Networked Microgrids for Improved Resilient Operation: A Case Study in Adjuntas Puerto Rico

Maximiliano Ferrari[1], Mohammed Olama[1], Aditya Sundararajan[1], Yang Chen[2]
Ben Ollis[1], Guodong Liu[1] Cynthia Arellano[2]

[1]Oak Ridge National Laboratory, Oak Ridge, USA. [2]North Carolina Agricultural and Technical State University, Greensboro, USA. [2]The Honnold Foundation

***Abstract*—This paper presents a case study of a network microgrid orchestrator designed to allow coordinated operation of microgrids. Through Control Hardware in the Loop (CHIL), the proposed microgrid orchestrator was validated using, as case study two community-owned microgrids in Adjuntas, Puerto Rico. These two microgrids in Adjuntas were designed to provide affordable and reliable access to electricity to 14 businesses located in the town square. In its current design, these two microgrids operate independently from each other. This paper studies how networking them would increase their resiliency metrics while operating as an island. A distributed optimization is implemented in the microgrid orchestrator due to its superior scalability compared to centralized approach as well as to maintain data privacy. Two operational modes are considered in this study to showcase the advantages of networking microgrids: a) normal island, and b) degraded island. CHIL simulations are performed to validate the proposed microgrid orchestrator. CHIL results show meaningful resiliency improvements obtained by networking microgrids during contingencies such as loss of PV generation.**

Index Terms-- ***Networked microgrids, microgrid orchestrator, energy resiliency, microgrids, distributed optimization, ADMM.***

I. Introduction

Hurricane Maria caused the longest blackout in the U.S. history, leaving 3.4 million residents in Puerto Rico without power. Disadvantaged and rural communities suffered the most extended blackout, with some remaining without power for almost a year [1]. As a response to the devastation of Hurricane Maria and its subsequent power outage, rural communities in the island have been deploying microgrids as an alternative source of electricity. Microgrids (MGs) are a resilient system as they can power user-end loads when the main grid is unavailable. When the grid is available, microgrids typically operate grid-tied to export surplus power from renewables, benefiting from policies such as net-metering.

Research sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6285; managed by UT Battelle, LLC, for the U.S. Department of Energy. This manuscript has been authored by UT- Battelle, LLC, under contract DE-AC05- 00OR22725 for the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number (CID or WBS): DE-EE 37771. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (https://www.energy.gov/doe-public-access-plan).

Solar-based microgrids are a clean alternative to traditional backup generators, such as diesel, to power end-user loads during outages. Diesel generators are commonly used in Puerto Rico to power businesses during prolonged outages. Although deploying diesel generators is a straightforward way for backup generation, accessing diesel fuel in the aftermath of a natural disaster is difficult and expensive. Furthermore, emissions from diesel engines contribute damages crops and vegetation, causes acid-rain, which affects lakes and streams and enters the human food chain via water [2]. In rural areas of the island, microgrids based on solar energy can achieve high level of resiliency as the energy source is plentiful and widely available.

In 2023, two solar-based community-owned microgrids were installed in the Adjunta's town square to provide reliable power to the 14 businesses and the community, which are expected to be fully operational later the same year. This project, led by Casa Pueblo [3] and Honnold Foundation, will serve as a resilience center in the event of future natural disasters while reducing the cost of electricity for participating businesses. A description of the project can be found in [4]. These two microgrids solely rely on |photovoltaic (PV) panels along with two large battery storages. In its current design, the two microgrids in Adjuntas implement their own microgrid controllers and operate independently of each other. This paper presents the development of a microgrid orchestrator that would allow the two microgrids to operate in coordination. Networking microgrids bring various benefits, including [5], [6] [7]: 1) Leveraging redundant infrastructure; 2) Integrating additional renewable energies; 3) Reducing costs and load shedding; and 4) Supporting reliable and efficient energy to the customers and providing resilient energy systems.

The optimization for the coordination of network of microgrids can be divided in two large groups: centralized and distributed [8,9]. Centralized energy management is typically based on a multi-layered structure. Centralized approaches are advantageous in terms of simplicity of implementation and achievable global optimality. However, centralized methods assume that data are widely available, which may bring privacy concerns for the end-users. Furthermore, centralized methods don't scale well as the complexity of the network and the number of distributed energy resources (DERs) increase. Examples of centralized optimization can be found in [10], where a two-layer energy management system is presented. The lower layer's objective is to minimize the operating cost and maximize the use of renewable generation, while the upper layer minimizes the system losses and voltage deviations through optimal power flow. Other works follow a similar structure. In [11], the voltage regulation and power balancing between phases are considered in the upper layer. Due to the intermittent and uncertain nature of renewables, researchers have proposed stochastic programming models for microgrids with high penetration of renewables [12,13].Due to the issues of centralized optimization approaches, this paper proposes the use of distributed optimization for coordinating microgrids. Distributed optimization is a good fit for network microgrid applications as they preserve data privacy and are highly scalable. Approaches such as dual decomposition, multi-agent system, and consensus-based algorithms have been proposed for networked microgrids applications [14,15]. However, these methods come with their own shortcomings. For instance, agent-based methods typically omit the distribution network, while dual-decomposition has poor convergence. Consensus-based approaches usually assume linear marginal cost function. However, the marginal cost can be non-linear considering the start-up and shutdown of DERs.

The proposed microgrid orchestrator adopts the alternating direction method of multipliers (ADMM) algorithm. This method preserves data-privacy, is highly scalable and can be applied to minimize the system operating cost as well as optimizing other network objectives, e. g. bus voltage balancing, power factor improvements and minimizing power losses. Previous work done by the authors presents the mathematical formulation of the optimization problem using ADMM [16]. This paper presents the microgrid orchestrator's architecture and presents the CHIL results to showcase the gains in resiliency when the microgrids operate as a network. The proposed microgrid orchestrator is then applied to coordinate the operation of the Adjuntas microgrids to achieve high resiliency and a cost-effective operation. This paper presents results for the normal islanded and degraded islanded operation, the latter of which considers loss of PV generation in one of the microgrids. Through CHIL simulations and using real data from the MGs in Adjuntas, the resiliency gains by networking the microgrids is validated by comparing the results against the baseline of independent microgrid operation.

II. Overview of The Adjuntas Microgrids

Fig. 1 shows the 3D render of the microgrids (north-east and west) deployed in Adjuntas, Puerto Rico. These community-owned MGs consists of parallel MGs on a single feeder that use PV along with energy storage system (ESS) to provide electricity to the community. This MG is designed to benefit the community in two ways. During normal conditions, it will reduce the electricity cost of 14 business located in the town's square. If an extreme event occurs, the MG becomes a resiliency center and provides power to these businesses to serve the affected community. Currently, these two microgrids work independently. To evaluate the microgrid orchestrator, this paper assumes the interconnection of these two MGs through a common point of coupling (PCC).

Fig. 1. Initial 3D render of two MGs in Adjuntas, Puerto Rico. Rooftop PV and participating businesses may differ from final installation (Photo credit, Casa Pueblo). Businesses include bakery, pizzeria, furniture stores, hardware stores, optical store, a church and critical facilities such as a pharmacy among others.

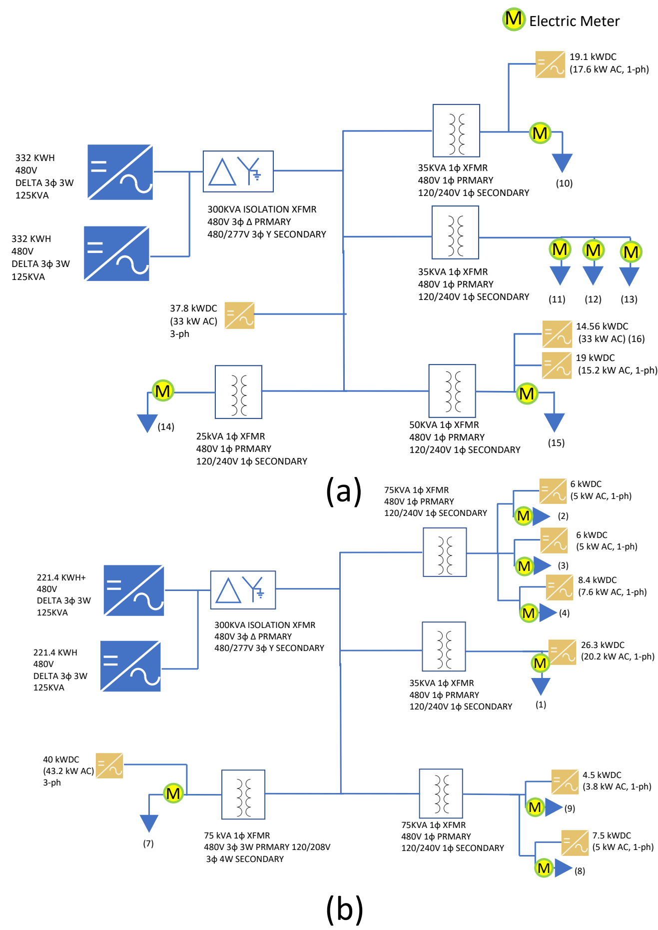

Fig. 2. The single line diagram of the two MGs in Adjuntas Puerto Rico. (a) West MG has 76 kWdc of PV generation and 662 kWh of ESS, (b) North-East MG has 98 kWdc of PV generation and 442 kWh of ESS. Each business has a meter denoted as M.

The single line diagram for the two MGs together with the power rating of the ESS and generation mix are shown in Fig. 2. These two MGs operate at 480V and the businesses have various service entrance voltages (120V/240V) split phase. The ground is formed in the isolation transformer connected to the ESS. These microgrids serve a wide range of businesses, including a bakery, a pizzeria a hardware store and critical facilities such as pharmacy. In the figures, the numbers (1-14) correspond to a business, which are anonymized for privacy's sake. The two MGs are physically co-located what makes them ideal for interconnection and operating them as a network.

The simplified single line diagram of the north-east MG is shown in Fig. 2(a). This MG consists of 11 distributed PV inverters, of which 3 are three-phase and 8 are single phase inverters. The battery pack provided by ELM has a rating of 442 kWh, and it is connected to a 125kW energy storage inverter, see Fig. 3. Fig. 2(b) shows the single line diagram of the west microgrid, which is composed of 6 distributed PV inverters, of which 1 is three-phase and 5 are single phase inverters. The battery pack has a rating of 663 kWh, and it is connected to 2 ESS inverters rated at 125 kW that work in parallel. For both MGs, the ESS inverters are connected to a delta-wye 300kVA grounded transformer that provides electrical isolation and a grounding reference for the MGs.

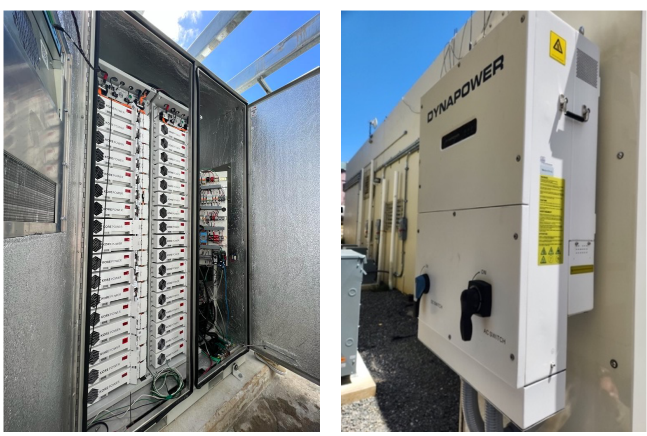

Fig. 3. ESS unit for the west microgrid. ELM, 125 with 442 kWh of ESS capacity. (Photo credit, UPRM)

III. Microgrid Orchestrator Use Cases

Fig. 4 highlights the benefits of networked MGs by sharing resources and loads in different modes of operations. During normal operation, the microgrid can network to increase the economic benefit by reducing the cost of operation. During extreme scenarios, the redundant topology of the networked MGs increases the configuration flexibility, which enhances the resiliency and reliability of the MGs and extends the operation time in island mode. The orchestrator implements three operating modes for the network of MGs: normal grid connected, normal islanded, and degraded islanded.

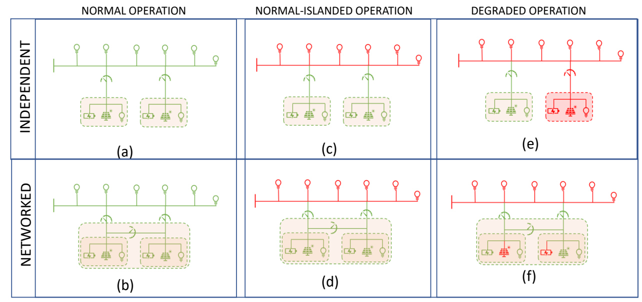

Fig. 4. Microgrid orchestrator modes of operation comparison. Normal grid-tied operation: (a) Independent MGs. (b) Networked microgrids. Normal islanded operation: (c) Independent MGs. (d) Networked MGs. (e) Independent degraded. (f) Networked degraded

Mode 1: Normal grid-connected – The MG is connected to the grid and operates primarily for economic gains through demand side management. Network of MGs can bring additional economic benefits by importing/exporting power to adjacent MGs. Additionally, the load-shedding can be improved by increasing the probability of successful islanding.

Mode 2: Normal-islanded – Individual MGs can significatively enhance resiliency, for example, end-use loads can benefit from off-grid operation. However, this resiliency can be further improved if the MGs can operate as a network. Networked MGs can import or export power from other MGs, which extends the islanding time as compared to individual MGs. The work in [16] has demonstrated that networked MGs reduce cost of operation as compared to individual MGs.

Mode 3: Degraded-islanded – For MGs operating independently, contingencies in the generation can drastically impact the islanding operation. The MG controller must shed load to maintain stable operation after losing generation (such as PV panels/inverters). If the voltage/frequency (V/F) device is compromised, the entire MG would have to shut down if no backup V/F generation is available. Networked MG operation can significatively enhance the islanded operation during contingency by sharing battery as V/F resources to avoid one MG completely shutting down. Local critical use loads of the affected MG can be supported by external generation, thus reducing load shedding, or extending the sustained period [17].

IV. Distributed Energy Management Stragegy

Typically, microgrid optimization is done through a centralized optimization, where a central controller collects information from each device, performs an optimal power flow, and sends the dispatch orders to each device. Centralized approaches are simpler to formulate, however, they require full data availability and do not scale well when the number of nodes increase [8,9]. To address the data privacy and scalability concerns, this work proposes to apply a distributed optimization for the microgrid orchestrator [16,17].

Fig. 5 shows a simplified diagram of the microgrid orchestrator based on the distributed approach. The upper layer (I) hosts the distributed optimization, and the lower layers (II, III) represents the local microgrid controllers, which implement a conventional centralized optimization. As shown, the distributed optimization only receives the net power (forecasted generation minus load) from the local MG controllers. The nodal price algorithm adjusts the nodal price signal, and the local MG controllers can then decide to purchase or sell power to the network based on their preferences. The price signal λ is updated based on the power unbalance at each bus P_N, and ρ is a penalty factor. Eventually, the price signals will converge, meaning the participants reach an agreement on the price and amount of generation/consumption.

Under distributed approach, the distributed optimization does not have to control the microgrid assets directly. The local MG controllers simply needs to respond to the received price signals λ, and based on its own objectives or considerations (e.g., economics and resilience) schedule the devices inside its boundaries. Though this approach, the autonomy and privacy of microgrids are maintained. The objective of microgrid orchestrator optimization includes operating cost of distributed generation (DGs) directly connected to distribution network, startup costs of DGs, degradation cost of ESS, cost of shedding loads, and the energy exchanging cost/benefit at distribution substation. Furthermore, the microgrid orchestrator optimization might also include other grid performance related indices, e.g., bus voltage deviations, exchanged reactive power at substation and network power loss. These objectives could be simply integrated into a single objective through weighted summation. The objective of the local microgrid controller optimization typically includes operating cost of DGs in microgrids, startup costs of DGs, degradation cost of ESSs, load shedding cost of microgrids and purchasing/selling cost/benefits at the PCC.

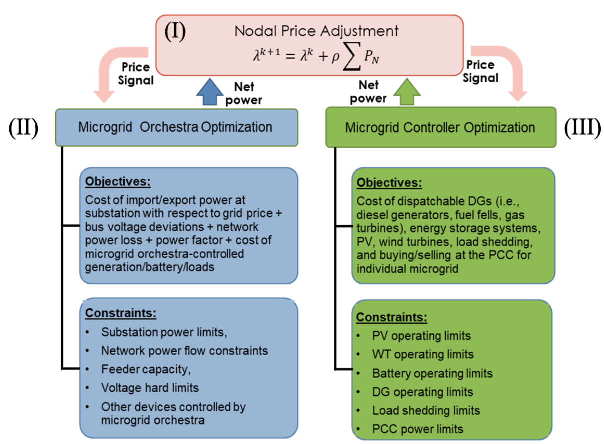

Fig. 5. Distributed energy management for networked MGs.(I) proposed distributed optimization. (II, III) local microgrid controllers

V. CONTROL-HARDWARE IN THE LOOP

To verify the effectiveness of the proposed optimization strategy, several CHIL simulations were performed. The CHIL testbed used in this study is shown Fig. 6. It is composed of two paralleled Typhoon HIL 604, DER managers that perform protocol translation between the Typhoon model and external PC, and a Typhoon amplifier that is used for amplifying signals for HIL applications. For this paper, the MG orchestrator runs on an external PC which directly communicates to the Typhoon through Modbus. The load forecast was based on the businesses load data collected in the field in 2019. This dated load data may create discrepancies between the CHIL results and the behavior of the real microgrids in Adjuntas. Future work includes the integration of the DER managers for secure protocol translation as well as updating the results using newer load measurements.

Fig. 7(a) and Fig. 7(c) show the results for the normal-islanded operation when the MGs work independently or as a network, respectively. Based on the data collected in 2019, for both independent and networked configurations, the MGs can run indefinitely during normal conditions. For the network operation, a fairness constrain was applied to maintain the battery state of charge (SOC) of both MGs closer to each other. This is desirable to prevent over cycling of one battery over the other.

Fig. 7(b) and Fig. 7(d) show the results for the degraded-islanded operation when the MGs work independently or as a network, respectively. In the degraded-islanded mode, the large 40kW 3-phase PV inverter in the west microgrid was brought offline, to reflect a loss of generation of close to 50%. This emulates the effect of losing PV generation due to a storm damaging the infrastructure. In the independent operation, Fig. 7(b), the SOC of the west microgrid plummets as result of the generation lost and load shedding is needed to maintain the SOC above 20%. Fig. 7(d) shows that networking the MGs maintains the SOC higher than 20%, and no-load shedding is asserted.

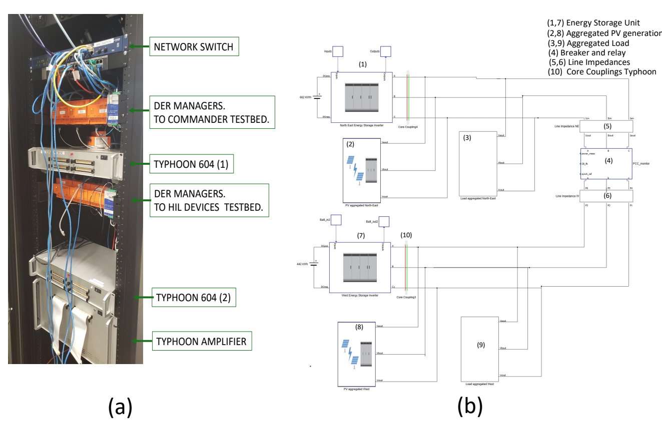

Fig. 6. (a) HIL testbed consisting of 2 Typhoon 604 working in parallel. (b) Simplified MG model with aggregated PV and loads.

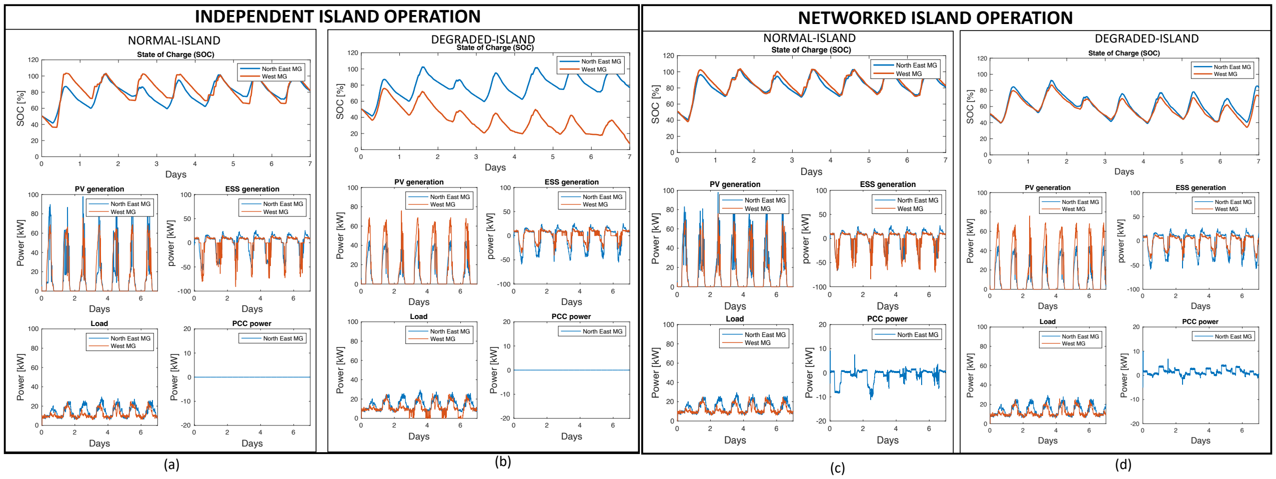

Fig. 7. HIL testing results for (a) normal-islanded, independent operation, (b) degraded-islanded, independent operation, (c) normal-islanded, networked operation mode, and (d) degraded-islanded, networked operation mode.

VI. Conclusion and Future Work

This paper proposed a network microgrid orchestrator designed to increase the energy resiliency of two MGs located in the town of Adjuntas, Puerto Rico. The microgrid orchestrator is designed to coordinate the operation of these two independent MGs, achieving higher resiliency during emergency operation. A distributed optimization approach was implemented in the microgrid orchestrator due to its superior scalability and data privacy. The CHIL results showed that the network of MGs can significatively enhance the islanded operation during contingency by sharing resources such as PV generation and energy storage systems. End-user loads of the affected MG can be supported by importing power from the adjacent microgrid, reducing load shedding and/or extending the sustained period.

Acknowledgment

We express our sincere gratitude to Dr. Arturo Massol, the executive director of Casa Pueblo de Adjuntas, and Cynthia Arellano, the project manager at the Honnold Foundation, for their contributions and dedication in bringing this community microgrid project to life.

References

[1] N. Kishore et al., "Mortality in Puerto Rico after Hurricane Maria," N Engl J Med, vol. 379, no. 2, pp. 162–170, Jul. 2018, doi: 10.1056/NEJMsa1803972.

[2] United States Environmental Protection Agency (EPA). "Learn About Impacts of Diesel Exhaust and the Diesel Emissions Reduction Act (DERA)." Accessed June 13, 2023. URL: https://www.epa.gov/dera/learn-about-impacts-diesel-exhaust-and-diesel-emissions-reduction-act-dera

[3] Casa Pueblo. https://casapueblo.org (Accessed: Jun, 13, 2023).

[4] Walle, P. (2020) *Press release: Casa Pueblo and acesa are transforming adjuntas into the first 'pueblo solar'*, *Honnold Foundation*. Available at: https://www.honnoldfoundation.org/news/press-release-casa-pueblo-and-small-business-owners-advance-their-vision-of-transforming-the-town-of-adjuntas-into-the-first-pueblo-solar (Accessed: 13 June 2023).

[5] Y. Guan, B. Wei, J. M. Guerrero, J. C. Vasquez, and Y. Gui, "An overview of the operation architectures and energy management," *iEnergy*, 2022, doi: https://doi.org/10.23919/IEN.2022.0035.J.

[6] Yeh H, Gayme DF, Low SH. "Adaptive VAR control for distribution circuits with photovoltaic generators," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp.1656–1663, Aug. 2012.

[7] J. A. Villanueva-Rosario, F. Santos-Garc´ıa, M. E. Aybar-Mej´ıa, P. Mendoza-Araya, and A. Molina-Garc´ıa, "Coordinated ancillary services, market participation and communication of multi-microgrids: A review," *Appl. Energy*, vol. 308, p. 118332, 2022.

[8] Zou, H.; Mao, S.; Wang, Y.; Zhang, F.; Chen, X.; Cheng, L. A Survey of Energy Management in Interconnected Multi-Microgrids. *IEEE Access* **2019**, *7*, 72158–72169.

[9] Islam, M.; Yang, F.; Amin, M. Control and optimisation of networked microgrids: A review. *IET Renew. Power Gener.* **2021**, *15*, 1133–1148

[10] Xie, H.; Wang, W.; Wang, W.; Tian, L. Optimal Dispatching Strategy of Active Distribution Network for Promoting Local Consumption of Renewable Energy. *Front. Energy Res.* **2022**, *10*, 826141.

[11] Liu, G.; Moorthy, R.S.; Choi, J.; Chinthavali, M.S. Linearised three-phase optimal power flow for coordinated optimisation of residential solid-state power substations. *IET Energy Syst. Integr.* **2021**, *3*, 344–354.

[12] Haghifam, S.; Najafi-Ghalelou, A.; Zare, K.; Shafie-khah, M.; Arefi, A. Stochastic bi-level coordination of active distribution network and renewable-based microgrid considering eco-friendly compressed air energy storage system and intelligent parking lot. *J. Clean. Prod.* **2021**, *278*, 122808.

[13] Liu, G.; Xu, Y.; Tomsovic, K. Bidding Strategy for Microgrid in Day-ahead Market based on Hybrid Stochastic/Robust Optimization. *IEEE Trans. Smart Grid*

[14] Rahbar, K.; Chai, C.C.; Zhang, R. Energy cooperation optimization in microgrids with renewable energy integration. *IEEE Trans. Smart Grid* **2018**, *9*, 1482–1493.

[15] Malekpour, A.R.; Pahwa, A. Stochastic networked microgrid energy management with correlated wind generators. *IEEE Trans. Power Syst.* **2017**, *32*, 3681–3693.

[16] G. Liu, T. B. Ollis, M. F. Ferrari, A. Sundararajan, and K. Tomsovic, "Robust scheduling of networked microgrids for economics and resilience improvement," *Energies*, vol. 15, no. 6, Article ID, 2249, 2022.

[17] Liu, G.; Ferrari, M.F.; Ollis, T.B.; Sundararajan, A.; Olama, M.; Chen, Y. Distributed Energy Management for Networked Microgrids with Hardware-in-the-Loop Validation. *Energies* **2023**, *16*, 3014. https://doi.org/10.3390/en16073014