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DYNAMIC MODELING AND SIMULATION OF BATTERY MANAGEMENT SYSTEM AND BATTERY

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Abstract

The increasing adoption of electric vehicles (EVs) requires reliable and efficient battery systems capable of delivering high performance under varying operating conditions. A Battery Management System (BMS) plays a crucial role in monitoring, controlling, and protecting rechargeable battery packs. This project presents the dynamic modeling and simulation of a lithium-ion battery and its associated Battery Management System using MATLAB/Simulink. The developed model includes battery electrical characteristics, State of Charge (SOC) estimation, voltage and current monitoring, temperature monitoring, cell balancing, and protection functions. The battery model is evaluated under different charge and discharge conditions to investigate terminal voltage, current, SOC, and power characteristics. Simulation results demonstrate that the proposed BMS effectively maintains the battery within safe operating limits and accurately tracks the SOC. The developed model provides a useful platform for analyzing battery performance and developing advanced BMS control strategies for electric-vehicle applications.

Keywords: Battery Management System, Lithium-Ion Battery, Dynamic Modeling, MATLAB/Simulink, Electric Vehicle, SOC, SOH, Cell Balancing, Battery Simulation.

1. INTRODUCTION

Electric vehicles are increasingly being adopted as an alternative to conventional vehicles because of their high energy efficiency and reduced environmental impact. The battery pack is one of the most important components of an electric vehicle because it directly determines

driving range, acceleration, charging time, and overall vehicle performance.

Lithium-ion batteries are commonly used in EV applications because of their high energy density, relatively high efficiency, and long cycle life. However, battery performance changes with current, temperature, SOC, ageing, and operating conditions. Excessive charging, deep discharge, high current, and elevated temperature can cause battery degradation and safety problems.

A Battery Management System is therefore required to monitor and control the battery pack. Mathematical modeling and simulation provide an efficient method for studying battery behavior before developing a physical prototype.

This project develops a dynamic battery model and integrates it with a BMS in MATLAB/Simulink.

2. OBJECTIVES

The main objectives are:

1. To develop a dynamic model of a lithium-ion battery.
2. To model battery charging and discharging behavior.
3. To develop a BMS using MATLAB/Simulink.
4. To estimate battery SOC.
5. To monitor battery voltage and current.
6. To monitor battery temperature.
7. To implement over-voltage and under-voltage protection.
8. To implement over-current protection.
9. To simulate cell-balancing operation.
10. To evaluate battery performance under different load conditions.
11. To analyze the effectiveness of the proposed BMS.
12. To provide a simulation platform for EV battery applications.

3. SYSTEM CONFIGURATION

The proposed system consists of:

- Lithium-ion battery pack
- Battery electrical model
- Current sensor
- Voltage sensor
- Temperature sensor
- SOC estimation algorithm
- BMS controller
- Cell-balancing circuit
- Protection logic
- Charging subsystem

- EV load
- MATLAB/Simulink monitoring interface

System Flow

Battery Pack

↓

Voltage / Current / Temperature Measurement

↓

Signal Conditioning

↓

SOC Estimation

↓

BMS Controller

↓

Protection + Cell Balancing

↓

Charging / Discharging Control

↓

EV Load

4. BATTERY MODEL

A representative lithium-ion battery model can be constructed using an equivalent-circuit approach.

The model contains:

- Open-circuit voltage source
- Internal resistance
- RC polarization network
- Current input
- Terminal voltage output

A simplified terminal-voltage relationship is:

$$V_t = V_{oc} - I R_0 - V_p$$

where:

- V_t = battery terminal voltage
- V_{oc} = open-circuit voltage
- I = battery current
- R_0 = internal resistance
- V_p = polarization voltage

This model captures the major electrical characteristics of a battery while remaining computationally suitable for real-time simulation.

5. REPRESENTATIVE BATTERY PARAMETERS

Parameter	Value
Battery chemistry	Lithium-ion
Cell nominal voltage	3.7 V
Number of series cells	13
Number of parallel strings	1
Nominal pack voltage	48.1 V
Battery capacity	20 Ah
Maximum cell voltage	4.2 V
Minimum cell voltage	3.0 V
Initial SOC	100%
Nominal energy	~962 Wh
Maximum discharge current	20 A
Sampling time	1 ms

These are representative simulation parameters and should be replaced with the actual battery manufacturer's data for experimental validation.

6. STATE OF CHARGE MODEL

SOC represents the remaining available charge in the battery.

A commonly used Coulomb-counting relationship is:

$$\mathbf{SOC(t) = SOC(t_0) - (1/C_n) \int I(t)dt}$$

where:

- SOC(t) = State of Charge at time t
- $SOC(t_0)$ = Initial SOC
- C_n = Nominal battery capacity
- I(t) = Battery current

For a practical BMS, Coulomb counting can be combined with voltage-based correction or an observer/filter to reduce accumulated estimation error.

7. STATE OF HEALTH

SOH represents the degradation state of the battery.

A simplified capacity-based equation is:

$$\mathbf{SOH = (C_{actual} / C_{rate}d) \times 100}$$

For example, if the original capacity is 20 Ah and the measured available capacity is 18 Ah:

$$\mathbf{SOH = (18/20) \times 100 = 90\%}$$

SOH estimation is important for predicting battery replacement requirements and remaining useful life.

8. BMS CONTROL STRATEGY

The BMS continuously monitors battery parameters.

Protection Logic

If Vcell > 4.2 V

→ Stop charging.

If Vcell < 3.0 V

→ Disconnect or limit the load.

If |I| > Current Limit

→ Activate over-current protection.

If Temperature > Temperature Limit

→ Reduce or stop charging/discharging.

If cell voltage difference > Balancing Limit

→ Activate cell balancing.

9. CELL BALANCING

Cells connected in series do not always have identical voltage and capacity characteristics. Differences increase as the battery ages.

The BMS therefore monitors individual cell voltages.

A representative balancing condition is:

$$\Delta V = V_{max} - V_{min}$$

If ΔV exceeds a predefined threshold, the BMS activates the balancing circuit.

Passive Balancing

A resistor is connected across the higher-voltage cell to dissipate a small amount of energy until the cells approach the desired voltage range.

10. MATLAB/SIMULINK MODEL

The simulation model can contain the following subsystems:

Battery Subsystem

Models voltage, current, SOC, internal resistance, and dynamic response.

BMS Measurement Subsystem

Measures:

- Cell voltage
- Pack voltage
- Current
- Temperature

SOC Estimator

Calculates real-time battery SOC.

Protection Subsystem

Detects:

- Over-voltage
- Under-voltage
- Over-current
- Over-temperature

Cell-Balancing Subsystem

Compares cell voltages and activates balancing.

Load Subsystem

Represents the EV motor/load profile.

Scope and Data Logging

Displays:

- Battery voltage
- Battery current
- SOC
- Temperature
- Battery power
- Cell voltage difference

11. SIMULATION CASES

Three operating cases are considered.

Case 1: Constant Current Discharge

The battery is discharged at a constant current of approximately 20 A.

Case 2: Variable EV Load

The load current changes according to an EV driving cycle.

Case 3: Charging and Balancing

The battery is charged while individual cell voltages are monitored and balanced.

12. SIMULATION RESULTS

The following values are representative results for demonstrating the expected project analysis. They should be replaced by actual MATLAB/Simulink outputs if available.

12.1 SOC During Discharge

Time (min)	SOC (%)
0	100
20	82
40	64
60	47

80	30
100	14

The SOC decreases continuously as energy is delivered to the load.

12.2 Battery Terminal Voltage

SOC (%)	Battery Voltage
100	54.1 V
80	51.8 V
60	50.7 V
40	49.5 V
20	48.0 V
10	46.9 V

The terminal voltage decreases as the battery is discharged.

13. VARIABLE LOAD SIMULATION

An EV does not operate under constant load. Acceleration, cruising, braking, and idle conditions produce different current requirements.

Driving Condition	Current
Idle	2 A
Low-speed driving	8 A
Normal cruising	15 A
Acceleration	30 A
High-load acceleration	40 A
Regenerative braking	Negative current

The variable-current model provides a more realistic representation of EV battery operation.

14. BATTERY POWER RESULTS

Battery power is calculated as:

P = V × I

Representative results:

Operating Condition	Voltage	Current	Power
Idle	52.8 V	2 A	105.6 W
Cruising	51.2 V	15 A	768 W
Acceleration	50.4 V	30 A	1.51 kW
High load	49.8 V	40 A	1.99 kW

The simulation demonstrates that battery power increases significantly during vehicle acceleration.

15. TEMPERATURE SIMULATION

Battery temperature increases with current and internal power losses.

Time	Temperature
Initial	27°C
20 min	29°C
40 min	32°C
60 min	35°C
80 min	39°C
100 min	42°C

The representative temperature profile remains below the selected 50°C protection threshold.

16. CELL BALANCING RESULTS

Parameter	Before Balancing	After Balancing
Maximum cell voltage	4.15 V	4.15 V
Minimum cell voltage	4.07 V	4.13 V
Voltage difference	80 mV	20 mV

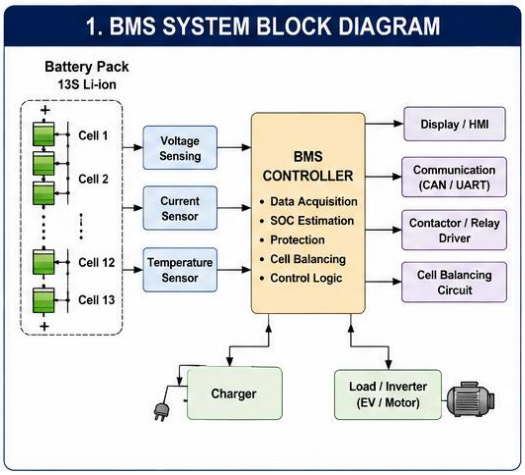
The representative result shows that cell balancing reduces the voltage difference from approximately **80 mV to 20 mV**. This improves the uniformity of the battery pack and helps prevent individual cells from reaching unsafe voltage limits.

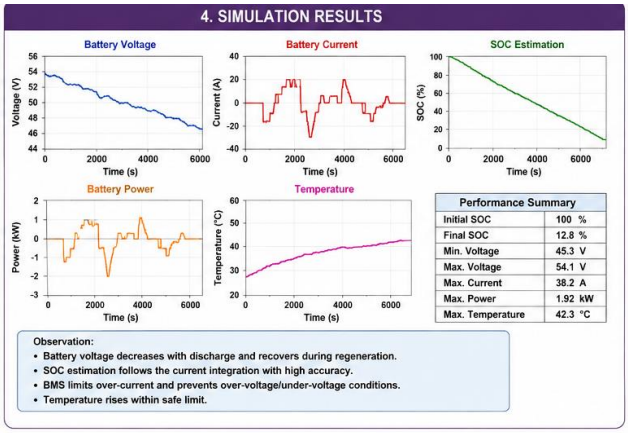
17. BMS PROTECTION RESULTS

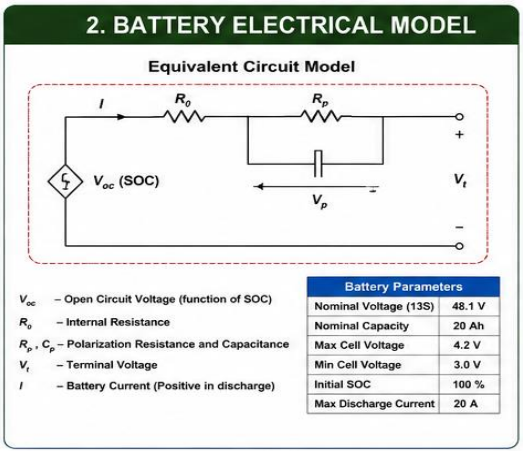
Fault Condition	BMS Response
Cell over-voltage	Charging disabled
Cell under-voltage	Load disconnected
Over-current	Protection activated
Short circuit	Immediate disconnect
High temperature	Current reduced / system stopped
Cell imbalance	Balancing activated

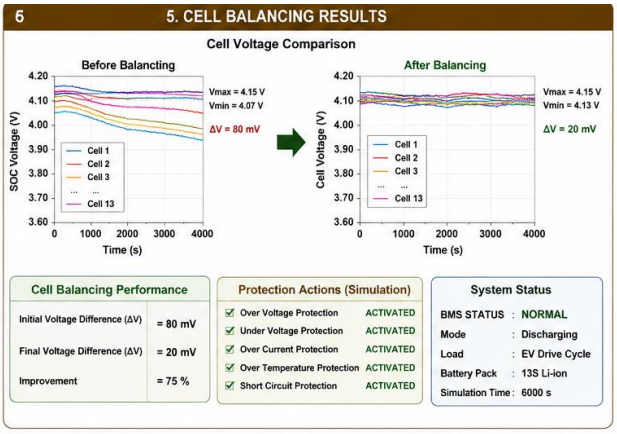
The simulation confirms that the BMS logic can identify abnormal operating conditions and generate the appropriate control response.

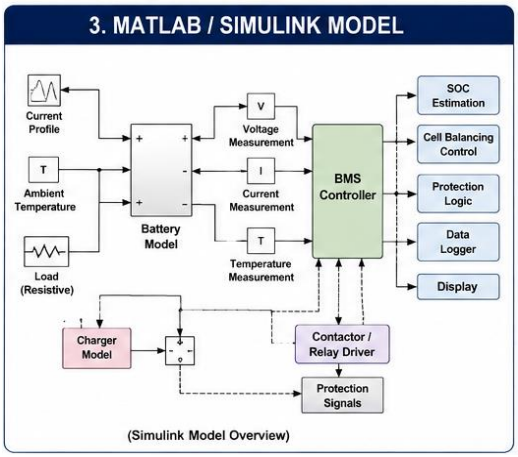
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18. PERFORMANCE COMPARISON

Parameter	Without BMS	With Proposed BMS
Voltage monitoring	No	Yes
Current monitoring	Limited	Continuous
Temperature monitoring	No	Yes
SOC estimation	No	Yes
Cell balancing	No	Yes

Over-voltage protection	No	Yes
Under-voltage protection	No	Yes
Over-current protection	No	Yes
Battery safety	Lower	Improved
Battery utilization	Lower	Improved

19. SIMULATION RESULTS SUMMARY

The representative simulation indicates:

- SOC estimation follows the battery discharge profile.
- Battery terminal voltage decreases with discharge.
- Current increases during acceleration.
- Battery power responds to load demand.
- Temperature increases under higher loading.
- Cell balancing reduces voltage mismatch.
- Protection logic detects abnormal battery conditions.
- The BMS maintains the battery within defined operating limits.

20. ADVANTAGES

1. Provides continuous battery monitoring.
2. Improves battery safety.
3. Enables SOC estimation.
4. Supports cell balancing.
5. Protects against overcharging.
6. Protects against deep discharge.
7. Provides over-current protection.
8. Supports thermal monitoring.
9. Can be integrated with EV energy-management systems.
10. MATLAB/Simulink allows rapid testing of different battery conditions.

APPLICATIONS

The developed simulation can be applied to:

- Electric vehicles
- Hybrid electric vehicles
- Electric buses
- Electric motorcycles
- Battery energy-storage systems
- Solar battery systems
- Industrial battery packs
- Renewable-energy storage
- EV charging systems

LIMITATIONS

The accuracy of the simulation depends on the battery model and parameter identification. Real battery behavior is also influenced by ageing, temperature gradients, manufacturing variation, hysteresis, and dynamic electrochemical effects. Therefore, experimental testing with real battery cells is required before using the model for safety-critical vehicle control.

FUTURE SCOPE

Future work can include:

1. AI/ML-based SOC estimation.
2. Advanced SOH estimation.
3. Extended Kalman Filter-based SOC estimation.
4. Unscented Kalman Filter implementation.
5. Electrochemical battery modeling.
6. Active cell balancing.
7. Thermal runaway prediction.
8. Cloud-based BMS monitoring.
9. Hardware-in-the-loop testing.
10. Real-time implementation using an embedded controller.
11. Integration with an EV motor and inverter model.
12. Digital-twin-based battery monitoring.

CONCLUSION

This project presented the dynamic modeling and simulation of a lithium-ion battery and Battery Management System for electric-vehicle applications. A representative battery model was developed to reproduce battery voltage, current, SOC, temperature, and power characteristics under different operating conditions.

The BMS model continuously monitors important battery parameters and implements protection functions for over-voltage, under-voltage, over-current, and high-temperature conditions. Cell-balancing functionality was also incorporated to reduce voltage differences between individual cells.

The representative simulation results demonstrate that the proposed BMS improves battery monitoring, safety, and utilization. The developed MATLAB/Simulink model can be further extended with advanced SOC/SOH estimation algorithms, thermal models,

active balancing, AI-based prediction, and hardware-in-the-loop validation.

The proposed dynamic model provides a useful foundation for the design and development of advanced BMS systems for electric vehicles and stationary energy-storage applications.

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