Lessons Learned in Implementing Battery-Inverter System Controls in Low-Inertia Systems

Dustin Schutz, Scott Perlenfein
Northern Plains Power Technologies
Brookings, SD USA
Brief introduction to NPPT

• Power engineering consulting firm in Brookings, SD
• Provides engineering, simulation, and design services:
  • EMTP- and PSS/E-type studies and simulation
  • Hardware-in-the-loop testing of relays, controllers and other devices
• Key application areas:
  • Distributed energy resource (DER) interconnections
  • Low-inertia systems (microgrids, emergency/standby power systems, remote community and island grids, off-grid power systems)
What is a low-inertia system?

• Power system in which the total rotational inertia of the rotating generation is small

• USUALLY relatively small power systems (< 20 MW), but not always; examples of 100+ MW low inertia systems do exist

• Examples
  • Microgrids
  • Remote communities
  • Many island grids
  • Remote facilities
    • Military
    • Resource extraction
Mitigation needs as renewable penetration level (P) rises in a low-inertia system

PV variability disappears into load variability

\[ P = \frac{PV}{Total\,Energy} \]

- \( \approx 10\% \): PV variability disappears into load variability
- \( \approx 30\% \): PV variability impacts mainline gens, but problems can generally still be solved by gen control adjustments OR LOAD CONTROLS
  - Mass tripping events start to become a problem—need FRT in PV inverters (H and L!)
  - Minimum diesel loading constraints may be reached
- \( \approx 50\% \): PV must act as a system asset
  - Storage, curtailment, coordination, grid support, ramp rate controls all important
  - Minimum diesel loading becomes a BIG problem

Definitions of “mains” and “DG” questionable; generators = backup for PV? Must have storage above 60% PV.
Case study: BIS for frequency support in island grid

- Goal: controls/protection design for a battery-inverter system (BIS) to provide frequency regulation to an island grid
- Approximately 5 MW peak load; heavy PV penetration (~30%)
  - Backbone of the system is diesel; baseload gens ~ 2.2 MW, 2.75 MVA
  - At times, almost 90% of island’s power from distributed PV
- H on the order of 1-2 s
- Combination of new and legacy equipment
Requirements

• BIS must keep the system frequency between 59.3 and 60.5 Hz during Case Studies tested

• BIS is not allowed to “tap” or otherwise change or connect to the existing generator controls (don’t mess with what works)

• BIS should be of the minimum size required to meet the need, including such factors as minimum diesel startup time and effective battery capacity under load
Model of example system

- 6 feeders, 5 have UFLS breakers
- BIS to be located at the Main Gen Station
Load modeling

• Used ZIP-motor load for this work to properly capture dynamic effects (e.g., FIDVR)

<table>
<thead>
<tr>
<th>Component</th>
<th>Fraction of the total load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Z</td>
<td>0.4</td>
</tr>
<tr>
<td>Constant I</td>
<td>0.0</td>
</tr>
<tr>
<td>Constant P</td>
<td>0.4</td>
</tr>
<tr>
<td>Single-phase asynchronous machine</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Distributed PV plant modeling

• What is modeled:
  • PLLs, self- and system protection relays, active anti-islanding

• What is not modeled:
  • MPPT, PV array, current regulators, switch bridge (commanded current sources)

Relay settings (1547 max values but with widened frequency trips):

<table>
<thead>
<tr>
<th>Setting</th>
<th>Threshold value</th>
<th>Pickup time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undervoltage Fast</td>
<td>0.5 pu</td>
<td>160 ms</td>
</tr>
<tr>
<td>Undervoltage Slow</td>
<td>0.88 pu</td>
<td>2 s</td>
</tr>
<tr>
<td>Overvoltage Slow</td>
<td>1.1 pu</td>
<td>1 s</td>
</tr>
<tr>
<td>Overvoltage Fast</td>
<td>1.2 pu</td>
<td>160 ms</td>
</tr>
<tr>
<td>Underfrequency</td>
<td>57 Hz</td>
<td>160 ms</td>
</tr>
<tr>
<td>Overfrequency</td>
<td>62 Hz</td>
<td>160 ms</td>
</tr>
</tbody>
</table>
BIS model

• Battery model
  • R-C-R structure with Rs and Voc dependent on battery state of charge (SOC)
  • Based on detailed manufacturer and Sandia National Laboratories test data at the cell level
  • Built and validated a single cell then “chunks” of the battery until the complete battery system was modeled (7P*412s = 2912 total cells)

• Inverter model
  • Similar to PV model, with a bit more detail
  • Modeled DC/AC filters, switch avg’d bridge, power and current regulators, and PLL

• Sized based on largest potential loss to the system
  • 2.2MW baseload Gen, ~1.5MW of PV, or ~1.75MW of load on a single feeder
  • Selected 2MW, 400kWh BIS

• Picked resting SOC to be 60% to allow more time for a diesel gen to be started and brought online
Control design philosophy

• First experimented with standard frequency-watt droop function (IEC function FW22), but response was unsatisfactory

• Needed a multirate controller
  • BIS should “get in fast” during onset of event in order to arrest frequency excursion
  • BIS should then respond sufficiently slowly that generators have time to “catch up”

• Needed an adaptive controller
  • Generator governors not fixed
  • BIS needs to remain robust over a wide range of governor settings
State Transition Diagram

#0 Idle Mode

- Battery SOC back to setpoint

#1 Help Mode

- \(|ΔF| > \text{threshold}\)

#2 Freeze Mode

- Freq. error stops increasing
- Freq. error grows again or changes sign
- Freq. error “small” and freeze timer expired

#3 Reset Mode

- Freq. error larger than threshold

#4 Charge/Discharge Mode

- P&Q commands at zero
Cases tested

<table>
<thead>
<tr>
<th>Case number</th>
<th>Event</th>
<th>Load level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Loss of generator</td>
<td>Peak</td>
</tr>
<tr>
<td>2</td>
<td>Loss of generator</td>
<td>Minimum</td>
</tr>
<tr>
<td>3</td>
<td>Loss of load</td>
<td>Peak</td>
</tr>
<tr>
<td>4</td>
<td>Loss of load</td>
<td>Minimum</td>
</tr>
</tbody>
</table>
Frequency response: Case 1

- Without BIS, large freq. excursion, PV mass trips and multiple feeders shed
- With BIS frequency remains inside design limits, no UFLS, no loss of PV
Voltage response: Case 1

- Large voltage fluctuation without BIS (~25%), large overshoot
- Much smaller voltage fluctuation with BIS (~8%), small overshoot
Frequency response: Case 2

- Without BIS PV mass trips and multiple feeders shed
- With BIS frequency remains inside PV trip limits
Frequency response: Case 3

- Without BIS PV mass trips on OF
- With BIS frequency remains inside PV trip limits
Frequency response: Case 4

- Without BIS PV mass trips on OF
- With BIS frequency remains inside PV trip limits
Effect of control path time delay

- <= 50ms delay desirable
- Wider PV frequency trips would allow slightly longer delay
Difficulty with fault case

• BIS controller worked well in tested contingencies because BIS is able to “get in” very quickly and hold the system up while generators have time to “catch up”

• However, may not be desired behavior during faults
  • Do not necessarily want the BIS to feed a fault
  • Do not want to worsen the system’s fault response

• Solution: added a fault suppression mode to the BIS controls
  • Suppresses BIS frequency response when fault conditions are detected
Fault case with BIS fault suppression

- Close-in fault
- BIS impact is small, but detrimental
- Main reason for the worsening of the frequency response: see next slide
Fault case with BIS fault suppression

- Close-in fault
- Main reason for the worsening of the frequency response is a W/VAr “blip” that is a function of the BIS regulator responses (not a function of the control algorithm)
- May be improved by inverter regulator adjustments—ongoing work
Need for new form of islanding detection

• This is Case 1 but with different generator governor settings.
• BIS still arrests frequency transient, but notice oscillation after recovery.
• Oscillation due to PV inverter active anti-islanding kicking in and out at oscillation peaks/troughs.
Conclusions

• It was possible to design a BIS that met the requirements, without “tapping” the existing generator controls

• Developed solution is an adaptive controller using a state-machine approach

• Works extremely well for all frequency support cases tested, but had challenges in fault cases
  • Resolved by fault suppression function
  • Still some work to do in this case

• Work is still ongoing; present discussion over whether hysteresis might do the job better than a time delay
Thank you!