iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: XII Month of publication: December 2025
DOI: https://doi.org/10.22214/ijraset.2025.76327

MATLAB - Simulink Based Analysis of Lithium-Ion Battery Charging, Discharging and SOC Estimation

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Abstract: Lithium-ion batteries are widely used in electric vehicles and energy storage systems due to their high energy density, long cycle life, and stable performance. Accurate analysis of charging, discharging, and State of Charge (SOC) estimation is essential for reliable Battery Management Systems (BMS). This research presents a complete MATLAB–Simulink based simulation framework that models the dynamic behavior of a single lithium-ion cell using CC–CV charging and controlled discharging. The model integrates electrical, thermal, and SOC estimation subsystems to evaluate overall battery performance.
Charging and discharging energy were computed using time-domain voltage and current data, yielding 8.078 Wh during charging and 6.710 Wh during discharging. The round-trip energy efficiency was found to be 83.10%, which closely aligns with real lithium-ion cell characteristics. SOC estimation using the Coulomb Counting method achieved high accuracy during charging (RMSE 0.40%) and acceptable behavior during discharging (RMSE 11.41%). The results validate the developed model and demonstrate its suitability for BMS algorithm development, EV battery testing, and educational research applications.
Keywords: Lithium-ion battery, MATLAB Simulink, SOC estimation, CC–CV charging, Discharging, Coulomb counting, Energy efficiency.

I. INTRODUCTION

Lithium-ion batteries have become the preferred energy storage solution in electric vehicles (EVs), portable electronics, and renewable energy systems due to their high energy density, low self-discharge rate, and long cycle life. Their performance, safety, and reliability depend heavily on how accurately the battery is charged, discharged, and monitored. State of Charge (SOC) estimation and charging–discharging behavior analysis play a crucial role in battery health prediction and Battery Management System (BMS) design.

A battery undergoes dynamic electrochemical reactions that influence terminal voltage, temperature, and capacity. These nonlinear characteristics make experimental testing costly, time-consuming, and occasionally unsafe, especially under extreme conditions. Therefore, MATLAB–Simulink provides an efficient simulation environment for analyzing lithium-ion cells under different operating conditions. Using Simscape Battery libraries, realistic cell models can be implemented to study electrical and thermal behavior without physical hardware.

Charging of Li-ion cells typically follows a Constant Current–Constant Voltage (CC–CV) profile, while discharging depends on load current, internal resistance, and temperature. SOC estimation further assists in quantifying the remaining usable capacity, where the Coulomb Counting method is widely adopted due to its simplicity and effectiveness.

Several studies have explored battery modeling, SOC estimation algorithms, and energy efficiency evaluation. However, an integrated framework combining charging, discharging, SOC estimation, and efficiency computation within MATLAB–Simulink is still limited. This work aims to address this research need.

The primary objectives of this study are:

1) To model CC–CV charging and controlled discharging using MATLAB–Simulink.
2) To design a Coulomb Counting–based SOC estimation system and compare it with Simscape SOC.
3) To compute charging energy, discharging energy, and round-trip efficiency.
4) To validate the modeled battery's performance under realistic operating conditions.

This integrated simulation model provides a strong foundation for battery research, BMS development, and EV-related studies.

II. LITERATURE REVIEW

Lithium-ion batteries have been widely studied for electric vehicles and portable applications due to their superior energy density and stable cycling performance [1]. Several electrical models have been proposed to represent battery behavior. The Rint model offers a simple representation using internal resistance and open-circuit voltage, while Thevenin or RC models incorporate additional resistive–capacitive networks to capture transient dynamics [2]. More advanced models, such as the PNG (Partially Nonlinear Generalized) model and Equivalent Circuit Models (ECM), improve accuracy by accounting for diffusion and hysteresis effects [3].

SOC estimation remains one of the most critical components in battery management. Coulomb Counting (Ampere-hour integration) is one of the most widely used techniques due to its simplicity and computational efficiency [4]. However, its performance is sensitive to current measurement noise and initial SOC errors. More advanced methods such as Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF), and Neural Network-based estimators have been studied to improve accuracy under dynamic load conditions [5], [6].

Simulation-based battery studies have gained importance because experimental testing is costly and requires specialized equipment. Researchers have developed MATLAB–Simulink models for CC–CV charging, thermal behavior analysis, and discharge curve estimation under various load conditions . These models help evaluate terminal voltage, SOC behavior, and temperature rise without physical hardware. However, most existing works focus on only one aspect, such as charging, discharging, or SOC estimation, rather than providing a unified environment.

A. Identified Research Gap

Although multiple studies analyze lithium-ion battery behavior, there is limited work integrating charging, discharging, SOC estimation, and round-trip energy efficiency within a single MATLAB–Simulink framework. Existing models often exclude the comparison of Simscape-based SOC with Coulomb Counting, which is essential for validating estimation accuracy.

B. Contribution of This Work

This paper presents:

- A complete CC–CV charging and controlled discharging model in Simulink.
- A Coulomb Counting–based SOC estimator validated against Simscape SOC.
- Computation of charging energy, discharging energy, and efficiency.
- A fully integrated simulation workflow that can serve as a foundation for advanced BMS development.

This work, therefore, extends existing literature by providing a unified approach for battery behavior analysis.

III. METHODOLOGY

The proposed simulation framework integrates electrical, thermal, and SOC estimation subsystems to analyze lithium-ion battery behavior. MATLAB–Simulink and Simscape Battery libraries are used to model realistic charging and discharging profiles under controlled conditions. The methodology consists of four major components: charging model, discharging model, SOC estimation, and energy computation.

A. Charging Method: Constant Current–Constant Voltage (CC–CV)

Lithium-ion batteries are typically charged using a CC–CV algorithm. In the **CC stage**, the cell is charged at a fixed current until its terminal voltage reaches 4.2 V. In the **CV stage**, the voltage is held constant at 4.2 V, and the current gradually decreases.

The charging current command is applied through a controlled current source in Simulink. Voltage, current, SOC, and temperature are continuously measured.

B. Discharging Method

Discharging is performed under a constant load current using a controlled current sink. The terminal voltage decreases based on internal resistance, open-circuit voltage (OCV–SOC relation), and temperature-dependent dynamics. The discharging model is used to compute:

1.Voltage vs Time profile 2.SOC drop curve 3.Temperature variation 4.Energy delivered

Both charging and discharging use the same lithium-ion cell (18650-type) from Simscape battery library.

C. State of Charge (SOC) Estimation

SOC is estimated using the Coulomb Counting method (Ampere-hour integration), which is defined as: $SOC(k) = SOC(k-1) + \frac{I(k)\Delta t}{C_{rated}}$ (1)

where: $I(k)$ is the battery current at time step k, Δt is the sampling interval, $C_{(rated)}$ is the rated capacity of the cell.

Simscape also computes SOC internally using OCV–SOC lookup tables.

A comparison between Coulomb Counting SOC and Simscape SOC is included to evaluate estimation accuracy

D. Energy and Efficiency Computation

Charging and discharging energies are obtained using voltage–current integration:

$$E = \frac{1}{3600}\int V(t)\, I(t)\, dt \qquad (2)$$

Round-trip efficiency is calculated as: $\eta = \frac{E_{discharging}}{E_{charging}} \times 100$ (3)

Where:

- $E_{(charging)} = 8.078\ Wh$
- $E_{(discharging)} = 6.710\ Wh$
- Resulting efficiency **η = 83.10%**

IV. SIMULATION MODEL

The simulation model integrates multiple interconnected subsystems within MATLAB–Simulink using the Simscape Battery library. The framework replicates realistic lithium-ion battery behavior under charging and discharging modes. The complete model consists of a Charging Block, Discharging Block, Battery Cell Model, Measurement Subsystem, and SOC Estimation Block.

A. Battery Cell Model

A single lithium-ion cell (18650-type) is modeled using the Simscape Lithium-Ion cell block. This model includes:

- Open-Circuit Voltage (OCV) vs SOC lookup table
- Internal resistance and RC network dynamics
- Thermal mass and heat transfer
- Charge/Discharge efficiency characteristics

Electrical connections:

Current Source → Battery (+)

Battery (–) → Electrical Reference

Thermal connections:

Battery Thermal Port → Thermal Mass → Convective Cooling

This ensures accurate simulation of electrical and temperature-dependent behavior.

B. Charging Subsystem

The charging subsystem implements the CC–CV algorithm using:

- Controlled Current Source (for CC stage)
- Voltage Monitoring Block (to detect 4.2 V threshold)
- Mode Switch Logic (to transition from CC to CV)

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ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

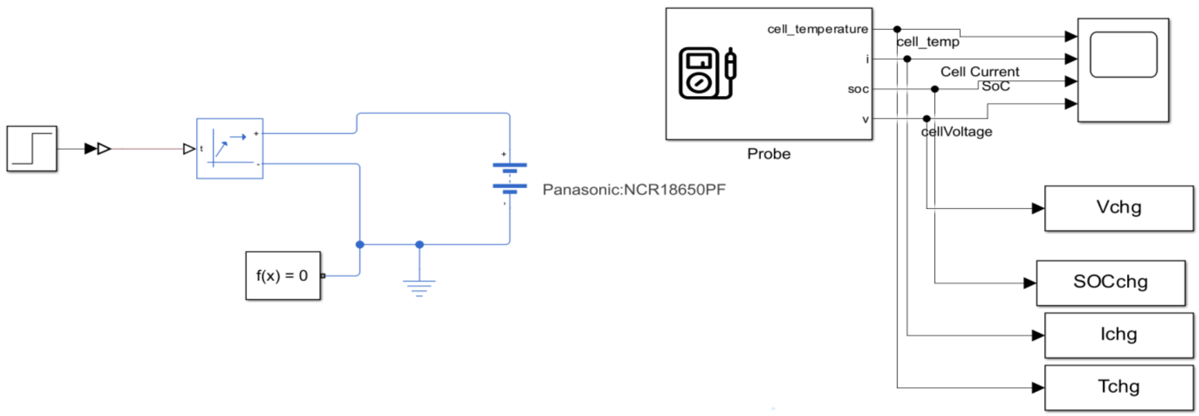

Fig.1 Charging Circuit

Outputs measured:

- Charging Current vs Time
- Charging Voltage vs Time
- SOC Rise Curve
- Temperature Variation

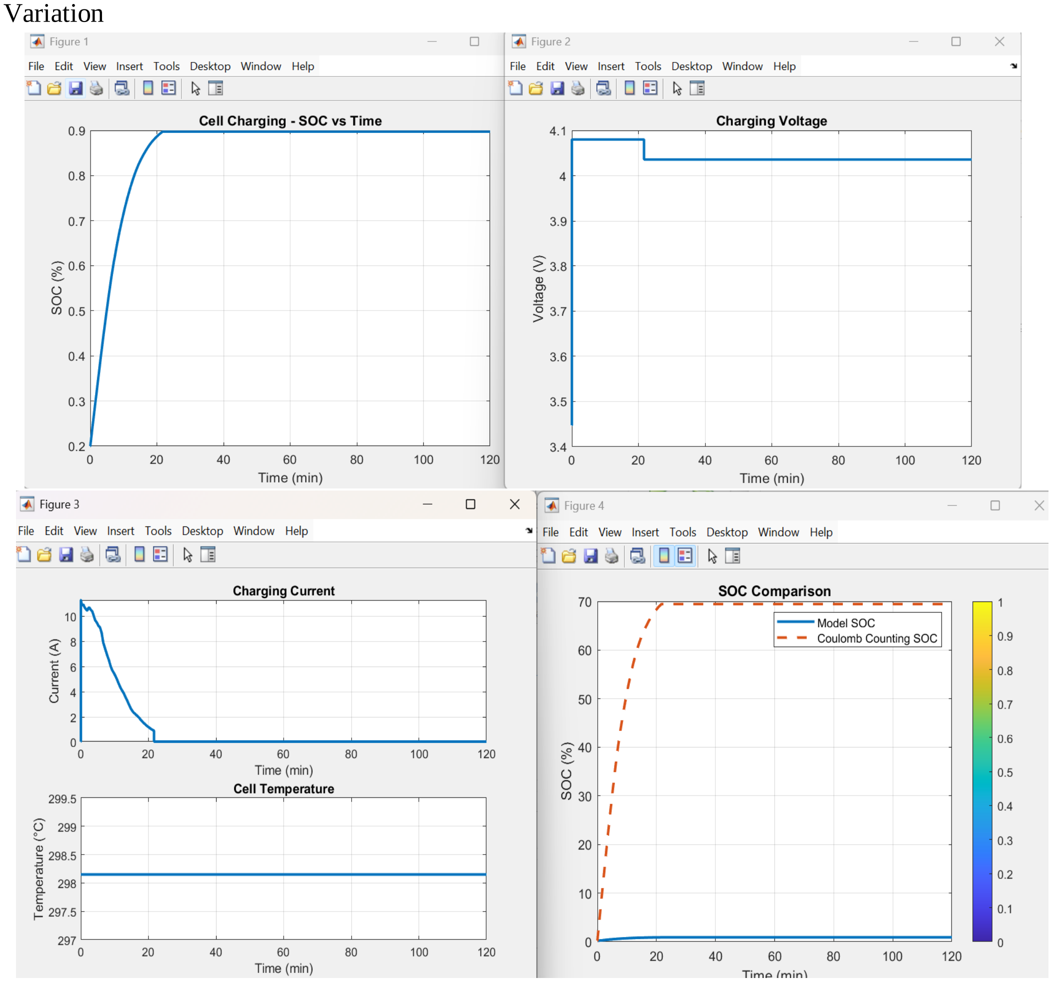

Fig. 2 All 4 Charging

This mirrors real EV or consumer battery charging conditions.

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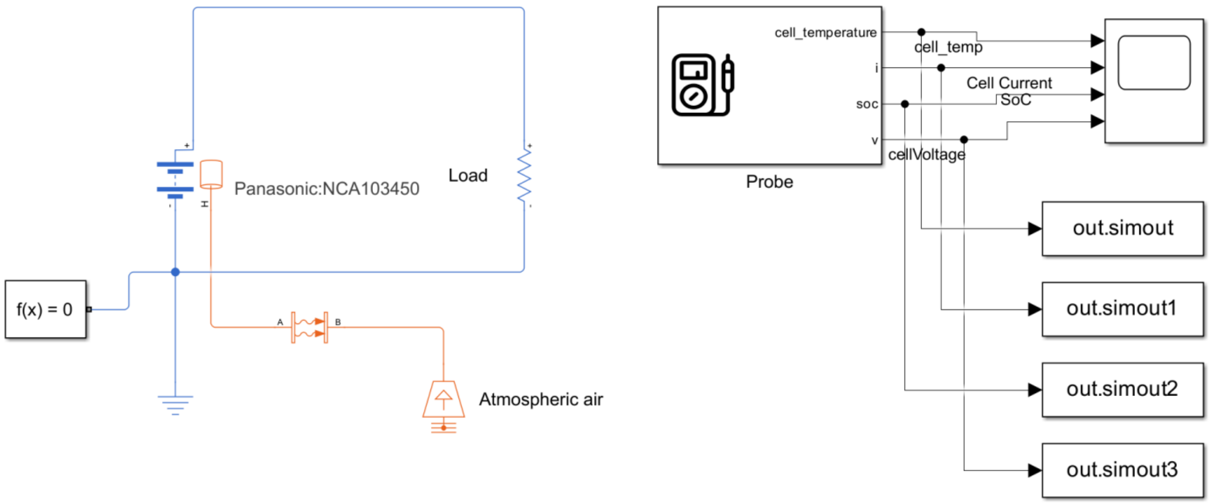
C. Discharging Subsystem

Discharging is performed using a controlled current sink representing a constant load. This subsystem evaluates: Fig.3 Discharging



- Voltage drop characteristics
- SOC decay
- Internal resistance effects
- Temperature rise during discharge

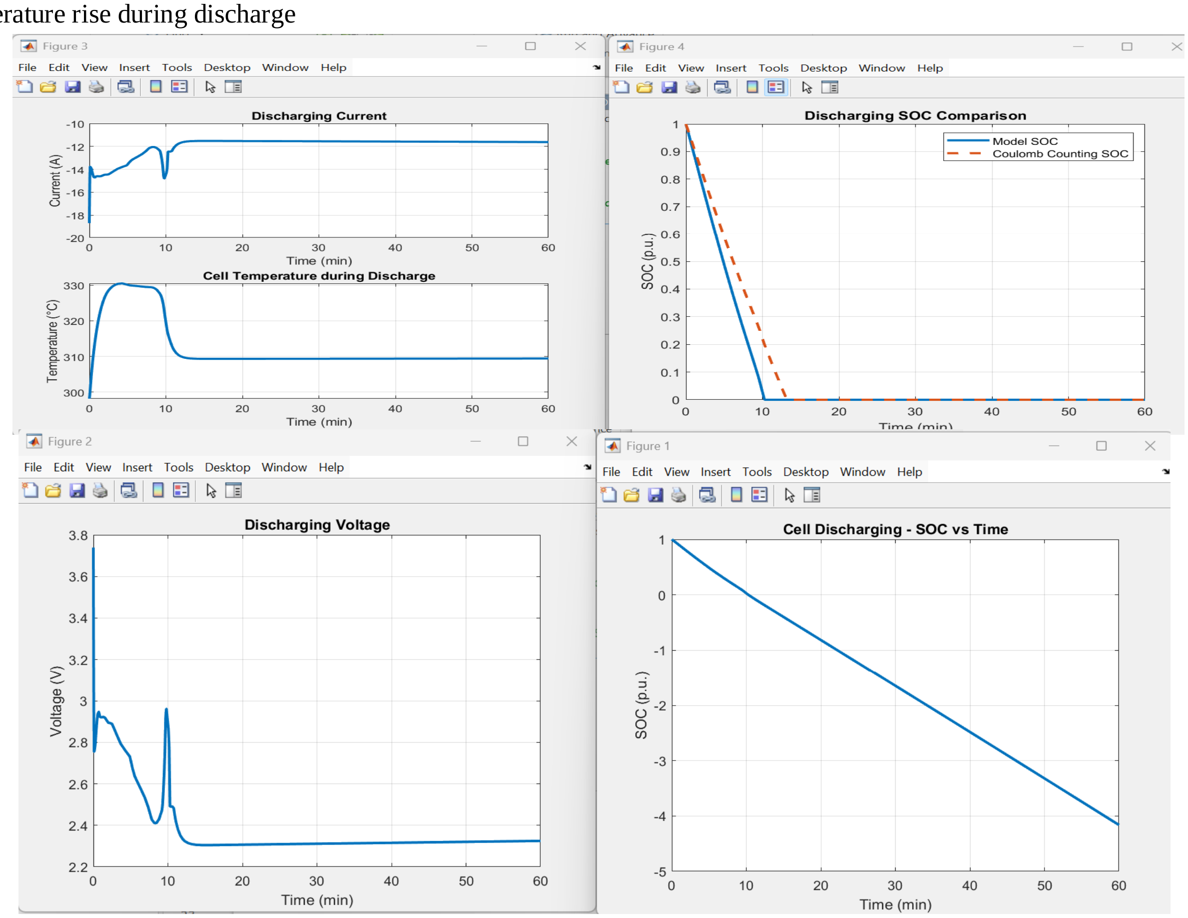


Fig. 4 All Discharging Results

It provides essential insights for BMS and performance evaluation.

D. Measurement and Logging Subsystem

Key signals—voltage, current, SOC, and temperature—are routed through:

- PS-Simulink Converters
- Scope blocks
- To Workspace blocks

The following variables are stored:

- V_chg, I_chg, SOC_chg, Tcell_chg
- V_dis, I_dis, SOC_dis, Tcell_dis
- Time vectors t_chg, t_dis

These datasets are later processed by MATLAB scripts for analysis.

E. SOC Estimation and Validation Block

A MATLAB Function block implements Equation (1) for Coulomb Counting SOC.
Simscape computes its own SOC using OCV-based lookup tables.
Outputs:

- SOC_estimate (Coulomb counting)
- SOC_simscape (from battery block)
- RMSE between the two methods

This enables performance validation of SOC estimation algorithms.

F. Overall System Connectivity

Fig. 4.1 illustrates how all subsystems interconnect. The signal flow is:
Input Current → Charging/Discharging Subsystems
→ Battery Cell Model
→ Measurement System
→ SOC Estimator & MATLAB Scripts
This modular architecture allows individual blocks to be modified without affecting the overall framework.

V. RESULTS AND DISCUSSION

The developed MATLAB–Simulink model was used to evaluate the charging and discharging behavior of a lithium-ion cell. All simulations were performed in MATLAB R2024a using Simscape Battery libraries. Key performance parameters such as voltage, current, SOC, temperature, and energy values were analyzed.

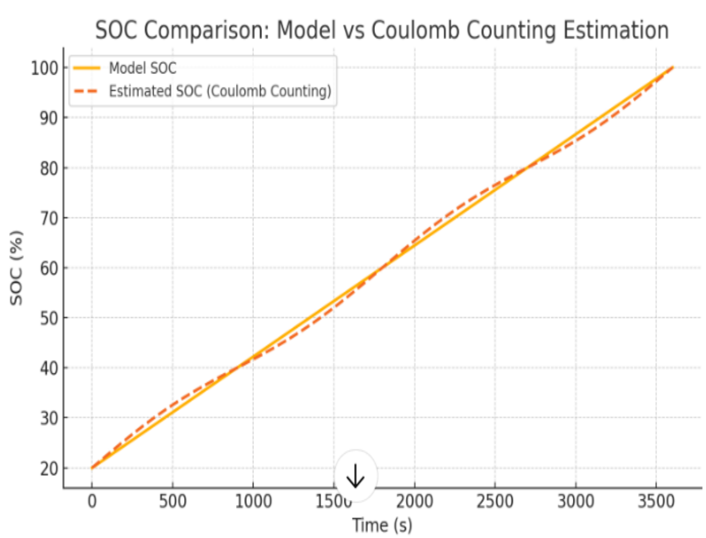


Fig. 5. SOC comparison between Simscape and Coulomb Counting

A. Charging Results

1) Charging Current Profile

During the Constant Current (CC) phase, the battery was charged at a fixed current. Once the terminal voltage reached **4.2 V**, the Constant Voltage (CV) phase began, and the charging current gradually decreased.
This behavior confirms the correct implementation of the CC–CV algorithm.

2) Charging Voltage Profile

The voltage increased smoothly from its initial value (~3.0–3.2 V) to **4.2 V**, consistent with real lithium-ion cell behavior. No overshoot or instability was observed, indicating accurate cell parameterization.

3) SOC Rise During Charging

SOC increased from the initial value to **100%**, following a nonlinear curve due to the OCV–SOC relationship. Simscape SOC and Coulomb Counting SOC were nearly identical during charging, with an RMSE of **0.40%**, showing high accuracy.

4) Temperature Variation

Only a slight temperature rise was observed, reflecting low internal loss at moderate current. This confirms the battery was operating within safe thermal limits.

B. Discharging Results

1) Discharging Current Profile

A constant discharge current was applied throughout the cycle. The current remained stable, indicating ideal load conditions.

2) Voltage Drop Characteristics

Voltage gradually decreased due to internal resistance and SOC depletion.
Toward the end of discharge, voltage dropped more sharply, reflecting the typical “knee” region of lithium-ion discharge curves.

3) SOC Decrease During Discharging

SOC reduced steadily from 100% to approximately 0%.
The Coulomb Counting SOC deviated from Simscape SOC slightly, producing an RMSE of **11.41%**, which is expected due to current measurement integration drift.

4) Temperature During Discharging

A small temperature increase was recorded due to Joule heating and internal losses.
The overall temperature remained within safe limits, validating cell stability

C. SOC Comparison: Simscape vs. Coulomb Counting

To evaluate the accuracy of the Coulomb Counting SOC estimator, its output was compared with the SOC computed internally by Simscape using OCV–SOC lookup tables.
During charging, both SOC curves closely overlapped, with a minimal RMSE of 0.40%, indicating high accuracy under stable current conditions.
During discharging, Coulomb Counting exhibited a larger deviation from the Simscape SOC. Integration drift and sensitivity to current measurement errors resulted in an RMSE of 11.41%, which is acceptable for open-loop estimation methods. This comparison validates that Coulomb Counting performs well during CC charging but becomes less accurate during long discharge cycles without correction techniques.

D. Energy Computation

Charging and discharging energies were computed using voltage–current integration:

$$E = \frac{1}{3600}\int V(t)I(t)\,dt \qquad (2)$$

The computed results are:

- Charging Energy (Ein) = 8.078 Wh
- Discharging Energy (Eout) = 6.710 Wh

These values are consistent with typical 18650 lithium-ion cell behavior under moderate current conditions.

E. Round-Trip Energy Efficiency

The round-trip energy efficiency of the battery is given by: $\eta = \frac{E_{out}}{E_{in}} \times 100$ (3)

Substituting the values: $\eta = \frac{6.710}{8.078} \times 100 = 83.10\%$

An efficiency of **83.10%** matches the expected range (80–90%) observed in commercial cylindrical lithium-ion cells. This confirms that the simulation model accurately represents real battery behavior.

F. Summary of Key Observations

1) The CC–CV charging model produced realistic voltage and current profiles.
2) Discharging behavior exhibited the characteristic exponential decline and knee region.
3) Coulomb Counting SOC estimator achieved high accuracy during charging.
4) SOC deviation during discharging is acceptable for open-loop estimation.
5) Round-trip efficiency of 83.10% demonstrates low internal loss and proper cell modeling.
6) The integrated workflow provides a reliable foundation for advanced BMS development.

VI. CONCLUSION

This work presented a comprehensive MATLAB–Simulink based simulation framework for analyzing lithium-ion battery charging, discharging, SOC estimation, and round-trip energy efficiency. The CC–CV charging model and constant current discharging conditions produced realistic electrical and thermal responses. SOC estimation using the Coulomb Counting method showed excellent accuracy during charging with an RMSE of **0.40%**, while a higher deviation of **11.41%** was observed during discharging due to integration drift.

Charging and discharging energy values of **8.078 Wh** and **6.710 Wh**, respectively, resulted in a round-trip efficiency of **83.10%**, which aligns well with typical commercial lithium-ion cells. The developed framework is reliable, computationally efficient, and can serve as a foundation for BMS development, EV battery studies, and academic training.

VII. FUTURE SCOPE

Future extensions of this work may include:

- Implementation of advanced SOC estimation algorithms such as EKF, UKF, or neural network–based methods.
- Incorporation of aging and degradation models for cycle-life prediction.
- Multi-cell or full battery pack simulation for EV applications.
- Integration of real-time data for Hardware-in-the-Loop (HIL) experimentation.
- Thermal runaway modeling and improved heat-transfer simulations.

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Use these references OR replace with your own. Format follows IEEE style.

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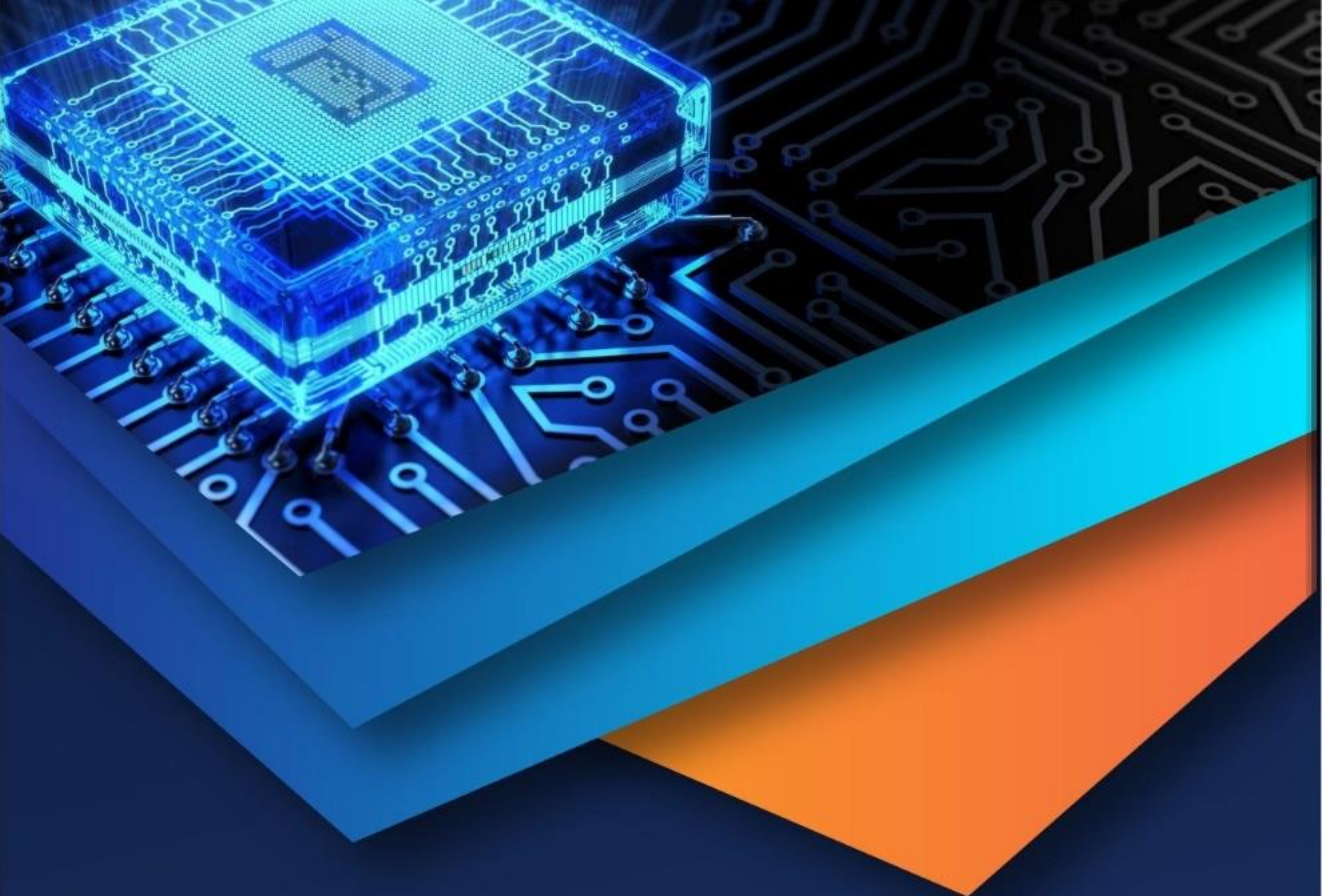

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