Generated Pattern Current in Impressed Current Cathodic Protection: Overcoming Direct Current Limitations in Pipeline, Marine Structure, and Reinforced Concrete Corrosion Mitigation

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PCT/TR2025/051176 | USPTO 19/298,223 | Priority date: July 23, 2025

Abstract

Generated Pattern Current (GPC) is a temporally structured current control framework derived from Jensen's inequality applied to the nonlinear electrochemistry of corroding metal-electrolyte interfaces. This paper applies the GPC framework to impressed current cathodic protection across three principal application domains: buried pipeline protection, marine structure and ship hull protection, and reinforced concrete corrosion mitigation. In each domain, conventional impressed current cathodic protection delivers protection via time-invariant direct current, a practice that fails to exploit the nonlinear Butler-Volmer kinetics governing the metal-electrolyte polarization response. GPC addresses this limitation by engineering purpose-specific temporal current structures derived from the polarization curve characteristics of each application: Butler-Volmer-matched cathodic polarization delivery for pipeline steel, impedance-adaptive protection current for marine structures in seawater, and threshold-controlled depolarization management for chloride-contaminated reinforced concrete. The GPC framework is implemented through the GP Lab reference platform, which provides real-time structure potential monitoring, closed-loop scalar parameter adjustment via the Dynamic Defined Pattern Charging algorithm, and current interruption-free protection continuity. Experimental validation protocols are proposed for each application domain. The GPC framework offers a unified first-principles basis for advancing impressed current cathodic protection efficiency across the corrosion engineering field.

Keywords: *Generated Pattern Current; GPC; Dynamic Defined Pattern Charging; DDPC; Cathodic Protection; Impressed Current Cathodic Protection; Corrosion; Pipeline Protection; Marine Corrosion; Reinforced Concrete; Butler-Volmer Kinetics; Jensen's Inequality*

1. Introduction

Corrosion of metallic infrastructure represents one of the most economically consequential materials degradation phenomena in modern industrial society. Global direct corrosion costs are estimated to exceed three percent of global gross domestic product annually, with pipeline corrosion, marine structure degradation, and reinforced concrete deterioration accounting for the majority of corrosion-related expenditure in the infrastructure, energy, and transportation sectors [1, 2]. Cathodic protection has been the dominant active corrosion control technology for buried and submerged metallic structures since Sir Humphry Davy first described its principles in 1824, and impressed current cathodic protection systems now protect billions of dollars of pipeline, marine, and civil infrastructure globally [3].

Despite this long history and widespread deployment, a fundamental limitation persists in impressed current cathodic protection practice: the protective current is delivered as a time-invariant direct current. Rectifier-based impressed current cathodic protection systems supply steady-state direct current to polarize the protected structure to a protective potential range, typically -850 mV to -1100 mV versus copper-copper sulfate reference electrode for carbon steel pipelines [4]. This direct current delivery practice is not a consequence of hardware limitations — modern programmable rectifiers and power electronics are capable of producing temporally structured current profiles — but a conceptual convention established decades before systematic electrochemical process control was feasible.

The consequences of this direct current convention are observable across cathodic protection applications. In buried pipeline protection, time-invariant direct current produces a polarization response governed by the nonlinear Butler-Volmer equation, yet the current level is calibrated empirically rather than derived from the polarization curve's nonlinear structure [5]. Hydrogen evolution at overprotected surfaces, calcareous deposit formation in marine environments, and alkali-silica reactivity in concrete all represent consequences of uniform direct current delivery that does not adapt to the spatially and temporally variable electrochemical environment [6, 7]. In reinforced concrete cathodic protection, the passivation threshold at which chloride-induced depassivation is suppressed is a strongly nonlinear function of steel potential, yet the current required to maintain passivation across varying chloride concentrations, moisture conditions, and temperature is delivered as a fixed direct current calibrated to a design condition that rarely matches instantaneous field conditions [8].

The existence of empirical pulse current cathodic protection investigations in the literature [9, 10] indicates that the field has recognized the potential of temporally structured current to improve protection efficiency, but these investigations have proceeded without a unified theoretical framework connecting the structure of the applied current to the nonlinear electrochemistry of the protection mechanism. Square wave pulses, intermittent current interruption, and variable frequency approaches have been evaluated experimentally but their advantages have been attributed to empirical observations rather than first-principles derivation from the Butler-Volmer kinetics of the metal-electrolyte interface.

Generated Pattern Current (GPC), defined in patent filings PCT/TR2025/051176 and USPTO 19/298,223 [11], provides a unified theoretical framework for systematically addressing these limitations. GPC applies Jensen's inequality for nonlinear functions to establish that a temporally structured current at the same time-averaged intensity as a direct current will, in general, produce different and potentially superior electrochemical outcomes whenever the underlying polarization response function is nonlinear. Because the Butler-Volmer equation governing cathodic polarization kinetics at metal-electrolyte interfaces is exponentially nonlinear, GPC provides a rigorous theoretical basis for anticipating that purpose-engineered current structures will outperform direct current in cathodic protection, and for deriving the optimal structure from first principles for each application.

This paper presents the first systematic application of the GPC framework to impressed current cathodic protection. Three principal application domains are analyzed in sequence: buried pipeline protection (Section 3), marine structure and ship hull protection (Section 4), and reinforced concrete corrosion mitigation (Section 5). The GP Lab reference implementation platform is described in Section 6. Experimental validation protocols are proposed in Section 7, and the discussion and conclusions follow in Sections 8 and 9.

2. Generated Pattern Current Framework Applied to Cathodic Protection

2.1 Jensen's Inequality and Butler-Volmer Nonlinearity

Generated Pattern Current I(t) = A · s(t) + I0 is defined by a shape function s(t) encoding the temporal structure of the protective current, an amplitude scalar A, and an offset I0. The time-averaged current is preserved by design, ensuring that energy delivery and mean charge flux remain equal to the direct current reference. Dynamic Defined Pattern Charging adjusts the scalar parameters A, I0, and duty cycle D in real time based on measured structure potential and electrolyte resistance, while the engineered GPC form geometry of s(t) remains fixed.

The theoretical foundation of GPC in cathodic protection applications is the exponential nonlinearity of the Butler-Volmer equation governing the cathodic partial current density at the steel-electrolyte interface. The Butler-Volmer equation is expressed as i = i_corr * [exp(alpha_a * F * eta / RT) - exp(-alpha_c * F * eta / RT)], where i_corr is the exchange current density, alpha_a and alpha_c are the anodic and cathodic transfer coefficients, F is Faraday's constant, R is the universal gas constant, T is absolute temperature, and eta is the overpotential relative to the open circuit corrosion potential E_corr. In the cathodic protection regime, the overpotential eta is strongly negative and the cathodic term dominates, simplifying to i_c = i_corr * exp(-alpha_c * F * eta / RT). This cathodic partial current density is an exponential function of the applied overpotential, making the metal-electrolyte interface an inherently nonlinear transducer of applied current to electrode potential.

Jensen's inequality states that for a convex function f and a random variable x, f(E[x]) <= E[f(x)], with strict inequality when f is strictly convex and x is non-degenerate. Applied to cathodic protection, where the polarization response function mapping applied current to structure potential is nonlinear, a temporally structured current at the same average value as a direct current will produce a different time-averaged structure potential, charge distribution, and polarization state. The direction and magnitude of this Jensen gap depends on the curvature of the polarization response function at the operating point, which is a function of the local corrosion potential, electrolyte composition, and temperature — all of which vary across the cathodic protection applications analyzed in this paper.

GPC form design for cathodic protection therefore consists of three steps: identifying the polarization response function for the target application; characterizing the curvature of this function at the intended operating point; and engineering the shape function s(t) to exploit this curvature toward the desired protective outcome — enhanced polarization at equal average current, reduced hydrogen evolution at equal protection potential, or more uniform potential distribution across geometrically complex structures.

2.2 Limitations of Direct Current in Impressed Current Cathodic Protection

The four principal limitations of direct current delivery in impressed current cathodic protection arise directly from the mismatch between a time-invariant input and a temporally and spatially variable nonlinear electrochemical system.

The first limitation is static operating point confinement. Direct current places the protected structure at a fixed point on the polarization curve. Because the polarization curve is exponential, small deviations in electrolyte resistance, temperature, or local current density produce large deviations in protection potential. Direct current cannot adapt to these variations without manual rectifier adjustment.

The second limitation is hydrogen evolution inefficiency. At potentials more negative than approximately -1100 mV versus copper-copper sulfate electrode, cathodic hydrogen evolution dominates over oxygen reduction as the principal cathodic reaction [6]. Direct current systems overprotect coating holidays and bare steel areas when the rectifier output is calibrated for the worst-case high-resistance soil condition, driving hydrogen evolution and the associated risks of hydrogen embrittlement in high-strength steel and cathodic disbondment of pipeline coatings.

The third limitation is calcareous deposit non-uniformity. In marine environments, direct current cathodic protection drives the formation of calcareous deposits — mixtures of calcium carbonate and magnesium hydroxide — on steel surfaces. These deposits serve a beneficial secondary protective function, but their formation rate, composition, and adhesion quality are strongly dependent on the current density temporal structure [7]. Direct current produces deposits with uncontrolled composition and potentially inferior protective quality compared to those that could be formed under structured current delivery.

The fourth limitation is potential distribution non-uniformity. For geometrically complex structures — ship hulls with shaft and propeller recesses, offshore platform jacket legs, or long buried pipelines with varying coating damage — direct current systems produce non-uniform potential distributions that leave some areas underprotected and others overprotected. The static nature of direct current delivery prevents adaptive redistribution of protective current toward underprotected regions without physical relocation of anode assemblies.

3. Generated Pattern Current for Buried Pipeline Cathodic Protection

3.1 Electrochemical Limitations of Direct Current Pipeline Protection

Buried pipeline impressed current cathodic protection systems protect carbon steel and low-alloy steel pipelines in soil environments ranging from highly conductive clay soils to high-resistivity sandy or rocky terrain. The NACE SP0169 standard specifies a protective potential criterion of -850 mV versus copper-copper sulfate electrode as a minimum protection threshold, with an upper limit of approximately -1200 mV to avoid hydrogen embrittlement and cathodic disbondment [4]. The required current density to maintain this potential window varies with soil resistivity, coating condition, temperature, and moisture content, changing seasonally and over the pipeline's operational lifetime.

Conventional impressed current cathodic protection for pipelines delivers a fixed direct current from a surface-mounted transformer-rectifier unit to a deep anode groundbed. The rectifier output is set to a fixed voltage that drives the required current under design soil resistivity conditions. As soil resistivity varies seasonally — dropping in winter as moisture content increases and rising in summer in arid climates — the actual current delivered varies with the soil resistance, potentially underprotecting the pipeline in high-resistivity summer conditions or overprotecting it in low-resistivity winter conditions. This mismatch is addressed in modern systems by automatic potential-controlled rectifiers that adjust output voltage to maintain a target structure-to-soil potential at a single test point, but this feedback operates at the timescale of minutes and cannot address spatially variable protection across the pipeline length.

The deeper limitation is that the rectifier output, whether manually or automatically controlled, delivers a uniform time-averaged current density to the entire anode groundbed zone. The Butler-Volmer polarization response of the steel surface is nonlinear: at potentials near the free corrosion potential E_{corr}, the polarization resistance is highest and small current increments produce large potential changes. Near the upper protection limit, the cathodic hydrogen evolution reaction dominates and further current increments produce diminishing returns in corrosion rate reduction but increasing hydrogen flux. Direct current cannot exploit this curvature structure because it operates at a single static point on the polarization curve.

3.2 Generated Pattern Current Form Design for Pipeline Protection

The GPC form for buried pipeline cathodic protection is derived from the Butler-Volmer cathodic polarization curve of carbon steel in the target soil electrolyte. The cathodic polarization curve in the protection potential window exhibits a Tafel region at intermediate overpotentials where log(i_c) is approximately linear in overpotential, and a limiting current region at higher overpotentials where oxygen reduction approaches the diffusion-limited current density and cathodic hydrogen evolution becomes dominant.

The optimal GPC form for pipeline protection operates within the Tafel region where the polarization curve is strongly convex when viewed as a function mapping current density to protection potential. A purpose-engineered GPC form that alternates between a primary cathodic polarization phase at a current density above the minimum protection threshold and a secondary maintenance phase at reduced current density exploits the convexity of the Tafel region: at the same time-averaged current density, the primary phase drives the structure potential more deeply into the protection window, while the secondary phase allows partial depolarization before the next primary phase cycle re-establishes full protection. This temporal structure maintains a higher time-averaged protection potential than a direct current at the same average density, because the exponential Butler-Volmer response amplifies the current during the primary phase more than it reduces protection during the secondary phase.

The temporal structure of the pipeline GPC form is further constrained by the double layer capacitance of the steel-electrolyte interface. The steel-electrolyte interface behaves as a capacitance in parallel with the faradaic impedance, with a time constant that governs the rate of potential response to current transients. The transition time between the primary and secondary phases of the GPC form must be matched to this time constant to ensure that the structure potential responds fully to the applied current before the phase transitions. GP Lab measures the interface capacitance and effective series resistance in real time from the potential transient response, enabling continuous calibration of the GPC form transition times to the measured interface characteristics.

For long-distance pipeline systems with distributed anode groundbeds, the GPC form can be deployed simultaneously from multiple rectifier stations with coordinated temporal phasing. Out-of-phase GPC delivery from adjacent rectifier zones creates temporal current gradients that drive potential equalization along the pipeline length, reducing the spatial non-uniformity of protection potential that is a fundamental limitation of direct current systems with fixed anode spacing.

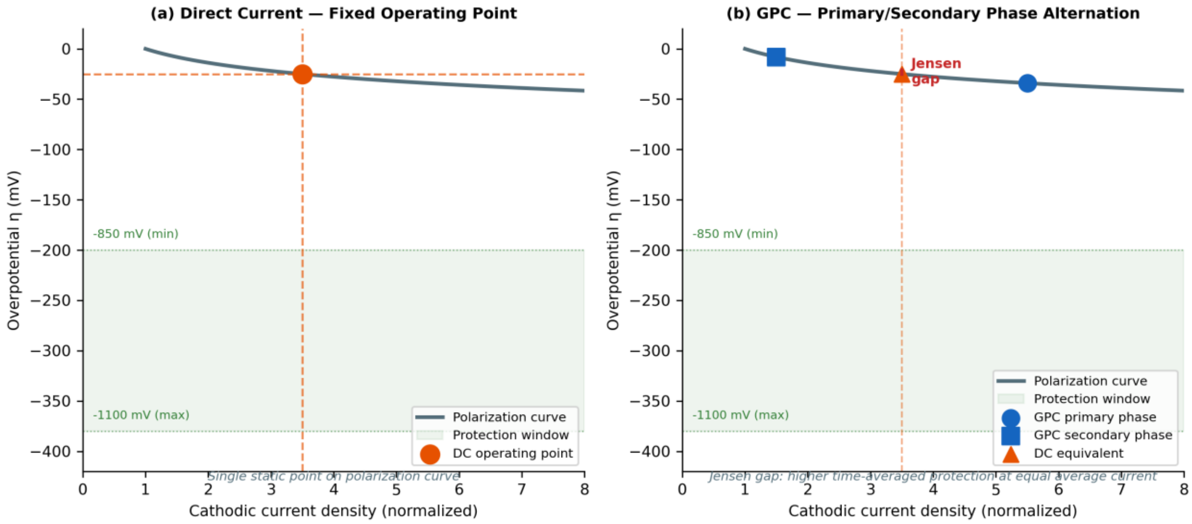

Figure 1. Butler-Volmer cathodic polarization curve for carbon steel in soil electrolyte showing the Tafel region convexity exploited by the GPC framework. (a) Direct current operating at a fixed point on the polarization curve. (b) GPC primary and secondary phase alternation exploiting Tafel region convexity to achieve higher time-averaged protection potential at equal average current density. The Jensen gap between the time-averaged GPC response and the direct current response at equal average current is indicated.

4. Generated Pattern Current for Marine Structure Cathodic Protection

4.1 Seawater Electrolyte and Calcareous Deposit Dynamics

Impressed current cathodic protection of marine structures — ship hulls, offshore platforms, harbor facilities, and subsea pipelines — operates in seawater electrolyte with substantially higher ionic conductivity than soil environments. The low resistivity of seawater (approximately 0.25 ohm-m for temperate ocean water) enables efficient current distribution from a small number of impressed current anodes, and cathodic current densities for bare steel protection typically range from 50 to 200 mA/m2 depending on flow velocity, temperature, and dissolved oxygen concentration [12, 13].

A secondary protective mechanism unique to marine cathodic protection is the formation of calcareous deposits on cathodically protected steel surfaces. These deposits, composed primarily of calcium carbonate and magnesium hydroxide, precipitate from seawater when the local pH adjacent to the steel surface is elevated by the hydroxide ion generated by cathodic oxygen reduction. Calcareous deposits provide a supplementary diffusion barrier that reduces the oxygen transport rate to the steel surface, progressively decreasing the current required for continued protection — a beneficial current density decay that can reduce long-term energy consumption by 50 to 80 percent compared to initial commissioning current requirements [14].

The limitation of direct current delivery in marine cathodic protection is that the calcareous deposit formation rate, composition, and protective quality are sensitive functions of the local current density at the steel surface. Direct current produces spatially uniform calcareous deposits on flat surfaces but non-uniform deposits at edges, weld seams, and geometric discontinuities where current density concentrations exist. The deposit composition — the ratio of calcium carbonate to magnesium hydroxide — affects deposit porosity, adhesion, and long-term protective effectiveness. Direct current produces deposit compositions governed by the local current density at commissioning, without subsequent adaptation as deposit coverage changes the local electrochemical environment.

4.2 Generated Pattern Current Form Design for Marine Protection

The GPC form for marine structure cathodic protection is derived from two coupled nonlinear functions: the Butler-Volmer cathodic polarization kinetics of the steel-seawater interface, and the calcareous deposit formation kinetics as a function of local current density and surface pH.

For ship hull protection, the primary GPC form consideration is the variation in local current density requirements across the hull surface during operation. Ship hull current demand varies with vessel speed, because increasing flow velocity accelerates oxygen transport to the surface and removes partially formed calcareous deposits, increasing the instantaneous current demand. Direct current systems either underprotect at high speed or overprotect at rest. The GPC form for ship hull protection incorporates a speed-responsive modulation derived from the relationship between flow velocity and mass transfer coefficient for oxygen at the steel-seawater interface — a nonlinear function that varies as approximately the square root of flow velocity in the turbulent regime. The GPC scalar parameter A is updated by the DDPC algorithm based on measured hull potential, enabling continuous adaptation of current delivery to instantaneous speed while the engineered form geometry remains fixed.

For offshore platform jacket protection, the primary GPC form consideration is the multi-zone current distribution across structural elements at different depths. The electrochemical environment varies with depth: dissolved oxygen concentration decreases with depth in the thermocline, temperature decreases, and microbial activity varies. Direct current from surface-mounted impressed current anode arrays produces a current distribution that is geometrically determined by anode-to-structure geometry and cannot adapt to the depth-variable electrochemical environment. The GPC form for platform protection incorporates temporal alternation between deep-penetration phases — higher current density delivered to drive current to lower-conductivity, low-oxygen deep zones — and surface-maintenance phases calibrated to the high-oxygen shallow zone requirements. The nonlinearity of the Butler-Volmer response ensures that the time-averaged potential distribution across the structure is more uniform under GPC delivery than under direct current at the same average current.

Calcareous deposit quality engineering is a further application of the GPC framework in marine protection. The ratio of calcium carbonate to magnesium hydroxide in calcareous deposits depends on the local surface pH, which is controlled by the cathodic current density. GPC forms with structured current density profiles can be engineered to target specific deposit compositions by operating at current densities that maintain surface pH in the optimal range for the desired deposit mineral phase. This capability is not available with direct current delivery, where the deposit composition is determined by the fixed current density without subsequent adjustment.

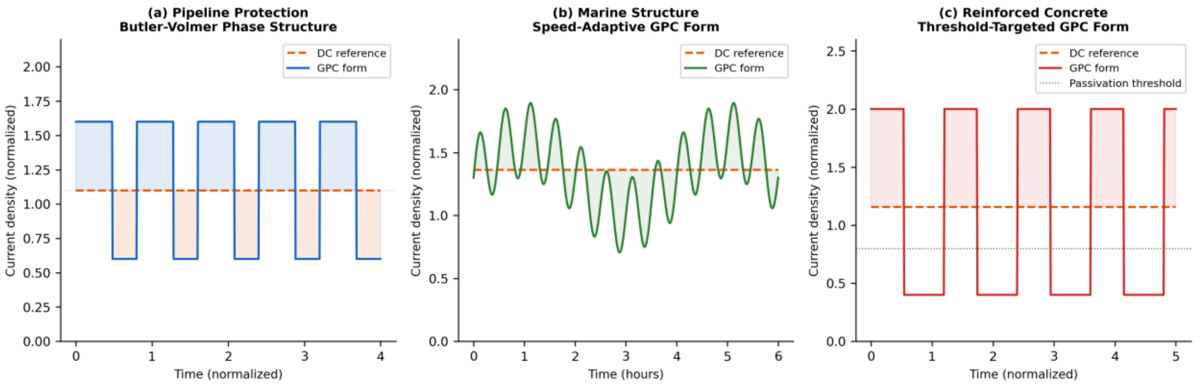

Figure 2. Process-specific GPC forms for the three cathodic protection application domains. (a) Pipeline GPC form: primary cathodic polarization phase and secondary maintenance phase, alternating at the interface time constant, exploiting Tafel region convexity. (b) Marine structure GPC form: speed-adaptive modulation envelope with depth-compensated phase structure for multi-zone platform protection. (c) Reinforced concrete GPC form: threshold-targeted polarization with chloride migration-synchronized temporal structure. All forms preserve time-averaged current density equal to the direct current reference.

5. Generated Pattern Current for Reinforced Concrete Cathodic Protection

5.1 Chloride-Induced Depassivation and Protection Threshold Nonlinearity

Cathodic protection of steel reinforcement in chloride-contaminated concrete presents a fundamentally different electrochemical environment from soil and seawater applications. The steel reinforcement in intact concrete exists in a passive state due to the high pH environment (pH approximately 12.5 to 13) created by calcium hydroxide and ettringite in the cement paste pore solution. Chloride ion ingress from marine exposure or de-icing salts progressively reduces the local pH adjacent to the steel surface and competes with hydroxide ions at the passive film, ultimately triggering depassivation and active corrosion initiation at localized sites [8, 15].

Impressed current cathodic protection for reinforced concrete operates by polarizing the reinforcement steel to a potential sufficiently negative to suppress active corrosion at chloride-contaminated sites, while simultaneously driving hydroxide ion generation that locally raises the pH adjacent to the reinforcement surface, restoring or maintaining the passive environment [16]. The protection threshold is a nonlinear function of local chloride concentration: at low chloride levels, a modest cathodic current density is sufficient to maintain passivity, while at high chloride concentrations approaching the depassivation threshold, the current density required for passivation increases steeply as the competition between chloride and hydroxide at the passive film site intensifies.

The nonlinearity of the protection threshold as a function of chloride concentration and applied current density is precisely the structural condition under which Jensen's inequality predicts that a temporally structured current will outperform direct current at the same average density. Direct current delivers equal current density to all reinforcement steel zones regardless of local chloride concentration, providing excess protection to low-chloride regions and potentially inadequate protection to high-chloride pitting initiation sites. This mismatch reflects the fundamental limitation of a time-invariant current applied to a spatially and temporally heterogeneous nonlinear electrochemical system.

5.2 Generated Pattern Current Form Design for Reinforced Concrete Protection

The GPC form for reinforced concrete cathodic protection is derived from the nonlinear relationship between applied current density and the local passivation thermodynamics of the steel-concrete pore solution interface at chloride contamination levels representative of service conditions.

The passivation response of steel in alkaline pore solution follows a strongly nonlinear potential-current relationship in the vicinity of the corrosion protection criterion. Below the free corrosion potential E_corr of active steel in chloride-contaminated concrete, increasing cathodic current density drives the potential toward the Flade potential at which the passive film forms — a threshold that is itself a nonlinear function of local chloride-to-hydroxide ratio. The GPC form for reinforced concrete protection operates with a primary re-passivation phase at sufficient cathodic current density to drive the steel potential below the Flade potential at the target chloride concentration, followed by a maintenance phase at reduced current density during which the passive film thickness grows and the protection potential is maintained without continued high current delivery.

This primary and maintenance phase structure exploits the nonlinearity of the passivation response: the high-current primary phase drives the steel through the nonlinear passivation threshold, while the reduced maintenance phase allows passive film consolidation without the energy expenditure of continued high-current delivery. At the same time-averaged current density, the GPC form achieves a more negative time-averaged steel potential than direct current in the passivation threshold region because the exponential relationship between current density and potential amplifies the primary phase contribution more than the secondary phase reduction.

The concrete pore solution ionic conductivity varies with moisture content, temperature, and chloride concentration, creating a time-variable resistance path between the surface-mounted anode and the reinforcement steel. The GPC form's scalar parameter adjustment capability through DDPC enables continuous adaptation of the current amplitude A to compensate for conductivity variations while maintaining the engineered temporal structure. GP Lab measures the concrete resistance from the current-potential transient response and updates A accordingly, ensuring that the effective current density at the reinforcement surface tracks the target GPC form regardless of concrete moisture state.

A further benefit of the GPC framework in reinforced concrete protection is the potential for chloride migration acceleration. Chloride ions in the concrete pore solution are negatively charged and respond to the electric field produced by the cathodic protection current. During the high-current primary phase of the GPC form, the electric field gradient between the surface anode and the reinforcement steel is elevated, driving chloride migration toward the anode and away from the reinforcement surface. This electrochemical chloride extraction effect supplements the cathodic protection mechanism, progressively reducing the chloride concentration at the reinforcement surface and lowering the long-term current demand for passive film maintenance.

6. GP Lab Reference Implementation

6.1 System Architecture for Cathodic Protection Applications

The GP Lab system provides a laboratory and field reference implementation of the GPC framework for cathodic protection research and system validation. GP Lab interfaces with any standard impressed current cathodic protection rectifier through its output stage interface, requiring only structure potential measurement and anode current monitoring at the rectifier output terminals. No modification of the existing anode groundbed, pipeline coating, or structural protection system is required.

GP Lab connects to the rectifier Power Source input terminals and transmits I_ref(t) control signals specifying the instantaneous current setpoint. The rectifier applies the commanded current through its existing anode assembly to the protected structure. The protected structure connects to the rectifier only — GP Lab is the control and intelligence layer, not a power source. Feedback signals including structure-to-electrolyte potential E(t), protection current I(t), and when available, local electrolyte resistance R_e(t), return from the rectifier measurement circuits to GP Lab. GP Lab computes the interface impedance Z(omega), effective polarization resistance R_p, protection status index, and depolarization rate in real time, and updates the scalar parameters A, I0, and D via the DDPC algorithm while maintaining the fixed GPC form geometry.

For pipeline applications, GP Lab interfaces with existing automatic potential-controlled rectifier units through a standard analog setpoint input, replacing the potential controller output with the GPC current reference signal. Structure-to-soil potential measurements from existing test stations are used as feedback inputs. For marine applications, GP Lab connects to the shaft-mounted or hull-mounted reference electrode circuit and the impressed current anode controller. For reinforced concrete applications, GP Lab interfaces with the surface anode current feed and the embedded reference electrode network.

6.2 Process-Specific Generated Pattern Current Form Deployment

For each cathodic protection application, GP Lab executes a purpose-specific GPC form engineered from first principles as described in Sections 3 through 5.

The pipeline GPC form is derived from the Butler-Volmer polarization parameters of the target steel grade in the representative soil electrolyte, with Tafel slope and exchange current density used to calibrate the primary-to-secondary phase current ratio and the inter-phase transition time constant. GP Lab measures the pipeline interface time constant from the potential decay response during periodic brief current interruptions and updates the transition timing accordingly.

The marine structure GPC form incorporates a speed-adaptive envelope parameter updated from the vessel dynamic positioning system or speed log, with the depth-compensated phase structure deployed through a multi-zone anode switching sequence. For offshore platforms, GP Lab coordinates the anode zone switching through a time-multiplexed control sequence that applies the GPC form to each protection zone in rotation, ensuring that all zones receive the engineered temporal structure.

The reinforced concrete GPC form deploys the primary re-passivation and maintenance phase sequence with phase durations calibrated to the measured concrete resistance and the estimated chloride concentration profile from inspection records or electrochemical noise measurements. The DDPC algorithm updates the primary phase amplitude A based on continuous structure potential monitoring to compensate for concrete moisture variations.

All GPC forms preserve the time-averaged current density equal to the direct current design specification. Each process-specific GPC form is loaded into GP Lab as a firmware configuration and is updatable as protection requirements evolve with structure age, coating degradation, or environmental condition changes.

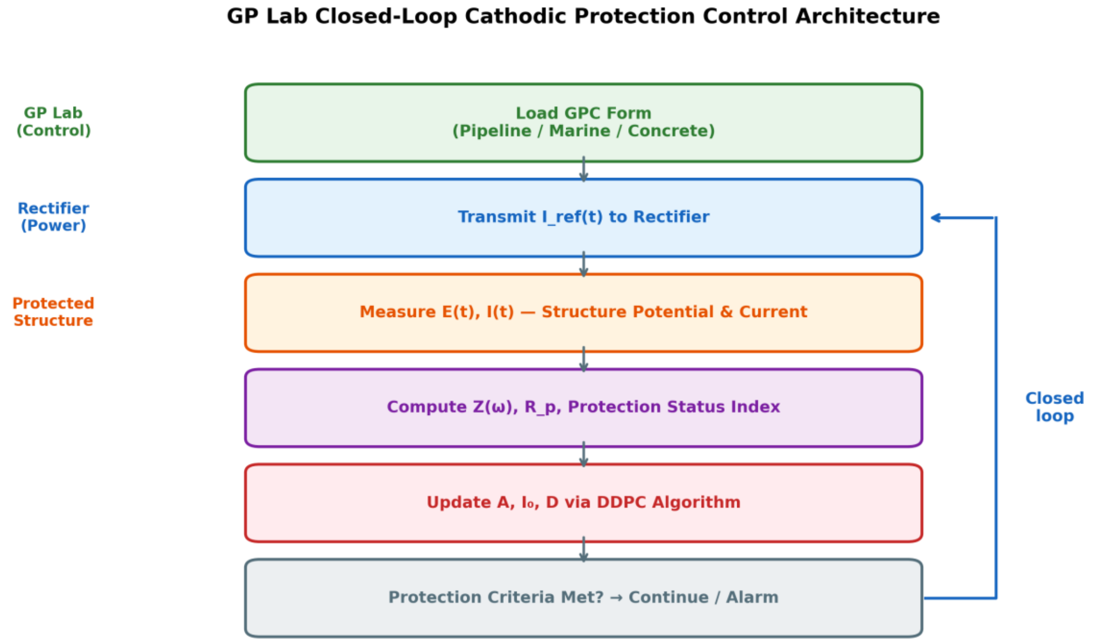

Figure 3. GP Lab closed-loop cathodic protection control architecture. GP Lab loads the process-specific GPC form, transmits I_ref(t) to the rectifier, receives structure potential E(t) and protection current I(t) feedback, computes interface impedance Z(omega), polarization resistance, and protection status index in real time, and updates scalar parameters A, I0, and D via the DDPC algorithm without modifying the engineered GPC form geometry. The cycle repeats continuously throughout the protection period.

7. Experimental Validation Framework

The GPC framework for cathodic protection generates specific, testable predictions for each application domain. The following validation protocols are proposed for researchers wishing to evaluate these predictions using standard laboratory and field electrochemical equipment in combination with the GP Lab reference platform.

For pipeline protection validation: prepare a carbon steel coupon of representative pipeline steel grade in a soil-equivalent electrolyte (saturated calcium carbonate solution, pH 8.5, resistivity 50 ohm-m). Establish a direct current baseline at a current density of 10 mA/m2 and record the polarization potential versus copper-copper sulfate reference electrode at 5-minute intervals over

4 hours. Measure the 24-hour depolarization potential following current interruption. Repeat with the process-specific GPC form at identical average current density of 10 mA/m2. Key metrics include time-averaged polarization potential (GPC prediction: 30 to 50 mV more negative than direct current at equal average current density based on Tafel slope analysis), 24-hour depolarization (GPC prediction: more complete depolarization indicating more effective initial polarization), and hydrogen evolution rate measured by gas collection (GPC prediction: equivalent or lower than direct current at equal average protection potential).

For marine structure validation: prepare a carbon steel coupon in natural seawater at 20 degrees Celsius. Establish a direct current baseline at 100 mA/m2 for 28 days, measuring calcareous deposit mass, composition by X-ray diffraction, and residual current demand at 28 days. Repeat with the process-specific GPC form at identical average current density. Key metrics include calcareous deposit mass at 28 days (GPC prediction: equivalent or greater deposit mass), deposit calcium carbonate to magnesium hydroxide ratio (GPC prediction: composition closer to optimal high-calcium ratio associated with superior barrier protection), and residual current demand at 28 days (GPC prediction: lower residual demand reflecting superior deposit quality).

For reinforced concrete validation: prepare a steel bar sample in simulated chloride-contaminated concrete pore solution (1 M NaOH, 0.35 M NaCl, pH 13). Establish a direct current baseline at 5 mA/m2 and record steel potential versus saturated calomel electrode daily for 30 days. Measure the AC impedance spectrum at 7, 14, and 30 days. Repeat with the process-specific GPC form at identical average current density. Key metrics include steel potential at 30 days (GPC prediction: 20 to 40 mV more negative than direct current at equal average density), passive film resistance from impedance analysis (GPC prediction: higher passive film resistance consistent with more complete re-passivation), and chloride migration rate derived from solution analysis (GPC prediction: measurably higher chloride transport away from the steel surface during GPC primary phase).

8. Discussion

The application of the GPC framework to impressed current cathodic protection reveals that the direct current convention that has defined this field for nearly two centuries is not a theoretical optimum but a practical default adopted before systematic electrochemical process control was feasible. The Butler-Volmer polarization kinetics governing cathodic protection in soil, seawater, and concrete environments are all exponentially nonlinear, and Jensen's inequality establishes unambiguously that a temporally structured current at equal average intensity will produce different electrochemical outcomes in each of these environments. The direction and magnitude of this difference — the Jensen gap — is a function of the curvature of the polarization response at the protection operating point, which can be characterized from standard electrochemical measurements and used to engineer a purpose-specific GPC form for each application.

The relationship of GPC to the existing pulse current cathodic protection literature requires careful positioning. Prior experimental studies of pulsed current cathodic protection [9, 10] have observed protection efficiency improvements attributable to temporal current structuring, but without a theoretical framework to explain or predict these improvements. GPC provides the missing theoretical basis: the improvements observed with square wave pulse currents reflect the Jensen inequality applied to the Butler-Volmer nonlinearity, operating without systematic optimization of the pulse parameters for the specific polarization curve of the target system. GPC form design derived analytically from the measured Tafel slope and exchange current density of the specific steel-electrolyte system enables the Jensen gap to be maximized, rather than realized partially by empirically selected pulse parameters.

The GPC framework does not require replacement of existing impressed current cathodic protection infrastructure. Existing rectifiers, anode groundbeds, pipeline coatings, and monitoring systems can be retained. The GPC form is delivered to the existing rectifier as a reference signal through GP Lab's analog control interface. The investment required is the GP Lab control platform and the engineering of the process-specific GPC form from the electrochemical characterization of the target structure. This implementation pathway enables GPC technology to be deployed as a retrofit upgrade to existing cathodic protection systems at the cost of control software rather than infrastructure replacement.

The application to reinforced concrete cathodic protection raises an additional consideration regarding the interaction between the GPC temporal structure and chloride migration. The electrochemical chloride extraction effect during the GPC primary phase represents a synergy between cathodic protection and electrochemical chloride removal that does not exist under direct current delivery. This synergy may reduce the long-term current demand for maintaining passivation by progressively lowering the chloride concentration at the reinforcement surface, potentially extending the effective service life of cathodic protection systems in severely chloride-contaminated structures beyond what is achievable with direct current at equal average energy consumption.

9. Conclusion

This paper has established the Generated Pattern Current framework as a unified first-principles basis for advancing impressed current cathodic protection across three principal application domains: buried pipeline protection, marine structure protection, and reinforced concrete corrosion mitigation. The common foundation in all three domains is Jensen's inequality applied to the nonlinear Butler-Volmer polarization kinetics of the steel-electrolyte interface: a temporally structured current at equal average intensity to a direct current will produce different and exploitable electrochemical outcomes whenever the polarization response function is nonlinear.

For pipeline protection, GPC provides Tafel-region current structuring that achieves more negative time-averaged protection potential at equal average current density, reducing hydrogen evolution at overprotected zones while maintaining adequate cathodic polarization at high-resistivity coating holidays. For marine structure protection, GPC provides impedance-adaptive current delivery that optimizes calcareous deposit composition and achieves more uniform potential distribution across multi-zone structures at equal energy consumption. For reinforced concrete cathodic protection, GPC provides threshold-targeted passivation current delivery with a chloride migration-enhancing primary phase that progressively lowers the long-term current demand for passive film maintenance.

The experimental validation protocols proposed in Section 7 provide a roadmap for the research community to evaluate these predictions using standard electrochemical equipment and the GP Lab reference platform. The patent filings PCT/TR2025/051176 and USPTO 19/298,223 protect the core GPC architecture while the complete theoretical framework is disclosed here to enable independent experimental evaluation and adoption by the corrosion engineering community.

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Acknowledgments

The GPC formation protocol and ChemPat synthesis method are protected under PCT/TR2025/051176 (formally defined as Dynamic Defined Pattern Charging, DDPC) and USPTO Application No. 19/298,223, priority date July 23, 2025. The author is the named inventor on both filings.

Declaration of Competing Interest

The author declares a financial interest as the inventor and developer of the technology described in this work. Ibrahim Karakoc holds commercial rights to the described platform and protocols.

Data Availability

ChemPat calibration file format, pattern library parameters, and formation protocol specifications are available from the corresponding author upon reasonable request.