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Original Research Article

Optimizing Unit Commitment in Micro Grid Hybrid Power Systems Through Synchronization for Cost-Effective Energy Production

[1]Gwaivangmin, B.I., [1]Bakare, G.A., [1]Haruna, Y.S., [1]Amoo, A.L. and [2]Ali, M.T.

[1]Department of Electrical and Electronics Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria.
[2]Computer Engineering Technology Department, Ramat Polytechnic, Maiduguri, Nigeria.
gwaivangminb@gmail.com

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ABSTRACT

The global scarcity of electrical energy necessitates exploring cost-effective power production methods, particularly through hybridizing power sources. Synchronization is a key process that facilitates seamless transitions between power sources and reduces power generation costs in hybrid systems. This study examined the unit commitment of a microgrid comprising four power generation sources: diesel generators, solar photovoltaic (PV) systems, pumped hydro energy storage systems, and public power supply. Two scenarios are analyzed: one without a synchronizer and the other incorporating a synchronizer. The results demonstrate that the scenario with a synchronizer achieves a lower unit commitment cost, highlighting the economic benefits of synchronization in hybrid power generation systems. Specifically, using Hybrid particle swarm optimization-Ant colony optimization (HPSO-ACO) with a synchronizer for a 24 hours period reduces costs to ₦55,088.00, compared to ₦78,888.00 without a synchronizer, reflecting a 30.16% cost reduction.

1. INTRODUCTION

Synchronization in a microgrid aligns the phase, frequency, and voltage of different power sources before connecting them to the grid or each other, ensuring a stable and reliable power supply. This is especially important for hybrid systems integrating diesel generators, solar PV systems, and pumped hydro energy storage. As the demand for sustainable and cost-effective energy solutions increases, synchronization becomes increasingly crucial (Molu *et al.,*2024; Ali *et al.*2024). Recent advancements have shown that synchronization significantly impacts the cost of power supply generation. Effective synchronization enables seamless transitions between power sources, optimizing renewable energy use and reducing reliance on more expensive or less environmentally friendly options. For instance, synchronized switching to diesel generators or energy storage systems when solar PV output fluctuates ensures continuous power supply without incurring substantial costs (Shayan *et al.*, 2023; Nemova *et al.,* 2024). Synchronization enhances operational efficiency and contributes to economic savings by reducing fuel consumption and maintenance costs from frequent start-stop cycles of diesel generators. It also helps maintain the balance between supply and demand, avoiding penalties related to load shedding and improving power system reliability (Shahzad *et al.,* 2023; Naseri *et al.*, 2024; Adeyinka *et al.* 2024). Several studies have highlighted the economic benefits of synchronization in hybrid power systems. Nemova *et al.* (2021) demonstrated that integrating synchronization mechanisms in microgrids reduced operational costs by 15% and improved power supply reliability in remote areas. Similarly, Elalfy *et al.* (2024) and Habibi *et al.* (2024) found that synchronized operation of renewable energy sources and traditional generators significantly lowered the levelized cost of electricity in islanded microgrids.

Research highlighted the importance of advanced synchronization techniques, such as phase-locked loops and virtual synchronous machines, in enhancing the stability and economic performance of microgrids (Arrar and Xioaning, 2022; Dangeti., 2023). These studies underscore the critical role of synchronization in achieving cost-effective and sustainable energy solutions.

In this context, the present study examines the unit commitment of four power generation sources—diesel generators, solar PV systems, pumped hydro energy storage systems, and public power supply—under two scenarios: one without a synchronizer and the other incorporating a synchronizer. The findings demonstrate that incorporating synchronization enhances operational efficiency and leads to significant cost savings in power generation.

Saeed *et al.* (2021) and Agupugo *et al.* (2024) emphasized that proper synchronization mechanisms are vital for the stable operation of microgrids, especially when incorporating intermittent renewable energy sources. They argue that synchronization enhances reliability and reduces operational complexity and costs associated with balancing supply and demand in real-time. Studies have shown that advanced synchronization techniques can lead to significant cost savings by optimizing the dispatch of various energy resources within a microgrid (Shafiullah *et al.,* 2021; Khan *et al*., 2024; Ahamed., 2021; Dawoud *et al*., 2018). The increasing penetration of renewable energy sources in microgrids introduces variability and intermittency, posing significant challenges for maintaining a reliable power supply. Synchronization technologies, including advanced control algorithms and smart inverters, play a vital role in addressing these challenges. By enabling smooth transitions between power sources, synchronization helps minimize energy losses, reduce wear and tear on equipment, and optimize fuel usage in conventional generators (Li *et al*., 2016; Li *et al.,* 2024; Nyong-Bassey.,2022). Recent studies have demonstrated the economic advantages of synchronized hybrid power systems including cost savings associated with synchronized operation in a hybrid microgrid, revealing substantial reductions in operational costs compared to unsynchronized systems (Nemove *et al*., 2024; Yu et al., 2024; Tarife *et al*., 2022). Similarly, (Odetoye *et al*.,2023; Shufian e*t al*.,2022) showed that effective synchronization could significantly lower the levelized cost of electricity (LCOE) by optimizing the utilization of renewable energy sources and minimizing reliance on expensive fossil fuels.

The aim of this study is to demonstrate the significance of incorporating a synchronizer in a hybrid microgrid system for reducing cost of power production compared to a system lacking a synchronizer. The power supply within the 11 kV dedicated feeder network of the University of Jos, which spans an 8.7 km network as illustrated in Figure 1, typically provides an average of 22 hours of availability with a voltage range of 215-240V single phase. While this high availability supports educational activities, it imposes a considerable financial burden on the institution due to elevated electricity costs. Efforts to alleviate this financial strain have included attempts to reduce electricity expenses by limiting the hours of electricity use in student hostels and prohibiting the use of heavy electrical equipment. However, these measures have not yielded significant savings. This study aims to optimize power generation scheduling at the University of Jos to minimize costs over a 24-hour period. The objectives include developing a hybrid microgrid model both without a synchronizer and with a synchronizer to evaluate cost-effective unit commitment strategies. By comparing these models, the study seeks to highlight the potential cost savings and efficiency improvements achievable through synchronization.

2. METHODOLOGY

2.1. Mathematical Formulation of Unit Commitment with a Microgrid Synchronizer

According to Katiraei and Iravani (2006), Ali *et al.* (2024), and Shayan *et al.* (2023), the unit commitment problem in a hybrid microgrid system involves determining the on/off status and the power output of each generation unit to meet the demand at the lowest cost while adhering to various operational constraints. The inclusion of a synchronizer in the microgrid enhances the seamless transition between different power sources, optimizing fuel consumption and reducing costs.

Objective function:

The primary objective is to minimize the total operational cost of the microgrid system over a 24-hour period. This includes the costs associated with solar PV, diesel generator, pumped hydro energy storage, and public power supply as shown in Equation (1) whereas the constraints are shown in Equation (2).

$$min\sum_{t=1}^{24}(C_{solar}\left(P_{solar,t}\right)+C_{diesel}\left(P_{diesel,t}\right)+C_{pump}\left(P_{pump,,t}\right)+C_{public}\left(P_{public,t}\right) \tag{1}$$

where:

- $C_{solar}\left(P_{solar,t}\right)$ is the cost of solar PV generation at time *t*.
- $C_{diesel}\left(P_{diesel,t}\right)$ is the cost of diesel generation at time *t*.
- $C_{pump}\left(P_{pump,,t}\right)$ is the cost associated with pumped hydro energy storage at time *t*.
- $C_{public}\left(P_{public,t}\right)$ is the cost of public power supply at time *t*.

Constraints:

Power balance constraint**:**

$$P_{solar,t}+P_{diesel,t}+P_{pump,,t}+P_{public,t}=P_{load,t}+P_{loss,t}, \qquad \forall t \tag{2}$$

where $P_{load,t}$ is the power demand at time *t*, and $P_{loss,t}$ is the power loss at time *t*.

Generation limits**:**

The generation operational limits are shown below:

$$0\le P_{solar,t}\le P_{solar,max} \qquad \forall t$$

$$0\le P_{diesel,t}\le P_{diesel,max} \qquad \forall t$$

$$0\le P_{pump,t}\le P_{pump,max} \qquad \forall t$$

$$0\le P_{public,t}\le P_{public,max} \qquad \forall t$$

Ramping constraints for diesel generator:

The ramping constraints for the diesel generator are shown below:

$$-R_{diesel}\le P_{diesel,t}-P_{diesel,t-1}\le R_{diesel} \qquad \forall t$$

Where R_{diesel} is the ramp rate of the diesel generator.

Pumped hydro storage constraints**:**

The Pumped hydro storage constraints are shown in Equation (3).

$$E_{t+t}=E_t+\eta_p P_{pump,t}-\frac{P_{pump,t}}{\eta_g} \qquad \forall t \tag{3}$$

$$E_{min}\le E_t\le E_{max} \qquad \forall t$$

Where E_t is the energy stored in the pumped hydro system at time *t*, $\eta_p$is the pump efficiency, and η_g is the turbine efficiency.

Start-Stop Costs for Diesel Generator:

The start – stop costs for the diesel generator is as shown in Equation (4)

$$C_{start/stop} = \sum_{t=1}^{24} S_{diesel}\left(U_{diesel,t,}U_{diesel\ t-1}\right) \tag{4}$$

where S_{diesel}represents the start-stop costs, and $U_{diesel,t,}$ is the on/off status of the diesel generator at time *t.*

Synchronizer constraints:

To model the synchronization process, additional constraints ensure smooth transitions between different power sources and this is shown in the expression below:

$$\sum_{i} \Delta P_i\,(t) \leq \Delta P_{sync} \qquad\qquad \forall t$$

where $\Delta P_i(t)$ represents the change in power output of each source, and ΔP_{sync} is the maximum allowable change in power output to ensure synchronized operation.

2.2. Study Area

This study focuses on optimizing the power supply at the University of Jos by employing various components and methodologies. It utilizes predicted demand, validated with real-world data from the Jos Electricity Distribution Company, to forecast the 24-hour demand for the university's feeder, incorporating demand response strategies. Meteorological data, including solar irradiance, temperature, and cloudiness index, are employed to model solar power generation. The study implements Hybrid Particle Swarm Optimization enhanced Ant Colony Optimization (HPSO-ACO) both without and with a synchronizer, using Python within the Spyder/Anaconda software environment, aiming to reduce the power production cost of the microgrid system. In this study, the 24-hour electricity demand forecast from the 11kV dedicated feeder of the University of Jos, primary data, and meteorological data from the Nigerian Meteorological Agency (NIMET) are used to write a code in Python for the execution of the program. In the study several trials were carried out to determine the parameters that gave optimal values in the study. These parameters are as shown below:

PSO parameters:

Swarm size: 30
Max iteration: 100
Inertia weight: 0.7
Cognitive parameter (C1): 1.5
Social parameter (C2): 1.5

ACO parameters:

Number of ants: 5
Pheromone: 1.0
Evaporation: 0.5

Microgrid synchronizer parameters:

Phase tolerance: 1.0 (maximum allowable phase angle difference in radians)

Frequency tolerance: 1.0 (maximum allowable frequency difference in hertz.

3. RESULTS AND ANALYSIS

3.1. Simulation Results of the HPSO-ACO without Synchronizer

The collected data were simulated using the PSO-ACO toolbox in Anaconda (Spyder) on the Python platform. The load demand data of the demand response and the meteorological data were used to write a code in Python with the unit commitment model, and the results are shown in Figure 1.

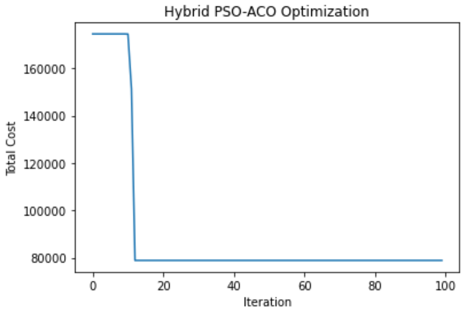

Figure 1: The total cost and number of iterations for hybrid PSO-ACO without a synchronizer

Figure 1 demonstrates the effectiveness of the HPSO-ACO in optimizing unit commitment costs for the microgrid. The graph shows a clear downward trend in total cost, starting at roughly ₦200,000.00 for the first generation and rapidly decreasing to ₦78,888.00 from the 18th to the 100th generation. This significant cost reduction over generations strongly suggests that HPSO-ACO converges towards an optimal solution, successfully minimizing costs for the unit commitment problem. The convergence graph from the "Hybrid PSO-ACO Optimization" shows a significant drop in total cost from just above 160,000 units to approximately 80,000 units within the first few iterations. After this sharp decrease, the cost remains flat for the remaining iterations, indicating that the algorithm quickly found a near-optimal solution and stabilized without further improvements. This suggests that the hybrid approach effectively optimized the problem early on, but it may have reached a point of diminishing returns where additional iterations do not provide further cost reduction. The algorithm's rapid convergence and stabilization suggest it efficiently minimized the total cost, but it might be worth investigating whether it has settled in a local minimum or truly reached the global optimum.

Figure 2 shows the status of each of the power sources within the 24 hours period depicting which power source is on or off within the 24 hours without the synchronizer in circuit as outlined by each of the power sources position below.

i. Diesel:
   - Frequent Usage: Diesel is used intermittently throughout the day, suggesting it's a primary or backup power source.
   - Peak Usage: The highest usage appears to be between hours 10 and 15, possibly during peak demand or when other sources are unavailable.

ii. Public:
   - Limited Availability: The public power source seems to be intermittent, with periods of usage interspersed with outages.
   - Reliability Issues: The frequent on/off cycles suggest potential reliability problems with the public grid.

iii. Solar:
  - Daytime Usage: As expected, solar power is primarily used during daylight hours (approximately hours 6 to 18).
  - Dependency on Weather: The solar source's usage pattern might be influenced by factors like cloud cover and sunlight intensity.

iv. Pumped:
  - Sporadic Usage: Pumped power appears to be used less frequently compared to the other sources.
  - Possible Backup: It might be a backup or supplementary source, used when other sources are unavailable or insufficient.

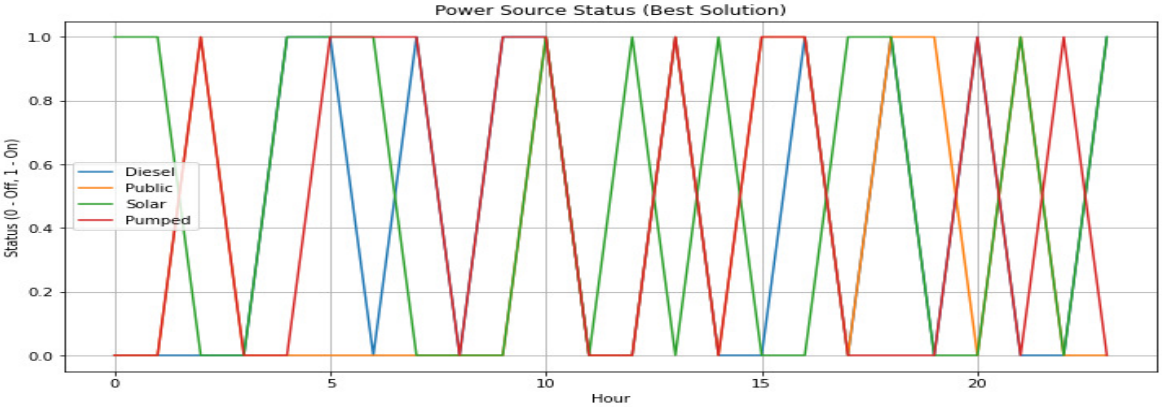

Figure 2 The 24 hours ran of each of the power source

3.2. Simulation Results of the PSO-ACO with Synchronizer Model

The collected data were simulated using PSO-ACO for Python. The 24-hour data collected and the meteorological data were used to write a Python script with the unit commitment with a synchronizer model, and the results are shown in Figure 3.

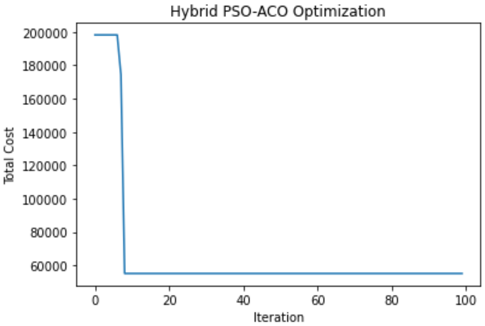

Figure 3 The total cost and number of iterations for hybrid PSO-ACO with synchronizer

Figure 3 shows the total cost of the unit commitment with a synchronizer using Hybrid PSO-ACO. From the graph, it can be seen that the total convergence cost decreased from about ₦200,000.00 at the first generation to about ₦55,088.00 from the 8th to the 100th generation. The convergence graph from a "Hybrid PSO-ACO Optimization" shows a rapid decrease in total cost within the first few iterations, dropping from nearly 200,000 units to around 60,000 units, after which the cost stabilizes and remains constant for the rest of the iterations. This suggests that the hybrid algorithm quickly identifies a good solution, effectively minimizing the cost early in the optimization process. The early convergence indicates the algorithm's success in finding an optimal or near-optimal solution, though it may have settled in a local minimum. To explore potential further improvements, adjusting parameters or introducing perturbations could help, but overall, the optimization appears effective and stable, achieving a significant cost reduction efficiently.

Figure 4 shows the status of each of the power sources within the 24 hours period depicting which power source is on or off within the 24 hours with the synchronizer in circuit as outlined by each of the power source position below.

i. Diesel:
  - Frequent Usage: Diesel is used intermittently throughout the day, suggesting it's a primary or backup power source.
  - Peak Usage: The highest usage appears to be between hours 10 and 15, possibly during peak demand or when other sources are unavailable.

ii. Public:
  - Limited Availability: The public power source seems to be intermittent, with periods of usage interspersed with outages.
  - Reliability Issues: The frequent on/off cycles suggest potential reliability problems with the public grid.

iii. Solar:
  - Daytime Usage: As expected, solar power is primarily used during daylight hours (approximately hours 6 to 18).
  - Dependency on Weather: The solar source's usage pattern might be influenced by factors like cloud cover and sunlight intensity.

iv. Pumped:
  - Sporadic Usage: Pumped power appears to be used less frequently compared to the other sources.
  - Possible Backup: It might be a backup or supplementary source, used when other sources are unavailable or insufficient.

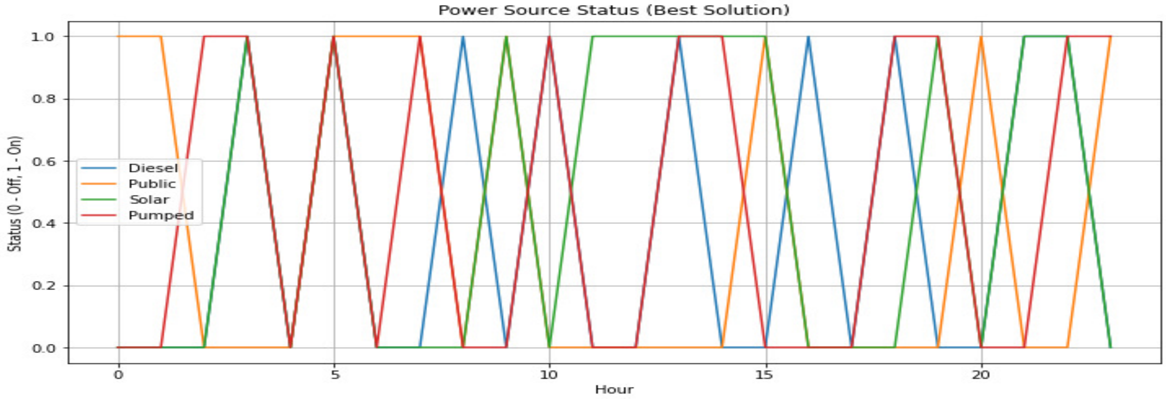

Figure 4. The 24 hours ran of each of the power source

Table 1 demonstrates that the HPSO-ACO with a Synchronizer outperforms HPSO-ACO without a Synchronizer in cost-effectiveness for the microgrid system. The HPSO-ACO with a Synchronizer achieves the lowest total generation cost of ₦55,088.00, showcasing its proficiency in minimizing costs. The HPSO-ACO without a Synchronizer result in a higher cost of ₦78,888.00, suggesting its method may be less efficient for this specific microgrid setup. This highlights the impact of a synchronizer in unit commitment. Table 1 demonstrates that the HPSO-ACO with a Synchronizer outperforms HPSO-ACO without a Synchronizer in cost-effectiveness for the microgrid system. The HPSO-ACO with a Synchronizer achieves the lowest total generation cost of ₦55,088.00, showcasing its proficiency in minimizing costs. The HPSO-ACO without a

Synchronizer result in a higher cost of ₦78,888.00, suggesting its method may be less efficient for this specific microgrid setup. This highlights the impact of a synchronizer in unit commitment.

Table 1: Minimized cost of power

Power source generation method	Total cost of generation (₦)
HPSO-ACO without synchronizer	78,888.00
HPSO-ACO with a synchronizer	55,088.00

4. CONCLUSION

This study investigated the application of Hybrid Particle Swarm Optimization and Ant Colony Optimization (HPSO-ACO) for optimizing unit commitment costs in a microgrid system. By employing a Python-based simulation environment, the impact of both a standard HPSO-ACO model and one incorporating a synchronizer was evaluated. The results demonstrate the efficacy of HPSO-ACO in significantly reducing unit commitment costs. Both models achieved substantial cost reductions compared to initial values. However, the HPSO-ACO with a synchronizer exhibited superior performance, yielding a lower total generation cost of ₦55,088.00 compared to ₦78,888.00 for the standard model, reflecting a 30.16% cost reduction. This highlights the importance of incorporating a synchronizer in optimizing the microgrid's operation.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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