Grid Forming Inverters in Microgrid Systems

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St. Mary’s, Alaska GFI Microgrid

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Grid Forming Inverters (GFM) Introduction

Two fundamental types of voltage sourced inverter controls:

<table>
<thead>
<tr>
<th>Grid Following Control (GFL)</th>
<th>Grid Forming Control (GFM)</th>
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<tbody>
<tr>
<td>Controls current and phase angle</td>
<td>Controls voltage magnitude and frequency</td>
</tr>
<tr>
<td>Controls active &amp; reactive power as well as fault currents</td>
<td>Instantaneously balances loads without coordination controls</td>
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<tr>
<td>Cannot operate standalone</td>
<td>Can operate standalone</td>
</tr>
<tr>
<td>Cannot achieve 100% penetration</td>
<td>Can achieve 100% penetration</td>
</tr>
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</table>

Grid-following: Current control with PLL

Grid-forming: Virtual oscillator control

Grid-forming: Droop control

Courtesy Brian Johnson, Univ. Wash.
GFI inverters were studied and deployed in DOE/CERTS microgrids

- Consortium for Electric Reliability Technology Solutions (CERTS) formed in 1999

CERTS Microgrid Concept

- Testing at a full-scale microgrid demonstration test bed operated by American Electric Power (AEP)
- Peer-to-peer
  - Droop control to allow flexible hybrid microgrids
  - $\alpha\beta$ reference (not DQ)
  - Continue operating with loss of an individual component or generator
  - No single component (e.g. master controller or a central storage unit) required for operation of the microgrid
- Plug-and-play
  - Unit can be placed at any point within the microgrid
  - No need to re-engineering controls
  - Similar to the flexibility one has with home appliances.
GFI inverters were studied and deployed in DOE/CERTS microgrids

When a disturbance to the utility grid occurs, the automatic disconnect switch enables the facility to “island” itself from the main utility grid.
GFM inverters were studied and deployed in DOE/CERTS microgrids

- Seamlessly switches between grid and island operation and back
- Stable without communications
- Sources are plug-and-play
- Proven in microgrid applications
GFM Inverters can ensure stability in larger grids

- GFM **required** for 100% renewable grid
  - Historically have been used for high penetration microgrids
  - But can be used in larger grids
  - Now seeing integration onto island grids
    - High renewable portfolio standards, high cost of generation

- High penetration of inverter-based generation decreases system inertia
  - Can result in reliability issues during contingencies
  - GFL inverters have advanced inverter functions to respond to contingencies

- GFM sources will increase or decrease their output power **instantaneously** to balance loads and maintain local voltage and frequency
  - **no significantly delay** in change of output
  - GFM sources can respond much faster to any contingencies than a GFL
    - (for GFM that do not utilize DQ controls)
Case study – O’ahu, Hawai’i, 50% distributed PV

System at **920** MW load, **466** MW PV

Event is loss of **62** MW load

GFL controls w/ frequency-watt function

GFI CERTS controls

GFI inverters responds much faster

**Frequency**  

**Aggregated PV output**
Case study – O’ahu, Hawai’i, 50% distributed PV

System at **1,080** MW load, **540** MW PV
Event is loss of **200** MW generator


**Frequency**

**Total System Load**
St. Mary’s and Mountain Village, AK

St. Mary’s, AK. Pop. 550
Peak load: 600 kW (winter)
Min load: 150 kW

Mountain Village, AK. Pop. 820
Peak load: 500 kW (winter)
Min load: 150 kW

Energy Resilience Challenge:

- Both villages are rural microgrids supplied by diesel gensets
- Diesel fuel shipped up Yukon River, impassable August-April
- Life threatening issues if diesel runs out during winter
  - Necessity for high reliability, low maintenance components
- High energy cost, >25% of average household income
Currently three diesel gensets (499 kW to 908 kW)

Three-stage plan to lower costs and increase reliability and resilience

1. Wind turbine-generator to reduce fuel use (DOE/IA)
   - EWT 900 kW Type IV pitch-controlled wind turbine generator
2. Storage-based grid bridge system (GBS) for spinning reserve (DOE/OE + DOD/ONR)
3. Network St. Mary’s MG with Mountain Village MG via 12.47 kV tie-line

Currently Commissioning

RFP Drafted, est. Fall 2019

Winter 2019/2020
Grid Bridge System (GBS)

- For high stochastic distributed generation
  - potential loss of power quality due to constant shifting between generation sources
  - less efficient to provide operational (spinning) reserves from diesel generators
- Significant operational cost savings from shifting spinning reserves to ‘synthetic’ reserves
- Grid forming inverter backed by high power, low energy capacity storage system
- Primary use as spinning reserve and associated step-load capabilities
  - Fast frequency and voltage support whenever active (~200kW, 3 seconds, ~100,000 cycles/year)
  - Inherently stiff (low impedance) voltage source that will provide good transient support during events
  - Adjustable droop response for both frequency and voltage deviations
- Eventual goal to run in diesels-off mode
- Desire to replicate successful approach across other their hybrid-diesel microgrid systems
  - Applicable for any similarly sized microgrid faced with increasing penetration of renewables
Open-source models for RE-based networked MG

- Developed full Matlab Simulink model for the St. Mary’s microgrid
  - includes developed models for diesel gensets (installed)
  - wind turbine (being commissioned) at St. Mary’s
- System size based on average winter high consumption, provided by AVEC
- System has voltage imbalance of ~5%
- Implemented on Real Time simulator (Opal RT)
  - Allows for Hardware-in-loop testing

- 900 kW wind turbine model
- 3 parallel 600 kW Diesel Genset model
GFM can be used to provide spinning reserve

Contingency event:

Wind penetration 85% → 15% in 2s
GFM can be used to provide spinning reserve

Contingency event:

Wind penetration 85% → 15% in 2s
GFM can be used to provide spinning reserve

**GFM as spinning reserve:**

1. Can stabilize voltage and frequency in a contingency
2. Shift reserve from diesel to GFM
3. Allow for more effective loading of generators
4. Slows system dynamics → slower gov. response → fuel savings

- GFM being procured by AVEC and commissioned by ACEP
- Commissioning data to be use to validate simulations
Sandia’s Distributed Energy Technology Laboratory GFMs

- Sandia premier facility since
- Specialize on DER systems integration: inverters, energy storage, gensets, microgrids, controllers
  - AC and DC System performance characterization/optimization
    - DER assets
    - Microgrids (DC and AC)
    - Grid integration
  - Advanced Inverter R&D and grid compatibility assessment
  - Focused on developing GFM transient models
    - Open source
    - Validated
    - Generic
  - Valuable for use by system and protection designers to understand transient GFM behavior during faults
Currently developing models

Testing transient response for validation:
- Single-phase
- ”Three-phase”
- Three-phase

![Diagram of voltage at inverter's terminals](image1.png)

![Graph showing stepping the load from 0.00pu to 4.35pu](image2.png)

![Graph showing stepping the load from 0.00pu to 3.00pu](image3.png)
Sandia’s Distributed Energy Technology Laboratory GFIs

Custom Hardware-in-Loop (HIL) GFM testbed being developed

- Testing of commercial units
  - Evaluation of behavior to large number of microgrid conditions (esp. fault behavior)

- Testbed to implement flexible control schemes in hardware
  - Evaluate dynamics of the internal signals of the inverter under unbalanced or fault conditions
  - Current work is ongoing to fabricate and commission the hardware testbed above

![Power hardware & controls at DETL](image-url)
Design/Performance Challenges for Microgrids

- **Transition from GFL to GFM mode**
  - Grid Following must have anti-islanding protection (UL1741)
  - Grid Forming must initiate an island
  - How do we reconcile these disparate requirements in a **seemless transition**?
    - Technically being done
    - Significant standards issues

- **GFIs and protection**
  - Current protection designed for synchronous machines (short circuit ~10 pu)
  - Majority of GFI provide <2.5 pu (steady-state, 4-6 pu possible at <10 cycles)
  - How do we adapt protection for GFIs (or other inverter-based resources)
    - Increase short-circuit (requires control/hardware upgrades)?
    - Utilize synchronous condensers?
    - Do we need to totally **rethink protection paradigm** for power electronics?

- In general, synchronous generation is well defined
  - Need **standardized models** to understand impacts of GFM on protection schemes
  - Need **standardized behavior** for variety of control schemes

- **GFMs and unbalanced loads**
  - GFMs (and GFL) could be able to source negative and zero-sequence current
  - Most do not
    - Due to control schemes (PQ) and grounding (3- vs. 4-wire)
    - Significant implications to protection and response time
GFIs must transition from Microgrid to Bulk Grid

- GFI most likely occur through phased implementations
  - starting with smaller, more constrained microgrids
  - moving towards larger grids

![Diagram of GFI transition from microgrid to bulk grid](image)

- GFIs in microgrids
  - rural villages, military bases, university campuses, etc.
  - ~Present-10 years

- GFIs in larger island grids
  - Puerto Rico, Hawaii, etc.
  - ~10-15 years

- GFIs in bulk grid transmission
  - WECC, ERCOT, etc.
  - ~20-30 years

Courtesy Brian Johnson, Univ. Wash.
Challenges of moving from Microgrid to Bulk Power Space

- **Protection issues**
  - Protection becomes more complicated in bulk system
  - Bidirectional power flow for DERs on distribution system
  - Need for zero and negative-sequence currents
  - Inconsistent behavior inverter to inverter

- **Black start capabilities**
  - GFM could be a major black start resource
  - Saturation behavior important due to inductive motor start
  - Black start/reserve by PV/wind → curtailment

- **Aggregation of DERs**
  - Current system is composed of centralized plants ~100 MVA
  - Future system will be distributed resources of 0.1-100 kVA
  - How do we accurately represent aggregations of small units?
  - Especially when connected on distribution system?

Courtesy Brian Johnson, Univ. Wash.