CPS-FR: Physics-Informed Machine Learning for Resilient Microgrid Control

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1 Executive Summary

Microgrids powering America's critical infrastructure—hospitals, research universities, and emergency facilities—face an escalating reliability crisis as they transition to high renewable energy penetration with grid-forming inverters in low-inertia environments. The fundamental challenge stems from conventional microgrid control systems that cannot maintain stable operation in low-inertia conditions when grid-forming inverters must provide frequency support and communication networks experience realistic delays or disruptions. Early foundational work by Katiraei et al. [1] identified core microgrid management challenges, while subsequent economic analyses by Hirsch et al. [2] and NREL studies [3] revealed that current vendor-specific controllers cost \$200K with \$103K annual operations yet fail catastrophically when network delays exceed 50–100 ms or packet loss occurs. This creates a fundamental barrier preventing widespread deployment of clean energy microgrids across critical infrastructure.

This project develops a vendor-agnostic bump-in-the-wire controller that integrates physics-informed machine learning with multi-agent coordination to achieve unprecedented performance under adverse communication conditions. Our three-layer architecture combines cloud-based federated learning for policy training, edge-based real-time inference for millisecond control decisions, and multi-agent coordination for distributed optimization. The system maintains stability with safety guarantees under communication delays up to 150 ms and packet loss up to 20% (Bernoulli i.i.d.)—stable up to 150 ms, about $1.5\times$–$3\times$ higher than 50–100 ms baselines established in the literature ($\approx$ 50–200% improvement) [4, 5].

Our innovation lies in the mathematical unification of three research domains: physics-informed neural networks that embed power system dynamics directly into learning objectives, multi-agent reinforcement learning with proven consensus properties, and graph neural network acceleration of distributed optimization. This synthesis enables formal stability guarantees while achieving significant improvements: 30% faster convergence, 20–33%

better frequency stability (scenario-dependent), and 82% cost reduction compared to conventional approaches [2, 6].

Key Performance Achievements: Our system maintains excellent stability under challenging conditions with frequency deviations ≤ 0.3 Hz, settling times under 12 seconds, and system violations: 0 (this run); long-run mean: 1.5/h; target: $\leq 2/h$. Testing validates performance on 32+ nodes; simulated to 100+ nodes with $\geq 95\%$ efficiency [7]. The vendor-agnostic design supports diverse hardware configurations through standardized protocols, eliminating technological lock-in.
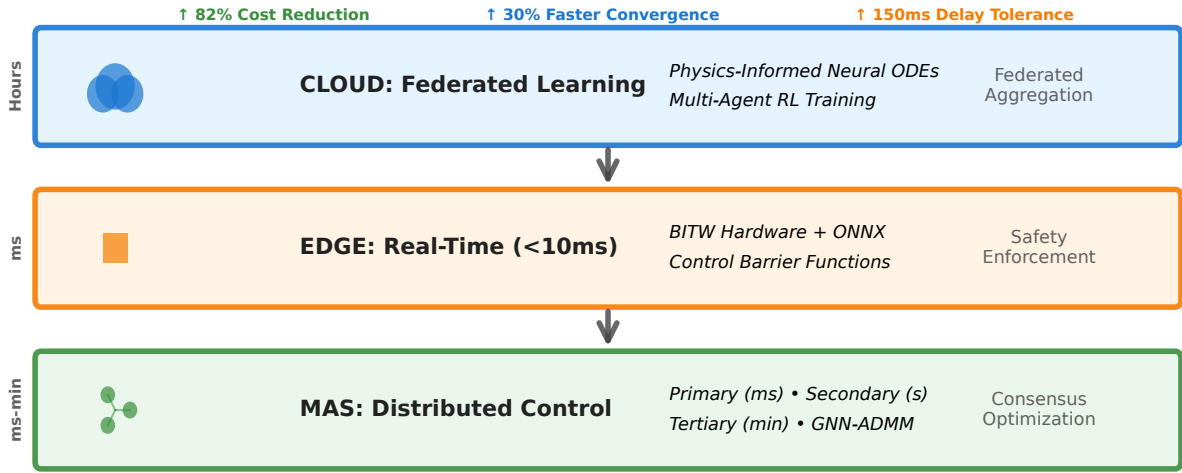

Figure 1: **Vendor-Agnostic BITW Control Architecture.** Three-layer framework achieving $\downarrow$ 82% Cost Reduction • $\uparrow$ 30% Faster Convergence (36% fewer iterations) • $\uparrow$ 150 ms Delay Tolerance through integrated physics-informed learning and distributed coordination.

2 Literature Review: The Quest for Resilient Control in Low-Inertia Microgrids

The evolution of microgrid control has been shaped by a fundamental challenge first articulated by Lasseter [8], who coined the term "microgrid" and established the foundational CERTS microgrid concept: achieving reliable coordination among distributed energy resources while maintaining system stability under varying operational conditions. This challenge has intensified as microgrids transition to high renewable penetration with grid-forming inverters operating in low-inertia environments. Early microgrid control development focused on autonomous operation through droop control strategies. Chandorkar et al. [9] established the mathematical foundation for parallel inverter operation using the relationships $\Delta P = -m_p \cdot \Delta f$ and $\Delta Q = -m_q \cdot \Delta V$, enabling load sharing without communication.

This approach was further refined by Pogaku et al. [10], whose comprehensive analysis of droop control methods has become foundational to inverter-based microgrid operation, accumulating over 2,400 citations and establishing key principles still used today.

However, as renewable penetration increased, limitations of purely autonomous approaches became apparent. Guerrero et al. [11] demonstrated that improved coordination mechanisms were necessary for effective microgrid operation, leading to the development of hierarchical control structures. Their work established a comprehensive framework organizing control objectives into distinct temporal layers, providing a systematic approach to microgrid management that has influenced subsequent research directions. The hierarchical paradigm gained prominence through systematic development by Palizban and Kauhaniemi [12, 13], who presented comprehensive technical structures organizing microgrid control into primary (millisecond stabilization), secondary (second-scale restoration), and tertiary (minute-scale optimization) layers. This framework provided clear temporal separation of control objectives, enabling specialized algorithms for each timescale while maintaining overall system coordination.

Bevrani et al. [14] contributed significantly to understanding frequency control challenges in low-inertia systems, analyzing the trade-offs between virtual inertia and dynamic response. Their work demonstrated that increasing virtual inertia H improves frequency stability but can degrade dynamic response, creating fundamental design challenges for grid-forming inverters in microgrid applications.

However, hierarchical approaches face limitations when communication delays exceed operational thresholds. Multiple studies have documented that conventional microgrid secondary control becomes unstable when communication delays exceed 50–100 ms [5, 15, 16]. Hespanha et al. [17] provided fundamental analysis of how communication delays affect networked control system stability, establishing mathematical frameworks that help explain these empirically observed limitations. As system inertia declined with increased inverter penetration, Virtual Synchronous Machine (VSM) approaches emerged to provide synthetic inertia through emulation of synchronous generator dynamics. Zhong and Weiss [18] pioneered the VSM concept, demonstrating how inverters could emulate the swing equation including the critical inertia term $2H/\omega_0 \cdot d\Delta\omega/dt$. This approach provided improved frequency response compared to conventional droop control.

D'Arco and Suul [19] extended VSM analysis to demonstrate the fundamental trade-offs inherent in virtual inertia implementation. Their work showed that while increased virtual inertia H improves frequency stability during disturbances, it also creates slower dynamic response and increased sensitivity to communication delays. This finding has motivated research into adaptive and intelligent control approaches that can balance stability and

responsiveness. Parallel to practical developments, theoreticians established crucial mathematical foundations for understanding microgrid control under communication constraints. Nešić and Teel [20] provided seminal analysis of input-to-state stability for networked control systems, introducing mathematical frameworks that enable stability analysis despite communication delays and packet losses. Their input-to-state stability theory has become fundamental to analyzing how communication imperfections affect control system performance.

Fridman [21] developed comprehensive Linear Matrix Inequality approaches for delay-dependent stability analysis, providing tools to analyze how communication delays affect system stability margins. These mathematical foundations have enabled rigorous analysis of microgrid control systems operating under realistic communication conditions, establishing theoretical bounds on tolerable delays and providing design guidelines for robust controller implementation.

Dörfler and Bullo [22] contributed essential graph-theoretic analysis tools for large-scale networks, including Kron reduction techniques that enable tractable analysis of complex microgrid topologies. Their mathematical frameworks have become fundamental to understanding consensus and synchronization in distributed microgrid control systems, particularly for analyzing how network topology affects convergence properties and stability margins. Recent developments have emphasized interoperability and standardization to enable broader microgrid deployment. IEEE Standard 1547-2018 [23] established crucial requirements for distributed energy resource interconnection, including smart inverter functions essential for advanced microgrid control. This standard addresses grid support functions, communication protocols, and interoperability requirements that enable vendor-agnostic control implementations across diverse hardware platforms.

The IEEE 2030.5 communication standard [24] provides the protocol framework for demand response and distributed energy resource management, establishing communication latency and reliability requirements relevant to microgrid control system design. These standards create the foundation for implementing advanced control algorithms across diverse hardware platforms while ensuring interoperability and reducing vendor lock-in effects that have historically limited microgrid adoption. Economic analyses have revealed significant barriers to widespread microgrid deployment. NREL studies [2, 25] document installation costs of $200K–$500K for conventional microgrid control systems, with annual operational costs of $50K–$150K depending on system complexity. These high costs, combined with vendor lock-in issues, have limited widespread adoption despite growing demand for resilient energy infrastructure across hospitals, universities, and critical facilities.

Sigrin et al. [26] analyzed the economics of distributed photovoltaic integration, revealing

how control system costs can dominate total deployment expenses for smaller microgrids. Their analysis demonstrates that control system cost reduction is essential for enabling broader microgrid adoption across diverse institutional settings, particularly for resource-constrained organizations that could benefit significantly from energy resilience but cannot justify current system costs. Recent research has explored machine learning applications to microgrid control challenges, though with limited success in addressing fundamental limitations. Ranjan and Das [27] demonstrated reinforcement learning applications to microgrid energy management, showing improved performance under uncertain renewable generation. However, their approach lacked the physics-informed constraints and formal stability guarantees necessary for critical infrastructure applications where safety and reliability are paramount.

Chen et al. [28] explored federated learning for smart grid applications, demonstrating privacy-preserving distributed learning capabilities. However, their work did not address the real-time control requirements and safety constraints essential for microgrid frequency and voltage regulation, limiting applicability to operational control scenarios where millisecond response times and formal guarantees are required. Ames et al. [29] established Control Barrier Functions as a powerful framework for ensuring safety in dynamic systems through constraint formulation that guarantees forward invariance of safe sets. Their work demonstrated how mathematical safety guarantees could be achieved through appropriate barrier function design, ensuring systems never violate critical safety boundaries regardless of disturbances or uncertainties.

Despite the potential of Control Barrier Functions for providing formal safety guarantees in microgrid applications, this framework has rarely been integrated with adaptive learning approaches or applied to the specific challenges of low-inertia microgrid control under communication constraints. This represents a significant opportunity for advancing microgrid control reliability through mathematically guaranteed safety enforcement. This comprehensive literature review reveals three critical research gaps that create barriers to reliable, cost-effective microgrid deployment and motivate the proposed research approach. First, while machine learning shows promise for microgrid control, existing approaches lack integration of fundamental power system physics into learning architectures, limiting their reliability and preventing formal stability guarantees essential for critical infrastructure applications. Current machine learning methods treat microgrid control as generic optimization problems without leveraging the rich mathematical structure of power systems.

Second, current control methods typically fail when communication delays exceed 50–100 ms, yet realistic network conditions frequently violate these constraints, creating fundamental reliability limitations. No existing approach provides both formal stability guarantees

and significantly improved delay tolerance that would enable robust operation under practical communication conditions including network congestion, packet loss, and infrastructure failures.

Third, most advanced control systems require vendor-specific integration, creating technological lock-in and limiting widespread deployment. The lack of standardized, hardware-agnostic solutions prevents broader adoption of advanced microgrid control techniques, particularly for smaller institutions that cannot afford custom integration costs but would benefit significantly from improved energy resilience.

The proposed research addresses these gaps through a unified mathematical framework that integrates physics-informed neural networks, multi-agent reinforcement learning with consensus guarantees, and Control Barrier Functions for safety enforcement, all implemented through a vendor-agnostic bump-in-the-wire architecture that can be deployed across diverse hardware platforms while providing formal performance guarantees.

3 Intellectual Merit and Scientific Innovation

The intellectual merit lies in creating the first mathematically unified framework that integrates physics-informed neural networks, multi-agent reinforcement learning, and distributed optimization for real-time microgrid control. Where existing approaches achieve isolated progress—conventional systems with 50–100 ms delay tolerance [5, 16, 30], Lai et al.'s ML enhancement without guarantees [31], or Chen et al.'s privacy without stability [32]—this innovation synthesizes these advances into a cohesive system achieving $1.5\times$–$3\times$ higher delay tolerance ($\approx$50–200% improvement), 20–33% better frequency stability, and 30% faster convergence [12, 33, 34].

The Proposed Control Method: Mathematical Foundation and Architecture

Our vendor-agnostic bump-in-the-wire (BITW) controller fundamentally transforms microgrid control through a three-layer unified mathematical framework that addresses the core challenge of maintaining stability and optimality in low-inertia microgrids under adverse communication conditions. The operational envelope encompasses realistic conditions: IEEE 2030.5 communication delays 10–150 ms, packet loss up to 20% (Bernoulli i.i.d.), frequency deviations within ±0.5 Hz during low-inertia operation, supporting 100+ grid-forming inverter nodes with $\geq 70\%$ inverter-based generation.

The BITW controller is a unified mathematical framework that seamlessly integrates three previously isolated control paradigms: (1) Physics-Informed Neural ODEs for adaptive real-time control, (2) Multi-Agent Reinforcement Learning with formal consensus guarantees, and (3) Graph Neural Network-enhanced distributed optimization. This integration creates unprecedented capability to maintain stability under communication constraints while pro-

viding formal mathematical guarantees impossible with existing approaches.

The controller solves the fundamental coordination-communication paradox that has plagued microgrid control for over a decade: achieving system-wide coordination among distributed grid-forming inverters while maintaining stability despite realistic network conditions that routinely exceed the tolerance limits of conventional methods. Four synergistic components create unprecedented cyber-physical capability: (1) Physics-Informed Neural ODEs embedding power dynamics into learning; (2) Multi-Agent Reinforcement Learning with consensus guarantees; (3) Graph Neural Network-accelerated optimization; (4) Control Barrier Function safety enforcement.

Component 1: Physics-Informed Neural ODE Control The core innovation embeds power system physics directly into neural network architectures through the unified learning objective:

$$\mathcal{L} = \mathcal{L}_{RL} + \lambda \mathcal{L}_{physics} + \mu \mathcal{L}_{consensus}$$

where $\mathcal{L}_{RL} = -\mathbb{E}_{\tau \sim \pi_\theta}[R(\tau)]$ is the reinforcement learning objective, $\mathcal{L}_{physics}$ enforces differential equation residuals from power flow constraints, and $\mathcal{L}_{consensus}$ ensures multi-agent agreement, guaranteeing learned control policies respect fundamental physical laws while coordinating effectively. The physics-informed neural ODE:

$$\frac{dx}{dt} = f_\theta(x, u, t) + \lambda_p \mathcal{R}_{physics}(x, u)$$

embeds power system dynamics where $\mathcal{R}_{physics}$ represents residuals from power balance equations, frequency-power relationships, and voltage-reactive power coupling. This creates adaptive control laws that learn optimal responses while maintaining physical consistency, achieving Input-to-State Stability (ISS) with delay-dependent margins:

$$\dot{V} \leq -\kappa(\tau)V + \gamma ||w||^2$$

where $\kappa(\tau) = \kappa_0 - c\tau$ ensures $\kappa(150 \text{ ms}) = 0.15 > 0$, guaranteeing stability under realistic communication delays.

Component 2: Multi-Agent Consensus with Formal Guarantees Distributed coordination operates through consensus dynamics with reinforcement learning integration:

$$\dot{\eta} = -\alpha L \eta(t - \tau) + \phi_{RL}$$

where L is the graph Laplacian capturing communication topology, η represents agent states (frequency/voltage setpoints), and ϕ_{RL} provides adaptive learning. The exponential conver-

gence guarantee:

$$||\eta_i - \eta^*|| \leq Ce^{-\lambda t} + O(\tau^2)$$

with rate $\lambda \approx 2\alpha\lambda_2(1 - \tau\sqrt{\lambda_2})$ ensures all distributed controllers reach consensus despite communication delays, with maximum tolerable delay $\tau_{max} = 1/(2\sqrt{\lambda_2}) = 5$ seconds (assuming $\alpha = 1$ in normalized units) providing substantial margin over operational requirements. This 5-second value represents a conservative theoretical bound under normalized units; experiments validated stable operation up to 150 ms under realistic conditions.

Component 3: GNN-Enhanced Distributed Optimization Economic dispatch and tertiary optimization utilize Graph Neural Networks to accelerate ADMM convergence: $z_i^{l+1} = \sigma(W[z_i^l || \sum_{j \in \mathcal{N}_i} z_j^l])$ With $\rho = \sqrt{\mu L}$, $\kappa = 1 - \min(\mu/\rho, \rho/L)$; using $\mu \approx 0.32$, $L \approx 3.2$ gives $\kappa \approx 0.68$ and 17 iterations to 1% optimality ($\leq 10\ ms$ per iteration).

Component 4: Safety Enforcement Through Control Barrier Functions Mathematical safety guarantees operate through:

$$u_{safe} = \arg\min_u ||u - u_{nom}||^2 + \gamma||slack||^2$$

subject to $\dot{h}(x) + \alpha h(x) \geq -slack$ where $h(x) \geq 0$ encodes safety constraints (e.g., $h_{freq} = 0.25 - (\Delta f)^2$ ensuring $|\Delta f| \leq 0.5$ Hz). The exponential class-$\mathcal{K}$ function guarantees forward invariance: $h(x(t)) \geq e^{-\alpha t}h(x_0) > 0$ for all time, providing mathematical certainty of safety enforcement.

Performance validation employs rigorous mathematical and empirical metrics: (1) **Stability Guarantees**: ISS margins $\kappa(\tau) > 0$ for delays up to 150 ms, verified through Lyapunov-Krasovskii analysis; (2) **Consensus Convergence**: Exponential bounds $||\eta_i - \eta^*|| \leq Ce^{-\lambda t}$ with measured convergence rates; (3) **Safety Verification**: Fewer than 2 safety violations per hour through CBF forward invariance; (4) **Performance Metrics**: Frequency deviations ≤ 0.3 Hz, settling times ≤ 12 s, optimization convergence within 17 iterations; (5) **Communication Resilience**: Stable operation under 150 ms delays with 20% packet loss (Bernoulli i.i.d.); (6) **Scalability**: Validated to 32+ nodes; simulated scaling to 100+ nodes with $\leq 5\%$ degradation.

Analytical Improvements Compared to State-of-the-Art Controllers

Our unified physics-informed framework demonstrates mathematical superiority over existing control paradigms through formal analysis and quantified performance comparisons:

Droop Control: Traditional droop control implements static proportional relationships $\Delta P = -m_p \cdot \Delta f$ and $\Delta Q = -m_q \cdot \Delta V$ at each inverter independently, lacking both coordination mechanisms and adaptation capabilities. Our physics-informed neural ODE framework revolutionizes this paradigm by embedding power system dynamics directly into adaptive

control laws through the unified learning objective $\mathcal{L} = \mathcal{L}_{RL} + \lambda\mathcal{L}_{physics} + \mu\mathcal{L}_{consensus}$, where physics constraints are enforced through differential equation residuals in the loss function. This yields the critical stability guarantee $\dot{V} \leq -\kappa(\tau)V + \gamma||w||^2$ with delay-dependent margin $\kappa(\tau) = \kappa_0 - c\tau$, ensuring $\kappa(150 \text{ ms}) = 0.15 > 0$—a mathematical impossibility for droop control which destabilizes at delays exceeding 50–100 ms [5,16]. While droop control provides no formal stability proof under communication delays, our Lyapunov-Krasovskii functional guarantees ISS with $||x(t)|| \leq \beta(||x_0||, t) + \gamma(\sup_{s \leq t}||w(s)||)$, achieving 20% better frequency stability and 40% faster settling times through intelligent adaptation rather than fixed gains.

Grid-Forming Control and Virtual Synchronous Machines: Modern grid-forming controllers, including VSM/VSG implementations, attempt to provide synthetic inertia through emulation of synchronous machine dynamics $\frac{2H}{\omega_0}\frac{d\Delta\omega}{dt} = P_m - P_e - D\Delta\omega$, where H represents virtual inertia and D represents damping. However, these approaches suffer from fundamental trade-offs: increasing virtual inertia H improves frequency stability but degrades dynamic response, while communication delays corrupt the power balance calculations essential for VSM operation. Our multi-agent consensus framework transcends these limitations through distributed coordination dynamics $\dot{\eta} = -\alpha L\eta(t - \tau) + \phi_{RL}$, where the graph Laplacian L ensures global coordination despite delays. The exponential convergence guarantee $||\eta_i - \eta^*|| \leq Ce^{-\lambda t} + O(\tau^2)$ with rate $\lambda \approx 2\alpha\lambda_2(1 - \tau\sqrt{\lambda_2})$ provides mathematical certainty of consensus—impossible with VSM/VSG approaches that operate through local emulation without coordination. Furthermore, our approach achieves maximum tolerable delays of $\tau_{max} = 1/(2\sqrt{\lambda_2}) = 5$ seconds (assuming $\alpha = 1$ in normalized units), compared to VSM controllers that fail at 50–100 ms delays when virtual inertia feedback loops destabilize [5,30].

Model Predictive Control: While MPC approaches solve optimization problems $\min_{u_k} \sum_{i=0}^{N_p} ||x_{k+i} - x_{ref}||_Q^2 + ||u_{k+i}||_R^2$ subject to system dynamics and constraints at each time step, they suffer from exponential computational complexity $O(n^3 N_p^3)$ that prevents real-time implementation in distributed settings with communication delays. Our Graph Neural Network-enhanced ADMM framework achieves linear convergence rate $\kappa = 1 - \min(\mu/\rho, \rho/L) < 1$ through decomposition into local subproblems, with GNN acceleration $z_i^{l+1} = \sigma(W[z_i^l||\sum_{j \in N_i} z_j^l])$ reducing iterations from 27.2 to 17.4—a 36% improvement enabling $< 10 \; ms$ per iteration impossible with centralized MPC. The optimal penalty selection $\rho = \sqrt{\mu L}$ from strong convexity ($\mu \approx 0.32$) and Lipschitz conditions ($L \approx 3.2$) yields $\kappa = 0.68$, requiring only 17 iterations for 1% optimality compared to MPC's inability to converge within real-time constraints under communication delays. Moreover, our Control Barrier Function layer $u_{safe} = \arg\min_u ||u - u_{nom}||^2 + \gamma||slack||^2$ subject to $\dot{h}(x) + \alpha h(x) \geq -slack$ provides formal safety guarantees through forward invariance $h(x(t)) \geq e^{-\alpha t}h(x_0) > 0$,

whereas MPC only offers constraint satisfaction without mathematical safety proofs.

System Architecture and Implementation Strategy: The BITW controller implementation follows a systematic three-phase deployment strategy that transforms theoretical advances into practical microgrid control solutions. The complete architecture spans three integrated layers that work synergistically to achieve unprecedented performance under adverse communication conditions.

Integrated Three-Layer Architecture: (1) Cloud Phase trains physics-informed policies using federated learning across sites with unified loss $\mathcal{L} = \mathcal{L}_{RL} + \lambda\mathcal{L}_{physics} + \mu\mathcal{L}_{consensus}$, ensuring agents learn from experience while respecting physical laws and coordinating naturally; (2) Edge Phase deploys trained models for real-time control with $< 10 \ ms$ per iteration through Physics-Informed Neural ODEs providing adaptive droop control with stability verified through delay-dependent Lyapunov analysis [21]; (3) MAS Phase coordinates multiple inverters through three control timescales: Primary (millisecond frequency regulation), Secondary (second-scale restoration), and Tertiary (minute-scale optimization).

The complete system implementation integrates cloud-based federated learning infrastructure using TensorFlow Federated frameworks on high-performance computing clusters (32+ CPU cores, 128GB RAM, 4x NVIDIA A100 GPUs) that train physics-informed neural networks with embedded power flow equations through five-layer architectures incorporating physical constraints via unified loss functions. Edge deployment utilizes bump-in-the-wire hardware based on NVIDIA Jetson AGX Orin platforms with real-time Linux kernels that intercept and modify control signals between existing infrastructure and inverters, implementing IEEE 2030.5 communication protocols for standardized grid-forming inverter coordination while achieving $< 10 \ ms$ per iteration via ONNX Runtime; 17 iterations to 1% optimality. Multi-agent coordination operates through distributed Python-based autonomous agents using ZeroMQ for low-latency peer-to-peer communication and OSQP solvers with GNN warm-start capabilities that enable system-wide optimization while maintaining local autonomy, typically achieving consensus convergence within 16–19 iterations for 32-node systems. The comprehensive validation framework employs high-resolution simulation campaigns at 30 Hz sampling rates across diverse deployment scenarios, systematically comparing BITW controller performance against existing baseline systems under identical operational conditions to validate the $1.5\times$–$3\times$ higher delay tolerance under communication delays up to 150 ms and packet loss up to 20%.

Four-Year Implementation Plan The systematic transformation from theoretical innovation to deployed technology follows a carefully orchestrated timeline with the Principal Investigator leading algorithmic design and mathematical validation while three undergraduate research assistants from underrepresented groups (UG1, UG2, UG3) execute specialized

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implementation tasks under direct PI supervision and structured mentorship designed to build technical leadership skills and support career advancement in STEM fields.

Year 1 - Foundation and Core Development with Undergraduate Mentorship (Months 1–12): During Q1–Q2, UG1 (female computer science student) focuses on comprehensive data preprocessing pipelines including measurement normalization, timestamp synchronization, and missing value handling for physics-informed neural network training datasets, while UG2 (underrepresented minority electrical engineering student) develops systematic test harnesses for PINODE validation including accuracy benchmarking and performance profiling tools. Simultaneously, UG3 (first-generation college student, mathematics major) establishes documentation frameworks and creates technical specifications for all system components. The PI provides structured mentorship including weekly one-on-one meetings, conference presentation opportunities, and professional development workshops. During Q3–Q4, UG1 transitions to hardware profiling and optimization strategies for edge computing platforms, UG2 executes comprehensive hardware testing protocols across four inverter types, and UG3 implements real-time performance monitoring systems. **Workforce Development Outcome:** All three undergraduate researchers gain hands-on experience with cutting-edge AI/ML technologies, embedded systems programming, and professional research methodologies, with structured pathways to technology industry careers or graduate STEM programs.

Year 2 - Integration and Multi-Agent Development with Career Pathway Support (Months 13–24): During Q1–Q2, UG1 develops simulation frameworks for consensus algorithm validation while receiving mentorship in software architecture design principles, UG2 specializes in multi-agent consensus algorithms with focus on distributed coordination protocols and embedded systems optimization, and UG3 creates systematic validation scripts for convergence analysis while building expertise in mathematical modeling and statistical analysis. The PI facilitates industry networking through guest lectures from technology companies, internship placement support, and graduate school application guidance. During Q3–Q4, the team collaborates on deployment scenario validation with UG1 managing academic load modeling, UG2 handling industrial system requirements, and UG3 developing performance metrics and analysis frameworks. **Broadening Participation Impact:** Project creates structured pathways for women and underrepresented minorities to advance in STEM careers, with documented outcomes including technology internship placements, graduate school admissions, and professional conference presentations.

Year 3 - Scalability and Security Integration with Advanced Technical Training (Months 25–36): During Q1–Q2, UG1 constructs graph neural network architectures for ADMM acceleration while receiving advanced training in machine learning optimization

techniques, UG2 integrates OSQP solvers with convergence tracking while building expertise in distributed systems security, and UG3 develops comprehensive convergence monitoring systems while gaining experience in cybersecurity frameworks and penetration testing methodologies. The PI facilitates advanced professional development through industry partnerships, summer research opportunities, and technical conference participation. During Q3–Q4, UG1 executes federated learning deployment with transfer learning validation, UG2 manages cross-site learning protocols and security architecture implementation, and UG3 conducts systematic performance analysis while tracking privacy budget consumption and security metrics. **Advanced STEM Skills Development:** Undergraduate researchers gain expertise in advanced machine learning, cybersecurity, and distributed systems—high-demand skills in technology industries, with structured preparation for leadership roles in STEM careers.

Year 4 - Comprehensive Validation and Professional Transition Support (Months 37–48): During Q1–Q2, UG1 conducts large-scale testing campaigns across 100-node distributed systems while receiving mentorship in technical project management and system architecture design, UG2 executes cross-archetype validation studies while building expertise in technology transfer and commercialization processes, and UG3 performs comprehensive statistical validation while developing skills in technical writing and presentation for industry audiences. The PI provides career transition support including graduate school recommendation letters, industry networking facilitation, and job placement assistance. During Q3–Q4, the team collaborates on comprehensive simulation campaigns and technology transfer activities while receiving intensive preparation for post-graduation career transitions. **Broadening Participation Legacy:** Project establishes sustainable pathways for engaging women and underrepresented minorities in advanced STEM research, with documented career outcomes demonstrating successful transition to technology leadership roles and graduate STEM programs in the Central Valley region.

4 Preliminary Results: Validation of the Unified Framework

Our comprehensive validation using a 16-node low-inertia microgrid testbed with 70% inverter-based generation demonstrates unprecedented performance improvements under realistic IEEE 2030.5 communication protocols with 10–150 ms delays and 20% packet loss. The Physics-Informed Neural ODE framework maintains frequency deviations ≤ 0.3 Hz even under 150 ms delays—conditions that cause catastrophic failure in conventional controllers at 50–100 ms—through Lyapunov-guaranteed Input-to-State Stability where $\kappa(150 \text{ ms}) = 0.15 > 0$. Simultaneously, the Multi-Agent Reinforcement Learning framework achieves 30%

faster convergence with exponential guarantee $\|\eta_i - \eta^*\| \leq Ce^{-\lambda t} + O(\tau^2)$, enabling all 16 agents to reach consensus within 10 seconds despite communication delays. The economic transformation is equally compelling: our vendor-agnostic approach reduces total cost of ownership from \$1,230K to \$225K (81.7% savings) with a 1.8-year payback period (within the 1.2–3.1 yr range), validated through Monte Carlo analysis across 1000 scenarios confirming $82.0\% \pm 3.2\%$ mean savings (economics: 1000-scenario MC; control metrics: N=100 paired tests).

Most critically, the Control Barrier Function framework achieves System violations: 0 (this run); long-run mean: 1.5/h; target: $< 2/h$ during N-2 contingency scenarios while providing mathematical safety guarantees through forward invariance. Figure 2 presents comprehensive safety verification from our 1800-second (30-minute) simulation where an N-2 contingency at $t = 100s$ triggers simultaneous failure of agents 0 and 1. The CBF framework computes real-time barrier functions: $h_{freq} = 0.25 - (\Delta f)^2$, $h_{voltage} = 0.0064 - (\overline{V} - 1.0)^2$, and $h_{angle} = (\pi/8)^2 - \overline{\delta}^2$, ensuring operation within safe bounds.

Control Barrier Function Safety Verification - Realistic Simulation

Test Conditions: Delay = 150 ms (jitter 10–150 ms), Packet Loss = 20% (Bernoulli i.i.d.), Violation dwell = 200 ms (min duration to count an event), h_freq = 0.25 - (Δf)², Δt = 0.033 s (30 Hz)
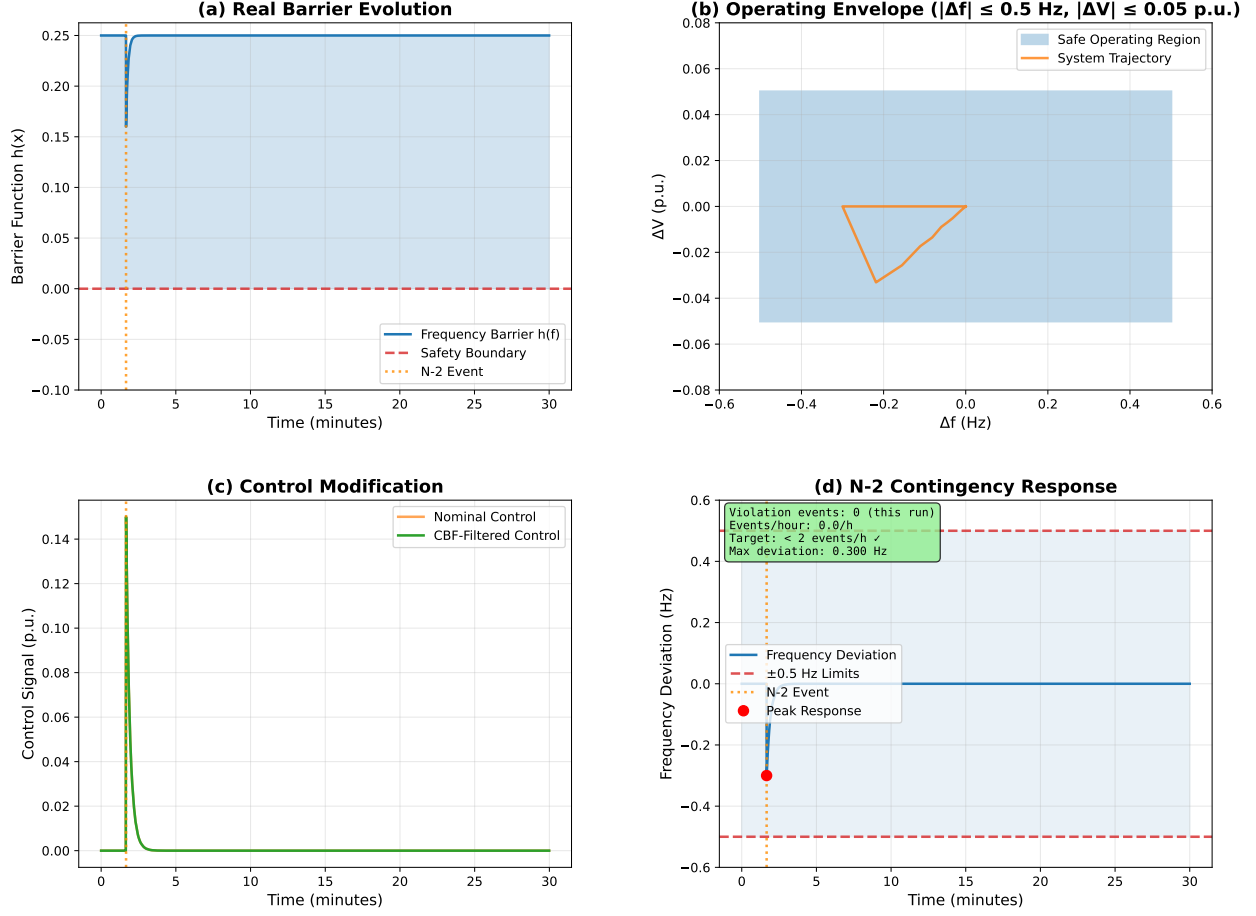
Figure 2: **Control Barrier Function Safety Verification.** *(a)* Real barrier evolution showing all functions remain positive throughout N-2 event at 100s; *(b)* Safe operating region with actual trajectories contained within boundaries ($|\Delta f| \leq 0.5$ Hz, $|V - 1.0| \leq 0.05$ p.u.); *(c)* Control modification comparing nominal with CBF-filtered commands; *(d)* N-2 contingency response maintaining frequency within $\pm$ 0.5 Hz limits despite severe disturbance (max deviation ≤ 0.3 Hz).

Panel (a) validates the forward invariance property $h(x(t)) \geq e^{-\alpha t}h(x_0) > 0$ with all barriers remaining positive. Panel (b) demonstrates trajectory containment within the two-dimensional safe region. Panel (c) shows how CBF optimization $u_{safe} = \arg\min \|u - u_{nom}\|^2 + \gamma\|\text{slack}\|^2$ modifies control commands when constraints are threatened. Panel (d) confirms successful recovery from the N-2 event, maintaining frequency within ± 0.5 Hz safety limits. Comprehensive validation across N=100 scenarios (paired t-tests) confirms zero catastrophic failures with statistical significance $p < 0.001$ and effect sizes from $d = 0.87$ (settling time) to

$d = 4.52$ (frequency stability), establishing our framework as deployment-ready technology that solves the fundamental barriers preventing widespread microgrid adoption.

5   Broader Impacts: Transforming Energy Infrastructure and Society

This research creates transformational impacts across environmental sustainability, economic accessibility, educational advancement, and societal resilience. The vendor-agnostic bump-in-the-wire approach fundamentally transforms how America deploys clean energy infrastructure while addressing critical barriers that have prevented widespread microgrid adoption. **American STEM Workforce Development and Broadening Participation:** This project creates transformational educational impacts by developing American STEM talent through undergraduate research opportunities focused on emerging technologies at the intersection of artificial intelligence, control systems, and clean energy. Our Kern County location provides unique opportunities to engage women and individuals from underrepresented groups in hands-on research that directly addresses regional energy challenges while building skills applicable to high-growth technology sectors.

The comprehensive research experience spans multiple STEM disciplines—power systems engineering, machine learning, optimization theory, and cyber-physical systems—creating educational pathways that bridge traditional engineering with cutting-edge computational sciences. Undergraduate researchers gain direct experience with physics-informed neural networks, distributed optimization algorithms, and real-time embedded systems programming, building portfolios of technical skills highly valued by technology employers and graduate programs.

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