

Multi-microgrids system's resilience enhancement

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ABSTRACT

Nowadays, electricity consumption is increasing rapidly which leads to conventional power systems exhaustion. Therefore, micro-grids (MGs) implantation can enhance the resilience of power systems by implication of new resources, such as renewable energy sources (solar panel and wind power systems), electric vehicles (EV), and energy storage systems (ESS). This paper proposes a new strategy for optimal power consumption inside one microgrid; then, the approach will be extended to optimize the power consumption to enhance the resilience in the case of multi-MGs systems. The system controller of each microgrid has been implemented using ESP32 microcontroller and Raspberry IP4. The proposed approach intends to enhance the resilience of the system to react to any contingency in the system such as loss of power linkage between MG and the network in case of any natural disaster, especially in the rural area. Two controllers are implemented; the first one ensures MG autonomy by the efficient use of its own sources. The second one handles the system resilience cases by demanding/delivering power from/into neighbor microgrids. Hence, this work enhances the system resilience with an optimal cost. Thus, the MG can offer ancillary services for the neighboring MGs.

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1. INTRODUCTION

As digital technologies continue to advance, the concept of a smart grid has gained prominence. A smart grid builds upon the foundation of microgrids (MGs) by incorporating advanced communication, monitoring, and control systems. This intelligent system enables real-time monitoring, management, and integration of electricity flow to improve efficiency, reliability, and cost-effectiveness. Today's globe is more aware of renewable energy sources due to the scarcity of electricity, rising fuel costs, and negative environmental repercussions of conventional energy sources [1]. Especially, in remote or rural areas, where the power grid infrastructure is often limited, unreliable, and expensive to maintain, stand-alone MGs provide a reliable and sustainable energy solution [2], [3].

A MG can operate in two different modes: islanded, when it can run autonomously, and grid-connected in case it runs non-autonomously [4]. In the grid-connected mode, MGs are linked to the conventional grid; whereas, in the islanded mode, electricity from the main grid is disconnected, and the MG relies solely on its available distributed energy resources (DERs) to meet demand; if demand exceeds generation, it must be reduced in case of flexible loads [5]. An efficient and adaptable control system for managing energy flows between power sources, loads, and the utility grid is named the energy management

system (EMS) [6]. In EMS for MG, several approaches are used, ranging from the employment of heuristic algorithms to the application of optimization techniques [7]-[9]. However, in some situations, reducing the load is very critical. Hence, the MG has to require extra power from its neighboring MGs; thus, involves a very high resilience [10].

Resilience refers to a power system's ability to meet demand in the face of an event with a high effect but a low possibility of occurring [11]. In this work, a MG with a demand exceeding its DERs supplied power must have a very high resilience factor. Consequently, it is called a MG in a resilience situation and referred by a Resilience Register equal to one and this will be explained in the paper context.

Several researchers are investigating MGs' technology advancement. They aim to propose effective concepts to ensure an efficient, consistent, and steady electricity delivery during the current transition era especially in decentralized grids [12]-[14]. Hence, the most important challenge is making these microgrids efficiently cooperate and exchange power in case of system resilience [15]. Hence, this paper addresses this issue to smooth the progress of the DES' implementation [16], [17]. The principle of the multiagent system (MAS) has gained more use in recent years even for the management of centralized power systems or of the decentralized management and control strategy for distributed microgrids [18]-[20].

A renewable energy management system (REMS) is a gadget that monitors power in a microgrid. The goal of this system is to optimize power utilization generated by renewable energy, reducing power demand from the grid [21], [22]. However, due to the massive communication and computation requirements of linked power systems across a large region, it is challenging to implement a centralized REMS strategy. Though, the decentralized strategy necessitates a high level of coordination, which is made difficult by the availability of just local data when considering extended MGs [23]. Thus, a need for powerful MGs' REMS. Accordingly, our aim throughout this work is to implement a REMS, based on Raspberry PI4 board, able to optimize energy consumption in multiple systems and respond to the loads' dynamic changes in real time.

Therefore, this work starts by proposing a control strategy to allow one microgrid to operate independently and/or collaboratively with the other microgrids based on the MAS concept [24]. The microgrid used in this paper joins many distributed power sources and home loads. Then, each microgrid is considered a separate agent which cooperates with the other agents in our MAS. The proposed system architectures and their control strategy are explained in the second section. Whereas the obtained results and the evaluation of the proposed strategy are presented in the third section. Therefore, the paper is concluded in the fourth section with the proposition of some perspectives.

2. METHOD

This section explains the proposed energy management strategy grounded in multi-agent systems for multi-microgrids' collaboration. Through efficient coordination and resource sharing, microgrids can better handle power demand, ensure self-sufficiency, and enhance overall system resilience. This research showcases the potential for creating smarter, interconnected energy systems that are reliable and adaptable.

2.1. One microgrid system's power management

In the case of one microgrid agent, the controller manages load demand and ensures the system autonomy following the diagram shown in Figure 1. The solar panel being the power source is used to supply the load and charge the battery when it is enabled, the battery is used to supply the load when the solar panel is disabled; thus, the controller has two modes: charging and discharging. It controls the power going into the battery; it also stops power from running back into the photovoltaic (PV) arrays and prevents the battery from completely discharging or from overcharging as well by efficiently controlling its state of charge (SoC). The capacity to charge and discharge the battery at various voltage levels is one benefit of utilizing a bidirectional DC-DC buck-boost converter with a battery. The buck-boost converter functions as a buck converter when the PV array has surplus energy available; thus, the power flow route is from the DC bus to the battery bank in order to charge the battery with requested current. Whereas the buck-boost converter uses the current control feature to function as a boost converter during overcast conditions or at night; hence, the power flows from the battery bank to the DC bus and discharges the battery with requested current.

The proposed controller has been modelled in MATLAB Simulink. The controller compares different values of output power for all the primary platforms and then decides which one will be the best. The flowchart given in Figure 2 demonstrates the different states that can be executed by the controller. To apply this protocol in Simulink a series of measurements and comparison operations are performed. These operations result in Boolean control signals that are used to control ideal switches; each switch connects a power source to the grid. Table 1 defines the different controller inputs and outputs.

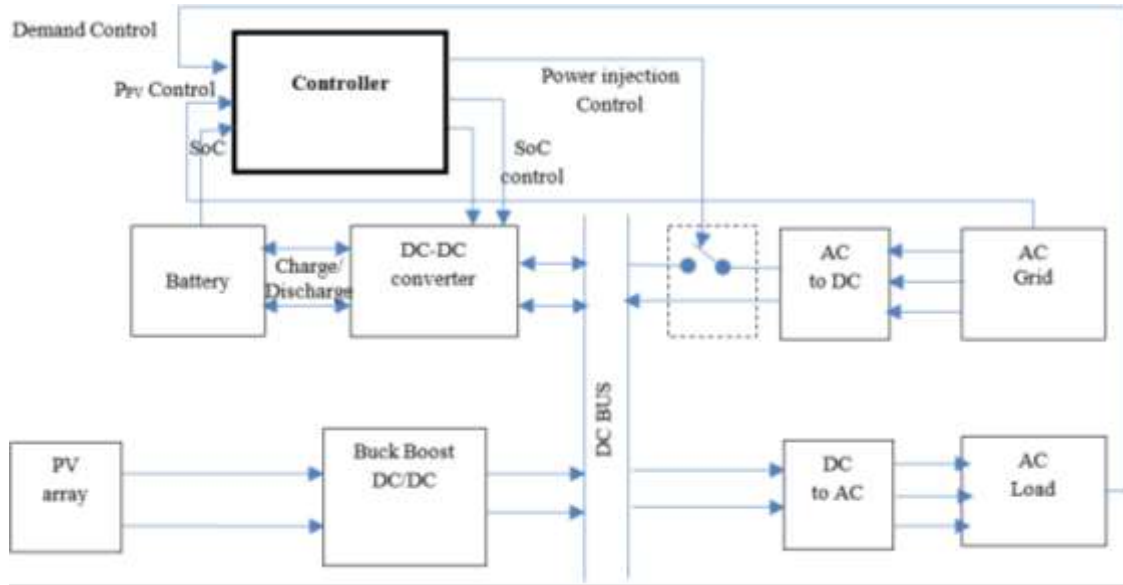


Figure 1. One microgrid controller scheme

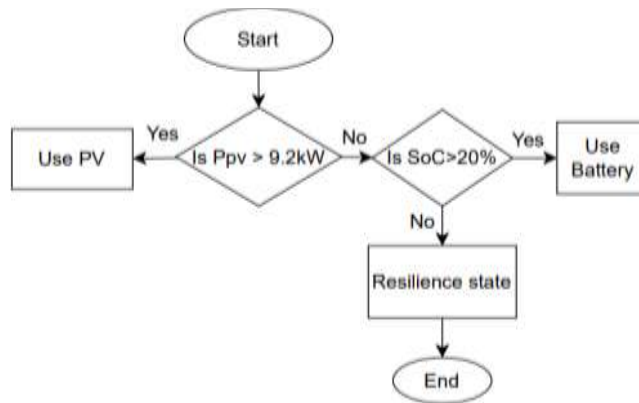


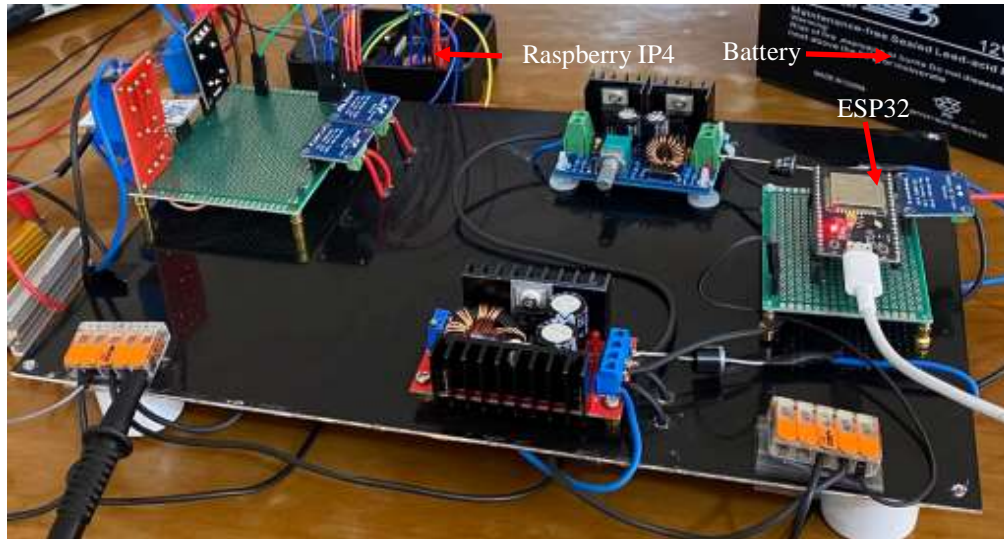
Figure 2. Flowchart describing the different states that can be executed by the microgrid’s controller

Table 1. Inputs and outputs of the controller

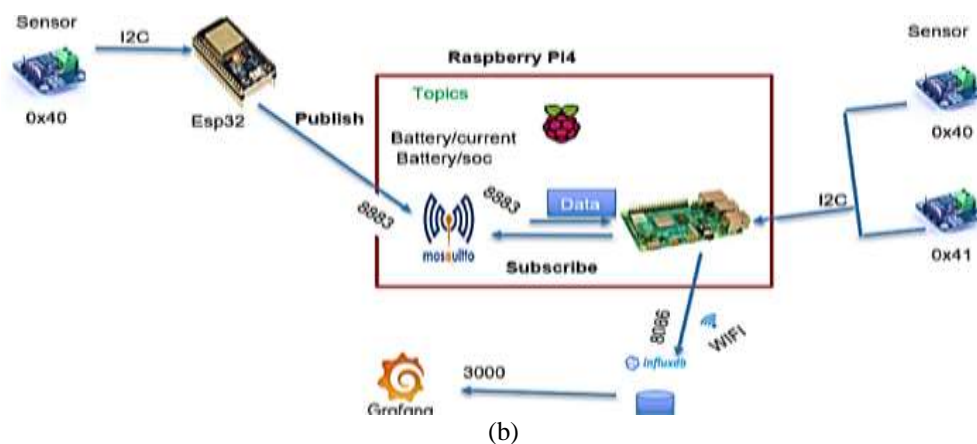
Inputs/Outputs	Description
P_pv	It represents the instantaneous power delivered from the PV array.
SoC	It represents the instantaneous SoC of the battery, recorded using the system implemented in our laboratory [25].
SurplusRegister	It represents the availability of Surplus power (in case the MG has produced extra power SurplusRegister state will be 1).
ResilienceRegister	It represents the state where the MG is in need for help from its neighbor MGs (MG in resilience situation in case ResilienceRegister=1).
MG response	Presents the response message of the MG to its neighbors.
PV_ESU	Control signal between PV and energy storage unit (Battery).
PV_load	Control signal between PV and MG’s load.
PV_extra_load	Control signal between PV and extra load from neighbor MGs.
ESU_load	Control signal between battery and load.

Figure 3 describes the realized prototype to control the system. For each microgrid, a controller system equivalent to the one shown in Figure 3(a) has been implemented and connected to the corresponding MG’s load, PV, battery, and to the other MGs. The primary purpose of the ESP32 is to read the initial open-circuit voltage (OCV) of the battery. It then proceeds to interpolate the data to obtain the initial SoC. After that, the ESP32 enters an infinite loop where it continuously calculates the SoC using the coulomb counting method. The calculated SoC is then published to the Raspberry Pi for further processing, as depicted in the flowchart given in Figure 2. ESP32 microcontroller is responsible for recording the status of the load and the

different power supplies inside the MG; moreover, it triggers the corresponding relay to switch between the appropriate sources. Furthermore, the relays are triggered by Raspberry Pi 4 commands enabling seamless transitions between the various MGs according to the communicated states of Surplus and Resilience registers as will be described in the coming section as shown in Figure 3(b).



(a)



(b)

Figure 3. Implemented microgrid controller system of (a) MG's controller system and (b) overall communication diagram

The communication starts with reading data from the sensor attached to an ESP32 microcontroller using the inter-integrated circuit (I2C) communication protocol. The sensor precisely measures the battery's current and voltage, and the resulting data is interpolated to calculate the battery's SoC. After acquiring the data, the ESP32 works as a message queuing telemetry transport (MQTT) client, publishing data wirelessly to the Raspberry Pi. The MQTT protocol [26], known for its lightweight and efficient nature, allows reliable connection between the ESP32 and the Raspberry Pi, and between the neighbor MGs [27]. The Raspberry Pi can also be used as a MQTT subscriber, subscribing to certain MQTT topics. When data is published to a subscribed topic, the MQTT broker accepts it and sends it to the Raspberry Pi subscriber. In addition to MQTT communication, two sensors, each with a unique address, are attached to the Raspberry Pi. These sensors read voltage and current data independently. The Raspberry Pi gathers all data and prepares it for transmission. An InfluxDB database is created to store and analyze the acquired data [28], [29]. The Raspberry Pi connects to WiFi and provides data to the InfluxDB database and to the other MGs. InfluxDB, which was created for the effective storing and structuring of time-stamped data, provides the seamless integration and retrieval of the acquired measurements. Grafana has been incorporated with the system to

provide a strong visualization and monitoring tool after the data has been securely saved in InfluxDB. Customized dashboards have been constructed using the Grafana web interface to display data in useful and visually appealing visualizations. The needed data was retrieved from InfluxDB in real-time by setting panels and queries within Grafana. This dynamic data retrieval allows users to obtain up-to-date insights and a comprehensive picture of the data.

2.2. Multi_microgrid system

In MAS, each device functions as an agent performing a specific task and communicating with other devices (agents). The MAS controller serves as a management or coordinating agent, facilitating communication and energy exchange among the microgrids. The MG requests help from the other MGs when the battery is depleted of power, and the solar panel is not generating electricity; thus, the load has to draw power from other MGs’ resources. In the case of MAS, the controller manages the power going into an agent with resilience status; it responds to the other agents in resilience once it has a surplus of power. Our proposed MAS autonomy is ensured by the implementation of the architecture illustrated in Figure 4.

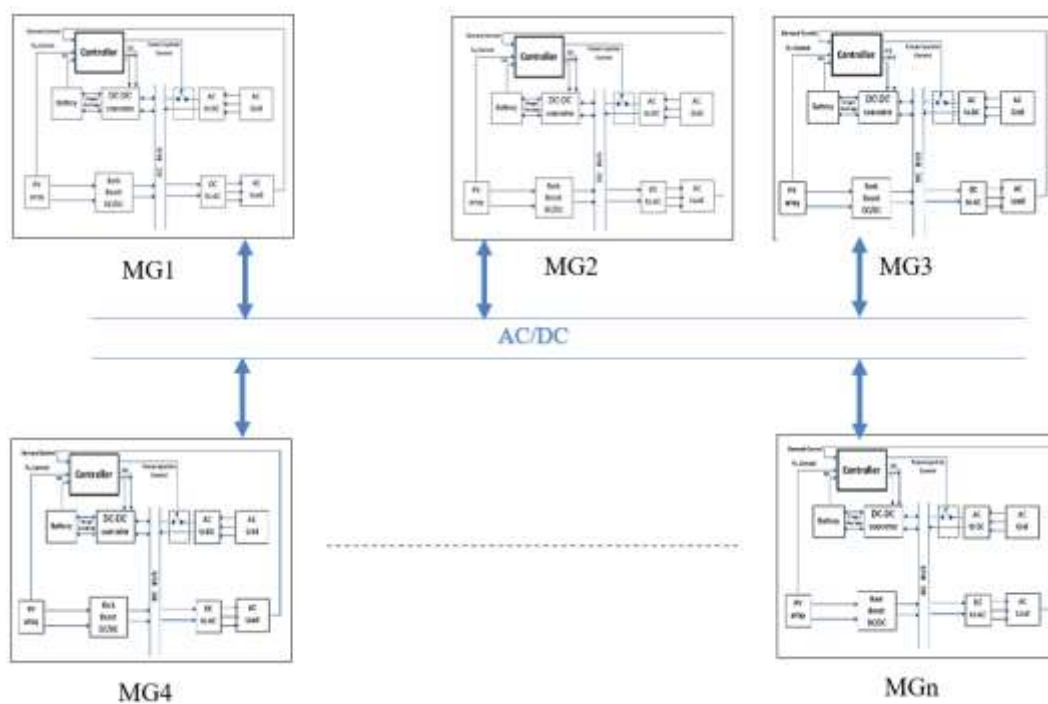


Figure 4. Multi-microgrids’ controller scheme

Initially, the two buffers indicating the presence of surplus/resilience of power are reset to zero (SurplusRegister=0 and ResilienceRegister=0). Once, a microgrid’s resources are not satisfying its load’s need, the ResilienceRegister is set to one. Therefore, the MG broadcasts a message expressing its need to the other MGs indicating (‘in need of PResilience=PLoad-PProduced’); with PResilience is the amount of the needed power. Algorithm 1 explains the process executed by the MG to indicate its state.

Algorithm 1. Definition of the MG situation (resilience/surplus)

```

SurplusRegister=0
ResilienceRegister=0
If PProduced>PLoad Then
    SurplusRegister=1
    ResilienceRegister=0
ElseIf PProduced<PLoad Then
    SurplusRegister=0
    ResilienceRegister=1
    Broadcast msg: 'in need of help for PResilience=PLoad-PProduced'
End if
    
```

The other MGs, with $\text{SurplusRegister}=1$, hear the message of the MG in resilience and respond by a message indicating ('I can help you with $\text{PSurplus}=\text{Pproduced}-\text{PLoad}$). Hence, the MG in resilience accepts the help of the first MG responding to it if the amount of the delivered power satisfies its need ($\text{PSurplus}>\text{Presilience}$) and stops the broadcast; otherwise, it keeps broadcasting a message indicating the amount of the missed power ($\text{Presilience}=\text{Presilience}-\text{Psurplus}$). This approach is summarized in the given Algorithm 2 with N indicating the number of MGs.

Algorithm 2. MGs' energy exchange

```

For i=1 to N
  If SurplusRegister i=1 Then
    PSurplus i=Pproduced i-PLoad i
    Respond to MGj (Microgrid in resilience) →'I can help you with PSurplus i'
    If MGj response = 'Accept' Then
      Transmit extra power to MGj
    Else
      Keep listening for other MGs broadcast
    End if
  Else if ResilienceRegister i=1 Then
    If PSurplus j>=Presilience i Then
      If MGj response = 'Accept' Then
        Get missed power from MGj
        Stop broadcast
      Else
        MGj response = 'Accept'
        Presilience i=Presilience i-PSurplus j
        Keep broadcasting to get morepower from other MGs
      End if
    End if
  End if
End for

```

3. RESULTS AND DISCUSSION

3.1. Single MG management

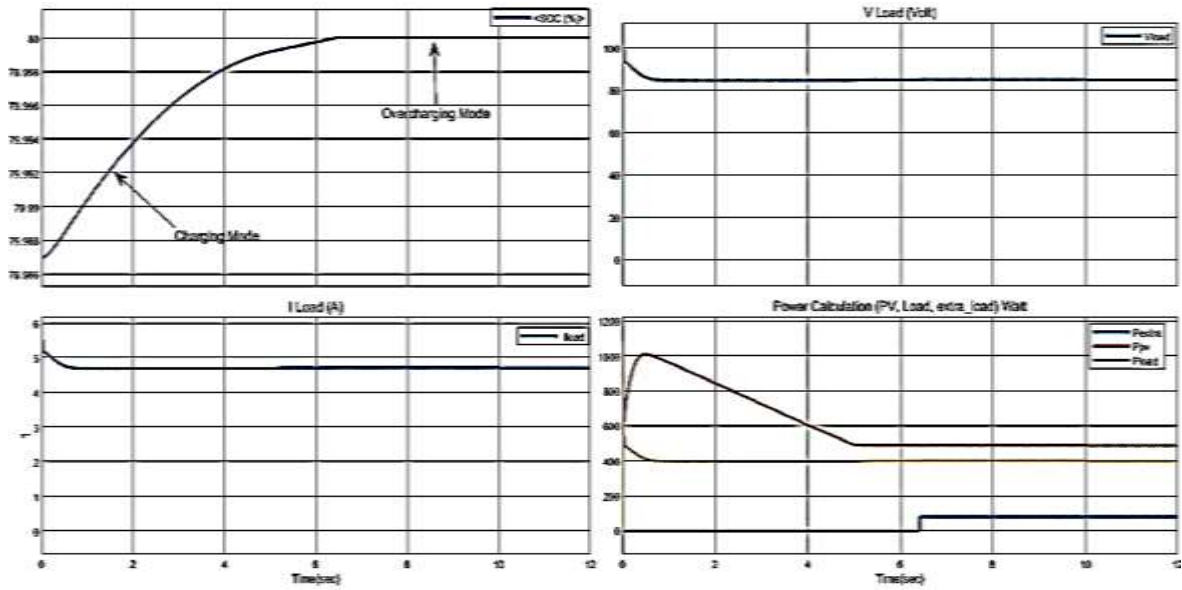
To evaluate the efficiency of the proposed approach, we started by testing a single MG behavior. Simulation results obtained from Matlab Simulink are given in Figure 5. Batteries are the first backup systems that store excess energy generated by PV. The first portion of Figure 5(a) depicts the battery's state of charge (SoC). To safeguard the batteries from damage, they were charged from 0% to a maximum of 80%.

During the period $[0 < t \leq 6.5]$, the PV system is exposed to sunlight, leading to an increase in irradiance. Consequently, the PV system generates power levels in the range of $400 \text{ W} \leq P_{pv} < 1,000 \text{ W}$, which is more than sufficient to meet the load's demand. By selecting the PV_load control signal, the power generated by the PV system is directly supplied to the load. Additionally, since the battery is initially at $\text{SoC} < 80\%$, it is not fully charged. The excess power generated by the PV system is used to charge the battery by selecting the PV_ESU control signal as illustrated in Figure 5(b) third graph.

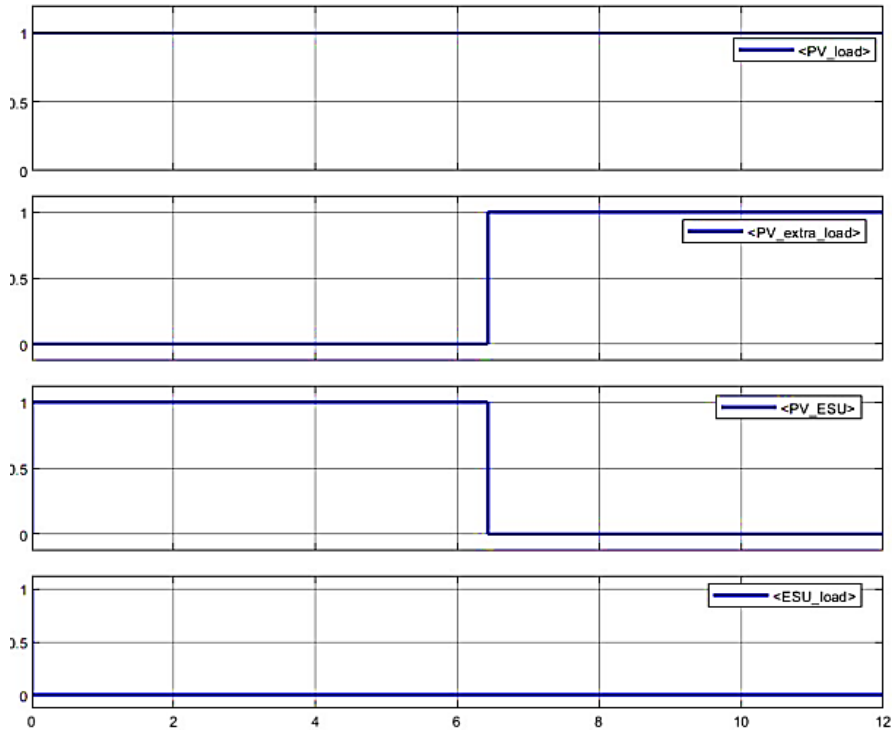
In this case, the bidirectional converter operates as a buck converter, reducing the DC bus voltage and allowing the flow of current into the battery for charging. The continuity of charging the battery yields it to reach the SoC max where the battery becomes fully charged ($\text{SoC}=80\%$) when being supplied with power from the PV system ($P_{pv}=500 \text{ W}$) during $[6.5 \leq t \leq 12]$. At this point, the control system takes action to halt the battery charging by disabling the PV_ESU control signal as shown in Figure 5(b) third graph.

Consequently, the PV system exclusively provides power to the load, and any excess energy is transferred to supply the load of the neighbor MG in resilience situation as illustrated in Figure 5(b) second graph. This approach effectively prevents the battery from overcharging and potential damage and helps the other MGs in need. The last signal shown in Figure 5(b) ESU_load will be enabled once the load is supplied by the battery.

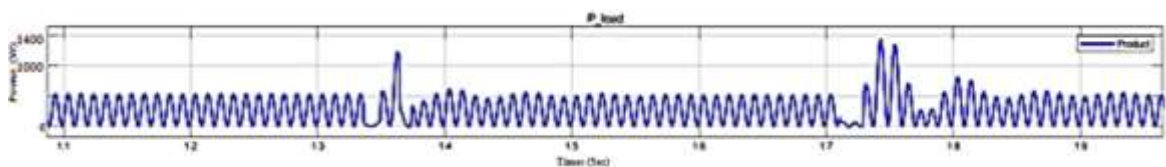
Once the battery is charged and the PV steel provides enough energy to power the load, a surplus state is generated ($\text{SurplusRegister}=1$), indicating that this MG can generate energy for neighboring MGs in a resilience state. An illustration of the MG's load power is shown in Figure 5(c) which will be used for the evaluation of multi-MGs approach. It is clearly shown that the load is variable, and in some situations, it generates peaks that cannot be handled by the existing MG's DERs, and it requires help from the neighbor MGs.



(a)



(b)



(c)

Figure 5. One MG control Matlab Simulink results: (a) one MG obtained simulation results, (b) one MG’s control signals, and (c) load power consumption scenario

3.2. Multi-MGs management

Three MGs are interconnected to illustrate the efficiency of the proposed approach. Moreover, three scenarios are tested to evaluate the possible MG's situations as shown in Figures 6 and 7. Table 2 summarizes the SurplusRegister and ResilienceRegister of the three MGs corresponding to each scenario recorded from the Raspberry controllers. Scenario 1 has been captured in midday (between 12:00 to 16:00); when the PVs are satisfying the loads' needs, and the batteries are already charged by the extra amount of PVs power. Therefore, ResilienceRegister are reset to zero; whereas surplus registers of the three MG's are set to one indicating that there is an extra power that can be injected to MGs in need.

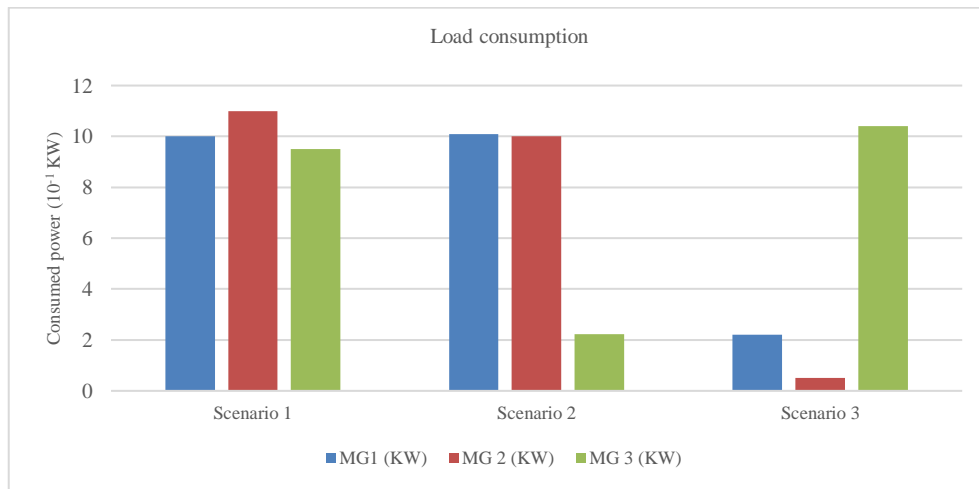


Figure 6. The MGs' consumed power amount

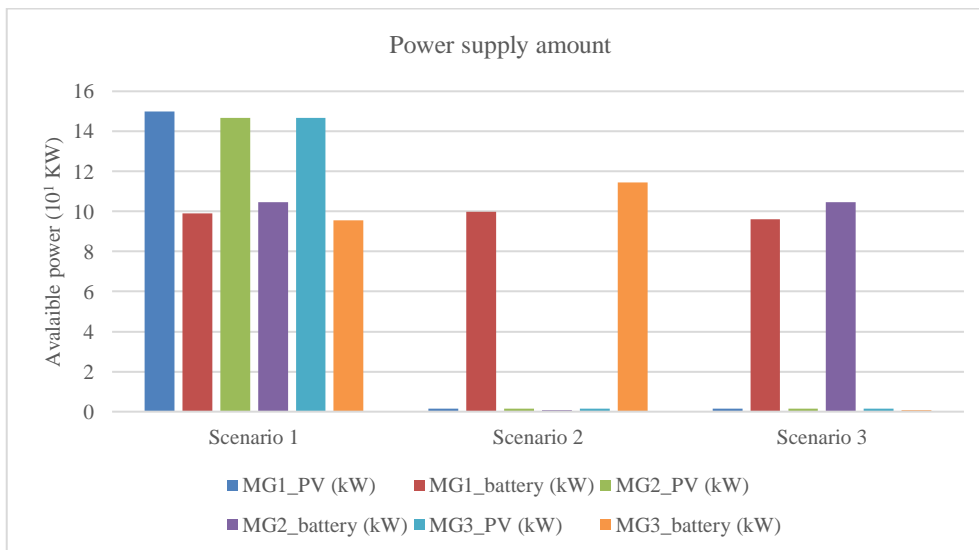


Figure 7. The MGs' delivered power amount

Table 2. SurplusRegister and ResilienceRegister status

	MG1		MG2		MG3	
	Surplus register	Resilience register	Surplus register	Resilience register	Surplus register	Resilience register
Scenario 1	1	0	1	0	1	0
Scenario 2	0	0	0	1	1	0
Scenario 3	1	0	1	0	0	1

Scenario 2 was recorded at night when PVs were not able to produce any power. It illustrates the case where the load of MG1 is supplied via its own battery; therefore, both its registers are reset to zero (ResilienceRegister and SurplusRegister). On the other hand, MG2 is in a resilience situation indicated by setting ResilienceRegister=1. The load of MG3 is very low and can largely be supplied by its battery; at the same time, its SurplusRegister=1 indicates that it has extra power that can be injected into neighboring MGs. Hence the load of MG2 will be supplied via MG3, which has enough power.

Scenario 3 was also recorded at night. In this scenario, both loads of MG2 and MG3 require load power of less than 300 W, which can be supplied by their batteries. At the same time, they can produce together a surplus of power enough to supply the load of MG3 which is in a resilience situation.

3.3. The proposed control strategy benefits and comparison

Compared to the literature, demand-side management (DSM) lowers the carbon environmental impact of traditional generators while also providing a large economic benefit to all parties participating in and interacting with one another in the existing energy network [30]. Nevertheless, the idea of energy management has evolved from utility-driven regulation to one where end users are involved in setting prices and clearing the market. Consequently, the invented DSM's methods appear out of date at this point. Another challenge that faces the newly developed technics is due to the operation of distributed generation (DGs) which is unpredictable and depends on the environment. This unpredictability makes it difficult to integrate DGs into the energy market and necessitates sufficient stability and flexibility in the system. Furthermore, the positioning and kinds of DG have a big influence on how the electrical market is planned and run. This problem is particularly noticeable in bigger distribution networks that have numerous connected microgrids [31]. As well as, among the difficulties that must be overcome to effectively employ microgrids and realize their potential are the fast switching between the different modes.

These challenges were addressed in our work. The successful deployment of the MAS multi-MG management system has been facilitated by the application of several procedures and methodologies. Over the course of the battery's operating cycles, a precise SoC estimation was attained. The data was transmitted seamlessly between the ESP and Raspberry Pi thanks to the wireless MQTT protocol, although a possible drawback could be the wireless network's available bandwidth. The Raspberry Pi's switching time has shown to be incredibly quick and effective in controlling the system's power supply. In addition, the Raspberry Pi plays a key role in the collection and real-time transmission of important data to the user database. This facilitates the microgrid interaction with the other MGs, importing additional power as needed to maintain a reliable load supply. In summary, the proposed multi-MG system's adoption has produced positive outcomes, proving its ability to meet loads' power requirements in a variety of situations.

4. CONCLUSION

The management of MGs operating in island mode is very critical, especially at peak load demands. Hence, this paper proposed an approach to increase the system's resilience to respond to any incident in the system resources. The proposed controller ensured MG autonomy by efficient use of its own supplies. Moreover, the controller handles system resilience cases by requesting and providing power from/to neighboring microgrids by creating status registers indicating the existence of surplus or deficiency of energy in the system. The status of the two registers is broadcast between the MGs to enable them to communicate and respond to help each other.

The system's ability to maintain consistent and dependable energy to meet load consumption was shown by its implementation. This offered useful information for additional research and development. Additionally, the Raspberry Pi's switching capabilities have been shown to be incredibly quick and effective in controlling power flow throughout the system, guaranteeing a high level of supply continuity. Real-time data collection and transmission from/to the MG ensures that data is available for additional analysis and usage via the Grafana user interface. The system's successful operation has been considerably aided by the smooth integration of its various components.

After the implementation of the proposed architecture and its simulation, the system efficiency is enhanced, and the system resilience is handled effectively by the controllers. However, the system can be improved by considering multicriteria optimization such as considering the nearest MG first and the one with the lowest cost, to get an optimized cost function. These issues will be addressed in our future works.

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REFERENCES

- [1] C. P. Ohanu, G. N. Egbo, and T. Sutikno, "Sizing and analysis of a standalone photovoltaics system for a three-bedroom residence in Nigeria," *Indonesian Journal of Electrical Engineering and Computer Science (IJECS)*, vol. 33, no. 1, p. 1, Jan. 2024, doi: 10.11591/ijeecs.v33.i1.pp1-9.
- [2] R. Zahira, D. Lakshmi, G. Ezhilarasi, P. Sivaraman, C. N. Ravi, and C. Sharmeela, "Stand-alone microgrid concept for rural electrification: a review," in *Residential Microgrids and Rural Electrifications*, Elsevier, 2022, pp. 109–130.
- [3] A. Amir, H. Shareef, and F. Awwad, "Energy management in a standalone microgrid: a split-horizon dual-stage dispatch strategy," *Energies*, vol. 16, no. 8, p. 3400, Apr. 2023, doi: 10.3390/en16083400.
- [4] D. Kaddour and H. Belaidi, "Impact of integrating DERs and ESS on smart-grid supply continuity: a review," in *2022 3rd International Conference on Human-Centric Smart Environments for Health and Well-being (IHSH)*, Oct. 2022, pp. 7–12, doi: 10.1109/IHSH57076.2022.10092035.
- [5] C. Schwaegerl and L. Tao, "The microgrids concept," in *Microgrids*, Chichester, United Kingdom: John Wiley and Sons Ltd, 2013, pp. 1–24.
- [6] T. Jothi, M. Arun, and M. Varadarajan, "Power flow analysis in a distributed network for a smart grid system," *Indonesian Journal of Electrical Engineering and Computer Science (IJECS)*, vol. 33, no. 1, p. 42, Jan. 2024, doi: 10.11591/ijeecs.v33.i1.pp42-52.
- [7] G. H. Alves, G. C. Guimarães, and F. A. M. Moura, "Battery storage systems control strategies with intelligent algorithms in microgrids with dynamic pricing," *Energies*, vol. 16, no. 14, p. 5262, Jul. 2023, doi: 10.3390/en16145262.
- [8] M. K. Behera and L. C. Saikia, "A novel spontaneous control for autonomous microgrid VSC system using BPF droop and improved hysteresis band control scheme," *Electric Power Systems Research*, vol. 220, p. 109262, Jul. 2023, doi: 10.1016/j.epsr.2023.109262.
- [9] G. S. Thirunavukkarasu, M. Seyedmahmoudian, E. Jamei, B. Horan, S. Mekhilef, and A. Stojcevski, "Role of optimization techniques in microgrid energy management systems—a review," *Energy Strategy Reviews*, vol. 43, p. 100899, Sep. 2022, doi: 10.1016/j.esr.2022.100899.
- [10] S. Chalah, H. Belaidi, L. Merrad, and T. Alili, "Microgrid energy management strategy based on MAS," in *2022 3rd International Conference on Human-Centric Smart Environments for Health and Well-being (IHSH)*, Oct. 2022, pp. 1–6, doi: 10.1109/IHSH57076.2022.10092010.
- [11] A. Khodaei, "Resiliency-oriented microgrid optimal scheduling," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1584–1591, Jul. 2014, doi: 10.1109/TSG.2014.2311465.
- [12] E. Hernández Mayoral *et al.*, "Power quality in renewable energy microgrids applications with energy storage technologies: issues, challenges, and mitigations," in *Electric Power Conversion and Micro-Grids*, IntechOpen, 2022.
- [13] R. Jabeur, Y. Boujoudar, M. Azeroual, A. Aljarbouh, and N. Oualine, "Microgrid energy management system for smart home using multi-agent system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 2, p. 1153, Apr. 2022, doi: 10.11591/ijece.v12i2.pp1153-1160.
- [14] A. Y. Ali, A. Hussain, J.-W. Baek, and H.-M. Kim, "Optimal operation of networked microgrids for enhancing resilience using mobile electric vehicles," *Energies*, vol. 14, no. 1, p. 142, Dec. 2020, doi: 10.3390/en14010142.
- [15] N.-M. Zografou-Barredo, C. Patsios, I. Sarantakos, P. Davison, S. L. Walker, and P. C. Taylor, "MicroGrid resilience-oriented scheduling: a robust MISOPC model," *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 1867–1879, May 2021, doi: 10.1109/TSG.2020.3039713.
- [16] Z. Li, L. Zhang, R. Zhang, X. Wang, Z. Xue, and H. Sun, "Unscented Kalman filtering method for scheduling photovoltaic power generation system fluctuations," *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol. 235, no. 3, pp. 608–619, May 2021, doi: 10.1177/0957650920950085.
- [17] F. Jiao, Y. Zou, X. Zhang, and R. Zou, "Multi-objective optimal energy management of microgrids including plug-in electric vehicles with the vehicle to grid capability for energy resources scheduling," *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol. 235, no. 3, pp. 563–580, May 2021, doi: 10.1177/0957650920942998.
- [18] H. Belaidi and Z. Rabiai, "Decentralized energy management system enhancement for smart grid," in *Research Anthology on Smart Grid and Microgrid Development*, IGI Global, 2022, pp. 77–90.
- [19] C. M. Colson, M. H. Nehrir, and R. W. Gunderson, "Distributed multi-agent microgrids: a decentralized approach to resilient power system self-healing," in *2011 4th International Symposium on Resilient Control Systems*, Aug. 2011, pp. 83–88, doi: 10.1109/ISRCS.2011.6016094.
- [20] H. Belaidi, H. Bentarzi, Z. Rabiai, and A. Abdelmoumene, "Multi-agent system for voltage regulation in smart grid," in *Artificial Intelligence and Renewables Towards an Energy Transition*, Springer International Publishing, 2021, pp. 487–499.
- [21] E. Tridianto, P. D. Permatasari, and I. R. Ali, "Experimental study of mini SCADA renewable energy management system on microgrid using Raspberry Pi," *Journal of Physics: Conference Series*, vol. 983, p. 012061, Mar. 2018, doi: 10.1088/1742-6596/983/1/012061.
- [22] U. B. Tayab, J. Lu, S. Taghizadeh, A. S. M. Metwally, and M. Kashif, "Microgrid energy management system for residential microgrid using an ensemble forecasting strategy and grey wolf optimization," *Energies*, vol. 14, no. 24, p. 8489, Dec. 2021, doi: 10.3390/en14248489.
- [23] R. G. Allwyn, A. Al-Hinai, and V. Margaret, "A comprehensive review on energy management strategy of microgrids," *Energy Reports*, vol. 9, pp. 5565–5591, Dec. 2023, doi: 10.1016/j.egyr.2023.04.360.
- [24] M. W. Khan and J. Wang, "The research on multi-agent system for microgrid control and optimization," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 1399–1411, Dec. 2017, doi: 10.1016/j.rser.2017.05.279.
- [25] A. Zermout, H. Belaidi, and A. Maaache, "Implementation of battery characterization system," in *ICCEIS 2022*, Jan. 2023, p. 12, doi: 10.3390/engproc2023029012.
- [26] H.-J. Jun and H.-S. Yang, "Performance of the XMPP and the MQTT protocols on IEC 61850-based micro grid communication architecture," *Energies*, vol. 14, no. 16, p. 5024, Aug. 2021, doi: 10.3390/en14165024.
- [27] S. Kumar, S. Islam, and A. Jolfaei, "Microgrid communications - protocols and standards," in *Variability, Scalability and Stability of Microgrids*, Institution of Engineering and Technology, 2019, pp. 291–326.
- [28] E. D. Escobar, D. Betancur, T. Manrique, and I. A. Isaac, "Model predictive real-time architecture for secondary voltage control of microgrids," *Applied Energy*, vol. 345, p. 121328, Sep. 2023, doi: 10.1016/j.apenergy.2023.121328.
- [29] M. A. Haidekker, M. Liu, and W. Song, "Alternating-current microgrid testbed built with low-cost modular hardware," *Sensors*, vol. 23, no. 6, p. 3235, Mar. 2023, doi: 10.3390/s23063235.





- [30] V. Stavrakas and A. Flamos, "A modular high-resolution demand-side management model to quantify benefits of demand-flexibility in the residential sector," *Energy Conversion and Management*, vol. 205, p. 112339, Feb. 2020, doi: 10.1016/j.enconman.2019.112339.
- [31] S. Panda *et al.*, "A comprehensive review on demand side management and market design for renewable energy support and integration," *Energy Reports*, vol. 10, pp. 2228–2250, Nov. 2023, doi: 10.1016/j.egy.2023.09.049.

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