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Resiliency Enhancement of Networked DC Microgrids through a Decentralized Energy Management System

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***Abstract*—Power systems are evolving from centralized power grid structures to a network of intelligent microgrids (MGs) that can share power more independently. The interconnection between these MGs, forming the networked MGs (NMGs), will increase the power system's stability and expand its capabilities. However, a critical concern that necessitates sophisticated management strategies for voltage stabilization across the microgrids is the optimal and effective power sharing between renewable resources and energy storage devices. This paper introduces a decentralized energy management system (EMS) based on primary and secondary control levels for a system of NMGs. In the primary control level, the local controller controls the local sources within each microgrid to satisfy the load demand, the standard operating limits of sources, and the charging/discharging processes of local Energy Storage Systems (ESSs). The secondary control level will only interact when the load demand increases, or the general load connected to a common bus goes beyond a particular value. The decision will determine each MG's contribution according to their available capacities. Several study cases were created to test and verify the proposed EMS with different load demands. The simulation results supported by the hardware-in-the-loop implementation emphasize the efficacy of the proposed EMS.**

***Keywords*— Energy Management Systems, Microgrids, Networked Microgrids, Renewable Energy Systems.**

I. Introduction

Microgrids (MGs) have primarily been used to supply standalone loads in emergencies or main utility outages. While pursuing sustainable and carbon-free resources, they gradually witnessed a high penetration of renewable energy resources such as wind and photovoltaic systems, which rely on utilizing power electronic converters to maximize their generated power. However, due to their intermittent nature, incorporating energy storage systems (ESSs) to compensate for the unpredictable absence of generation is mandated. The widespread integration of these distributed energy resources (DERs) has dramatically changed the infrastructure of traditional power networks, leading to what is known as decentralized energy systems, which consequently collide with multiple challenges [1,2]. For instance, low inertia incorporated with these inverted-based systems can negatively affect the system's reliability and stability under severe operation scenarios. Additionally, uncoordinated utilization of the ESS can result in insufficient available energy, which is unacceptable with some load types, such as constant power loads (CPL) [3]. Moreover, in some circumstances, the imbalance between generation and load demand might result in load-shedding or even generation curtailment, which is not economically feasible. To address these technical issues, clustering these MGs together to build networked microgrids is considered a promising solution [4].

The main objectives of NMGs are to expand system capabilities by scavenging power from scattered resources, increase system stability, balance the state of charge (SoC) of the ESS, and enhance network resilience against contingency events by facilitating the coordination between these aggregated resources and the load demands. To achieve this goal, various data are needed, including but not limited to the capability of each resource, local current and voltage measurements, the capacity of the ESS and its SoC, and the prospective demand load. However, the control capacity needed for manipulating this consequence data might exceed the available computational burden for a single centralized controller [5].

Different control structures were introduced to facilitate these data manipulations, especially when the NMG system grew larger. Part of that is to provide a communication link between these distributed agents to minimize the required processing time and enhance the decision-making results. Distributed and hierarchical control systems are well-known architectures for systems that rely highly on a reliable communication network for exchanging data among appropriate controllers [5]. However, these communication networks are prone to different cyber threats, such as man-in-the-middle (MITM) and false data injection (FDI) attacks, which mandate additional capabilities to detect and mitigate these threats. Moreover, the continuity of these data could be affected by other technical issues related to the communication network itself, for instance, bandwidth limitations and communication delays, which might lead to catastrophic failure of the entire system [6].

Decentralized controllers are considered the optimum solution because they can handle a certain number of

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networked MGs with minimal or no communication burdens. Although droop control is one of the most common techniques to share power between NMGs [7], its low transient performance and neglect of load dynamics limit its utilization [8]. Other management approaches were introduced, including a two-stage algorithm to manipulate the data within the MGs at the first stage according to forecasted scenarios. In contrast, the second stage adapts the MG's output power according to the load demands, necessitating historical data availability and well-trained data-driven models to achieve accurate forecasting [9]. In [10], the authors proposed another two-level hybrid energy management system to figure out the transactive energy throughout MGs while considering the surplus and shortage energy periods by varying the generated power up and down to reach the optimal energy level. The main drawback of this method is the repeated waste of energy in each optimization cycle to reach the desired point, in addition to the inaccurate control signals at the MG level, which can't be granted for later decisions. Model predictive control (MPC) [11], multi-agent systems (MAS) [12,13], and consensus algorithms [14] are also introduced as promising solutions for large-scale NMGs. However, additional complexity and computational burdens will be added to the EMS due to the needed optimization process, which will be reflected in a larger time per decision.

The main contribution of this work is to introduce a novel decentralized energy management system-based hardware implementation for DC NMGs incorporating two control levels toward enhancing resiliency during normal and pulsed load scenarios, in addition to balancing the available capacity within the energy storage systems in each MG to raise system stability against any disturbances. The rest of this paper is organized in the following way: Section II covers the proposed architecture in detail, the rated capacity of each resource, and the load profiles for each MG. Section III presents the proposed EMS in detail, and Section IV introduces the simulation results. The hardware implementation is covered in Section V and ends with the conclusion in Section VI.

II. Proposed Architecture

As mentioned earlier, the MG architecture used in this study is a networked microgrid (NMG), which consists of multiple interconnected MGs over a broader area. It is essential to realize that the NMG architecture is designed so that the MGs within the network may operate in islanded, and networked modes, depending on the requirements and conditions. Moreover, the NMG structure provides networking and interconnection between multiple microgrids, adding a layer of flexibility, efficiency, and resilience. It allows for optimizing the generation of assets across the entire network. Most importantly, NMG can reroute power and support each other during emergencies. On the other hand, in faulty conditions, MGs inside the NMG can operate independently as isolated systems without intertwining with other microgrids in the vicinity.

Figure 1 illustrates that the NMG consists of three interconnected microgrids (MG1, MG2, and MG3) with a common bus voltage of 100 volts DC. Each MG is comprised of energy-generating units, energy storage units, and local loads. Moreover, NMG has a central load that the MGs share. Dynamic pulsed load characteristics are included in the common load profiles for each MG and the common load to construct versatile load scenarios. The pulsed load is used to mimic a surge of current requirements in short bursts or pulses over a short period. Typical pulsed load applications include EV charging, military weapons, food processing, arc cutting, and water treatment, to name a few.

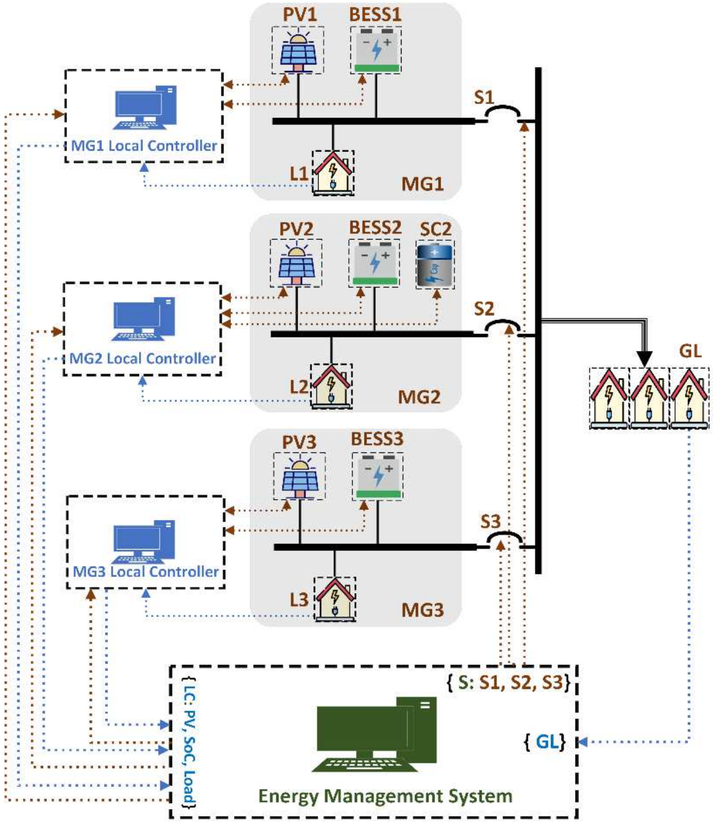

Fig. 1. Proposed NMGs architecture.

TABLE I. Parameters of the NMG

Parameter	Unit	MG1	MG2	MG3
Bus Voltage	V	100	100	100
Power Generation (PV)	W	360	360	360
Li-ion Battery	V, Ah	51.2, 20	51.2, 20	51.2, 20
Supercapacitor	V, F	-	64.8, 58	-
Load Range	W	340 – 440	340	340 – 480
Common Load	W	0 – 2000		

MG1 contains 360W solar PV for power generation and a 51.2V, 20Ah lithium-ion battery (LIB) for energy storage. Moreover, the local loads are variable, ranging from 340W to 440W. Similar to MG1, MG2 consists of 360W solar PV for power generation; however, MG2 has two different energy storage units: a 51.2V, 3Ah lithium-ion battery, and a 58F, 64.8V supercapacitor (SC) for energy storage and pulse load impact reduction. MG2 is the slack bus of this NMG. Although it serves a 340W constant load, the supercapacitor supplies power to meet sudden changes, demand, and pulsed load requirements. Identical to the MG1, the MG3 is comprised of 360W solar PV for power generation and a 51.2V, 20Ah lithium-ion battery for energy storage. However, the local load varies from 340 W to 480 W. In addition, a shared or central load of up to 2 kW maximum demand at the common busbar. Table I summarizes the parameters of the NMG, while Fig. 2 presents the utilized irradiance and load profiles for each MG. The loads have the characteristics of high dynamics, periodicity, and uncertainty.

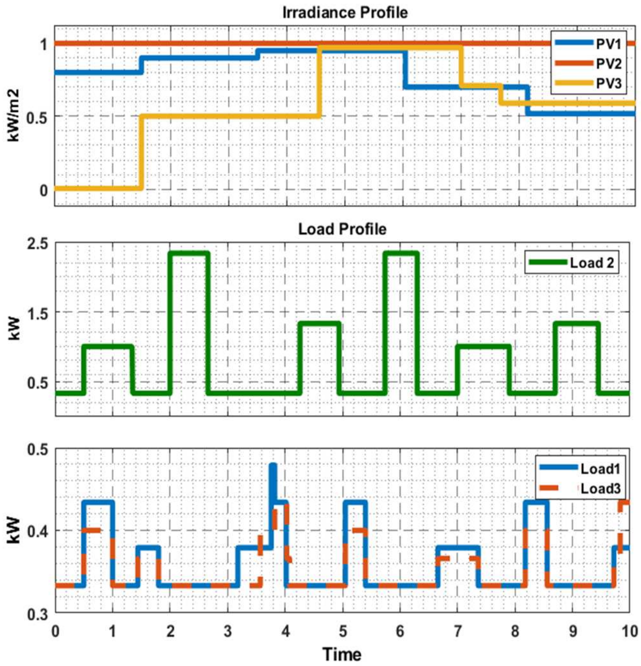

Fig. 2. PV generation and load profiles

The control of the presented NMG is implemented through hierarchical control systems operating at the microgrid/primary and secondary levels. At the MG level, DC-DC converters implement advanced voltage and current control loops to control the power flow and exploit the distributed energy resources to balance generation and load. In the case of the study, MG2 is used as the slack generation, which optimizes and maintains the DC bus voltage. At the top secondary control level, master controllers coordinate power transfer between the multi-terminal NMG. Moreover, they optimize the power flow for cost-effective operation for large-scale NMG deployments in terms of efficiency, scalability, and resilience. Furthermore, secondary controllers facilitate NMG, where MGs can support each other during islanding events. This hierarchical control scheme allows plug-and-play integration of DC microgrids into smart DC distribution grids by combining decentralized device control with centralized optimization and supervisory coordination.

III. Decentralized Energy Management System

In this paper, the proposed energy management systems employ only the available capacity of each PV system to handle the shared power from each resource. The electric network can be modeled as a undirected connected graph with possible DGs and connected loads. For a system of DC NMGs of n buses, the power flow through the DC MGs can be calculated as follows:

$$P_i = V_i \sum_{j=1}^{n} \frac{(V_i - V_j)}{R_{ij}} + P_{Li} \quad (1)$$

where R_{ij} is the resistance between any two nodes in the network, while V_i, P_i, and P_{Li} are the voltage, DG's output power, and the load power at the given bus i, respectively. Such systems typically include different kinds of loads, like constant impedance (P_{Li}^{Z}) and constant power (P_{Li}^{P}) loads. Hence, the total load power of any bus can be defined as:

$$P_{Li} = P_{Li}^{Z} + P_{Li}^{P} = \frac{V_i^2}{R_{ij}} + P_i' \quad (2)$$

By substituting (2) into (1), yields,

$$P_i = V_i \sum_{j=1}^{n} \frac{(V_i - V_j)}{R_{ij}} + \frac{V_i^2}{R_i} + P_i' \quad (3)$$

During the power-sharing mode among the NMGs, this much power will be surplus in one or more of the MGs to supply the gap in another MG. The proposed EMS, consisting of two control levels (primary and secondary), works concurrently to enhance the system's resilience by coordinating the aggregated resources under specific operation scenarios. At the primary level, local controllers handle and enhance the robustness of each MG separately by stabilizing its local DC bus voltage and mitigating the pulsed load impacts within its local zone. The secondary control level allows power sharing between the NMGs when certain needs are met during normal and abnormal conditions. To makes the proper decision, the proposed algorithm is designed to classify the total load demand into three levels: minor, median, and critical. This classification is based on the maximum expected generation from the PV systems. Several events were created to test and verify the proposed EMS with different load demands, whereas the PV generation varied identically to the daily normal irradiance variation.

Algorithm 1: Proposed Energy Management System (EMS)

```
Initialize MGs controller and EMS parameters.
Read PV and Local loads in each MG.
for i = 1
  Compute P_L = Σ Lj    where  j=1, 2, 3
    if P_L > 2 kW      "Critical"
      MG1 = MG3 = 1.
    else if 1.2 kW < P_L ≤ 2 kW     "Median"
      Select the MG with a higher PV.
    else if P_L ≤ 1.2 kW             "Minor"
        if SoC2 ≥ 80%
          MG1 = MG3 = 0
        else
          Select MG with higher PV.
    else
      MG1 = MG3 = 0.
end for
```

IV. Simulation Results

Through this study, the rated capacity for all the PV systems is similar, and they all operate in MPPT mode. Therefore, the irradiance profile will directly reflect the generated power from each PV system. Further, the goal is to keep the DC bus voltage fluctuation less than the recommended 5% during all pulsed load portions. This section introduced six main events to test the proposed EMS under variable generation and load profiles.

A. Events 1 and 5

Starting with the minor load condition, the proposed EMS in this case, should check the state of charge (SoC) of BESS2. During these two events, the SoC condition is achieved. Hence, the load demand in these cases is fully covered by MG2, as shown in Fig. 3. This appears clearly in the shared power results.

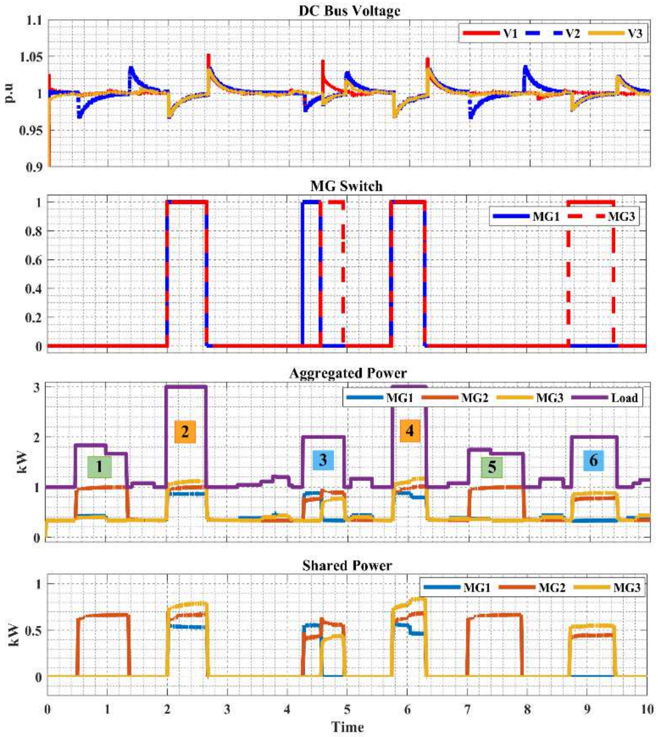

Fig. 3. Simulation results.

B. Events 3 and 6

In these events, the EMS is switched into another load category defined as median. In this case, the selection will be based on the MG with the highest PV generation. During event 3, there is an immense increase in PV3's generation, which presents a change in the coming power between MG1 and MG3. It also appears during event 6 with the existence of MG2 and MG3 since the power coming from PV3 is higher than from PV1, as shown in Fig. 3.

C. Events 2 and 4

According to the proposed EMS, at the highest load demand, all the MGs must collaborate to meet the load demand with no certain limitations. During these two events, the three MGs collaborated to supply the critical load demands. However, there is a difference between the shared power of each resource during these events. For instance, the generated power from PV1 is more significant than that from PV3 during event 2. Nonetheless, the selection criteria for MGs are not available in this critical case where all the resources, regardless of their operating conditions, must share the load under this operating condition. It is worth mentioning that in between these events, the proposed EMS was noticeably able to balance the distributed resources by allowing power sharing during the lower load demand portions, as shown in Fig. 3, which is the main goal of NMGs, as stated in the introduction section.

V. Hardware Implementation

After the proposed EMS was tested and verified through MATLAB/Simulink, the next phase is to validate the results through hardware implementation utilizing the smart grid testbed at the energy systems research laboratory at FIU, as shown in Fig. 4. The two MGs, each composed of a 6kW PV emulator, are connected to their local 50V DC bus through a DC/DC boost converter. Further, 12V/100Ah LIBs are attached to the DC bus through a DC/DC bidirectional converter to allow the charging and discharging of the batteries. The two MGs are clustered around a common DC bus. The load profile at each MG, in addition to the shared load at the common DC bus, is summarized in Table II. The PV emulators are controlled through MPPT or conventional PI controllers according to their loading conditions. To be specific, if the load demands in MG1 and MG2 go beyond 200W and 100W, respectively, their boost converters will switch into MPPT modes. The typical V-P and I-P characteristics of each PV emulator are shown in Fig. 5.

At the same time, the batteries are used to stabilize the DC-bus voltage with outer and inner voltage and current control loops, respectively. The hardware-in-the-loop implementation was done through the dSPACE1104 platform at each MG to control the DC-DC converters. The load variations and interconnection between the two MGs are controlled through the dSPACE1104 using 5/250VDC–10A solid-state relays. The interconnection between the two MGs will occur when the load demand exceeds 350W, which is the scenario here from case two to case five. The hardware validation was done through five consecutive study cases, as shown in Fig. 6, based on the loading conditions given in Table II.

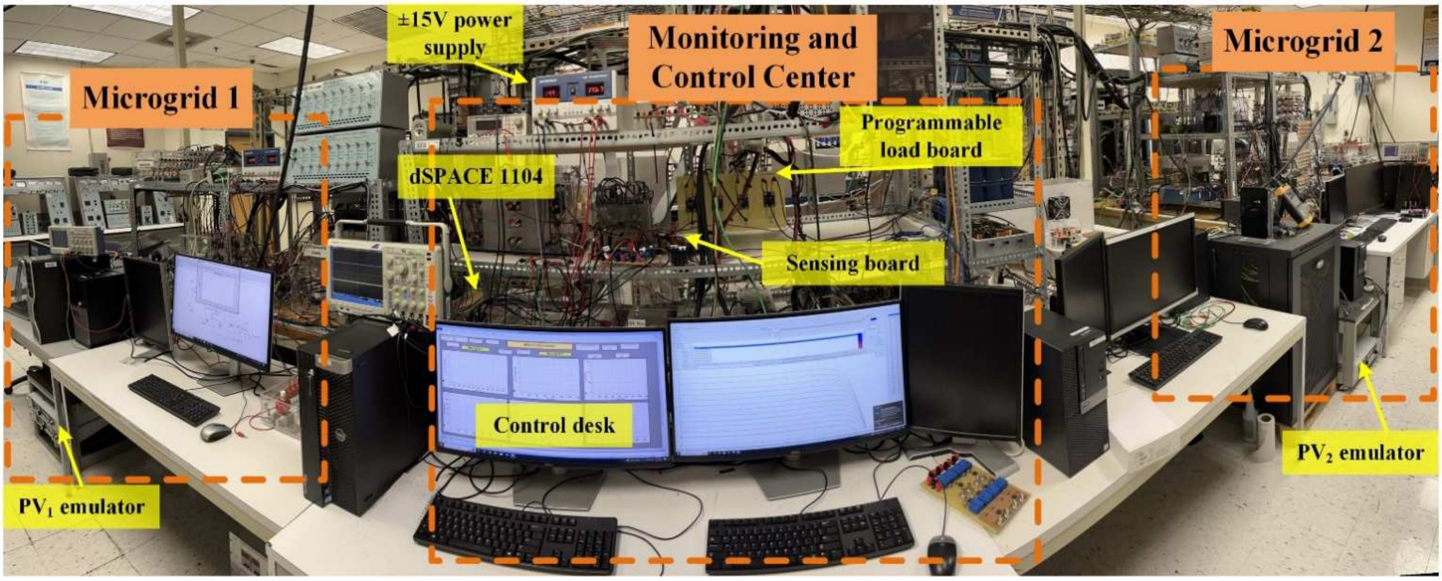

Fig. 4. NMG at the ESRL testbed.

TABLE I. SUMMARY OF THE EXPERIMENTAL CASES

Cases	Load demand (W)		
	MG1	Common load	MG2
Case 1	125	40	80
Case 2	250	40	80
Case 3	250	40	150
Case 4	250	80	150
Case 5	125	80	150

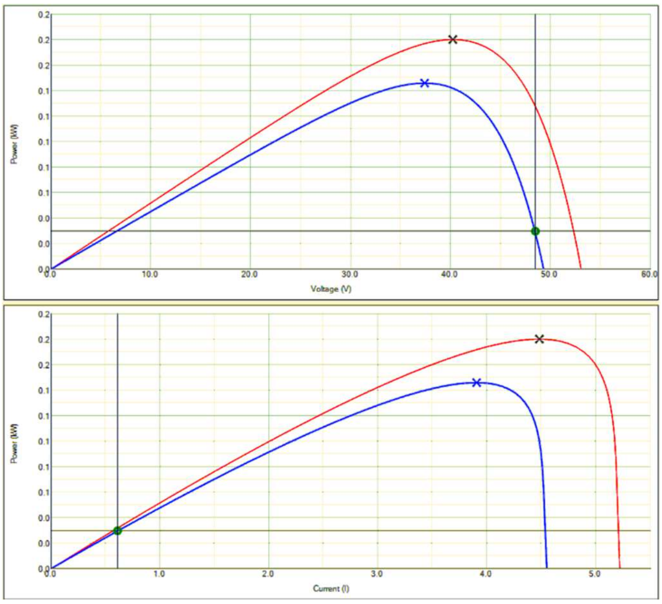

Fig. 5. PV voltage and current profiles vs. power (red:PV1, blue:PV2)

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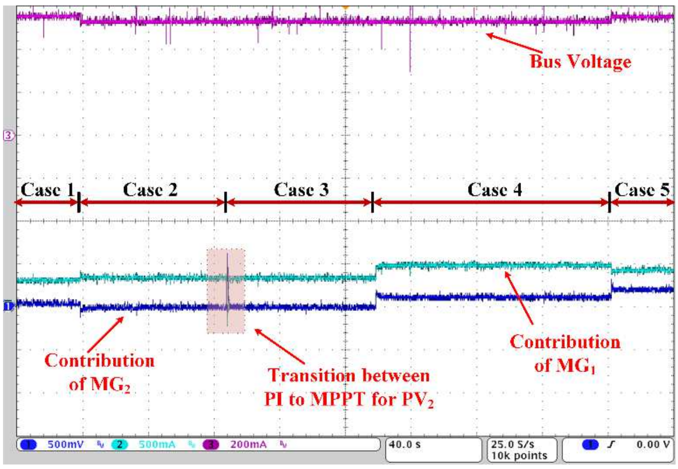

Fig. 6. Shared power for the common load

A. Case 1 (Initial state)

In this case, the PV emulators were controlled using traditional PI controllers. The generated power from PV1 and PV2 is 120W and 85W, respectively, while the rest comes from the BESSs, as shown in Fig. 7 and Fig. 8. As the MG1 is the slack bus through this work, the common load demand in this case is supplied from that MG, as shown in Fig. 6.

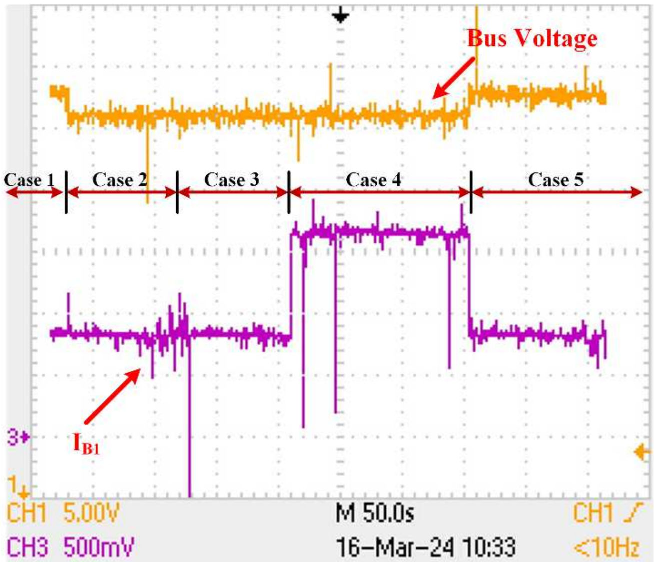

Fig. 7. Contribution of BEES1

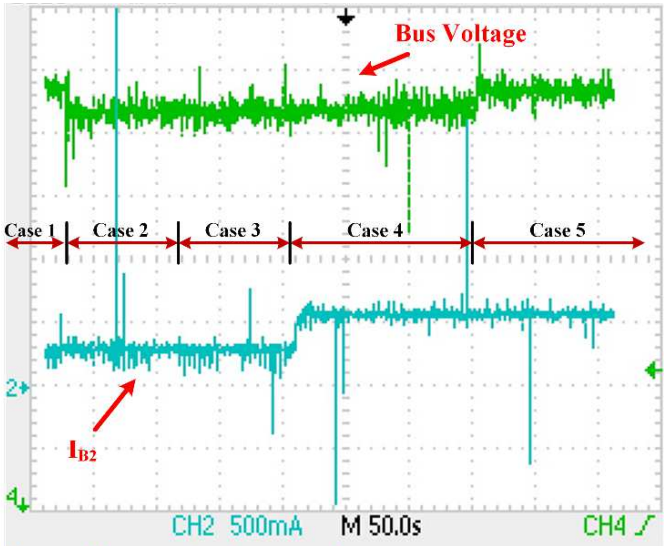

Fig. 8. Contribution of BEES2

B. Case 2: Increase in MG1 load

In the present case, the local load of MG1 is doubled. As mentioned previously, the local controllers are responsible for supplying their local loads, and further assistance from neighboring MG will occur when there is a lack of generation. Therefore, the PV1 controller is switched from PI to MPPT to supply the new demand. Hence, the generated power from PV1 went up to 200W. During this transition, there is a slight difference in the shared power shown in Fig. 6. This mainly occurred in weak microgrid systems due to voltage fluctuations. That reduction in the bus voltage is clearly visible in Fig. 6, which is within the acceptable ± 5% standard deviation limits.

C. Case 3: Increase in MG2 load

Similar to case 2, the load demand in MG2 increased by around 90%. Consequently, PV2 switched into MPPT with a new generating power of 155W. This transition appeared as highlighted in Fig. 6. It's clearly visible through cases one up to three that there are no changes in BESS1 and BESS2, as shown in Fig. 7 and Fig. 8, respectively. This emphasizes that the load demand is fully covered by the new PV generated power in each MG.

D. Case 4: Variation in the common load

In this instance, we reached the point where all the PV systems generated their maximum allowable power. Hence, the energy storage systems must cover any additional load demands. In this case, the common load is doubled. The contribution of BESS1 and BESS2 to supply that load is shown in Fig. 7 and Fig. 8, respectively. Even though the system during this study case is experiencing the highest load demand compared to case 1, the BESSs can stabilize the DC bus voltage within the recommended fluctuation levels.

E. Case 5: reduction in MG1 load

In the current case, the local demand in MG1 is reduced. Therefore, the PV1 will be switched back into PI mode. This reduction in the PV1 generation can be seen clearly in Fig. 6. However, the total generated power in MG2 includes the PV and the BESS, which are still constant, as shown in Fig. 8. This power will cover the requested demand for the common load, as shown in Fig. 6. This was easily achieved through the recovery of the bus voltage during this case study.

CONCLUSION

The primary goals of NMGs are to extend system capacities by scavenging power from distributed resources, boost system stability, balance energy storage devices' capacities, and improve network resilience against contingency occurrences. This work presents a decentralized energy management architecture utilizing primary and secondary control levels to manipulate the operation of DC NMGs during typical and pulsed load operation scenarios. The proposed management architecture handled the shared power efficiently among the NMGs through six different simulation-based operation events, witnessing different and dynamic load and generation variations. Furthermore, the provided energy management system was tested and validated through the hardware implementation of two interconnected MG systems in five different cases. The suggested EMS can manage the operation of local resources toward meeting their local demands while stabilizing the DC bus voltage even during extreme load fluctuation instances.

REFERENCES

[1] M. H. Saeed, W. Fangzong, B. A. Kalwar and S. Iqbal, "A Review on Microgrids' Challenges & Perspectives," in IEEE Access, vol. 9, pp. 166502-166517, 2021, doi: 10.1109/ACCESS.2021.3135083.

[2] M. S. Abdelrahman, H. Hussein and O. A. Mohammed, "Rule-Based Power and Energy Management System For Shipboard Microgrid With HESS To Mitigate Propulsion and Pulsed Load Fluctuations," 2023 IEEE Green Technologies Conference (GreenTech), Denver, CO, USA, 2023, pp. 224-228, doi: 10.1109/GreenTech56823.2023.10173813.

[3] Hussein, Hossam M., Mustafa Esoofally, Abhishek Donekal, SM Sajjad Hossain Rafin, and Osama Mohammed. "Comparative Study-Based Data-Driven Models for Lithium-Ion Battery State-of-Charge Estimation." Batteries 10, no. 3 (2024): 89.

[4] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab and Y. Al-Turki, "Networked Microgrids for Enhancing the Power System Resilience," in Proceedings of the IEEE, vol. 105, no. 7, pp. 1289-1310, July 2017, doi: 10.1109/JPROC.2017.2685558.

[5] Hussein, Hossam M., SM Sajjad Hossain Rafin, Mahmoud S. Abdelrahman, and Osama A. Mohammed. "Hardware Implementation of a Resilient Energy Management System for Networked Microgrids." World Electric Vehicle Journal 15, no. 5 (2024): 209.

[6] Q. Zhou, M. Shahidehpour, A. Paaso, S. Bahramirad, A. Alabdulwahab and A. Abusorrah, "Distributed Control and Communication Strategies in Networked Microgrids," in IEEE Communications Surveys & Tutorials, vol. 22, no. 4, pp. 2586-2633, Fourthquarter 2020, doi: 10.1109/COMST.2020.3023963.

[7] Y. Fu, Z. Zhang, Y. Mi, Z. Li and F. Li, "Droop Control for DC Multi-Microgrids Based on Local Adaptive Fuzzy Approach and Global Power Allocation Correction," in IEEE Transactions on Smart Grid, vol. 10, no. 5, pp. 5468-5478, Sept. 2019, doi: 10.1109/TSG.2018.2883559.

[8] Mehrizi-Sani, A. "Distributed control techniques in microgrids." microgrid (2017): 43-62.

[9] Z. Wang, B. Chen, J. Wang and J. kim, "Decentralized Energy Management System for Networked Microgrids in Grid-Connected and Islanded Modes," in IEEE Transactions on Smart Grid, vol. 7, no. 2, pp. 1097-1105, March 2016, doi: 10.1109/TSG.2015.2427371.

[10] Jani, Ali, Hamid Karimi, and Shahram Jadid. "Hybrid energy management for islanded networked microgrids considering battery energy storage and wasted energy." Journal of Energy Storage 40 (2021): 102700.

[11] A. Parisio, C. Wiezorek, T. Kyntäjä, J. Elo, K. Strunz and K. H. Johansson, "Cooperative MPC-Based Energy Management for Networked Microgrids," in IEEE Transactions on Smart Grid, vol. 8, no. 6, pp. 3066-3074, Nov. 2017, doi: 10.1109/TSG.2017.2726941.

[12] A. El Zerk, M. Ouassaid and Y. Zidani, "Multi-agent System for Decentralized Energy Management Approach in Collaborative Microgrids," 2020 IEEE 7th International Conference on Engineering Technologies and Applied Sciences (ICETAS), Kuala Lumpur, Malaysia, 2020, pp. 1-6, doi: 10.1109/ICETAS51660.2020.9484325.

[13] Keshta, H. E., A. A. Ali, E. M. Saied, and F. M. Bendary. "Real-time operation of multi-micro-grids using a multi-agent system." Energy 174 (2019): 576-590.

[14] K. P. Schneider et al., "A Framework for Coordinated Self-Assembly of Networked Microgrids Using Consensus Algorithms," in IEEE Access, vol. 10, pp. 3864-3878, 2022, doi: 10.1109/ACCESS.2021.3132253.