Intelligent Operation and Coordinated Control of Networked Microgrid Systems

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***Abstract*—The growing penetration of renewable energy resources (RESs) and distributed generation has accelerated the need for intelligent and resilient operation of networked microgrid systems. Effective coordination among interconnected microgrids is crucial for maintaining power balance, voltage stability, and reliable operation under dynamic and uncertain conditions. This paper presents a coordinated control framework for the intelligent operation of networked microgrids, with a focus on real-time energy management and distributed decision-making. The proposed framework integrates hierarchical control layers—local, inter-microgrid, and central coordination—to achieve seamless power sharing and adaptive operation during load variations and islanding transitions. Simulation results demonstrate that the coordinated strategy effectively maintains voltage deviations within ±1% and reduces power-sharing error by over 30% compared to conventional droop-based control.**

Index Terms-- Multi-microgrids (MMGs), Cyber-Physical Systems, Hardware Implementation, Power Sharing, denial-of-service (DoS) Attack, Resiliency.

I. Introduction

The global energy landscape is rapidly changing as renewable energy resources (RESs), distributed generation (DG), and advanced energy storage technologies become more widely used [1]. These trends have created additional operational complexity for traditional centralized power systems, accelerating the shift to decentralized and intelligent architectures. Microgrids have emerged as a viable method for integrating local generation and storage while maintaining system resilience, reliability, and sustainability. When numerous microgrids are interconnected and coordinated, they form a networked microgrid system capable of optimizing power exchange, increasing energy utilization, and strengthening the grid's overall resiliency.

Despite these advantages, the intelligent operation of networked microgrids poses significant challenges [2]. The inherent variability of RESs, stochastic demand behavior, and inter-microgrid power connections require sophisticated control and coordination systems. Real-time power balance, voltage, and frequency stability, as well as reliable communication between microgrids, all require scalable and adaptive control frameworks. Conventional centralized control architectures frequently have limitations due to single points of failure, communication latency, and computational burden, highlighting the need for distributed and hierarchical strategies that enable autonomous decision-making at the local level while maintaining global coordination [3].

Recent research on networked microgrids has explored various control and coordination mechanisms to enhance system stability, energy efficiency, and reliability. Distributed control approaches, such as consensus-based methodologies, multi-agent systems, and hierarchical coordination, have demonstrated promise in implementing power sharing and voltage management among interconnected microgrids.

Recent research has focused on modeling, operating, and coordinating microgrids in the context of the increasing use of distributed energy resources (DERs), energy storage, and electric vehicles (EVs). For example, the study in [4] demonstrates how stochastic EV charging behavior and unequal load distribution can cause voltage fluctuations and unintended load rise. However, this study is essentially theoretical, with no real-time validation or adaptive control techniques to address transient instability and pulsed load.

Similarly, [5] shows the practical application of DC microgrids in commercial buildings, but it focuses more on static design and economic considerations. The study does not investigate dynamic control coordination between renewable generation, storage, and load variations, which is essential for maintaining bus voltage stability during unexpected load transitions or bidirectional power flow.

On the system level, [6] and [7] use optimization frameworks to enhance coordinated and probabilistic energy management strategies. These studies are successful in reducing costs and facilitating cooperative operation under uncertainty, but they primarily rely on off-line or game-theoretic optimization, without incorporating hardware-level feedback or dynamic controller design to ensure real-time stability during abrupt shocks. Furthermore, [8] describes a multi-agent communication system that uses prioritized

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particle swarm optimization (P-PSO) for distributed decision-making. While it excels at managing distributed energy scheduling, it presupposes perfect communication and overlooks the latency and control synchronization concerns that arise in real-world contexts. Despite these advances, major gaps exist. Most present research focuses on theoretical analysis or constrained simulation scenarios, often overlooking practical restrictions such as communication latency, cyber-physical interactions, and the presence of pulsed or dynamically fluctuating loads. Furthermore, the validation of intelligent coordinating strategies employing hybrid physical-simulation testbeds is limited, making proposed methods less applicable in real-world microgrid networks. As a result, there is a clear need for a comprehensive framework that integrates hierarchical control, real-time coordination, and experimental validation to ensure the robust and resilient operation of networked microgrids under realistic dynamic conditions. The primary contributions of this paper are summarized as follows:

1. Hierarchical Coordinated Control: A multi-layer control framework managing local and inter-microgrid operations to ensure real-time power balance and voltage stability.
2. Hybrid Testbed Validation: Experimentally validated on the FIU ESRL Testbed, combining physical hardware, real-time simulation, and communication.
3. Performance Improvement under Dynamic Events: Simulation and experimental results demonstrate significant enhancements in operational performance during disturbances such as pulsed loads or renewable intermittency.

The remainder of this paper is organized as follows: Section II describes the system architecture and control framework of the networked microgrid. Section III presents the results and discussions of the experiments. Finally, Section IV concludes the paper and outlines future research directions.

II. System Architecture and Power Coordination

The proposed networked microgrid system establishes a uniform framework for the coordinated operation of multiple interconnected microgrids, aiming to enhance energy sharing, operational stability, and resilience. Each microgrid functions as a semi-autonomous energy hub, with distributed energy resources (DERs) such as photovoltaic (PV) panels, wind turbines, and energy storage devices, all managed by local controllers that assure real-time generation and demand balance. A hierarchical communication structure based on Software-Defined Networking (SDN) connects all microgrids, enabling more flexible control, adaptive data routing, and enhanced system cybersecurity.

Each microgrid has a local control layer that continuously analyzes its generating output, storage capacity, and load profile. Primary control utilizes voltage and frequency droop to maintain internal equilibrium and adjust the DER's power contribution. The local energy balance is stated as follows:

$$P_{gen,i} = P_{load,i} + P_{storage,i} + P_{loss,i} \tag{1}$$

where $P_{gen,i}$ denotes renewable and backup generation, $P_{load,i}$ represents local demand, $P_{storage,i}$ the net energy exchange with storage, and $P_{loss,i}$ internal conversion and transmission losses. Long-term energy balancing is handled by battery units, whilst ultracapacitors are used for rapid adjustment of transient load fluctuations, ensuring voltage stability during high-frequency events.

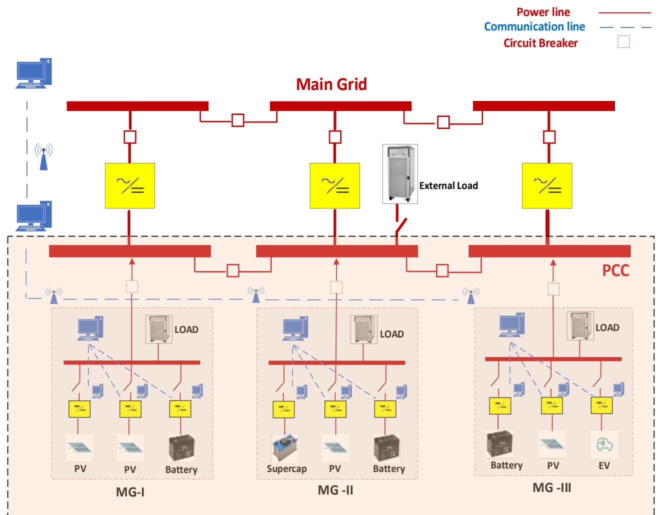

Figure 1. Proposed Multi-Microgrid System

At the coordination layer, a centralized energy management system (CEMS) regulates all aspects of operation by aggregating real-time measurements from all connected microgrids. When local power imbalances occur due to renewable variability or pulsed loads, the CEMS calculates the global deviation and sends correction commands, which include allocating surplus energy to nearby microgrids or scheduling controlled discharge from available storage. This dynamic exchange supports system-wide balance while preventing cycle instabilities. Furthermore, surplus renewable energy is favored for inter-microgrid sharing over grid support or non-critical load curtailment, increasing operational efficiency and sustainability.

The proposed system, shown in Fig. 1, enables coordinated power management, reduced voltage variations, and increased energy usage across the network due to its layered control architecture. The combination of local autonomy and global coordination creates a solid platform for experimental validation in the FIU ESRL Hybrid Smart Grid Testbed, capturing the intricate interplay between physical, cyber, and communication domains.

Pulse power loads (PPLs), which are electrical loads that rapidly shift between low and high-power demand levels as depicted in Fig. 2, pose a significant operational issue in such arrangements [9]. Radar systems, electric propulsion engines, and modern data centers are examples of typical technologies. These loads induce abrupt power changes, resulting in voltage and current oscillations, especially in isolated or weakly connected DC microgrids [10]. The power demand from a PPL can be considered to have two components: average power, which represents the steady baseline energy required to support the system over time, and dynamic power, which refers to short,

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sharp bursts of energy that occur when the load transitions from low to high demand.

Mathematically, the total load can be expressed as:

$$P_{load}(t) = P_{avg} + P_{dyn}(t) \quad (2)$$

The dynamic component can be modeled using the pulse amplitude P_{peak} and duty cycle D as:

$$P_{dyn}(t) = \begin{cases} P_{peak} & 0 \leq t \bmod T < D.T \\ 0 & D.T \leq t \bmod T < T \end{cases} \quad (3)$$

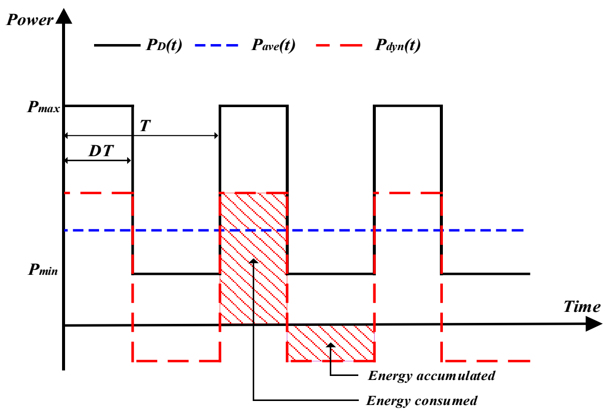

Figure 2. Pulse Load Structure

A. Microgrid Management and Coordination Algorithms

Each microgrid acts as an autonomous energy hub, integrating renewable generation, conventional backup, and energy storage systems (including batteries and ultracapacitors) to maintain a local power balance. Local controllers utilize droop control to adjust generation in response to fluctuations in load or renewable energy. Batteries manage long-term energy variations, while ultracapacitors provide short-term support for transient events, such as pulsed power loads (PPLs).

Algorithm 1: Local Microgrid Management

Inputs:

for each microgrid *i* in *{1, 2, 3}* **do:**
  Measure: $P_{gen,i}$, $P_{load,i}$, $P_{storage,i}$, $P_{loss,i}$, $SOC_{bat,i}$
  Set $P_{Balance,i}$= $P_{gen,i}$ - $P_{load,i}$ - $P_{storage,i}$ - $P_{loss,i}$
  if $P_{Balance,i}$ > 0 **then:**
    if $SOC_{bat,i}$ < $SOC_{threshold}$ **then:**
      Command battery charge with:
        $P_{charge,i}$ = min ($P_{Balance,i}$, $BatteryMaxCharge_i$)
    else:
      Maintain local droop control to regulate voltage/frequency.
  else if $P_{Balance,i}$ < 0 **then**
    if $SOC_{bat,i}$ > SOC_{min} **then:**
      Command battery discharge with:
        $P_{discharge,i}$= min $P_{Balance,i}$| , $BatteryMaxDischarge_i$)
    else:
      Disconnect noncritical loads or flag a deficit for EMS action.
  end if
end for

Algorithm 2: Upper-Level Power Sharing

Compute ΔP_{global} = ($P_{Bal,1}$ + $P_{Bal,2}$ + $P_{Bal,3}$) - P_{EPL}
if ΔP_{global} > TH_{high} **then:**
  for each microgrid *j* with $SOC_{bat,j}$ < $SOC_{threshold}$ **do:**
    Command battery charge in microgrid j with:
    $P_{charge,j}$ = min(ΔP_{global}, $BatteryMaxCharge_j$)
  end for
  Optionally export surplus energy externally or curtail renewable generation.
else if ΔP_{global} is between -TH_{low}w and TH_{high} **then:**
  Continue nominal operation with minor SOC adjustments and rely on local droop control.
else if ΔP_{global} < -TH_{low} **then:**
  for each microgrid *k* with $SOC_{bat,k}$ > SOC_{high} **do:**
    Command battery discharge in microgrid k with:
    $P_{discharge,k}$ = min(|ΔP_{global}|, $BatteryMaxDischarge_k$)
  End for
  if deficit persists **then:**
    Initiate demand response actions (e.g., shed non-critical loads).
    If further deficit persists:
      Temporarily disconnect or throttle the external pulsed load (EPL).
end if

III. Results and Discussion

A. Experimental Setup

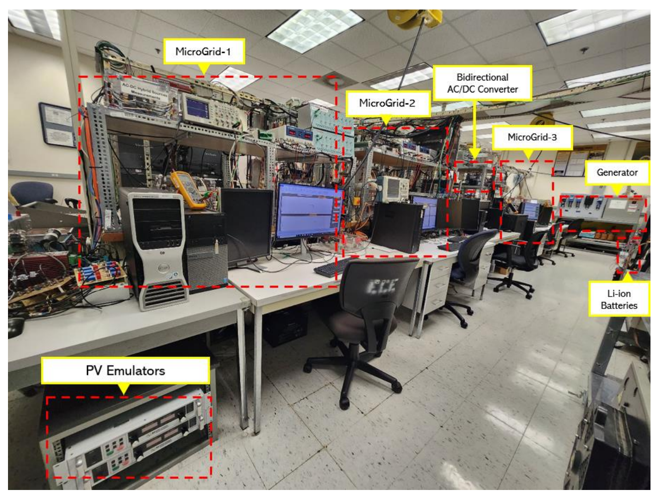

Figure 3. FIU Smart Grid Testbed

The experiments were conducted on the FIU hybrid testbed, as shown in Fig. 3, which comprised three interconnected DC microgrids connected by a common bus to facilitate coordinated power sharing and system stability. Each microgrid includes a photovoltaic (PV) source, a Lithium-ion battery, and a bidirectional converter for regulated energy transfer. To boost dynamic reactions, some microgrids incorporate a wind turbine emulator, an ultracapacitor bank, and an electric vehicle. Local loads are controlled using a hierarchical control strategy.

B. Step Load Change

To evaluate the system's dynamic response, a step load was introduced at MG3 at t = 12 s, intentionally exceeding its local generation capacity (Fig. 4). This created an immediate power

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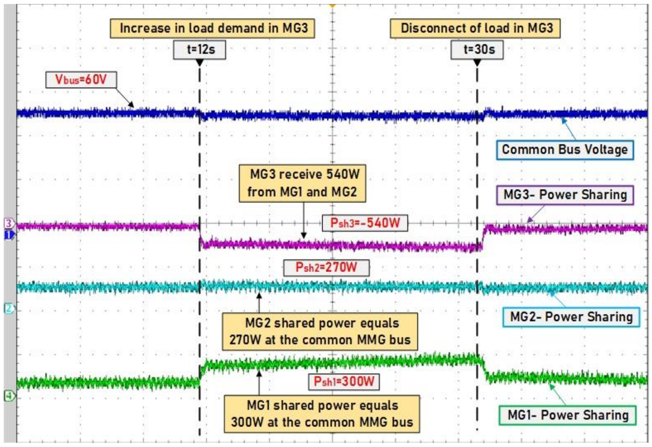

Figure 4. MMG system performance under step load

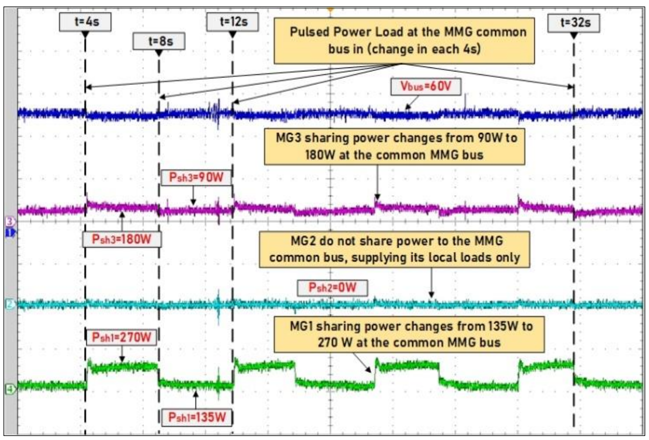

Figure 5. MMG system performance under critical load

deficit at the common DC bus, challenging the MMG's ability to maintain load-generation balance. The MMCC promptly detected the imbalance through its supervisory measurements and initiated a coordinated redistribution of power among the interconnected microgrids. MG1 responded by increasing its output from 150 W to 300 W, while MG2 maintained a steady contribution of 270 W, together with compensating approximately 540 W to support MG3.

The transient response settled within 2 s, with a peak overshoot of less than 3%, demonstrating the hierarchical control's fast corrective action. The inner converter-level controllers handled rapid current regulation, while the MMCC provided supervisory coordination to prevent overloading any individual MG. Voltage deviations were constrained within ±1% of the nominal value, and frequency variations remained below ±0.5 Hz, highlighting the system's ability to maintain power quality during abrupt load changes. These results confirm that the combined action of distributed local controllers and centralized supervisory control enables the MMG to maintain stable operation and prevent voltage collapse in response to sudden disturbances.

C. Pulsed Load Response

The MMG system was further evaluated under a pulsed load profile, alternating between 200 W and 425 W with a 50% duty cycle and 5s period (Fig. 5), simulating high-dynamic applications such as electric propulsion or radar systems.

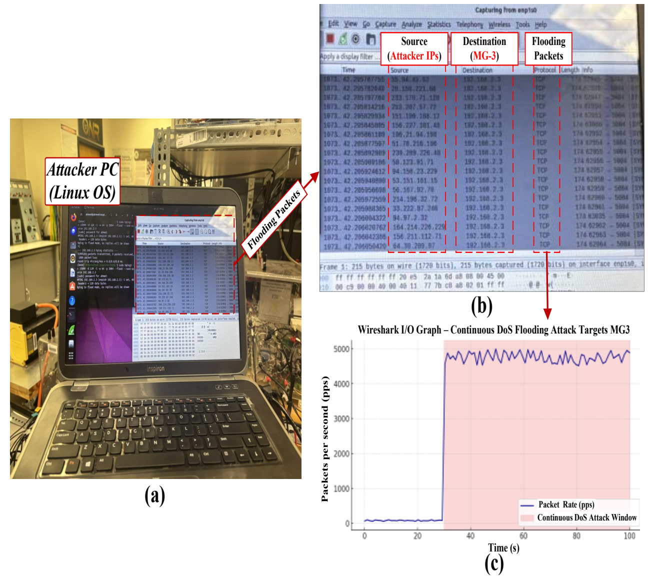

Figure 6. Hardware Implementation of DoS attack: (a) Attacker PC (Linux OS). (b) Wireshark capture of flooding attack. (c) Wireshark I/O graph during DoS attack

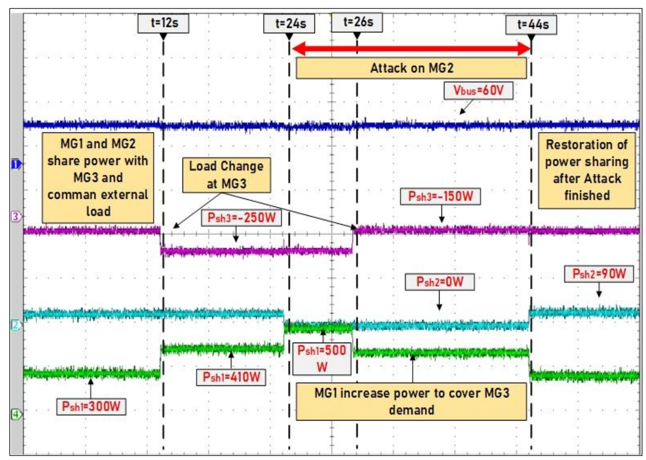

Figure 7. MMG system performance under DoS attack

During each high-demand phase, the MMCC dynamically redistributed the load across available resources, assigning MG1 and MG3 to supply the additional power based on real-time available energy and converter operating margins. MG1's current varied between 2.25 A and 4.5 A, while MG3 ranged from 1.5 A to 3 A, compensating for load swings of approximately 250 W per pulse.

Despite the rapid fluctuations, the common bus voltage remained tightly regulated within ±1.5% of the nominal value. This stability is achieved through the operation of fast local controllers and hierarchical supervisory logic, where inner voltage and current loops quickly counteract sudden transients, while the MMCC continuously adjusts setpoints to achieve optimal energy sharing. Batteries and ultracapacitors acted as complementary energy buffers. These results demonstrate the robustness of the proposed energy management approach under dynamic pulsed-power load (PPL) conditions. The system effectively mitigates high-frequency disturbances, maintains voltage stability, and ensures that no single microgrid is overloaded. Furthermore, the coordinated control strategy

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highlights the MMG's ability to adaptively manage energy in real-time, ensuring reliable operation under both continuous and rapidly varying load profiles.

D. Cyber Threat Resilience.

During cyber-physical resilience testing, the multi-Microgrid's ability to maintain stable power sharing and voltage regulation under a Denial-of-Service (DoS) attack was evaluated as shown in Fig. 7. The DoS experiment was executed in real time by an attacker agent running on an external Linux computer that generated a high-rate TCP flooding stream aimed at the affected microgrid's communication interface. Fig. 6 shows the hardware setup used to inject the flooding traffic directly into the generation-unit communication links.

The attack occurred at t = 26 s and rapidly prevented incoming setpoint updates, causing the targeted microgrid (the affected unit's measured active power output) to drop to 0 W, resulting in a sudden supply deficit on the DC bus. The MMCC detected a loss of telemetry and/or command acknowledgement and initiated autonomous reconfiguration actions. MG1 increased its delivered power from 300 W to 500 W to compensate for the deficit, while MG3 reduced its local absorption from −250 W to −150 W, rebalancing the bus power and preventing a large voltage collapse.

During the entire attack window, the bus voltage remained tightly regulated around the nominal 60 V with deviations smaller than ±2%. This limited excursion reflects (i) the fast response of the inner current control loops and (ii) the effectiveness of the MMCC's redistribution strategy in providing graceful degradation of service rather than abrupt failure. At t = 44 s, the network returned to normal operation; as communication was re-established, the isolated microgrid gradually resumed its commanded operation and synchronous power-sharing without exhibiting overshoot or sustained oscillations.

TABLE I
POWER SHARING AT THE MMG COMMON BUS

Scenarios	Microgrid 1		Microgrid 2		Microgrid 3	
	Current (A)	Power (W)	Current (A)	Power (W)	Current (A)	Power (W)
Step Load Change	2.5 to 5	150 to 300	4.5	270	-4.5	-540
Pulsed Load Change	2.25 to 4.5	135 to 270	0	0	1.5 to 3	90 to 180
DoS Attack	2.5 to 5	150 to 300	2	120	-4 to -6	-250 to -400

Table I summarizes the experimental power-sharing results at the MMG common DC bus under various operating conditions. The data confirm the effectiveness of the proposed hierarchical control framework in maintaining balanced power distribution among interconnected microgrids.

IV. CONCLUSION

This paper presented an intelligent control framework for coordinated operation of networked DC microgrids under dynamic and uncertain conditions. The proposed hierarchical strategy, which combines local control, inter-microgrid coordination, and centralized energy management, was experimentally validated on a real hybrid testbed. Results under step and pulsed load scenarios confirmed stable voltage and frequency regulation, with deviations within ±1% and ±0.5 Hz, respectively. The system also maintained reliable operation during a Denial-of-Service attack, demonstrating strong cyber-physical resilience. Through coordinated energy sharing and effective use of hybrid storage systems, the network achieved fast dynamic response and efficient power balancing across multiple microgrids. The framework provides a scalable and resilient foundation for future smart energy systems, integrating renewable sources, adaptive control, and cybersecurity awareness.

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