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# Optimizing real-time energy control in hybrid low-voltage microgrids using a multi-agent approach

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**ABSTRACT**

This research proposes a real-time framework for energy management and control in hybrid low-voltage microgrids (LVMGs) through multi-agent systems (MAS). The proposed framework enables decentralized and autonomous coordination among renewable energy sources, energy storage systems, loads, and the utility grid to dynamically optimize power flows under varying operating conditions. Each agent adjusts its setpoints using local information while cooperating with other agents to achieve global objectives. The MAS is implemented using The Java Agent Development Framework (JADE) and co-simulated with MATLAB/Simulink to accurately represent the microgrid's physical behavior. Simulation results under grid-connected and islanded modes demonstrate that the proposed approach increases renewable energy utilization by up to 10% and reduces total energy costs by 7.6% compared to conventional centralized control schemes. Moreover, the system exhibits strong adaptability and robustness in the presence of renewable intermittency and load fluctuations, ensuring reliable real-time operation. These results confirm that MAS-based control provides an effective, scalable, and resilient solution for real-time energy management in hybrid LVMGs.



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## 1. INTRODUCTION

The growing incorporation of renewable energy sources (RES) like solar photovoltaic (PV) and wind turbines into low-voltage microgrids (LVMGs) supports the development of robust, eco-friendly power networks [1], [2]. Yet, their variable output poses major hurdles in energy oversight, especially for matching supply, storage, and demand. Hybrid microgrids (MGs) that blend diverse RES with energy storage systems (ESS) address these issues, but demand sophisticated management tactics for optimal performance [3].

Traditional centralized energy management systems are often insufficient to address the complexity and decentralization of modern hybrid microgrids [4]. In this context, multi-agent systems (MAS) have emerged as a promising solution. MAS allows the use of autonomous agents representing different components of the microgrid, such as renewable generators, storage systems, and loads, that can independently make decisions based on local conditions while collaborating to achieve system-wide objectives [5]. The decentralized decision-making process enabled by MAS makes it possible to dynamically adjust energy flows, thereby improving energy efficiency and operational resilience [6].

Recent studies have demonstrated that MAS-based control strategies significantly enhance the flexibility and scalability of energy management in microgrids, especially when dealing with fluctuating RES outputs [7]. The real-time adaptability of MAS makes it particularly suitable for environments where rapid changes in supply and demand are the norm, as is the case with hybrid LVMGs [1]. In addition, MAS allows for the integration of various optimization techniques that can minimize operational costs and enhance the use of renewable energy resources [8].

This study outlines a MAS structure for managing energy in real-time within hybrid LVMGs. Built on the Java Agent Development Framework (JADE) platform, it facilitates collaboration among agents that embody various microgrid elements, refining energy allocation by factoring in pricing dynamics, load variations, and supply constraints [9]. MATLAB/Simulink simulations verify the framework's capability to streamline power flows effectively in hybrid setups. The document proceeds with section 2 surveying prior MAS applications in microgrid oversight; section 3 detailing the MAS design and optimization steps; section 4 analyzing simulation outcomes on efficiency, expenses, and reliability; and section 5 summarizing insights alongside prospective research paths.

## 2. RELATED WORK

Research on MAS for microgrid control has gained prominence owing to their effectiveness in addressing the decentralized and intricate dynamics of contemporary power networks. Conventional centralized methods frequently falter when coping with the erratic output from renewables like solar panels and wind generators, notably within hybrid LVMGs [10].

Logenthiran *et al*. [11] developed a MAS approach for real-time microgrid control. Their findings showed that distributed agents modeling different generators and consumers effectively respond to shifts in power generation and usage. By distributing control tasks among multiple agents, the system achieved greater flexibility and resilience compared to centralized control schemes.

Similarly, Sun *et al.* [6] investigated the integration of MAS with real-time optimization algorithms in hybrid energy systems. Their research focused on managing energy resources under carbon trading regulations, showing that MAS could reduce energy costs while maintaining compliance with environmental regulations. The study emphasized the potential of MAS to facilitate energy trading between microgrids and improve overall system efficiency.

El Mezdi *et al.* [12] applied MAS in a grid-connected hybrid microgrid, incorporating renewable energy sources and battery storage systems. Their findings indicated that MAS could optimize energy flow in the system, resulting in reduced operational costs and enhanced grid stability. The decentralized nature of MAS allowed for local decision-making while maintaining global coordination among all microgrid components.

Despite these advancements, challenges remain, particularly in terms of scalability. As microgrids grow in complexity, the ability of MAS to scale while maintaining efficient coordination between agents becomes increasingly important. Furthermore, integrating machine learning techniques into MAS for predictive [13], [14].

In summary, prior research endorses the reliability of MAS for hybrid microgrid oversight. Yet, additional studies must tackle scalability hurdles and predictive analytics fusion within MAS designs. This paper extends those foundations through a MAS-centric strategy for real-time energy control in hybrid LVMGs, stressing energy distribution optimization and cost cuts.

## 3. METHOD

The introduced energy management structure relies on a MAS to regulate and refine power flows within a hybrid LVMG. This section describes the configuration and deployment of the MAS structure, which integrates diverse renewable sources, energy storage systems (ESS), and demand elements for real-time monitoring.

### 3.1. Multi-agent system architecture

The MAS architecture consists of autonomous agents, each representing a specific component of the microgrid, such as PV panels, wind turbines, battery storage, and loads. Each agent is responsible for managing the energy generation or consumption of its respective component. These agents make decisions based on local data (e.g., current energy production or consumption), but they also communicate with other agents to ensure the global objectives of the microgrid are met [8]. Agents' roles in the MG are the following:

i) Generation agents (PV and Wind): These agents continuously monitor their energy production based on local environmental conditions (e.g., solar irradiance, wind speed). They adjust their output accordingly and communicate with the battery storage agent when there is excess energy available for storage [15].

ii) Battery storage agent: This agent manages energy storage and dispatch. It stores excess energy during periods of high production and releases energy when production is low or demand is high [16]. The battery agent also communicates with the generation agents to ensure optimal use of stored energy.
iii) Load Agents: These agents represent the consumption points within the microgrid. They communicate their demand to the generation and battery agents, allowing the system to balance supply and demand in real-time [17].
iv) Grid connection agent: This agent is responsible for managing imports or exports of electricity between the microgrid and the external grid. When local generation is insufficient to meet demand, it imports energy. Conversely, if there is an energy surplus, it exports excess electricity to the grid.

Agents function autonomously yet collaborate via communication to maximize system-wide energy performance. For example, when renewable output peaks, production agents liaise with storage agents to stockpile surplus power [18]. During periods of low renewable energy generation, the agents work together to decide whether to draw energy from the battery storage or import electricity from the grid, depending on current conditions [17].

### 3.2. Algorithm for energy management

Algorithm 1 outlines the steps taken by the MAS to manage the energy distribution and ensure stability in the microgrid. The algorithm provides a high-level overview of the decision-making process used by the MAS to manage energy flows within the microgrid. It ensures that energy demand is met either through local generation, battery storage, or grid imports, depending on the real-time state of the system.

Algorithm 1. MAS-based energy management algorithm

Input: $P_{PV}$ (power from PV), $P_{Wind}$ (power from wind), $P_{Loads}$ (load demand), $SoC$ (state of charge of battery),
$P_{Grid}$ (power from grid), $P_{Gen}$ (power from generator), $P_{Batt}$ (power from battery), Set thresholds for $SoC$ (30% min, 100% max) and desired system parameters
Measure power from all sources ($P_{PV}$, $P_{Wind}$) and loads ($P_{Loads}$). Compute total generation: $P_{Prod} = P_{PV} + P_{Wind}$
while *True* do
  if $PProd \geq PLoads$ then
    Case 1: Production meets or exceeds demand; Supply loads directly from $P_{Prod}$
    if $SoC$ < 100% then
      Store excess energy in battery: $P_{Batt} \leftarrow P_{Prod} - P_{Loads}$
    else
      Export excess energy to grid: $P_{Grid} \leftarrow P_{Prod} - P_{Loads}$
    end
  else
    Case 2: Production is less than demand
    if $SoC$ > 30% then
      Supply loads from $P_{Prod}$ and use battery to cover the deficit: $P_{Batt} \leftarrow P_{Loads} - P_{Prod}$
    else
      Import energy from the grid or start generator
      if $P_{Grid} > 0$ then
        Import from grid: $P_{Loads} \leftarrow P_{Prod} + P_{Grid}$
      else
        Activate generator: $P_{Gen} \leftarrow P_{Loads} - P_{Prod}$
      end
    end
  end
  Update $SoC$ and agent states
end

### 3.3. Optimization process

The core of the MAS optimization process involves determining the optimal setpoints for each microgrid component to minimize energy costs and ensure reliability. The optimization is performed in real-time using predictive algorithms based on the current state of the microgrid and forecasted energy demand and supply [19]. The optimization follows a decentralized approach: Each agent independently makes decisions based on its local conditions while coordinating with other agents through a communication protocol [20]. The MAS implementation employs the Java Agent Development Framework (JADE), facilitating decentralized choices and instantaneous agent synchronization [11], [21].

### 3.4. Simulation environment

To validate the proposed MAS framework, a simulation setup is created using MATLAB/Simulink. This environment replicates energy dynamics in the microgrid, factoring in real fluctuations in energy pricing, demand variability, and renewable intermittency [12]. The hybrid LVMG includes photovoltaic panels, wind turbines, diesel generators, and battery storage systems, capable of operating in grid-connected or islanded modes (see Figure 1) [22]. In grid-connected mode, the MAS prioritizes renewable energy usage while reducing grid imports; during islanded mode, it manages storage and invokes load shedding to stabilize the system amid energy shortfalls [6].

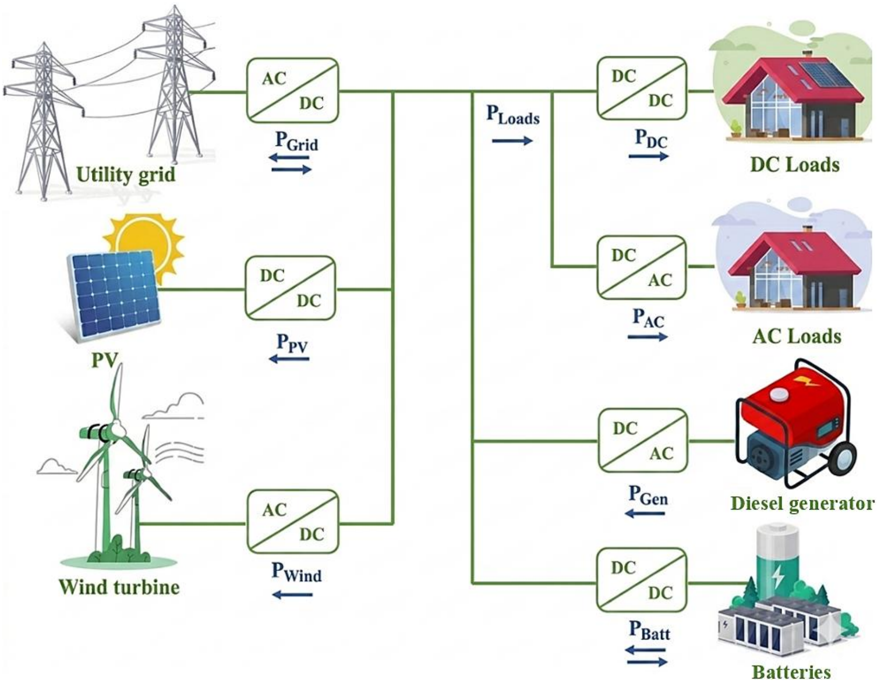



Figure 1. Hybrid low-voltage microgrid architecture system

### 3.5. Key performance indicators (KPIs)

Energy cost savings, renewable energy utilization, and system stability are key performance indicators (KPIs) employed to evaluate the MAS framework's effectiveness [17]. Simulation outcomes are assessed against these KPIs to measure the success of the MAS in optimizing energy management within the hybrid LVMG key performance indicators (KPIs), energy cost savings, renewable energy utilization, and system stability [13], [23].

## 4. RESULTS AND DISCUSSION

The proposed MAS framework was evaluated through extensive simulations using MATLAB/Simulink, with the key objective of optimizing energy distribution in a hybrid LVMG under varying operational conditions. This section presents the key findings from the simulation, highlighting the impact of the MAS on energy efficiency, cost reduction, and grid stability.

### 4.1. Scenario conception

The hybrid energy system is composed of a PV installation with a capacity of 9.9 kW, utilizing 30 solar panels rated at 330 W each. Additionally, a 10 kW wind turbine complements the energy production. The system is equipped with batteries providing 12.5 kWh of storage capacity, allowing excess energy to be stored for later use. A 10 kW hybrid inverter manages the energy flows, ensuring efficient operation both with and without battery support.

Renewable energy production is subject to seasonal and climatic variations, with solar panels affected by sunlight and temperature, while wind turbines depend on wind patterns. To account for these factors, various production scenarios are considered across the year. Each scenario represents an average daily energy output for a specific period, taking into account the fluctuations in energy generation and consumption [24]. Figure 2 presents one of the analyzed scenarios, showing the available energy production under typical conditions for this period. This figure illustrates the variability in renewable energy generation, driven by factors such as solar radiation and wind activity, and offers insights into the system's performance during this time.

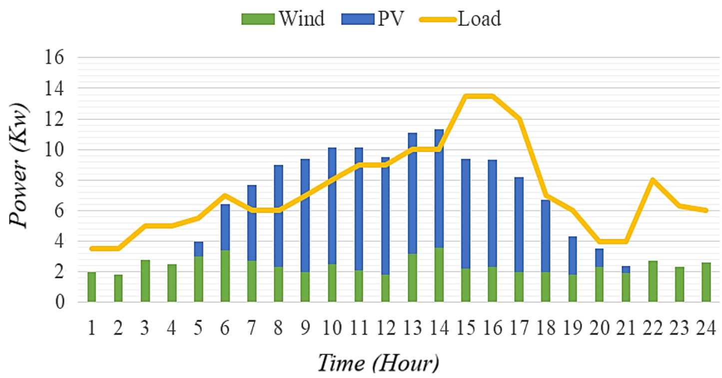
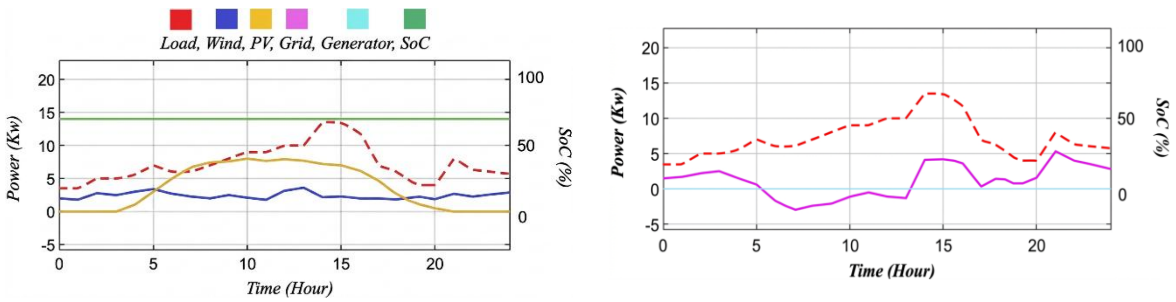



Figure 2. Projected renewable energy production scenario for a key month in the analysis

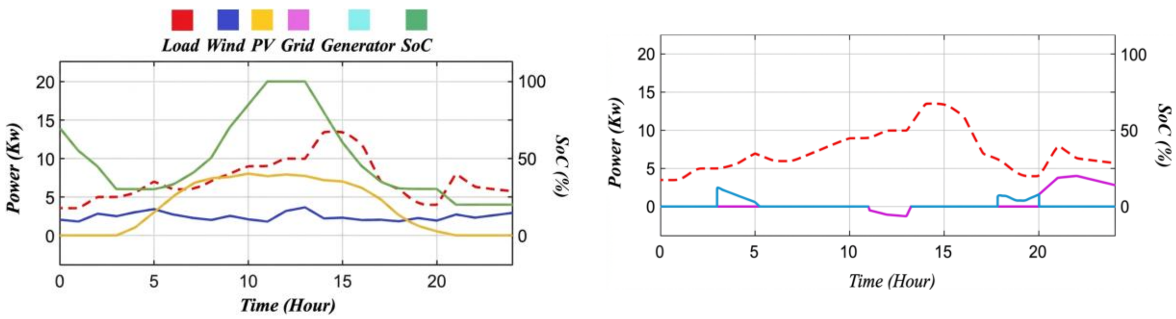
## 4.2. Energy efficiency

The MAS-based control system significantly improved energy efficiency by dynamically adjusting the power flows between renewable sources, battery storage, and loads. The optimization of energy allocation resulted in a 10% increase in the utilization of renewable energy sources compared to a traditional centralized control approach. Figures 3 and 4 compare renewable energy utilization with and without MAS optimization.




(a) (b)

Figure 3. Energy utilization and supply without MAS optimization: (a) RES and batteries and (b) diesel generators and utility grid




(a) (b)

Figure 4. Energy utilization and supply with MAS optimization: (a) RES and batteries and (b) diesel generators and utility grid

To not impact the microgrid's stability during the transition from the isolated mode to the grid-connected mode, the call to the grid is made progressively by covering a part of the demand by the batteries. As shown in Figure 4, starting from time 20:00, the call to the grid is made progressively, which limits the peak load by the batteries. The battery is initially at 70%, it stops supplying energy at 30% for safety reasons, except when switching to the grid with a peak load it is necessary to cover part of the load for utility grid stability. Diesel generators are also needed when the batteries cannot supply the load and electricity from the grid is no longer available due to a power outage. A microgrid's energy efficiency gauges its capacity to generate power relative to usage demands. In the hybrid LVMG, renewables comprise wind (2.4 kW average, 57.8 kWh daily) and PV systems (5.4 kW average over 17 hours, 91.8 kWh daily), yielding 149.6 kWh total. Loads include steady demand (3.5 kW × 24h = 84 kWh) plus variable loads (3.5-13.5 kW over 22 h = 90.72 kWh), totaling 174.72 kWh consumption. The renewable coverage ratio—produced RES divided by total consumption—reaches 85.6%, demonstrating robust sustainability through predominant clean energy reliance, as shown in Table 1.

Table 1. Energy production and consumption in the hybrid LVMG

| Energy source | Production (kWh) | Consumption (kWh) |
|---|---|---|
| Wind energy | 57.8 | - |
| Photovoltaic energy | 91.8 | - |
| Total renewable energy produced | 149.6 | - |
| Constant load (10 hours, 10 kW) | - | 84 |
| Variable load (16 kW to 19.6 kW, 10 hours) | - | 90.72 |
| Total energy consumed | - | 174.72 |
| Renewable energy coverage rate | 85.6% | |

### 4.3. Cost reduction

The MAS framework also contributed to significant reductions in operational costs. By optimizing the timing of energy imports from the grid and the use of battery storage, the total energy costs were reduced by 7.6%. The cost savings achieved through the MAS optimization are presented in Table 2.

Table 2. MAS cost-saving achievement

| Scenario | Centralized control | MAS optimization |
|---|---|---|
| Energy costs (€/kWh) | 0.18 | 0.15 |
| Renewable utilization (%) | 78 | 85.6 |
| Total savings (%) | - | 7.6 |

### 4.4. System stability

The MAS framework demonstrated robust performance in maintaining system stability, particularly during periods of fluctuating energy supply from renewable sources [25]. The decentralized decision-making process enhances real-time adaptation of the system to changes in energy availability, preventing grid overloads and ensuring a continuous, stable energy supply even when disconnected from the main grid. In the scenario illustrated, the system operates in grid-islanded mode for the majority of the day, but from 20:00 to 24:00 and from 11:00 to 13:23, the system transitions into grid-connected mode. During this period, the MAS efficiently manages the available renewable energy and energy storage systems to meet demand. The system's ability to preserve a balanced supply and demand without relying on grid imports showcases the robustness of the MAS in managing off-grid operations under varying conditions. Figure 4 illustrates this transition, highlighting the system's performance when disconnected from the grid, and demonstrates how the MAS maintains stability by prioritizing energy storage and load management during islanded operation.

## 5. CONCLUSION

This study introduces a MAS framework aimed at enhancing energy management within hybrid LVMGs. The decentralized MAS facilitates real-time interaction among renewable sources, battery storage, and load demands, leading to better energy efficiency and improved system stability. Simulation outcomes reveal a 10% rise in renewable energy utilization and a 7.6% decrease in total energy costs. Furthermore, the system showed remarkable resilience when operating in islanded mode, effectively balancing supply and demand during grid disconnections. The ability of the MAS to adapt to fluctuating energy supply from renewable sources, and to manage energy storage and load shedding during off-grid operation, highlights its potential for enhancing the reliability and sustainability of microgrids.

Future work will focus on enhancing the MAS by incorporating predictive algorithms and machine learning techniques to further improve energy forecasting and optimization. Additionally, the scalability of the framework will be explored to ensure that it can manage larger, more complex microgrid architectures and integrate with other microgrids for energy trading and collaboration. Overall, the MAS offers a robust, flexible, and modern alternative for energy systems that prioritize both economic and environmental sustainability.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| Adil Mansouri | ✓ | | | | | | | | | ✓ | ✓ | | | |
| Rachid Lajouad | | | | | ✓ | | ✓ | | | ✓ | ✓ | ✓ | | ✓ |

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

## CONFLICT OF INTEREST STATEMENT
Authors state no conflict of interest.

## DATA AVAILABILITY
Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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