Dynamic Information-Density Pulse Charging (DIDPC): A Falsifiable, Pilot-First Adaptive Protocol for Lithium Plating Mitigation

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Status. Design only. No data. No performance claims. Written to be pre-registered before any cell is cycled.

Abstract

This design isolates closed-loop adaptation of micro-pulse amplitude and duty cycle from ordinary fixed-parameter pulsing and from classical CC/CV charging. A mandatory pilot first establishes whether a chosen high-frequency impedance feature tracks lithium plating onset against a time-resolved independent reference, and whether the control timing parameters themselves change plating behaviour. Only a successful pilot authorises a three-arm main campaign with hard-bounded control laws, matching on delivered charge, a pre-specified primary endpoint, a sample-size rule and a four-outcome decision tree (superior / non-inferior / worse / inconclusive). Pack-level effects are out of scope. An optional fourth arm against a published adaptive baseline is strongly recommended when such a baseline is available.

1. Scope and Terminology

Lithium plating and dendritic growth limit fast charging and lithium-metal anodes [1, 2]. Pulsed charging can change dendrite growth [3], and the choice of charging protocol measurably affects cycle life [7]. What has not been isolated is the value of closing the loop on the pulse parameters. The protocol addresses single-cell, BMS-level implementation only. Pack-level integration (cell-to-cell current imbalance, interconnect inductance, bus-bar resistance, module thermal gradients) is a separate problem and outside scope. All results are single-cell results.

“Information density” is an operational name, not a physical claim. In this protocol it denotes the normalised plating indicator M*(t): the signed deviation of a high-frequency impedance feature from its reference trajectory (a function of accumulated charge), scaled by pilot noise and clipped to [−1, 1]. Positive values indicate plating-like behaviour (reduce current); negative values indicate headroom (move toward target). Whether M* carries useful information about plating is exactly what pilot questions Q1–Q2 test.

Table 1. Symbols.

Symbol	Meaning
$R_{hf}(t)$	High-frequency resistance, obtained from $\Delta V/\Delta I$ at pulse edges
$R_{ref}(q)$	Reference R_{hf} trajectory versus accumulated charge q, fixed in the pilot
$M^*(t)$	Plating indicator (written M-hat in v2.3): $\mathrm{clip}((R_{hf} - R_{ref}(q)) / (k \cdot s_R), -1, 1)$; s_R = pilot noise SD, k = scale fixed in the pilot
$I_p(t)$	Pulse peak current at update t
I_{target}	Peak current needed to meet the arm's average-current schedule
I_{min}, I_{max}	Hard current bounds ($I_{max} \le$ manufacturer pulse limit)
γ, κ	Reduction and recovery gains; $0 < \gamma < 1$, $0 < \kappa \le 1$
$\delta(t)$	Duty cycle; $\delta 0$ nominal, $\delta_{min} \le \delta \le \delta_{max}$
$C_{acc}(t)$, C_{ref}	Accumulated charge in the current charge step; reference charge (nominal capacity)
Δt, N	Control update interval; consecutive implausible samples that declare a sensor fault

2. Arms

A — classical CC/CV. B — DIDPC (hard-bounded closed loop). C — fixed-parameter pulsed charging using the median amplitude and duty cycle of arm B from the pilot, matched on delivered charge and end SOC.

Arm D (a published adaptive, impedance-based method run under identical matching rules) is optional because a well-characterised adaptive baseline is not available in every laboratory. When available it is strongly recommended. The scientific core claim (isolating closed-loop adaptation, B vs C) does not need Arm D; any practical claim of advantage over existing adaptive methods does. The two justifications are kept separate.

3. Chemistry Track

One track is chosen before pre-registration: graphite anode (commercial or pouch cells) or lithium-metal anode. The tracks differ in plating mechanism and reference methods, so pilot thresholds, reference methods and gains are pre-registered separately per track. Results are never pooled across tracks.

4. Mandatory Pilot — Three Questions

Q1 — Discrimination. Does M* separate conditions with and without plating, judged against a time-resolved independent reference? Reference: anode potential below 0 V vs Li/Li^+ in three-electrode cells, together with the voltage-relaxation stripping plateau after charge [4]. *Success threshold (pre-registered):* area under the ROC curve ≥ 0.80, lower 95% bound ≥ 0.70.

Q2 — Timing. Does M* cross its trigger before the reference detects plating? Post-mortem mass or density alone is insufficient. *Success threshold:* median lead time > 0 with the lower 95% bound > 0, in at least 80% of plating events.

Q3 — Timing-parameter neutrality. Do the chosen Δt, N and hold window themselves change plating or morphology relative to a slower but still adaptive update (10× Δt)? *Success threshold:* difference in the primary endpoint within the non-inferiority margin of Section 7. If not, the timing parameters are confounders and are revised before the main campaign.

A pilot that fails any question does not authorise the main campaign. The pilot also supplies the variance estimate used for sample size.

5. Numerical Starting Ranges and Measurement

Control update interval Δt: 100–500 µs. Sensor-fault counter N: 5–10 consecutive implausible samples. Hold window after fault: 1–2 s of the last valid command, then safe CC/CV fallback. Micro-pulse frequency: 2–10 kHz; duty cycle δ: 0.25–0.75.

R_hf is computed from the voltage step divided by the current step at each pulse edge, sampled within a fixed window after the edge, so that each update uses at least one edge pair (Δt ≥ pulse period). Final values are fixed after the pilot and recorded in the pre-registration. Feasibility on production BMS hardware (sampling rate, ADC resolution) is a stated risk, not an assumption.

6. Control Laws (hard-bounded)

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I_raw = I_p(t) − γ · max(0, M*) · I_p(t) + κ · max(0, −M*) · (I_target − I_p(t))
I_p(t+1) = clip(I_raw, I_min, I_max)
δ(t) = clip(δ0 · C_acc(t)/C_ref, δ_min, δ_max)
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Because $|M^*| \le 1$ and $0 < \gamma < 1$, a single reduction step keeps $I_{raw} \ge (1 - \gamma) \cdot I_p > 0$ before clipping; with $0 < \kappa \le 1$ a recovery step cannot overshoot I_target. I_target is computed so that the average current $I_{avg} = \delta \cdot I_p$ follows the arm's throughput-matching schedule. Sensor fault (missing, out-of-range or implausible R_hf for N consecutive samples) freezes the last valid command for the hold window, then reverts to CC/CV; every fault is logged and reported.

7. Endpoints, Matching and Statistics

Matching. All arms deliver the same charge (Ah) from the same start SOC to the same end SOC at the same ambient temperature. Total charge duration is reported as an outcome, so a slower charge cannot appear as a free benefit.

Primary endpoint. Cumulative irreversible capacity loss over the campaign, measured as Σ(1 − coulombic efficiency) with high-precision coulometry [5]. **Key secondary:** plated lithium per cycle from the voltage-relaxation stripping plateau [4]; capacity retention at the final cycle; charge duration; post-mortem morphology (SEM) on a pre-specified subset.

Unit and allocation. The unit of analysis is the cell. Cells are randomised to arms in blocks by production batch. The analyst is blind to arm labels until the analysis plan is locked.

Sample size. n per arm = $2(z(1-\alpha) + z(1-\beta))^2 \sigma^2 / \Delta^2$, with σ from the pilot. Pre-registered defaults: one-sided $\alpha = 0.025$, power 0.80. For $\Delta/\sigma = 1.0$ this gives 16 cells per arm; smaller effects need more cells.

Comparisons. Primary: B vs C (isolation of adaptation). Secondary: B vs A, and B vs D if run. Holm correction across the primary family. The non-inferiority margin is fixed before unblinding; the pre-registered default is 10% of arm C's mean primary endpoint.

8. Decision Tree

Reported in this order, from the two-sided 95% confidence interval of the difference (B minus comparator, lower is better) [6]:

Superior — the whole interval is below zero. **Non-inferior** — the upper bound is below the margin but the interval contains zero. **Worse** — the whole interval is above zero. **Inconclusive** — anything else. A ‘worse’ result is never folded into ‘inconclusive’.

9. What This Document Is

A sequential, single-cell, BMS-level experimental design that tests the most fragile assumptions first, keeps control commands physically bounded, matches arms on charge throughput, fixes its primary endpoint and sample-size rule in advance, and reports all four outcomes. It is not an industrial algorithm, not a pack-level solution and not a performance claim. Its possible lasting value is as a concrete example of how an adaptive pulsed-charging protocol can be written so that it can fail.

10. Invitation

Any laboratory that runs this design chooses the chemistry track and impedance feature, fixes the numerical parameters inside the stated ranges, and pre-registers the pilot thresholds before unblinding. Joint pilot specification is welcome; a failed pilot is a valid and publishable result.

References

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