Grid-Forming Inverter Modeling and Real-World Demonstration

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OUTLINE

➢ Grid-Forming and Grid-Following Concepts
➢ WECC-Approved Grid-Forming Inverter Model (REGFM_A1)
➢ Demonstration of Grid-Forming Inverter at a 380 MW Wind, Solar, and Battery Storage Combined Power Plant (led by Portland General Electric)
Voltage-Sourced Inverter

Grid-Following (Current Source)
+ Current control (e.g., PLL+ current loop)
+ Control P & Q
- Do not directly control voltage and frequency
- Cannot work without a grid

Grid-Forming (Voltage Source)
+ Direct Voltage & frequency control
+ Can work in islanded mode
- No direct control of current
- Overload/over-current Issues

At the beginning of a small disturbance, the inverter output current is “approximately” constant, and then external controls adjust $I_{ref}$.

At the beginning of a small disturbance, the inverter internal voltage is constant, and then external controls adjust $E$ and $\delta$. 
WECC adopted the grid-forming inverter model (REGFM_A1) led by PNNL

- Grid-forming inverters are vital for renewables and energy storage to maintain the stability of power grids
- PNNL-developed model specification of droop-controlled, grid-forming inverters was approved by WECC
- This is the first WECC-approved grid-forming inverter model
- The REGFM_A1 model has been included in the model libraries of PSS/E, PSLF, PowerWorld, and TSAT

This work is funded by the DOE OE Microgrid program, PNNL Laboratory Directed Research and Development (LDRD) Program, and the UNIFI consortium under the DOE SETO Award Number 38637
Droop-Controlled, Grid-Forming Inverters

• A grid-forming inverter behaves as a controllable voltage source behind impedance

• Two ideal voltage sources cannot be paralleled. The coupling reactance $X_L$ is very important for controller design
  ➢ If $X_L$ is well designed (e.g., 5%-20%): $P \propto \delta, Q \propto E$

\[
\delta_p = \delta_E - \delta_v \\
\delta_p = \int (\omega - \omega_0) dt \\
P = \frac{E V}{X_L} \sin \delta_p \approx \frac{E V}{X_L} \delta_p \\
Q = \frac{E^2 - E V \cos \delta_p}{X_L} \approx \frac{E(E - V)}{X_L}
\]

• Droop Control: Parallel multiple voltage sources in a system
  ➢ $P$ vs. $f$ droop ensures the phase angles of multiple voltage sources are synchronized
  ➢ $Q$ vs. $V$ droop avoids large circulating vars between voltage sources

\[
\delta_p \rightarrow P \rightarrow \omega \rightarrow \delta_p \quad \text{(Negative feedback control)}
\]
Model Specification of a Droop-based Grid-Forming Inverter (REGFM_A1)

- The model includes a voltage source representation, $P$-$f$ and $Q$-$V$ droop controls, $P/Q$ limiting controls, and a transient fault current limiting function.
- Most of the control blocks came from the CERTS Microgrid Project funded by DOE.
- SMA suggested to add the $Q_{\text{max}}/Q_{\text{min}}$ control block, and the $V_{\text{flag}}=0$ option.

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Model Validation against Field Test Results
CERTS/AEP Microgrid Testbed

- AEP/CERTS testbed: one of the earliest inverter-based microgrids in the world, funded by DOE
- Principle Investigator: Prof. Bob Lasseter from University of Wisconsin-Madison
- The CERTS Microgrid Program has been running for almost 20 years

A 100% Grid-Forming-Inverter-based testbed


http://certs.lbl.gov/certs-der-pubs.html
Overload Issues in Microgrids and the Overload Mitigation Controller

- Grid-forming inverters can be overloaded during large step changes in loads
- CERTS Microgrid address the overload issue by actively controlling the inverter’s frequency
- When some of the inverters are overloaded: Overload Transfer
- When all the inverters are overloaded: Under Frequency Load Shedding

![Overload Mitigation Controller Diagram](image-url)
Function 1: When Some of the Inverters are Overloaded (Overload transfer)

- When one grid-forming inverter is dispatched near its maximum generation, a load step can result in overload.
  - Overload can collapse the dc bus of inverters, stall the synchronous generators, etc.

A Two-Source System

\[
Z_1 \quad K \quad Z_2
\]

\[
X_{LA1} \quad (E_{A1}, \delta_{A1}) \quad A1 \quad \text{Load 1} \quad \text{Load 2} \quad X_{LA2} \quad (E_{A2}, \delta_{A2}) \quad A2
\]

Without \( P_{\text{max}} \) Controller

\[
P_{\text{max}} = 60\, \text{kW}
\]

\[
P_{\text{set-A2}} = 5\, \text{kW}
\]

\[
P_{\text{set-A1}} = 55\, \text{kW}
\]

\[
P_{A2} = 25\, \text{kW}
\]

\[
P_{A1} = 70\, \text{kW}
\]
Function 1: When Some of the Inverters are Overloaded (Overload transfer)

- When one grid-forming inverter is dispatched near its maximum generation, a load step can result in overload.
  - Overload can collapse the dc bus of inverters, stall the synchronous generators, etc.

Overload Mitigation Controller: Change the phase angle between sources: $\Delta \delta$
Function 1: When Some of the Inverters are Overloaded (Overload transfer)

- Transfer the extra load to non-overloaded sources by reducing the frequency rapidly
- The change of phase angle redistributes power flow between inverters

![Graphs showing overload and change of phase angle]

Function 2: When the entire system is overloaded (under-frequency load shedding)

- The loss of ESS results in the overload of the entire microgrid
- All sources’ droop curves become vertical, triggering under-frequency load shedding
- GridLAB-D simulation, PSCAD simulation, and field test results match well with each other

Field test results from CERTS/AEP testbed

Industry Engagement and Use Case Study

--Transmission Level Simulation and Analysis
Industry Engagement

• The generic/standard library GFM model development received significant supports from OEMs, WECC MVS, and software vendors
• The models have been used by many utilities and ISOs to evaluate how the grid-forming technology will impact their power grids

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WECC Report of GFM technology using the model provided by PNNL

PNNL's GFM model is used to support the Puerto Rico work

ERCOT presentation using the GFM model provided by PNNL

Preliminary assessment of Grid Forming Inverter-based Energy Storage Resources (GFM-IBR-ESR) in the ERCOT Grid

Yunzhi Cheng
Manager of Operations Analysis, ERCOT

ERCOT IBRGWG
August 15, 2023
Dynamic Response of GFMs

- A GFM approximately behaves as a voltage source behind impedance, which is much like a synchronous generator.
- Because of the voltage source characteristic, the GFM responds to disturbances almost instantaneously, which is much faster than traditional grid-following inverters (GFLs).

Response of gas generators, hydro generators, grid-forming and grid-following inverters near outage
(source: WECC report of the grid-forming inverter)
System Frequency Response Study

**Question 1: How many GFLs can synchronous-machine-dominated T&D system hold?**

- When the penetration of GFLs increases in the T&D system, the frequency nadir decreases after tripping the two Palo Verde generation units.
- When the GFL penetration reaches 80%, the system cannot maintain stability.

![Diagram showing frequency response with GFL penetration and 100% synchronous machine](image)

**Question 2: How many GFM are needed to maintain the stability of future IBR-dominated T&D systems?**

- For the 80% IBR penetration case, if we replace 4.7% GFLs with GFM, the system becomes stable.
- As the penetration of GFM continues to increase, the frequency nadir is significantly improved.
- For the 100% IBR case, the primary frequency response is even much better than the 100% synchronous machine case.

New GFM Model Development
Virtual Synchronous Machine GFM Model (REGFM_B1)
PNNL is working with GE, Siemens, EPRI, and others to develop another type of generic grid-forming inverter model—VSM GFM model (REGFM_B1).

The model is also expected to be included in the model libraries of commercial tools including PSS/E, PSLF, PowerWorld, and TSAT in collaboration with WECC.

The generic GFM model development work will be a multi-year effort to support industry better understand/evaluate this technology.
Real-World Demonstration of Grid-Forming Inverter
Demonstration of Grid Services by a 380 MW Wind, Solar, and Battery Storage Combined Power Plant

- Wheatridge Renewable Energy Facility is **North America’s first energy center to combine wind, solar, and battery storage in one location**, with 300 MW of wind, 50 MW of solar, and 30 MW of energy storage systems.
- This will be **the first time that grid forming IBRs, including both wind and battery storage, are connected to the US bulk power systems**, and demonstrated at the same site for grid services.

380MW Wheatridge wind, solar and battery storage power plant

One line diagram

The project is funded by the solar and wind grid services and reliability demonstration funding program by the DOE SETO.
Conclusions and Future Work

- As the penetration of IBRs continue to increase in power systems, GFM s will play a critical role in maintaining the system stability.
- The WECC-approved GFM model (REGFM_A1) led by PNNL helps transmission planners understand the GFM technology and its potential impacts on their grids.
- As the GFM technology continues to evolve, PNNL will continue leading the work on developing and enhancing generic grid-forming inverter models for industry use in collaboration with our partners.
Thank you

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