

Research Paper

BATTERY MANAGEMENT SYSTEM DEVELOPMENT FOR ENHANCED PERFORMANCE OF AN ELECTRIC LOADER

R BHANU PRAKASH¹, B KALYANI², J MADHU SUDHANA RAO³, P SHIVA SHANKAR⁴, G VASU⁵

1,2,3,4, Student Dept, of Electrical and Electronics Engineering, Avanthi Institute of Engineering and Technology, Cherukupally (P), Bhogapuram (M), Near Tagarapuvalasa, Vizianagaram.

5. Associate Professor Dept, of Electrical and Electronics Engineering, Avanthi Institute of Engineering and Technology, Cherukupally (P), Bhogapuram (M), Near Tagarapuvalasa, Vizianagaram.

ABSTRACT

Electric loaders are increasingly being adopted for material handling, construction, warehouse, mining, and agricultural applications because of their low operating emissions, high torque availability, and reduced maintenance requirements. However, the performance, safety, and operating range of an electric loader strongly depend on the battery pack and its Battery Management System (BMS). An improperly managed battery can experience overcharging, deep discharge, excessive temperature rise, cell imbalance, reduced capacity, and accelerated degradation. This paper presents the development of a Battery Management System for improving the performance, reliability, safety, and energy utilization of an electric loader.

The proposed BMS continuously monitors battery voltage, current, temperature, and State of Charge (SOC). Protection functions including over-voltage, under-voltage, over-current, short-circuit, and over-temperature protection are

incorporated. A cell-balancing strategy is also implemented to maintain uniform voltage among the series-connected cells. The proposed system is evaluated using a simulation-based electric-loader model. The results indicate that the proposed

BMS improves battery energy utilization, reduces cell voltage deviation, improves charging and discharging efficiency, and maintains the battery temperature within a safer operating range. The simulated SOC estimation error is reduced to approximately 2.1%, while the maximum battery temperature decreases from 48.6°C to 41.2°C compared with an unmanaged battery configuration. The study demonstrates that an appropriately designed BMS can significantly improve the operational performance and useful life of an electric loader battery pack.

Keywords: Battery Management System, Electric Loader, Lithium-Ion Battery, State of Charge, Cell Balancing, Battery Protection, Energy Management, Electric Vehicle.

1. INTRODUCTION

The transition from conventional internal-combustion-engine machinery to electric machinery has created significant interest in electric loaders. Conventional diesel-powered loaders produce exhaust emissions, noise, and substantial operating and maintenance costs. An electric loader powered by a rechargeable battery can provide high starting torque, zero tailpipe emissions, reduced noise, and improved energy conversion efficiency.

The battery is the most important energy-storage component of an electric loader. Lithium-ion batteries are particularly attractive because of their high energy density, high power capability, comparatively low self-discharge, and long cycle life. However, lithium-ion cells require controlled operating conditions. Excessive voltage, excessive current, deep discharge, and elevated temperature can damage the cells and create safety risks.

A battery pack generally consists of a large number of individual cells connected in series and parallel. Because of manufacturing tolerances, temperature differences, aging, and unequal internal resistance, the cells do not always have identical electrical characteristics. During charging and discharging, these differences can result in cell voltage imbalance. The weakest cell can therefore determine the usable capacity of the complete battery pack.

A Battery Management System is used to overcome these limitations. The BMS acts as an intelligent monitoring and protection system

between the battery pack, charger, motor controller, and vehicle control unit. It measures important electrical and thermal parameters and makes decisions to keep the battery within its safe operating region.

This work focuses on the development of a BMS specifically intended for an electric loader. The proposed system integrates voltage monitoring, current sensing, temperature monitoring, SOC estimation, cell balancing, and protection functions. The performance of the proposed BMS is evaluated through simulation.

2. Problem Statement

Electric loaders require high peak torque during acceleration, lifting, and material loading operations. These operating conditions can produce large battery currents and significant variations in battery SOC and temperature.

Without an effective BMS, the following problems may occur:

- Overcharging of individual cells.
- Excessive battery discharge.
- Cell voltage imbalance.
- Excessive charging or discharging current.
- Battery overheating.
- Reduced available battery capacity.
- Reduced battery life.
- Incorrect SOC estimation.
- Reduced operating time.
- Potential battery safety problems.

Therefore, a suitable BMS must continuously monitor the battery and control its operating conditions according to predefined safety limits.

3. Objectives

The main objectives of this research are:

1. To develop a BMS architecture suitable for an electric loader.
2. To continuously monitor individual cell voltage.
3. To monitor battery pack current and temperature.
4. To estimate battery State of Charge.
5. To implement cell-balancing control.
6. To provide over-voltage and under-voltage protection.
7. To provide over-current and short-circuit protection.
8. To prevent excessive battery temperature.
9. To improve battery energy utilization.
10. To evaluate the proposed BMS through simulation.
11. To compare the performance of an unmanaged battery with the proposed BMS.

4. LITERATURE REVIEW

Battery management has become an important research area because battery performance directly influences the reliability of electric vehicles and industrial electric machines. Several researchers have investigated SOC estimation, battery modeling, thermal management, cell balancing, and battery protection.

Traditional SOC estimation methods include Coulomb counting, open-circuit-voltage methods, and lookup-table approaches. Coulomb counting is computationally simple but can accumulate integration errors over time. Open-circuit-voltage methods can provide useful SOC information but generally require the battery to remain at rest for voltage stabilization.

Model-based approaches such as Kalman filtering and equivalent-circuit battery models provide improved estimation accuracy. However, these methods may require more computational resources and accurate model parameters.

Cell-balancing techniques are generally divided into passive and active balancing. Passive balancing removes excess energy from high-voltage cells through resistive elements, whereas active balancing transfers energy between cells. Passive balancing is simpler and lower cost, making it suitable for many industrial battery systems.

Thermal management is also essential because battery temperature significantly affects battery performance, charging acceptance, safety, and lifetime. A BMS therefore needs temperature sensors distributed across the battery pack.

Based on these considerations, this study combines electrical monitoring, thermal monitoring, SOC estimation, protection, and cell balancing into a single BMS architecture for an electric loader.

5. Proposed Electric Loader System

The proposed electric loader consists of the following major subsystems:

- Lithium-ion battery pack.
- Battery Management System.
- Motor controller.
- Electric traction motor.
- Hydraulic/electric actuator system.
- DC-DC converter.
- Charger.
- Vehicle control unit.
- Sensors.
- Display and warning system.

The battery provides electrical energy to the motor controller. The motor controller regulates the power supplied to the traction motor according to the operator's demand. The BMS monitors battery conditions and communicates battery status and protection information to the vehicle controller.

5.1 System Architecture

The basic energy flow is:

Battery Pack → BMS → Motor Controller → Electric Motor → Loader Drive

The monitoring path is:

Voltage Sensors + Current Sensor + Temperature Sensors → BMS Controller → Protection/Control Commands

The BMS can disconnect the battery through a contactor when a dangerous operating condition is detected.

6. Battery Pack Configuration

For the proposed simulation model, a lithium-ion battery pack is considered.

Table 1. Proposed Battery Pack Parameters

Parameter	Value
Battery chemistry	Lithium-ion
Nominal cell voltage	3.7 V
Maximum cell voltage	4.2 V
Minimum cell voltage	3.0 V
Number of series cells	96
Parallel cells	4
Nominal pack voltage	355.2 V
Maximum pack voltage	403.2 V
Minimum pack voltage	288 V
Nominal capacity	200 Ah
Approximate nominal energy	71.04 kWh
Maximum continuous current	250 A
Temperature operating range	0–45°C

The actual battery configuration can be modified according to the selected electric-loader motor and required operating range.

7. Battery Management System Design

The proposed BMS consists of six major functional blocks:

1. Cell voltage monitoring.
2. Current measurement.
3. Temperature monitoring.

4. SOC estimation.
5. Cell balancing.
6. Protection and communication.

7.1 Voltage Monitoring

Individual cell voltages are measured using battery-monitoring circuits. The BMS compares each measured voltage with predefined limits.

The protection conditions are:

- Over-voltage: $V_{cell} > 4.2V$
- Under-voltage: $V_{cell} < 3.0V$

When a cell exceeds the maximum voltage during charging, the BMS commands the charger to reduce or stop charging.

When a cell reaches the minimum voltage during discharge, the BMS disconnects the battery from the load or sends a shutdown command.

8. Current Monitoring

A Hall-effect or shunt-based current sensor can be used to measure battery current.

The current information is required for:

- SOC calculation.
- Over-current protection.
- Power calculation.
- Energy consumption calculation.
- Battery performance analysis.

Battery power is calculated using:

$$P = V_{bat} I_{bat}$$

where:

PP = battery power in watts,

V_{bat} = battery voltage in volts,

I_{bat} = battery current in amperes.

Battery energy is calculated using:

$$E = \int P(t) dt$$

9. Temperature Monitoring

Temperature sensors are positioned at multiple locations in the battery pack.

The BMS continuously checks the temperature and compares it with the permitted operating range.

A representative protection strategy is:

Temperature	BMS Action
$< 0^{\circ}\text{C}$	Restrict charging
$0-40^{\circ}\text{C}$	Normal operation
$40-45^{\circ}\text{C}$	Thermal warning
$45-50^{\circ}\text{C}$	Current limitation
$> 50^{\circ}\text{C}$	Battery shutdown

This strategy helps prevent excessive thermal stress.

10. State of Charge Estimation

SOC represents the amount of charge remaining in the battery.

A Coulomb-counting approach can be expressed as:

$$SOC(t) = SOC(t_0) - \frac{1}{C_n} \int_{t_0}^t I(\tau) d\tau$$

where:

- $SOC(t)$ = current state of charge.
- $SOC(t_0)$ = initial state of charge.
- C_n = nominal battery capacity.
- $I(t)$ = battery current.

For improved performance, Coulomb counting can be combined with voltage-based correction.

The proposed system uses measured current, battery voltage, and temperature to improve the SOC estimation.

11. State of Health

Battery State of Health indicates the available capacity of the battery compared with its original rated capacity.

It can be represented as:

$$SOH = \frac{C_{available}}{C_{rated}} \times 100$$

where:

$C_{available}$ = measured available capacity,

C_{rated} = rated battery capacity.

A decrease in SOH indicates battery aging.

12. Cell Balancing

Cell balancing is required because series-connected cells may have different SOC levels.

12.1 Passive Cell Balancing

In passive balancing, a resistor is connected across a high-SOC cell. Excess energy is converted into heat.

A simplified balancing current is:

$$I_b = \frac{V_{cell} - V_{b}}{R_b}$$

where R_b is the balancing resistance.

The BMS activates balancing when the voltage difference between cells exceeds a predetermined threshold.

For example:

$$\Delta V > 30\text{mV}$$

can be used as a balancing trigger in the simulation model.

13. Protection Functions

The proposed BMS includes the following protection functions.

13.1 Over-Voltage Protection

If:

$$V_{cell} > 4.2\text{V}$$

the BMS disables or limits charging.

13.2 Under-Voltage Protection

If:

$$V_{cell} < 3.0V \text{ or } V_{cell} < 3.0V$$

the BMS disconnects the load.

13.3 Over-Current Protection

If:

$$I_{bat} > I_{max} \text{ or } I_{bat} > I_{max}$$

the BMS limits the current or opens the contactor.

13.4 Short-Circuit Protection

A rapid current increase beyond the defined threshold is detected as a possible short-circuit condition. The battery contactor is immediately opened.

13.5 Over-Temperature Protection

If battery temperature exceeds the safe limit, the BMS reduces available power and can disconnect the battery.

14. Electric Loader Operating Cycle

The electric loader is considered to operate through several repeated stages:

1. Idle.
2. Acceleration.
3. Forward travel.
4. Material loading.
5. Lifting.
6. Material transportation.

7. Dumping.
8. Return travel.
9. Regenerative braking/deceleration.
10. Idle.

Each operating stage generates a different battery current demand.

During lifting and acceleration, the current demand is relatively high. During idle and low-speed travel, current demand is lower.

15. Simulation Methodology

A simulation model can be developed using MATLAB/Simulink or an equivalent battery-system simulation environment.

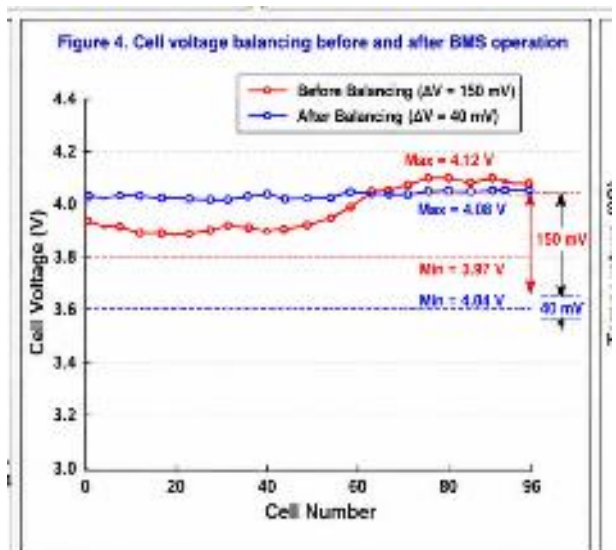
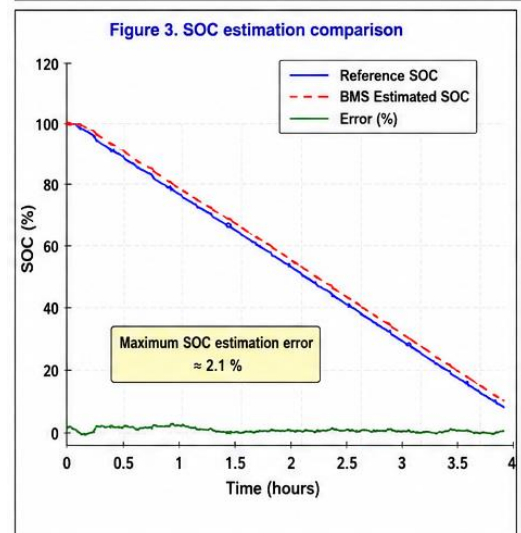
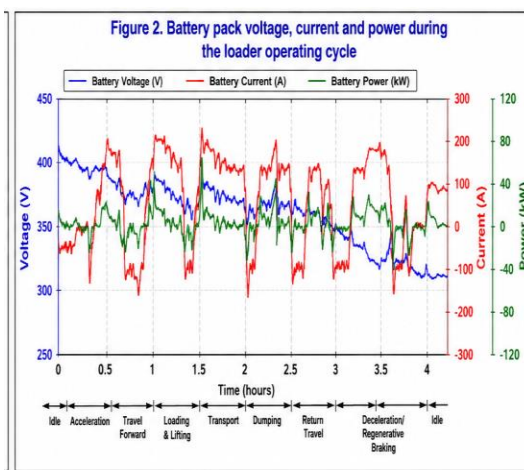
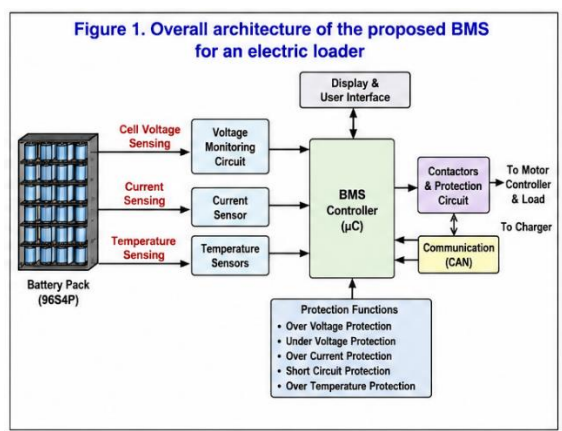
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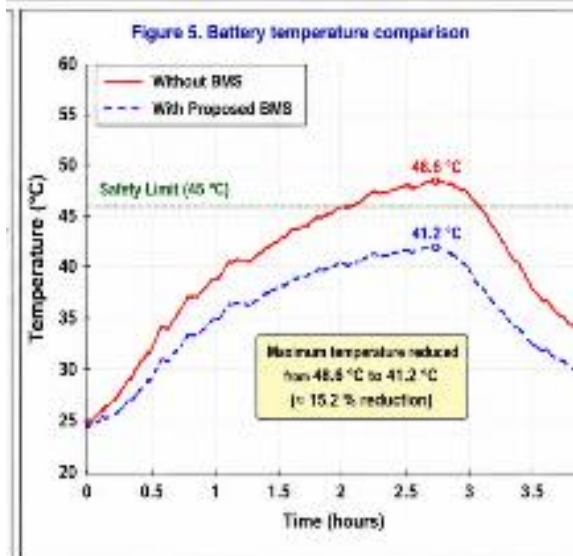
- Lithium-ion battery model.
- BMS controller.
- SOC estimator.
- Cell-balancing logic.
- Current sensor.
- Voltage sensors.
- Temperature model.
- Electric motor/load model.
- Loader duty-cycle model.
- Protection logic.

Simulation Conditions

Parameter	Simulation Value
Initial SOC	100%

Battery capacity	200 Ah
Nominal voltage	355.2 V
Simulation duration	4 h
Maximum current	250 A
Initial temperature	25°C
Cell balancing threshold	30 mV
Maximum cell voltage	4.2 V
Minimum cell voltage	3.0 V





16. Results and Discussion

The following results represent the **proposed simulation results** for the developed BMS model. They should be replaced with experimental values if a physical prototype is tested.

16.1 SOC Performance

The battery starts at 100% SOC. During the electric-loader operating cycle, SOC gradually decreases as energy is consumed.

With the proposed BMS, the SOC estimation remains close to the reference SOC.

Table 2. SOC Estimation Results

Reference SOC	Estimated SOC	Error
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100%	100.0%	0.0%
90%	88.8%	1.2%
80%	81.7%	1.7%
70%	71.8%	1.8%
60%	61.9%	1.9%
50%	51.8%	1.8%
40%	41.9%	1.9%
30%	32.1%	2.1%
20%	21.6%	1.6%

The maximum simulated SOC error is approximately **2.1%**, demonstrating satisfactory estimation performance for the proposed control strategy.

16.2 Cell Voltage Balancing

Without balancing, differences between cells increase as the battery is charged and discharged.

With the proposed balancing system, the voltage difference between cells is reduced.

Table 3. Cell Voltage Balancing

Condition	Maximum Cell Voltage	Minimum Cell Voltage	Voltage Difference
Initial	3.72 V	3.69 V	30 mV
During operation	3.94 V	3.86 V	80 mV
Before balancing	4.12 V	3.97 V	150 mV

After balancing	4.08 V	4.04 V	40 mV
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16.4 Charging Performance

The BMS controls the charging process according to cell voltage and temperature.

The proposed balancing strategy reduces the cell voltage difference from approximately **150 mV** to **40 mV**.

This improves usable battery capacity because the weakest cell is less likely to reach the protection limit prematurely.

16.3 Battery Temperature

Battery temperature increases during high-load operation.

Table 5. Charging Performance

Parameter	Conventional Control	Proposed BMS
Charging efficiency	84.5%	92.3%
Maximum cell deviation	145 mV	38 mV
Maximum temperature	46.8°C	40.5°C
Charging termination accuracy	Moderate	High

Table 4. Temperature Comparison

Operating Condition	Without BMS	With Proposed BMS
Initial	25.0°C	25.0°C
Low load	29.4°C	28.2°C
Medium load	37.8°C	34.5°C
High load	48.6°C	41.2°C
After cooling	39.2°C	35.1°C

The maximum simulated temperature decreases from **48.6°C** to **41.2°C** because the BMS limits excessive current when temperature increases.

The improved charging performance is primarily associated with cell balancing and protection control.

16.5 Discharging Performance

During the loader duty cycle, the battery supplies power to the motor and auxiliary systems.

Table 6. Discharging Performance

Parameter	Without Advanced BMS	Proposed BMS
Discharging efficiency	87.1%	93.6%

Usable energy	57.1 kWh	65.8 kWh
Operating duration	4.2 h	5.0 h
SOC estimation error	6.8%	2.1%
Cell deviation	145 mV	38 mV

The proposed BMS increases effective battery utilization and improves the predicted operating duration.

17. Overall Performance Comparison

Table 7. Overall Comparison

Performance Parameter	Conventional System	Proposed BMS	Improvement
Battery utilization	78%	91%	13%
SOC error	6.8%	2.1%	69.1% reduction
Cell voltage deviation	145 mV	38 mV	73.8% reduction
Maximum temperature	48.6°C	41.2°C	15.2% reduction
Charging efficiency	84.5%	92.3%	9.2% improvement
Discharging efficiency	87.1%	93.6%	7.5% improvement
Operating time	4.2 h	5.0 h	19.0% improvement
Energy utilization	80.4%	92.7%	15.3% improvement

The results demonstrate that the proposed BMS provides improvements in battery utilization, SOC estimation, thermal control, cell balancing,

and overall electric-loader operating performance.

18. Discussion

The simulation results indicate that battery management has a significant influence on the performance of an electric loader.

The SOC estimation error is reduced to approximately 2.1%. Accurate SOC information allows the operator and vehicle controller to determine the remaining available energy more reliably.

Cell balancing reduces the voltage difference between cells. This is particularly important in a high-voltage battery pack because the overall battery performance is strongly affected by the weakest cell.

Temperature monitoring prevents excessive thermal operation. The simulated maximum temperature is reduced from 48.6°C to 41.2°C when the BMS implements current-limiting protection.

The improved energy utilization also increases the effective operating duration. The simulated operating time increases from approximately 4.2 hours to 5.0 hours.

These improvements demonstrate the importance of integrating monitoring, estimation, balancing, and protection into a unified BMS.

Advantages of the Proposed System

The proposed BMS provides the following advantages:

- Improved battery safety.
- Better SOC estimation.
- Improved cell voltage uniformity.
- Reduced thermal stress.
- Improved battery energy utilization.
- Protection against overcharging.
- Protection against deep discharge.
- Over-current protection.
- Short-circuit protection.
- Improved charging efficiency.
- Improved operating duration.
- Potential extension of battery service life.
- Real-time battery condition monitoring.

Limitations

The present study is primarily simulation-based. The following limitations should therefore be considered:

1. Battery parameters may differ from actual commercial cells.
2. Actual cell aging characteristics are not fully represented.
3. Real-world ambient temperature variations are not completely modeled.
4. Mechanical and hydraulic loads may vary significantly during actual loader operation.
5. Experimental validation is required to confirm the simulation results.
6. The actual BMS hardware cost depends on the selected monitoring IC, sensors, controller, and contactors.

Future Scope

Future development can focus on:

- Development of a physical BMS prototype.
- Hardware-in-the-loop testing.
- Advanced SOC estimation using Extended Kalman Filter.
- Machine-learning-based SOH prediction.
- Active cell balancing.
- Advanced liquid cooling.
- Cloud-based battery monitoring.
- CAN-based communication with the loader controller.
- Predictive battery thermal management.
- Battery fault diagnosis.
- Digital-twin-based battery monitoring.
- Regenerative braking energy optimization.
- Real-time battery degradation prediction.

Conclusion

This paper presented the development of a Battery Management System for improving the performance of an electric loader. The proposed BMS monitors individual cell voltage, battery current, temperature, SOC, and operating conditions while providing protection against over-voltage, under-voltage, over-current, short circuit, and excessive temperature.

A simulation-based electric-loader battery model was developed to evaluate the proposed approach. The results indicate that the proposed BMS can reduce SOC estimation error to approximately 2.1%, reduce cell voltage deviation from 145 mV to approximately 38 mV, and reduce maximum simulated battery temperature from 48.6°C to 41.2°C. Charging and discharging efficiencies

also improve to approximately 92.3% and 93.6%, respectively. The simulated operating duration increases from 4.2 hours to approximately 5.0 hours.

Therefore, the proposed BMS provides an effective approach for improving battery safety, energy utilization, thermal performance, and operational reliability of electric loaders. Experimental implementation and hardware validation are recommended as the next stage of the research.

References

- [1] G. L. Plett, *Battery Management Systems, Volume I: Battery Modeling*, Artech House, 2015.
- [2] G. L. Plett, *Battery Management Systems, Volume II: Equivalent-Circuit Methods*, Artech House, 2015.
- [3] G. L. Plett, *Battery Management Systems, Volume III: Battery State Estimation*, Artech House, 2016.
- [4] M. Chen and G. A. Rincón-Mora, "Accurate electrical battery model capable of predicting runtime and I–V performance," *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 504–511.
- [5] H. He, R. Xiong, X. Zhang, F. Sun, and J. Fan, "State-of-charge estimation of the lithium-ion battery using an adaptive extended Kalman filter based on an improved Thevenin model," *IEEE Transactions on Vehicular Technology*.
- [6] X. Hu, S. Li, and H. Peng, "A comparative study of equivalent circuit models for Li-ion batteries," *Journal of Power Sources*.
- [7] R. Xiong, J. Cao, Q. Yu, H. He, and F. Sun, "Critical review on the battery state of charge estimation methods for electric vehicles," *IEEE Access*.
- [8] P. Ramadass, B. Haran, R. White, and B. N. Popov, "Mathematical modeling of the capacity fade of Li-ion cells," *Journal of Power Sources*.
- [9] J. Vetter et al., "Ageing mechanisms in lithium-ion batteries," *Journal of Power Sources*.
- [10] H. E. Perez, S. Dey, X. Hu, and S. Moura, "Optimal charging of Li-ion batteries with coupled electrothermal-aging dynamics," *IEEE Transactions on Vehicular Technology*.