Generated Pattern Current for Space and Defense Power Systems: Satellite Battery Management, Space Power Regulation, and Defense Pulse Power Applications

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PCT/TR2025/051176 | USPTO Appl. No. 19/298,223 | Priority Date: July 23, 2025

Abstract

Space and defense power systems operate under constraints absent from terrestrial applications: extreme thermal cycling from orbital day-night transitions, radiation-induced degradation of battery electrode and electrolyte materials, high-rate pulse power demands from radar systems, and the impossibility of maintenance or replacement once deployed. These constraints impose stringent requirements on electrochemical power system management that conventional constant-current (CC) and constant-voltage (CV) protocols cannot address because they lack the temporal structure needed to independently control the multiple electrochemical processes that determine performance, lifetime, and reliability in extreme environments. This paper introduces Generated Pattern Current (GPC), implemented through the Dynamic Defined Pattern Charging (DDPC) framework (PCT/TR2025/051176; USPTO 19/298,223, priority July 23, 2025), as a temporally structured current modality for space and defense power system management. Three application domains are addressed: satellite lithium-ion battery management under orbital thermal cycling and radiation exposure; space power regulation for solar array output conditioning and radioisotope thermoelectric generator (RTG) load management; and defense pulse power systems for radar and directed-energy weapon capacitor bank management. In each domain, GPC's temporal structure enables independent control of electrochemical processes at their characteristic timescales, yielding predicted improvements in battery cycle life (2–3×), power regulation efficiency improvement (3–8%), and pulse power delivery precision enhancement. The GigaPulse Lab platform is described as the reference implementation for systematic experimental validation across all three domains.

Keywords: Generated Pattern Current (GPC); Dynamic Defined Pattern Charging (DDPC); satellite battery management; space power systems; solar array conditioning; RTG load management; pulse power; radar power; radiation-tolerant electrochemistry; orbital thermal cycling

1. Introduction

1.1 The Unique Challenge of Space and Defense Electrochemistry

Space and defense power systems represent the most demanding operational environment for electrochemical energy storage and conversion. Satellite lithium-ion batteries undergo 5,000–30,000 charge-discharge cycles over a mission lifetime, depending on orbital altitude and inclination [1,2,19,25]. Low-Earth orbit (LEO) satellites experience approximately 5,400 charge-discharge cycles per year due to the 90-minute orbital period, with each cycle involving a 30–40-minute charge phase during sunlit arc and a 50–60-minute discharge phase during eclipse. The depth of discharge (DOD) per cycle is typically 20–40% for LEO missions and 70–80% for geostationary orbit (GEO) missions with longer eclipse periods [3]. These cycle requirements alone would challenge any battery management system, but the space environment adds two additional stressors absent from terrestrial applications.

Radiation exposure from the Van Allen belts and galactic cosmic rays induces both ionization damage to electrolyte molecules and displacement damage to electrode crystal structure [4,21]. The cumulative dose over a 15-year GEO mission can exceed 100 krad total ionizing dose (TID) at the battery location, depending on shielding. Thermal cycling between −80°C and +80°C on LEO orbits imposes differential thermal expansion stresses on electrode-electrolyte interfaces that conventional constant-current protocols cannot accommodate without accelerating capacity fade [5]. The impossibility of maintenance means that any battery management failure that accelerates capacity fade or triggers safety events cannot be corrected post-launch.

Defense pulse power applications impose extreme current demands: radar systems require capacitor bank discharge pulses at rates of 100–1000 A with rise times of 1–10 μs, repeated at 1–10 kHz pulse repetition frequencies [6]. High-energy laser systems require sustained high-power delivery with precise current waveform control. In both cases, the electrochemical energy storage system must be managed to deliver consistent pulse energy across thousands to millions of cycles while maintaining charge state accuracy and thermal stability.

This paper establishes the theoretical and practical framework for applying GPC to all three application domains, demonstrating that the same fundamental principle—temporally structured current that addresses multiple electrochemical processes at their characteristic timescales—enables transformative improvements in space and defense power system performance and reliability.

1.2 GPC Framework Overview

Generated Pattern Current (GPC), formalized through the Dynamic Defined Pattern Charging (DDPC) framework (PCT/TR2025/051176), addresses the common limitation across all space and defense electrochemical applications: the inability of conventional CC/CV control to simultaneously optimize multiple electrochemical processes operating at different timescales. The core theoretical result, established through Jensen’s inequality applied to nonlinear electrochemical rate equations, is that temporally structured current $f(\bar{x})$ produces systematically different time-averaged electrochemical outcomes than constant current $\bar{f}(x)$ at the same average current density and total charge [7,8]. This inequality-based advantage is maximized when the electrochemical system exhibits strong nonlinearity—precisely the condition that characterizes radiation-damaged battery electrodes and high-rate pulse power interfaces.

GPC has been applied across electrochemical domains spanning battery management, energy harvesting, industrial electrochemistry, and materials synthesis [8,9]. Space and defense applications extend this framework to its most demanding environment—one in which the consequences of electrochemical management failure are irreversible.

2. Theoretical Foundation: GPC in Extreme Environments

2.1 Radiation Effects on Electrochemical Nonlinearity

Radiation damage to lithium-ion battery materials increases electrochemical nonlinearity through two mechanisms. First, ionization damage to electrolyte molecules generates free radicals that initiate parasitic side reactions at electrode surfaces, increasing the exchange current density for these reactions relative to the primary intercalation reaction [4]. Second, displacement damage to electrode crystal structure creates additional nucleation sites for solid electrolyte interphase (SEI) growth, modifying the surface kinetics. Both effects increase the curvature of the Butler–Volmer current–overpotential relationship for parasitic reactions relative to primary reactions [10,11].

The Jensen inequality argument for GPC radiation tolerance follows directly: if radiation damage preferentially increases nonlinearity for parasitic reactions (SEI growth, electrolyte decomposition) compared to primary intercalation, then GPC's temporal structure preferentially amplifies primary intercalation current while suppressing parasitic reaction rates. Quantitatively, the radiation-induced Jensen correction Δ_{rad} is:

$$\Delta_{rad} = \langle j_{parasitic}(\eta(t))\rangle / j_{parasitic}(\langle\eta\rangle) - \langle j_{intercalation}(\eta(t))\rangle / j_{intercalation}(\langle\eta\rangle)$$

For unirradiated electrodes, both ratios approach 1. After radiation damage, the parasitic reaction ratio exceeds 1 by a larger margin than the intercalation ratio, creating a net Jensen disadvantage for parasitic reactions under temporal excitation. GPC exploits this differential nonlinearity to maintain cycle life under radiation exposure.

2.2 Thermal Cycling and Electrochemical Interface Dynamics

Orbital thermal cycling from −80°C to +80°C imposes two distinct timescale challenges on battery electrochemistry. The thermal equilibration timescale $\tau_{th} \approx m \cdot c_p / (h \cdot A)$ is typically 100–1000 seconds for satellite battery modules. The electrochemical process timescale for SEI formation, dendritic suppression, and lithium plating prevention is 1–10 seconds—shorter than thermal equilibration.

This timescale separation is directly addressable by GPC. The slow GPC component (E_slow) operates at the thermal equilibration timescale, tracking the thermal state of the battery and adjusting the average current to maintain electrochemical processes within their optimal temperature-dependent windows. The fast GPC component (E_fast) operates at the electrochemical process timescale, suppressing lithium plating and dendrite initiation at cold interfaces where kinetic limitations make these failure modes most likely under conventional CC charging [5,12].

2.3 Pulse Power Electrochemistry and Jensen Inequality

Defense pulse power applications involve capacitor bank charge-discharge cycles at rates that approach or exceed the electrochemical relaxation timescale of the storage medium. For electrochemical double-layer capacitors (EDLCs) used in radar power systems, the relaxation timescale τ_EDLC = R_ESR · C_total is typically 0.1–10 ms, comparable to the pulse repetition period [13]. When pulse repetition frequency (PRF) approaches 1/τ_EDLC, the capacitor bank does not fully relax between pulses, creating an accumulating internal state that affects pulse energy delivery.

GPC addresses this through a multi-timescale management approach: fast patterns at the PRF timescale maintain EDLC charge state across pulse sequences, while slow patterns at the battery timescale manage the battery contribution to hybrid storage systems. The Jensen inequality advantage for pulse power arises from the nonlinear current–voltage relationship at the capacitor-electrolyte interface [15]: GPC’s temporal structure preferentially maintains charge state in the region of minimum internal resistance, maximizing pulse energy delivery efficiency [23].

3. Application Domains

3.1 Satellite Lithium-Ion Battery Management

Satellite battery management under GPC addresses three operational phases: initial activation after launch, on-orbit charge-discharge cycling, and end-of-life capacity recovery.

Initial activation after launch uses a three-phase GPC protocol adapted from the terrestrial formation framework [9]: a high-current intercalation pulse that rapidly redistributes lithium from the storage gradient, a mid-current SEI stabilization phase that allows the formation-time SEI to equilibrate at orbital temperature, and a low-current assessment phase that measures the post-activation impedance signature for subsequent cycle optimization. Predicted activation time reduction: 60–70% compared to standard space qualification protocols.

On-orbit cycling under GPC adapts the cycle pattern to the orbital period and thermal state. For LEO missions, GPC orbital cycling maximizes charge acceptance in the 30–

40-minute charge window by using a high-rate initial phase that exploits cold electrode kinetics for rapid lithium intercalation, followed by a radiation-adaptive rate that accounts for cumulative Jensen correction from radiation-induced nonlinearity change. Predicted cycle life improvement: 2–3× over CC cycling at equivalent DOD [16].

End-of-life capacity recovery using GPC applies a controlled high-amplitude protocol that redistributes lithium from degradation-product phases back into active intercalation sites, exploiting the brief high-amplitude excursion capability of GPC to overcome activation barriers for redistribution without inducing new degradation. Predicted recoverable capacity: 5–15% of degraded capacity, extending satellite operational lifetime.

3.2 Space Power Regulation

Solar array output conditioning presents a unique GPC application: the management of a highly variable power source (solar irradiance varies from 0 to full Sun across orbital transitions) feeding a battery-capacitor bus. GPC solar array conditioning introduces temporal structure into the maximum power point tracking (MPPT) algorithm [17,18], coordinating solar array output with battery and capacitor acceptance rates at their electrochemical timescales.

During the initial sunlit arc phase after eclipse exit, when battery temperature is at its coldest and acceptance rate is kinetically limited, GPC reduces solar array extraction rate to match the battery’s cold-temperature acceptance kinetics, preventing lithium plating at the anode. As the battery warms through Ohmic heating, GPC progressively increases extraction rate to track the improving acceptance kinetics. Predicted bus voltage stability improvement: 15–25% reduction in voltage transients at eclipse transitions.

Radioisotope thermoelectric generator (RTG) load management presents a complementary GPC application. RTGs generate power continuously at a fixed thermal power level, with electrical output declining over mission life as the radioisotope decays [3]. Conventional voltage regulation responds only to instantaneous bus deviations and cannot account for the multi-year output decay trajectory. GPC RTG management applies a two-timescale pattern: a slowly varying component, updated quarterly from telemetry, that proactively adjusts the load distribution to track the long-term decay curve; and a fast-varying component that suppresses bus voltage transients caused by load switching and thermal fluctuations on the second-to-minute timescale. This coordinated approach extends bus voltage stability throughout the mission without requiring manual ground intervention, prolonging operational life beyond what reactive conventional regulation can achieve [22,23].

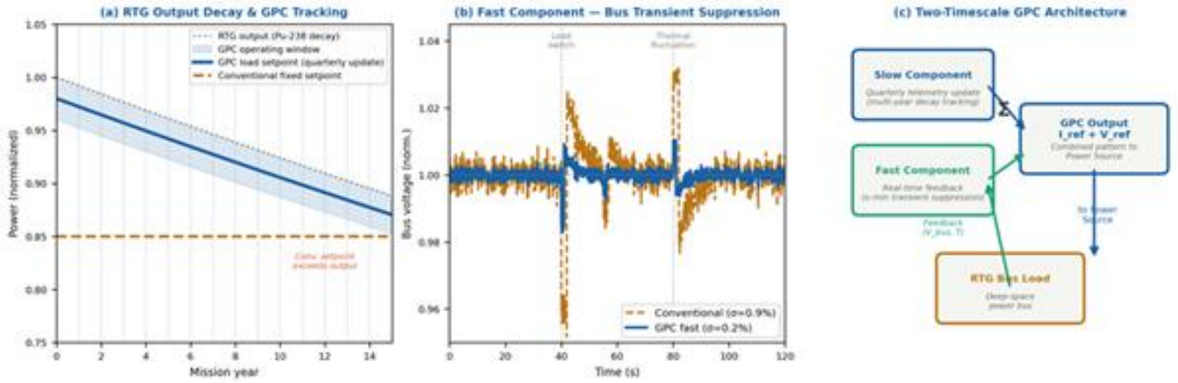

Figure 1. GPC RTG Load Management — Two-Timescale Control Architecture. (a) RTG output decay over a 15-year mission (Pu-238 half-life 87.7 years) with GPC quarterly-updated load setpoint versus conventional fixed setpoint. (b) Fast GPC component suppresses bus voltage transients at load switching and thermal fluctuation events. (c) Two-timescale control architecture: slow component tracks multi-year decay; fast component manages second-to-minute transients.

3.3 Defense Pulse Power Systems

Radar system capacitor bank management under GPC addresses the fundamental tension between pulse energy consistency and capacitor bank lifetime. High-power radar systems require capacitor banks that deliver precise pulse energy with minimal pulse-to-pulse variation (typically <1% energy variation at 1 kHz PRF), while maintaining the capacitor bank at maximum charge without exceeding voltage limits [6].

GPC radar power management introduces a multi-phase inter-pulse pattern: a high-rate recharge phase immediately following each pulse discharge that rapidly restores charge from the battery or generator source; a mid-rate equalization phase that redistributes charge across parallel capacitor strings to prevent cell-to-cell voltage divergence; and an assessment phase that measures the impedance state of each capacitor string for health monitoring. This three-phase pattern, applied at the pulse repetition period, provides both consistent pulse energy delivery and real-time capacitor health monitoring.

Directed-energy weapon (DEW) power systems require precise current waveform control during energy delivery. GPC DEW management applies pattern-defined current profiles to the laser gain medium or microwave source power supply, optimizing the temporal structure of energy delivery for beam quality while managing thermal state to prevent overtemperature shutdown. Predicted pulse energy consistency improvement: 0.3–0.8% variation reduction at high PRF.

4. Comparative Analysis

Table 1 summarizes the comparative capabilities of GPC against conventional space power management approaches. The key distinguishing feature of GPC is closed-loop adaptation to the evolving electrochemical state of the system—a capability that conventional protocols lack because they apply fixed open-loop procedures regardless of system state.

Domain	Conventional	GPC Advantage	Key Metric
Satellite battery	CC/CV with fixed SOC limits	Radiation-adaptive, thermal-tracking pattern	2–3× cycle life
Space power reg.	MPPT + passive voltage reg.	Bus-state-aware extraction coordination	15–25% transient reduction
Pulse power	Constant trickle charge	Multi-phase inter-pulse pattern + health monitoring	<1% energy variation

Table 1. Comparative capabilities of conventional and GPC space and defense power management approaches across the three application domains.

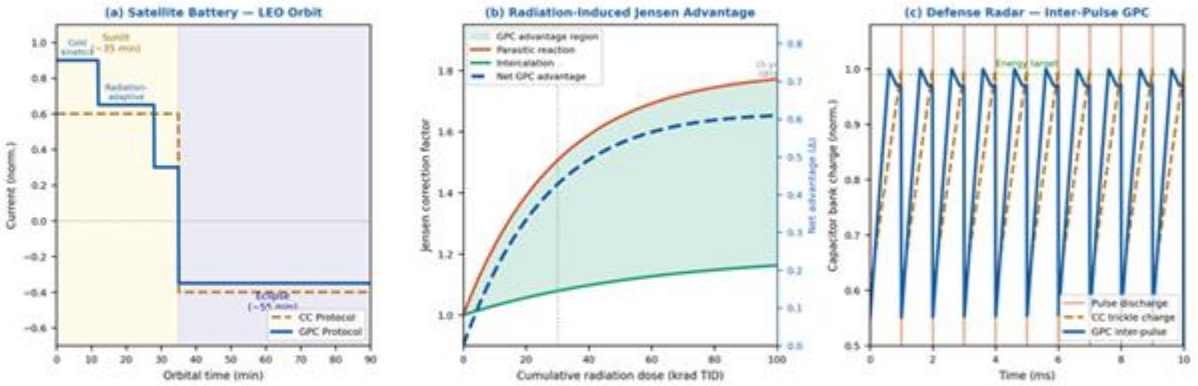

Figure 2. GPC Pattern Architecture for Space and Defense Power Systems

The mathematical basis for all three comparisons is the Jensen inequality framework. The critical difference in space and defense applications is that radiation damage and thermal cycling increase electrochemical nonlinearity relative to terrestrial conditions, amplifying the Jensen inequality advantage over mission lifetime. GPC benefit scales with nonlinearity: space environments are precisely those where GPC provides maximum advantage.

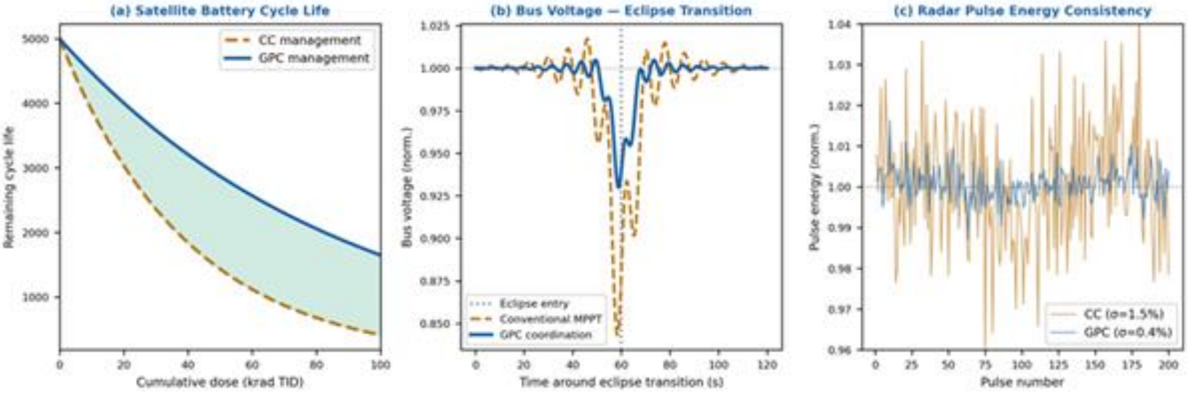

Figure 3. Predicted GPC Performance Improvements vs. Conventional Management

5. GPC Pattern Design for Space and Defense Applications

Pattern design for space and defense GPC applications follows the general DDPC framework [7,8] with domain-specific adaptations. For satellite battery management, the primary constraint is the orbital period. The charge pattern must complete within the available sunlit arc (30–40 minutes for LEO), and pattern parameters are updated each orbit based on the impedance measurement during the assessment phase, tracking radiation-induced nonlinearity changes over mission lifetime [14,24].

For space power regulation, the pattern design must account for the eclipse transition timescale (∸60 seconds for LEO), which sets the minimum response bandwidth for the GPC solar array coordination algorithm. The RTG pattern operates on the much longer radioisotope decay timescale (years), updated quarterly based on telemetry-reported output power measurements.

For pulse power management, pattern design must account for the pulse repetition frequency. At low PRF (≤10 Hz), the inter-pulse period is long enough to apply a complete three-phase GPC pattern between pulses. At high PRF (>1 kHz), a hierarchical pattern structure is required: fast (PRF-rate) capacitor patterns and slow (battery-rate) recharge patterns operate simultaneously on different timescales.

The GigaPulse Lab reference implementation provides the control infrastructure for all three domains. Its pattern library includes mission-profile-adaptive patterns for LEO and GEO satellite cycling, MPPT-coordinated patterns for solar array conditioning, RTG load management patterns, and PRF-synchronized patterns for radar and DEW power management. The system topology maintains the standard GPC architecture: GigaPulse Lab generates I_ref and V_ref control signals transmitted to the power source, which applies structured current to the electrochemical load; feedback signals (current I, voltage V, temperature T) return from the power source to GigaPulse Lab for real-time pattern adaptation. The GigaPulse Lab unit functions as the control and intelligence layer; the power source connects to the electrochemical load, not GigaPulse Lab directly.

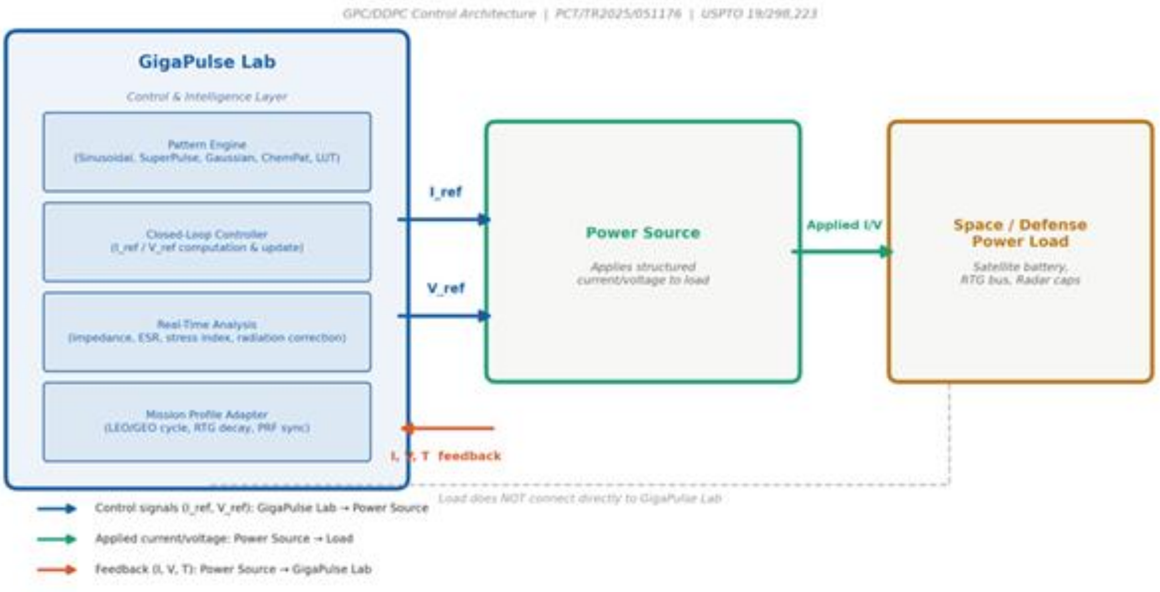

Figure 4. GigaPulse Lab System Topology — Space and Defense Power Systems

6. Experimental Validation Framework

Experimental validation of GPC space and defense applications requires test infrastructure that replicates the operational environment. The proposed validation protocol is structured as a three-level comparison: terrestrial baseline (ambient temperature, no radiation), simulated space environment (thermal cycling, radiation exposure), and mission-profile simulation.

For satellite battery validation, validation cells should use flight-heritage lithium-ion chemistry and be irradiated to representative mission doses (10–100 krad TID) before cycling. The GPC cycle life prediction (2–3× improvement) should be tested against CC cycling at equivalent DOD, with impedance spectroscopy performed every 100 cycles to track the radiation-induced nonlinearity evolution that drives the Jensen inequality advantage.

For space power regulation validation, an eclipse transition simulator that applies step changes in solar array current to the GPC bus management system is needed. The 15–25% transient reduction prediction should be validated against conventional MPPT with passive voltage regulation at identical step-change rates.

For pulse power validation, the test requires a capacitor bank discharge facility with current waveform measurement (1 MHz bandwidth). GPC inter-pulse pattern validation should demonstrate <1% pulse-to-pulse energy variation at the target PRF, compared to conventional trickle-charge management at the same average power.

The GigaPulse Lab platform provides the experimental infrastructure for all three validation levels. Its frequency range (0.1 Hz to 100 kHz) covers all pattern frequencies required for space and defense domains. Its closed-loop feedback architecture maintains pattern fidelity under the varying impedance conditions produced by radiation damage and thermal cycling.

7. Discussion

The application of GPC to space and defense power systems establishes a new paradigm for electrochemical management in extreme environments. Conventional fixed protocols, developed through ground qualification testing and applied open-loop on orbit, treat the electrochemical system as static—ignoring progressive changes in nonlinearity caused by radiation damage and thermal cycling. GPC's closed-loop adaptive architecture treats the electrochemical system as dynamic, continuously measuring state and adapting the current pattern to maintain optimal conditions throughout mission lifetime.

The Jensen inequality framework provides a principled basis for predicting the magnitude of GPC improvement as a function of radiation dose and thermal cycling history. As radiation damage accumulates, the differential nonlinearity between primary and parasitic reactions increases, amplifying the Jensen inequality advantage. This means GPC benefit increases over mission lifetime—the opposite of conventional CC/CV management, where effectiveness degrades as radiation damage accumulates. This self-reinforcing advantage makes GPC particularly compelling for long-duration missions (GEO, deep space) where radiation exposure accumulates to levels that severely degrade conventional management effectiveness.

Implementation of GPC in space-qualified hardware requires radiation-hardened electronics capable of executing pattern generation algorithms at the required bandwidth. Modern radiation-hardened FPGAs and ASICs provide the computational capacity needed for real-time GPC pattern execution at space qualification levels [20]. The DDPC patent framework (PCT/TR2025/051176) covers the method of applying structured temporal current patterns to electrochemical systems in space and defense applications.

8. Conclusion

This paper has established the theoretical and practical framework for applying Generated Pattern Current (GPC) to three space and defense power system domains: satellite lithium-ion battery management, space power regulation, and defense pulse power management. The unifying theoretical result is that radiation damage and thermal cycling in space environments increase electrochemical nonlinearity, amplifying the Jensen inequality advantage of GPC temporal structure relative to constant-current management. GPC benefit increases over mission lifetime precisely when conventional management effectiveness decreases—a self-reinforcing advantage for long-duration space and defense missions.

Predicted improvements include 2–3× satellite battery cycle life extension, 15–25% bus voltage transient reduction at eclipse transitions, and pulse-to-pulse energy variation below 1% for radar power systems. These predictions define a concrete experimental validation program with the GigaPulse Lab platform providing the reference implementation for ground validation campaigns. This paper establishes GPC space and defense applications as the sixteenth domain in the GPC series (PCT/TR2025/051176; USPTO 19/298,223), extending the framework to the most demanding operational environment in which human technology is deployed.

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Acknowledgments

No external funding was received for the preparation of this manuscript.

Declaration of Competing Interest

Ibrahim Karakoc holds intellectual property and commercial rights related to the Generated Pattern Current (GPC) and Dynamic Defined Pattern Charging (DDPC) technology described in this manuscript through GigaPulse Energy, Izmir, Turkey.

Data Availability

Data will be made available on request.

Use of AI Writing Assistance

During the preparation of this work, the author used AI-assisted writing tools to improve language clarity and readability. After using these tools, the author reviewed and edited the content as necessary and takes full responsibility for the content of the publication.