
METAHEURISTIC OPTIMIZATION STRATEGIES FOR SYNTHETIC INERTIA AND LOAD FREQUENCY CONTROL IN ISLANDED MICROGRIDS: A COMPREHENSIVE REVIEW

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

Islanded microgrids (IMGs) featuring high penetration levels of inverter-based renewable energy sources (RESs) suffer from severe dynamic instability, rapid rate of change of frequency (RoCoF), and deep frequency nadirs due to the low or zero physical inertia of power electronic interfaces. To compensate for lost rotational kinetic energy, Synthetic Inertia Control (SIC) and dynamic Load Frequency Control (LFC) have emerged as essential stabilization mechanisms. However, conventional linear controllers underperform under stochastic load variations, intermittent wind/solar generation, nonlinear governor deadbands, and variable time delays. Over the past decade, metaheuristic optimization algorithms (MOAs) spanning swarm intelligence, evolutionary computation, physics-based, and human-inspired paradigms have transformed control parameter tuning, objective function formulation, and hybrid controller design in IMGs. This paper provides a rigorous, state-of-the-art review of metaheuristic optimization strategies applied to joint or standalone SIC and LFC schemes in standalone microgrids. We classify contemporary control topologies, examine classical and high-order objective metrics (ITAE, ITSE, multi-objective trade-offs), and critically evaluate metaheuristic paradigms ranging from foundational algorithms to modern hybrid and adaptive variants. Furthermore, we detail the integration of physical energy storage systems and demand-side assets like Electric Vehicles (EVs) for frequency support. Finally, key open research challenges, including real-time computational overhead, hardware-in-the-loop (HIL) validation, cyber-physical security, and multi-objective Pareto optimization are systematically analyzed alongside local application perspectives to delineate future research directions.

Keywords: Islanded Microgrid; Synthetic Inertia Control (SIC); Load Frequency Control (LFC); Metaheuristic Optimization; Rate of Change of Frequency (RoCoF)

1. INTRODUCTION

The modern energy system faces the need to switch from centralized to distributed isolated microgrids that ensure reliable power supply to consumers through various renewable energy resources (RES). Such resources include photovoltaic (PV) generators and wind turbines (WT), which replace some of the traditional synchronous generators. One of the problems of such microgrids is the loss of rotational inertial characteristics due to the use of voltage source inverters and the absence of a wide range of inertial properties in the system. This effect is especially noticeable in the case of an isolated microgrid, which is separated from the main power grid (Abubakr et al., 2021; Davoudkhani et al., 2024; Akinwola & Alkuhayli, 2025; Saleh et al., 2022). Such a change in the system characteristics makes it necessary to use synthetic inertia and specific methods to regulate electricity frequency to achieve stable operation of the microgrid (Davoudkhani et al., 2024). Traditional control methods are not always efficient in complex microgrid environments. Therefore, researchers have proposed various metaheuristic optimization algorithms to optimize controller parameters for frequency adjustment, thereby improving system transient response (Kalu et al., 2025; Lesenyehyo & Krishnamurthy,

2025). The purpose of this article is to present a state-of-the-art review on microgrid control methods based on metaheuristic optimization algorithms. The paper analyzes and systematizes modern literature to improve understanding of diverse nature-inspired evolutionary computing techniques. It also highlights performance differences across algorithms in multi-objective optimization contexts involving multi-criteria trade-offs.

1.1 Methodology of literature search and selection

To ensure systematic coverage and reproducibility, a transparent search protocol was conducted following PRISMA guidelines across major databases, including IEEE Xplore, ScienceDirect, SpringerLink, MDPI, Wiley Online Library, and Scopus. The primary search query used Boolean operators: ("Islanded Microgrid" OR "Low-Inertia Microgrid") AND ("Synthetic Inertia" OR "Load Frequency Control") AND ("Metaheuristic Optimization" OR "Swarm Intelligence" OR "Evolutionary Algorithm"). The search prioritized peer-reviewed articles published between 2015 and 2026. Inclusion criteria mandated focus on islanded microgrids, metaheuristic controller gain tuning (K_p , K_i , K_d , fractional orders, inertia/damping gains), and quantitative dynamic evaluation (ITAE, ISE, RoCoF, nadir). Grid-connected studies without islanding capability and purely economic dispatch papers were excluded. Table 1 summarizes the review methodology.

Table 1: Review Methodology

Selection Parameter	Details / Criteria
Databases Searched	IEEE Xplore, ScienceDirect, SpringerLink, MDPI, Wiley Online Library, Scopus
Timeframe	2015–2026
Initial Records Identified	1,578 articles
Screened by Title/Abstract	373 articles retained after title screening; 132 after abstract review
Final Included Studies	56 primary core studies fully analyzed and cross-referenced

The remainder of this paper is structured as follows: Section 2 identifies challenges associated with microgrids in modern energy systems. Section 3 presents control topologies for synthetic inertia and frequency control. Section 4 provides a structured comparative analysis of metaheuristic optimization algorithms (evolutionary, swarm, physics/chemical, human/social, and hybrid paradigms). Section 5 synthesizes key open research challenges and local application perspectives. Finally, Section 6 summarizes the core findings.

2. CHALLENGES AND PROBLEMS OF MICROGRIDS IN MODERN ENERGY SYSTEMS

The development of modern electricity markets using microgrids has one primary advantage: enabling decentralized and low-carbon power systems. The main challenges microgrids encounter while being incorporated into the existing electricity system relate to their dissimilarities with classic power networks (Shahzad et al., 2023; Bhargava & Jaiswal, 2021). Microgrids require highly efficient power electronics during switching modes to provide stable power quality and voltage during transition to islanded mode with minimum losses (Shahzad et al., 2023; Bodewes et al., 2024; Zahira et al., 2014). This imposes technical difficulties associated with protection relay schemes capable of responding to grid-side power interruptions instantly while securing local electrical loads from voltage deviations. Designing protection schemes is challenging since legacy networks feature unidirectional power flows and conventional overcurrent relays (Binqadhi et al., 2024). Microgrids allow bidirectional power delivery due to distributed energy resources (DER), resulting in relay malfunctions, protection blindness, and sympathetic tripping (Ali et al., 2021). The limited fault current of inverter-based DERs is notably lower than grid-supplied currents, which conventional overcurrent relays cannot recognize during islanding (Faisal et al., 2018; Shahzad et al., 2023).

Inverter-based systems also face power quality challenges, particularly voltage and frequency regulation during steady-state and transient conditions (Kumar & Subudhi, 2023). Microgrids traditionally relied on synchronous generators to supply inertial response and voltage regulation. Recent microgrids experience greater frequency deviations (Δf) and voltage instability due to intermittent solar and wind power (Kumar & Subudhi, 2023). These technical limitations are

exacerbated by the lack of effective primary control strategies against frequency deviations, such as virtual inertial control and grid-forming inverter control.

Microgrids encounter additional control and cybersecurity challenges in energy management systems (EMS) and protection relays. Modern EMSs have adopted centralized or multi-agent control systems for secondary control and battery storage management (Kumar & Subudhi, 2023). Communication infrastructures between microgrid components play a crucial role in real-time generation and demand coordination (Shahzad et al., 2023). Communication integrity is a major concern; cyber-attacks, signal fading, and delays can disrupt control loops and jeopardize grid security. Furthermore, economic inefficiencies arise due to high battery storage costs, while existing regulatory frameworks offer limited compensation for ancillary services.

3. LOAD FREQUENCY CONTROL IN ISLANDED MICROGRID

An islanded microgrid is an electricity production and distribution system electrically isolated from the main grid. Lacking voltage reference sources and high rotating inertia, the main task of Load Frequency Control (LFC) in an islanded microgrid is to balance generated and consumed electric power to minimize frequency deviation (Pilehvar & Mirafzal, 2020; Ewias et al., 2023). The dynamic islanded microgrid control structure with virtual inertia loop is shown in Figure 1.

3.1 Fundamentals of synthetic inertia

Frequency control in islanded microgrids is managed via a hierarchical multi-loop system (Zaid et al., 2023):

3.1.1 Inertia control loop

Utilizes energy storage systems (ESS) and advanced inverter control for instantaneous active power support, mimicking synchronous machine kinetic energy (Faragalla et al., 2022; Zaid et al., 2023).

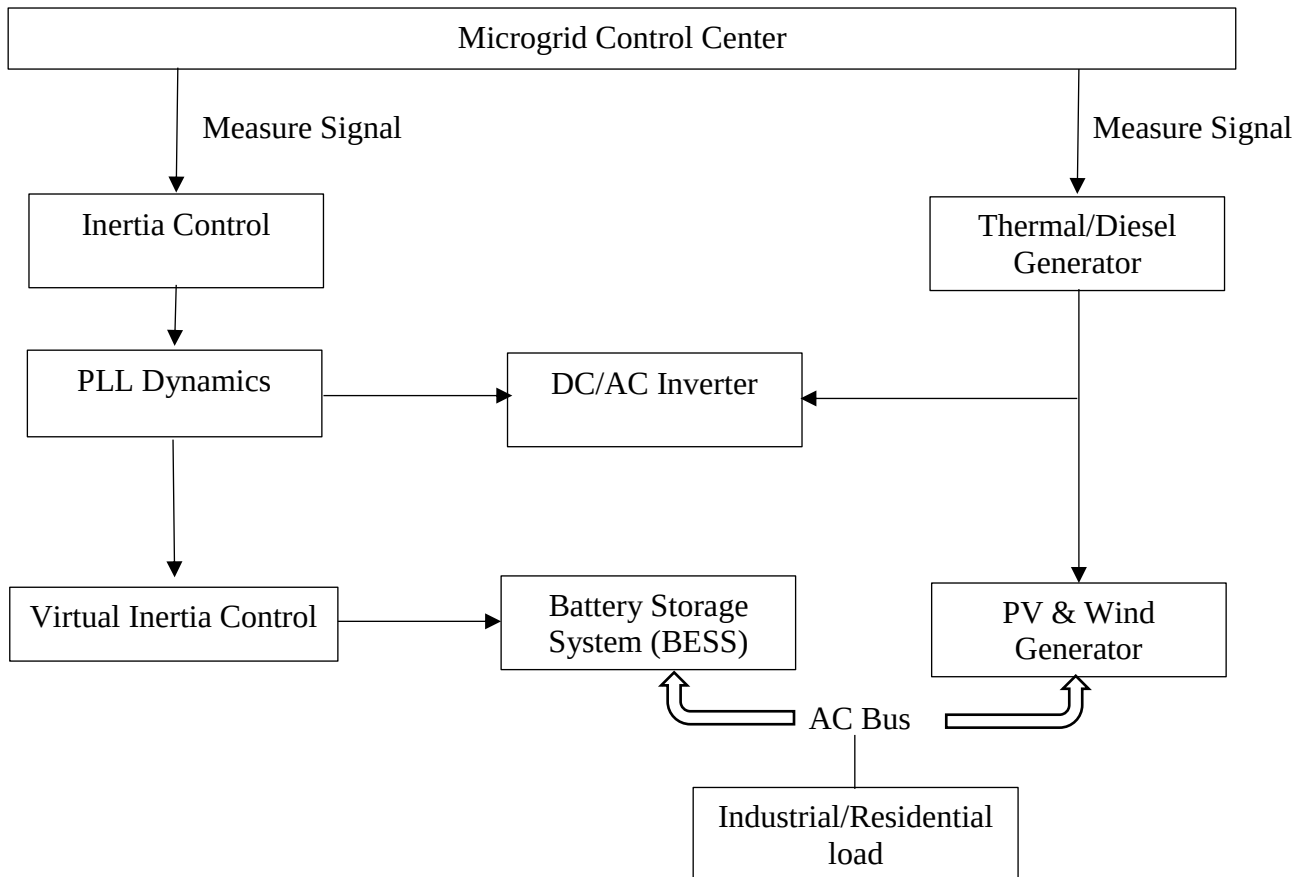


Figure 1: Dynamic Islanded Microgrid Control Structure with Virtual Inertia Loop

3.1.2 Primary control loop

Adjusts DER power output based on frequency deviation, typically through proportional droop control (Gulzar et al., 2022).

3.1.3 Secondary control loop (LFC)

Restores system frequency to nominal values (50/60 Hz) by modulating active power references of controllable units (Faragalla et al., 2022; Zaid et al., 2023). Controller architectures range from PID and Fractional-Order PID (FOPID) (Sahoo et al., 2023; Mohamed et al., 2022; Fadheel et al., 2024) to Model Predictive Control (MPC) (Saleh et al., 2023a) and Fuzzy Logic Control (FLC) (Nanda Kumar & Mohanty, 2022).

3.2 Synthetic inertia emulation and control topologies

In islanded low-inertia microgrids, dynamic frequency response is governed by the electromechanical swing equation as expressed in (1).

$$2H \frac{d\Delta f(t)}{dt} = P_m(t) - P_e(t) - D\Delta f(t) \quad (1)$$

where: H is the inertia constant (in seconds), $\Delta f(t)$ is the system frequency deviation ($\omega - \omega_0$), $P_m(t)$ and $P_e(t)$ are the per-unit mechanical input power and electrical output power, and D is the damping factor.

Inverter-interfaced storage units inject synthetic inertial power P_{syn} proportional to the derivative of frequency deviation as in (2) (Criollo et al., 2024).

$$P_{syn}(t) = -K_{inertia} \frac{d\Delta f(t)}{dt} \quad (2)$$

where $K_{inertia}$ represents the virtual inertia control gain ($2H_{vir}$).

When integrated into the active power balance, the effective total system inertia constant H_{sys} increases to as in (3).

$$H_{sys} = H_{phys} + H_{vir} \quad (3)$$

Synthetic inertia implementation strategies in inverter-based islanded microgrids generally fall into two primary control architectures (Kerdphol et al., 2019) as represent in Figure 2.

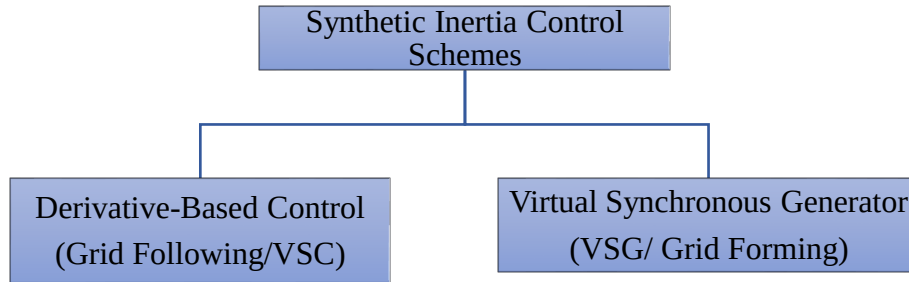


Figure 2: Synthetic Inertia Control Schemes (Kerdphol et al., 2019)

3.2.1 Virtual synchronous generators (VSG)

The VSG technology embeds synchronous machine mathematical models into the inverter digital control loop. Frequency dynamics follow the virtual swing equation as in (4).

$$J \frac{d\omega}{dt} = P_{ref} - P_e - D(\omega - \omega_0) \quad (4)$$

Where: J is the virtual moment of inertia, D is the damping coefficient (providing primary droop functionality), ω is the virtual rotor angular frequency, ω_0 is the nominal frequency, P_{ref} is the reference active power input, and P_e is the measured electromagnetic output power (Besati et al., 2024).

3.2.2 Derivative-based inertia emulation

Derivative control calculates (df/dt) in real-time to inject power (ΔP_{SI}) from storage during initial transient phases (100–500 ms). By applying a control gain (K_{in}) to this derivative, the controller

determines the required active power output (ΔP_{SI}) to be injected or absorbed by an Energy Storage System (ESS) or regulated Load-Side Rotational Inertia (LSRI) can be expressed as in (5).

$$\Delta P_{SI} = -K_{in} \cdot \frac{df}{dt} \quad (5)$$

Where: K_{in} is control gain, ΔP_{SI} is required output power and, $(\frac{df}{dt})$ is derivative of the system frequency (Fang et al., 2018; Roy et al., 2024).

To filter measurement noise, low-pass filtering with time constant T_f is applied in Laplace domain as expressed in (6).

$$\Delta P_{SI}(s) = \frac{K_{in} \cdot s}{1 + sT_f} \cdot f(s) \quad (6)$$

4. METAHEURISTIC OPTIMIZATION ALGORITHMS FOR VIC-LFC

Metaheuristic algorithms solve the optimization problem formulated using performance indices such as Integral Time Absolute Error (ITAE) or Integral Square Error (ISE) to tune controller gains (K_p , K_i , K_d , λ , μ), virtual inertia gains (H_v), and virtual damping gains (D_v) (Zaid et al., 2023; Mishra et al., 2024). Figure 3 shows the metaheuristics classification.

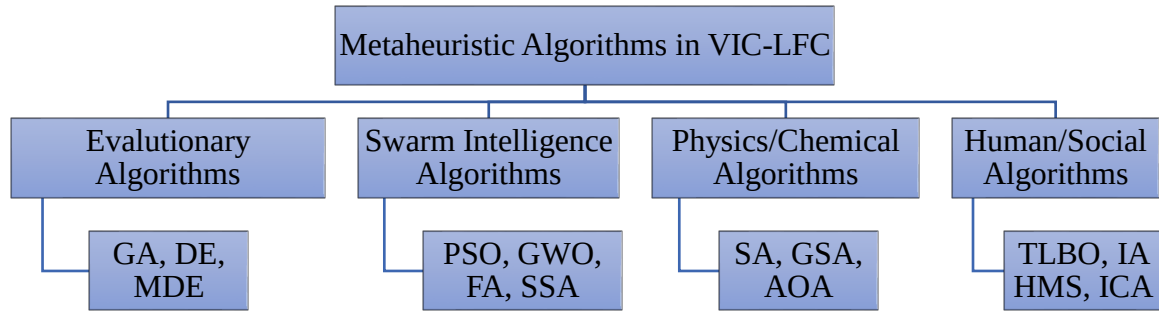


Figure 3: Classification of metaheuristic algorithms as applied in VIC-LFC (Mishra et al., 2024)

4.1 Evolutionary algorithms for VIC-LFC

Evolutionary Algorithms (EA) rely on population genetics to traverse continuous search spaces without gradient information (Jin et al., 2021). While Genetic Algorithms (GA) provide broad exploration, Modified Differential Evolution (MDE) enhances local searchability and convergence rates via dynamic scaling factors and adaptive mutation (Amr et al., 2022; Mishra et al., 2024). A comparative analysis of key Evolutionary Algorithms (EA) applied to Virtual Inertia Control (VIC) and Load Frequency Control (LFC) in islanded microgrids is presented Table 2.

4.2 Swarm intelligence algorithms for VIC-LFC

Swarm Intelligence (SI) algorithms model collective foraging and social organization. Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), Firefly Algorithm (FA), and Salp Swarm Algorithm (SSA) optimize controller parameters to shorten settling time and suppress dynamic frequency oscillations (Venkatesh et al., 2020; Ghodsi et al., 2022; Sharma & Pradhan, 2023; Amiri et al., 2023). Table 3 shows the comparative analysis of swarm intelligence algorithms as applied to microgrid.

Table 2: Comparative Analysis of Evolutionary Algorithms in Microgrid VIC-LFC

Algorithm	Swarm / Biological Analogy	Primary Control Topology in VIC-LFC	Key Operational Advantage	Primary Limitation
Genetic Algorithm (GA)	Natural selection, inheritance, chromosomal crossover	FOPID, standard PID, ADRC in BESS control loops	Simple structure; global exploration across discrete spaces	Slow execution; premature convergence in high dimensions
Differential Evolution (DE)	Vector difference mutation and recombination	Cascaded PIDFN, 2-DOF controllers, derivative VIC	Fast convergence; superior continuous-space exploitation	Vulnerable to search stagnation in non-convex spaces
Modified DE (MDE)	Dynamic scaling, adaptive crossover, opposition learning	Adaptive VIC (AVIC), multi-objective LFC, EV storage	Prevents local minima trapping; high RoCoF/nadir tracking accuracy	Higher memory and computational complexity per iteration

4.3 Physics and Chemical-Inspired Algorithms for VIC-LFC

Physics/chemical algorithms mimic thermodynamic cooling (Simulated Annealing - SA), gravitational forces (GSA), inter-atomic dynamics (Atom Search Optimization - ASO), molecular reactions (CRO/ACROA), and mass equilibrium (Equilibrium Optimizer - EO) (Duan et al., 2023; Rajaguru & Annapoorani, 2025; Behera et al., 2022; Agwa, 2020). Note that while Agwa (2020) originally evaluated EO in interconnected power systems, its mass-balance pool mechanism has been successfully adapted to standalone VIC-LFC gain synthesis. Table 4 provides a structured comparative analysis of physics- and chemical-inspired algorithms applied to VIC-LFC in islanded microgrids.

4.4 Human and Social-Inspired Algorithms for VIC-LFC

Human/social algorithms simulate imperialistic socio-political competition (ICA), classroom instruction (TLBO), cognitive thinking (HMS), and societal ideological evolution (IA) (Atashpaz-Gargari & Lucas, 2007; Rao et al., 2011; Mousavirad & Ebrahimpour-Komleh, 2017; Saber et al., 2023). Human- and social-inspired metaheuristic algorithms can be used to explore a search space of parameters and reduce time domain cost such as Integral Time Absolute Error (ITAE) and Integral Time Square Error (ITSE) by taking inspiration from social structures, learning models, human search processes and cultural evolution (Barisal, 2015; Dev et al., 2024). Table 5 presents a comparative analysis of human- and social-inspired algorithms applied to Virtual Inertia Control integrated with Load Frequency Control (VIC-LFC) in islanded microgrid architectures.

Table 3: Comparative Analysis of Swarm Intelligence Algorithms in Microgrid Applications

Algorithms	Swarm Inspiration	Primary Control Topology in VIC-LFC	Key Operational Advantage	Primary Limitation
PSO	Bird flocking / fish schooling.	Baseline PI/PID, Hybrid RL-VIC.	Computational simplicity and rapid initial search.	Susceptible to premature convergence in multi-modal landscapes.
GWO	Grey wolf social hierarchy & hunting	FOPID-IIC, Fuzzy Type-II Sugeno	Effective balance between global exploration and local refinement.	Search speed degrades with high parameter dimensionality.
FA	Bioluminescent firefly attraction	Cascaded PD-FOPID in BESS-VIC	Robust performance in non-convex gain landscapes	High computational complexity per iteration ($O(n^2)$)
SSA	Ocean Salp chain foraging	Tilt-Integral-Derivative (TID), Fuzzy-PID	Chain dynamics prevent local minima trapping	Sensitive to the decay schedule of convergence parameter c_1

Table 4: Comparative Analysis of Physics/Chemical Algorithms in Islanded Microgrid Applications

Algorithm	Physical / Chemical Inspiration	Primary Control Topology in VIC-LFC	Key Operational Advantage	Primary Limitation
SA	Metal annealing cooling	Classical PID and PI-Virtual Inertia Gain.	Probabilistic mechanism to escape local minima	Slow execution; highly sensitive to cooling schedules.
GSA	Universal gravity & mass interaction	Cascaded PID-FOPID / Adaptive Fuzzy-PID.	Strong initial global exploration via heavy mass attraction.	High risk of premature trapping in multi-variable spaces.
ASO / AOA	Lennard-Jones inter-atomic forces.	FOPID with Virtual Inertia & Damping Gain Tuning	High population diversity; resists local trapping	Requires precise tuning of interaction force parameters.
CBO	Collision momentum conservation.	Multi-stage PID with BESS / Flywheel VIC.	Parameter-free core search logic.	Slow boundary exploration on flat objective surfaces.
CRO / ACROA	Molecular collision and reaction energy.	FOPI-FOPD and Adaptive Fuzzy FOPI-FOPID.	Flexible search balancing decomposition and synthesis.	Tracking potential/kinetic energy increases computational overhead.
EO	Controlled volume mass balance.	Cascaded (I-P)-PDN and FO-Multistage VSG.	Rapid convergence rate; low settling time (T_s).	Prone to local stagnation if generation rate decays rapidly.

4.5 Novel and Hybrid Optimization Paradigms

To solve complex non-convex search spaces in modern hybrid microgrids, advanced novel and hybrid optimizers have been introduced (Iraj et al., 2024; Philip et al., 2025; Nanda-Kumar & Mohanty, 2022; Davoudkhani et al., 2024). Comparative summary of recent novel and hybrid optimization techniques Table 6.

Table 5: Comparative Analysis of Human/Social Algorithms in Islanded Microgrid Applications

Algorithm	Human / Social Model	Key Advantage in VIC-LFC	Convergence Behavior	Primary Limitation
ICA	Imperialist power dynamics & colony assimilation.	Robust against system parameter uncertainties.	Fast initial convergence; strong exploration.	Susceptible to local trapping if assimilation rate is high.
TLBO	Teacher guidance & peer learner interaction.	Algorithm parameter-free execution.	High consistency across independent runs.	Performance degrades if student diversity drops.
HMS	Cognitive search & mental grouping.	Superior at escaping local minima in constrained LFC.	Balanced exploration-exploitation via clustering.	Tracking mental strategy clusters adds computational overhead.
IA	Ideological evolution & societal debate.	Effective for multi-objective trade-offs (RoCoF vs. SoC).	Smooth convergence trajectory.	Slower fine-tuning exploitation in localized search spaces.

4.6 Comparative Analysis of Metaheuristic Performance Metrics

Controller performance evaluation relies on time-domain criteria (Maximum Overshoot - MOS, Settling Time T_s , Frequency Nadir, RoCoF) and error integral criteria (ITAE, ISE, ITSE, IAE). For instance, Walrus Optimization Algorithm (WaOA)-tuned PID controllers achieved lower frequency nadir drops and lower RoCoF compared to conventional Internal Model Control (IMC) and H_{∞} controllers under random load steps (Akinwola et al., 2025). Furthermore, Pelican Optimization Algorithm (POA)-tuned controllers demonstrated explicit minimization of error metrics, achieving an ITAE value of 1.9215 s under a 0.1 p.u. step load disturbance.

Across surveyed literature, metaheuristic parameter tuning consistently outperforms classical Ziegler-Nichols (Z-N) and manual trial-and-error methods, as demonstrated by comprehensive controller-optimizer benchmark studies. The controller optimizer comparisons for synthetic-inertia-relevant islanded microgrids are presented in Table 7.

Table 6: Comparative Summary of Recent Novel and Hybrid Optimization Techniques

Technique	Operational Inspiration / Mechanism	Primary Control Topology	Main Performance Outcome
Mountaineering Team (MTBO)	Team summiting behavior and leadership shift.	1PD-PI Controller	Outperformed PSO/WOA in ITSE and overshoot reduction.
Hybrid SSA-MGO	Sparrow Search + Mountain Gazelle co-evolution.	Adaptive VIC & Inverter Control	20% RoCoF reduction; 26.7% faster recovery (Philip et al., 2025).
Modified Golden Jackal (MGJO)	Variable Sine-Cosine adopted Scaling Factor.	Adaptive Fuzzy PIDF.	Enhanced tracking precision under non-linear deadbands.
Coati Optimization (COA)	Coati hunting and predator evasion dynamics.	1PD-3DOF-PID with EV Fleet.	Robust handling of stochastic mobile storage disturbances.
Walrus Optimization (WaOA)	Walrus social interaction and resting habits.	WaOA-PID for Autonomous Microgrids.	Lowest frequency nadir drop and minimal RoCoF (Akinwola et al., 2025).

5. OPEN RESEARCH CHALLENGES AND APPLICATION PERSPECTIVES

While metaheuristic optimization strategies significantly enhance VIC-LFC performance, several open challenges must be addressed:

- 🔧 **Real-Time Computational Overhead:** Iterative population updates incur substantial execution delays, limiting direct high-frequency online tuning. Offline tuning with adaptive gain-scheduling or real-time surrogate modeling presents a viable solution.
- 🔧 **Hardware-in-the-Loop (HIL) Validation:** Most existing literature relies on numerical MATLAB/Simulink simulations. Experimental validation via OPAL-RT or dSPACE HIL

Table 7: Summary Survey of Controller-Optimizer Literature in Synthetic Inertia-Relevant Microgrids

S/No.	Study	Focus Area	Optimizer Tuned	Structure	Main Reported Outcome
1	Magdy et al. (2020)	VIC under high-RES penetration	GOA	FOPID-VIC	Reduced Δf overshoot and enhanced nadir.
2	Khezri et al. (2021)	Coordinated LFC & synthetic inertia.	Hybrid PSO-GWO	FOPID	Superior dynamic settling compared to standalone PSO/GWO.
3	Al-Shetwi et al. (2021)	VSG parameter optimization.	PSO	Adaptive J & D	Limited RoCoF and suppressed active power oscillations.
4	Mohamed et al. (2022)	LFC with synthetic inertia	AOA	PIDD ²	Minimized ITAE under intermittent wind generation.
5	Oladipo et al. (2022)	Virtual inertia in low-inertia systems.	SMA	TID Controller	Suppressed dynamic oscillations better than standard PID.
6	Sahu et al. (2020)	Multi-microgrid frequency regulation.	WOA	Fuzzy-PID	Enhanced robustness under severe inertia drops.
7	Kishan et al. (2023)	Hybrid microgrid frequency support.	Snake Optimizer.	FOTID	Superior RoCoF suppression relative to GWO benchmarks.
8	Ali et al. (2021)	Ultra-low inertia microgrid VIC	GWO	2-DOF FOPID	Accelerated frequency recovery under RES variations.
9	Sharma & Singh (2022)	High PV microgrid adaptive VIC.	Jellyfish Search	PID-Tilt	Improved frequency nadir under fast cloud transients.
10	Taha et al. (2022)	AC microgrid inertia optimization	Wild Horse (WHO)	Cascaded FOPID-PI	Marked ITAE and RoCoF reduction under load steps.
11	Ferahtia et al. (2022)	Hybrid microgrid inertia control	Hunger Games (HGS)	FOPI-FOPD	Outperformed HHO under stochastic load profiles.
12	Latif et al. (2020)	Ultracapacitor & synthetic inertia LFC	Dragonfly (DA)	Dual-Stage FOPID	Damped transient frequency dips during generation loss.
13	Guha et al. (2021)	Isolated microgrid inertia support	QOALO	PID Controller	Reduced steady-state error and frequency nadir drops.
14	Yousri et al. (2021)	Storage-backed microgrid LFC	Marine Predators	FO Lead-Lag / PID	Maintained stability during sudden solar disconnections.
15	Rajesh et al. (2023)	Adaptive VSG control in autonomous grid	Water Cycle (WCA)	Fuzzy-FOPID	Robust tracking performance under parameter drift.

S/No.	Study	Focus Area	Optimizer Tuned	Structure	Main Reported Outcome
16	Sun et al. (2021)	Dynamic inertia/damping VSG tuning	Improved GA (IGA)	Dynamic J & D	Increased frequency nadir by over 18%.
17	Dey et al. (2022)	Multi-source microgrid VIC	ICA	3-DOF PID	Lower settling time compared to classical GA/PSO.
18	Ahmad et al. (2023)	Non-linear LFC with synthetic inertia	Kepler (KOA)	FOTIDF	Controller Robust against Governor Deadband and GRC constraints.
19		Storage-driven inertia emulation	HHO	PIDD ² Controller	Mehta & Patel (2021) Minimized initial RoCoF under heavy industrial load steps.
20	Ismail et al. (2023)	Low-inertia hybrid microgrid LFC	Northern Goshawk	FO Fuzzy PID	Achieved minimal ITAE metric among tested metaheuristics.
21	Akinwola et al. (2025)	Adaptive virtual inertia regulation	WaOA	PID	Lower nadir drop & RoCoF vs. IMC and H _∞

platforms is vital to verify controller execution under real-world sensor noise and signal quantization.

- 🔗 **Cyber-Physical Security:** Communication-assisted multi-agent LFC structures are vulnerable to Denial-of-Service (DoS) and False Data Injection (FDI) attacks. Resilient optimization frameworks integrating cyber-attack mitigation loops are required.
- 🔗 **Multi-Objective Pareto Optimization:** Single objective functions (e.g., ITAE) often neglect secondary constraints like battery State-of-Charge (SoC) degradation, thermal stress, and actuator saturation. Multi-objective Pareto formulations balancing dynamic performance and asset life are necessary.

5.1 Relevance to Regional Sustainable Development (e.g., Sub-Saharan & Nigerian Microgrid Infrastructure)

Addressing microgrid stability carries significant regional importance for developing nations prioritizing rural electrification and sustainable development. For example, in Sub-Saharan Africa and specifically Nigeria, national energy transition initiatives rely on standalone solar-PV-diesel-battery microgrids to electrify off-grid rural communities and industrial clusters. However, these isolated networks frequently suffer from trip-outs triggered by sudden load switching and cloud cover transients due to minimal system inertia. Implementing robust metaheuristic-tuned VIC-LFC frameworks provides an affordable, software-driven path to stabilize regional microgrids without requiring oversized physical storage, supporting sustainable economic expansion and grid independence.

6. CONCLUSION

Metaheuristic optimization algorithms provide an efficient framework for stabilizing low-inertia islanded microgrids. By optimizing synthetic inertia and load frequency control gains across evolutionary, swarm, physics-based, human-inspired, and novel hybrid variants (such as WaOA, SSA-MGO, and MTBO), dynamic responses under severe renewable intermittent conditions can be substantially enhanced. To translate theoretical advances into resilient grid infrastructure, future efforts must focus on lowering computational overhead, conducting HIL experimental validation, securing cyber-physical control links, and adopting multi-objective formulations tailored to real-world battery constraints and regional electrification challenges.

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