Battery Thermal and Range Simulation of an Electric Two-Wheeler Using ESP32 Based 2RC Equivalent Circuit Model

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Abstract

Electric two-wheelers are becoming an important solution for sustainable transportation due to their reduced emissions and lower operating cost. However, battery overheating, high current stress, and inefficient energy usage remain major challenges that affect performance, safety, and lifespan of electric vehicles. This research presents a real-time battery thermal and range simulation model for an electric scooter implemented using an ESP32 microcontroller. The system integrates vehicle longitudinal dynamics with a second-order RC equivalent circuit model (2RC-ECM) to simulate lithium-ion battery behavior.

The model evaluates parameters such as throttle input, rider load, ambient temperature, regenerative braking, battery current, temperature rise, C-rate, power consumption, state of charge (SoC), and vehicle speed. Three analog inputs using potentiometers simulate real-world driving conditions. The ESP32 executes the simulation algorithm at 100 ms intervals and outputs the computed values through serial communication.

Simulation results demonstrate that aggressive acceleration, heavy rider load, and high ambient temperatures significantly increase battery temperature and current stress. Regenerative braking improves overall energy efficiency by returning kinetic energy back to the battery pack. The proposed embedded simulation platform provides a low-cost and flexible solution for studying electric vehicle battery behavior and evaluating overheating conditions. The system can be further extended for battery management system development and predictive thermal monitoring in electric vehicles.

Key words: Electric Vehicle, Lithium-Ion Battery, Battery Thermal Modeling, ESP32 Simulation, State of Charge, Regenerative Braking, Electric Scooter.

1. INTRODUCTION

Electric vehicles (EVs) have emerged as a promising solution for reducing carbon emissions and dependence on fossil fuels. Governments and automotive manufacturers worldwide are investing heavily in EV technologies to achieve sustainable transportation systems. Among the various EV categories, electric two-wheelers have gained widespread popularity in developing countries due to their affordability, efficiency, and suitability for urban transportation.

Electric scooters typically use lithium-ion battery packs to power their electric motors. These batteries provide high energy density, require relatively low maintenance, and offer a longer operational life compared to traditional lead-acid batteries. Despite these advantages, lithium-ion batteries are sensitive to temperature fluctuations and high current loads. Excessive temperature rise during aggressive acceleration or prolonged high-speed operation can result in battery degradation, reduced efficiency, and in extreme cases may lead to thermal runaway

Battery thermal behavior depends on several factors including discharge current, internal resistance, ambient temperature, and cooling conditions. Therefore, understanding battery performance under various driving conditions is essential for improving electric vehicle safety and efficiency.

Simulation models are widely used to analyze battery performance without requiring expensive hardware testing. Equivalent circuit models provide a simplified representation of battery electrical behavior while maintaining reasonable accuracy. When combined with vehicle dynamics models, these simulations can estimate current draw, power consumption, and thermal behavior during vehicle operation.

This research proposes a real-time simulation model implemented on an ESP32 microcontroller to analyze battery and vehicle performance in an electric scooter. The model integrates battery equivalent circuit modeling, vehicle dynamics, regenerative braking, and thermal modeling to create a comprehensive simulation environment.

The main objectives of this work include:

• Developing a real-time embedded EV battery simulation platform

• Implementing a second-order RC equivalent circuit battery model

• Analyzing battery temperature rise under different driving conditions

• Evaluating the effect of rider load and ambient temperature

• Studying regenerative braking energy recovery

The developed system provides a practical tool for understanding EV battery behavior and supports future development of intelligent battery management systems.

2. ELECTRIC VEHICLE BATTERY SYSTEM

Electric vehicles rely on high-capacity battery packs to supply electrical energy to the traction motor. In electric scooters, lithium-ion battery cells are typically arranged in series and parallel configurations to achieve the required voltage and capacity.

In the proposed model, the battery pack is represented as a 14-series lithium-ion cell configuration. Each cell has a nominal voltage of approximately 3.7 V, resulting in a pack voltage close to 52 V. The total battery capacity is approximately 67 Ah, which corresponds to the energy requirements of a typical electric scooter.

Battery packs consist of multiple components including:

• Lithium-ion cells

• Battery management system (BMS)

• Thermal management system

• Protection circuitry

The BMS plays a critical role in monitoring battery voltage, current, temperature, and state of charge. It ensures safe battery operation by preventing overcharging, deep discharge, and overheating.

During vehicle acceleration, the electric motor draws current from the battery pack. This current causes internal voltage drop due to internal resistance. The power delivered by the battery can be calculated using:

Power = Voltage × Current

Heat generation inside the battery is primarily caused by resistive losses:

Heat = I^2R

Where I represent battery current and R represents internal resistance.

This heat must be dissipated to maintain safe battery operating temperature. Continuous operation at high temperature accelerates battery aging and reduces cycle life. Therefore, thermal monitoring and management are essential components of EV battery systems.

3. BATTERY MODELING USING 2RC EQUIVALENT CIRCUIT

Equivalent circuit models are widely used to simulate battery electrical behavior. These models represent the battery using electrical components such as resistors and capacitors that mimic electrochemical dynamics. The second-order RC equivalent circuit model (2RC-ECM) is commonly used in EV simulations because it provides a good balance between accuracy and computational efficiency.

The model consists of:

• Open Circuit Voltage (OCV)

• Internal resistance (R0)

• Two RC polarization branches (R1C1 and R2C2)

The battery terminal voltage is given by:

$$V = OCV - I(R0) - V1 - V2$$

Where V1 and V2 represent voltage drops across the RC networks. These RC branches simulate transient voltage behavior caused by electrochemical polarization. When current flows through the battery, these capacitive elements store and release energy, producing dynamic voltage response.

The state of charge (SOC) of the battery is updated using coulomb counting:

$$SOC = SOC - (I \times \Delta t) / Q$$

Where Q represents battery capacity.

The 2RC model is computationally efficient and suitable for real-time embedded simulation on microcontrollers such as the ESP32.

4. VEHICLE LONGITUDINAL DYNAMICS

Vehicle motion is determined by the forces acting on the vehicle. These forces include traction force produced by the motor and opposing forces such as aerodynamic drag and rolling resistance. The traction force is generated by the motor torque transmitted through the wheel.

$$Ftractive = Torque / Wheel\ Radius$$

The opposing aerodynamic drag force can be expressed as:

$$Fdrag = 0.5 \times \rho \times Cd \times A \times v^2$$

Where ρ represents air density, Cd represents drag coefficient, and v represents vehicle speed.

Rolling resistance is calculated as:

$$Froll = Cr \times m \times g$$

Where Cr is rolling resistance coefficient, m is vehicle mass, and g is gravitational acceleration.

The vehicle acceleration can be calculated using Newton’s second law:

$a = (F_{tractive} - F_{drag} - F_{roll}) / m$

Vehicle speed is then updated continuously based on the calculated acceleration. This dynamic model allows simulation of realistic scooter motion during acceleration and deceleration.

5. THERMAL MODELING

Battery temperature rise occurs due to internal resistive heating when current flows through the battery. The thermal behavior of the battery can be modeled using a simplified heat transfer equation.

The rate of temperature change is expressed as:

$dT/dt = (Q_{gen} - Q_{cool}) / C_{thermal}$

Where Qgen represents heat generated due to internal resistance and Qcool represents cooling heat dissipation.

Heat generation is calculated as:

$Q_{gen} = I^2R$

Cooling is modeled using a heat transfer coefficient dependent on vehicle speed.

$Q_{cool} = UA\ (T_{battery} - T_{ambient})$

As vehicle speed increases, airflow improves battery cooling efficiency. The thermal capacity of the battery determines how quickly temperature changes occur.

This thermal model enables prediction of battery overheating scenarios during aggressive driving conditions.

6. ESP32 HARDWARE IMPLEMENTATION

The simulation model is implemented on an ESP32 microcontroller. The ESP32 is widely used in embedded systems due to its high processing capability, built-in ADC channels, and Wi-Fi connectivity.

Three potentiometers are used to simulate real-world input parameters:

1. THROTTLE POSITION (0–100%)

2. RIDER LOAD (40–150 KG)

3. AMBIENT TEMPERATURE (30–50°C)

These inputs are read using the 12-bit ADC of the ESP32. The simulation algorithm processes these inputs and calculates battery and vehicle parameters every 100 milliseconds.

The outputs include:

- Battery current
- Battery temperature
- Vehicle speed
- Battery power
- State of charge

• Regenerative braking status

All results are transmitted through serial communication for visualization and analysis.

7. REGENERATIVE BRAKING

Regenerative braking improves EV efficiency by converting kinetic energy into electrical energy during deceleration. When the throttle input becomes zero and vehicle speed remains above a threshold value, the motor operates as a generator.

The generated electrical energy is fed back into the battery pack, reducing overall energy consumption.

However, regenerative braking is limited by several constraints:

• Maximum regenerative current

• Battery state of charge limits

• Minimum vehicle speed

These constraints prevent battery overcharging and ensure safe operation. The simulation model implements these conditions to replicate realistic EV regenerative braking behavior.

8. SIMULATION RESULTS

Simulation experiments were conducted under different operating conditions to analyze system performance.

Case 1: Normal Driving

Throttle = 40%, Rider Load = 70 kg, Ambient Temperature = 30°C

Battery current remains moderate and temperature rise is minimal.

Case 2: Aggressive Acceleration

Throttle = 90%

High current draw increases C-rate and battery temperature.

Case 3: Heavy Rider Load

Load = 150 kg

Increased mass requires higher traction force, resulting in greater battery current.

Case 4: High Ambient Temperature

Ambient temperature = 42°C

Cooling efficiency decreases, causing faster battery temperature rise.

These simulations highlight how driving conditions significantly influence battery performance.

9. ADVANTAGES OF THE PROPOSED SYSTEM

The developed system provides several advantages for EV research and education.

• Low-cost hardware implementation

• Real-time embedded simulation

• Adjustable driving parameters

• Useful for battery thermal studies

• Scalable platform for future research

The system can be extended by integrating real sensors and communication protocols used in electric vehicles.

10. CONCLUSION

This research presented an ESP32-based real-time simulation platform for analyzing battery thermal behavior and vehicle dynamics in electric scooters. The system integrates a 2RC equivalent circuit battery model with vehicle longitudinal dynamics and regenerative braking.

Simulation results demonstrate that aggressive acceleration, heavy rider load, and high ambient temperature significantly influence battery temperature and current stress.

The proposed system provides a practical platform for studying EV battery performance and supports development of advanced battery management systems.

Future work will focus on integrating real battery sensors, implementing predictive thermal monitoring algorithms, and developing cloud-based data analysis for electric vehicle diagnostics.

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