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Research Article

Improving Small Signal Microgrid Stability under Virtual Impedance Model–Using Modified Honey Bee Mating Optimization Algorithm

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Extended Abstract:

The increasing integration of inverter-interfaced Distributed Generation (DG) units—primarily from renewable sources like solar PV and wind—into islanded microgrids presents significant challenges to system stability. Unlike conventional synchronous generators, power electronic inverters lack inherent rotational inertia and exhibit complex dynamic interactions with control loops, network impedances, and load variations. These characteristics render microgrids particularly vulnerable to small-signal instabilities, which manifest as sustained low-frequency oscillations in voltage, frequency, and power flows following minor perturbations (e.g., load switching or solar irradiance fluctuations). Without proper damping and control coordination, such oscillations can degrade power quality, trigger protective relays, or escalate into full system collapse.

This paper addresses this critical issue by proposing a comprehensive small-signal stability enhancement framework that synergistically integrates virtual impedance-based droop control with a Modified Honey Bee Mating Optimization (MHBMO) algorithm. The core innovation lies not only in the formulation of a high-fidelity dynamic model that explicitly captures the coupling between the Phase-Locked Loop (PLL), virtual impedance, and inverter control dynamics, but also in the systematic, stability-driven tuning of virtual impedance parameters across multiple inverters to simultaneously maximize the microgrid stability margin and minimize reactive power sharing errors.

The paper begins by developing a state-space small-signal model of an islanded microgrid comprising two inverter-interfaced DG units, passive R–L lines, and composite R–L loads. The model explicitly incorporates:

(1) the power calculation block with low-pass filtering;
(2) voltage and current inner-loop PI controllers;
(3) droop-based outer-loop voltage/frequency control with active and reactive power feedback;
(4) a virtual impedance loop inserted between the droop controller and the voltage reference; and
(5) a PLL for frequency estimation and dq-frame synchronization.

This holistic modeling approach ensures that all dominant dynamic interactions—especially the often-overlooked coupling between the PLL and the virtual impedance—are preserved. The resulting

state matrix A for the 2-bus test system is a 36×36 matrix, whose eigenvalues fully characterize the system's small-signal stability.

The virtual impedance, typically modeled as a series R–L branch in the control loop, is leveraged not merely to decouple active and reactive power control (the conventional motivation) but as a tunable stability augmentation device. The paper formulates a multi-objective optimization problem where the design variables are the virtual resistance (Rv) and inductance (Lv) for each inverter. The dual objectives are:

(1) to maximize the microgrid stability index, defined as the absolute value of the real part of the dominant (least stable) eigenvalue of the system matrix A;
(2) to minimize the reactive power sharing error among parallel inverters, ensuring equitable sharing proportional to their ratings.

To solve this complex, non-convex problem, the paper introduces a Modified Honey Bee Mating Optimization (MHBMO) algorithm. MHBMO enhances the canonical HBMO by strengthening both its global exploratory and local exploitative capabilities, thereby mitigating premature convergence to local optima—a common pitfall in metaheuristic-based control tuning. The algorithm operates offline by:

- Simulating the microgrid's load-flow for a representative operating point;
- Linearizing the full nonlinear model around this point to extract A;
- Evaluating the stability index and reactive power mismatch for each candidate (Rv,Lv) pair;
- Iteratively refining the population of "queen bees" (candidate solutions) through simulated mating flights and worker bee local searches.

The proposed strategy is rigorously validated on a modified 2-bus islanded microgrid benchmark from the literature (M. Rasheduzzaman et al., IEEE JESTPE, 2014). The test scenario involves a step change in load at bus 1 at t = 2 s. The performance of the MHBMO-tuned virtual impedance is compared against the baseline case without virtual impedance tuning.

Key quantitative results demonstrate the efficacy of the proposed method:

- The microgrid stability index is dramatically improved from 1.41 (baseline) to 3.85, indicating a substantial increase in the damping of the most critical mode.
- All eigenvalues of the optimized system lie in the left-half plane (LHP), with the dominant mode exhibiting a damping ratio of 15.91%, confirming asymptotic stability.
- Post-disturbance, the reactive power sharing error is eliminated: both identical inverters share the reactive load equally (100 VAr each), whereas the baseline case shows a significant imbalance (180 VAr vs. 100 VAr).
- The transient response of active power is faster and with lower overshoot under the proposed control, reaching steady-state more quickly.
- The terminal and output currents of the inverters are balanced in both d- and q-axes, preventing uneven thermal stress and improving inverter utilization.
- Microgrid voltage and frequency remain within acceptable operational limits throughout the transient, with only a minor, well-damped voltage dip (~1.55 V on the q-axis) due to the intentional virtual impedance drop.

Crucially, the paper establishes a direct causal link between virtual impedance tuning and eigenvalue placement. By increasing the effective output impedance, the virtual impedance decouples inverter dynamics, reducing cross-coupling and enabling more independent, stable control. The MHBMO algorithm efficiently navigates the trade-off space to find parameters that provide the optimal balance between stability enhancement and acceptable steady-state voltage regulation.

In conclusion, this work presents a robust and systematic methodology for enhancing the small-signal stability of inverter-dominated islanded microgrids. By framing virtual impedance not just as a power-sharing tool but as a stability-critical control parameter, and by employing an advanced metaheuristic (MHBMO) for its optimal design, the proposed strategy offers a practical and high-performance solution. The results confirm significant improvements in stability margins, power-sharing accuracy, and transient response, all while maintaining compliance with standard operational constraints. This approach is particularly valuable for real-world microgrids with high renewable penetration and limited or no synchronous generation, where small-signal stability is a primary concern. Future work will extend this framework to larger, unbalanced multi-bus microgrids and incorporate robustness against communication delays and parameter uncertainties.

Keywords: Small-signal stability; Virtual impedances; Modified Honey Bee Mating Optimization (MHBMO).

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