“Tipping Point” Analysis for Coupled Inverter-Machine Systems

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Motivation

Grid-following controls

Present

Future

To next-generation grid-forming controls
1. “Tipping point” analysis
   - Small-signal stability of coupled inverter-machine systems

2. Inverter-dominant microgrid testbed
   - Grid-forming and grid-following
• **A fundamental question:** What happens as the ratio of inverter/machine ratings increases?
• A simple illustrative example system:

- Adjust the ratings of the inverter and machine to represent different inverter penetration level.
Model description: synchronous machine

- Standard machine model [1]:

\[
\begin{align*}
&\text{governor: } \frac{1}{\tau_g s + 1} + P_{\text{agc}} + \frac{1}{\omega} \delta_g \\
&\text{turbine: } \frac{1}{1 + sF_{\text{hp}} Tr} \left(\frac{1}{1 + sT_{\text{ch}}} (1 + sT_{\text{rh}})\right) + P_m + \frac{1}{2Hs + D} \omega
\end{align*}
\]

**Frequency Dynamics**

**Voltage Dynamics**

\[
\begin{align*}
\lambda^d i^d - \lambda^q i^q
\end{align*}
\]

\[
\begin{align*}
&\text{voltage controller: } \frac{T_c s + 1}{T_h s + 1} v_C \\
&\text{exciter: } \frac{k_a}{T_a s + 1} v_{C} \\
&\text{field: } \frac{v_{fd}}{T_a s + 1} v_{fd}
\end{align*}
\]

\[
\begin{align*}
&\lambda_{fd} = \lambda_{\text{nom}} (v_{fd} - r_{fd} i_{fd}) \\
&i_{fd} = \frac{\lambda_{fd} + L_{a,fd} i_{fd}}{L_{fd,fd}} \\
&\lambda^d = -L_d i^d + L_{a,fd} i_{fd} \\
&\lambda^q = -L_q i^q \\
&v^d = -\lambda^q - \tau_a i^d \\
&v^q = \lambda^d - \tau_a i^q
\end{align*}
\]

Model description: inverter

- Grid-following: synchronize to grid voltage reference
- Grid-forming: generate voltage autonomously

Grid-following inverter control
Grid-following inverter control: virtual oscillator controller (VOC)
Objective: obtain scalable model to represent a collection of inverters.

We showed that if the control and physical parameters of each inverter in a parallel system adhere to a set of scaling laws, then the output current of a multi-inverter system can be modeled exactly with one aggregated equivalent inverter model.


Results for grid-following case

- Instability at approximately 50%
- Result varies between 40%-90%, depends on parameters

• Which subsystems impact on the “tipping point” most heavily?
• Sensitivity analysis of the following subsystems:
  o Machine automatic voltage regulator (AVR) and excitation system
  o Inverter current controller
  o Inverter PLL
  o Machine mechanical inertia

Bypass AVR and excitation

Different current controller gain
Instability at approximately 50% in default case

The “tipping point” depends on the system parameters
- Reactive power droop slope plays a significant role
- System stability can be improved when parameters are chosen carefully
Multi-machine multi-inverter case

- IEEE 39-bus test system resembles the New England system.
- There are 10 generator/inverter buses.
- Approach: Sweep penetration level by replacing machine one-at-a-time with inverter of identical rating.
Multi-machine multi-inverter case

- Preliminary results are consistent with the single machine single inverter case.
Take home message

- Coupled inverter-machine system may become small-signal unstable when we increase the inverter penetration level.

- The “tipping point” where the system becomes unstable depends on system parameters.

- Grid-forming inverter can potentially improve the stability of the system.
Inverter-dominant microgrid testbed
Inverter-dominant microgrid testbed

- Micro-inverter from SunPower (320 W, 240 Vrms)
- 10 grid-forming inverter + 10 Grid-following controlled inverter
Inverter-dominant microgrid testbed
Test procedure

• Demonstrate feasibility of heterogeneous system with VOC & Grid-following inverters:
  o Black start with VOC inverters and load sharing
  o Cooperation with grid-following inverters
  o Load transients: resistive load and reactive load
Test procedure
Step 1: black start

- Successful Black Start by Grid Forming Inverters under 250W condition
  - Black Start
  - Dynamic Load Sharing
Step 2: load step change

- Load transient from 250W to 750W with five inverters sharing the load
  - Dynamic Load Sharing
  - Transient Voltage Regulation
Step 3: adding grid-following inverters

- Power Generation of Grid-Following Inverters
  - Grid Regulation under Grid-Following inverter operations
  - Compatibility with Grid Following Inverters
  - Tight Grid Voltage Regulation
Take home message

- Testbed with both grid-following and grid-forming inverters.
- VOC inverters are able to regulate the output voltage.
- VOC inverters are able to black start the system.
- Multiple VOC inverters can dynamically share loads.
- VOC inverters work well when connected with grid-following inverters.
Thank you!

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**Demo: Step 1**

- Successful Black Start by Grid Forming Inverters under 250W condition
  - Black Start
  - Dynamic Load Sharing
**Demo: Step 2**

- Load transient from 250W to 750W with five inverters sharing the load
  - Dynamic Load Sharing
  - Transient Voltage Regulation
Demo: Step 3

- Power Generation of Grid-Following Inverters
  - Grid Regulation under Grid-Following inverter operations
  - Compatibility with Grid Following Inverters
  - Tight Grid Voltage Regulation
Demo: Step 4

- Load Step form 750W to 1750W with 5 GFM MIs and 5 GFL MIs generating 500W
  - Grid Voltage Regulated by GFM MIs
Demo: Step 5

- GFL Inverter Power Gen Increase to 200W
  - Grid Voltage Regulated by GFM MIs
Demo: Step 6

- 10uF Capacitive Load Turn on (Load Voltage Compensation Simulation)
  - Reactive Power Transient Covered By GFM
Demo: Step 7

- GFM Inverters 6-10 Turned on to join
  ✔ Successful Synchronization between GFM Inverters + Load Sharing
Demo: Step 8

- GFL Inverters 16-20 Generate 250W
  - GFM Inverters Continue to Regulate Grid Voltage by Adjusting Their Power Generations Depending on the Load.