

A PROPOSAL OF ENERGY MANAGEMENT SYSTEM FOR THE PUERTECITOS ISOLATED MICROGRID USING PARTICLE SWARM OPTIMISATION

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RESUMEN

Este trabajo propone un sistema de administración de energía (EMS) para la microrred aislada de Puertecitos, Baja California. El EMS está basado en el uso de Optimización por Enjambre de Partículas (PSO), en donde la función objetivo a minimizar es el costo de generación de energía, y algunas de las restricciones son: el balance generación-demanda, los límites de generación de las diversas fuentes y los límites de carga-descarga de las baterías. Dada la estructura radial de la microrred, se identifica el nodo de generación y el nodo de carga, así que a fin de cuidar que la tensión en el nodo de carga se mantenga en valores admisibles, se propone un análisis de flujo de potencia que permite replantear cómo es la demanda de energía en el nodo de generación. El esquema de EMS propuesto se prueba en el entorno de simulación de MATLAB, en donde los resultados demuestran su eficacia.

Palabras Clave: EMS, PSO, Microrred aislada, Optimización.

ABSTRACT

This work proposes an energy management system (EMS) for the isolated microgrid of Puertecitos, Baja California. The EMS is based on the use of Particle Swarm Optimization (PSO), where the objective function to be minimized is the power generation cost. Some of the constraints include the generation-demand balance, the generation limits of the different sources, and the charge-discharge limits of the batteries. Given the radial structure of the microgrid, the generation node and the load node are identified. To ensure that the voltage at the load node is maintained at admissible values, a power flow analysis is proposed that reflects the energy demand at the generation node. The proposed EMS scheme is tested in the MATLAB simulation environment, where the results demonstrate its effectiveness.

Keywords: EMS, PSO, Isolated Microgrid, Optimization.

1. INTRODUCTION

In the face of growing global energy demand and environmental concerns, modern power systems are seeking a structural transformation [1]. The integration of renewable energy sources is increasing to reduce greenhouse gas emissions and mitigate the effects of climate change. Isolated microgrids have gained attention for providing reliable and sustainable electricity to remote areas not connected to the main grid [2]. Microgrids typically integrate diverse energy sources such as photovoltaics

(PV), wind turbines (WT), diesel generators (DG), and battery energy storage (BES) systems. Managing energy flows and minimizing operational costs while ensuring system constraints is critical to the economy and stability of the microgrids [3].

In remote areas where access to a central power grid is limited or costly, microgrids can serve as a practical alternative. They can provide electricity to individual homes, commercial buildings, or small communities. Several studies, such as [4] and [5], present case analyses of microgrids around the world, which are essential to examine in terms of various technical, economic, and operational factors. In particular, voltage regulation is crucial in microgrids, as it ensures stable and dependable operation under changing load and generation conditions. Poor voltage control can lead to equipment damage, power quality problems, or service disruptions, especially in systems with high renewable energy integration and limited support from the main grid.

On the other hand, the energy management system (EMS) in such microgrids must ensure the optimal dispatch of available resources, considering generation and demand profiles, objectives, and operational constraints. The specific formulation of optimal dispatch is different depending on the particular characteristics of each microgrid case study. The literature contains various optimization methods applicable to EMS for microgrids. These methods enable the scheduling of Distributed Energy Resources (DER) dispatch, thereby minimizing operating costs and losses, maximizing environmental benefits, and enhancing overall microgrid efficiency under various operational and economic objectives.

The authors in [6] propose an EMS based on linear programming (LP) optimization, which provides an economic dispatch schedule. The EMS determines the output price and loading conditions for optimally storing or selling energy from available solar units, enhancing overall optimization while minimizing operation costs. The proposed EMS for an isolated microgrid in [7] formulates the optimization problem as a Mixed Integer Linear Programming (MILP) model, enabling efficient resolution with commercial solvers for real-time applications. The EMS presented in [8] employs the Horse Herd Optimization

(HHO) technique combined with a Probabilistic Neural Network (PNN). In [9], the authors use the quasi-Newton method to minimize a nonlinear objective function under nonlinear constraints. While that, the EMS proposed in [10] is based on Model Predictive Control (MPC) to minimize operational costs while accounting for market participation and system constraints.

While numerous advanced optimization techniques have been successfully applied to EMS design, the high computational demands still pose a challenge, particularly in centralized architectures that limit their flexibility in dynamic and decentralized microgrid environments. These limitations are particularly significant when rapid, high-resolution dispatch decisions are required. In contrast, lightweight and iterative strategies, such as hourly decision-making, offer a more scalable and responsive alternative.

This paper presents an EMS for the isolated microgrid of Puertecitos, Baja California, designed to minimize total power generation costs using PSO. The proposed EMS considers operational constraints, including generation-demand balance, source limits, and battery charging/discharging restrictions. Additionally, due to the radial topology of the microgrid, a power flow analysis is incorporated to ensure voltage levels remain within acceptable bounds at the load node. Based on this analysis, an adjusted demand profile is derived at the generation node to ensure stable operation. Section 2 provides a detailed description of the microgrid case study. Section 3 explains the proposed EMS strategy and its formulation. Section 4 presents the simulation results obtained in MATLAB, and Section 5 summarizes the main conclusions of the study.

2. CASE STUDY

2.1. Microgrid structure

This work examines a case study based on the system described in [11], which examines an isolated low-voltage AC microgrid incorporating renewable energy sources and energy storage systems. The microgrid operates autonomously and comprises a PV, a WT, a BES system, and a DG. The PV, WT, and DG systems serve as the primary energy sources, while the battery bank supports energy management by storing excess energy and supplying power during deficits.

The microgrid of Puertecitos supplies electricity to a total of 20 households. To ensure appropriate voltage levels along the feeder, the system consists of a step-up transformer that facilitates power transmission and a step-down transformer that adjusts the voltage for end-user consumption. Fig. 1 illustrates this configuration of Puertecitos Microgrid.

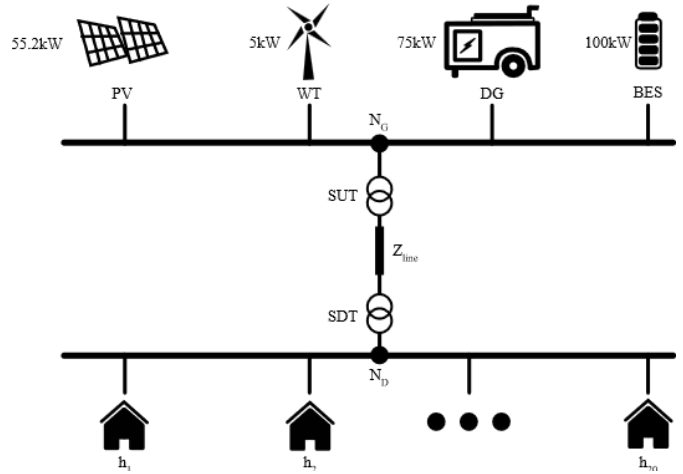


Figure 1. Puertecitos Microgrid.

The dispatch strategy focuses on cost-based optimization of each generator, without prioritizing renewable sources. As a result, the PV system, WT, DG, and BES are treated equally in the optimization process.

Table 1. Power System Parameters.

Description	Value
BES Minimum state of charge SOC_{min}	0.2 (20%)
BES Maximum state of charge SOC_{max}	1.0 (100%)
BES Time step ΔT	1 hour
Maximum energy capacity E_{BES}^{max}	522 kWh
Max. charge/discharge power P_{BES}^{max}	100 kW
PV Capacity	55.2 kW
WT Capacity	5 kW
DG Capacity	75 kW
Loads (D)	62 kW

2.2. Power Flow Analysis for Voltage Stability

A power flow analysis focused on maintaining voltage stability at the load node of an isolated microgrid in Puertecitos, Baja California, is utilized with a simplified two-node model: a generation node N_G , where all DERs are centralized, and a load node N_L , interconnected via distribution transformers and a medium-voltage line.

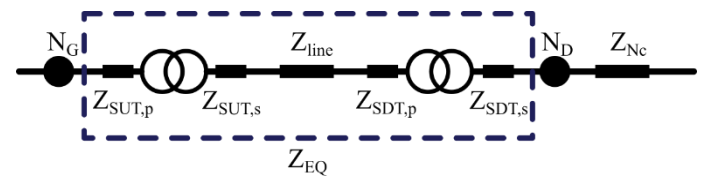


Figure 2. Impedances diagram of Puertecitos microgrid.

Fig. 2 illustrates the impedances into the Puertecitos microgrid. The microgrid is modelled through two main impedance components: (i) the equivalent impedance Z_{EQ} , which includes transformers and line impedances, and (ii) the load impedance Z_{Nc} , which is treated as a variable parameter that depends on the hourly power demand.

The per-unit representation of each element is obtained using the standard expression Eq. (1).

$$Z_{pu} = \frac{Z}{V_{base}^2} \quad (1)$$

The SUT and SDT impedances are simplified as Eq. (2) and Eq. (3), respectively.

$$Z_{SUT,pu} = Z_{SUT,p,pu} + Z_{SUT,s,pu} \quad (2)$$

$$Z_{SDT,pu} = Z_{SDT,p,pu} + Z_{SDT,s,pu} \quad (3)$$

Thus, the equivalent impedance Z_{EQ} is expressed in Eq. (4).

$$Z_{EQ,pu} = Z_{Nc,pu} + Z_{SUT,pu} + Z_{SDT,pu} \quad (4)$$

The load impedance Z_{Nc} is calculated hourly, which depends on the apparent power as is shown in Eq. (5). And consequently, $Z_{Nc,pu}$ is calculated using Eq. (1).

$$Z_{Nc}(t) = \frac{(\sqrt{2} * V)^2}{2 * S_{Nc}(t)} \quad (5)$$

Once the impedances are determined, the hourly voltage at the generation node is calculated in Eq. (6).

$$V_{NG}(t) = V_{Z_{EQ}}(t) + V_{Nc}(t) \quad (6)$$

Where $V_{Z_{EQ}}$ and V_{Nc} is voltage in $Z_{EQ,pu}$ and voltage in N_c respectively.

For the power required in N_G , the expression in Eq. (7) is used. The current I_{RMS} is obtained from Ohm's law, which is expressed in Eq. (8).

$$S_{NG}(t) = V_{NG}(t) \cdot I_{Nc,RMS}(t) \quad (7)$$

$$I_{Nc,RMS}(t) = \frac{S_{Nc}(t)}{V_{Nc,RMS}} \quad (8)$$

Note that $S_{NG}(t)$ is calculated for each hour of the demand profile. Fig. 3 illustrates the power demanded at N_D and the N_G over 24 hours.

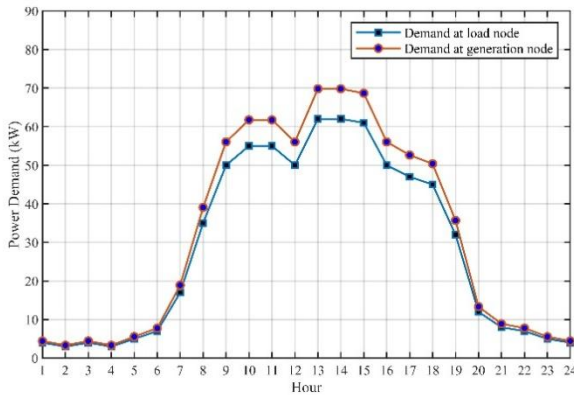


Figure 3. Demand profiles at the load node and the generation node.

2.3. Profiles

The PV, WT, and D profiles are defined based on real hourly data for a specific day [12]. In this case, the minimum generated power for all generators is assumed to be zero, indicating that

they cannot provide energy. The maximum power generation profiles of the PV and WT, and D are defined in Table 2.

Table 3 summarizes the generation costs associated with each energy source in the microgrid, including the costs for charging and discharging the battery. These costs are assumed to remain constant over the 24-hour simulation period.

Table 2. Hourly power profiles of generation sources and demand expressed in kW.

Hour	PV_{max}	WT_{max}	Demand in N_G
1	0.0	4.10	4.44
2	0.0	3.40	3.33
3	0.0	2.80	4.44
4	0.0	4.30	3.33
5	0.0	3.30	5.56
6	0.0	4.60	7.78
7	10.2	3.00	18.91
8	15.2	3.20	39.06
9	25.2	4.00	56.04
10	45.2	3.75	61.76
11	51.3	2.60	61.76
12	55.2	3.35	56.04
13	55.1	3.20	69.81
14	43.9	3.80	69.81
15	24.7	3.70	68.65
16	17.8	3.30	56.04
17	12.4	3.80	52.63
18	1.5	2.20	50.36
19	0.0	3.10	35.69
20	0.0	4.30	13.34
21	0.0	3.40	8.89
22	0.0	2.60	7.78
23	0.0	2.70	5.56
24	0.0	3.90	4.44

Table 3. Generation and storage costs (\$/kWh).

Source	Cost [\$/kWh]
Photovoltaic (PV)	0.00086 MXN
Wind Turbine (WT)	0.00064 MXN
Diesel Generator (DG)	0.00980 MXN
Battery Charging	0.00300 MXN
Battery Discharging	0.00500 MXN

3. EMS STRATEGY

EMS can be formulated as an optimization problem based on operational information, including generation and demand profiles, and energy costs. According to the data, the objective function and constraints can be defined. As a result, EMS determines decision variables for each DER of the microgrid, which include dispatch power for each generator unit. Fig. 4 represents the scheme of EMS as an optimization problem.

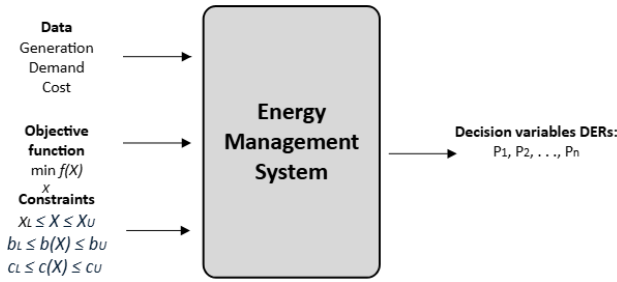


Figure 4. EMS as an optimization problem.

3.1. Objective Function

The objective function represented by Eq. (9) integrates the cost coefficients and the corresponding power outputs, aiming to minimize the total generation cost of the microgrid over the scheduling horizon.

$$\min f(x) = \sum_{t=1}^{24} (C_{Pv} \cdot P_{Pv}(t) + C_{WT} \cdot P_{WT}(t) + C_{DG} \cdot P_{DG} + C_{BES} \cdot P_{BES}(t) + Penalty) \quad (9)$$

where C_{Pv} , C_{WT} and C_{DG} are the generation costs associated with the PV, WT and DG, respectively. Also, the cost associated with the battery, C_{BES} , is defined in Eq. (10).

$$C_{BES} = u \cdot C_{BES}^C + (1 - u) \cdot C_{BES}^D \quad (10)$$

$u \in 0,1$

Which $u = 1$ indicates that the battery is charging, C_{BES}^C , and $u = 0$ indicates that the battery is discharging, C_{BES}^D . $P_{Pv}(t)$, $P_{WT}(t)$, $P_{DG}(t)$, and $P_{BES}(t)$ are the decision variables, representing the power outputs of the generation units in the microgrid. The Penalty term is included to penalize the objective function whenever any constraint is violated. The constraints are described in section 3.2.

3.2. Constraints

Despite each generator having a maximum generation power Table 3, the maximum capacity is limited hourly according to the generation profiles. Eqs. (11-14) are the constraints established for PV, WT, DG and BES system.

$$PV_{min,t} \leq PV(t) \leq PV_{max,t} \quad (11)$$

$$WT_{min,t} \leq WT(t) \leq WT_{max,t} \quad (12)$$

$$DG_{min} \leq DG(t) \leq DG_{max} \quad (13)$$

$$BES_{min,t} \leq BES(t) \leq BES_{max,t} \quad (14)$$

$$|PV(t) + WT(t) + DG(t) + BES(t) - D(t)| \leq \epsilon \quad (15)$$

Additionally, the energy balance of the microgrid is established, ensuring that the total energy supplied by the sources matches the demand. Therefore, a tolerance ϵ is introduced to maintain an acceptable power balance at each hour, as shown in Eq. (15). Although this is not a strict equality-based energy balance equation, the tolerance allows for minor deviations. If this condition is not satisfied, the objective function is penalized.

3.3. PSO-based optimization algorithm

A PSO strategy is employed to address the optimal energy dispatch of the Puertecitos microgrid. PSO is a population-based metaheuristic strategy, where each particle updates its velocity, Eq. (16), and position, Eq. (17), based on inertia, cognitive, and social components [13].

$$V_j^{(i+1)} = W \cdot V_j^{(i)} + C_1 \cdot r_1 \cdot (G_{best}^{(j)} - P_j^{(i)}) + C_2 \cdot r_2 \cdot (G_{best}^{(j)} - P_j^{(i)}) \quad (16)$$

$$P_j^{k+1} = P_j^k + V_j^{k+1} \quad (17)$$

PSO parameters were obtained from [12] and [14], which are defined in Table 4. The optimization process is summarized in Algorithm 1.

Table 4. PSO parameters.

Parameter	Value	Description
N_p	50	Number of particles (population size)
n	96	Number of variables
C_{min}	1	Minimum acceleration constant
C_{max}	1	Maximum acceleration constant
W_{min}	0.3	Minimum inertia weight
W_{max}	0.8	Maximum inertia weight
$Penalty$	10,000	Penalty factor
Max_{Iter}	3000	Maximum number of iterations

Algorithm 1: PSO-Based Optimal Energy Dispatch for Puertecitos Microgrid.

1. Initialize parameters: N_p , Max_{Iter} , W_{min} , W_{max} , C_{min} , C_{max} , $penalty$ factor
2. Import: Demand profile D , generation limits for PV , WT , DG , and dynamic limits for P_{BES}
3. Set initial conditions: SOC_0 , SOC_{min} , SOC_{max}
4. For $i = 1$ to N_p do:
 5. For $j = 1$ to 24 do:
 6. Randomly generate $PV_{i,j}$ and $WT_{i,j}$ within their bounds
 7. Compute $SOC_{i,j}$ based on $P_{BES,i,j-1}$
 8. Determine dynamic charging/discharging limits: $P_{BES,i,j}^{min}$ and $P_{BES,i,j}^{max}$
 9. Repeat:
 10. Generate $P_{BES,i,j}$ within dynamic bounds
 11. Compute $DG_{i,j} = D_j - PV_{i,j} - WT_{i,j} - P_{BES,i,j}$
 12. Until $0 \leq DG_{i,j} \leq P_{DG}^{max}$
 13. End For
14. End For
15. Concatenate $PI = [PV, WT, DG, P_{BES}]$
16. Initialize particle velocities: $V_i = 0.1 \times PI$
17. Evaluate the objective function: $F_o = FumObj(PV, WT, DG, P_{BES})$
18. Evaluate constraint violations: $R = Constraints(PI, \dots)$
19. Apply penalty: $F_{op} = F_o + R \times penalty$
20. Set personal bests: $P_{best} = PI, globalbest G_{best} = argmin(F_{op})$
21. For $Iter = 1$ to Max_{Iter} do:
 - I am running a few minutes late; my previous meeting is running over.22.
 - Update inertia weight: $W = W_{max} - ((W_{max} - W_{min}) \times Iter / Max_{Iter})$
 23. For $i = 1$ to N_p do:
 24. For $j = 1$ to 24 do:
 25. Update velocity and position for PV and WT using PSO equations
 26. Apply position bounds
 27. End For
 28. For $j = 1$ to 24 do:

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29. Recompute  $SOC_{i,j}$  and dynamic limits  $P_{BES_{i,j}}^{min}, P_{BES_{i,j}}^{max}$ 
30. Update velocity and position for  $P_{BES_{i,j}}$ 
31. Enforce dynamic bounds on  $P_{BES_{i,j}}$ 
32. Recalculate  $DG_{i,j} = D_j - PV - WT - P_{BES}$ 
33. End For
34. End For
35. Re-evaluate  $F_o$ ,  $R$ , and penalized objective  $F_{oP}$ 
36. For  $i = 1$  to  $N_p$  do:
37. If  $F_{oP_i} < F_{oP_{best_i}}$  then:
38. Update  $P_{best_i} \leftarrow P_i$ 
39. End If
40. End For
41. If  $\min(F_{oP}) < F_{oP_{best}}$  then:
42. Update  $G_{best} \leftarrow P_{best_{argmin}(F_{oP})}$ 
43. End If
44. End For
    
```

4. SIMULATION RESULTS

The results of the proposed dispatch strategy are presented and analyzed below. Fig. 5 illustrates the generation profiles and optimal dispatch outcomes for the four energy sources considered: PV, WT, DG, and BES, as determined by the hourly PSO optimization framework proposed. Each subplot compares the maximum available power with the corresponding optimal dispatch over 24 hours, highlighting how the system dynamically allocates resources to meet demand while respecting operational constraints.

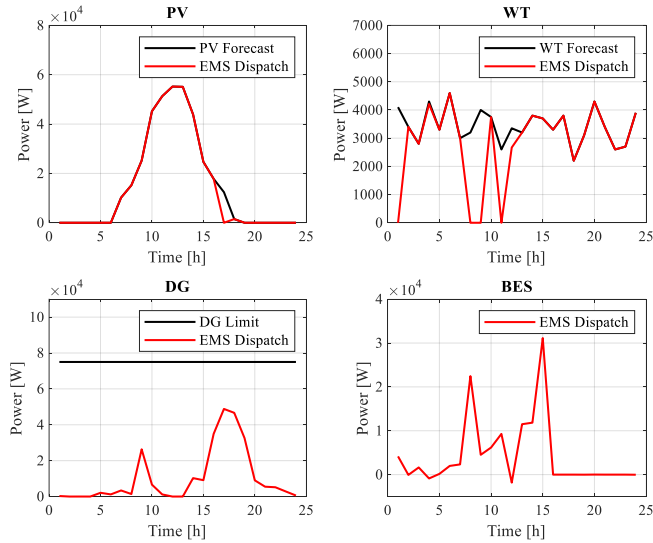


Figure 5. Dispatch profile of the microgrid energy sources.

For the PV system, the dispatch closely aligns with its maximum generation capacity, indicating near-complete utilization of available solar energy. Although the dispatch strategy does not explicitly prioritize renewable sources, their low generation costs naturally lead to high utilization when available. However, to maintain the power balance across the microgrid, the DG and BES are dispatched to supply the remaining power required to

meet the electrical demand at each hour, ensuring system reliability and operational continuity.

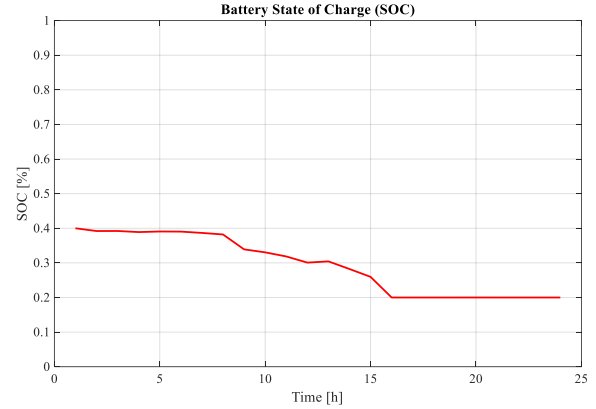


Figure 6. SOC in 24 hours.

Fig. 6 shows the SOC of the BES system, which shows that for the first 16 hours, the battery is discharged, and when it reaches the minimum SOC, the value is constant.

Fig. 7 illustrates the power balance verification over the horizon achieved using the proposed PSO-based dispatch. The black curve represents the hourly demand profile, while the red curve shows the total power dispatched from all generation units and the storage system. The close overlap between the two curves confirms that the PSO algorithm effectively maintains the energy balance at every hour while considering the constraints. This result highlights the capability of the PSO approach to coordinate diverse energy resources, ensuring the reliable and balanced operation of the microgrid.

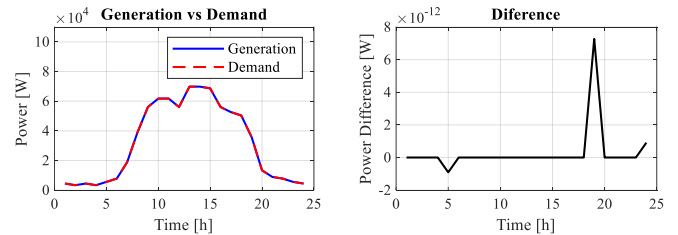


Figure 7. Comparison between dispatch and electricity demand profiles.

Fig. 8 shows the change in cost over each iteration of PSO, reaching the minimum cost of MXN 3,315.54 at iteration 806.

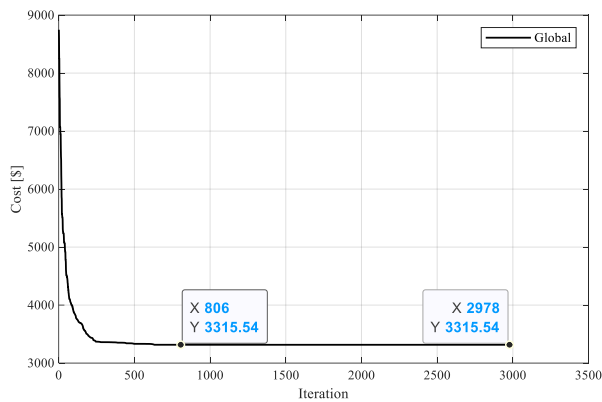


Figure 8. Cost convergence over iterations.

5. CONCLUSIONS

This study presented the development of an EMS for an isolated microgrid, specifically applied to the case of the Puertecitos community. The proposed approach adopts a node-based dispatch strategy, initiated from the generation units to ensure proper voltage regulation in the load node. A traditional Particle Swarm Optimization (PSO) algorithm was employed to determine the optimal hourly energy dispatch, considering the operational constraints of each resource. This formulation demonstrated improved economic performance over global optimization approaches, while enhancing voltage in the microgrid. Future work will involve integrating uncertainties in generation and demand, as well as developing hybrid or adaptive optimization strategies.

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