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Research Paper

Distributed Model Predictive Control for Multi-Microgrid Systems: Coordination and Stability Analysis in Vietnam's Rural Electrification Context

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Abstract
Rural electrification in Vietnam faces challenges from renewable intermittency, communication limitations, and typhoon disturbances. This paper proposes a consensus-based distributed model predictive control (DMPC) framework for multi-microgrid coordination, ensuring voltage/frequency stability and power sharing under delays and heterogeneity. The approach combines local MPC optimization with lightweight consensus protocols and Lyapunov-based stability guarantees. Simulations in MATLAB/Simulink with realistic rural Vietnam data show superior regulation, fast convergence, and resilience compared to centralized MPC and droop control. The framework supports PDP8 objectives for decentralized renewable microgrids in remote areas. Results highlight scalability, fault tolerance, and practical applicability, offering policy recommendations for R&D incentives, communication standards, and pilot deployments in rural Thai Nguyen.

Keywords
distributed model predictive control, multi-microgrid systems, rural electrification, consensus algorithm, stability analysis, PDP8 Vietnam, renewable integration, typhoon resilience

I. Introduction

Rural electrification plays a critical role in sustainable development, especially in emerging economies where reliable electricity access supports economic growth, improves living standards, and enables greater use of renewable energy sources (Ghahramani et al., 2025; Köbrich et al., 2022). In Vietnam, the National Power Development Plan VIII (PDP8) sets clear goals for expanding renewables (30–35% share by 2030, excluding large hydro) and strengthening rural power supply through distributed solutions like microgrids (Ministry of Industry and Trade, Vietnam, 2023; Ha-Duong, 2024). Despite near-universal national electrification, remote mountainous areas (e.g., parts of Thai Nguyen Province) and islands still face unreliable service, high diesel costs, and vulnerability to natural disasters like typhoons (Tran, 2021; Agha Kassab et al., 2024).

Multi-microgrid systems — clusters of interconnected microgrids — offer a promising way forward. They allow power sharing, load balancing, and coordinated control among diverse units (solar PV, battery storage, diesel backup), improving resilience and efficiency compared to isolated single microgrids (Samadi Gharehveran, 2025; Razmi et al., 2022). However, coordinating these systems is difficult. Decentralized operation requires local controllers to make decisions with incomplete information, while communication delays (common in rural 4G/satellite networks) can degrade performance. Renewable intermittency (variable solar and wind output) and disturbances (sudden load changes, typhoon outages) threaten voltage and frequency stability (Irmak et al., 2023; Rao et al., 2022).

Model Predictive Control (MPC) is a powerful tool for microgrid coordination because it explicitly handles constraints, optimizes multiple objectives (voltage/frequency regulation, economic dispatch, renewable use), and incorporates forecasts of generation and loads (Yaghoubi et al., 2025; Rajendran et al., 2025). Centralized MPC achieves global optimality by solving one large problem but becomes computationally heavy and vulnerable to single-point failures as the number of microgrids grows (Dairo, 2024; Alonso-Travesset et al., 2022). Distributed MPC (DMPC) overcomes this by letting each microgrid solve its own local optimization while exchanging limited information with neighbors, offering better scalability, fault tolerance, and privacy (Hinkelman et al., 2025; Köbrich et al., 2022).

Despite progress in DMPC, significant challenges remain for rural Vietnam contexts. Centralized MPC is impractical because of high computational demands and reliance on reliable communication, which is often limited in remote areas (Ghahramani et al., 2025). Existing DMPC methods frequently lack rigorous stability guarantees when facing communication delays, heterogeneous microgrids (different sizes, renewable mixes, diesel backup), and tropical disturbances like typhoons (Razmi et al., 2022; Irmak et al., 2023). Most studies assume stable communication and uniform microgrids, which does not reflect Vietnam's rural reality — sparse networks, variable connectivity, and frequent extreme weather (Samadi Gharehveran, 2025; Tran, 2021).

Vietnam's rural electrification context makes this research particularly relevant. PDP8 prioritizes hybrid microgrids (solar PV + battery + diesel) in remote mountainous and island regions, where extending the main grid is costly and typhoons often cause outages (Ministry of Industry and Trade, Vietnam, 2023; Agha Kassab et al., 2024). Limited communication infrastructure (intermittent 4G, satellite in remote areas) and diverse microgrid configurations make centralized control unfeasible. A robust DMPC approach that handles delays and disturbances is therefore essential for achieving PDP8's goals of reliable, renewable-integrated rural power supply.

The research problem is clear: centralized MPC is computationally intensive and prone to single-point failure, while existing distributed MPC methods often lack sufficient stability guarantees under the specific conditions of rural Vietnam (communication delays, heterogeneous microgrids, renewable intermittency, typhoon disturbances). This paper addresses that gap by reviewing DMPC methods, proposing a consensus-based DMPC framework with Lyapunov-based stability analysis, simulating its performance in realistic rural scenarios, and providing policy recommendations.

Objectives are to:

1. Review distributed model predictive control approaches for multi-microgrid coordination.
2. Propose a consensus-based DMPC algorithm with explicit stability guarantees under bounded delays and disturbances.
3. Simulate the framework in representative rural multi-microgrid scenarios, evaluating voltage/frequency regulation and resilience.
4. Offer policy recommendations for rural electrification under PDP8.

Scope focuses on islanded and grid-connected multi-microgrid coordination, emphasizing voltage and frequency regulation, power sharing, and renewable energy integration. The study assumes limited communication (delays 50–200 ms) and heterogeneous microgrids (solar PV + battery + diesel backup).

Methodology combines:

- Systematic literature review (IEEE Xplore, Scopus, Web of Science; 2015–2025 focus).
- Mathematical formulation of consensus-based DMPC with Lyapunov stability analysis.
- Simulation in MATLAB/Simulink with multi-agent framework (or OPAL-RT for real-time if available), using realistic rural Vietnam data (solar irradiance, load profiles, typhoon disturbances).

II. Literature Review

Model Predictive Control (MPC) has become one of the go-to methods for coordinating microgrids. It stands out because it can directly deal with constraints, handle multiple goals at once (like keeping voltage and frequency stable, optimizing costs, and using renewables efficiently), and factor in forecasts of generation and loads. In multi-microgrid systems — groups of interconnected microgrids that can run either islanded or tied to the main grid — MPC helps with power sharing, voltage/frequency stability, and staying resilient during disturbances. This section looks at centralized and distributed MPC approaches, the main techniques, ways to analyze stability, how they're used in multi-microgrid setups, and the gaps that still exist, with special attention to what this means for rural electrification in Vietnam.

Centralized MPC works by solving one big optimization problem in a single central controller that gets data from every unit (microgrids, distributed energy resources, loads). The controller figures out the best control actions (active/reactive power setpoints, battery dispatch, diesel generator output) over a prediction window and applies the first step, then repeats. It has clear advantages: it finds the globally optimal solution, minimizing the overall cost (deviations from voltage/frequency targets, running costs, renewable curtailment) while respecting system-wide limits (power balance, line capacities, SOC bounds). This approach works very well in small-to-medium systems where communication is reliable and computing power is enough (Olivares et al., 2014; Parhizi et al., 2015). Centralized MPC has been used successfully for voltage/frequency regulation, optimal power flow, and economic dispatch in islanded microgrids.

But the drawbacks become obvious in larger multi-microgrid networks. Scalability is a problem: as the number of microgrids grows, the optimization gets much heavier, taking too long to solve and often missing real-time requirements (sampling every 100 ms–1 s). The single central controller is a single point of failure — if communication drops or the controller fails, the whole system can collapse. Privacy is another issue: every local detail (generation costs, SOC, load forecasts) has to be sent to the center. In rural Vietnam — where microgrids are spread out, communication is spotty (intermittent 4G, satellite in remote spots), and typhoons often break links — these problems make centralized MPC almost impossible to use (Nguyen et al., 2021; Tran & Pham, 2023).

Distributed Model Predictive Control (DMPC) tries to fix these issues. It breaks the big global problem into smaller local ones, each solved by a microgrid's own controller. Local controllers focus on their own goals (tracking voltage/frequency references, minimizing costs, staying within power and SOC limits) while sharing only a little information with neighbors (predicted power references or coupling variables). This setup improves scalability, removes single points of failure, and keeps local data private. DMPC methods usually fall into four types: non-cooperative DMPC (each microgrid optimizes on its own with minimal sharing — simple but sometimes suboptimal or unstable); cooperative DMPC (controllers share predictions repeatedly to get close to a global optimum, often using ADMM); consensus-based DMPC (agents agree on shared variables like power flows or frequency references through consensus rules to ensure feasibility and stability); and event-triggered DMPC (communication only happens when needed, like when a state error crosses a threshold), which saves a lot of bandwidth and is especially useful in rural areas with weak connectivity.

Key methods in DMPC include ADMM-based DMPC (splits the problem and solves local parts iteratively with dual updates — Boyd et al., 2011; Christofides et al., 2013); dual decomposition (uses Lagrangian relaxation to separate constraints and coordinates via price signals — Negenborn& Maestre, 2014); plug-and-play DMPC (lets microgrids join or leave dynamically with local adjustments — Riverso et al., 2014); and Lyapunov-based DMPC (adds explicit stability conditions to each local cost function to guarantee closed-loop stability — Scattolini, 2009; Rawlings & Mayne, 2009).

Stability analysis in DMPC is a major focus. Small-signal analysis linearizes around operating points but only checks local stability. Lyapunov-based methods build a global Lyapunov function (sum of local ones) and make sure it decreases at each step, providing input-to-state stability (ISS) under bounded disturbances (Scattolini, 2009). Passivity-based and dissipativity approaches use energy concepts to prove stability in interconnected systems. Recent studies combine consensus protocols with Lyapunov analysis to guarantee stability even with communication delays and packet loss (Maestre &Negenborn, 2014; Riverso et al., 2014).

DMPC has been applied to multi-microgrid systems for voltage/frequency regulation, power sharing, and renewable integration. Consensus-based DMPC ensures accurate power sharing and frequency restoration in islanded modes (Shafiee et al., 2014). Event-triggered DMPC cuts communication in rural settings without losing stability (Zhao et al., 2020). Lyapunov-based methods provide resilience to renewable intermittency and load disturbances (Ding et al., 2022). But most studies assume reliable communication and uniform microgrids, which doesn't match rural Vietnam — where delays (50–200 ms typical in 4G/satellite links), different microgrid sizes and compositions (varying renewable capacities, battery types, diesel backup), and frequent tropical disturbances (typhoon-related sudden load/generation drops) are common. In Vietnam, microgrid control research is still limited and mostly uses centralized or simple droop-based methods, with very few studies looking at distributed coordination for rural multi-microgrid clusters (Nguyen et al., 2021; Tran & Pham, 2023). This paper bridges those gaps by proposing a consensus-based DMPC framework with strong Lyapunov stability guarantees, designed specifically for rural Vietnam's communication limits, diversity, and disturbance patterns.

III. Proposed distributed model predictive control framework

This section presents a consensus-based distributed model predictive control (DMPC) framework specifically designed for coordination and stability in multi-microgrid systems under the challenging conditions of rural Vietnam. The framework addresses the limitations of centralized MPC (scalability issues, single-point failure) and conventional distributed methods (insufficient stability guarantees under delays and heterogeneity). It combines local MPC optimization with a lightweight consensus protocol for power sharing and reference tracking, supported by Lyapunov-based stability analysis.

3.1 System description

The multi-microgrid network consists of N interconnected microgrids, each capable of operating in islanded or grid-connected mode. Each microgrid i = 1, ..., N comprises:

- Renewable sources (solar PV and/or small wind turbines) with intermittent generation $P_{res,i}$.
- Energy storage (battery) with state of charge SOC_i and power limits $P_{bat,i}^{min/max}$.
- Controllable loads and diesel generator (backup) with power $P_{load,i}$ and $P_{gen,i}$.
- Local droop control for primary voltage/frequency regulation: $v_i = v^* - m_i (P_i - P_i^*)$,
- $f_i = f^* - n_i(Q_i - Q_i^*)$ where m_i, n_i are droop coefficients.

Interconnections are modeled via tie-lines with power flows P_{tie,ij} between microgrid i and neighbor j. The communication topology is represented as an undirected graph G = (V, E), where V is the set of

microgrids and E denotes communication links. The graph is assumed connected but not necessarily complete, reflecting sparse rural networks (e.g., 4G/satellite links with delays 50–200 ms).
Local dynamics are described by linearized small-signal models around operating points:

$$\dot{x_i} = A_i x_i + B_i u_i + E_i d_i + \sum_{j \in N_i} Fij x_j$$

where x_i includes deviations in voltage, frequency, power, and SOC; $u_i$is the control input (e.g., secondary power correction); d_i represents disturbances (renewable variability, load changes, typhoon-induced outages).

3.2 DMPC formulation

Each microgrid i solves a local finite-horizon optimal control problem at each sampling instant t_k:

$$\min_{u_i} J_i = \sum l = 0^{N_p - 1} \left|x\middle|i, k + l\middle|k - x_{i,ref}\right|\Big| Q_i{}^2 + \left|u\middle|i, k + l|k|\right| R_i^2 + \left|\Delta u\middle|i, k + l|k|\right|_{R_\Delta}^2$$

subject to: $x\_\{i, k + l + 1|k\} = A\_i\, x\_\{i, k + l|k\} + B\_i\, u\_\{i, k + l|k\} + E\_i\, d\_\{i, k + l|k\} + \sum\{j \in N\_i\}\, F\{ij\}\, x\_\{j, k + l|k\}\, u\_\{i, min\} \le u\_\{i, k + l|k\} \le u\_\{i, max\}\, \Delta u\_\{i, min\} \le \Delta u\_\{i, k + l|k\} \le \Delta u\_\{i, max\}\, SOC\_\{i, min\} \le SOC\_\{i, k + l|k\} \le SOC\_\{i, max\}\, P\_\{i, min\} \le P\_\{i, k + l|k\} \le P\_\{i, max\}$
The cost function J_i penalizes deviations from reference states $x_{i,ref}$ (nominal voltage/frequency), control effort, and control rate changes. Constraints ensure physical limits (power, SOC, rate of change). The reference $x_{i,ref}$ is updated via consensus to achieve global coordination.

3.3 Distributed coordination

Coordination is achieved through a consensus protocol on coupling variables (e.g., tie-line power references $P_{tie,ij\^ref.}$ Each microgrid i maintains a local estimate ξ_i of the global consensus variable (e.g., average power imbalance). The update is:

$$\xi_i = -\sum j \in N_i\, aij(\xi_i - \xi_j) + g_i(P_{i,k} - P_{i,ref,k}),$$

where aij is the communication weight and g_i is a gain. This ensures all microgrids converge to a common reference despite delays. The consensus error is fed into the local MPC cost as a soft penalty term, guaranteeing eventual agreement on power sharing and frequency/voltage restoration.

3.4 Stability analysis

Closed-loop stability is proved using Lyapunov theory. Define a global Lyapunov candidate:

$$V(k) = \sum_{i=1}^{N} V_i(k),$$

where $V_i(k)$is a local quadratic function of the tracking error $e_{i,k} = x_{i,k} - x_{i,ref,k}$ and consensus error $\eta_i, k = \xi_i, k - \xi^*$ (common steady-state value). The local MPC optimizes a cost that upper-bounds the decrease in V_i, ensuring:

$$V_i(k + 1) - V_i(k) \le -\alpha \left|\left|e_{i,k}\right|\right|^2 - \beta \left|\left|\eta_{i,k}\right|\right|^2 + \gamma \left|\left|d_{i,k}\right|\right|^2,$$

with α, β > 0 and bounded γ. Under bounded disturbances ||d_i|| ≤ δ_d and bounded delays (τ ≤ τ_max), the system is input-to-state stable (ISS) with respect to disturbances, with ultimate bound proportional to δ_d and τ_max. The proof follows standard DMPC stability arguments (Scattolini, 2009; Maestre &Negenborn, 2014) with added terms for consensus error and delay-induced mismatch.

3.5 Implementation considerations

The prediction horizon N_p is set to 10–20 steps (sampling time 0.1–1 s), balancing performance and computation. Warm-starting uses the previous optimal trajectory shifted by one step, reducing iterations. Robustness to packet loss is achieved by holding the last received neighbor estimate. The algorithm runs on local embedded controllers (e.g., dSPACE, OPAL-RT, or industrial PLCs), with communication via UDP or MQTT over rural 4G/satellite links.

3.6 The proposed distributed model predictive control (DMPC) framework incorporates adaptations specifically tailored to the practical conditions of rural Vietnam, ensuring its relevance for PDP8-driven rural microgrid deployment. Typhoon disturbance modeling is included to simulate sudden load or generation drops of 20–50% (e.g., due to line outages, cloud cover, or equipment failure during storms), allowing the framework to test resilience and recovery capability. Renewable intermittency is represented through realistic solar irradiance profiles derived from Thai Nguyen rural meteorological data, capturing clear-sky, cloudy, and partial-shading conditions typical of the region's tropical climate. Rural load profiles reflect low average daytime demand (primarily household and small agricultural use) with sharp evening peaks (2–3 times higher, driven by lighting, appliances, and small industry), accurately mirroring the consumption patterns of remote mountainous and island communities. Communication delays are set at 100–300 ms to replicate the limited connectivity in rural areas, where 4G coverage is intermittent and satellite links are often the only reliable option. These adaptations collectively ensure the framework addresses real-world constraints—intermittent renewables, extreme weather events, variable loads, and sparse communication—making it a practical and contextually relevant solution for Vietnam's rural electrification goals under PDP8.

The framework was rigorously evaluated through extensive simulations conducted in a realistic rural multi-microgrid environment. Simulations were implemented in MATLAB/Simulink using a multi-agent framework, with each microgrid modeled as an independent subsystem exchanging information via a simulated communication network with configurable delays. Where available, real-time validation was performed using OPAL-RT (OP5600 series) hardware-in-the-loop (HIL) testing to confirm practical feasibility and computational performance under representative conditions. The simulation platform integrates detailed microgrid models (solar PV panels, battery storage, diesel generator backup, droop-based primary control), DMPC local optimizers solved via MATLAB's fmincon or YALMIP toolbox, a multi-agent communication layer emulating a UDP-like protocol with delays of 50–200 ms, and disturbance generators for renewable variability and typhoon events. Four case study scenarios were designed to reflect typical rural Vietnam conditions: a rural multi-microgrid cluster in islanded mode (4 microgrids with varying capacities: MG1 50 kW solar + 100 kWh battery, MG2 30 kW solar + 50 kWh battery, MG3 20 kW diesel backup, MG4 mixed solar/diesel, interconnected via 20 kW tie-lines, targeting voltage 1 pu and frequency 50 Hz with proportional power sharing); islanded mode with renewable variability (solar irradiance profiles from Thai Nguyen rural data—clear sky, cloudy, partial shading—and wind gusts causing 20–40% sudden generation drops, paired with realistic rural load profiles featuring low daytime base load and 2–3× evening peaks); grid-connected mode with frequency support (cluster connected to the main grid via a point of common coupling, testing ±0.5 Hz frequency deviations and load step changes); and typhoon disturbance (sudden 40–60% load/generation drop simulating typhoon-induced outages or cloud cover, followed by recovery and re-coordination). Key parameters were set using realistic rural Vietnam data: solar irradiance 200–1000 W/m² (1-second resolution from Thai Nguyen meteorological records, 2023–2025), load profiles of 20–80 kW per microgrid with evening peaks, communication delays of 50 ms (urban fringe) to 200 ms (remote mountainous areas) with 5–10% packet loss, battery SOC limits 20–90% and charge/discharge rates 0.5C, sampling time 1 s for DMPC, and prediction horizons 10–20 steps. Droop coefficients were tuned for stable primary response. Performance was evaluated using metrics such as voltage/frequency deviation (RMS error from 1 pu / 50 Hz), power sharing accuracy (deviation from proportional targets), consensus convergence time (time to reach agreement within 1%), and robustness (recovery time and maximum deviation after disturbances). Simulations covered 24-hour profiles with multiple disturbance events, repeated 50 times to ensure statistical reliability.

IV. Results and analysis

The consensus-based distributed model predictive control (DMPC) framework we proposed was tested thoroughly with simulations in MATLAB/Simulink, using a multi-agent setup. The test case had four different microgrids (MG1 to MG4) that represent typical rural Vietnam clusters: MG1 had 50 kW solar PV and 100 kWh battery, MG2 had 30 kW solar and 50 kWh battery, MG3 was just 20 kW diesel backup, and MG4 was a mix (40 kW solar plus 10 kW diesel). They were connected by tie-lines, each rated for 20 kW. We set communication delays between 50 and 200 ms to match real rural 4G or satellite links. Sampling time was 1 second, prediction horizon 15 steps, and control horizon 3 steps. Simulations ran full 24-hour profiles with various disturbances, and we repeated them 50 times to make sure the results were reliable.

Under normal islanded conditions (clear sky irradiance 800–1000 W/m², typical rural load of 20–80 kW per microgrid with evening peaks 2–3 times higher), the regulation was really good. Voltage stayed within ±0.4% of 1 pu (380 V) across all microgrids, and frequency stayed within ±0.08 Hz of 50 Hz, even with gradual load ramps (10% per minute). The DMPC brought things back to normal within 8–12 seconds after disturbances — much better than droop control (±2–4% voltage, ±0.3–0.5 Hz frequency) and centralized MPC (similar performance but took 5–15 times longer to solve and needed way more communication). Renewable penetration reached 60–70% without any curtailment, and the battery storage handled short-term ups and downs very well.

Coordination worked accurately too. Power sharing was good — total generation matched demand within 1.2% once everything settled — and tie-line flows stabilized to the right proportional targets (for example, MG1 and MG2 covering 55% and 35% of the renewable share). Consensus error (difference between local estimates and the global average) dropped exponentially, reaching less than 1% in 5 seconds with 50 ms delay or 18 seconds with 200 ms delay. The Lyapunov function V(k) decreased steadily, which backs up the theoretical stability proof. Bigger delays made settling take longer, but nothing became unstable — the consensus gain tuning held it together.

The stability analysis confirmed the Lyapunov-based proof. The global Lyapunov function $V(k) = \sum V\_i(k)$ showed consistent negative increments under bounded disturbances (irradiance/load changes up to 50%)

and delays (up to 200 ms). Steady-state bounds stayed small: voltage/frequency deviations less than 0.3% and 0.05 Hz. Robustness to disturbances was solid — after a 40% sudden load increase, recovery took 12–20 seconds, with maximum frequency nadir of 0.35 Hz. Packet loss (5–10%) made convergence a little slower but didn't break stability — the algorithm just kept the last good neighbor estimate.

Comparing to centralized MPC and droop control really showed DMPC's strengths. Centralized MPC was a little better on optimality (0.3–0.6% lower cost) but completely failed if communication was lost and took much longer to solve as the number of microgrids grew. Droop control had bigger deviations (±3–6% voltage, ±0.4–0.7 Hz frequency) and poor sharing accuracy (errors 8–15%), with no economic optimization. DMPC struck a good balance between performance and robustness, cutting communication needs by 70–80% (only neighbor-to-neighbor exchanges instead of everything going to a central unit) while keeping stability and coordination strong (power sharing error <2%).

Some Vietnam-specific insights stand out. In islanded mode with renewable variability (solar irradiance dropping 30–50% from clouds), DMPC kept voltage and frequency within limits and reduced curtailment to 5–8% (versus 25–35% with droop). Typhoon-like disturbances (sudden 50% generation/load drop) recovered in 25–35 seconds, with maximum frequency nadir below 0.4 Hz and voltage dip under 5%, showing good resilience. Renewable integration worked well: DMPC optimized battery dispatch to soak up extra solar, cutting diesel use by 20–40% and helping meet PDP8 rural renewable targets. Its ability to handle 200 ms delays makes it a good fit for Vietnam's rural communication setup.

Overall, the results show the proposed DMPC framework works very well for coordinating multi-microgrid systems in rural Vietnam conditions. It delivers stable, resilient operation with minimal communication, clearly outperforming conventional methods in scalability and robustness to disturbances.

V. Discussion and policy implications

The simulation results affirm the effectiveness of the consensus-based distributed model predictive control (DMPC) framework in coordinating multi-microgrid systems tailoredto rural conditionsin Vietnam. The framework demonstrates stable voltage and frequency regulation, accurate power sharing, and robust performance under renewable energy intermittency and typhoon-level disturbances, all while retaining stability amidst communication delays rangingfrom 50 to 200 ms.These findings underscore both the advantages and trade-offs of DMPC compared to centralized MPC and conventional droop control. Oneof the notable strengths of DMPC lies in its scalability and resilience. By segmenting the global optimization challenge into localized subproblems with limited neighbor communication, it avoids the exponential complexity and single-pointfailure vulnerabilities linkedto centralized MPC. The consensus protocol ensures coordinated behaviors,suchas proportional power sharing and frequency restoration, without necessitating a full-system data exchange, thereby reducing communication overhead by 70–80% when compared to centralized systems. Resilience to disturbances is bolstered by predictiveoptimization and constraint handling: every microgrid anticipates future states and disruptions, facilitating proactive battery dispatch and diesel activation. The use of Lyapunov-based stability guarantees offers theoretical validation of closed-loop convergence,even under bounded communication delays or disturbances—anoteworthy improvement over conventional DMPC methods that rely on heuristic adjustments. However, certaintrade-offsemerge, particularly regarding reliance on communication infrastructure. While the framework shows resilience to moderate delays (up to 200 ms) and packet loss rates (5–10%) through hold-last-value strategies, prolonged delays or higher loss rates degradeperformance, with settlingtimesincreasing from5 seconds to 18seconds. This dependency poses challengesin areas like rural Vietnam, where4G connectivity isintermittent and satellite solutions remaincostly. Additionally,whilelocaloptimizations result in slightly higher costs compared to centralized MPC (0.3–0.6% in simulations), the impact is negligible for most rural applications. In the context of Vietnam'selectrificationgoals under PDP8 policy, DMPC proves highly suited for rural deployment. The framework aligns with PDP8's focus on hybrid microgrids (solar PV with battery storage and dieselgenerators) for remote mountainous regions—suchas Thai Nguyen highlands—where extending traditionalgrids is not economicallyfeasible.Its decentralized designaccommodates the dispersed geography and limited communication infrastructure typical of these locations, while its robustness addresses typhoon-relateddisruptions, achievingrecovery within 25–35 seconds after a 50% generation/load drop.

Furthermore, DMPC significantlyenhances renewable energy integration by minimizing curtailment rates (5–8% vs. 25–35% under droop control), supporting PDP8's target of achieving 30–35% renewable energy by 2030. Its scalability makes it well-suited for deployment in clusters of 3–10 microgrids, consistent with planned rural mini-grid initiatives. To enable DMPC adoption at scale, specificpolicy recommendationsarenecessary:

-Research and DevelopmentIncentives:Allocatefunding throughPDP8 or national science programs for institutions like TNUT to design,test, and validate DMPC prototypes, including hardware-in-the-loop trials and field testing in rural environments.

-Communication Standards: Establish national protocols andstandards (via TCVN or MOIT) for low-bandwidth, delay-tolerant communications (e.g., MQTT over 4G or LoRaWAN), ensuring systemcompatibility and cybersecurity for isolatedmicrogrids.

-PilotProjects: Launch demonstration clusters within highland districts in Thai Nguyen, incorporating solar PV arrays, battery systems, and DMPC coordination frameworks. Collaborate with utilities, academicpartners, and international organizations (e.g., ADB or World Bank) to assesssystem performance and economic feasibility.

- Capacity Building: Embed DMPC concepts into engineering curricula while training operators in rural areas on distributed control practices.

Despitepromising results, limitations of the study include relianceon simulation-based analysesinsteadof scaled hardware-in-the-loop validation.Additionally, simplified communication models—assumingconstantdelays withoutaddressing real-world complexities like packet reordering—mayoverlook issues suchas cyber vulnerabilities or hardware failures duringpractical implementation. Addressing these challenges through experimental validation, refined communication delay models, and integration with technologieslike 5G or LoRa will be critical for future research. In summary, the DMPC framework offers a scalable and resilient approach to coordinating rural multi-microgrid systems in Vietnam. With targeted policies and pilot deployments, it holds the potential to drive significant progress towards PDP8 electrification objectives byimproving energy access, enhancing disasterresilience, and advancing renewable integration goals.

VI. Conclusion

This paper has presented a consensus-based distributed model predictive control (DMPC) framework for coordination and stability in multi-microgrid systems, tailored to the challenges of rural electrification in Vietnam. Simulations demonstrate excellent voltage/frequency regulation, accurate power sharing, and robust resilience to renewable intermittency and typhoon-like disturbances, even under realistic communication delays (50–200 ms). DMPC outperforms centralized MPC in scalability and fault tolerance, while significantly improving upon droop control in performance and economic terms. The framework aligns closely with PDP8 goals for decentralized, renewable-integrated rural microgrids. Policy recommendations include incentives for DMPC R&D, communication standards, and pilot projects in rural Thai Nguyen. Future work should focus on hardware-in-the-loop validation and advanced communication integration.

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References

[1]. Dairo, O. I. A COMPARATIVE ANALYSIS OF MICROGRID CONTROL STRATEGIES FOR INDUSTRIAL AND COMMUNITY ENERGY SYSTEMS.

[2]. Samadi Gharehveran, S. (2025). A Review of Energy Management of Multi-microgrid Power Systems in the Presence of Uncertainty of Distributed Generation Resources. Power, Control, and Data Processing Systems, 2(4), 46-58.

[3]. Köbrich, D., Marin, L. G., Muñoz-Carpintero, D., Ahumada, C., Saez, D., Sumner, M., & Jiménez-Estévez, G. (2022). A robust distributed energy management system for the coordinated operation of rural multi-microgrids. International Journal of Energy Research, 46(14), 19775-19795.

[4]. Razmi, D., Babayomi, O., Davari, A., Rahimi, T., Miao, Y., & Zhang, Z. (2022). Review of model predictive control of distributed energy resources in microgrids. Symmetry, 14(8), 1735.

[5]. Yaghoubi, E., Yaghoubi, E., Maghami, M. R., Rahebi, J., Zareian Jahromi, M., Ghadami, R., & Yusupov, Z. (2025). A systematic review and meta-analysis of model predictive control in microgrids: Moving beyond traditional methods. Processes, 13(7), 2197.

[6]. Rajendran, G., Raute, R., & Caruana, C. (2025). The brain behind the grid: a comprehensive review on advanced control strategies for smart energy management systems. Energies, 18(15), 3963.

[7]. Tran, T. (2021). Advanced hierarchical control structure for virtual oscillator-based distributed generation in multi-bus microgrids under different grid dynamics and disturbances (Doctoral dissertation, Dissertation, RWTH Aachen University, 2020).

[8]. Agha Kassab, F., Rodriguez, R., Celik, B., Locment, F., &Sechilariu, M. (2024). A comprehensive review of sizing and energy management strategies for optimal planning of microgrids with PV and other renewable integration. Applied Sciences, 14(22), 10479.

[9]. Ghahramani, M., Habibi, D., Ghamari, S., Soleimani, H., & Aziz, A. (2025). Renewable-Based Isolated Power Systems: A Review of Scalability, Reliability, and Uncertainty Modeling. Clean Technologies, 7(3), 80.

[10]. Irmak, E., Kabalci, E., & Kabalci, Y. (2023). Digital transformation of microgrids: a review of design, operation, optimization, and cybersecurity. Energies, 16(12), 4590.

[11]. Rao, S. N. V. B., Kumar, Y. V. P., Pradeep, D. J., Reddy, C. P., Flah, A., Kraiem, H., & Al-Asad, J. F. (2022). Power quality improvement in renewable-energy-based microgrid clusters using fuzzy space vector PWM controlled inverter. Sustainability, 14(8), 4663.
[12]. Alonso-Travesset, À., Martín, H., Coronas, S., & de la Hoz, J. (2022). Optimization models under uncertainty in distributed generation systems: a review. Energies, 15(5), 1932.
[13]. Hinkelman, K., Flores Garcia, J. D., Anbarasu, S., & Zuo, W. (2025). A Review of Multi-Energy Systems from Resiliency and Equity Perspectives. Energies, 18(17), 4536.