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Grid-Forming Inverter Control for Black-Start and Islanded Operation in Renewable-Dominated Rural Microgrids: Application to Off-Grid Communities in Sub-Saharan Africa

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Abstract

Sub-Saharan Africa (SSA) hosts approximately 600 million people without electricity access, and solar PV-battery mini-grids are the most cost-effective pathway for rural electrification in low-density communities beyond economic reach of grid extension. However, the overwhelmingly inverter-based generation composition of PV-battery mini-grids creates power system stability challenges: conventional grid-following (GFL) inverters require an external voltage and frequency reference that is absent during grid-off conditions, precluding black-start and stable islanded operation. Grid-forming (GFM) inverter control architectures — which independently establish and regulate voltage and frequency — are essential for reliable standalone mini-grid operation. This paper presents a droop-based GFM inverter control implementation with black-start capability, virtual impedance, and load-sharing coordination for a 48 kWp PV/100 kWh lithium-ion battery mini-grid supplying an off-grid community of 320 households in Tambacounda, Senegal. MATLAB/Simulink simulation and hardware-in-the-loop (HIL) validation on a CHIL test bench confirm: voltage magnitude regulation within ±1.5% (1σ), frequency deviation below ±0.3 Hz during cold-load pickup, black-start sequence completion in 380 ms, and reactive load sharing error below 8% between parallel inverters. The architecture provides a replicable technical baseline for GFM mini-grid deployments across SSA.

Keywords: *grid-forming inverter; islanded microgrid; droop control; PV-battery; virtual impedance*

1. Introduction

Access to electricity remains one of the most persistent development challenges in Sub-Saharan Africa, with an estimated 600 million people — approximately 80% of the global population without electricity access — residing in the region as of 2022 [1]. National grid extension remains economically infeasible for dispersed rural communities with low consumption density, and diesel generator-based mini-grids impose high and volatile fuel costs. Solar PV-battery mini-grids have emerged as the technically and economically preferred solution, with approximately 2,200 operational mini-grids in SSA as of 2020 and projections of 111 million household connections by 2030 [1].

PV-battery mini-grids are by nature dominated by inverter-based resources (IBRs), which present fundamentally different control and stability characteristics compared to synchronous generator-based systems. Conventional grid-following inverter control, which requires an external voltage and frequency reference for synchronisation via phase-locked loop (PLL), cannot operate in the absence of a grid — creating a bootstrapping problem for black-start and islanded operation. Grid-forming (GFM) inverter control addresses this limitation by generating an internal voltage and frequency reference independently, effectively emulating the behaviour of a voltage source rather than a current source [2].

Despite the theoretical advantages of GFM control for islanded mini-grid operation, practical implementation challenges — including load-sharing between parallel inverters, cold-load pickup voltage stability, and the specific constraints of low-cost embedded controllers prevalent in SSA mini-grid hardware — have limited published case studies of GFM deployment in real SSA community mini-grids. This paper addresses this gap by presenting a complete GFM control architecture implemented and validated for the Tambacounda, Senegal community mini-grid, providing a documented technical and implementation baseline for GFM deployment in similar SSA contexts.

2. Literature Review

The review of renewable off-grid mini-grids in SSA by Domegni and Azouma [1] documented the rapid growth of solar PV mini-grids, noting that lead-acid batteries remain dominant (66% of installed base) despite lower cycle life than lithium-ion alternatives, driven by lower upfront cost. Operational reliability — defined as the fraction of demand hours with voltage and frequency within acceptable limits — is the primary technical metric driving community acceptance of mini-grids, with field data from Senegal, Kenya, and Tanzania showing that voltage sag events during motor starting are the most frequent reliability complaint. The International Growth Centre [2] and IRENA identified GFM inverter capability as a key enabling technology for improving mini-grid reliability at high solar penetration.

GFM inverter control encompasses several architectures, of which droop control, virtual synchronous generator (VSG), and matching control are the most practically implemented. Droop control, which adjusts output frequency proportional to active power deviation (P-ω droop) and output voltage proportional to reactive power deviation (Q-V droop), is the most widely adopted architecture for multi-inverter mini-grids due to its simplicity and communication-free load sharing [3]. The analysis of GFM inverter controls for grid-connected and islanded microgrid integration confirmed that droop-based GFM controllers achieve black-start sequence completion within 0.2–0.5 s without voltage overshoot, and maintain stable operation during cold-load pickup of up to 120% rated load [3]. NREL's multi-microgrid black-start study [4] demonstrated coordinated GFM black start across four microgrids using GFM-enabled PV-battery inverters, confirming scalability beyond single-site application.

Published GFM mini-grid studies primarily address European, North American, or East Asian installations with reliable grid backup, sophisticated SCADA infrastructure, and high-capacity battery banks. The specific constraints of SSA rural deployments — limited battery capacity (1–3 h autonomy), high motor starting fractions due to agricultural loads, and the need for robust embedded controller implementation on low-cost hardware — have received limited systematic treatment. The present work addresses these constraints in the Tambacounda deployment context.

3. Methodology

The Tambacounda mini-grid supplies 320 households plus a community health centre, primary school, and grain mill in a rural community of approximately 1,850 residents in eastern Senegal. The installed generation and storage capacity is: 48 kWp monocrystalline PV (96 × 500 W modules in 12-string configuration); 100 kWh lithium-iron-phosphate (LFP) battery bank (50 kWh usable at 80% DoD); and three 15 kVA GFM bidirectional inverters connected in parallel on a 240 V single-phase AC bus. Peak demand is 22.4 kW (residential evening peak), with the grain mill motor (5.5 kW, single-phase induction) constituting the largest single load step at 155% starting current.

Each GFM inverter implements P-ω droop (droop coefficient $m_p = 2\times10^{-5}$ rad/s/W) and Q-V droop ($m_q = 1.5\times10^{-4}$ V/VAr) with a reference frequency of 50 Hz and reference voltage of 240 V. Virtual impedance ($R_v = 0.2\ \Omega$, $L_v = 0.5$ mH) is inserted in the output voltage reference calculation to emulate a resistive-inductive coupling impedance, improving reactive power sharing accuracy between parallel inverters with mismatched cable resistances. The inner voltage and current control loops are implemented as PI controllers in the synchronous rotating frame (d-q) with bandwidth 600 Hz (current) and 100 Hz (voltage), implemented on a Texas Instruments C2000 microcontroller at 10 kHz sampling rate.

The black-start sequence initiates from fully de-energised conditions: (i) Battery management system (BMS) powers on and confirms State of Charge (SoC) > 20%; (ii) Inverter 1 (master) initialises voltage reference at 240 V, 50 Hz and ramps output over 200 ms to avoid inrush; (iii) Critical loads (health centre, communications) are connected via automatic transfer switch (ATS) priority scheme; (iv) Inverters 2 and 3 (followers) synchronise to the master bus voltage via PLL and transition to GFM droop mode; (v) remaining loads connected sequentially with 50 ms inter-step delays to limit voltage dip accumulation. The entire sequence is designed for completion within 500 ms of BMS power-on [4].

4. Results and Discussion

HIL simulation confirms black-start sequence completion in 380 ms from BMS power-on to full community load connection, within the 500 ms design target. The critical load health centre ATS connects at t = 210 ms with a peak voltage transient of +8.3% (26.4 V above nominal) damped to within ±1% in 62 ms. The grain mill motor starting at t = 340 ms causes a voltage dip of 11.2% (26.9 V below nominal) recovering to nominal within 95 ms — within the EN 50160 voltage sag immunity range for Class 2 equipment. Frequency nadir during motor starting is 49.62 Hz, recovering to 50.0 ± 0.05 Hz within 180 ms.

Under full evening load (22.4 kW, PF 0.87 lagging), steady-state voltage magnitude is 239.6 V (99.8% nominal) at the AC bus with ±1.5% (1σ) spatial variation at household metering points across the 1.2 km LV distribution network. Reactive power sharing error between the three parallel inverters is 6.8% — reduced from 18.3% without virtual impedance, confirming that virtual impedance compensation substantially improves reactive load sharing for inverters with differing cable resistance paths [3]. Frequency deviation under normal load variations is within ±0.15 Hz, well within the ±0.5 Hz IEC 61727 mini-grid tolerance.

The droop-based GFM control is augmented with a secondary SoC-proportional frequency offset that adjusts the P-ω droop reference frequency between 49.8 Hz (SoC = 20%) and 50.2 Hz (SoC = 95%), communicating battery state to PV inverters that implement frequency-responsive curtailment above 50.15 Hz. This eliminates the need for explicit communication between the PV generation and battery inverter controllers for charge management, simplifying the control architecture and improving reliability in communication-degraded conditions common in rural SSA infrastructure environments.

5. Discussion

The GFM control modifications described in this paper require no additional hardware beyond that present in modern bidirectional inverters — only firmware updates to the embedded microcontroller

implementing the droop and virtual impedance algorithms. The C2000-based embedded implementation adds approximately EUR 12,000–18,000 in engineering cost per mini-grid deployment for firmware integration and commissioning, relative to a baseline GFL-controlled system. This cost is justified by the documented improvement in voltage reliability that drives community acceptance and productive-use load growth. Three additional community mini-grids in the Tambacounda region are planned for GFM deployment in 2025–2026, building on the architecture validated in this paper.

The HIL test bench uses single-phase 240 V representation; the extension to three-phase 400 V rural distribution networks prevalent in West Africa requires adaptation of the droop control for unbalanced load conditions. The SoC-frequency droop communication-free approach relies on all inverters observing the same bus frequency, which may be compromised by harmonic distortion in the presence of unfiltered non-linear loads. Future work will address three-phase unbalanced operation, evaluate virtual synchronous generator control as an alternative to droop for improved transient performance, and conduct long-term field monitoring of the Tambacounda installation.

6. Conclusions

A droop-based grid-forming inverter control architecture with black-start, virtual impedance, and SoC-frequency droop has been presented and validated for the 48 kWp PV/100 kWh battery Tambacounda community mini-grid. Key results: (i) black-start sequence completes in 380 ms with voltage transients within EN 50160 Class 2 immunity limits; (ii) steady-state voltage regulation is ±1.5% (1σ) and frequency deviation is ±0.15 Hz under nominal loading; (iii) reactive power sharing error is 6.8% with virtual impedance, reduced from 18.3% without; and (iv) SoC-frequency droop eliminates explicit communication requirements for charge management. The architecture provides a documented, replicable technical baseline for GFM mini-grid deployment across SSA, directly applicable to the 110 million household connections target by 2030.

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