Design and Development of Energy Management System for Hybrid Microgrid

Abdulhameed Aboumadi[1,3], Zekeriya Güneş[1,3], Yunus Yalman[3], Adnan Tan[2,4], Alper Terciyanlı[2], Erman Terciyanlı[1], Kamil Çağatay Bayındır[3]

[1]Inavitas, Yenimahalle, Ankara, Türkiye
abdulhameed.aboumadi@inavitas.com, zekeriya.gunes@inavitas.com, erman.terciyanli@inavitas.com
[2]Endoks, Yenimahalle, Ankara, Türkiye
alper.terciyanli@endoks.com, adnan.tan@endoks.com,
[3]Ankara Yıldırım Beyazıt University, Keçiören, Ankara, Türkiye
yunusyalman@aybu.edu.tr, kcbayindir@ybu.edu.tr
[4]Çukurova University, Sarıçam, Adana, Türkiye

Abstract

Microgrid is a key solution for integrating distributed generation and energy storage systems. An energy management system can achieve an efficient and optimal operation of microgrids. In this paper, an advanced energy management system algorithm is proposed for the hybrid microgrid to enable diverse energy management goals, including peak shaving, flat power flow, self-consumption, and zero import. Moreover, the controller is developed to discharge/charge the battery energy storage system to achieve goals. The microgrid is modeled in MATLAB/Simulink with a photovoltaic generation system, battery energy storage system, grid, and variable load. The proposed algorithm and controller have been tested in different case studies using actual photovoltaic generation and load data. The simulation results show that the proposed algorithm and controller effectively perform all energy management system operation modes.

1. Introduction

One of the most pressing global concerns today is climate change, driven primarily by human activities such as the widespread use of fossil fuels. These activities release greenhouse gases into the atmosphere, leading to global warming and its associated adverse effects [1].

To mitigate the impacts of climate change, it is imperative that we reduce greenhouse gas emissions. One highly effective approach is transitioning to renewable energy sources like solar and wind power. Recent advancements in energy and renewable technology have opened new possibilities for integrating Renewable Energy Sources (RESs) into distribution networks. However, this integration presents challenges, primarily due to the intermittent and variable nature of RESs [2].

Microgrids (MG) emerge as a promising solution to address these challenges. They provide localized power systems that can function independently from the main grid. A pivotal component of a microgrid is the Energy Management System (EMS), which plays a central role in coordinating the operation of all microgrid components, including RESs, Battery Energy Storage Systems (BESS), and loads. The EMS ensures efficient and sustainable energy distribution within the microgrid, contributing significantly to the overall effort to combat climate change [8].

Several recent studies [3-7] have proposed novel microgrid EMSs for peak shaving. Rana et al. [3] proposed a new peak load-shaving algorithm for hybrid PV-BESS connected isolated microgrids. Their algorithm outperformed existing algorithms in simulation case studies. Solaphom et al. [4] presented an operation strategy and EMS for a grid-connected microgrid with a micro hydropower plant, Photovoltaic (PV) system, BESS, and main grid. Their EMS uses actual data profiles from a real microgrid site to minimize energy flow from the main grid. The performance of the EMS was validated through experimental results. Silvera et al. [5] proposed a microgrid EMS that can perform multiple functions, including peak shaving, islanded operation, reactive power support, power reserve, self-consumption, flat power flow, and capacity firming. Their EMS was tested using simulation and was shown to achieve its required targets by managing imported and exported power and the overall power flow with the grid.

In [6], A single-controllable microgrid is implemented and tested with three battery technologies for self-consumption, energy time shift, peak shaving, and reactive power support. The microgrid was validated through full-scale experimental results using commercial devices. In [7], a fuzzy logic-based control algorithm for a hybrid energy storage system is proposed in a microgrid with renewable energy and uncontrollable loads. Their algorithms aim to balance active power, exploit battery advantages, and maximize HESS lifetime. Simulation results showed economic and degradation benefits. The authors of [14] highlighted the importance of reliable communication networks in microgrids and proposed a common platform to harmonize diverse communication standards used by microgrid components. The platform supports interoperability and demonstrates its effectiveness using the IEEE 9-bus network. The authors of [15] presented an EMS based on SCADA. The EMS aims to reduce energy exchange with the grid, which is done by calculating the BESS active power set value based on power calculations from different components. The microgrid and the overall system setup were explained in detail, and the EMS considered the SCADA system by Modbus and KNX protocols.

This paper presents an advanced EMS algorithm and controller for hybrid MG systems to perform peak shaving, flat power flow, self-consumption, and zero import. The controller is designed to charge/discharge for BESS to ensure EMS operation modes. Moreover, the actual data for PV generation and load are utilized to examine the performance of EMS in hybrid MG. In light of the simulation results, the energy management goals are achieved by the proposed algorithm and controller. These

algorithms and controllers can help to reduce power losses and greenhouse gas emissions, which is the main reason for climate change.

This paper is organized as follows: In Section 2, general system overview including MG system, controller, and algorithms for EMS. In section 3, results and discussions about the system are presented, and section 4 concludes the paper by summarizing the overall design and results in addition to presenting the main contributions of this paper.

2. System Overview

2.1. Microgrid

The single-line diagram of the microgrid on which the EMS was tested is given in Fig. 1. Both the EMS and the microgrid were developed and implemented in MATLAB Simulink. The microgrid comprises four key components and maintains a connection to the main grid. All components are connected to a 400 V bus. These components are as follows:

- Variable load (200 kW)
- PV production unit (200 kW)
- BESS (100 kW / 200 kWh)

This simulated microgrid model allowed for practical testing and validation of the EMS within a real-world context, providing valuable insights into its performance and effectiveness of the EMS. The simulation was performed in fixed-step discrete mode, and the sample time of the simulation was set to 50 µs, and the sample time of the controller was set to 100 µs. The simulation was also set to perform 24 seconds of simulation, where each second represents an hour of real-time.

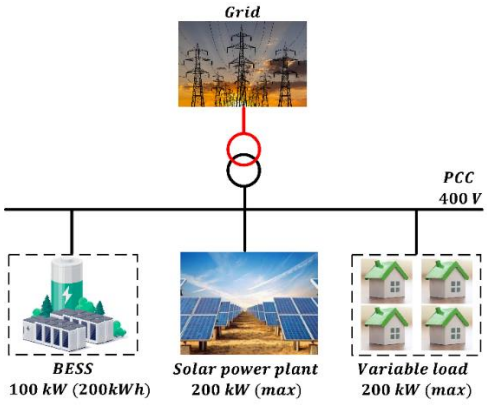


Fig. 1. Single-line diagram of the microgrid

The BESS, PV, and load modules utilized in the MG system have been imported from the microgrid library [9]. At the Point of Common Coupling (PCC), where all four components and the grid are interconnected, a measurement device is incorporated. This device takes the grid as its input and all other components as its outputs. Consequently, the calculated active power at the PCC (P_{grid}) will be positive when power is imported and negative when power is exported.

The PV module and variable load receive their respective inputs from external sources. The Global Horizontal Irradiance (GHI) is used to simulate the PV module's real production value [10]. On the other hand, consumption data is directly sent to the load module. The data used for microgrid simulation has been collected from historical sources. The load profile exhibits fluctuations between 13.5 kW and 192 kW, with an average load of 108.8 kW. In terms of GHI, it varies from 0 to 1000 W/m², with an average radiation level of 564 W/m² during sunny hours. The PV production corresponding to this defined GHI profile ranges from 0 to 200 kW, with an average of 112.8 kW during sunny hours. Fig. 2 presents plots of the load and production profile datasets, in addition to the calculated grid power based on load and production. This figure can be taken as a reference to the microgrid operation without the EMS.

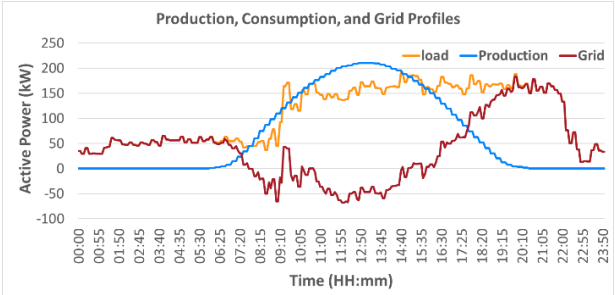


Fig. 2. Production, consumption, and grid profiles

2.2. Controller

The EMS comprises two PI controllers and a control algorithm. One PI controller is responsible for determining charging setpoints for the battery inverter, while the other handles generating discharging signals for the battery inverter. Simultaneously, the control algorithm sends appropriate setpoints to each controller based on the chosen operation mode. It also makes the critical decision of selecting charging or discharging signals to be transmitted to the battery inverter. An additional essential role of the control algorithm is to reset the integral error, a crucial operation during the transition between charging and discharging modes. The structure of the controller is presented in Fig. 3. In Fig. 3, $P_{upperlimit}$ and $P_{lowlimit}$ are maximum and minimum power at the PCC, respectively, and P_{set} is the BESS set point.

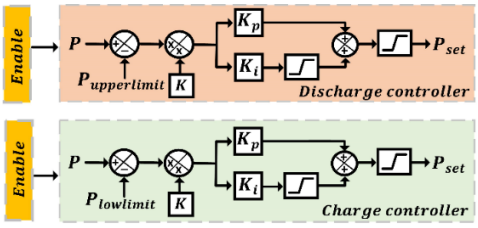


Fig. 3. General structure of the controller

2.3. Algorithm

As previously mentioned, the control algorithm plays a significant role in generating reference values for the controller, which are determined according to the operation mode selected by the user. The operation modes are described below:

- Peak-shaving (PS): This involves leveling out spikes in power demand from the grid by feeding excess consumption beyond a predefined threshold from the BESS [11][12].
- Flat Power Flow (FPF): the ability of EMS to maintain constant power (import/export) with the grid [5].
- Self-consumption (SC): The EMS prioritizes using locally generated energy to power all microgrid loads, storing any surplus energy in the BESS instead of exporting it to the grid [13].
- Zero-import (ZI): The EMS entirely relies on the BESS and local production to provide power for all microgrid loads, eliminating the need to import any electricity from the grid.

Since the controller's operation is based on the power at the PCC, achieving the control objective leads to the controller switching off. A hysteresis band is implemented to overcome this problem. The hysteresis band helps maintain stability by preventing rapid on-off cycling of the controller based on slight fluctuations, ensuring a more consistent and controlled operation.

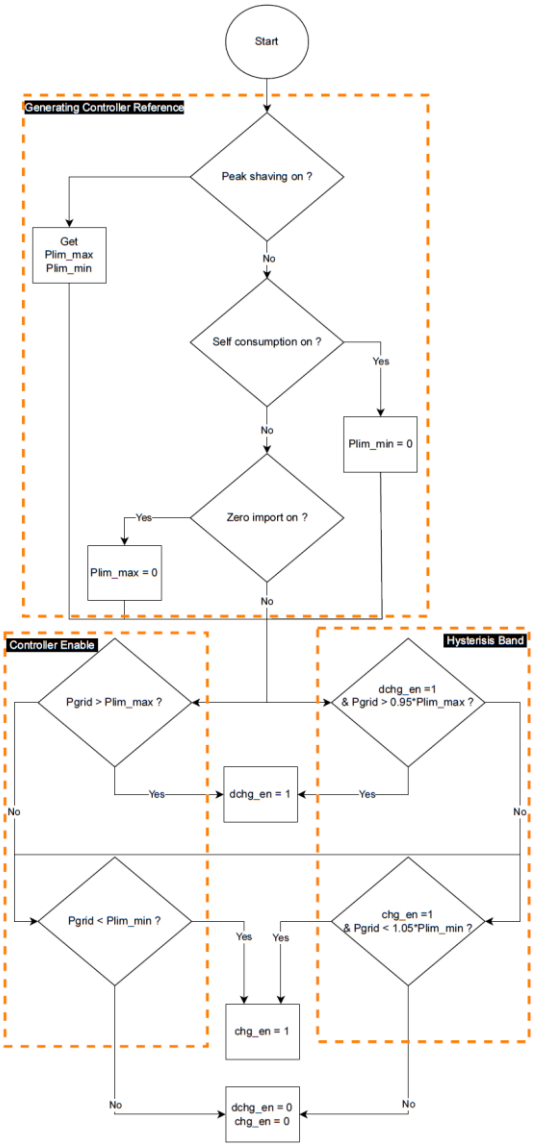


Fig. 4. Flow chart of the control algorithm

The Flow chart of the control algorithm is presented in Fig. 4. The first step in the control algorithm is to determine the operating mode selected and set the controller reference values. For peak-shaving, the upper and lower limits sent to the controller as references are directly set by the user. For self-consumption operation mode, the lower limit for P_{grid} is set to zero, and for zero-import mode, the upper limit for P_{grid} is set to zero. The next step is to send controller reference values to the controller and decide which part of the controller to activate (charging or discharging mode). An important part in this step is the hysteresis band, which ensures the stable operation of the EMS. Without the hysteresis band, the controller will be disabled once the limit is reached, which will cause the limit to be violated again, and the algorithm will re-enable the controller. This way, the controller will turn the inverter on and off frequently and the limit will be violated frequently.

3. Results and Discussion

The proposed EMS and BESS controller is tested in a hybrid MG testbed. All operation modes are examined to evaluate their functionality. A real profile dataset is utilized to ensure a realistic scenario where the selection of each operation mode aligns with the microgrid's requirements. The simulation results for all operation modes (PS, ZI, FPF, SC) based on a full-day scenario are shown in Fig. 5. Fig. 6, 7, and 8 present a closer look at the operation of each operation mode. Fig.5, 6, 7, and 8 include three subfigures. The graph on the top shows upper and lower limits in addition to active power exchange with the grid (P_{grid}), and the active power exchange with the grid based on production and consumption profiles (Cap $P_{gridprofile}$). $P_{gridprofile}$ is an essential signal for analyzing the results as it shows the power exchange with the grid in case the EMS is not operating. The middle graph shows BESS active power and P_{grid}, while the bottom graph shows the maximum state of charge (SoC) signal.

In zone 1, peak shaving was applied at a 50-kW limit. The active power of BESS, P_{grid}, upper and lower limit for the grid, and SoC is shown in Fig.6 for peak shaving operation mode. As demonstrated in Fig.6, although the $P_{gridprofile}$ excess the $P_{gridupperlimit}$, P_{grid} is not excess the $P_{gridupperlimit}$ thanks to EMS algorithm by providing peak shaving. The rapid and precise response of the EMS ensured that the power limits were not violated.

As depicted in Fig. 5, the self-consumption mode was initiated in zone 2 when PV production exceeded local consumption. The active power of BESS, P_{grid}, upper and lower limit for the grid, and SoC is shown in Fig.7 for self-consumption operation mode. This mode was activated to maximize energy stored in BESS for later use when renewable energy production becomes insufficient to supply load. Despite variations in P_{grid}, the EMS displayed rapid and precise responsiveness, consistently maintaining zero exported power. The EMS terminated self-consumption mode when the maximum SoC was reached (90%).

In zone 3, shown in Fig. 5, the zero-import function was tested, but since the load was much higher than production (power imported from the grid should have exceeded 100 kW) for some time, the BESS responded by discharging at maximum power (100 kW), but still was not able to supply all loads and the excess need of energy was imported from the grid. The active power of BESS, P_{grid}, upper and lower limit for the grid and SoC is shown in Fig.8 for zero export mode. The zero-import mode was

terminated when the BESS reached the minimum SOC value (10%).

Flat power flow operation can be observed during self-consumption, peak shaving, and zero-import operation modes at all three zones. The results illustrated in Fig. 5 affirm the EMS's effectiveness and its ability to adapt to changing conditions dynamically, demonstrating its capability to optimize energy management in a microgrid with real-world applicability.

4. Conclusion

Microgrids, with their localized power systems, are emerging as a solution to integrate RESs. The EMS serves as the cornerstone of microgrid operation, ensuring efficient and sustainable energy distribution. In this paper, a comprehensive microgrid simulation model with an advanced EMS is presented. Furthermore, the BESS controller is developed to ensure EMS function. The main objective is to develop a robust EMS and controller capable of coordinating various energy management objectives within the microgrid, including peak shaving, flat power flow, self-consumption, and zero import. The performance and effectiveness of the EMS and controller for operation modes are validated through simulation in the MG testbed. The simulation results clearly present the effectiveness of the proposed EMS algorithm and BESS controller. This research contributes to the ongoing efforts to combat climate change by advancing microgrid technology and EMS design. It also aligns with the broader goal of transitioning to cleaner and more sustainable energy sources.

5. Acknowledgments

The first author acknowledges the support given by the Scientific and Technological Research Institution of Türkiye (TÜBİTAK) under project number 119C128.

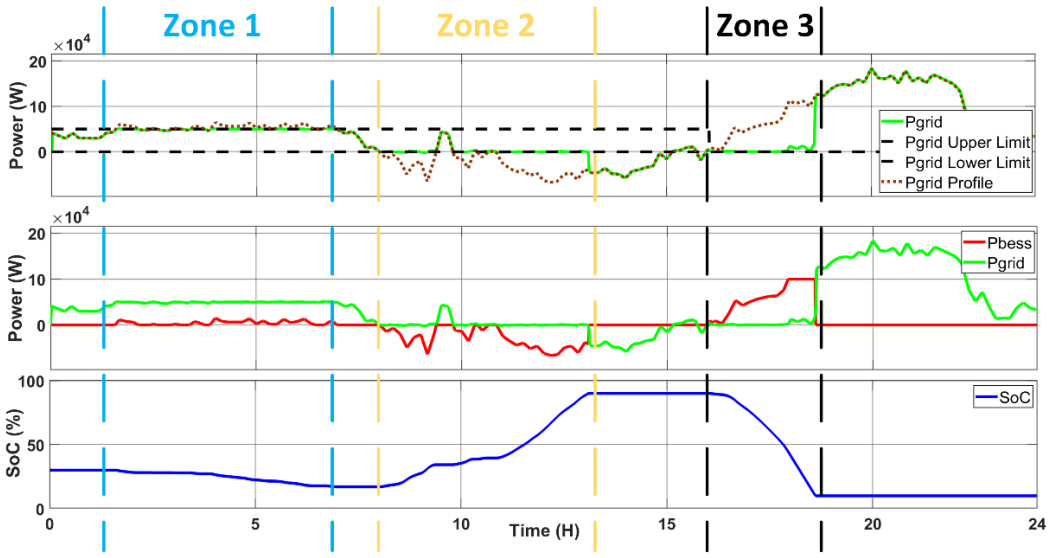


Fig. 5. MG Simulation results with EMS for one day

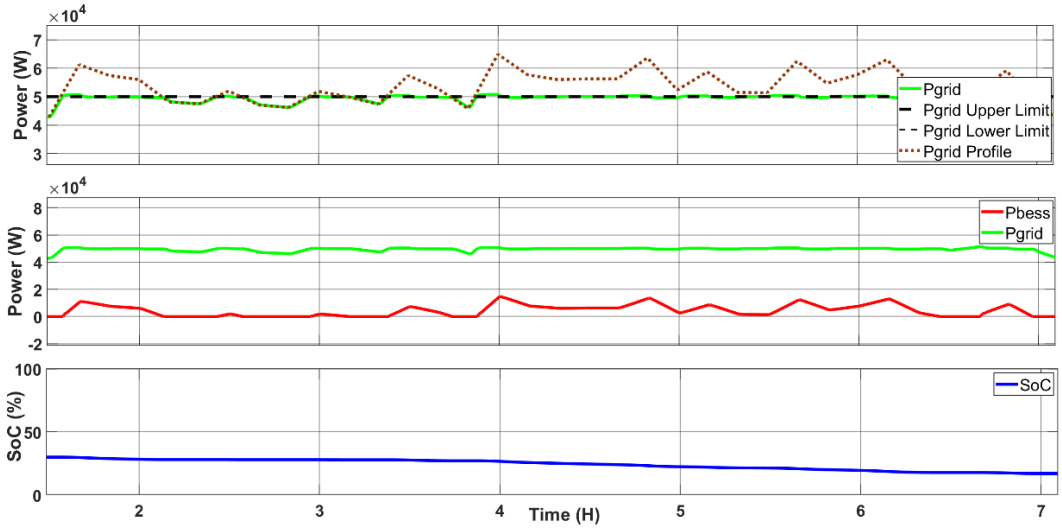


Fig. 6. Peak shaving operation mode

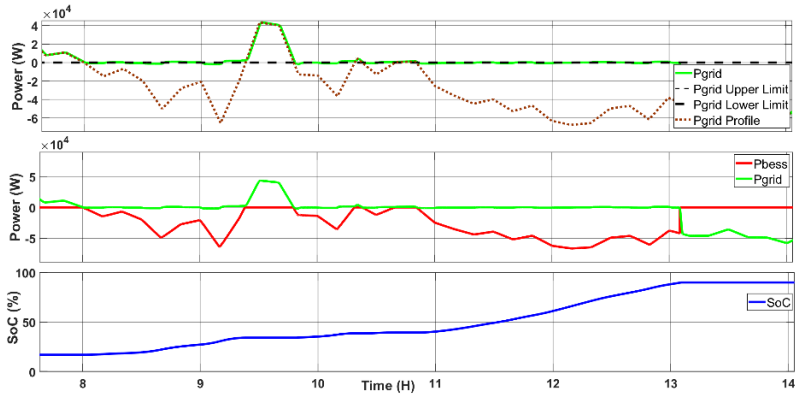


Fig. 7. Self-consumption operation mode

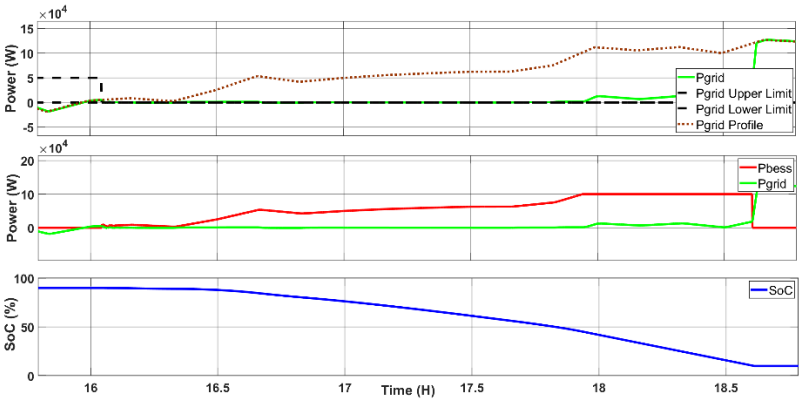


Fig. 8. Zero-import operation mode

6. References

[1] UNFCCC, V. "Adoption of the Paris Agreement." Proposal by the President 282 (2015): 2.

[2] Chen, Siyuan, Zheng Li, and Weiqi Li. "Integrating high share of renewable energy into power system using customer-sited energy storage." Renewable and Sustainable Energy Reviews 143 (2021): 110893.

[3] Rana, Md Masud, et al. "A novel peak load shaving algorithm for isolated microgrid using hybrid PV-BESS system." Energy 234 (2021): 121157.

[4] Solaphom, Ketsavanh, et al. "Operation strategy of microgrid for rural area of northern Thailand." International Journal of Smart Grid and Clean Energy 9.1 (2020): 126-134.

[5] Junior, Jose Ronaldo Silveira, et al. "Multifunctional dispatchable microgrids." Applied Energy 282 (2021): 116165.

[6] Reis, Geovane L., et al. "Case Study of Single-Controllable Microgrid: A Practical Implementation." Energies 15.17 (2022): 6400.

[7] Biedka, Hubert, and Krzysztof Rafał. "Control Algorithms of Hybrid Energy Storage System Based on Fuzzy Logic." 2021 Progress in Applied Electrical Engineering (PAEE). IEEE, 2021.

[8] Michaelson, D., and J. Jiang. "Review of integration of small modular reactors in renewable energy microgrids." *Renewable and Sustainable Energy Reviews* 152 (2021): 111638.

[9] Jonathan LeSage (2023). Systems-Level Microgrid Simulation from Simple One-Line Diagram (https://www.mathworks.com/matlabcentral/fileexchange/67060-systems-level-microgrid-simulation-from-simple-one-line-diagram), MATLAB Central File Exchange. Retrieved October 8, 2023.

[10] https://www.homerenergy.com/products/pro/docs/3.11/how_homer_calculates_the_pv_array_power_output.html

[11] Hong, Yuan, Shengbin Wang, and Ziyue Huang. "Efficient energy consumption scheduling: Towards effective load leveling." *Energies* 10.1 (2017): 105.

[12] Deeba, Shohana Rahman, et al. "Evaluation of technical and financial benefits of battery‐based energy storage systems in distribution networks." IET Renewable Power Generation 10.8 (2016): 1149-1160.

[13] Luthander, Rasmus, et al. "Photovoltaic self-consumption in buildings: A review." Applied energy 142 (2015): 80-94.

[14] Kim, Jun-Sung, et al. "Microgrids platform: A design and implementation of common platform for seamless microgrids operation." *Electric Power Systems Research* 167 (2019): 21-38.

[15] Kermani, Mostafa, et al. "Intelligent energy management based on SCADA system in a real Microgrid for smart building applications." Renewable Energy 171 (2021): 1115-1127.