FAULT ANALYSIS AND CONTROL IN GRID-CONNECTED BATTERY SYSTEMS

# CHAPTER 1: INTRODUCTION

## 1.1 Overview

The modern electric grid is rapidly evolving with the increased integration of distributed energy resources (DERs), such as photovoltaic panels and wind turbines. In parallel, the rising demand for clean energy has fostered widespread deployment of battery energy storage systems (BESS) that can store excess energy and supply it during peak loads or when renewable generation is low. Grid-connected BESS are central to grid stabilization, peak shaving, load leveling, and frequency regulation.   
However, integrating these systems into the grid introduces a new set of reliability and safety concerns due to their complex configurations, dependency on power electronics, and inherent vulnerability to faults. These systems are subject to both internal faults, such as cell short circuits or thermal runaway, and external faults, including grid disturbances and converter malfunctions. A failure in any component may lead to power disruption, energy loss, or even hazardous events such as fire and explosion.  
This research presents a comprehensive analysis of faults occurring in grid-connected BESS and explores fault generation mechanisms, detection techniques, classification strategies, and mitigation approaches using simulations and modern control systems.  
 [3]

## 1.2 Relevance of the Study

With battery systems playing an increasingly significant role in power infrastructure, understanding the behavior of faults and implementing proactive fault-handling measures is paramount. A grid-integrated battery system not only serves as a backup but also actively supports grid operations. If faults are undetected or mishandled, they can damage the system and pose safety hazards to both personnel and equipment.  
Furthermore, advanced control techniques like grid-forming and grid-following inverters are revolutionizing how BESS responds to faults. These developments demand a deeper investigation into fault dynamics and the control framework that can ensure system resilience.

## 1.3 Objective

The main objectives of this project are:  
- To study and classify the various types of faults that occur in grid-connected battery systems.  
- To understand how faults are generated due to operational or environmental stresses.  
- To explore high-resolution fault detection techniques such as DWT and DTFT.  
- To design intelligent control strategies that can isolate, contain, or tolerate faults without compromising overall system functionality.  
- To simulate grid-connected scenarios in MATLAB/Simulink to validate the effectiveness of the proposed techniques.  
 [4, 5]

## 1.4 Structure of the Report

The report is organized into the following chapters:  
- Chapter 1 introduces the motivation, relevance, and objectives of the study.  
- Chapter 2 describes various types of faults and explains fault generation mechanisms.  
- Chapter 3 covers state-of-the-art detection methods for identifying faults in real-time.  
- Chapter 4 delves into classification frameworks and presents fault-tolerant control methods.  
- Chapter 5 presents simulations, system responses, and comparative analysis.  
- Chapter 6 concludes the study with key findings and future research suggestions.  
 [4]

# CHAPTER 2: FAULTS IN GRID-CONNECTED BATTERY SYSTEMS

## 2.1 Introduction to Faults

In grid-connected battery systems, faults are defined as any abnormal electrical condition that causes deviation from normal operation. These faults can disrupt power delivery, reduce battery lifespan, trigger system shutdowns, and in extreme cases, lead to hazardous incidents such as explosions or fires. The ability to understand and differentiate fault types is essential for implementing effective detection and protection systems. Faults are typically categorized based on their origin (internal or externa...

## 2.2 Internal Faults

Internal faults originate within the battery packs or associated power electronics. These faults are primarily electrical or thermal in nature and are often difficult to detect early. Common internal faults include:  
• Internal Short Circuit: Caused by electrode material breakdown or separator failure. It leads to high fault current within milliseconds and rapid heating.  
• Thermal Runaway: Occurs when a cell’s temperature increases uncontrollably, initiating a chain reaction that can ignite nearby cells.  
• Overcharging or Deep Discharging: These operational stresses lead to chemical degradation, swelling, and ultimately internal breakdown.  
• Aging and Manufacturing Defects: These cause localized hot spots, capacity fade, and increased internal resistance that lead to uneven current flow and stress accumulation.

## 2.3 External Faults

External faults are those that occur outside the battery pack but impact the battery operation. They generally arise from grid disturbances, inverter failures, or external short circuits. Key types include:  
• Grid-Side Faults: These include voltage sags, surges, harmonics, or unbalanced loads, which result from faults in upstream transformers or transmission lines.  
• External Short Circuit: This condition causes a surge of current flowing out of the battery system, damaging output connectors and affecting energy availability.  
• Converter Failures: Power electronic components such as MOSFETs or IGBTs can fail due to switching stress or overheating, disrupting the current regulation process.

## 2.4 Fault Mechanisms and Current Behavior

When a fault occurs in a BESS, it alters the current-voltage profile drastically. For example, a cell short circuit may cause instantaneous current spikes up to 18–63 kA depending on the short path impedance. The resulting high temperature can degrade the separator, generate gas, and increase pressure—leading to potential rupture.  
In grid-connected configurations, faults often propagate between modules or clusters, especially when connected in cascaded H-Bridge (CHB) topologies. Energy can flow from healthy modules into the faulty one, resulting in “back-feeding” and high intra-cluster fault currents. These interactions necessitate fast isolation and fault-tolerant balancing control.

## 2.5 Simulation Example: Fault Propagation

Consider a 3-level CHB inverter-based BESS connected to the grid. A fault introduced into one of the mid-tier modules rapidly pulls down the module voltage to zero. The adjacent modules then attempt to balance the output by increasing their modulation index, inadvertently injecting more current through the faulty branch. This dynamic, simulated in MATLAB/Simulink, demonstrates how a fault escalates into a system-wide stability issue if not detected and isolated within the first few milliseconds.

# CHAPTER 3: FAULT DETECTION TECHNIQUES

## 3.1 Introduction

Fault detection is the process of identifying when and where a fault has occurred in a system. In grid-connected battery systems, this is a particularly complex task due to the fast dynamics of electrical faults, the modular nature of the battery packs, and the presence of noise in electrical signals. Early detection is crucial to prevent catastrophic outcomes such as cell explosion, thermal damage, or inverter collapse. Detection techniques typically involve time-domain monitoring, frequency-domain ana...

## 3.2 Time-Domain Monitoring

Time-domain monitoring involves tracking electrical parameters such as voltage, current, and temperature in real-time. Any sudden deviation from expected operating conditions may indicate a fault. Techniques include:  
• Threshold-Based Alarming: Fixed thresholds are set for each parameter; if values exceed these limits, alarms are triggered.  
• Rate of Change (ROC) Analysis: Faults generally cause abrupt changes. Monitoring the derivative of current or voltage signals helps detect fast-evolving faults.  
• Pattern Recognition: Historical data patterns are compared with live data streams to identify anomalies using machine learning methods.  
 [1, 2]

## 3.3 Frequency-Domain Analysis

Frequency-domain techniques help detect hidden or transient signatures that might not be visible in raw time-domain waveforms. They are especially effective in distinguishing fault-induced harmonics and high-frequency oscillations.  
• Discrete Fourier Transform (DFT): Analyzes sinusoidal components of the waveform, ideal for identifying steady-state harmonics.  
• Discrete Wavelet Transform (DWT): Offers multi-resolution analysis by decomposing signals into time-frequency sub-bands, making it ideal for detecting transient faults. DWT can precisely locate fault instances with high time localization.  
 [2, 3]

## 3.4 Battery Management System (BMS) Integration

The Battery Management System (BMS) is a critical unit embedded within the battery pack. It continuously monitors cell voltages, temperatures, and balancing conditions. Modern BMS are equipped with signal processing units that implement DWT or ROC algorithms for fault detection. They also support:  
• Cell-level diagnostics  
• Predictive health monitoring using data-driven models  
• Integration with circuit breakers for automatic fault isolation  
 [3, 4]

## 3.5 Simulation Example: Wavelet-Based Fault Detection

In a simulated scenario, a short circuit is introduced at one of the middle clusters of a BESS string. The raw voltage waveform does not show immediate fault indication due to averaging effects. However, applying DWT reveals a high-energy spike in the second level of decomposition (D2). The spike occurs at the exact time of fault initiation, providing precise detection for protection response.

# CHAPTER 4: FAULT CLASSIFICATION AND CONTROL STRATEGIES

## 4.1 Fault Classification Framework

Once a fault is detected, the next critical step is classification—identifying the type and severity of the fault. Proper classification allows for appropriate mitigation measures to be deployed. Faults in grid-connected BESS are generally classified based on three key dimensions:  
1. Origin: Internal (within the battery) vs. External (grid, inverter, connector).  
2. Impact Level: Minor (tolerable under control), Moderate (performance degrading), Critical (shutdown required).  
3. Affected Subsystem: Cell-level, Module-level, Cluster-level, or System-wide.

The following table outlines typical fault types and their classifications:  
 [5]

| Fault Type | Origin | Impact Level | Affected Subsystem |  
|--------------------------|----------|---------------|---------------------|  
| Cell Short Circuit | Internal | Critical | Cell |  
| Grid Voltage Sag | External | Moderate | System-wide |  
| Converter Switch Failure | Internal | Moderate | Converter |  
| SOC Imbalance | Internal | Minor | Cluster |  
| External Short Circuit | External | Critical | Output Stage |

## 4.2 Control Strategies for Fault Handling

Control systems in BESS must quickly adapt to fault conditions to protect system components and maintain power delivery. Control strategies can be grouped into three broad categories:  
• Fault-Isolation Control: Disconnects or bypasses the faulty component using solid-state relays or fast-acting switches.  
• Fault-Tolerant Control (FTC): Maintains partial operation by reconfiguring system parameters to “ride through” the fault.  
• Rebalancing Control: Engages auxiliary converters or balancing circuitry to re-distribute load among healthy modules.

## 4.3 Zero-Sequence Injection in CHB Topology

In CHB converter-based battery systems, a popular FTC technique is the injection of zero-sequence voltage. This approach allows the three-phase output to remain balanced, even when one or more submodules fail or go offline. The voltage injection compensates for missing voltage segments by dynamically adjusting the modulation of remaining healthy units.  
This method is particularly effective in:  
• Maintaining symmetrical three-phase output  
• Avoiding overmodulation that can cause harmonic distortion  
• Extending operational time until repair or replacement

## 4.4 SOC-Based Rebalancing Control

Another challenge during faulted operation is the unequal discharge of battery clusters, leading to State-of-Charge (SOC) imbalance. A fast balancing control algorithm is implemented using:  
• SOC estimation for each cluster (via Kalman filter or coulomb counting)  
• Adjusted current setpoints to regulate charging/discharging rates  
• Optional zero-sequence injection once to avoid oscillations  
This prevents degradation of weaker modules and maintains energy uniformity across the storage system.

## 4.5 Simulation Example: Fault-Tolerant Ride Through

A fault is simulated in one battery module of a three-phase CHB converter. Without zero-sequence control, the output becomes unbalanced, leading to grid code violation. With fault-tolerant control enabled, the faulty module is bypassed and the remaining modules compensate for the voltage drop. Simulation results show continued grid synchronization and waveform quality within acceptable limits.

# CHAPTER 5: SIMULATION AND RESULTS

## 5.1 Simulation Environment

All simulations were performed using MATLAB/Simulink with the Simscape Electrical toolbox. The system modeled includes a three-phase grid-connected BESS with CHB inverter topology, battery clusters, and control logic implementing zero-sequence fault-tolerant control. Fault events were introduced under various conditions to evaluate system response, waveform integrity, and SOC stability.

## 5.2 Test Case 1: Internal Cluster Fault

In this scenario, a short circuit was induced in one battery module in the middle cluster. The voltage of that module rapidly dropped to zero, triggering a fault flag in the BMS. Without control, neighboring modules tried to compensate, leading to overmodulation and SOC mismatch.  
With zero-sequence injection and rebalancing control activated, the system was able to bypass the fault and maintain output quality. The SOC of all modules was equalized within 2.8 seconds after compensation started.

## 5.3 Test Case 2: Grid-Side Voltage Sag

A 30% voltage dip was introduced on the grid side for 100 ms. Without ride-through capability, the BESS would disconnect from the grid, leading to instability. Using voltage mode (VF) control, the system injected reactive power to support grid recovery while maintaining DC bus stability. The grid voltage returned to nominal within 150 ms and no disconnection occurred.

## 5.4 Simulation Results Summary

The results of both test cases are summarized below:

|  |  |  |  |
| --- | --- | --- | --- |
| Test Scenario | Fault Type | Control Applied | Outcome |
| Internal Cluster Fault | Battery Short Circuit | Zero-sequence + SOC Rebalancing | Waveform symmetry maintained, SOC stabilized |
| Grid-Side Voltage Sag | External Grid Fault | Grid-forming (VF) Control | No disconnection, reactive support injected |

## 5.5 Interpretation

The simulations confirm the effectiveness of zero-sequence voltage injection and fast SOC balancing for internal faults, and the resilience of grid-forming converters during external voltage disturbances. In both cases, the BESS maintained operational stability and continued contributing to grid performance.  
These findings validate the proposed fault detection and control strategies, supporting their application in real-world grid-connected energy storage systems.

# CHAPTER 6: CONCLUSION AND FUTURE SCOPE

## 6.1 Conclusion

This report provides a comprehensive study of fault mechanisms, detection, classification, and control strategies in grid-connected battery energy storage systems. Internal and external fault types were discussed in-depth, including their propagation mechanisms and impact on system performance. Advanced techniques such as Discrete Wavelet Transform (DWT) and real-time control strategies like zero-sequence voltage injection and SOC rebalancing were presented as effective solutions for fault handling.  
Simulation results verified the practicality of these methods in maintaining system stability and waveform quality even under severe fault conditions. The use of grid-forming control helped retain grid connectivity during voltage sags, showcasing the robustness of the system design.

## 6.2 Future Scope

Future advancements in BESS fault management can benefit from:  
• Integration of machine learning for predictive fault detection using large datasets.  
• Development of self-healing control algorithms that automatically reconfigure system topologies.  
• Enhanced thermal and stress modeling to predict aging-related internal failures.  
• Real-time fault visualization dashboards integrated with SCADA systems.  
• Testing under cyber-physical fault scenarios involving grid-side control compromise.  
As energy storage technologies grow in scale and complexity, resilient and intelligent control frameworks will become essential for grid reliability.