Circuit-Level Design And Simulation Of A Multi-Parameter Iot-Based Battery Monitoring And Protection System Using Esim

Theory

The Multi-Parameter Battery Monitoring and Protection System is a critical mixed-signal architecture designed to ensure the safe operation of battery systems by continuously monitoring key parameters such as temperature, smoke level, and battery voltage. In this implementation, the system utilizes multiple comparator circuits to evaluate real-time input signals against predefined safety thresholds within a circuit-level simulation environment.

The theoretical foundation of this design is based on hardware-level threshold detection and decision-making using operational amplifiers configured as comparators. Each parameter is independently analyzed, and whenever any parameter exceeds its safe operating limit, a fault signal is generated. This signal is processed using analog logic circuitry and is used to activate a protection mechanism. By relying entirely on analog and mixed-signal components, the system ensures fast response time, reliability, and independence from external controllers.

Principle of Operation

● **Multi-Parameter Monitoring:**
The system employs three LM741 operational amplifiers configured as comparators to monitor temperature, smoke level, and battery voltage conditions.

● **Threshold Detection:**

Each comparator compares the input signal with a reference voltage set using resistor divider networks. The reference thresholds for the three comparators are approximately:

- **Temperature Comparator (X_1): $V_{ref} \approx 2.5$ V**
- **Smoke Comparator (X_2): $V_{ref} \approx 3.0$ V**
- **Battery Voltage Comparator (X_3): $V_{ref} \approx 2.5$ V**

When the input voltage exceeds the corresponding reference threshold, the comparator output switches to a logic HIGH state, indicating a fault condition.

● **Diode OR Logic Network:**
The outputs of all comparators are combined using a diode-based OR network. This ensures that if any one parameter exceeds its limit, a unified fault signal is generated.

● **Relay Driver Circuit:**
The combined fault signal is applied to the base of an NPN transistor (BC547). Under normal conditions, the transistor remains in the cut-off region. When a fault is detected, the transistor enters saturation, enabling current flow.

● **Protection Mechanism:**
When the transistor conducts, current flows through the relay coil, activating the protection mechanism such as load disconnection or alarm triggering.

● **Inductive Protection:**
A flyback diode is connected across the relay coil to suppress voltage spikes generated due to inductive kickback during switching, thereby protecting the transistor.

Nomenclature

Input Stage

- **VCC:** DC supply voltage for the circuit
- **Vtemp, Vsmoke, Vbat:** Simulated sensor inputs representing temperature, smoke level, and battery voltage
- **Vref:** Reference voltage

Processing Stage

- **X1, X2, X3:** LM741 operational amplifiers functioning as comparators
- **R1–R8:** Resistor networks used for setting threshold reference voltages
- **D1–D3:** Indicator LEDs showing individual fault conditions

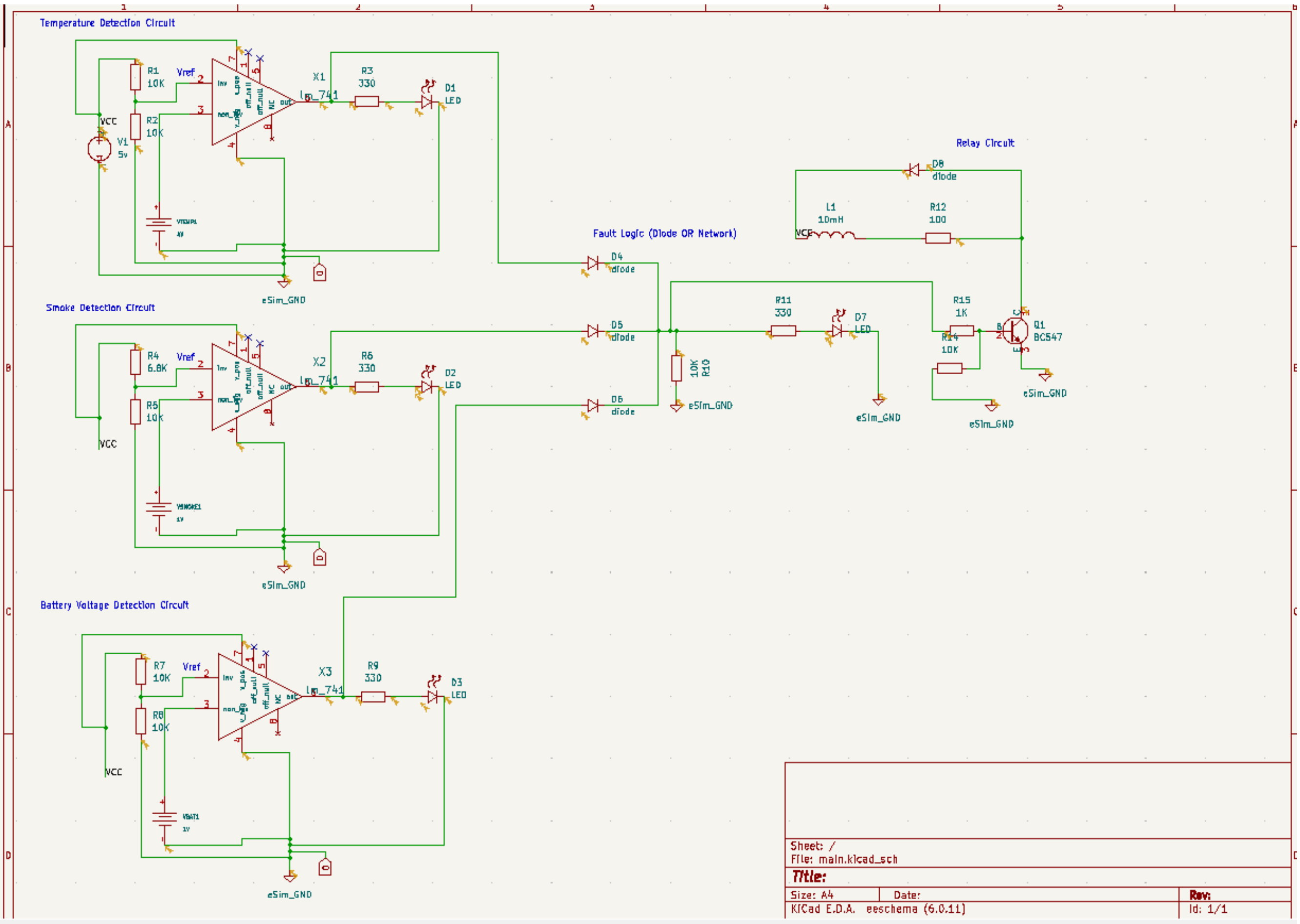
Logic Stage

- **D4, D5, D6:** Diodes forming OR logic for combining comparator outputs
- **R11:** Pull-down resistor stabilizing the logic node

Output Stage

- **Q1 (BC547):** Transistor used for switching and amplification
- **R15, R14:** Base biasing and control resistors
- **L1:** Relay coil representing the protection output
- **D8:** Flyback diode for inductive protection

Schematic Diagram:



Data Flow and Execution Sequence

1. **Sensing:**
   Analog inputs representing temperature, smoke, and battery voltage are applied to the non-inverting terminals of the comparators.

2. **Comparison:**
   Each comparator compares the input signal with its reference voltage. When $V_{in} > V_{ref}$,the output switches to saturation (HIGH).

3. **Indication:**
   Corresponding LEDs (D1–D3) glow, indicating which parameter has exceeded its threshold.

4. **Logic Combination:**
   The diode OR network forwards the highest active signal to the common fault node.

5. **Signal Conditioning:**
   The combined fault signal is stabilized using a resistor and then applied to the base of transistor Q_1.
6. **Switching Action:**
   The transistor turns ON when base voltage exceeds approximately 0.7V, allowing collector current to flow.
7. **Actuation:**
   The relay coil $L_1$is energized, thereby activating the protection mechanism such as load disconnection.

Simulation Results:

Figure 1: Comparator Response

Demonstrates the comparison between the input signal and the output of the temperature comparator. The graph shows that when the input voltage exceeds the threshold, the comparator output switches from LOW to HIGH.

Plotted nodes: net-_vtemp1-pad_ (blue), x1.net-_q19-pad(red)

Observation

The input voltage V_{in}(blue line) is maintained at approximately 4 V, which is higher than the reference voltage (2.5 V). The comparator output (red line) is observed at approximately 4.08 V, indicating a logic HIGH state. Under this condition, the temperature comparator $X_1$is in the ON state, while the other two comparators X_2(smoke) and X_3(battery) remain in the OFF state as they are below the threshold.

The output reaches saturation (~4.08 V), which is slightly lower than the supply voltage due to non-ideal characteristics of the operational amplifier.

Conclusion:

Since $V_{in} > V_{ref}$, the comparator output remains HIGH, confirming correct operation of the comparator under fault condition.

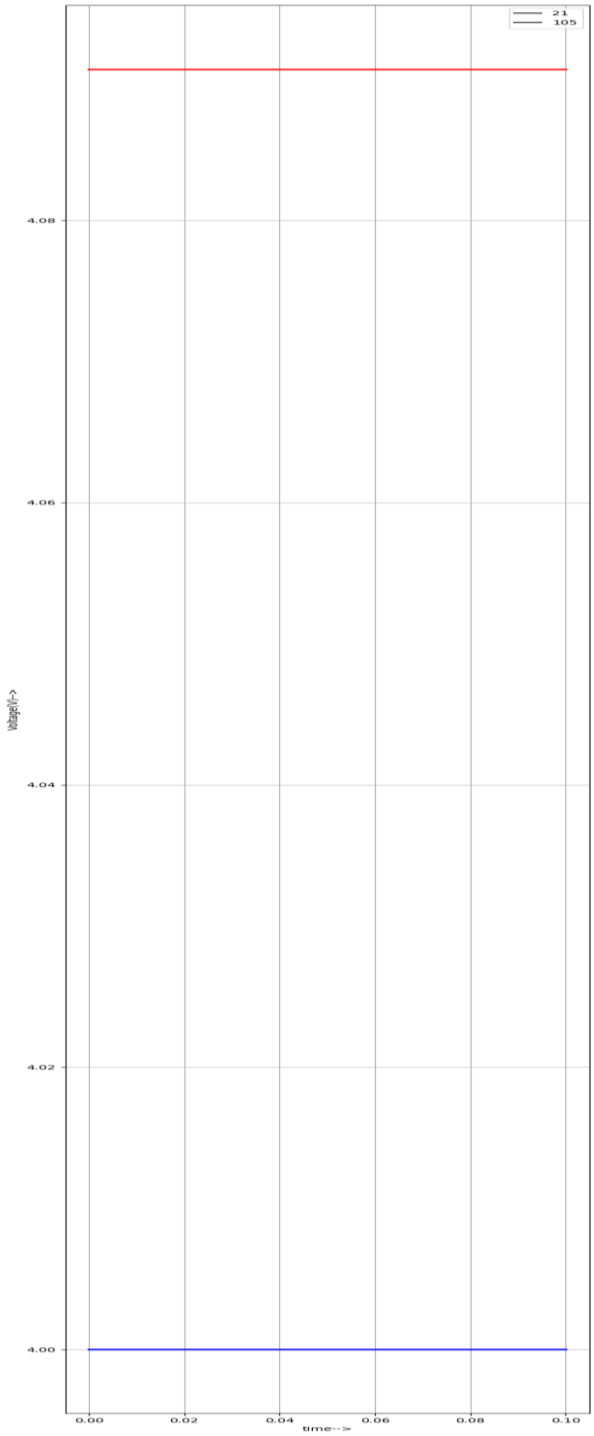
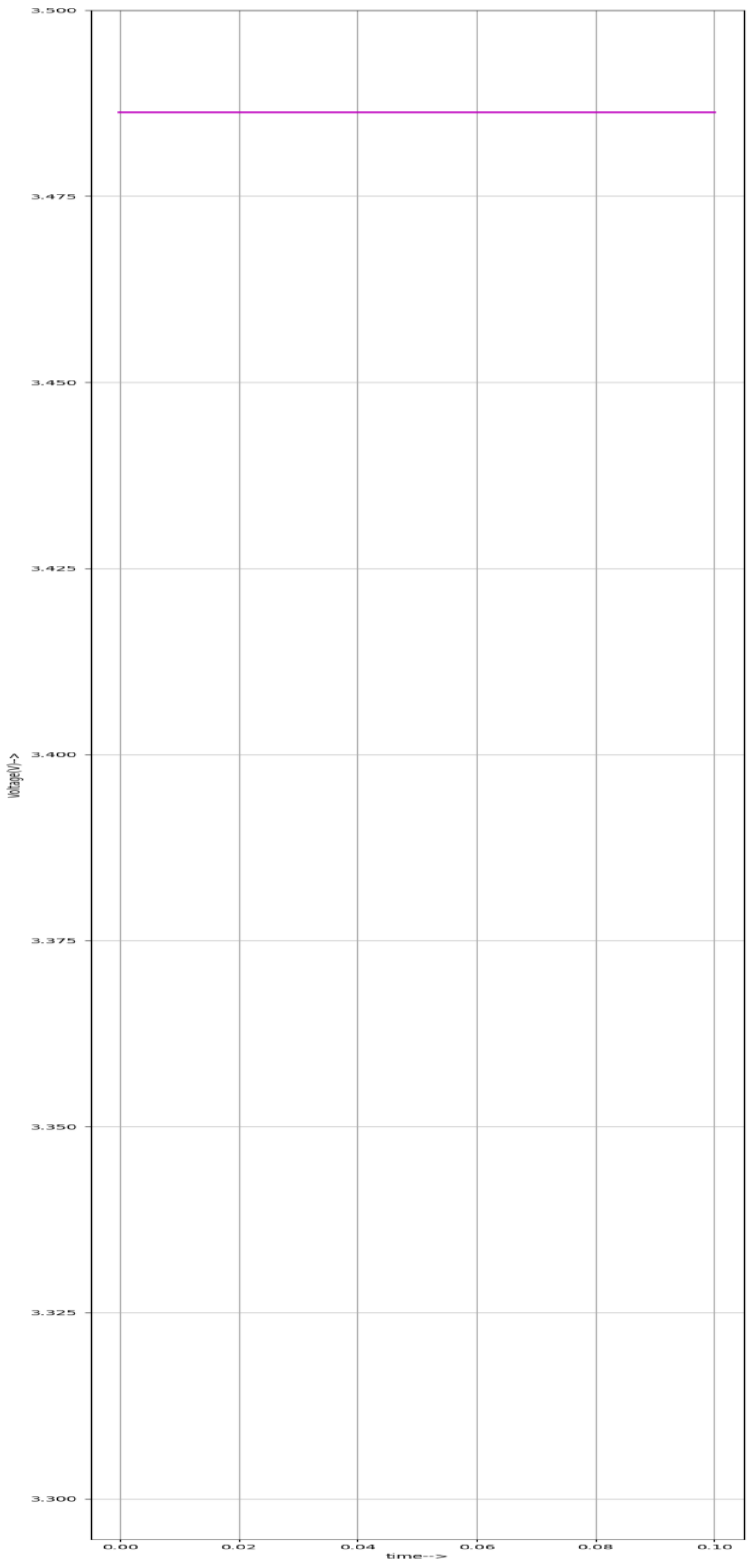


Figure 2: Fault Logic Node
Shows the combined output of the diode OR network, confirming that any active fault maintains the signal HIGH.

Plotted node: net-_d4-pad2_ (magenta)



3.500
3.475
3.450
3.425
3.400
3.375
3.350
3.325
3.300
Voltage(V)->
0.00
0.02
0.04
0.06
0.08
0.10
time-->

Observation:
The node voltage (magenta line) is observed to be approximately 3.4 V, indicating a HIGH logic level. Under this condition, the temperature comparator X_1 is in the ON state, while the smoke and battery comparators X_2 and X_3 remain in the OFF state.

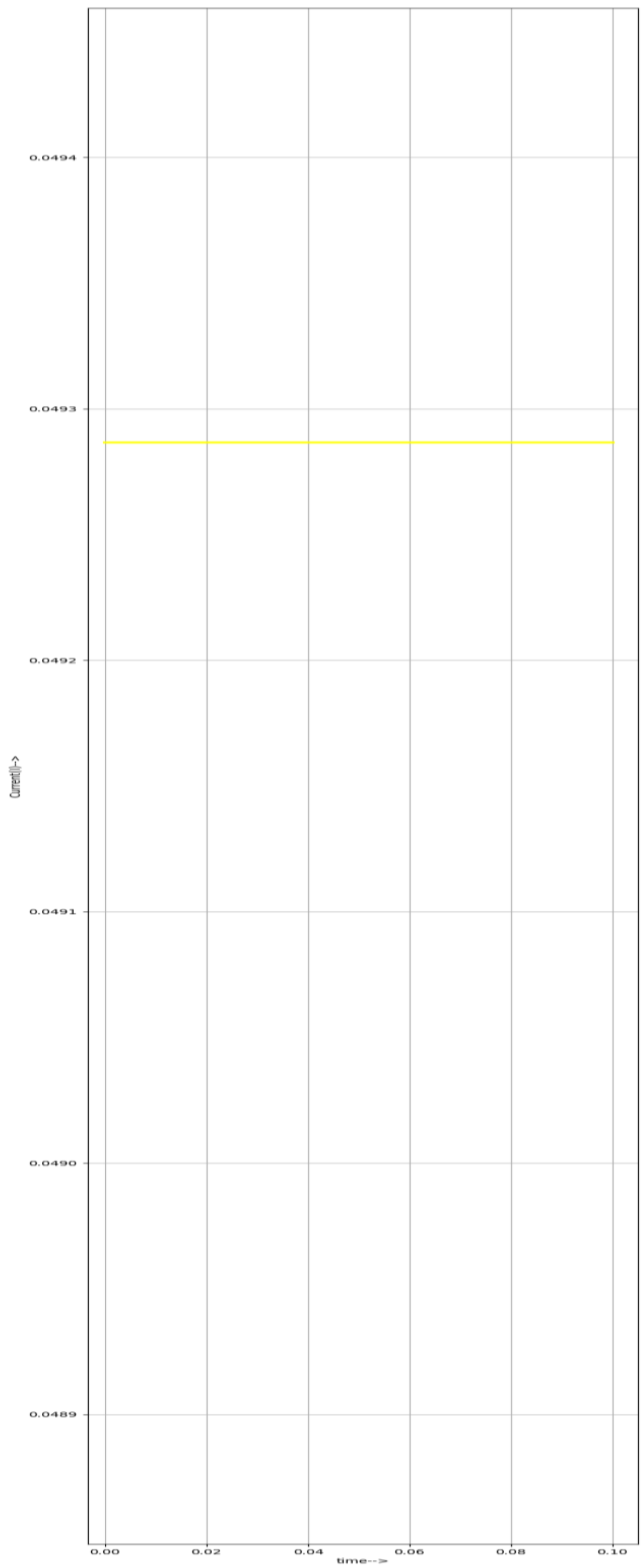
The diode OR network successfully combines the outputs of the comparators and produces a HIGH signal even when only one comparator is active.

Conclusion:
This confirms correct operation of the fault detection logic, where a single fault condition is sufficient to generate a HIGH output.

Figure 3: Relay Activation

Transient response showing the relay current when the transistor is driven into saturation under fault conditions.

Plotted branch: l1#branch (yellow)



Observation:

Under fault condition, the temperature comparator X_1switches to the ON state, indicating that a fault has been detected. This fault signal is propagated through the diode OR network and applied to the base of transistor Q_1. As a result, the transistor conducts, and the relay current (yellow line) rises to approximately 0.049 A (49 mA), indicating that the relay is energized.The detection of a fault condition successfully drives the relay through the transistor, confirming correct operation of the protection mechanism.

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Conclusion

The simulation in eSim successfully validates the circuit-level implementation of a multi-parameter battery monitoring and protection system. The design effectively demonstrates the integration of analog sensing, comparator-based decision-making, and hardware-level logic control. The system reliably activates the relay under fault conditions while remaining inactive during normal operation. This approach ensures fast response, robustness, and cost-effective implementation for real-time battery safety applications.

Reference:

https://www.researchgate.net/publication/395914508_A_review_on_battery_thermal_management_system_in_EV