Modeling and Reliability
Implications of Inverter Based Resources

Impact on stability of bulk power system

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General topics covered in this presentation…

- Modeling of inverter based resources connected to bulk power system
- Modeling of distributed energy resource’s impact on bulk power system
- Protection implications of inverter based resources
Bulk Power System Inverter Based Resources
Background/Motivations...

- Predominant use of positive sequence software such as GE-PSLF™, Siemens PSS®E, PowerWorld Simulator, PowerTech Labs TSAT for bulk power system simulation studies.
  - DlgSILENT PowerFactory has an RMS simulation mode for large power systems

- Use of **generic models** for system wide impact/planning study
  - All converters used to interface generation are in reality voltage sources!
  - Current source interface with the network to mimic high bandwidth fast inner current control loops

- These state of the art generic models are named as:
  - REGC_A – representative of renewable energy generation converter
  - REEC_A – representative of renewable energy electrical controller
  - REPC_A – representation of renewable energy plant controller
Background on Existing REGC_A Model in Simulation Software…

- **Current source model**
  - True representation of grid following inverters

- But in low short circuit interconnections,
  - Can result in numerical stability issues
  - Cannot represent the oscillatory instability that may occur

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Limitations of existing positive sequence converter models...

• Controller instability not captured in the positive sequence simulation.
• The limitation of the generic positive sequence model is shown in this scenario.
• How can results from such simulations be trusted?

• More generally, fast current and angle tracking loops of inverter controls can be stable only in high short circuit systems.
• They have to be made slower in low short circuit systems
• As they get slower, their dynamics cannot be ignored as is presently done in REGC_A

An improved positive sequence generic model...

- Voltage source interface to be true to actual inverter topology
- Representation of PLL and inner current control loop
- Model presently created as a user defined model in GE-PSLF™ for testing
- Small timestep required (1ms)

In addition to improved numerical stability, this model can serve as an intermediate model between positive sequence and three phase EMT type of simulations

Can it really show oscillations that were observed in EMT simulations?

- For the same fault as before, positive sequence simulations can now represent the oscillatory instability while also being numerically robust
- Controller gains values of course do not translate 1-1 from EMT simulations

- What is the impact of this?
  - Problematic converter locations can be screened out faster
- Can the oscillations be damped out?
  - Yes, by tuning controllers in both EMT and positive sequence
- Can the model represent small signal oscillations observed in real life?
  - Yes. It has been validated against measurements obtained from a PV plant

DISCLAIMER: This new model is not meant to replace detailed EMT simulations. Engineering judgement must be employed
Is this model then a form of grid forming control…?

- Possibly yes!
  - Inverters are inherent voltage sources
  - Kirchhoff’s laws cannot be violated

- Focus is on system stability so,
  - As with any controls, it can go unstable, but can be tuned to be stable.
  - Voltage source interface provides the necessary sub-cycle stability

- It needs additional backend power sharing controls
  - Provided by angle droop control

<table>
<thead>
<tr>
<th>Grid following</th>
<th>Viewed by grid as</th>
<th>Requires strong grid?</th>
<th>Current control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid following</td>
<td>Current source</td>
<td>Yes</td>
<td>Strict</td>
</tr>
<tr>
<td>Grid forming</td>
<td>Voltage source</td>
<td>No</td>
<td>Loose</td>
</tr>
</tbody>
</table>

Would it work in a large system with synchronous machines present…?

<table>
<thead>
<tr>
<th>Case</th>
<th>Source Type</th>
<th>Control Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>All 433 synchronous machines</td>
<td>Simple governor and static excitation system</td>
</tr>
<tr>
<td>Case 2</td>
<td>417 grid forming converters</td>
<td>Constant frequency and voltage control</td>
</tr>
<tr>
<td></td>
<td>16 synchronous machines</td>
<td>Simple governor and excitation system</td>
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<td>417 grid following converters</td>
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</table>

- In cases 2 – 5, sixteen synchronous machines are present in addition to IBR, accounting for around 16% of capacity (and 11% of MW) of all generation.
- Inter area ‘AGC’ control has also been implemented.


Generation Trip Response

- Trip of two largest generators (approximately 1.2 GW each) sequentially at $t = 10\text{s}$ and $25\text{s}$

Robust power sharing and frequency control
How would other forms of grid forming control be modeled…?

- A potential alternative way has been investigated:
  - In the model described previously, remove the inner current control loop and phase locked loop, but keep the voltage source interface and keep the outer loop voltage/frequency control and current limits.
  - Tested on WECC system by replacing all sources with converters of similar rating and headroom

Sensitivity of magnitude of response with all sources being converter interfaced of similar rating...


In WECC:

- Energy sources only in Arizona, Northwest, and major portion of California were replaced by grid forming converter models of appropriate MVA rating.
- Load changed in response to acceleration of frequency.
Other types of converter interface and control topologies studied...

- Ideal (unlimited current) grid forming topology
- Controlled grid forming topology
- Controlled grid forming topology with source behind inverter

- All modeled as positive sequence models
Should grid forming be defined from a bulk power system point of view…?

- For this discussion, black start is not considered.
  - Not every synchronous machine power plant can provide black start services. Special controls are required to be installed in order to provide this service.
- Limit on value of absolute current injection is not a function of type of control.
- Every type of control system has its stability region limits.

- It may be very restrictive to categorize grid forming as any controls without a PLL
  - Because then, requirement of grid forming controls would directly imply that PLL cannot be used
  - An analogy of this requirement for synchronous machine plants would be to specify the exact type of excitation system that has to be used (e.g. only static exciter can be used and not ac excitation)

As long as a control structure is robust, stable, and grid friendly – is that sufficient?

Let us all channel our inner Shakespeare
Distribution System Inverter Based Resources
The Three Pillars of Accurate Modeling of DER for Transmission Planning Studies

<table>
<thead>
<tr>
<th>I. Accurate Model Specification</th>
<th>II. Accurate Model Integration</th>
<th>III. Accurate Model Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Aggregate generator in power flow case</td>
<td>• Power flow case</td>
<td>• Feeder aggregation/equivalent impedances</td>
</tr>
<tr>
<td>• Generic or dynamic equivalent model in dynamic case</td>
<td>• Dynamic case</td>
<td>• Split of legacy/modern DER</td>
</tr>
<tr>
<td>➢ 2nd generation renewables models</td>
<td>➢ Aggregated DER Model Integration (ADMI) Tool (3002014316)</td>
<td>• Partial Voltage Trip Parameters</td>
</tr>
<tr>
<td>➢ Aggregated DER (DER_A) model (3002015320) – public!</td>
<td></td>
<td>➢ Feeder Aggregation Research (3002013500)</td>
</tr>
</tbody>
</table>

Research commenced in 2015 and continues over the next few years as joint project of programs P40.016 & P173A
Block tripping of DERs is a concern to improved resiliency

- Each indicated sag depth is multiplied by initial substation voltage for actual depth.
- Represents a simulation carried out with 100 DERs each of 10kW

How does a transmission planner get this visibility?
The DER_A Model

Partial voltage tripping:
- Legacy ↔ modern DER (param. Vrfrac)
- Voltage drop over distribution feeder (vl0, vl1, vh0, vh1)
- Corresponding trip times (tl0, tl1, th0, th1)

How to find parameter values for the model? Present focus is on voltage thresholds.
Results from analysis of two separate feeders

IEEE 8500 Node Feeder

Southern California feeder

Protection Implications of Inverter Based Resources
Impact of Inverter-Based Generation on Power Swing Protection

• Large levels of inverter-based resources might impact the rate of change of the impedance (due to fast controls) and the impedance trajectory measured by power swing relays potentially resulting in:
  • Power Swing Blocking (PSB) function potential misoperation due to faster power swings under high levels of IBR – swings misinterpreted as faults
  • Out of Step Tripping (OST) function misoperation due to modified impedance trajectories under high levels of IBR

IEEE PSRC-D29 Test System

• Simulated power swing under two scenarios:
  • Scenario 1: no wind generation
  • Scenario 2: 50% wind generation (synchronous generators 6, 15, and 16 replaced by wind generators).
• Investigated response of relay Maple-Spruce
Demonstrating Results – PSB Misoperation

No wind

- The relay successfully detects the power swing and issues a PSB signal to block zone 1 and 2 of the distance relay.

50% wind

- PSB misoperation under 50% wind integration. Relay doesn’t detect the power swing and fails to block distance protection zones.
  
  - Reason: measured impedance moves from the outer element to the inner element in less than 2 cycles (PSB time-delay) due to the increased rate of change of impedance
  
  - Swing misinterpreted as fault. Zone 1 instantaneously issues a tripping signal which results in undesired tripping of Line8_16.
Protection System Performance Evaluation - Guidelines

- Study relays response & identify relay misoperation scenarios on benchmark systems with inverter based resources
- Provide recommendations and study practices to protection engineers when conducting protection studies to prevent relay misoperation/miscoordination

Negative Sequence Based Protection
- Typically inverter-based resources are designed to suppress negative sequence current partially or entirely
- Inverter controls define the phase angle relationship between negative sequence voltage and current
- Negative sequence overcurrent and negative sequence directional elements potential misoperations

Communication Assisted Protection
- Permissive overreaching transfer trip (POTT)
- Permissive underreaching transfer trip (PUTT)
- Directional comparison blocking (DCB)

Line Distance Protection
- Dynamic expansion of distance mho
- Under IBR SIR depends on pre-fault generation level and grid strength

Power Swings Protection
- Power Swing Blocking (PSB) function potential misoperation due to faster power swings under high levels of IBR – swings misinterpreted as faults
- Out of Step Tripping (OST) function misoperation due to modified impedance trajectories under high levels of IBR
Summary

Mathematical Models Today
• State of the art models may face limitations as inverters increase
• This is due to their current source interface with the network

Mathematical Models Tomorrow
• Grid forming converter → constant frequency system operation
• Development of converter models and associated controls in positive sequence and three-phase point-on-wave simulation platforms

Reliability Implications
• Investigation into adequacy and need of new control technologies is required
• DERs may play a huge role in system stability
• Present protection schemes may have to be revisited
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