



Grid-Forming Inverters – Enabling the Next Generation Grid

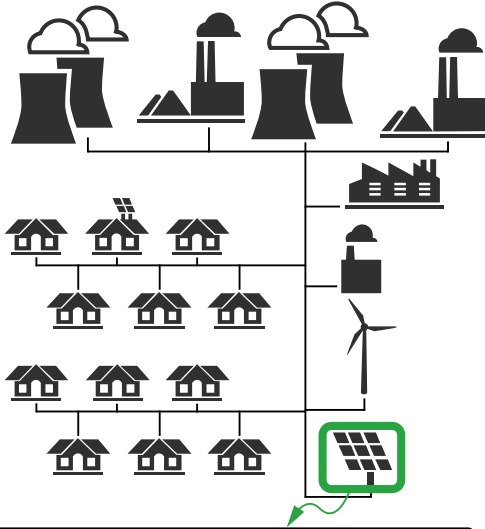
Yashen Lin

PEGI workshop

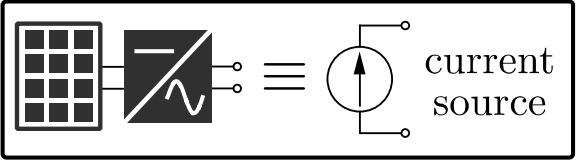
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Next Generation Grid

Present



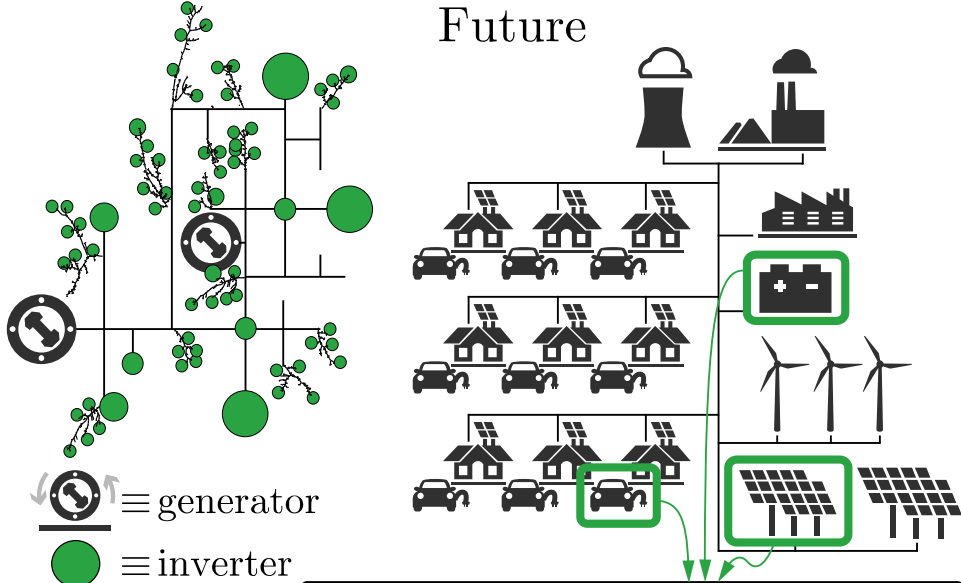
≡ generator
● ≡ inverter



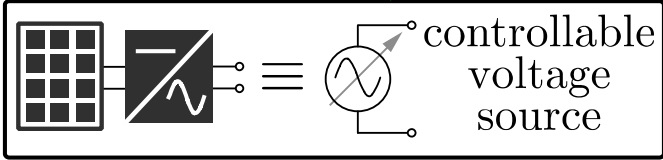
Grid-following controls



Future



≡ generator
● ≡ inverter

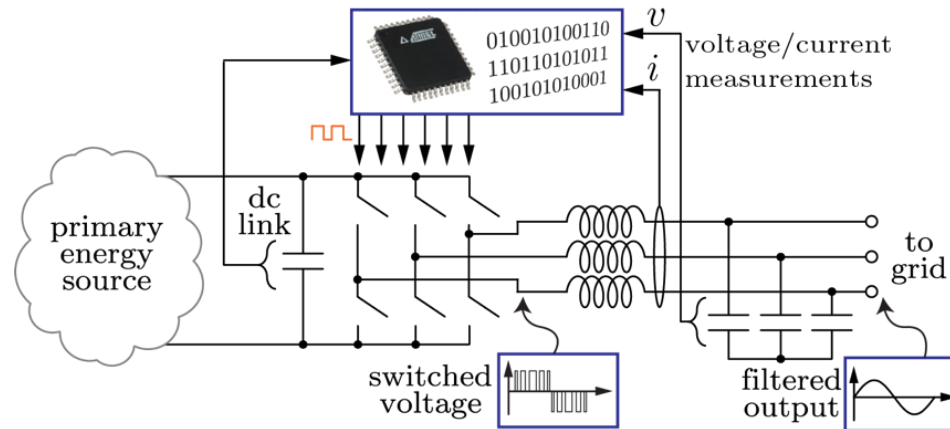


To next-generation grid-forming controls

Grid-Forming Inverters

Grid-Forming Inverters

- **Inverter-base resources**



- **Grid-forming inverter control**

- Regulate terminal voltage
- Islanded operation, maintain grid stability, black start, etc.
- Types of grid-forming inverter control: droop [1], virtual synchronous machine [2], **virtual oscillator controllers (VOC) [3]**

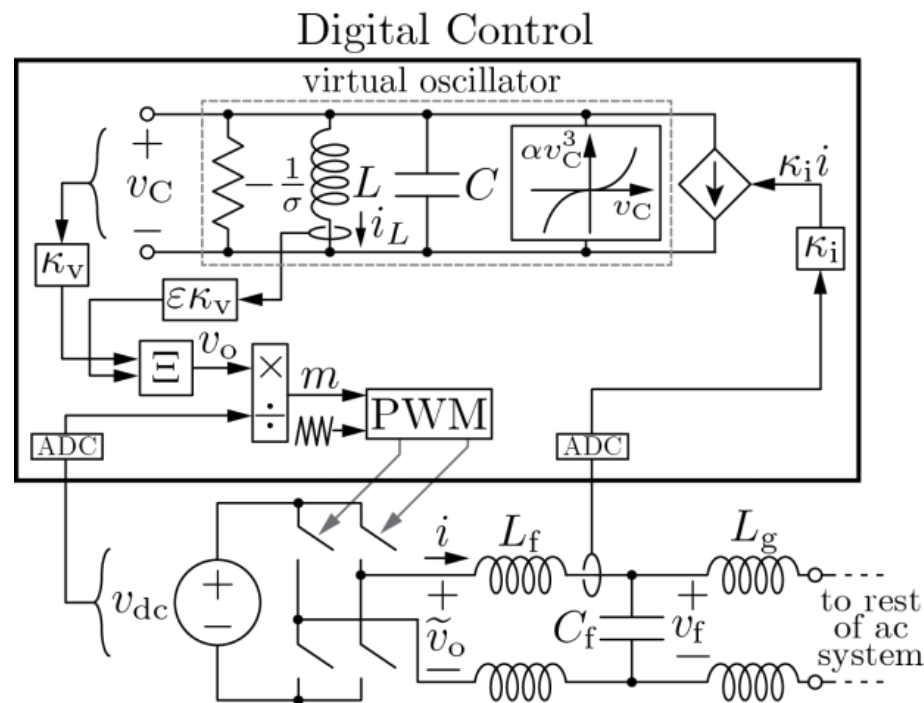
[1] Chandorkar, M.C., et al. 1993. "Control of Parallel Connected Inverters in Standalone ac Supply Systems." IEEE Transactions on Industrial Applications.

[2] Beck, H.-P., and R. Hesse. 2007. "Virtual Synchronous Machine." Proceedings of the Electrical Power Quality and Utilisation (EPQU 2007).

[3] Johnson, B.B., et al. 2016. "Synthesizing Virtual Oscillators to Control Islanded Inverters." IEEE Transactions on Power Electronics.

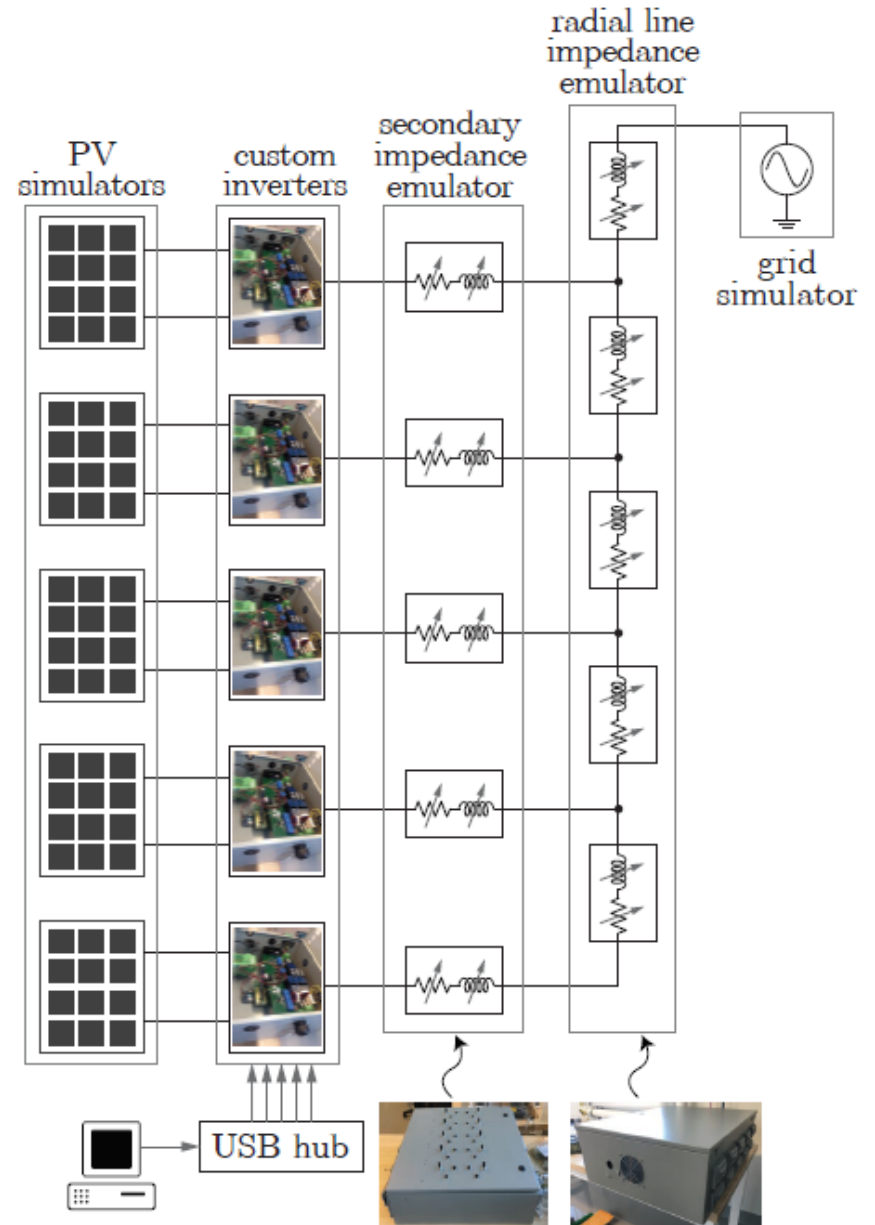
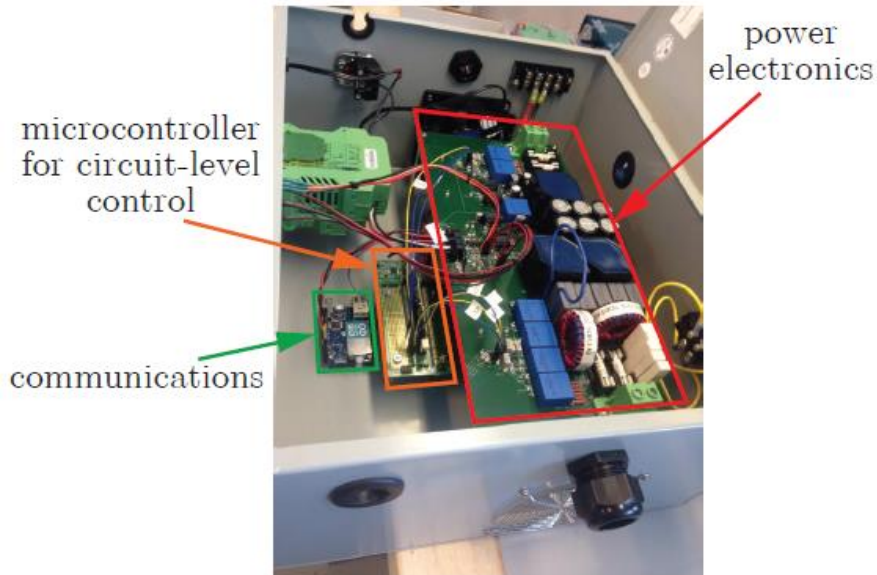
Virtual Oscillator Controller (VOC)

- VOC is a time-domain control approach in which the inverter is programmed (through its digital controller) to emulate the dynamics of a non-linear electrical oscillator.
 - Synchronize among multiple units; droop-like behavior
 - Does not require power filters



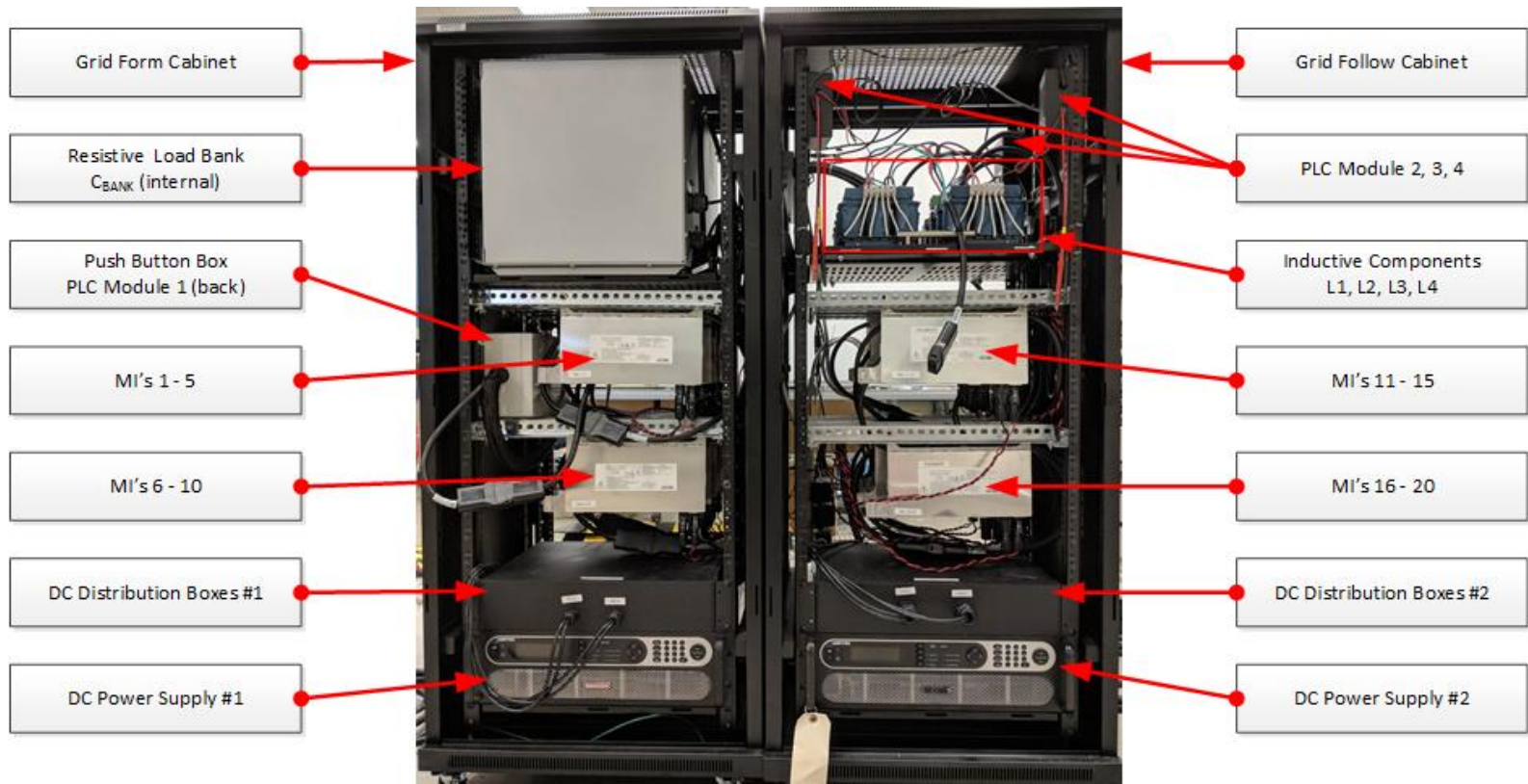
Hardware testing

- **Customized test bed**

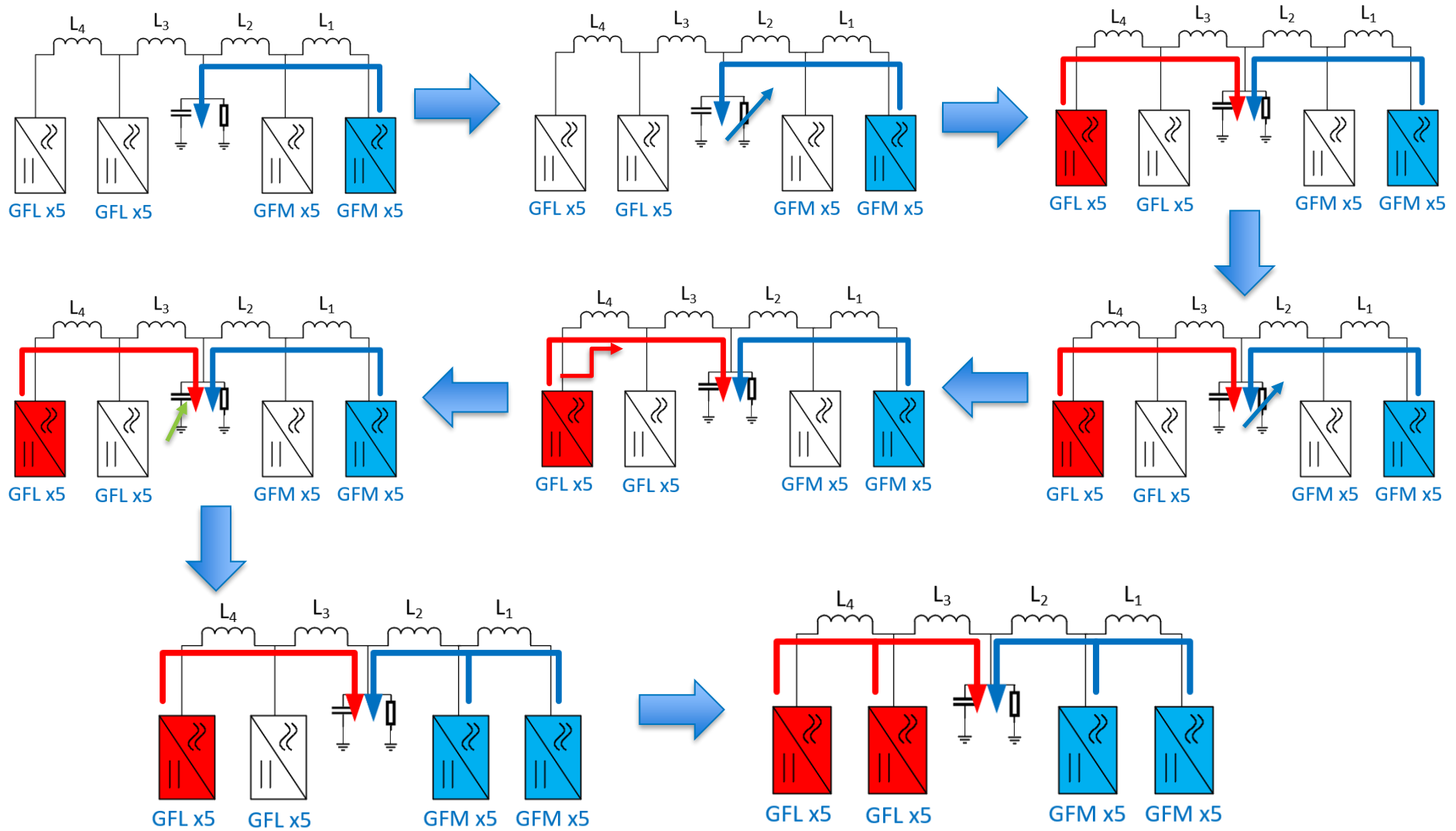


Hardware testing

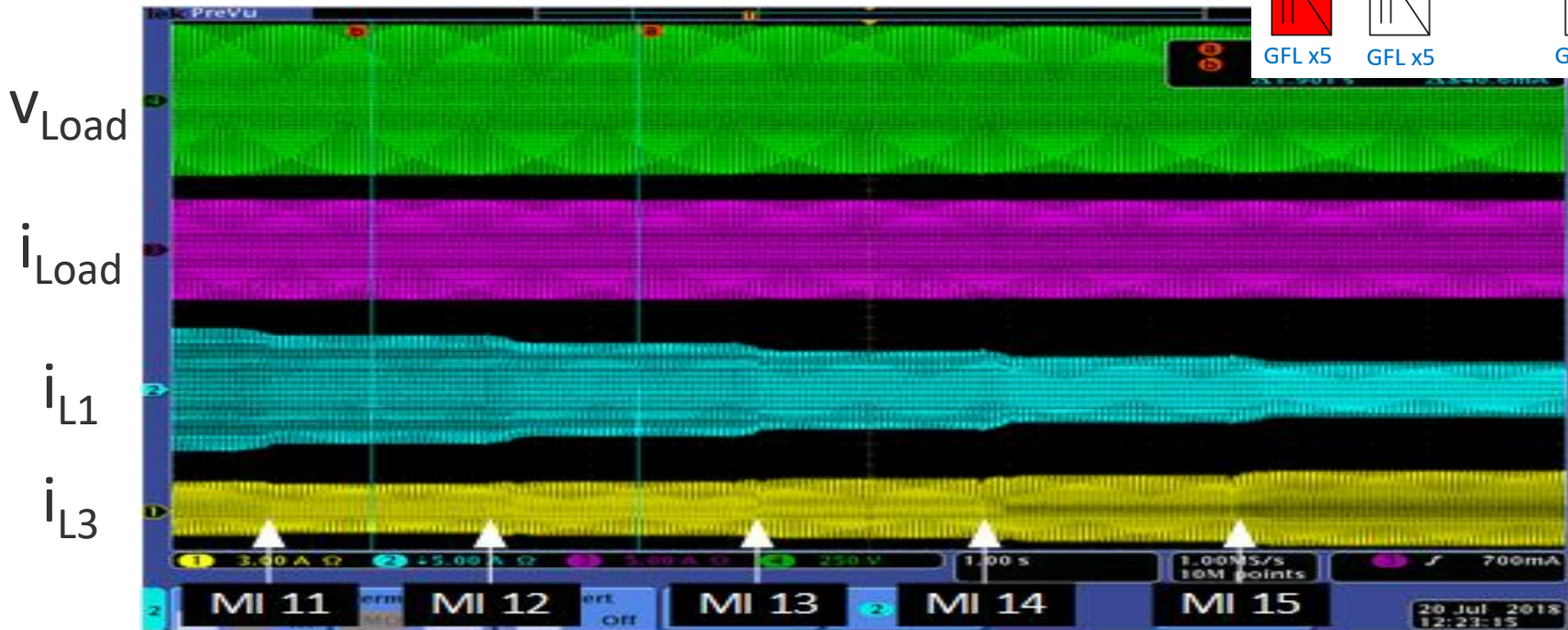
- **Commercial micro-inverter test bed**
 - 20 SunPower micro-inverters



Hardware testing



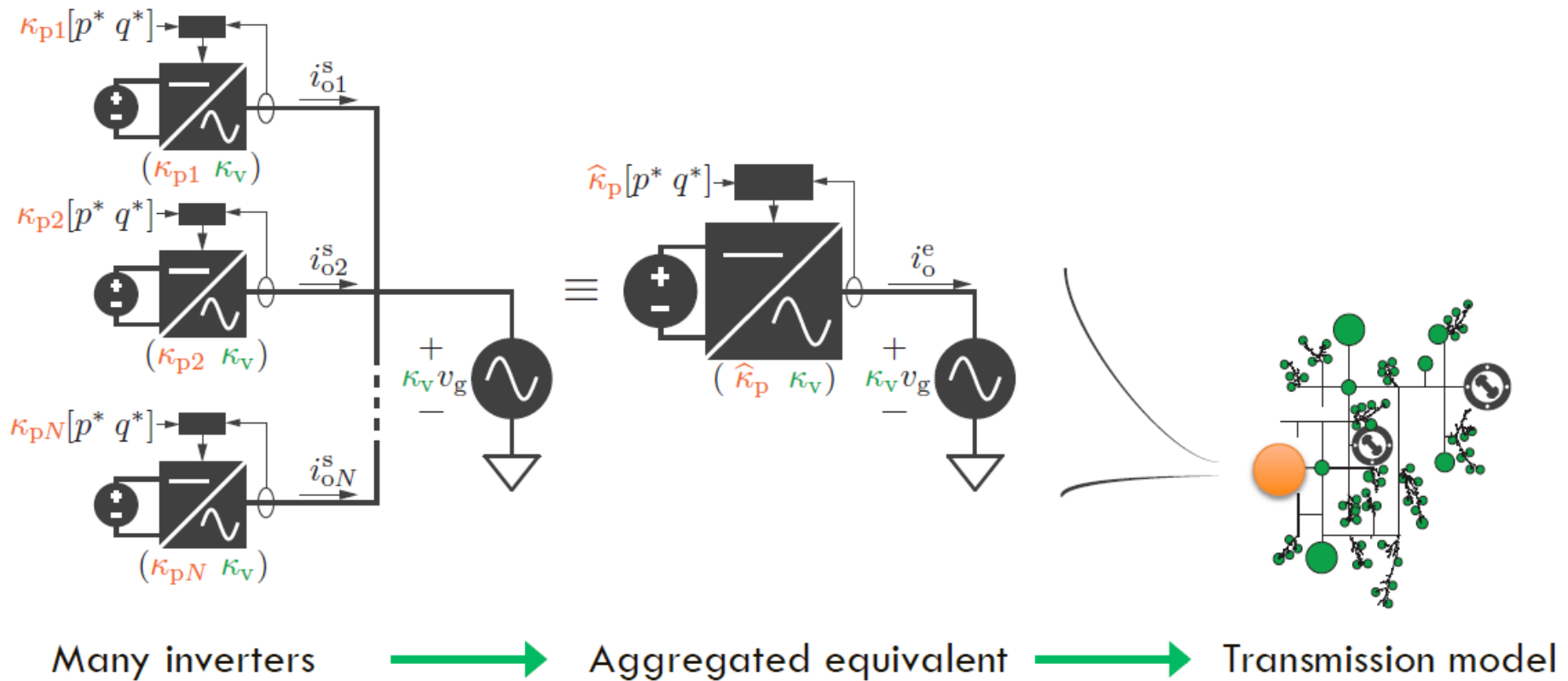
Hardware testing



- 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.

Inverter Aggregation

- How to represent a large number of inverters?
 - Scaling law to determine the aggregated model parameters

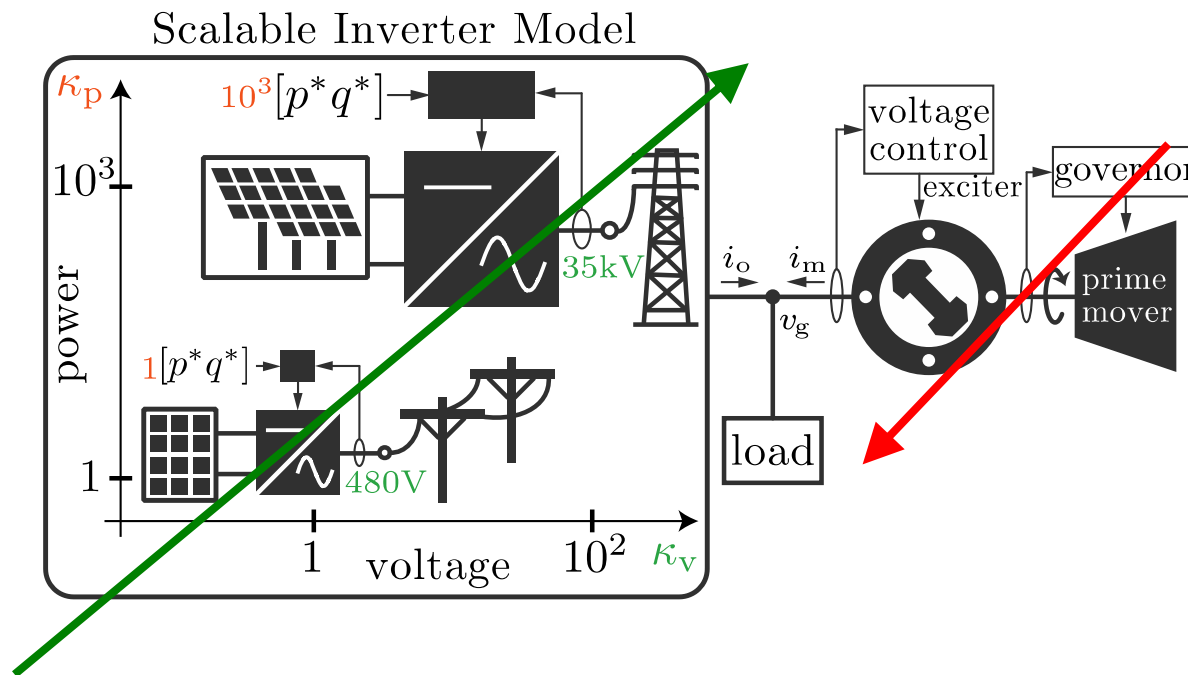


[1] Purba, V., et.al. 2018. "Reduced-Order Aggregate Model for Parallel-Connected Single-Phase Inverters." IEEE Transactions on Energy Conversion.

[2] Khan, M.M.S., et.al. 2018. "A Reduced-Order Aggregated Model for Parallel Inverter Systems with Virtual Oscillator Control." Proceedings of the 2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL).

Stability Analysis

- **Stability analysis: 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.



Stability Analysis

- Examined single-machine single-inverter system, and multi-unit systems (20 MI system, IEEE 39-bus system).
- Summary of results:
 - 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.

Dispatchable-VOC

- dVOC allows users to specify power setpoints for each inverter.
- If no setpoints are given, dVOC subsumes VOC control and inherits all its favorable dynamical properties.
- dVOC is asymptotically stable in 100% inverter system.
- Validated in NREL hardware test bed.

Research Roadmap on Grid- Forming Inverters

Research Roadmap

- **Team collaboration**
 - NREL, SNL, LBNL, Univ of Washington, Univ of Wisconsin, DOE SETO
- **Feedback from experts with diverse background**
 - Grid-forming inverters for low-inertia power system workshop
- **To be published**

Research Roadmap on Grid-Forming Inverters



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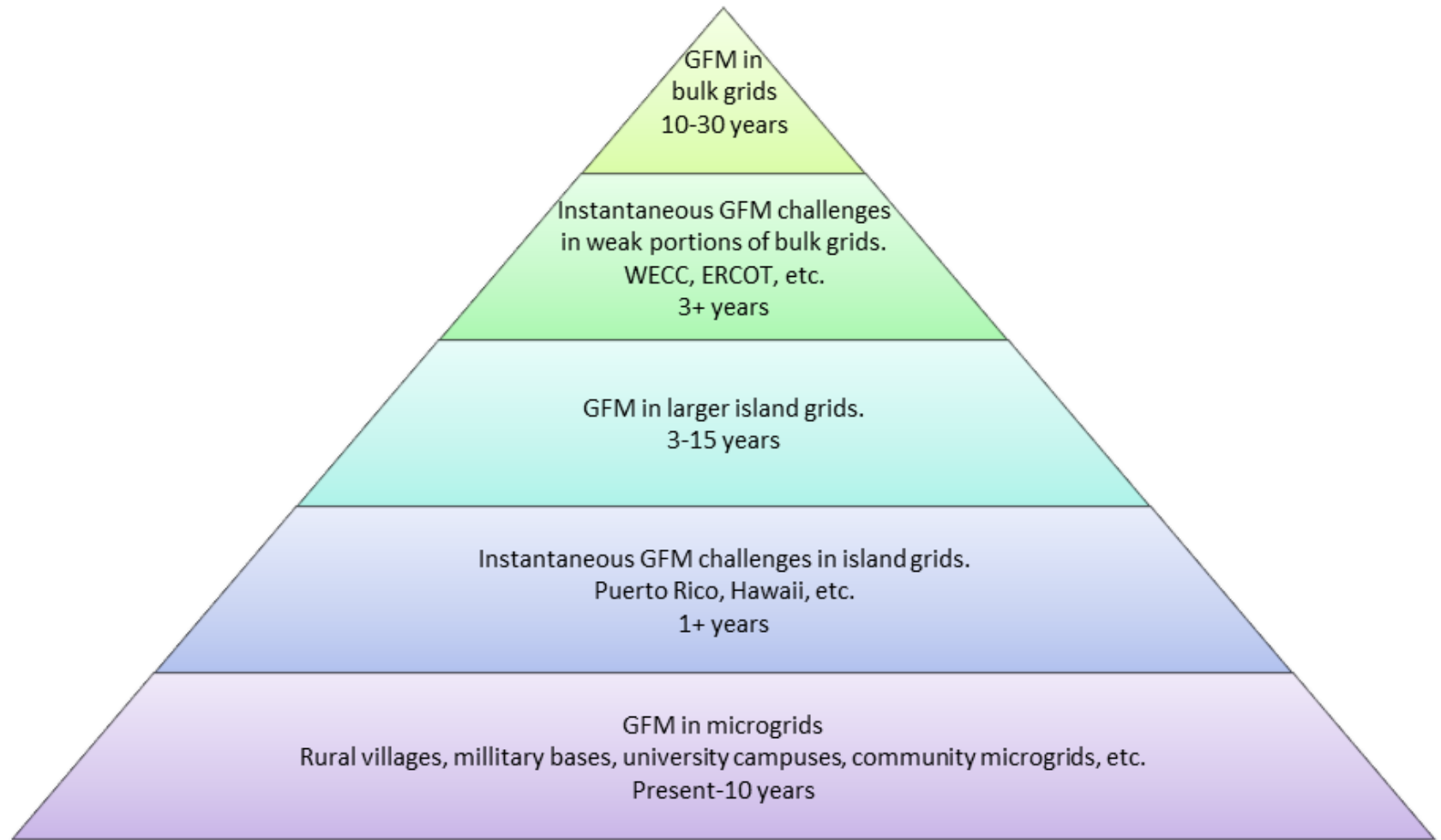
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Research Roadmap



Research Roadmap

- **Near-term research priorities:**
 - The review of regulatory and technical standards.
 - The development of advanced modeling techniques.
- **State-of-the-Art Inverter Controls and Open Research Directions:**
 - Frequency Control
 - Voltage Control
 - System Protection
 - Fault Ride-Through and Power System Recovery
 - Modeling and Simulation Approaches

Frequency Control

- **Classic frequency control:**
 - Hierarchical: primary, secondary, tertiary
- **Open research questions:**
 - What are the issues related to GFM inverters providing for loss of inertia?
 - What signals, if any, must be communicated between distribution-level inverters and system operators?
 - Can heterogeneous systems containing GFL inverters, GFM inverters, and machines operate together to guarantee frequency regulation and stability?
 - What shares of rotating generators and GFL and GFM inverters can guarantee power system stability?
 - How important is frequency regulation in a system dominated by power electronics?

Voltage Control

- **Classic voltage control:**
 - Generally, reactive power control
- **Open research questions:**
 - How do thousands of GFM and GFL inverters at medium voltages and lower affect system voltage stability and control?
 - How should VAR flow be controlled—at each inverter, at locally aggregated inverters, or through a coupled communication networks?
 - What are the interactions between machine excitation systems and inverters with either GFM or GFL controls? Can inverter and machine-side controls be tuned to eliminate such interactions?

System Protection

- GFL inverters can negatively affect protection system, GFM maybe able to alleviate the issue, but very few study on actual effects of GFM on protection.
- **Open research questions:**
 - Short-circuit response of GFMs including the effect of control schemes?
 - The ability of GFMs to produce zero- and negative-sequence fault current under unbalanced fault events?
 - GFM dynamic response and its effect on Out-of-Step protection Tripping (OST) and Power Swing Blocking (PSB) protection at the transmission level?
 - Analytical and simulation models for GFM under fault scenarios?
 - Anti-islanding with GFM?

Fault Ride-Through and System Recovery

- Capability to remain connect to the grid through abnormal transients; prevent system level cascading events.
- No trip zone determined by simulations of the current system.
- **Open research questions:**
 - Will modern FRT grid codes apply to power systems with high penetrations of inverter-based generation with GFM controls?
 - How does the FRT codes need to evolve?
 - What voltage regulation capability will inverters with GFM controls need to provide to recover grid voltages after faults?
 - How to control GFM to remain in the no trip zone? What tools are needed for this analysis?
 - How should FRT codes be coordinated with the operation of protective relays?

Modeling and Simulation

- Positive sequence model and simulation tools based on the assumption that frequency remains close to nominal during fault.
- Fast dynamics from inverters may render this assumption invalid.
- EMT simulation captures more dynamics but high computational burden.
- **Open research questions:**
 - What is the appropriate inverter-based generations model for existing positive-sequence simulation tools?
 - What modeling fidelity of the transmission system and inverter-based generation is necessary/appropriate for a comprehensive study on electric grids undertaking large transients?

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- **Collaborators**

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- LNL: Joseph Eto
- SNL: Abraham Ellis, Jack Flicker, Brian Pierre
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Thank you!

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