Solar Energy
And Sustainable Development
Refereed, biannual scientific journal issued by:
The Libyan Center for Solar Energy Research and Studies

Towards Stable and Efficient Microgrids: Integrating Centralized and Droop Control Techniques

A. Boukaibat[1*], N. Krami[2], Y. Rochdi[3], Y. El Bakkali[4].

[1,2,3,4]National school of applied sciences, Kénitra, Morocco.

E-*mail:* [1]achrabkt@gmail.com ,[2]Nissrine.krami@gmail.com ,[3]youssef.rochdi@uit.ac.ma ,
[4]elbakkali.yassir@gmail.com .

SPECIAL ISSUE ON:

3rd International Conference on Mechanics, Materials, and Energy. (MME-2024)
May 20- 22, 2024
at: International University of Rabat, Morocco.

KEYWORDS

Droop control, Energy management system, Microgrid control, Renewable energy integration.

ABSTRACT

This study proposes a hybrid control strategy to address critical challenges in microgrids with distributed energy sources, particularly voltage stability and power-sharing issues. The approach combines centralized day-ahead scheduling using a Microgrid Central Controller (MGCC) with local droop control techniques. The MGCC optimizes source dispatch based on real-time forecasts and load profiles, while droop control provides fast voltage regulation against fluctuations. Evaluations under multiple scenarios, using real meteorological data and MATLAB/Simulink simulations, demonstrate improved voltage stability, reduced grid dependency, and enhanced renewable energy utilization. The results confirm the potential of this strategy to improve microgrid reliability and support sustainable energy management

*Corresponding author.

DOI: https://doi.org/10.51646/jsesd.v15iMME.371

نحو شبكات كهربائية صغرى مستقرة وفعالة: دمج التحكم المركزي وتقنية التحكم بالتدلي

أ. بوكعيبات، ن. كرامي، ي. رشدي، ي. البقالي

ملخص: تقترح هذه الدراسة استراتيجية تحكم هجينة لمعالجة التحديات الحرجة في الشبكات المصغرة التي تحتوي على مصادر طاقة موزعة، ولا سيما مشكلات استقرار الجهد وتقاسم الطاقة. تجمع المنهجية بين الجدولة المركزية المسبقة (قبل يوم التشغيل) عبر وحدة التحكم المركزية للشبكة المصغرة (MGCC) وتقنيات التحكم بالتراجع (Droop) المحلية. تعمل الـ MGCC على تحسين جدولة تشغيل المصادر استنادًا إلى التنبؤات الفورية والملفات الزمنية للأحمال، في حين يوفر التحكم بالتراجع استجابة سريعة لتنظيم الجهد في مواجهة التقلبات. أظهرت التقييمات في سيناريوهات متعددة، باستخدام بيانات أرصاد جوية حقيقية ومحاكاة في بيئةMATLAB/Simulink ، تحسنًا في استقرار الجهد، وانخفاضًا في الاعتماد على الشبكة، وزيادة في استخدام الطاقة المتجددة. وتؤكد النتائج فاعلية هذه الاستراتيجية في تحسين موثوقية الشبكات المصغرة ودعم إدارة الطاقة المستدامة

الكلمات المفتاحية: التحكم بالتدلي،نظام إدارة الطاقة،التحكم في الشبكات الصغرى، دمج مصادر الطاقة المتجددة.

1. INTRODUCTION

Renewable energy sources (RES), such as PV systems and wind turbines, operate intermittently, leading to power fluctuations in the grid. To address this challenge, microgrids play a vital role in integrating RES by mitigating power fluctuations [1]. Moreover, microgrids offer a range of benefits, including improved power quality, reduced demand, and increased energy efficiency [2, 3]. Smart microgrids have emerged as a cutting-edge solution, amalgamating the benefits of AC and DC microgrids [4]. The DC bus acts as a platform for incorporating renewable energy sources (RES), energy storage systems (ESS), and variable DC loads [5], while the AC bus ensures interoperability with conventional AC loads and the main grid. Seamless power and energy exchange between the AC and DC buses is facilitated by bidirectional AC-DC inverters [6]. To ensure stable microgrid operation, a primary control strategy is implemented, prioritizing voltage and frequency stability. This strategy focuses on maintaining optimal voltage levels and steady frequency within the microgrid. Additionally, a secondary control mechanism is deployed to coordinate between various energy sources and correct any voltage and frequency fluctuations that may arise [8]. Furthermore, the coordination of multiple microgrids is achieved through a third control approach. This mechanism facilitates the smooth integration and synchronization of interconnected microgrids, promoting efficient and reliable operation [9].

Extensive research has been conducted to develop Energy Management Systems (EMS) aimed at ensuring energy quality in microgrids. One notable example is the designed EMS presented in [10], which effectively maintains a constant DC bus voltage in the microgrid. Additionally, a control algorithm was proposed in another study [11] to enhance microgrid efficiency and reduce electricity costs.

There are several methods that have been developed for energy management and microgrid control. Centralized control systems [14, 15] provide global resource optimization but are strongly dependent on a solid communication infrastructure and are not failure- and cyberattack-tolerant. Decentralized methods using droop control [16, 17] are less susceptible to local disturbances and communication failures but are unable to optimize performance globally and can lead to inefficient dispatching of energy.

Recent hybrid control strategies have sought to combine the advantages of both. In [18], the authors propose a two-level approach where the MGCC performs scheduling, while local controllers ensure primary stability. Similarly, [19] integrates a model predictive control (MPC) framework with voltage droop at the local level, improving dynamic response and energy balance. In addition, optimization-based EMS have gained momentum. Techniques such as genetic algorithms [20], deep reinforcement learning [21], and predictive scheduling [22] have been employed to maximize RES penetration, reduce energy costs, and maintain grid stability. However, these often lack real-time adaptability or rely on computationally intensive solutions. Table-based comparisons in [23] and [24] show that while existing methods often prioritize either adaptability or optimization, few approaches provide both in a scalable and modular way. To address these limitations, this study proposes a hybrid control strategy that integrates the centralized capabilities of a MicroGrid Central Controller (MGCC) with the local robustness of droop control. This dual-layer approach enhances voltage stability, ensures effective power sharing, and enables real-time coordination of distributed energy resources, even under fluctuating renewable generation and load conditions. Simulation results across various scenarios confirm the strategy's effectiveness in improving microgrid reliability, adaptability, and overall performance.

The paper is organized as follows: Section 2 describes the AC microgrid network and its components. Section 3 introduces the proposed control strategy. Section 4 presents simulation results demonstrating the effectiveness of this strategy. Finally, Section 5 concludes the paper with key findings and future work.

2. AC BUS VOLTAGE REGULATION

2.1. AC Microgrid Network

The global adoption of microgrid networks has been on the rise due to their self-sustainability and ability to operate independently without relying on external power sources. This trend is driven by the growing emphasis on renewable energy technologies, such as photovoltaic (PV) systems, in response to environmental concerns. Additionally, microgrid networks offer the potential for integration into existing electrical grids.

This paper considers a three-phases microgrid shown in figure 1, operating at a 400Vrms voltage and a 50Hz frequency, with:

- Two renewable energy sources: (i) a 3 kW photovoltaic system, (ii) a 3 kW wind generation emulation system.
- A 10kW Battery storage (autonomy 512 AH).
- A 4 KW variable load.

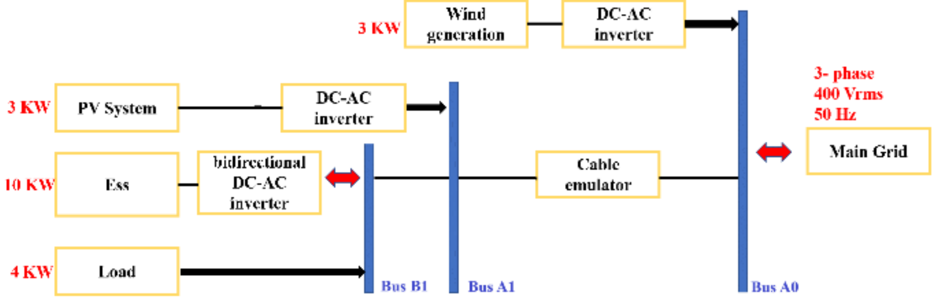

Figure 1. Microgrid Configuration.

The microgrid in Figure 1 is part of the Smart-grid lab at Ibn Tofail University, which serves as a flexible platform to study and develop energy management systems for microgrids.

The microgrid model offers versatility, allowing it to function either in isolation or as part of the wider electricity distribution network. When connected to the grid, the PV system's DC output voltage undergoes conversion into AC voltage via an inverter before being integrated into the grid system. Conversely, the AC voltage produced by the wind turbine (WT) and generator is directed to a bridge rectifier, which transforms it into DC voltage. This DC voltage is subsequently converted back into AC voltage using an inverter.

Alongside the photovoltaic system and wind turbine, the microgrid incorporates a battery storage system. The battery storage is seamlessly integrated with a bidirectional inverter, facilitating operation in both discharge and charging modes.

In this microgrid, Photovoltaic (PV) panels generate electricity from sunlight. Their output voltage depends on solar irradiance and temperature. Cloud cover or shading can cause rapid voltage changes. Wind turbines produce voltage based on wind speed. Variations in wind speed lead to voltage fluctuations. Changes in load demand affect the overall grid voltage. Sudden load increases or decreases impact voltage stability. To overcome this issues, this paper proposes, a new control strategy for the energy management and validates its efficiency in multiple scenarios by simulation, as a first stage before the implementation and the validation by experimentation in a future work.

2.2. The Load System

The load is a variable resistive load with a power rating of 4 kW. In simulation, it is possible to continuously vary the load from 0 to P_{max}=4 kW, replicating the same load variation conditions anticipated in future experiments with the proposed control strategy. By incorporating a variable resistive load, we can accurately model the dynamic nature of the load profile and simulate consistent variations in power demand.

2.3. Distributed Generators

The PV System: The solar cell uses sun rays to change them into electricity known as direct current (DC) using the photovoltaic effect. For a 3kWc system demand to be met, sixteen modules are needed in a configuration where each module is connected to two others parallel strings while the eight modules in each string are connected.

Table 1. PV System Specifications

Parameters	Values
parallel String	2
series connected modules per string	8
Peak Power (P(W))	250
Maximum Power Pmax (Watt)	4000

To convert the DC voltage output from the photovoltaic system to AC voltage, a DC-AC inverter is utilized. In order to minimize harmonic distortion in the output signal, a passive filter is incorporated along with the inverter. The passive filter helps mitigate any undesirable harmonic components present in the converted AC voltage.

The Wind Energy System: The micro-sources in the form of wind turbines (WT) harness wind speed and utilize it to generate electrical power. The conversion process involves the rotation effect, where the kinetic energy of the wind is converted into direct current (DC) electricity. In order to emulate, in smart grid -Ibn Tofail university Labs, a 3 kW wind micro generator, a widely utilized permanent magnet generator (PMG) is adopted, commonly found in different variations of horizontal axis micro turbines. The PMG is energized by an induction motor controlled through a variable speed drive mechanism. This setup allows for precise control over the speed of the induction engine, thereby enabling efficient operation of the micro generator.The variable speed drive facilitates adjusting the speed of the generator according to a wind speed profile, maximizing the energy extraction from the wind and optimizing the overall performance of the WT system. Table 2 gives the wind turbine specifications.

Table 2. Wind System Specifications.

Parameters	Values
Rated Power	3000 w
Wind Speed Cut-In	2,5m/s
Wind speed Rating	10m/s
Maximum wind speed	50m/s

2.4. The Energy Storage System:

An energy storage system (ESS) is almost essential when integrating renewable energy sources into the grid for three reasons:

- Renewable energy sources (such as solar and wind) are intermittent. Their output depends on weather conditions, time of day, and other factors. ESS helps bridge the gap between energy generation and demand by storing excess energy when renewables produce more than needed.
- Energy storage allows time shifting. Excess energy generated during sunny or windy periods can be stored and used during cloudy or calm periods.
- Fluctuations in renewable output impact grid stability. ESS provides grid support by regulating frequency and voltage. They act as a mechanical damper, absorbing excess energy or releasing stored energy as needed.
- To ensure long-term battery health and prevent degradation, it is crucial to apply state-of-charge (SOC) limits, such as maintaining SOC between 40% and 90%. These constraints prevent deep discharge or overcharging, which can extend the lifespan of the battery.

The ESS used in the considered microgrid is based on battery cells with deep cycle lead acid battery cells associated with a controlled bidirectional DC-AC converter.

Table 3. ESS Specifications.

Parameters	Values
Number of Battery	8
Nominal Voltage(V)	48
Rated Capacity(AH)	554
Nominal Discharge Current (A)	27,7

The versatility of a battery storage system, known for its ability to store and release electrical energy, makes it a practical choice for standalone networks seeking self-sustainability. The battery serves dual roles as a virtual load and a power source under different circumstances, making it an attractive solution for diverse electrical networks. Table 3 summarizes the energy storage system specifications that are able to provide a power supply of 10 kW to the network.

2.5. Cable Emulator

The cable emulator in this microgrid system simulates the electrical characteristics of real transmission cables, including resistance and inductance, which induce voltage drops and power losses during energy transfer. Positioned between the main grid's Bus A0 and the RES-connected Bus A1, the cable emulator replicates the physical properties of long-distance transmission lines.

This emulation introduces a consistent voltage drop, demonstrating the effect of real-world cable losses on system performance. By incorporating this emulator, we can assess the impact of transmission line losses on the voltage stability and power flow, ensuring that the microgrid's control strategies are effective under realistic operating conditions.

3. NEW CONTROL STRATEGY OF THE MICROGRID

3.1. The Microgrid combined control strategy

In this paper, we propose a dual (Combined) control strategy based on:

- A closed control (therefore distributed) in the form of droop control at the level of each renewable energy source (PV and Wind turbine) and at the level of the ESS.
- Centralized control and global supervision of the microgrid at the level of the microgrid central controller (MGCC)

These two types of control are described in detail in the following sections.

3.2. Microgrid Central Controller.

Various energy management algorithms have been created to enhance the effectiveness, stability, and security of microgrid operations. In our research, we have developed an algorithm to be implemented at the microgrid central controller (MGCC) to govern the functioning of the AC/ DC microgrid.

The Microgrid Central Controller (MGCC) plays a crucial role in managing the various energy sources within the microgrid. It serves as a centralized control system that collects measurements from different sources and communicates configuration and control actions.

The core of the proposed control strategy is a day-ahead scheduling algorithm, operating at the level of the MGCC. This algorithm schedules the production of the sources for the next 24 hours, using forecasted meteorological conditions, the load demand profile, and the state of charge (SOC) of the batteries.

The input data of the day-ahead scheduling algorithm consists of:

a) Load demand profile
b) Sources of energy and generation limits
c) Limitations of the energy storage system
d) Meteorological data (irradiation, temperature, wind speed)

The outputs of the algorithm are sets of sequential power set-points for each source and ESS. The data provided to the algorithm are meteorological data every 10 minutes. This data is used to estimate the maximum output power of each one of the renewable energy sources, and therefore the maximum of all the renewable energy sources output power at every 10 minutes. These estimations are then used to cover the energy requirement imposed by the consumption profile. To optimize system performance, the MGCC minimizes the total operational cost using the following objective function:

$$min \sum_{t=1}^{N} [C_{Grid}(t) \cdot P_{Grid}(t) + C_{ESS} \cdot |P_{ESS}(t)|] \quad (1)$$

Where:

$P_{Grid}(t)$: Power imported from the main grid
$C_{Grid}(t)$: Unit cost of energy from the grid
$P_{ESS}(t)$: Power charged (+) or discharged (−) from the energy storage system
C_{ESS}: Virtual cost of ESS usage (battery wear factor)

N: Total number of time steps in the 24-hour horizon

The power dispatch must also satisfy the following power balance constraint at every time step:

$$P_{Load}(t) = P_{Pv}(t) + P_{Wind}(t) + P_{Ess}(t) + P_{Grid}(t) \quad (2)$$

$P_{Pv}(t)$,$P_{Wind}(t)$: Power generated by PV and wind turbine at time step t.

$P_{Load}(t)$: Power load consumption at time step t.

Combining this estimation, the load demand profile and the initial and the evolution of the ESS SOC, an optimal dispatching of the output power for each source (Power Set-point) is determined by a step of 10 minutes.

By doing so, the system aims to cover the load demand using local resources while minimizing the amount of energy imported from the main grid. To ensure technical feasibility, the MGCC also enforces grid import constraints, which limit the power drawn from the utility grid at each

time step:

$$0 \leq P_{Grid}(t) \leq P_{Grid}^{max} \quad (3)$$

This condition prevents overloading the grid interface and ensures that the optimization remains within operational boundaries.

However, this centralized macroscopic control does not account for rapid intra-interval fluctuations or forecasting errors, meaning it cannot guarantee real-time balance between generation and consumption. As a result, voltage deviations may occur within the microgrid. To overcome this limitation, a more reactive local control layer—such as droop control—is needed to dynamically regulate voltage and power-sharing in real time.

3.3. Droop Control method

Under certain operating conditions, the operator has the ability to proactively activate power control droop.

This feature allows the microgrid to respond to the voltage deviations by adjusting power generation and consumption. if there's an increase in the load demand in a power system, the system's voltage might drop. In response to this voltage drop, generators operating under droop control will increase their active power output, following the power droop characteristic (see figure 2). By activating power control droop, the microgrid can effectively regulate its own operations and maintain stability even in isolated operating conditions.

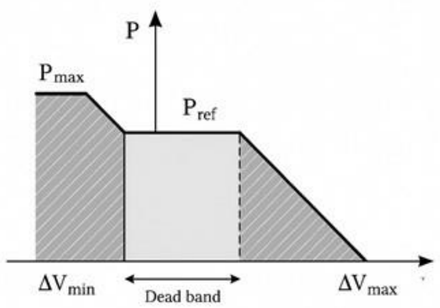

Figure 2. P-V droop for the micro-generation units.

Each renewable energy source—such as the photovoltaic (PV) array and the wind turbine (WT)—has a local P−V droop controller. These controllers operate autonomously, adjusting their power output based on locally sensed voltage values. The general droop control law applied to a source is defined as:

$$P(t) = \begin{cases} P_{ref} + K_p\left(V(t) - V_{ref}\right) & if\ \left(V(t) - V_{ref}\right) > \frac{\Delta V}{2} \\ P_{ref} & overwise \end{cases} \quad (4)$$

Where:
- P(t): Output power of the DER at time t.
- P_{ref}: Nominal or scheduled power set-point (from MGCC)
- V(t): Measured local voltage at time t.
- V_{ref}: Voltage reference
- kp: Droop gain (negative for sources, positive for storage)
- ΔV: Dead band width around Vref

This dead band ΔV ensures that small fluctuations around V_{ref} do not trigger unnecessary adjustments, enhancing system stability.
For the PV system, the droop controller reduces output power when the bus voltage exceeds $V_{ref} + \Delta V/2$, and increases power when voltage drops below $V_{ref} - \Delta V/2$ as long as the power remains within inverter limits.

This is possible due to the ability to continuously adjust the operating point on the V−I characteristic of the PV module. as presented in Figure 3, the ESS power droop control acts in the same manner but activates increasing (resp. decreasing) incoming power (grid to ESS) in response to an overvoltage (resp. Under- voltage). When this power is positive (resp. negative) the battery is in charging (resp. discharging) mode i.e. energy storage, (resp. energy release).
The wind turbine's power droop control employs a dump load to increase/decrease the energy injected in the microgrid effectively. This technique is less flexible and reactive than the power droop control implemented in the PV source.

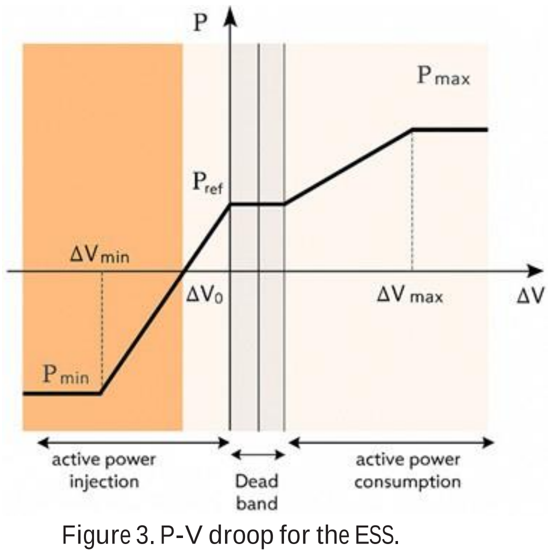

Figure 3. P-V droop for the ESS.

The MGCC's ability to coordinate and regulate the microgrid's energy sources, coupled with the option to activate power control droop, ensures efficient and reliable operation of the microgrid in various grid operating conditions. This will be demonstrated by simulation of different scenarios in the next section.

4. SIMULATION AND RESULT

4.1. Simulation scenarios

An energy management strategy is applied to a microgrid to achieve an objective under certain constraints. Different scenarios can be envisaged. However, whatever the objective, and the considered scenarios, it is fundamental that the applied energy management strategy leads to safe and acceptable microgrid operating voltage and/or frequency. In this section we will show by simulation how the proposed energy management strategy contributes to maintaining voltage to desired interval. The micro grid system is modeled and simulated using MATLAB/Simulink software. The simulation covers a microgrid operating period of 24 hours. Since the available meteorological forecasting data are sampled with period of 10 min, the day-ahead MGCC scheduling algorithm will produce 3*144 power set-points for renewable energy sources and ESS (144*10 min=24 hours, two sources plus one ESS=3). The load is modeled in the simulator as a variable load according to a known (predicted) profile.

To gauge the efficacy of the integrated management system within the low-voltage network, diverse test scenarios were undertaken, encompassing the following conditions:

Scenario 1 – MG operation linked to the main grid during off-peak hours, with a substantial surplus of energy derived from sustainable sources.

Scenario 2 – MG operation connected to the main grid under conditions of high demand, lacking renewable energy generation.

Scenario 3 – The microgrid operating without using the MGCC and the droop control.

Let's emphasize here that, in the considered scenarios, the proposed combined centralized and droop control strategy is not activated all the time. Droop control is deliberately disabled at intervals on one or more renewable sources and/or the ESS, to show the impact on the voltage at microgrid buses, and the dependency on the operation of the microgrid on the main grid.

Furthermore, only what will happen in scenario 1 will be detailed in the subsection 4.2. Scenario 3 gives the behavior of the microgrid without the proposed control strategy, and what will happen in scenario 2 can be easily deduced by the reader from the key points detailed in scenario 1.

4.2. Scenarios Analysis

Scenario 1: Taking into account the system described in Figure 1, the test carried out for Scenario 1 includes the subsequent phases demonstrated by the simulation results presented in Figure 4:

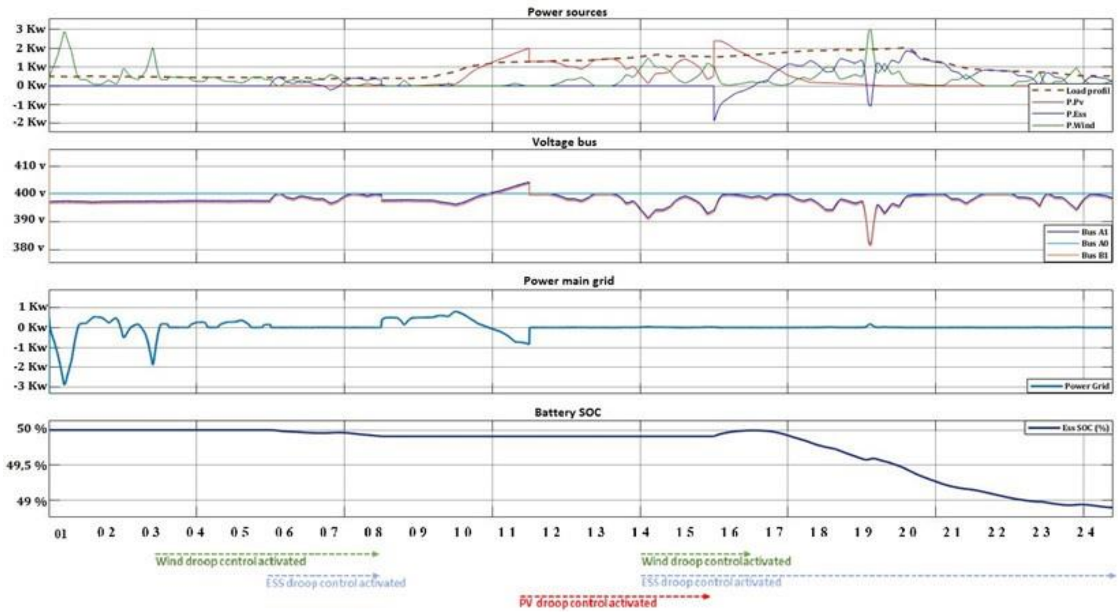

Figure 4. Simulation Results for Scenario 1 (Power Sources(Kw), Voltage(Volts), Grid Power(Kw), State of Charge – SOC(%).

- During the first two hours, only the wind turbine produces fluctuating energy without the droop control activated (PV and ESS are not involved). The main grid contributes to compensate for the negative difference between WT power and load power, and to drain the positive difference of these powers. Thanks to this balancing contribution of the main grid, the voltage remains stable.
- At t1=3h, the MGCC initiates the implementation of the energy management strategy with
- only WT involved as renewable source with droop control activated and main grid as a support, resulting in a reduction in the injected power into the main grid. The latter, however, continues to balance the negative difference (PWT- Pload). The voltage remains stable.
- At t2= 5:30 h, The P-V droop control is activated for the ESS. This allows the ESS to modulate its charge or discharge rate in response to fluctuating WT production minimizing the exchange of energy with the main grid. The Bus B1 voltage fluctuation remains small.
- At t3=8 h, the MGCC decides to deactivate the droop control for both the WT (low production) and the ESS, the main grid contributes to balance the load demand, which becomes increasing. Subsequently, at t=10 h, the solar power generation is involved.
- Due to the fact that the voltage at node B1 fluctuation becomes consistent at t4=11 h, the MGCC initiates the strategy to activate the P-V droop control in PV. The power no longer injected into the grid is shared between the two micro-generation units (PV with droop control and WT without); Note the Bus B1 voltage before and during the WT production.
- At t5=14 h, the WT production becomes more consistent The MGCC activates droop control also on the WT and the ESS, but at this stage, the ESS neither produces nor consumes energy, WT and PV cover the load demand. Bus B1 voltage fluctuates since WT and PV are not on the same bus.

- At t6=15:30h, the MGCC deactivates droop control for the solar power generation system. This means that the solar system will no longer adjust its output based on grid voltage changes. The surplus of PV production is stored in the ESS. The Bus B1 voltage becomes more stable.
- At t7= 16h30 while droop control is only activated for the ESS, the WT production experiences at instant t8=19h30 a high positive impulse, which involves the ESS for compensation, since the PV production is very small, consequently, there is a high under-voltage on Bus B1.

Scenario 2: In this scenario the microgrid central controller (MGCC) continues to employ the same actions when activating the distributed droop control, as in the first scenario, while facing a high load demand that exceeds the available renewable energy generation.

Scenario 3: Scenario 3 evaluates the microgrid's baseline operation with all control layers disabled: MGCC scheduling inactive, droop control deactivated, and grid-connected mode to compensate for imbalances.

4.3. Results

What we can retain from figure 4 is summarized by the following:

- At the beginning of Scenario 1 (1h-3h), and without any droop control, the microgrid relies on the main grid to balance production (fluctuating from WT) and consumption. While the consumption is constant, the injected/absorbed energy by the microgrid in/from the main grid has the same fluctuation of the WT source. The voltage remains constant.
- When the WT droop control (3h-6h) is activated by the MGCC, the energy exchange with the main grid becomes very limited. This exchange vanishes when the droop control is activated on the ESS (6h-8h: the power flow from/to the ESS adjustment is driven by the voltage fluctuations.
- The microgrid relies on the main grid when the WT and ESS droop control are disabled again (8h-11h30). The level of Over/under voltage reflects the flow energy direction and quantity to/ from the main grid.
- When the droop control is activated on the WT, the PV and the ESS and the load is increasing, it is up to the MGCC to dispatch the production to the sources and the ESS to balance the consumption, using the production forecast (14h-16h30)
- When the droop control on the only source WT with available production is disabled, and it is activated on the ESS, a high impulse in the source production leads in high under-voltage at level of the bus where the ESS is connected, if the objective is to store all the surplus of WT production (t=19h30).

In this phase, results demonstrated a 72% reduction in grid power exchange during droop-controlled operation compared to uncontrolled periods, while voltage deviations were limited to ±3% versus ±7.8% without control. Additionally, ESS participation helped reduce peak grid imports by 63% during renewable production variability

In Scenario 2, the microgrid (MG) encounters a situation where the load demand surpasses the available renewable energy generation. However, the MGCC continues to use the same actions as in the first scenario to maintain stable operation. In this case, the MGCC relies on the energy stored in the energy storage system (ESS) to ensure the continuity and stability of the service, without interacting with the main grid. In quantitative terms, the ESS successfully covered 89% of power deficits during high-demand periods and the Voltage remained within ±2,7% of nominal values. Furthermore, the required support from the main grid was reduced by 82% compared to an uncontrolled scenario.

By effectively utilizing the energy stored in the ESS, the MGCC successfully bridges the gap between the high load demand and the limited renewable energy generation, enabling uninterrupted power supply and maintaining the stability of the microgrid system, as shown in Figure 5.

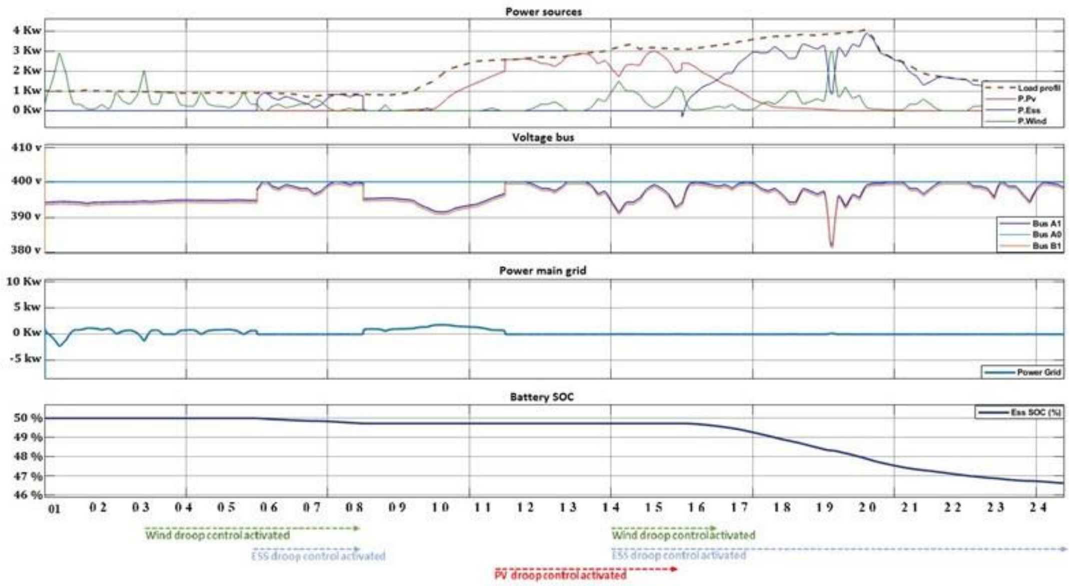

Figure 5. Simulation Results for Scenario 2 (Power Sources(Kw), Voltage(Volts), Grid Power(Kw), State of Charge – SOC(%).

The findings from Scenario 3 presented in Figure 6 highlight the microgrid operating without using the MGCC. While this demonstrates typical functioning, it also exposes the difficulties caused by voltage fluctuations due to the intermittent nature of renewable energy sources.

During this uncontrolled case, voltage deviations exceeded ±7.8% of the nominal value. Grid power exchange variability was 3.2 times higher than in Scenario 1, and the frequency of triggering protection events increased.

In real-life situations, these challenges could trip the protection systems of the low-voltage distribution network, disconnecting the microgrid's production sources. This emphasizes the need for sophisticated control strategies, such as those provided by the MGCC, to successfully manage and mitigate the impact of variable voltage from renewable energy sources. The implementation of such control measures is critical to maintaining the stable and reliable performance of the microgrid.

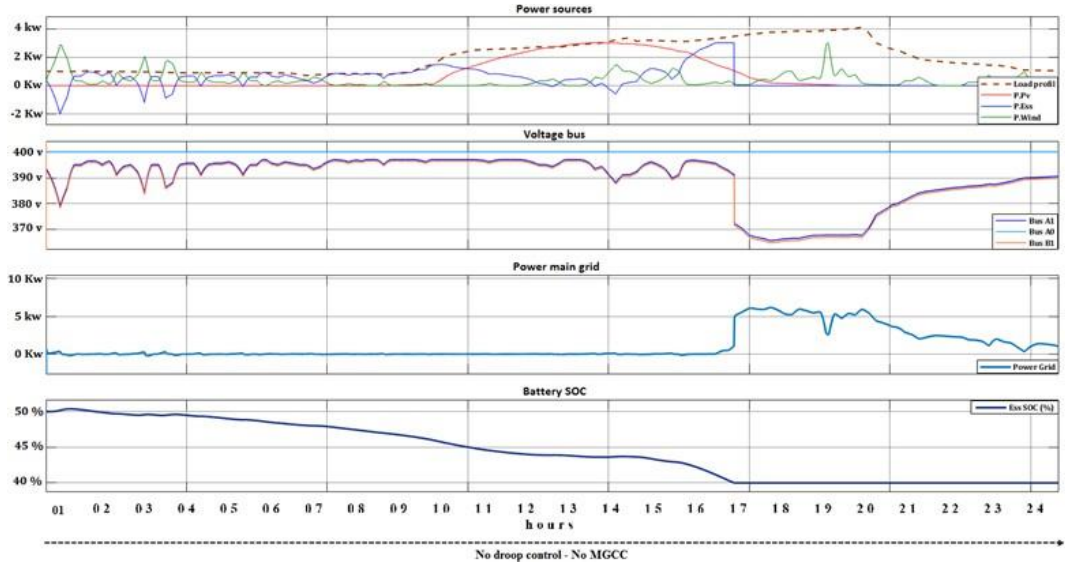

Figure 6. Simulation Results for Scenario 3 (Power Sources(Kw), Voltage(Volts), Grid Power(Kw), State of Charge – SOC(%).

5. CONCLUSION

This paper proposed a hybrid control strategy that integrates a centralized Microgrid Central Controller (MGCC) with local droop controllers to enhance the stability and operational efficiency of an AC microgrid. Simulation results across various scenarios demonstrated notable improvements in voltage regulation, reduced grid dependency, and optimized energy dispatch. Compared to uncontrolled operation, the proposed method achieved up to a 72% reduction in grid power exchange. In the high load demand scenario, voltage deviations were kept within ±2.7%, and peak grid imports were reduced by as much as 82% during renewable energy fluctuations. These findings confirm the robustness of the dual-layer control strategy and highlight its potential for real-time experimental validation in future work.

Authors contribution: Achraf Boukaibat, Contribution: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing the Original Draft.
Nissrine Krami, Contribution: Conceptualization, Resources, Writing – Review & Editing, Supervision, Project Administration
Youssef Rochdi, Contribution: Conceptualization, Validation, Supervision
Yassir El Bakkali, Contribution: Validation
Funding: The work presented in this paper was funded by the Moroccan Research Institute for Solar Energy and New Energies (IRESEN) under the HOLSYS project.
Data Availability Statement: The data generated and analyzed in this study are proprietary to the Smart-Grid Laboratory of Ibn Tofail University and cannot be shared publicly.
Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. I have nothing to declare.

Acknowledgements:
The authors would like to thank the Smart-Grid Laboratory at Ibn Tofail University for providing the experimental platform and technical support necessary for this work. The authors also acknowledge the valuable guidance and feedback provided by colleagues and supervisors throughout the development of this study.

REFERENCES

[1] Wang Y, Liu Y, Sun H, Li F. 2023. Distributed secondary control for frequency restoration and power sharing in islanded AC microgrids. IEEE Transactions on Smart Grid. 14(1):321–332.
[2] Zhang L, Alammari RA, Guerrero JM. 2022. Robust hierarchical control of grid-connected microgrids with renewable energy sources. International Journal of Electrical Power & Energy Systems. 138:107903.
[3] Zranzese P, Ribera M, Cervone A, Iannuzzi D. 2023. Optimized control strategy for single-phase multilevel cascaded converter in a distributed PV-BESS system. Electric Power Systems Research. 214:108818.
[4] Zhao J, Wang Z, Ma K. 2022. Real-time decentralized energy scheduling in multi-microgrid systems under uncertainty. Applied Energy. 314:118983
[5] Rezaei M, Ghassemi A. 2023. Coordinated secondary control of low-voltage DC microgrids based on adaptive sliding mode techniques. IEEE Access. 11:43478–43489.
[6] Shukla RR, Garg MM, Panda AK. 2024. Driving grid stability: Integrating electric vehicles and energy storage devices for eficient load frequency control in isolated hybrid microgrids. Journal of Energy Storage. 89:111654.
[7] Liu T, Li X, Han Y. 2022. Stability-oriented distributed control of DC microgrids with electric springs. Renewable Energy. 194:936–949.
[8] Jha SK, Kumar D, Lehtonen M. 2021. Modified V-I droop based adaptive vector control scheme for demand side management in a stand-alone microgrid. International Journal of Electrical Power & Energy Systems. 130:106950.
[9] Bayat M, Farahani M, Ghadimi AA, Tostado-Véliz M, Miveh MR, Jurado F. 2023. Optimal siting, sizing and setting of droop-controlled DERs in autonomous microgrids: A new paradigm in microgrid planning. Electric Power Systems Research. 225:109850.
[10] Rajasekar N, Bilakanti N, Miyatake M, Thirunavukkarasu GS, Seyedmahmoudian M, Jamei E, Horan B, Mekhilef S, Stojcevski A. 2022. Role of optimization techniques in microgrid energy management systems—A review. Energy Strategy Reviews. 43:100899.
[11] Choudhury S, Varghese GT, Mohanty S, Kolluru VR, Bajaj M, Blažek V, Prokop L, Mišák S. 2023. Energy management and power quality improvement of microgrid system through modified water wave optimization. Energy Reports. 9:6020–6041.
[12] Liu J, Wang H. 2023. Hierarchical centralized control of smart microgrids under communication latency. IEEETransactions on Industrial Informatics. 19(1):345–356.
[13] Al-Ghussain L, Guerrero JM. 2022. Centralized energy scheduling for islanded microgrids:Challenges and solutions. Energies. 15(6):2120.
[14] Bukhsh WA, Qureshi R. 2023. Enhanced droop control for resilient microgrid operation in high-R/X ratio systems. Electric Power Systems Research. 213:108918.
[15] Ramos-Paja CA, Peña RA. 2022. Decentralized secondary voltage regulation using consensus-based control. Renewable Energy. 195:875–884.
[16] Zhang X, Sun Y. 2023. Multi-level coordinated control of MGCC and local agents in hybrid microgrids. International Journal of Electrical Power & Energy Systems. 146:108775.
[17] Shahnia F, Ghosh A. 2022. Real-time hybrid control of inverter-based microgrids using predictive droop schemes. IEEE Access. 10:53324–53338.
[18] Ranjbar AM, Taheri S. 2023. Energy optimization in hybrid microgrids using genetic algorithm-based EMS. Applied Soft Computing. 132:109953.
[19] Nasiri M, Golkar MA. 2024. Real-time adaptive EMS in microgrids using deep reinforcement

learning. Journal of Cleaner Production. 438:140499.
[20] Yilmaz A, Ceylan I. 2023. Predictive energy management with uncertainty modeling for renewable-based microgrids. Renewable Energy. 207:1088–1102.
[21] Khalid M, Rehman S. 2023. Review of EMS techniques in microgrids: Classification, comparison, and challenges. Energy Reports. 9:502–519.
[22] Da Silva CA, Torres L. 2022. Comparative analysis of centralized, decentralized, and distributed energy management approaches. Sustainable Energy Technologies and Assessments. 53:102517.
[23] Rezaei M, Ghassemi A. 2023. Coordinated secondary control of low-voltage DC microgrids based on adaptive sliding mode techniques. IEEE Access. 11:43478–43489.
[24] Shukla RR, Garg MM, Panda AK. 2024. Driving grid stability: Integrating electric vehicles and energy storage devices for eficient load frequency control in isolated hybrid microgrids. Journal of Energy Storage. 89:111654.
[25] Liu T, Li X, Han Y. 2022. Stability-oriented distributed control of DC microgrids with electric springs. Renewable Energy. 194:936–949.
[26] Jha SK, Kumar D, Lehtonen M. 2021. Modified V-I droop based adaptive vector control scheme for demand side management in a stand-alone microgrid. International Journal of Electrical Power & Energy Systems. 130:106950.
[27] Bayat M, Farahani M, Ghadimi AA, Tostado-Véliz M, Miveh MR, Jurado F. 2023. Optimal siting, sizing and setting of droop-controlled DERs in autonomous microgrids: A new paradigm in microgrid planning. Electric Power Systems Research. 225:109850.
[28] Rajasekar N, Bilakanti N, Miyatake M, Thirunavukkarasu GS, Seyedmahmoudian M, Jamei E, Horan B, Mekhilef S, Stojcevski A. 2022. Role of optimization techniques in microgrid energy management systems—A review. Energy Strategy Reviews. 43:100899.
[29] Choudhury S, Varghese GT, Mohanty S, Kolluru VR, Bajaj M, Blažek V, Prokop L, Mišák S. 2023. Energy management and power quality improvement of microgrid system through modified water wave optimization. Energy Reports. 9:6020–6041.
[30] Liu J, Wang H. 2023. Hierarchical centralized control of smart microgrids under communication latency. IEEETransactions on Industrial Informatics. 19(1):345–356.
[31] Al-Ghussain L, Guerrero JM. 2022. Centralized energy scheduling for islanded microgrids:Challenges and solutions. Energies. 15(6):2120.
[32] Bukhsh WA, Qureshi R. 2023. Enhanced droop control for resilient microgrid operation in high-R/X ratio systems. Electric Power Systems Research. 213:108918.
[33] Ramos-Paja CA, Peña RA. 2022. Decentralized secondary voltage regulation using consensus-based control. Renewable Energy. 195:875–884.
[34] Zhang X, Sun Y. 2023. Multi-level coordinated control of MGCC and local agents in hybrid microgrids. International Journal of Electrical Power & Energy Systems. 146:108775.
[35] Shahnia F, Ghosh A. 2022. Real-time hybrid control of inverter-based microgrids using predictive droop schemes. IEEE Access. 10:53324–53338.
[36] Ranjbar AM, Taheri S. 2023. Energy optimization in hybrid microgrids using genetic algorithm-based EMS. Applied Soft Computing. 132:109953.
[37] Nasiri M, Golkar MA. 2024. Real-time adaptive EMS in microgrids using deep reinforcement learning. Journal of Cleaner Production. 438:140499.
[38] Yilmaz A, Ceylan I. 2023. Predictive energy management with uncertainty modeling for renewable-based microgrids. Renewable Energy. 207:1088–1102.
[39] Khalid M, Rehman S. 2023. Review of EMS techniques in microgrids: Classification, comparison, and challenges. Energy Reports. 9:502–519.
[40] Da Silva CA, Torres L. 2022. Comparative analysis of centralized, decentralized, and distributed energy management approaches. Sustainable Energy Technologies and Assessments. 53:102517.