE AND PCB DESIGN

This work presents a compact, product-level smart battery charging and control module designed for a 3S lithium-ion battery system. The proposed PCB integrates power conver-sion, protection, sensing, and digital control within a single hardware platform, enabling safe and controlled charging operation suitable for experimental and applied research.

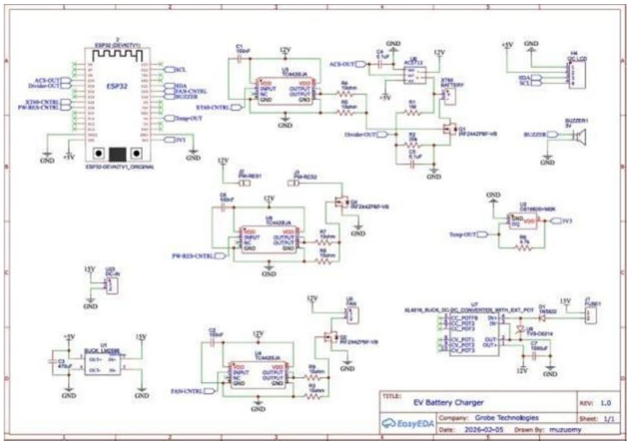


Fig. 6. PCB Schematic of the DDC Mode Battery Charging Module.

In Fig. 6, the detailed PCB schematic highlights the separa-tion of power and ground planes to minimize noise interference on the ADC lines from the switching regulators.

A. Power Input and Protection

The system operates from a 15 V DC input source. Input-stage protection is implemented using a series fuse for over current protection, a Schottky diode (1N5822) for reverse-polarity protection, and a TVS diode to suppress transient voltage spikes. Bulk decoupling is provided using a 1000 μF electrolytic capacitor, ensuring supply stability during load transients.

B. CC–CV Charging Stage

A dedicated CC–CV buck converter (XL4016-based) is employed to regulate the charging voltage and current for a 3S lithium-ion battery configuration. The converter is configured for a constant-voltage limit of 12.6 V, with output filtering implemented using a 470 μF capacitor to reduce ripple and improve regulation performance.

C. Battery Interface and Modular Configuration

The battery interface is implemented using an XT60 con-nector, enabling safe connection and disconnection of an external 3S4P modular battery bank. Each 3S battery module is intended to be independently fused, ensuring fault isolation and preventing uncontrolled circulating currents. This modular architecture enhances safety and scalability without requiring balance-node interconnections.

D. Current Sensing and Digital Current Control

Real-time current measurement is achieved using an ACS712 Hall-effect current sensor, providing galvanic isola-tion between the power and control domains. Charging current is digitally regulated using a low-side N-channel MOSFET, driven by a TC4420 gate driver IC, enabling fast switching and reduced switching losses. This arrangement supports PWM-based Digital Dynamic Current (DDC) control implemented by the microcontroller.

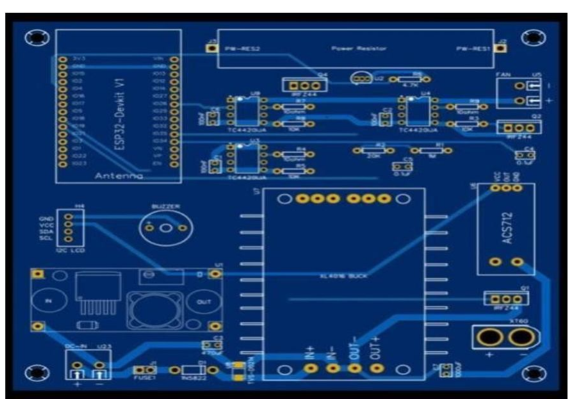


Fig. 7. Top view of the fabricated PCB module.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

In Fig. 7, the top view of the PCB assembly demonstrates the compact layout, with high-power components positioned near the edges for better thermal dissipation.

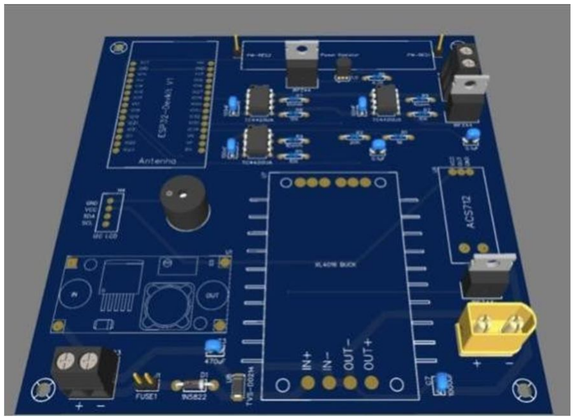


Fig. 8. Angled view of the PCB showing component placement.

In Fig. 8, the angled view provides perspective on the vertical clearance of capacitors and heatsinks, confirming the compact form factor suitable for integration.

E. Thermal Load and Cooling Control

A 10 Ω, 25 W power resistor is integrated as a control-lable thermal load to emulate high-current and thermal stress conditions. Active cooling is provided through a 12 V DC fan, controlled via a MOSFET-based low-side switch. Both elements are driven using dedicated MOSFET driver stages, allowing firmware-controlled thermal management.

F. Control Unit and User Interface

An ESP32 microcontroller serves as the central control unit, handling PWM generation, ADC-based sensing, thermal supervision, and system logic. The controller is powered via a regulated 5 V rail generated by an LM2596 buck converter, while internal logic operates at 3.3 V. System parameters are displayed on a 16×2 I^2C LCD, and audible alerts are generated using a buzzer driver stage.

G. Grounding and Layout Considerations

The PCB layout follows a star-grounding strategy, sepa-rating high-current power paths from low-level control and sensing circuits. High-current traces are routed with increased width and minimal length, while sensitive analog signals are isolated from switching nodes to reduce electromagnetic interference.

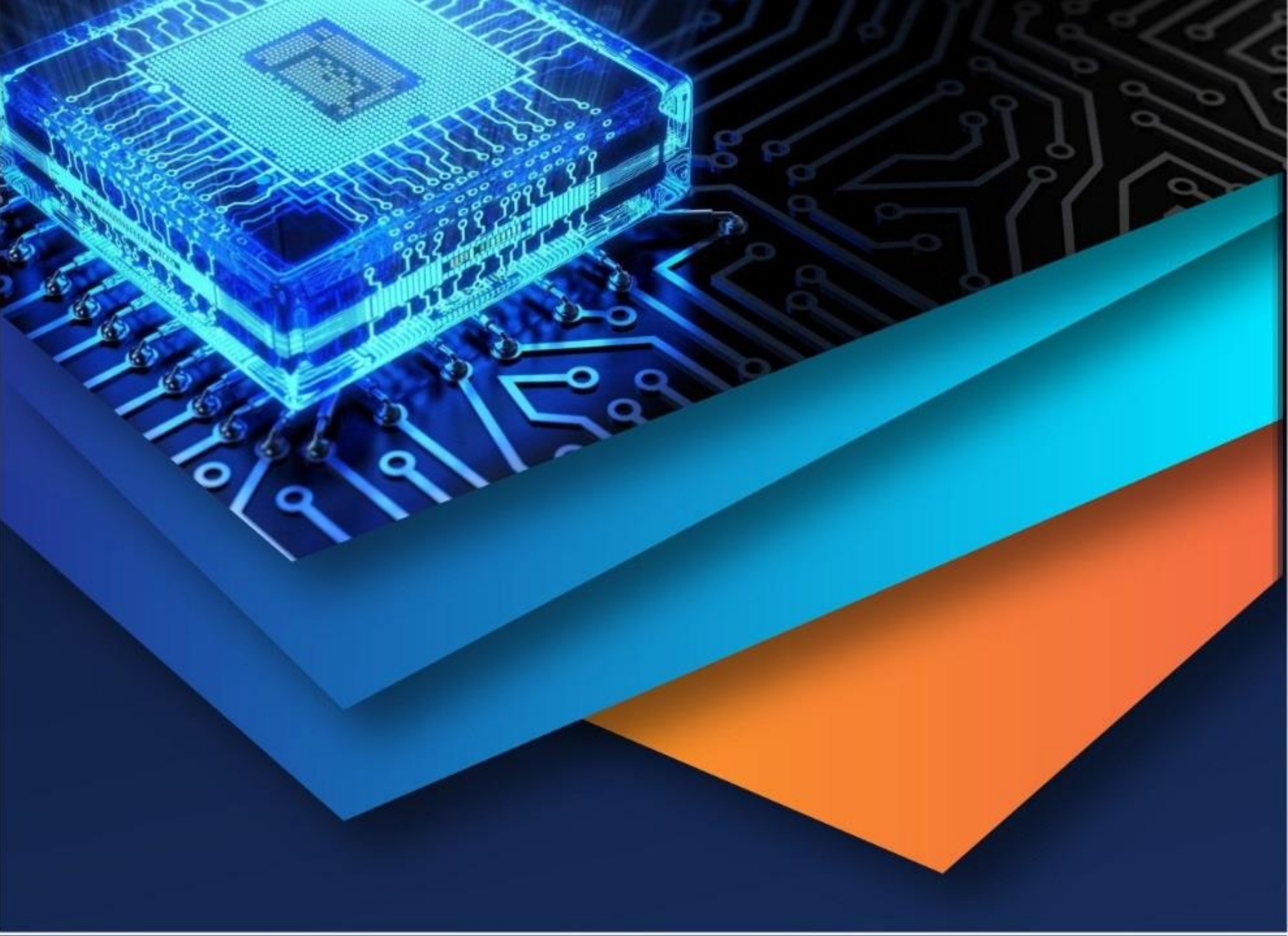
VIII. CONCLUSION

This project successfully developed a smart charging mod-ule that integrates Dynamic Duty Cycle control with standard BMS functions. The ESP32-based system provides real-time monitoring and adaptive control, mitigating overheating risks. The theoretical analysis using the Arrhenius law and thermal balance equations, combined with hardware validation, con-firms that the DDC approach extends battery life and enhances safety. The proposed modular PCB design offers a scalable platform for future EV battery management research.

REFERENCES

[1] Z. Lu et al., “Integrated Optimal Fast Charging and Active Thermal Man-agement of Lithium-Ion Batteries in Extreme Ambient Temperatures,” IEEE Trans. Power Electron., Mar. 2025.
[2] D. Karnehm et al., “Core Temperature Estimation of Lithium-Ion Batter-ies Using Long Short-Term Memory (LSTM) Network and Kolmogorov-Arnold Network (KAN),” IEEE TechRxiv, 2024.
[3] C. Bibin et al., “A review on thermal issues in Li-ion battery and recent advancements in battery thermal management systems,” Mater. Today: Proc., vol. 33, 2020.
[4] F. Leng et al., “Effect of temperature on the aging rate of Li-ion batteries operating above room temperature,” Sci. Rep., vol. 5, 2015.
[5] C. Chen et al., “Critical understanding of temperature gradient during fast charging of lithium-ion batteries,” IEEE, 2023.
[6] J. Jaguemont et al., “Thermal modeling of Li-ion battery systems for electric vehicles,” Renew. Sustain. Energy Rev., vol. 117, 2020.

©IJRASET: All Rights are Reserved



10.22214/IJRASET

INDEX COPERNICUS

45.98

IMPACT FACTOR: 7.129

TOGETHER WE REACH THE GOAL

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Call : 08813907089 (24*7 Support on Whatsapp)