Grid Forming Inverter-Based Resources

Applications and Requirement discussion- BESS, Wind and Solar

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Outline

- Low System Strength – Relevance to GFM
- How higher IBR penetration of scenarios affect SCR index and fault behavior evaluation
Aspects of low-system-strength challenges

Power Transfer Challenges

- Remote IBR plant or clusters
- Main challenges related to fault behavior and recovery during N-1 or weaker
- Frequent challenge in current and past projects or systems
- Mature GFL IBR design processes and controls

Long Transmission

Bulk System

High IBR Penetration Challenges

- Relevant in the context of de-carbonization of electricity
- Less frequent in current and past projects
- Transferring power over long electrical distance is not necessarily the challenge
- Instability risks of GFL inner loops or interactions
- Larger ROCOF and Angle fluctuations
- System operation and restoration

Pre/existing Solar/Wind Plant

Non-Predominant Synchronous Generation

Weak connection

Bulk System

What problem are we trying to solve with GFM?
Low-system-strength challenges and SCR

**Power Transfer Challenges (PTC)**

- Long Transmission
- Bulk System
- New Plant

**High IBR Penetration Challenges (HPC)**

- Non-Predominant Synchronous Generation
- Weak connection
- Bulk System

Simple conceptual equivalents considering power flow with respect to source of system strength related mostly to **steady state, fault and recovery performance**

For example, if in both circuits $\text{SCR} = 0.5$, $X = 2\text{pu}$

- PTC equivalent does not have a feasible steady state operating condition
- HPC, if the load is 1pu, there is a feasible steady state operating condition. If the IBR controls are small signal stable, an IBR system may operate stably

Same SCR value has a different interpretation in these circuits
### System strength challenges and GFM/GFL performance expectations

#### Power Transfer Challenges (PTC)

<table>
<thead>
<tr>
<th>Load Power [pu] (1)</th>
<th>SCR (2)</th>
<th>GFL (3)</th>
<th>GFM</th>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1.5+</td>
<td>✔️</td>
<td>✔️</td>
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</tr>
<tr>
<td>0</td>
<td>1.0 to 1.5</td>
<td>Could work</td>
<td>Could work</td>
<td>PTC</td>
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<tr>
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<td>&lt;1.0</td>
<td>❌ (apple)</td>
<td>❌</td>
<td>PTC</td>
</tr>
<tr>
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<td>0.75+</td>
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<tr>
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<td>0.5 – 0.75</td>
<td>Could work</td>
<td>Could work</td>
<td>PTC and HIPC</td>
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<tr>
<td>0.5</td>
<td>&lt;0.5</td>
<td>❌ (2)</td>
<td>❌</td>
<td>PTC and HIPC</td>
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<tr>
<td>1</td>
<td>&lt;0.2</td>
<td>❌(4)</td>
<td>✔️</td>
<td>HIPC</td>
</tr>
</tbody>
</table>

(2) \( X = 1/\text{SCR} \)

(1) Load

(3) Advance commercially available GFL IBR technology

(4) May work in some conditions

Comparisons of apples 🍎 with bananas 🍌 are not recommended

This assessment does not evaluate all important HPC performance aspects
**System strength challenges and GFM/GFL performance expectations**

Other performance associated with High IBR Penetration Challenges

- Voltage angle jump response expectations:
  - Requirements related to tolerating voltage angle jumps without tripping – GFL and GFM
  - Requirements to “oppose” voltage angle changes by injecting or absorbing active power very quickly after event.
    - GFM is intended to do this within the limitations of equipment
    - GFL would be expected to have no significant response or potentially a delayed response if specifically designed for it

- Fast rate of change of frequency (ROCOF)
  - Requirements related to tolerating ROCOF events without tripping – GFL and GFM
  - Requirements to “oppose” ROCOF events by injecting or absorbing active power with a mitigating effect similar to synchronous machines.
    - GFM is intended to do this within the limitations of equipment
    - GFL would be expected to have no significant response or potentially a delayed response if specifically designed for it

- Comments on Voltage Control
  - Low system strength – Voltage Control usually more adequate than Reactive Power Control
  - Voltage control at plant level
    - GFL IBR terminal voltage control - superior performance in low system strength, but not widely used or required
    - GFM IBR terminal voltage control – likely not to go through current control

Noticeable GFM differentiation to GFL
GFM inverter vs GFM resource

- Resources designed for GFL operation need **more than inverter control modifications** to provide reliable GFM behavior
- Angle jump or ROCOF trigger different behavior from GFM than GFL
- Load/Generation balance is **more complex in PV solar systems and wind turbines than with BESS**
  - Fast bidirectional active power fluctuations demanded by grid angle fluctuations
  - Drive train has stored energy and constrains (wind)
  - Additional hardware (energy buffer/storage) may be required depending on performance requirements
  - Curtailment
- Current rating and fault contributions

![Image showing large P variation in response to voltage angle variation](image_url)

(P output in pu from IBR, GFM vs. GFL with and without inertia-like response
GFM BESS MW scale projects

- BESS projects are usually not GFM

**Key GFM BESS Projects:**
- Metlakatla Power & Light 1MW/1.4MWh-1995 [1]
- Vernon CA 5MW/2.5MWh- 1996 [2]
- IID 30MW/22MWh- 2017. Black start of GT auxiliaries and other services
- Entergy Perryville - Black start of GT auxiliaries with 7.5 MW x 7.5 MWh BESS – 2019
- Black start of GT auxiliaries with 13 MW x 13 MWh BESS - 2020

**Projects demanded:**
- Black start of industrial and complex load (SCR= 0)
- Black start field demonstration
- Modular solutions with distributed BESS

Distributed BESS systems with GFM control approach compatible with interconnected grids
GFM BESS MW scale projects

- Large drives fed from BESS
- Motor and transformer energizations/ Inverter rating optimizations
- Performance Requirement definition are key to design and not simple
  - Current rating vs frequency and voltage sags for critical events
  - Complexity of applications drives need for extensive study efforts
- Few control observations:
  - Hierarchical control with plant-level supervisory controller which sends commands to inverters based on POI measurements (same as most sizable IBR plants)
  - Co-ordinated control between multiple inverters without need for fast communications
  - In islanded mode, plant controller controls voltage and keeps frequency close to nominal

Direct start of large asynchronous machines

Performance requirements definitions are complex
How much GFM is GFM enough?
GFM Wind turbine experience

From GFL to GFM...

- Converter, Turbine and plant controls coordination is different
- More Frequent and faster active power fluctuations has impact on drive train
- Several GFM performance aspects benefit from overload capabilities

Type 3 GFM WTG electrical system lab demonstrations well underway

Performance requirement definition

- Performance definitions are different from some of the BESS projects mentioned
- Likely to continue changing as more markets request features
- GFL vs GFM requirement approach may need to be different
- Consideration of equipment limitations
Final Comments

- Grid forming technology can support mitigation of several aspects of low system strength...not all of them.
- GFM performance options are very broad. Performance requirement definition is not simple. Manufacturers require good level of performance definition to design products.
- Several BESS grid forming applications deployed
- PV systems and Wind Turbine design/control based on maximum energy capture. Grid forming operation could lead to significantly reduced energy capture
- GFM capabilities in wind and solar progressing
  - GFM performance requires more than controller code modifications
  - Market size associated to increased performance requirements
- Likely increase in application complexity for stakeholders (Reliability entity, Transmission operator, plant developer, OEMs). Effect in project award/deployment cycles.