



## The Role of Ripple Current on Lithium Battery's Lifecycle



# White Paper

## Lithium Battery Degradation and Failure Mechanisms: The Role of Ripple Current on Lithium Battery's Lifecycle

### 1. Introduction

Lithium-ion batteries (LIBs) are at the heart of modern electrification, powering electric vehicles (EVs), renewable energy storage systems (ESS), and portable electronics. While they offer high energy density and efficiency, their long-term reliability and safety are threatened by degradation and failure mechanisms. Among the numerous stressors influencing cycle life, Ripple Current — generated by inverters and power conversion systems — has emerged as a significant but often underestimated factor.

This paper synthesizes insights from experimental inverter ripple current testing (16 kW energy storage inverter) and recent academic studies to highlight how ripple currents and operational conditions accelerate lithium-ion battery degradation and failure.

### 2. Fundamentals of Lithium-Ion Battery Degradation

Lithium-ion batteries degrade through electrochemical, mechanical, and thermal pathways. The three primary categories include:

- **Loss of Lithium Inventory (LLI):** Continuous growth of the solid electrolyte interphase (SEI) and cathode electrolyte interphase (CEI) consumes active lithium, reducing capacity.
- **Loss of Active Material (LAM):** Electrode particle cracking, lithium plating, and transition metal dissolution reduce the number of sites available for lithium intercalation.
- **Conductivity Loss (CL):** Formation of dendrites, binder decomposition, and separator degradation increase internal resistance.

Key accelerants of degradation include state-of-charge (SOC) extremes, high depth of discharge (DOD), elevated temperatures, and irregular current profiles. Studies show that degradation pathways often interact, compounding negative effects.

### 3. Ripple Current as a Stress Factor

While laboratory battery cycling tests typically use smooth DC currents, real-world power electronics introduce ripple — oscillations superimposed on the DC current. These ripple currents can vary in amplitude, frequency, and waveform depending on inverter design.

Recent findings highlight:

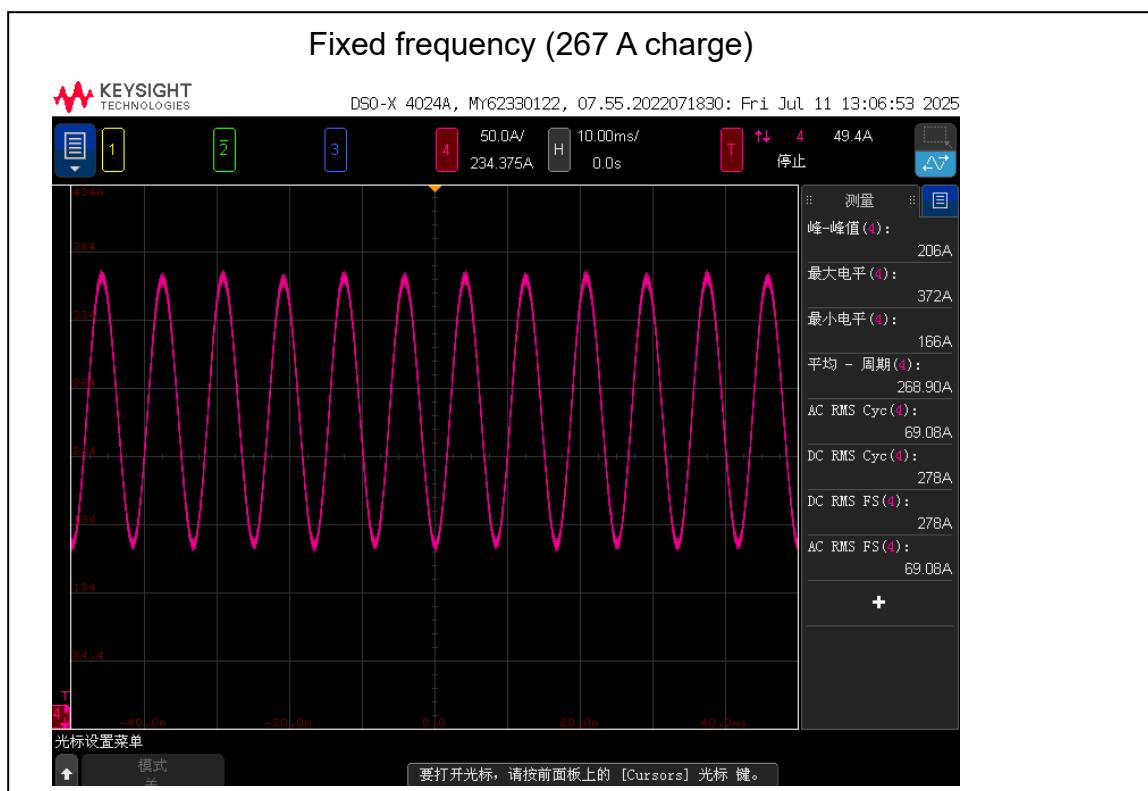
- Ripple currents of 6 A peak-peak at ~300 Hz accelerated capacity fade by up to **15%** compared to smooth DC cycling.
- Ripple current increases equivalent series resistance (ESR), reducing coulombic efficiency and accelerating SEI (Solid Electrolyte Interphase) growth.
- Mechanistic drivers include localized heating, uneven lithium intercalation, and faster electrolyte breakdown.

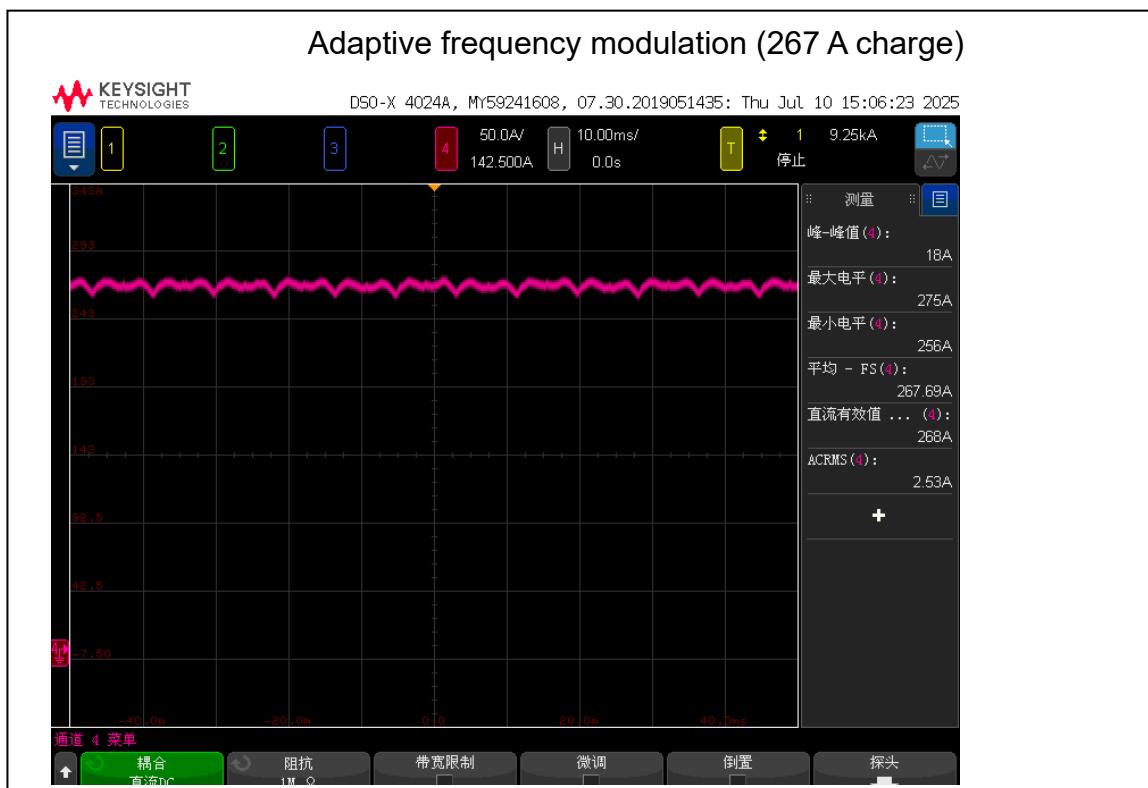
In short, ripple current introduces micro-cycling and thermal gradients that amplify conventional degradation mechanisms.

### 4. Case Study: Comparison of Battery Ripple Current under Different Frequency Modulation Topologies

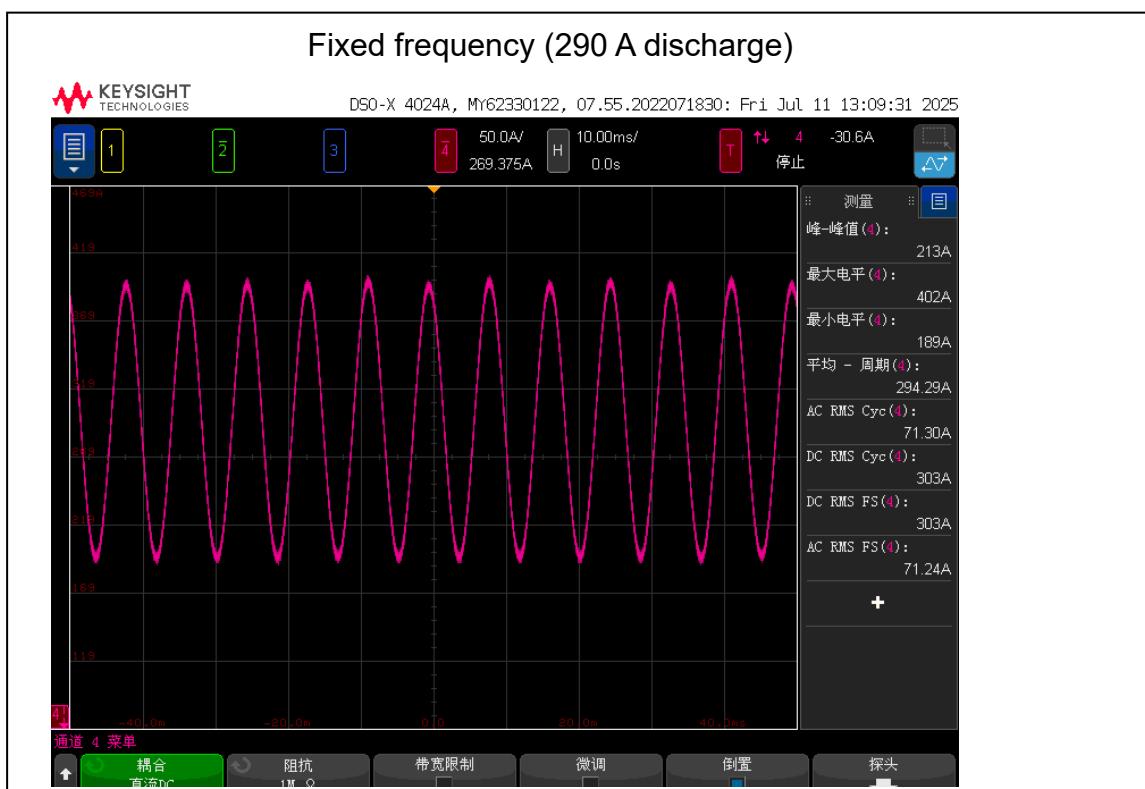
A recent engineering study tested the **S6-EH2P16K03-SV-YD-L-US** inverter under two different conversion topologies. The study compared fixed-frequency and adaptive frequency modulation. Key results include:

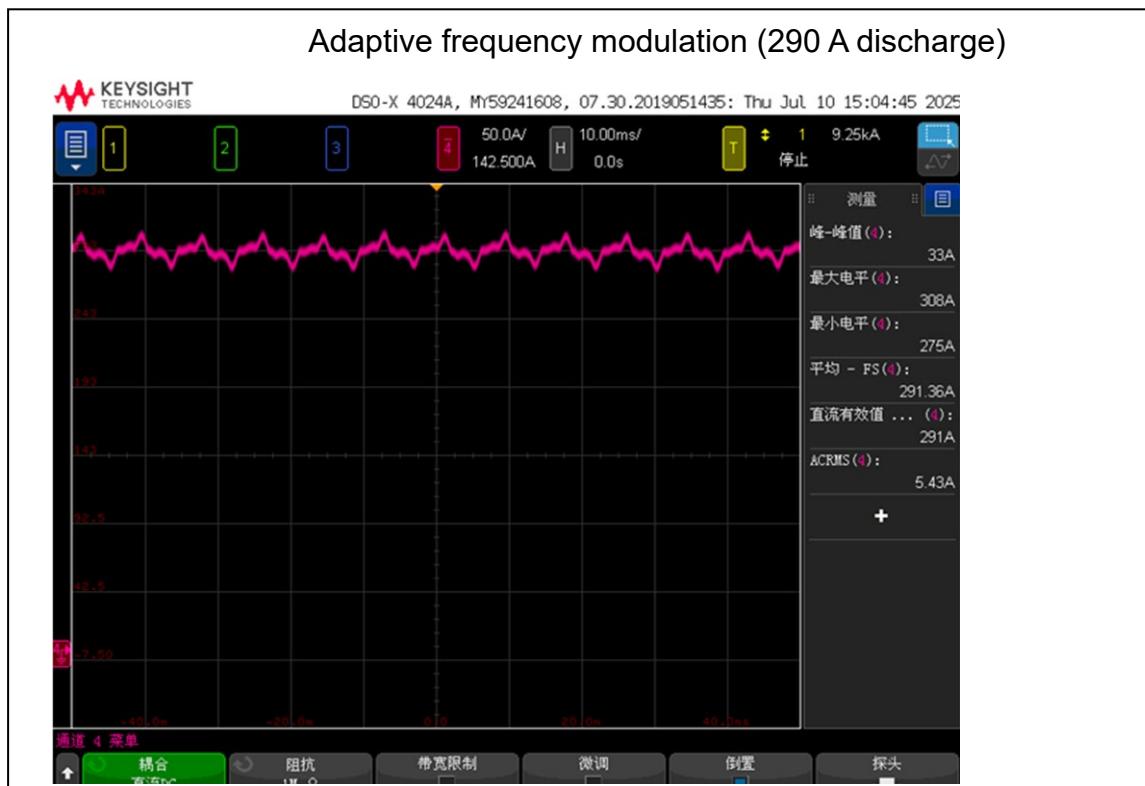
- **Charge mode:** At 267 A, RMS ripple current decreased from **69.08 A (25.9%)** to **2.53 A (0.95%).**





- **Discharge mode:** At 290 A, RMS ripple current decreased from **71.3 A (24.6%)** to **5.43 A (1.87%)**.





- **Conclusion:** Adaptive frequency modulation reduced ripple current by ~90–95%.

This demonstrates that inverter design directly influences battery stress, with optimized modulation dramatically improving current quality.

## 5. Broader Failure Mechanisms and Interaction with Ripple Current

Ripple Current-induced stresses rarely act alone. They couple with other degradation mechanisms:

- **Temperature coupling:** Ripple current increases  $I^2R$  losses, raising localized temperatures that accelerate SEI growth and electrolyte oxidation.
- **High C-rates:** At elevated currents, ripple exacerbates lithium plating and dendrite formation.
- **Material sensitivity:** NMC/NCA cathodes are more prone to ripple current-driven degradation at high voltages, while LFP cathodes, though thermally stable, still suffer from localized hotspots.

The interaction between ripple current and other operational stressors accelerates end-of-life compared to predictions from ripple-free laboratory testing.

## 6. Implications for Design and Management

Mitigating ripple current-related degradation requires a holistic approach:

- **Inverter and PCS design:** Larger bus capacitors, refined modulation strategies, and harmonic filters can significantly reduce ripple current.
- **Battery Management Systems (BMS):** Should monitor ripple currents alongside average DC parameters for a more accurate picture of stress.
- **Testing standards:** Current lifetime protocols often omit ripple, leading to overly optimistic performance projections. Ripple current -inclusive testing should become standard.

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## 7. Conclusions

Lithium-ion battery degradation is a complex interplay of electrochemical, thermal, and electrical stressors. Among these, Ripple Current is a measurable and controllable factor that accelerates capacity fade and internal resistance growth. Experimental inverter testing confirms that ripple current suppression through design and control strategies can reduce ripple current amplitude by more than 90%, directly prolonging battery life.

Solis's latest LV hybrid has been engineered to accommodate a low ripple current while others have reported a ripple current of 20-30% of rate charge/discharge current.

Future standards, testing, and BMS strategies must recognize ripple current as a critical operational stressor. By designing ripple-aware power electronics and management systems, industry stakeholders can significantly enhance the safety, longevity, and reliability of lithium-ion batteries.

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