



Grid-Forming Inverter Control and Frequency Stability in Low-Inertia Island Microgrids: A Review of the Literature

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Abstract

Island power systems that replace diesel generation with photovoltaic plant, wind turbines and batteries lose the rotating mass that has always slowed frequency excursions after a disturbance. Grid-forming inverters, which behave as controlled voltage sources and set their own frequency, are widely proposed as the remedy. This narrative review examines what the published literature says about grid-forming control and frequency stability in small, low-inertia island microgrids. It first restates the frequency problem in terms of the swing equation and explains why it is sharper on an island than on a continental grid. It then describes the four main families of grid-forming control, namely droop control, virtual synchronous machines, virtual oscillator control and matching control, and sets out what analytical and simulation studies report about their effect on the rate of change of frequency and the frequency nadir. Constraints that the simpler models leave out are treated next: current limiting, finite energy behind the converter, and interaction with the remaining diesel sets. The review closes with the questions that remain open, among them the lack of agreed performance specifications, the shortage of published field evidence from operating islands, and the modelling fidelity needed for planning studies.

Keywords: *Grid-forming inverter, Low-inertia power system, Frequency stability, Island microgrid, Virtual synchronous machine, Droop control*

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1. Introduction

For most of the last century an island power system meant a diesel station. Frequency was held by the kinetic energy stored in the generator rotors and, a few seconds later, by the governors that admitted more fuel. As photovoltaic arrays, wind turbines and battery storage displace diesel running hours, the stored kinetic energy falls, and the frequency moves further and faster after the same disturbance (Tielens and Van Hertem, 2016). Islands meet this problem earlier than continental grids. Their systems are small, a single generator or feeder can carry a large share of the load, and there is no neighbour to lean on.

Most inverters installed to date are grid-following. They measure the terminal voltage with a

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phase-locked loop and inject a current in step with it, which presupposes that something else is holding the voltage. A grid-forming inverter reverses the roles: it presents a voltage of controlled magnitude and frequency behind an impedance and lets the current be decided by the network (Rocabert *et al.*, 2012). The idea is not new. Parallel inverters sharing load by frequency droop were described three decades ago (Chandorkar *et al.*, 1993), and the microgrid concept was built around it. What has changed is the scale at which system operators now contemplate running with few or no synchronous machines on line (Matevosyan *et al.*, 2019; Lasseter *et al.*, 2020).

This article reviews the published work on grid-forming control from the standpoint of one question: what it does for frequency stability on a small island system where inertia is scarce. It describes the control families, summarises what analysis and simulation have established, and identifies the limits and the unanswered questions that matter to an island utility.

2. Scope and Approach

The article is a narrative review of the published literature. It draws on the journal papers that introduced each control concept, on later comparative and survey articles, on standard textbooks and on the interconnection standards and roadmap reports that frame current practice. No claim is made to an exhaustive or systematic search, and no new simulations or measurements are reported. Stability terms follow the classification of the IEEE and CIGRE task forces (Kundur *et al.*, 2004) as extended to converter-dominated systems (Hatziaargyriou *et al.*, 2021) and adapted to microgrids (Farrokhhabadi *et al.*, 2020). The emphasis is on islanded alternating current systems of the size found on small and medium islands, in which diesel sets, batteries and renewable plant share a medium-voltage network.

3. Frequency Dynamics When Inertia Is Scarce

In a system of synchronous machines, frequency is a physical state. The swing equation relates the rate of change of rotor speed to the imbalance between mechanical and electrical power, scaled by the inertia constant H , the stored kinetic energy at rated speed divided by the machine rating (Kundur, 1994). Immediately after the loss of a generator, the initial rate of change of frequency is proportional to the size of the power imbalance and inversely proportional to the total stored kinetic energy. The lowest point reached, the nadir, depends in addition on how quickly governors and other reserves respond. Halving the inertia doubles the initial rate of change and leaves primary control half the time to act before under-frequency load shedding begins.

Milano *et al.* (2018) argue that the difficulty in converter-dominated systems is deeper than a smaller H . A converter has no rotor, the energy in its DC-link capacitor is negligible on the time scale of a frequency event, and its output frequency is whatever the controller computes. Frequency ceases to be a shared physical quantity and becomes a signal that the controls must create and agree upon. Microgrids add features of their own: feeders are short and often resistive, so the textbook decoupling of active power from voltage and reactive power from angle holds only approximately, and voltage and frequency stability cannot be studied apart (Farrokhhabadi *et al.*, 2020).

4. Families of Grid-Forming Control

The literature contains many named schemes, but they fall into a small number of families that differ in how the converter derives its frequency. Figure 1 groups them, and Table 1 compares their synchronising principle, their contribution to frequency containment and the reservation most often raised against each.

4.1. Droop control

Droop control gives each inverter a frequency set-point that falls linearly with its measured active power and a voltage set-point that falls with reactive power, in imitation of governor and exciter characteristics. Units then share a load change in proportion to their ratings without communicating (Chandorkar *et al.*, 1993). The small-signal behaviour of an inverter microgrid under droop was worked out by Pogaku *et al.* (2007), who showed that the low-frequency modes are governed by the droop gains and the power

measurement filter. Because droop leaves a steady-state frequency error, a slower secondary layer restores the nominal value, giving the hierarchical structure set out by [Guerrero et al. \(2011\)](#).

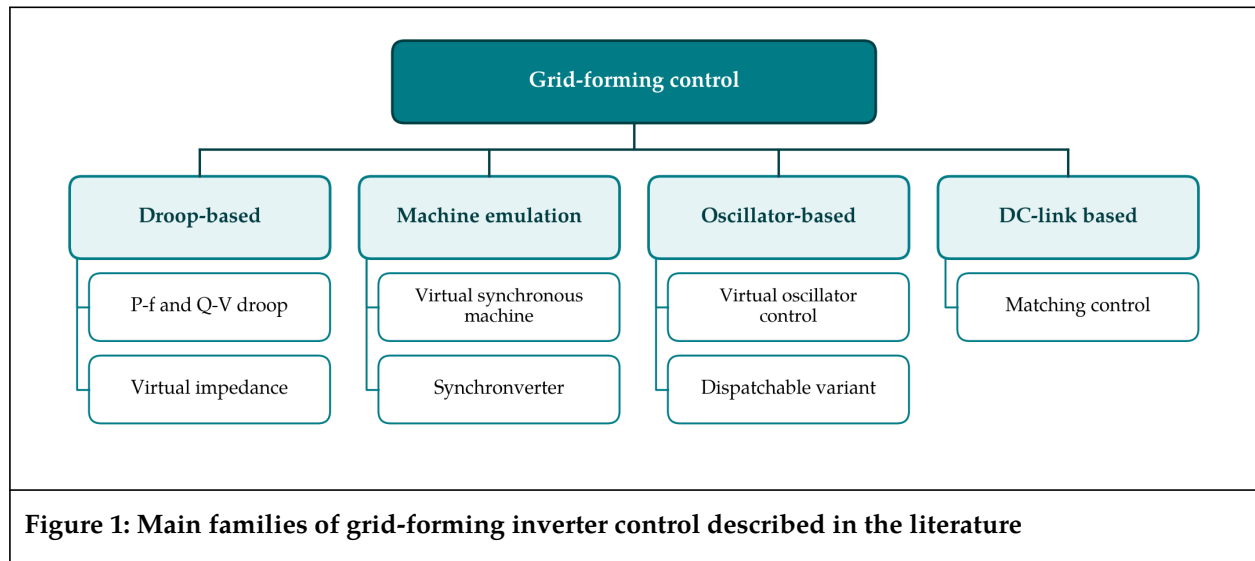


Table 1: Grid-forming control families and their bearing on frequency stability, as described in the literature

Family	How frequency is set	Effect on frequency response	Reservation commonly raised
Droop control	Frequency lowered in proportion to measured active power	Fast proportional sharing of a load step; inertia only through the power filter	Steady-state frequency offset; coupling on resistive feeders
Virtual synchronous machine	Swing equation solved in the controller	Tunable inertia and damping terms	Oscillatory if poorly damped; needs energy headroom
Synchroverter	Full machine model including flux and torque	Machine-like response with a familiar parameter set	Inherits machine dynamics that may not be wanted
Virtual oscillator control	Nonlinear oscillator driven by output current	Rapid synchronisation from arbitrary initial conditions	Power set-points harder to dispatch in the basic form
Matching control	Frequency tied to DC-link voltage	DC-side energy signals imbalance, as rotor speed does in a machine	Performance bound to DC-link sizing and source dynamics

4.2. Virtual synchronous machines

A second family programs the converter to behave like a synchronous machine. The virtual synchronous machine of [Beck and Hesse \(2007\)](#) and the closely related virtual synchronous generator solve a swing equation in the controller, so that the inverter frequency responds to power imbalance with a chosen inertia and damping. The synchroverter of [Zhong and Weiss \(2011\)](#) goes further and reproduces the electrical equations of the machine. Reviews of the many variants are given by [Bevrani et al. \(2014\)](#) and [D'Arco et al. \(2015\)](#). An influential result is that a droop controller with a first-order filter on measured power is mathematically equivalent to a virtual synchronous machine, the filter time constant playing the part of inertia ([D'Arco and Suul, 2014](#)). The two families are therefore closer than their names suggest, and the practical differences lie in tuning and in what is added around the core loop.

4.3. Oscillator-based and matching control

Virtual oscillator control abandons phasor quantities altogether. Each inverter emulates a nonlinear oscillator, of the Van der Pol type in the original proposal, driven by its own output current; coupled through the network, such oscillators synchronise without any explicit power calculation (Johnson et al., 2014). A later dispatchable form admits power and voltage set-points and comes with formal guarantees of global synchronisation (Colombino et al., 2019). Matching control starts from the observation that the DC-link capacitor of a converter is the structural counterpart of a rotor: making the output frequency proportional to the DC voltage lets the DC side signal power imbalance in the way rotor speed does in a machine (Arghir et al., 2018).

5. What the Literature Reports on Frequency Stability

Comparative simulation studies agree on the main point. When grid-forming converters replace grid-following ones at a high converter share, the system remains stable at shares where it would otherwise fail, and the frequency after a load step is better contained (Lasseter et al., 2020). A grid-forming unit responds to a change in network angle within its own control bandwidth and without first having to detect a frequency deviation, so the first reaction to an imbalance is not delayed by measurement. Tayyebi et al. (2020) compared droop, virtual synchronous machine, dispatchable virtual oscillator and matching controls in a common test system with synchronous machines and reported that all four improved the standard frequency metrics relative to the all-machine case, with differences between them that were modest in normal operation.

The same body of work shows where the trouble lies. The differences between schemes emerge under stress, when a converter reaches its current limit or its DC source cannot follow the demanded power, and the fast converter controls can interact adversely with the slow turbine and governor dynamics of the machines that remain (Tayyebi et al., 2020). For an island that keeps diesel sets for security and energy adequacy, this mixed regime is the normal one, and it is less thoroughly studied than either extreme. The stability classification for microgrids accordingly treats converter control interactions and power-sharing instability as categories in their own right (Farrokhhabadi et al., 2020).

6. Constraints That Idealised Models Omit

Three constraints recur. The first is current. A synchronous machine can deliver several times its rated current for a short period, whereas the semiconductor switches of an inverter tolerate little more than rated current. During a fault or a large load step the inverter must limit its output, by saturating a current reference or by inserting a virtual impedance (Paquette and Divan, 2015), and while it does so it no longer behaves as the voltage source that the stability analysis assumed. Synchronism can be lost during the limited period, and protection designed around large fault currents from rotating plant may not operate as intended.

The second constraint is energy. Synthetic inertia and fast frequency support are deliveries of real energy, and they must come from a battery, from curtailed renewable output held in reserve, or from the DC link. A virtual inertia constant can be set to any value in software, but the response is available only while the source behind the converter has headroom in both directions. The third is the network itself. On resistive low-voltage and medium-voltage feeders the active and reactive droop loops are coupled, and virtual impedance or transformed droop laws are needed to restore accurate sharing (Guerrero et al., 2011; Rocabert et al., 2012).

Standards have not yet caught up with these questions. IEEE Std 1547 is written for distributed resources that connect to an area system operated by others (IEEE, 2018), and IEEE Std 2800 sets requirements for inverter-based resources on transmission systems (IEEE, 2022). Neither defines in testable terms what a grid-forming unit on an isolated system must do, a gap noted in the research roadmap prepared by Lin et al. (2020).

7. Gaps and Directions for Further Work

Several gaps follow from the foregoing. There is no agreed performance specification for grid-forming behaviour that an island utility could write into a tender and verify at commissioning; the term currently covers devices with quite different responses. Planning tools are a second gap. Phasor models that neglect network and inner-loop dynamics can miss the control interactions described above, while electromagnetic transient models are costly to build and depend on vendor data that are seldom public. Guidance on which level of detail is sufficient for which study remains thin.

Third, most of the evidence is analytical or simulated. Operating islands that run for long periods on inverters alone exist, but detailed disturbance records from them rarely reach the journals, so the models have been checked against field behaviour less often than their number would suggest. Fourth, the literature on systems with units from several manufacturers, each with a proprietary control, is small, although this is the situation every utility will face after its second procurement. Black start and re-synchronisation of diesel sets to an inverter-formed network also deserve more systematic treatment than they have received.

8. Conclusion

The published work supports a clear but qualified position. Grid-forming control allows a small island system to hold frequency with few or no synchronous machines, and the main control families behave alike in normal operation because, at their core, they implement closely related laws. The decisive differences appear at the limits: when current saturates, when the energy source behind the converter is exhausted, and when fast converter controls meet slow diesel governors. An island utility assessing the technology is therefore better served by asking how a candidate unit behaves at those limits than by asking which control family it belongs to. Agreed specifications, validated models and published field records are the contributions that would most help it to do so.

Conflict of interest

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