Low-inertia Grids and the Role of Oscillator-based Controllers

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University of Washington

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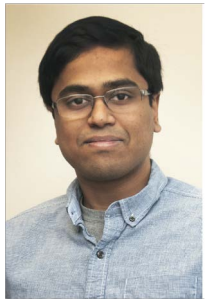
ELECTRICAL ENGINEERING

UNIVERSITY *of* WASHINGTON

Collaborators

Yashen Lin



Sairaj Dhople

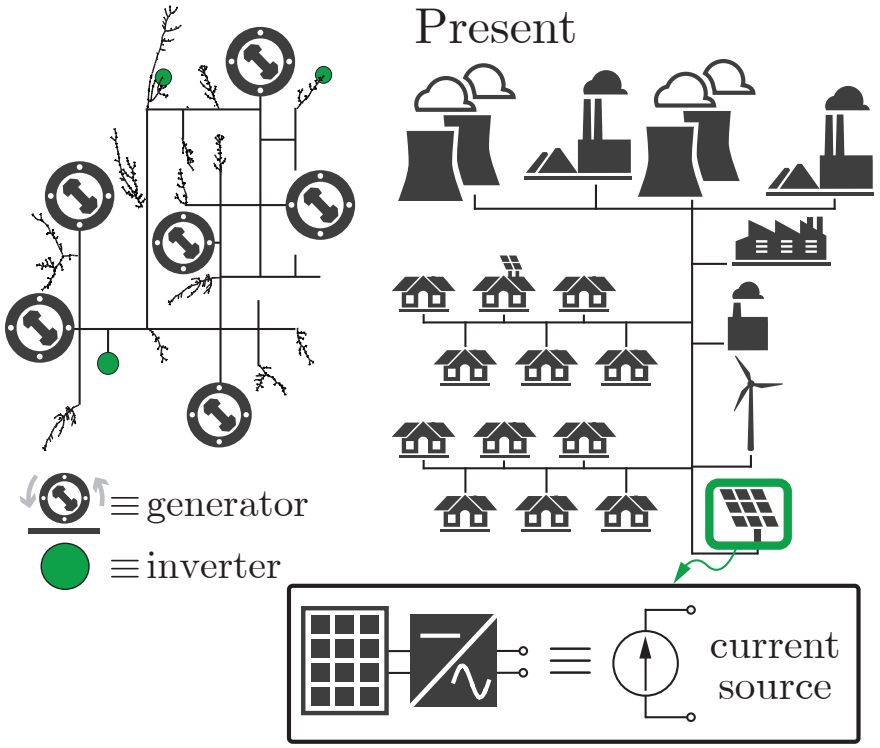
Fransesco Bullo

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

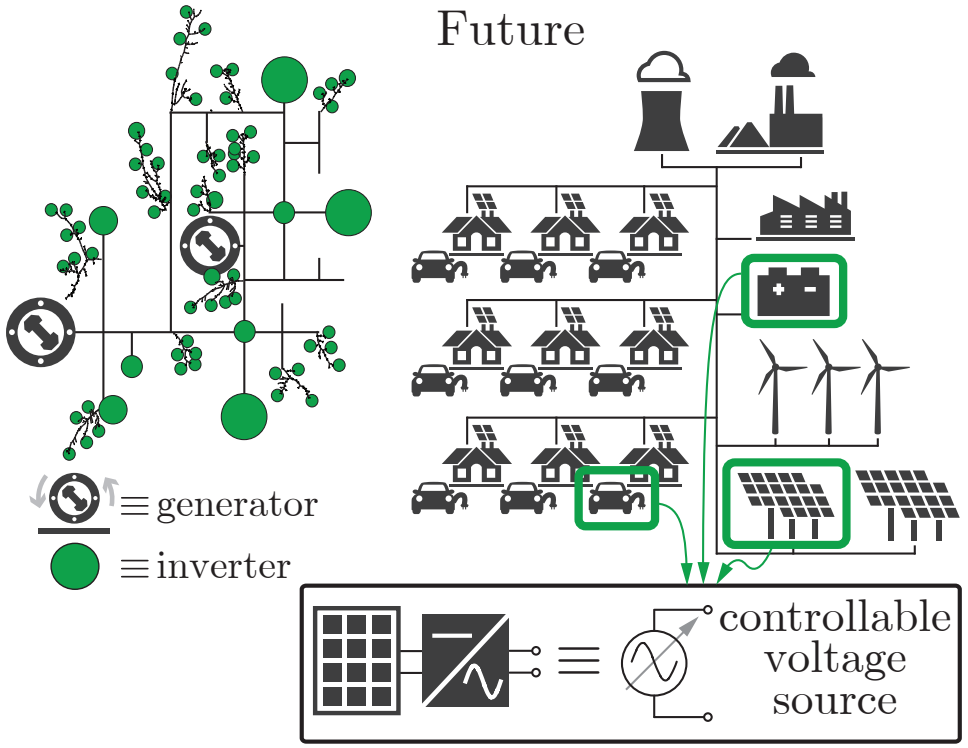
Funding:

Powered by SunShot
U.S. Department of Energy

Evolution of the Grid



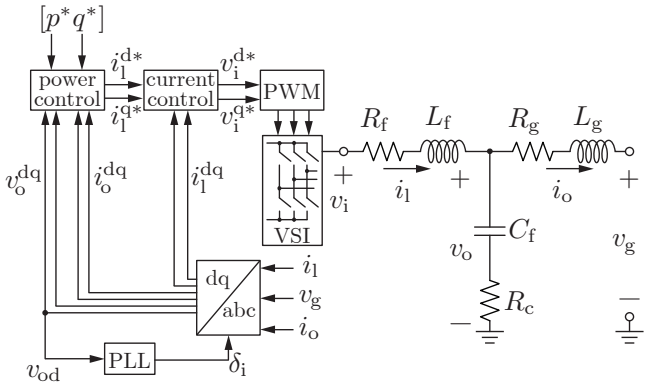
Grid-following controls

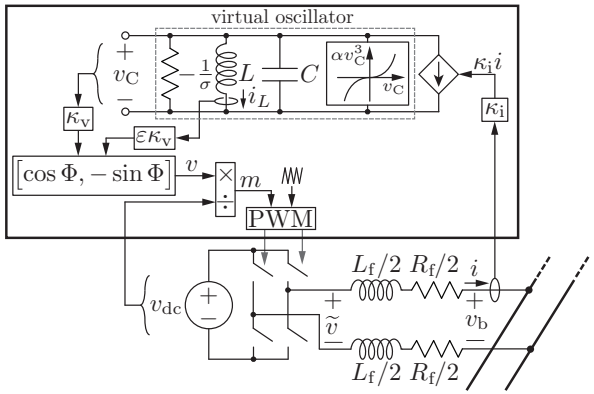


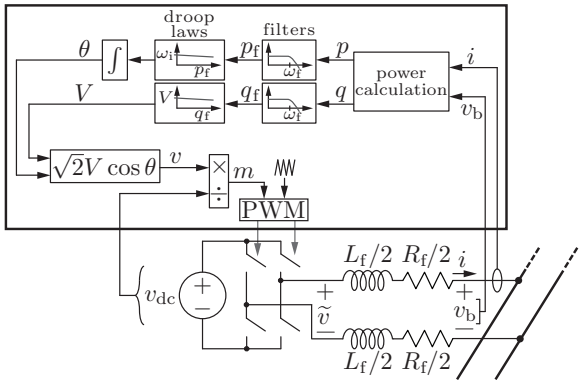
to next-generation grid-forming controls

Controllers Under Consideration

Discussed today







Grid-following:
Current control with PLL

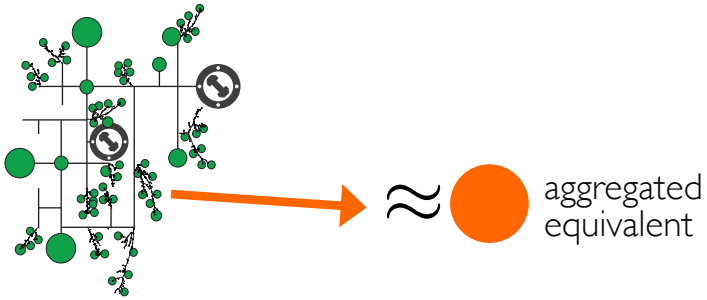
Grid-forming:
Virtual oscillator control

Grid-forming:
Droop control

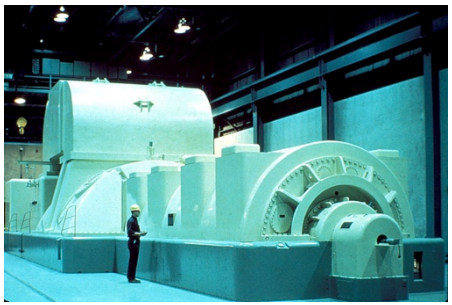
Have similarities

Outline

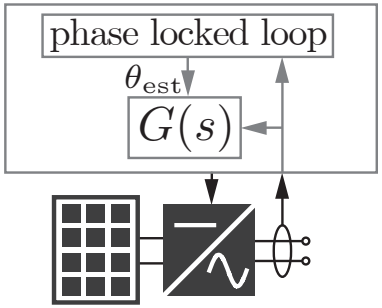
1. How do we solve the modeling complexity problem?



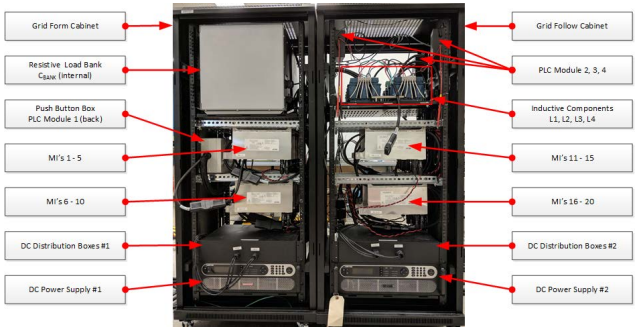
2. Is there an upper limit for inverter penetration before stability is lost?

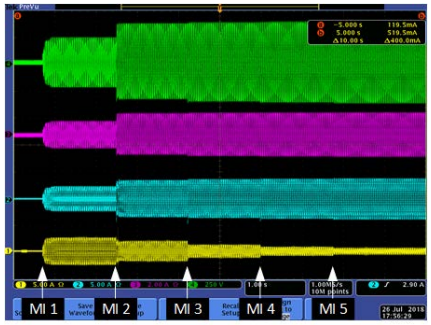


How many machines can we replace with electronics?



3. A hardware demo with 20 commercial inverters.





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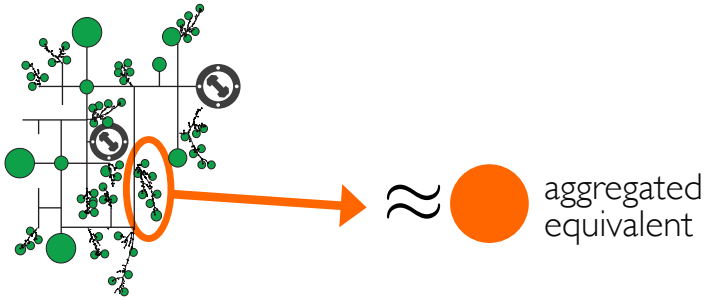

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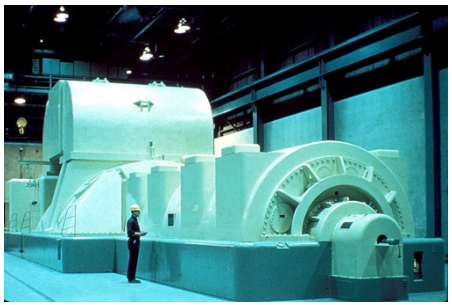

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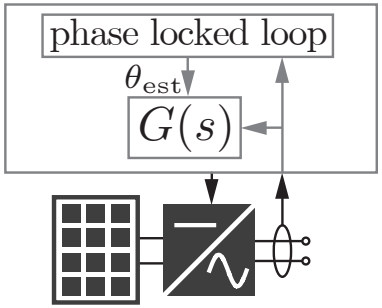

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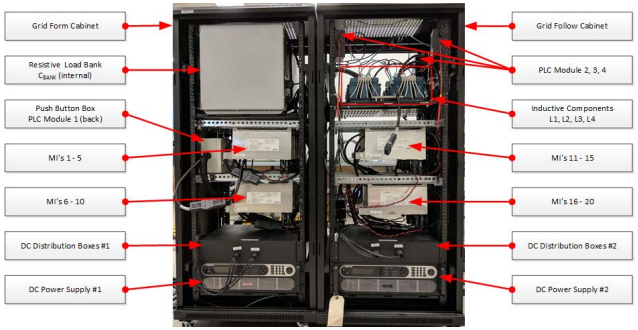
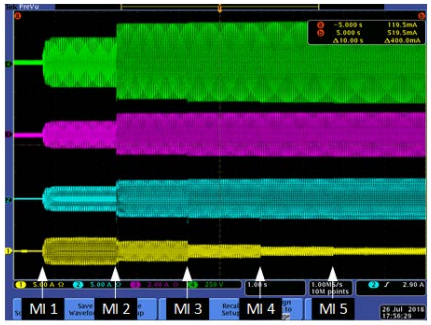
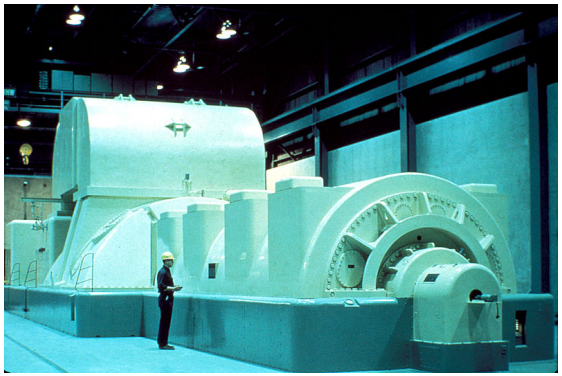
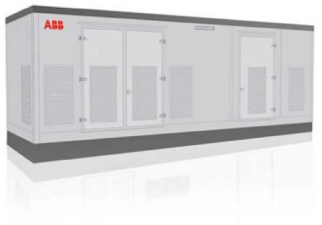




The Scaling Problem

A large disparity in ratings

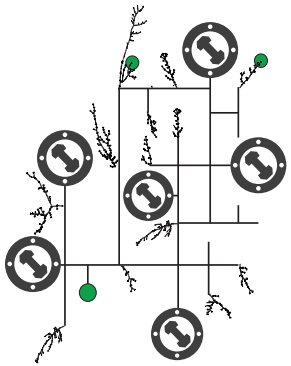


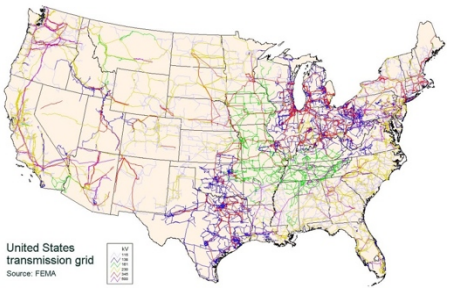


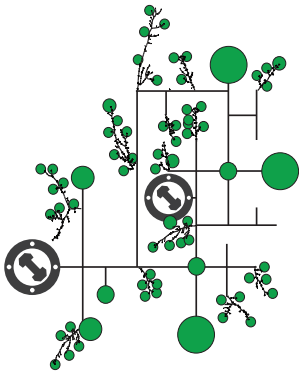
100's of MVA

100's of VA – 100's of kVA

… implies a larger number of generating devices to satisfy load



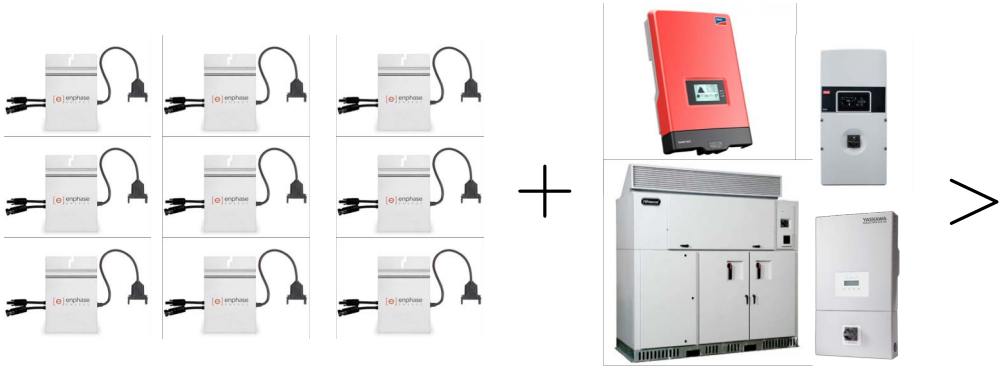




From ~7,500 power plants → ? → To millions of inverters?

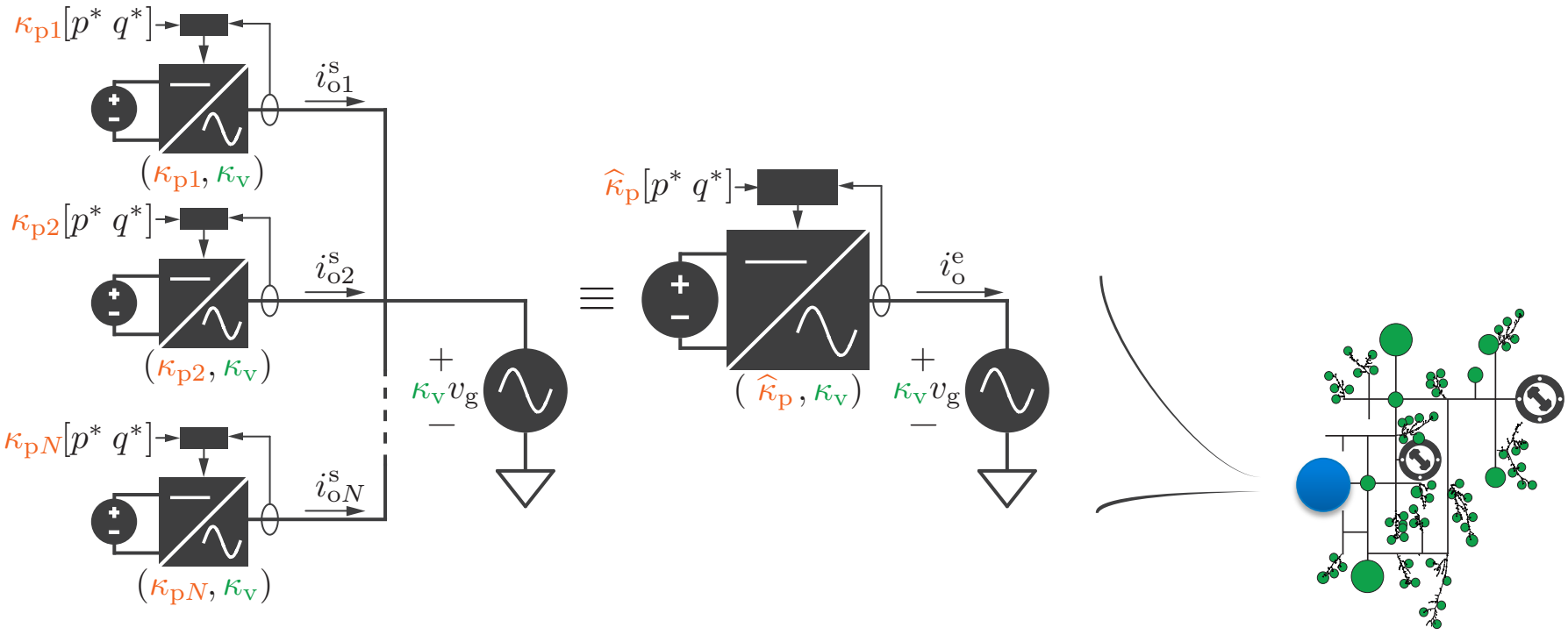
Motivational Example: Oahu

An island of 950,000 people and 800,000 Enphase microinverters



"800,000 Microinverters Remotely Retrofitted on Oahu in One Day." http://spectrum.ieee.org/energywise/green-tech/solar/in-one-day- 800000-microinverters-remotely-retrofitted-on-oahu.

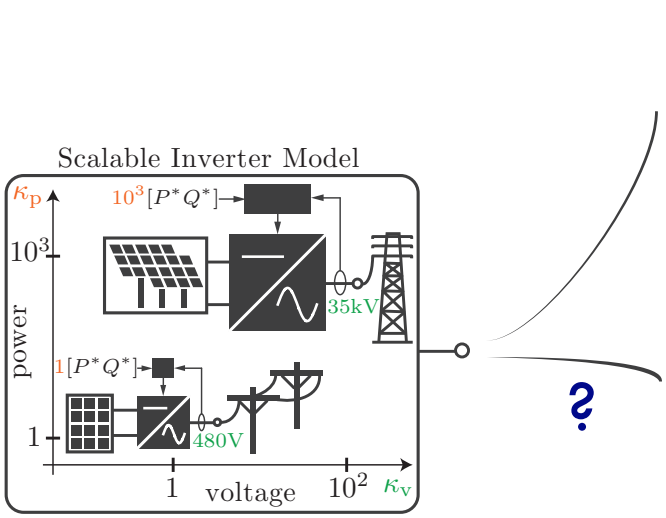
Our Solution: Aggregation



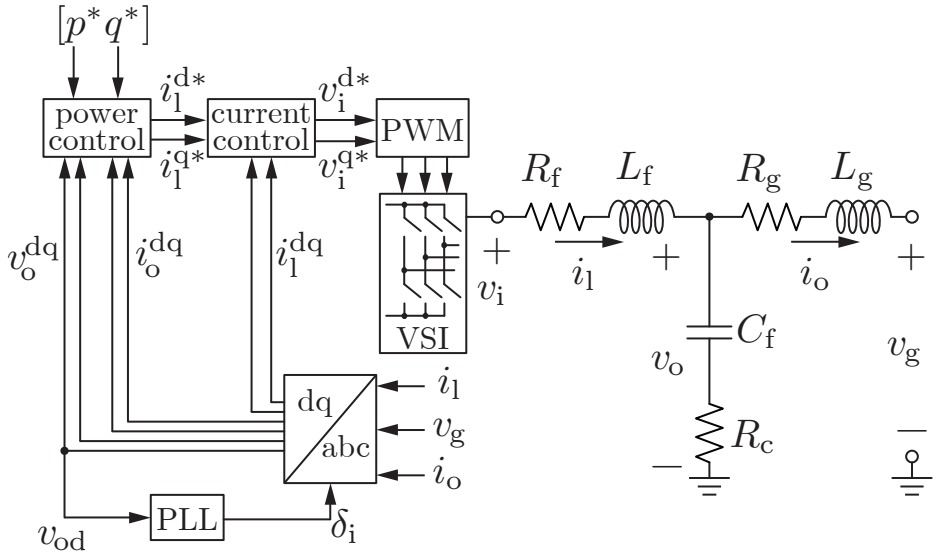
Many inverters → Aggregated equivalent → Transmission model

Foundation of Aggregation Approach: Scaling Laws

Introduce power and voltage scaling factors, κ_p and κ_v



?



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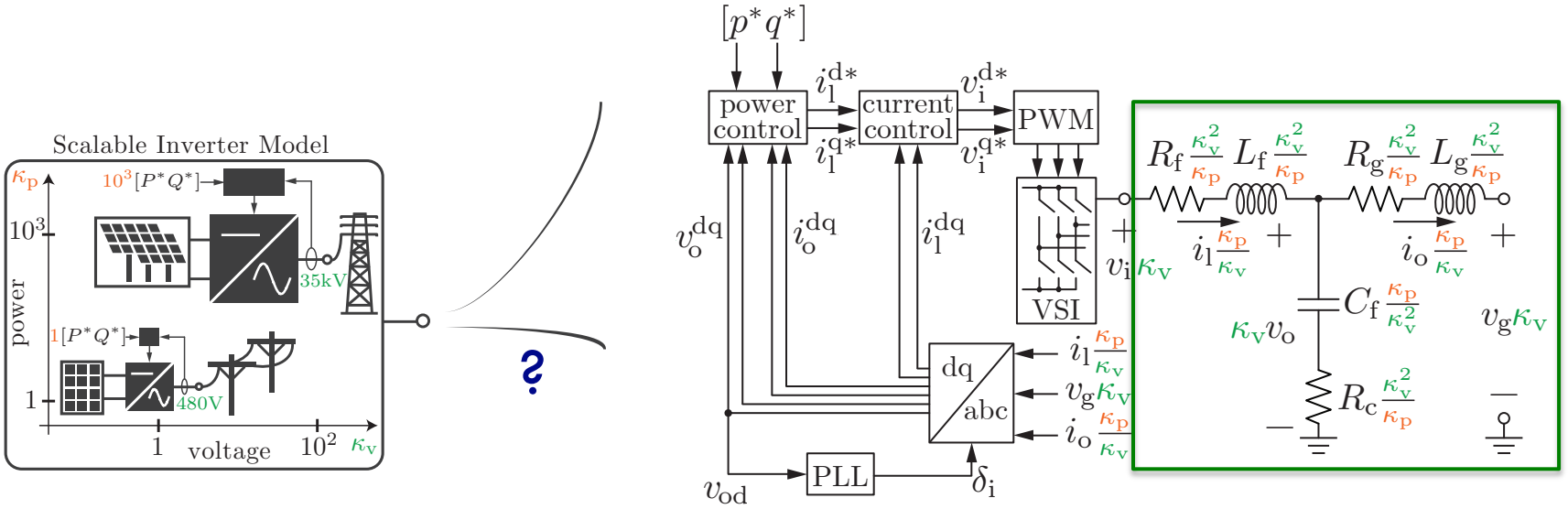

- Based on power electronics & controls rules of thumb
  - Fixed voltage drop across filter
  - Fixed total harmonic distortion across ratings: $\frac{\text{switching ripple}}{I_{\text{rated}}} = \text{constant}$

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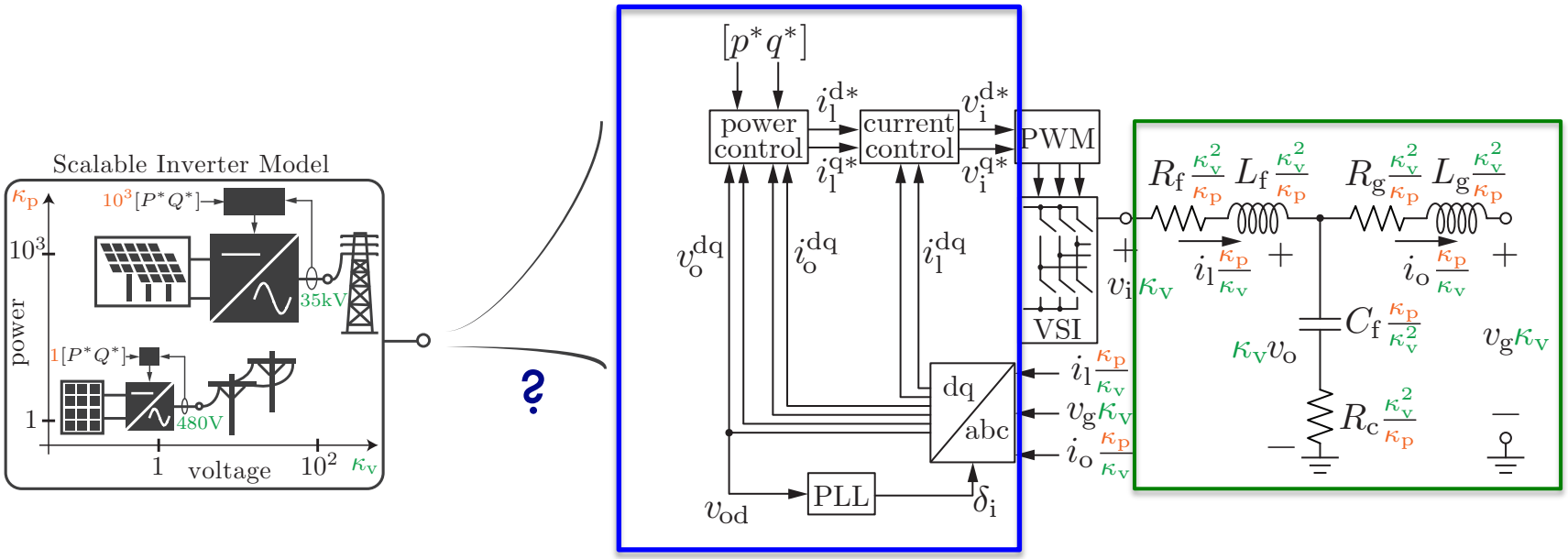
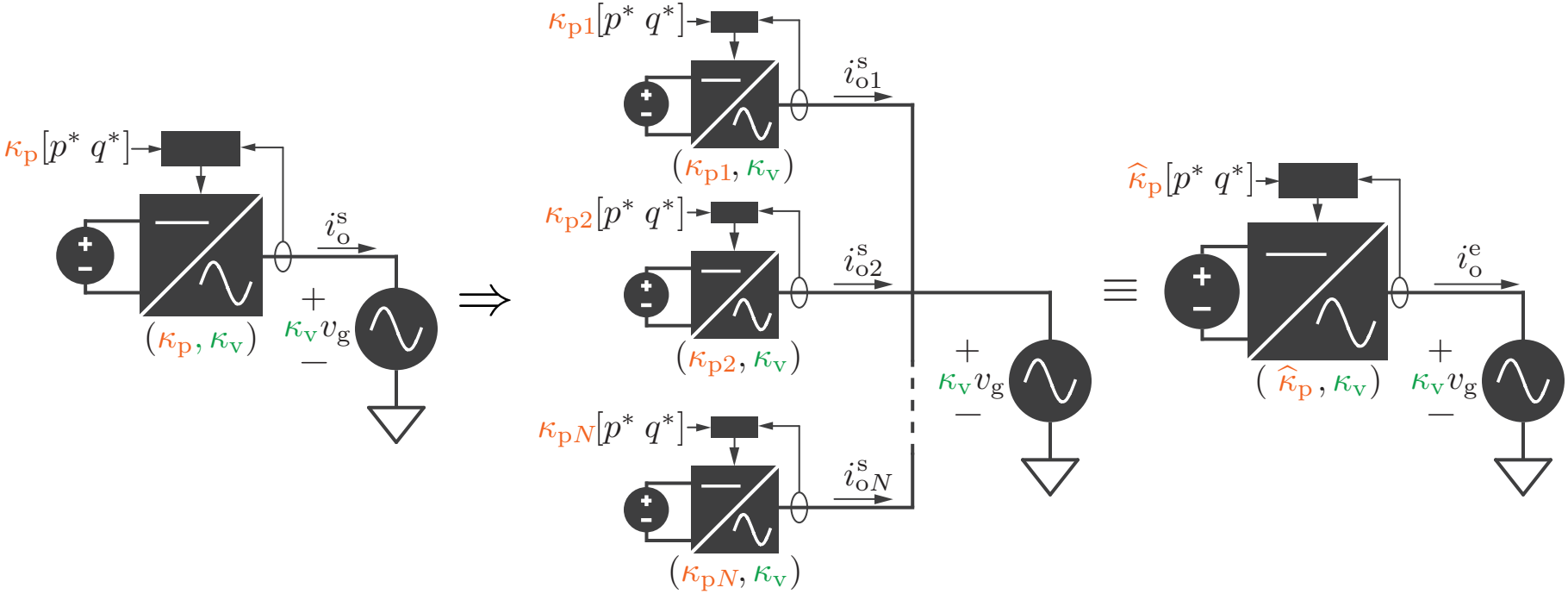


- Based on power electronics & controls rules of thumb
  - Fixed voltage drop across filter
  - Fixed total harmonic distortion across ratings: $\frac{\text{switching ripple}}{I_{\text{rated}}} = \text{constant}$
  - Preserve closed-loop response with scaled control gains

Scaling Laws and Aggregation



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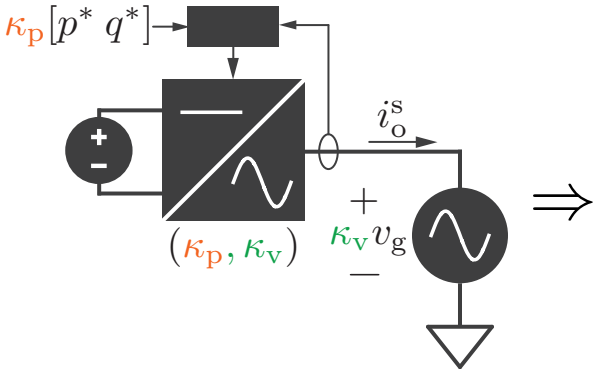
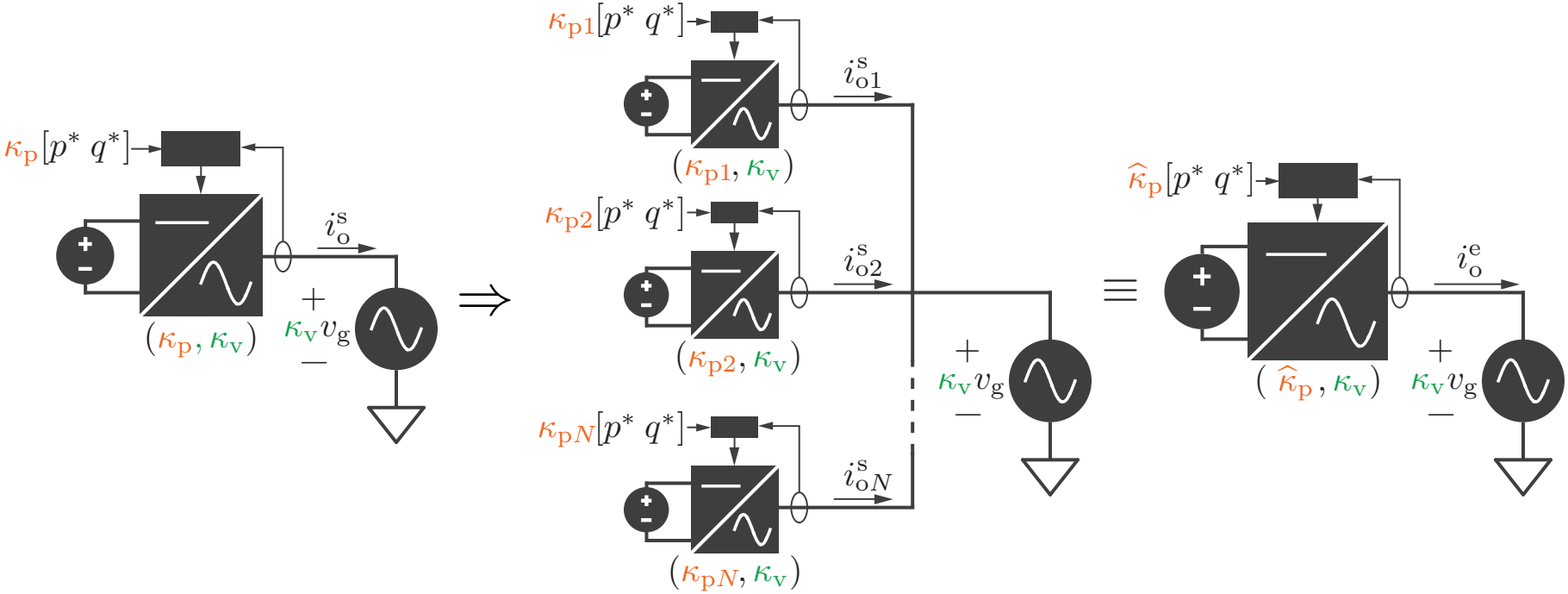


(a) Single **grid following** or **grid forming** inverter

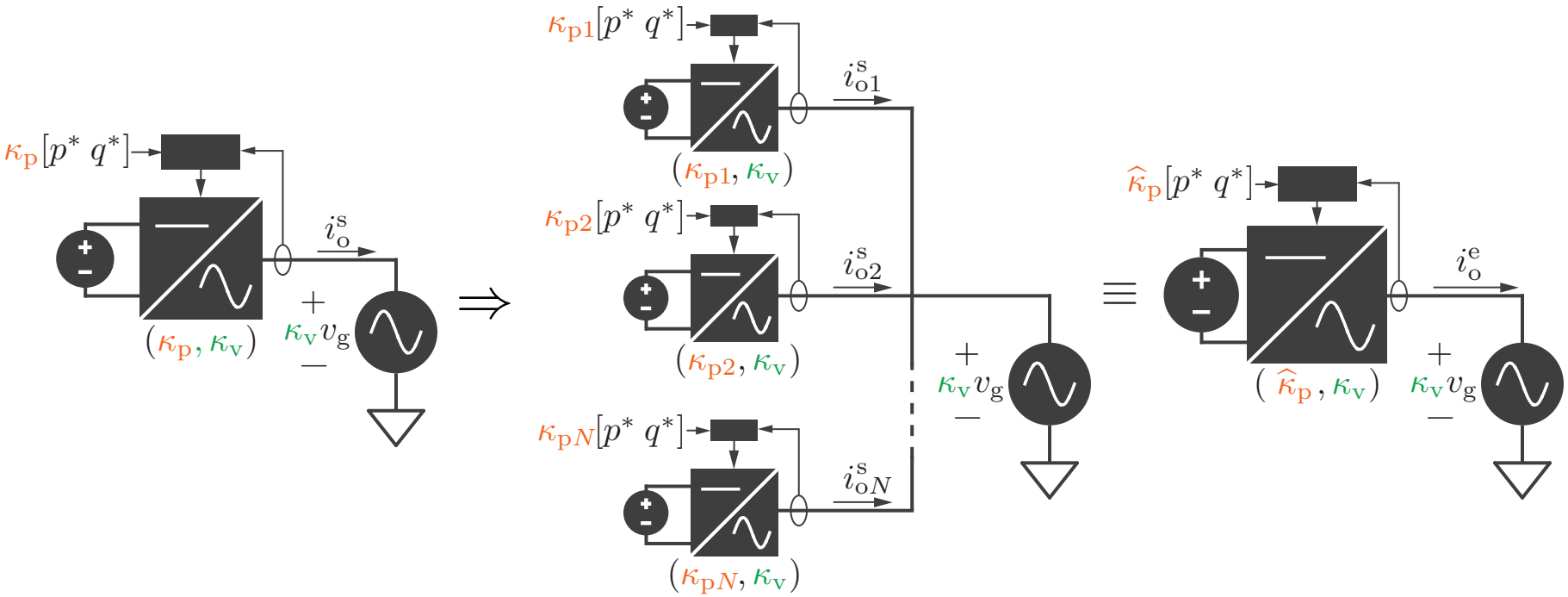
Scaling Laws and Aggregation



(a) Single **grid following** or **grid forming** inverter

(b) System of *N* such parallel inverters

Scaling Laws and Aggregation

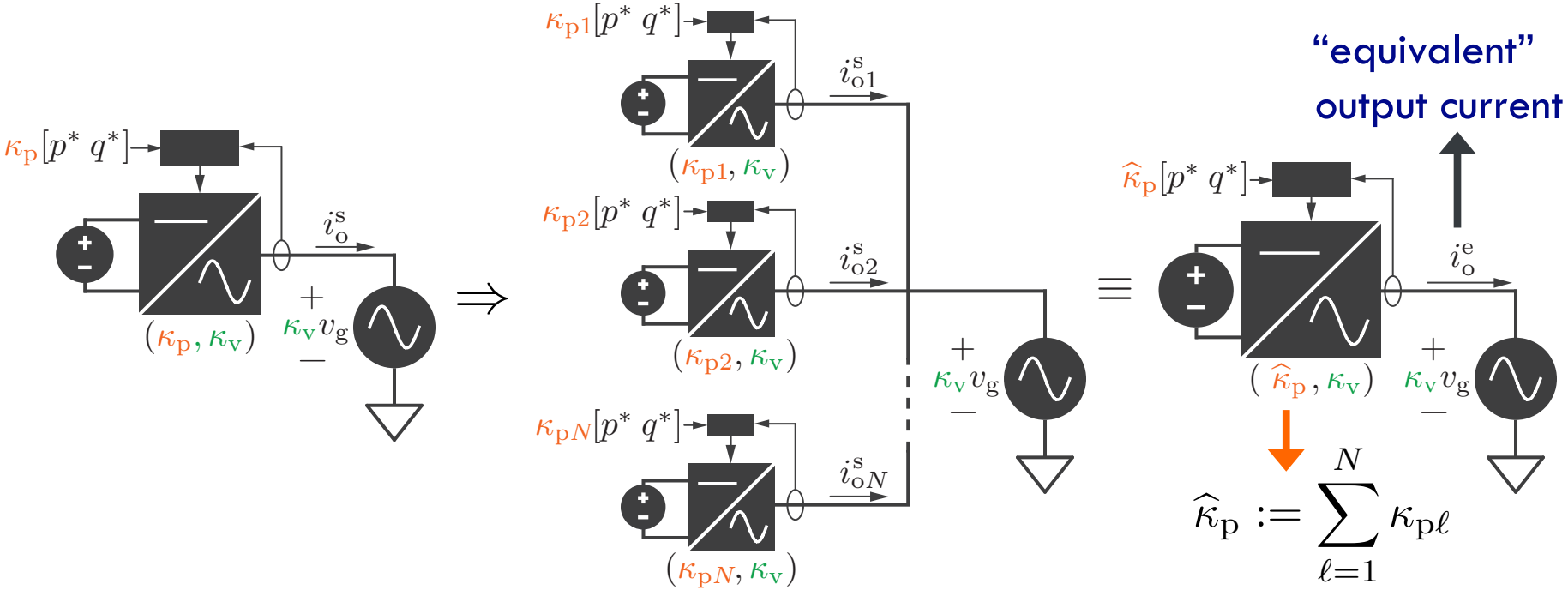


(a) Single **grid following** or **grid forming** inverter

(b) System of *N* such parallel inverters

(c) Aggregated equivalent

Scaling Laws and Aggregation



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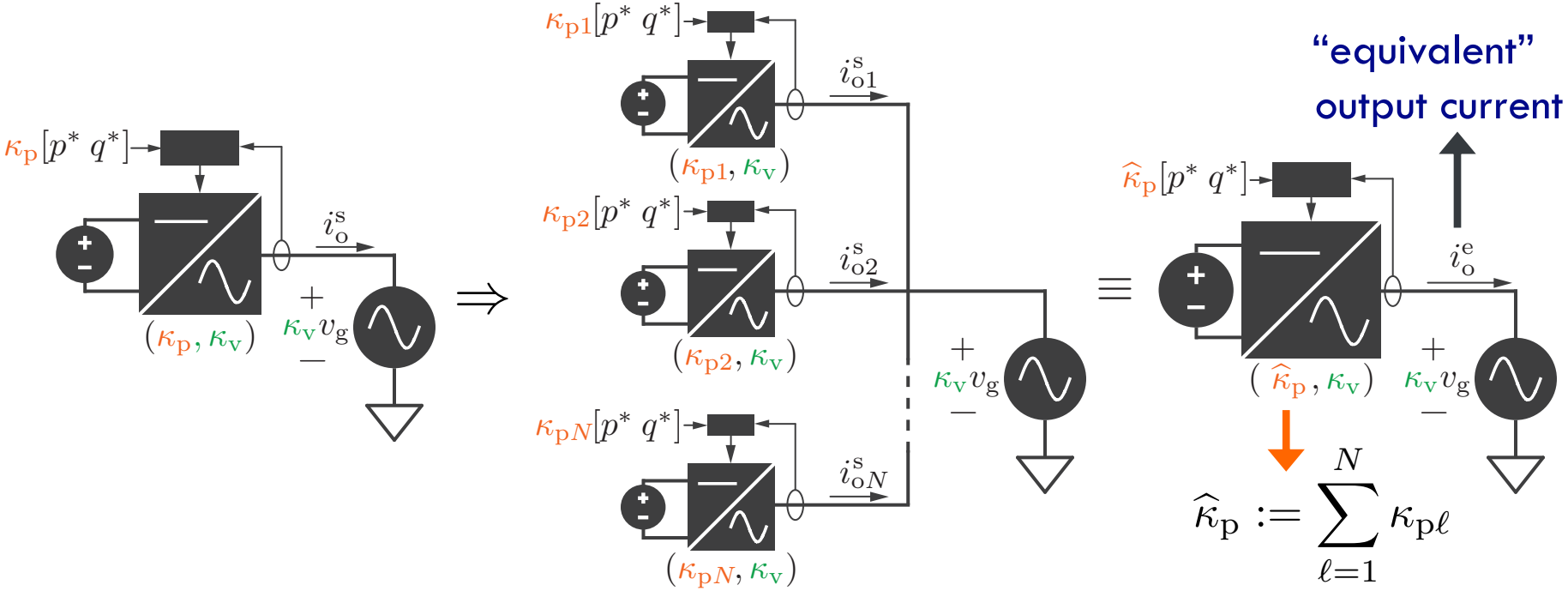


(a) Single **grid following** or **grid forming** inverter

(b) System of *N* such parallel inverters

(c) Aggregated equivalent

- If each inverter conforms to scaling laws in [1]-[2], then

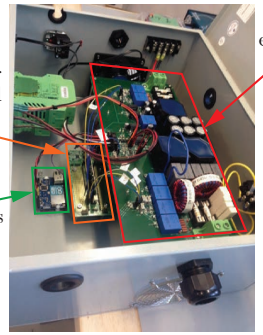
$$i_{\mathrm{o}}^{\mathrm{e}} = \sum_{\ell=1}^{N} i_{\mathrm{o}\ell}^{\mathrm{s}}$$

for $t \geq t_{\mathrm{o}}$.

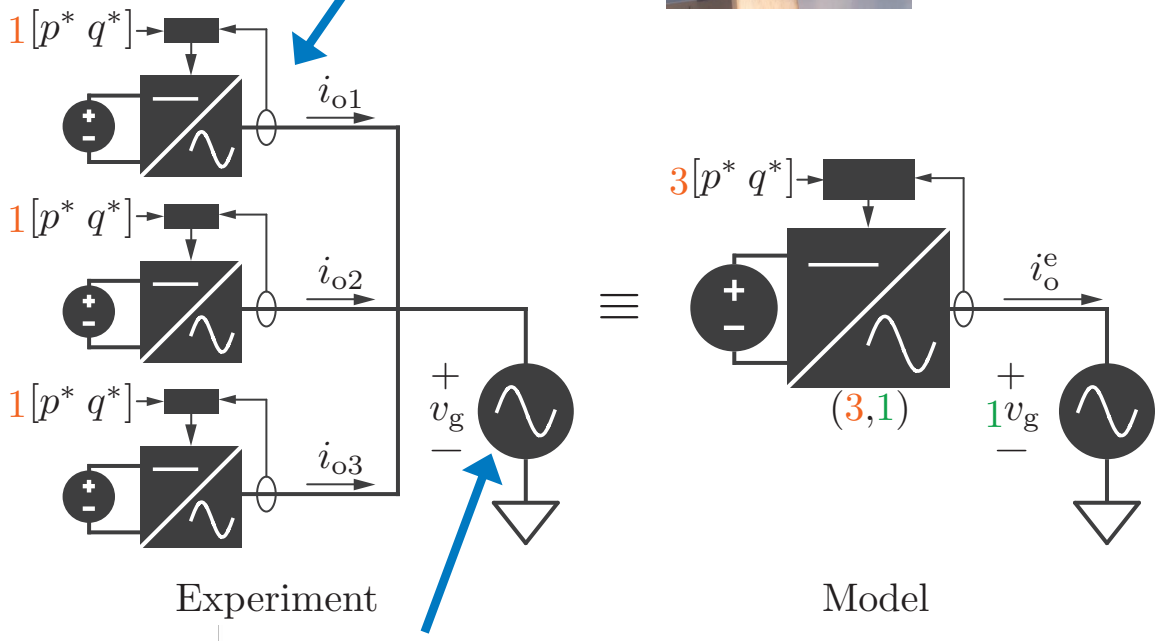
[1] Scaling laws for **grid following**: V. Purba, B. Johnson, S. Jafarpour, F. Bullo, and S. Dhople, "Reduced-order Structure-preserving Model for Paralleled Three-phase Grid-tied Inverters," *Workshop on Control and Modeling for Power Electronics*, 2017.

[2] Scaling laws for **grid forming**: M. Khan, B. Johnson, V. Purba, and S. Dhople, "A Reduced-order Aggregated Model for Parallel Inverter Systems Controlled with Virtual Oscillator Control," *Workshop on Control and Modeling for Power Electronics*, 2018.

Experimental Validation of Aggregation



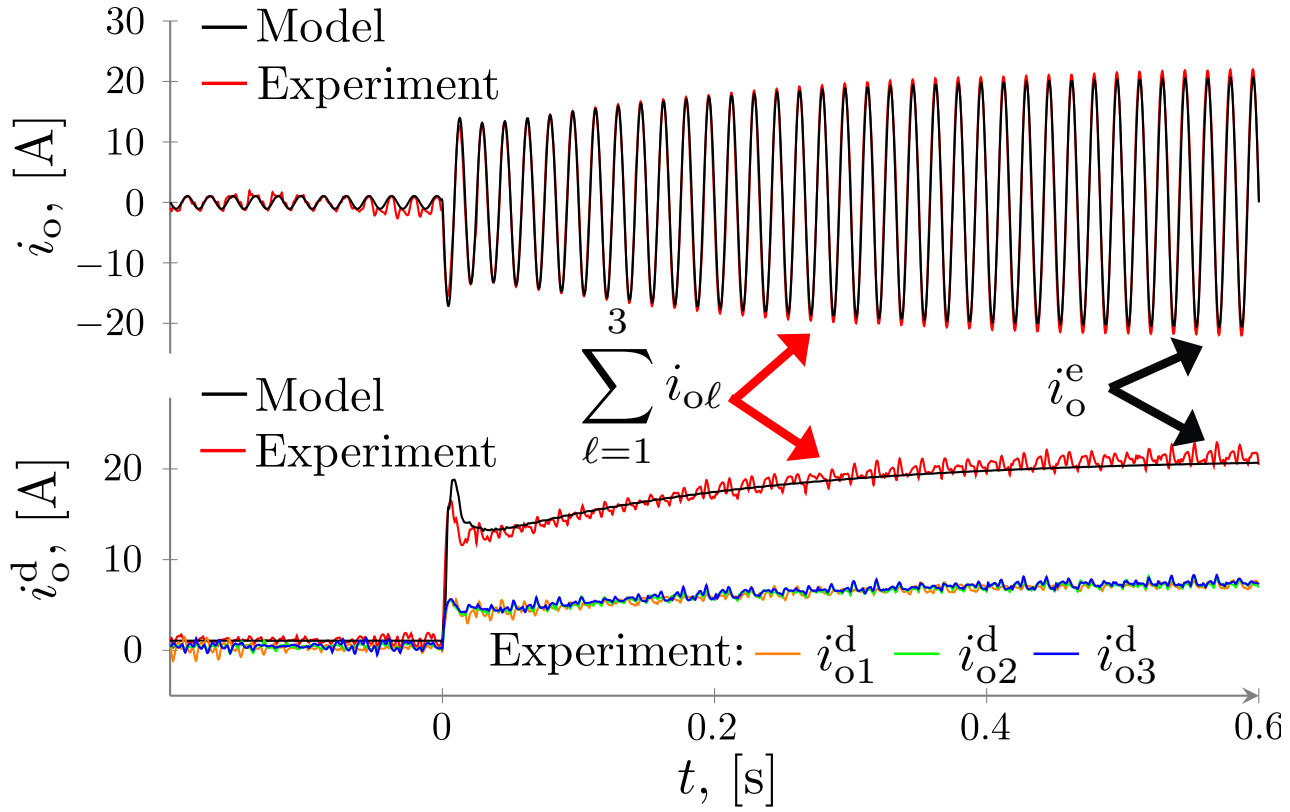
1kW inverter



120V
60Hz supply

Experimental Validation: Grid-Following Controls

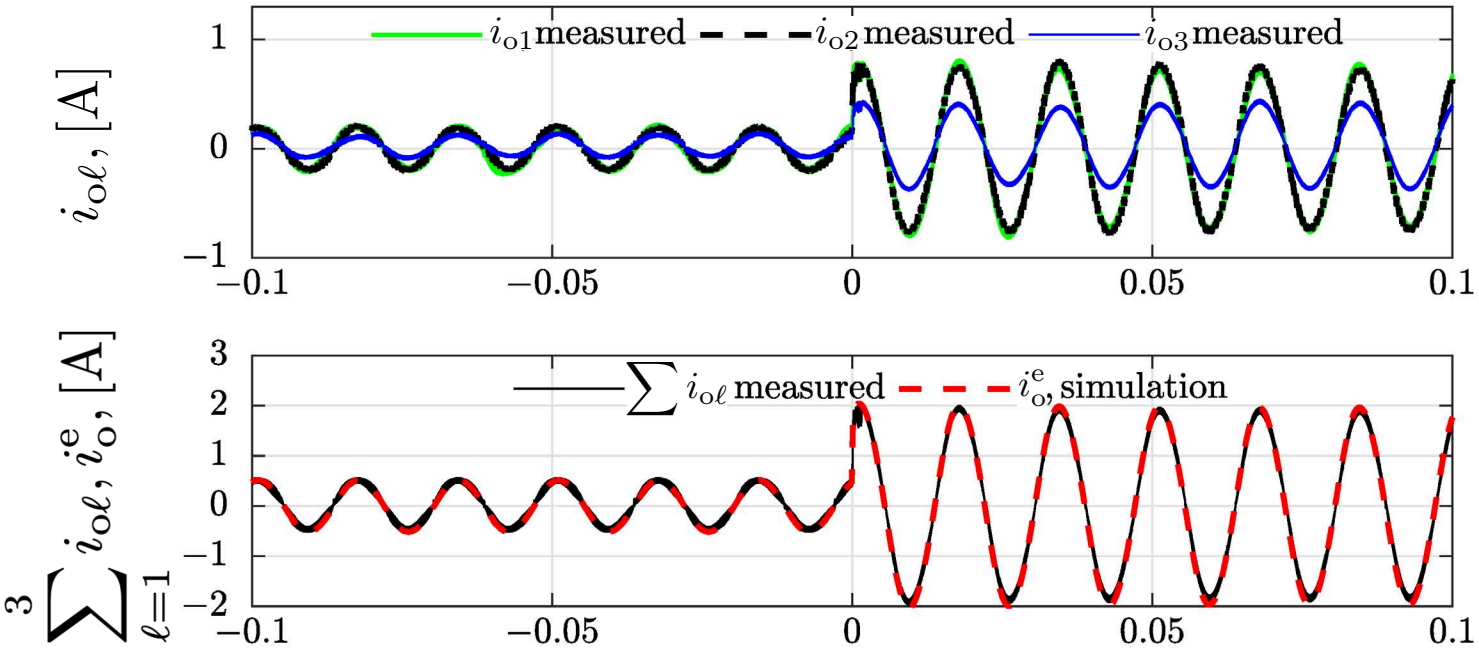
- System of 3 grid-following inverters during power command step change.



V. Purba, B. Johnson, M. Rodriguez, S. Jafarpour, F. Bullo, and S. Dhople, "Reduced-order Aggregate Model for Parallel-connected Single-phase Inverters," *IEEE Transactions on Energy Conversion*, Submitted.

Experimental Validation: Grid-Forming Oscillator Controls

- System of 3 inverters with Virtual Oscillator Control during load steps.



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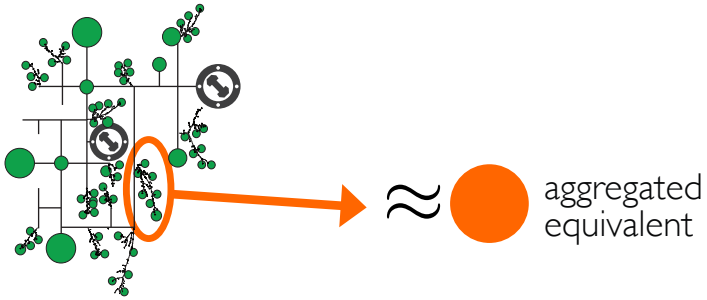

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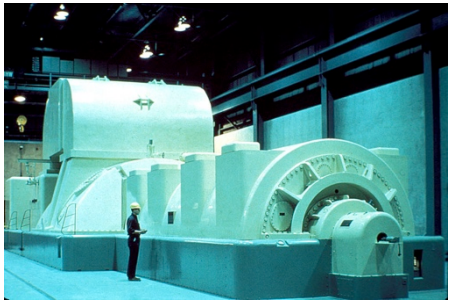

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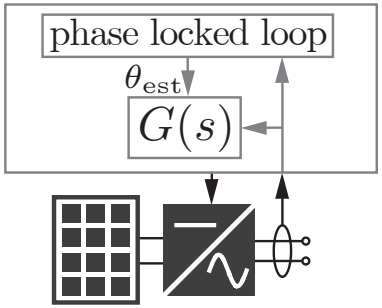

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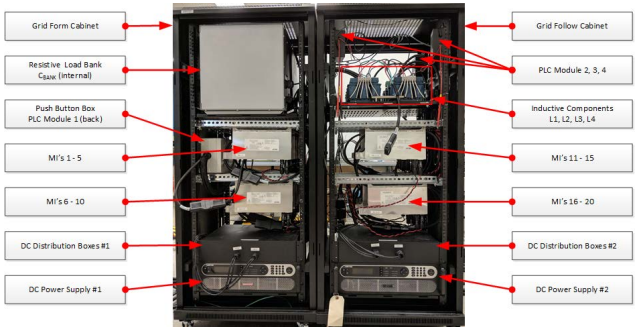
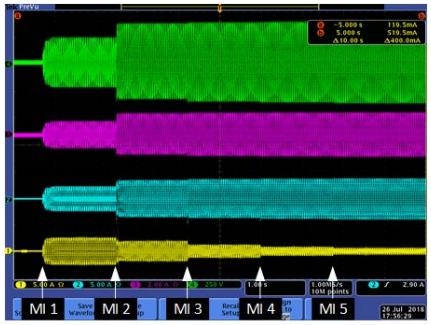




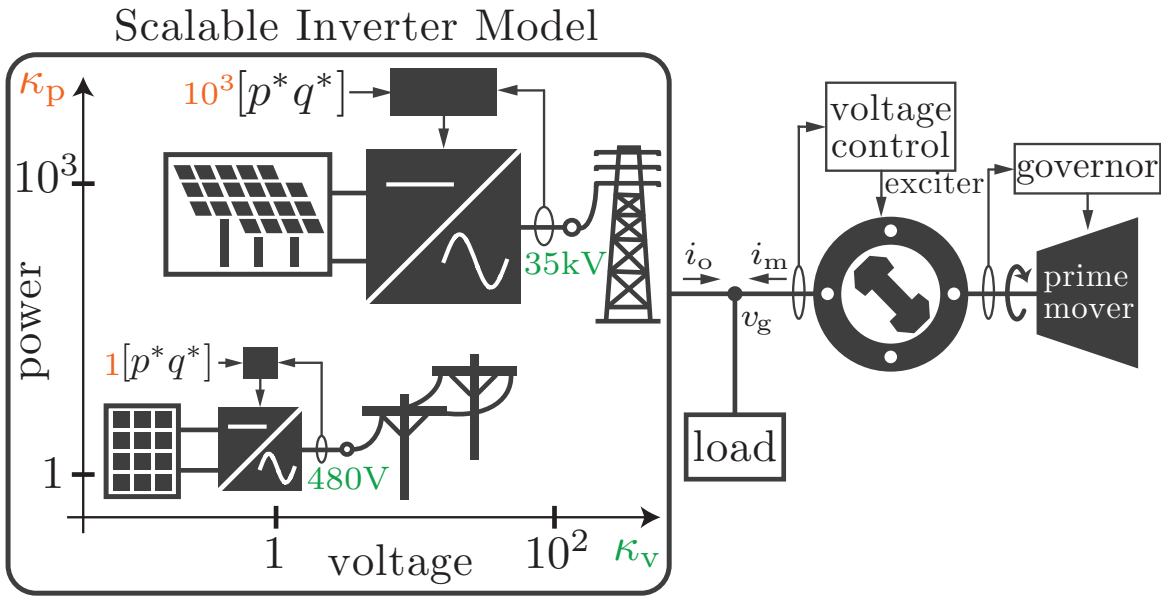
The Key Question

Can we get from here to here?

- Look at this question with both **grid-following** and **grid-forming** inverters.

An Elementary Model

A good starting point:



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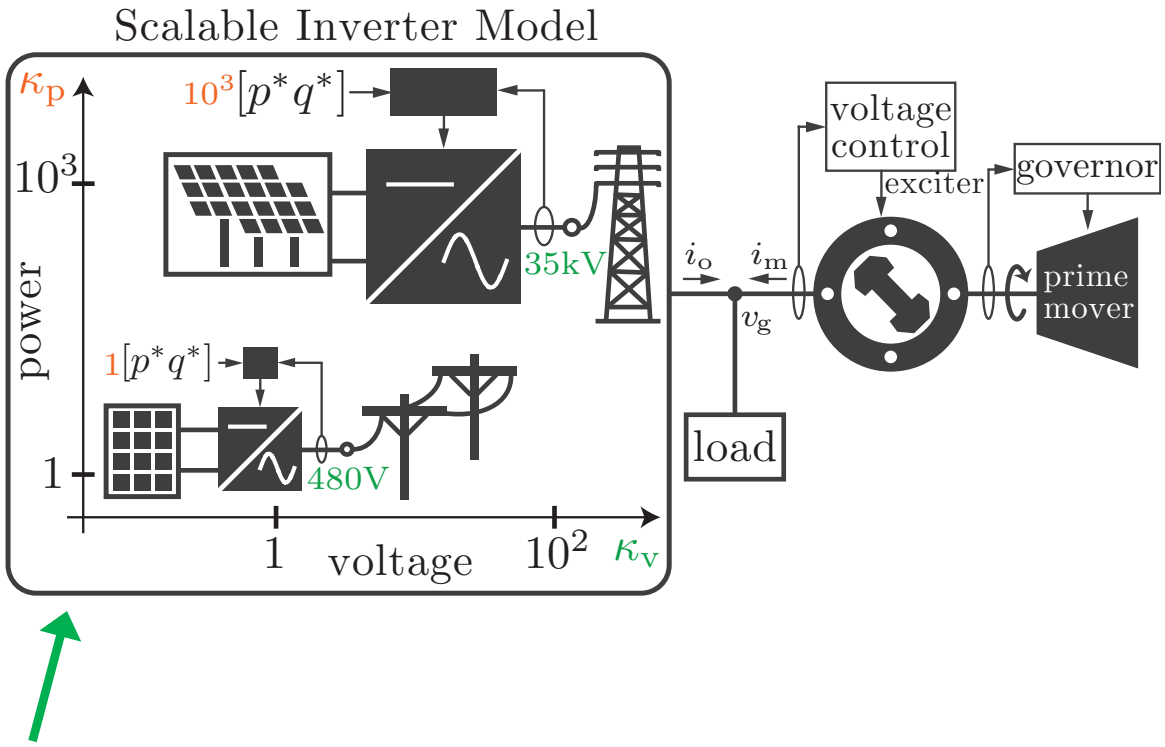

Represents an aggregated collection of inverters

An Elementary Model

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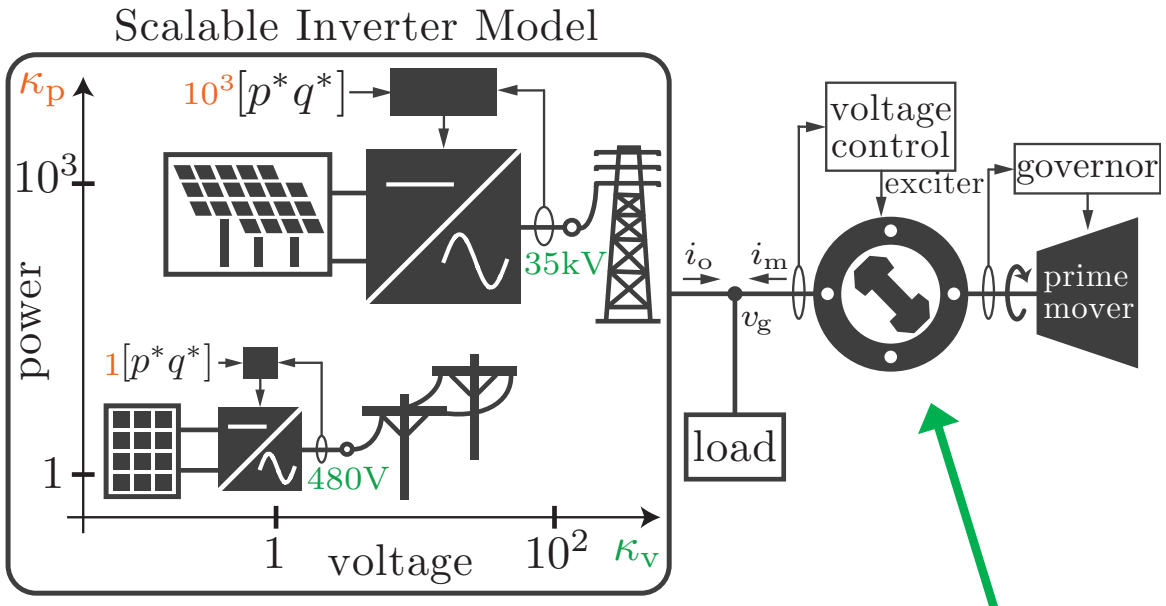
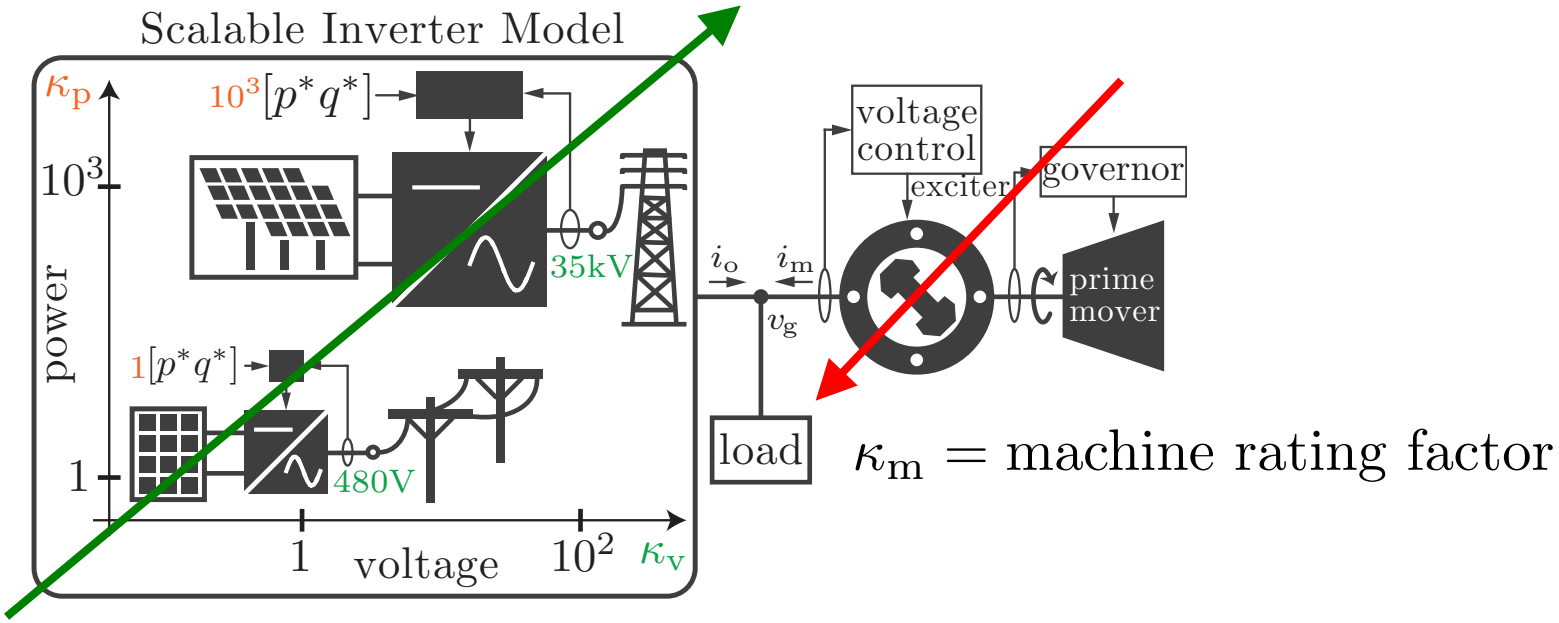


Represents an aggregated collection of inverters

Prototypical steam-driven generator at fossil-fuel plant

A Fundamental Question

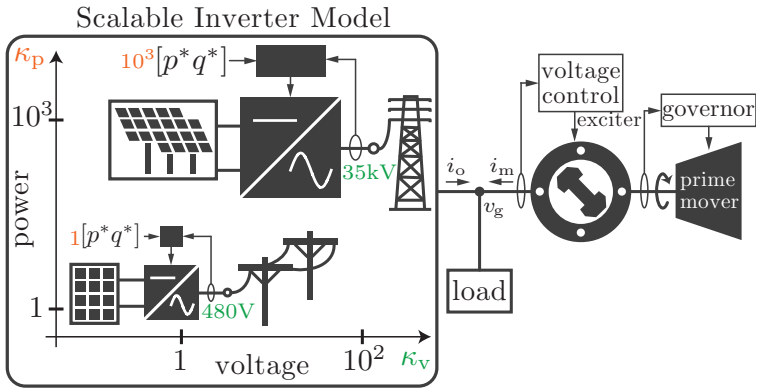
Q: What happens as the ratio of inverter/machine ratings increases?



Approach: Adjust scaling concurrently such that $\kappa_p + \kappa_m = \text{constant}$

Model Framework

- Start with zero inverter penetration: $\kappa_{\mathrm{m}} = \mathrm{nominal}, \kappa_{\mathrm{p}} = 0$



$$\dot{x} = f(x, u)$$

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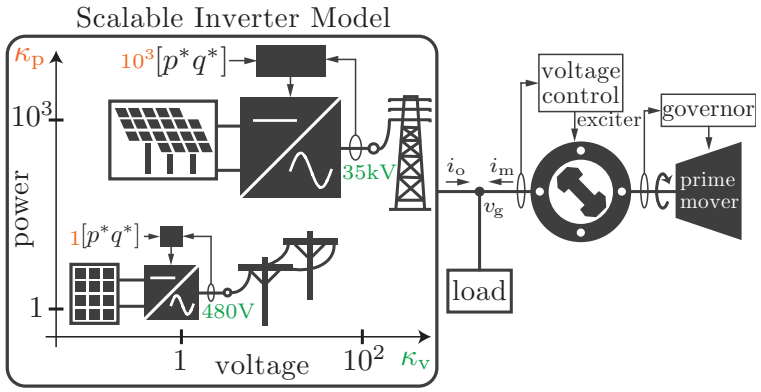
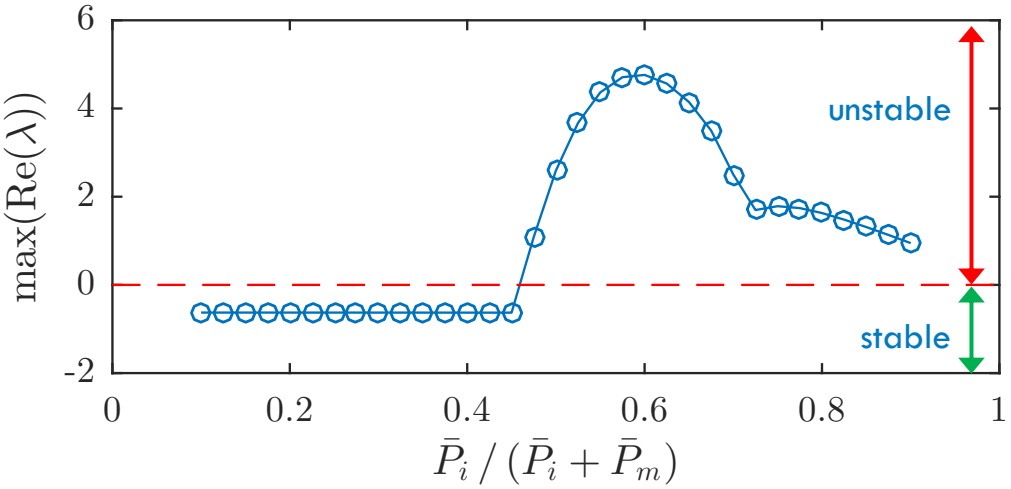


$$\dot{x} = f(x, u)$$

- Find equilibrium x^*
- Linearize to get $\Delta\dot{x} = A\Delta x + B\Delta u$
- Compute eigenvalues $\lambda \in \mathbb{C}^{|x|}$
- Increase κ_{p} and decrease κ_{m}

Results: Small-signal Stability with Grid-Following Inverter

- Fixed machine rating $\bar{P}_{\mathrm{m}} = 555$MVA, parameters from [1]
- Unscaled inverter rating $P_{\mathrm{i}} = 1$kVA, parameters for NREL hardware

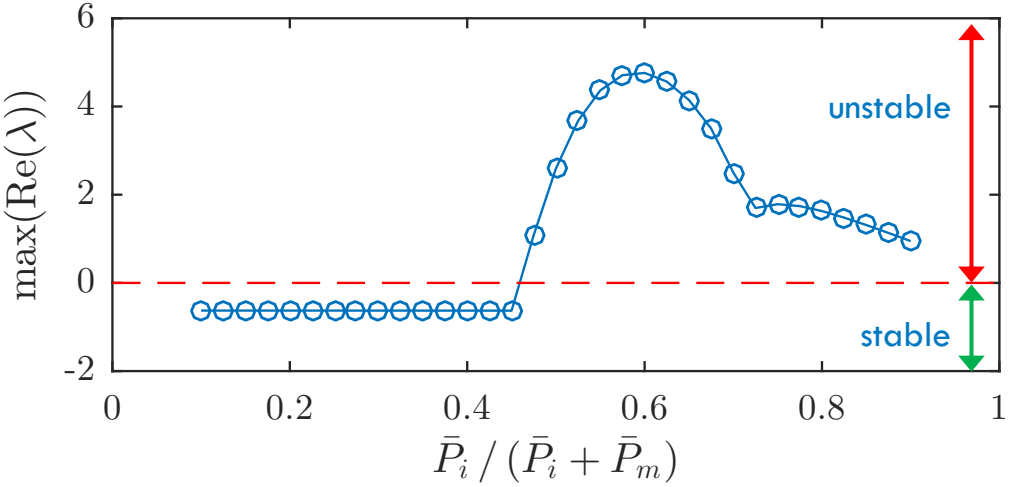


[1] P. Kundur, N. J. Balu, and M. G. Lauby, Power system stability and control. McGraw-hill New York, 1994.

[2] Y. Lin, B. Johnson, V. Purba, S. Dhople, V. Gevorgian, "Stability Assessment of a System Comprising a Single Machine and Inverter with Scalable Ratings," *North American Power Symposium*, 2017.

Results: Small-signal Stability with Grid-Following Inverter

- Fixed machine rating $\bar{P}_{\mathrm{m}} = 555$MVA, parameters from [1]
- Unscaled inverter rating $P_{\mathrm{i}} = 1$kVA, parameters for NREL hardware



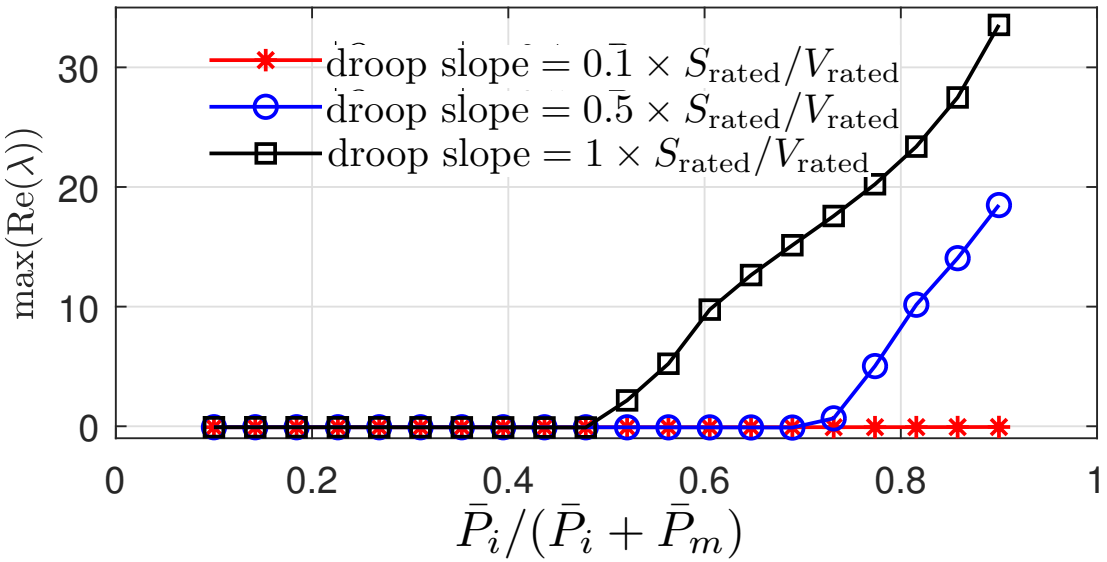
- Instability in this example at approximately 50% [2]
- Result varies between 40%-90%, depends on parameters

[1] P. Kundur, N. J. Balu, and M. G. Lauby, Power system stability and control. McGraw-hill New York, 1994.

[2] Y. Lin, B. Johnson, V. Purba, S. Dhople, V. Gevorgian, "Stability Assessment of a System Comprising a Single Machine and Inverter with Scalable Ratings," *North American Power Symposium*, 2017.

Results: Small-signal Stability with **Grid-Forming** Inverter

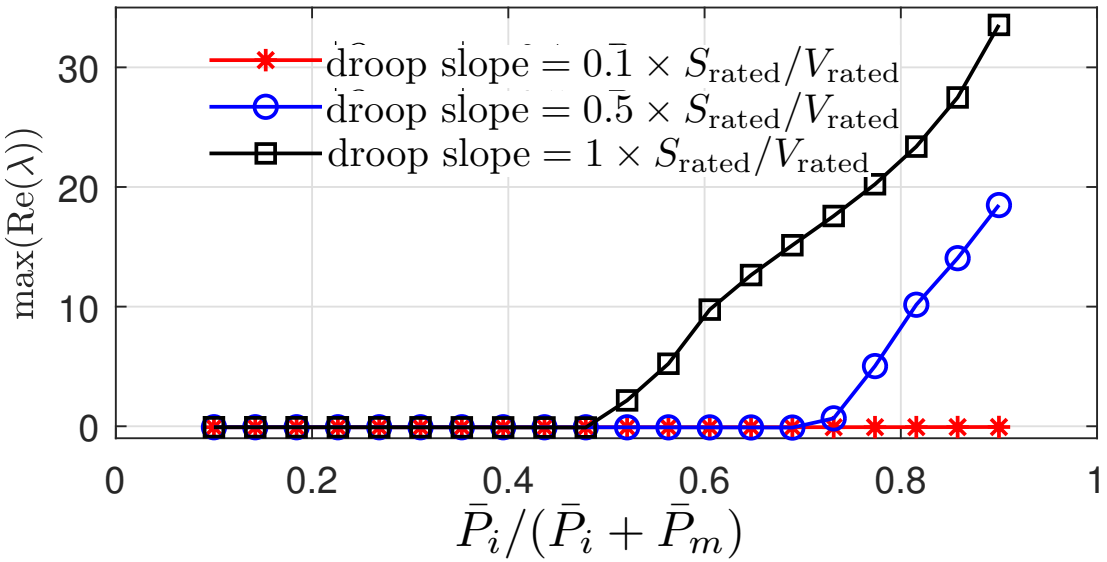
- Now look at inverter with Virtual Oscillator Control
- Machine same as before



[1] M. Khan, Y. Lin, B. Johnson, M. Sinha, S. Dhople, "Stability Assessment of a System Comprising a Single Machine and a Virtual Oscillator Controlled Inverter with Scalable Ratings," *Industrial Electronics Conference*, 2018.

Results: Small-signal Stability with **Grid-Forming** Inverter

- Now look at inverter with Virtual Oscillator Control
- Machine same as before

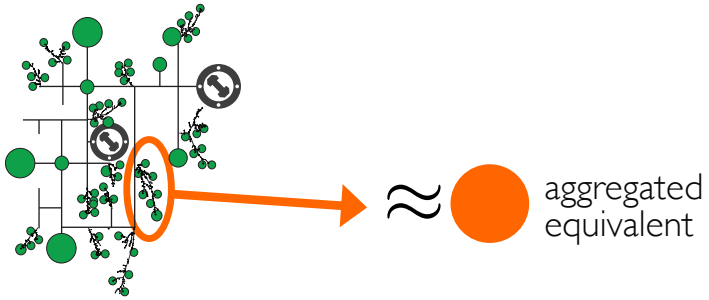


- Key finding: Instability can be eliminated with flatter Volt/VAR droop slope [1]

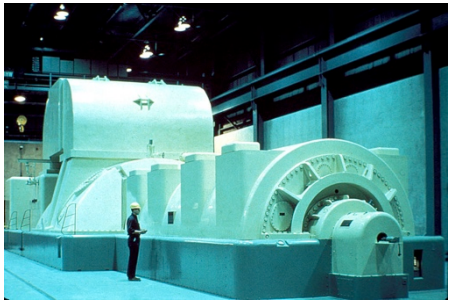
[1] M. Khan, Y. Lin, B. Johnson, M. Sinha, S. Dhople, "Stability Assessment of a System Comprising a Single Machine and a Virtual Oscillator Controlled Inverter with Scalable Ratings," *Industrial Electronics Conference*, 2018.

Outline

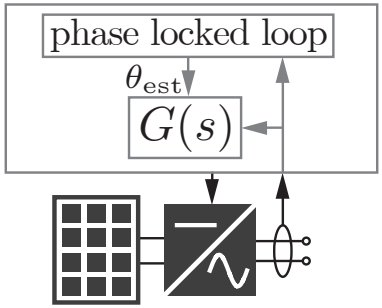
1. How do we solve the modeling complexity problem?



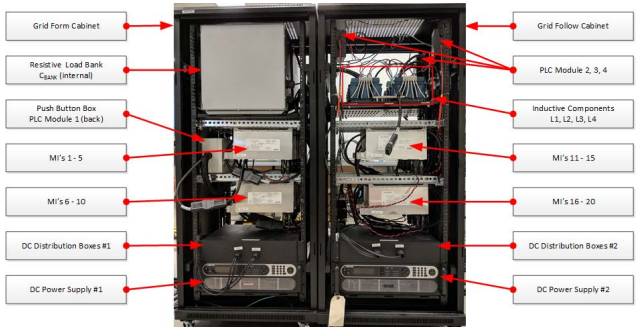
2. Is there an upper limit for inverter penetration before stability is lost?

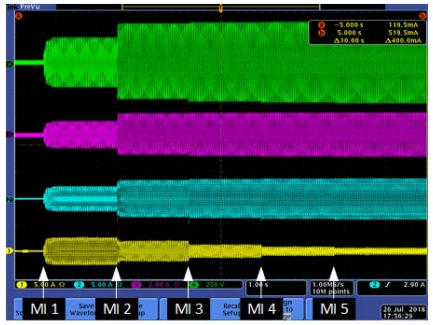


How many machines can we replace with electronics?



3. A hardware demo with 20 commercial inverters.

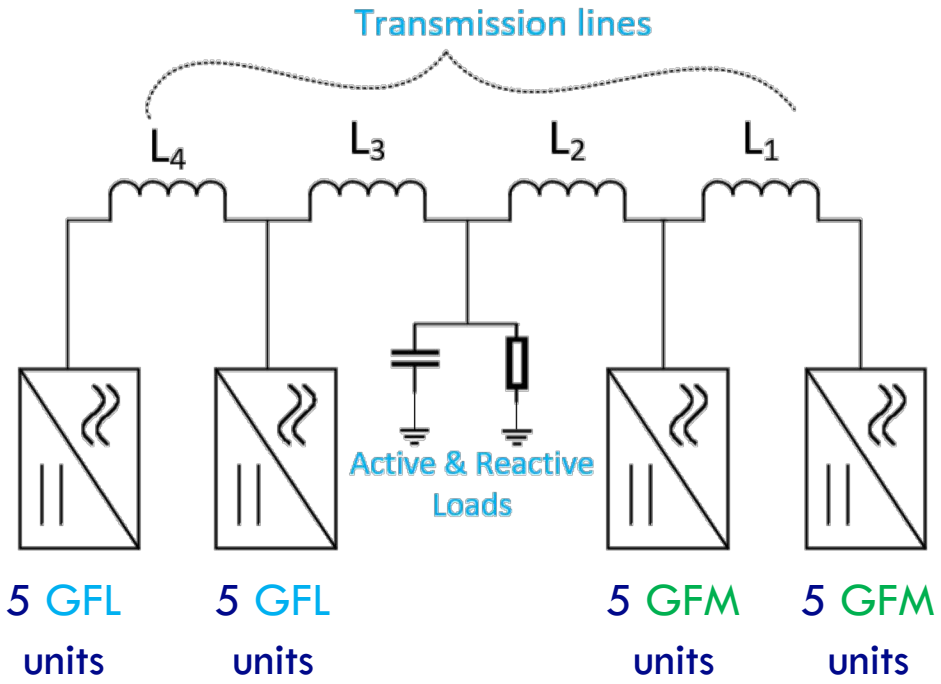




A Demo of a Complex Network

Characteristics:

- Heterogenous grid-forming (GFM) + grid following (GFL)
- Relatively complex: 20 units total = 10 GFM + 10 (GFL)
- Radial distribution network with **line impedances + cap bank**
- Operation on **commercial hardware**



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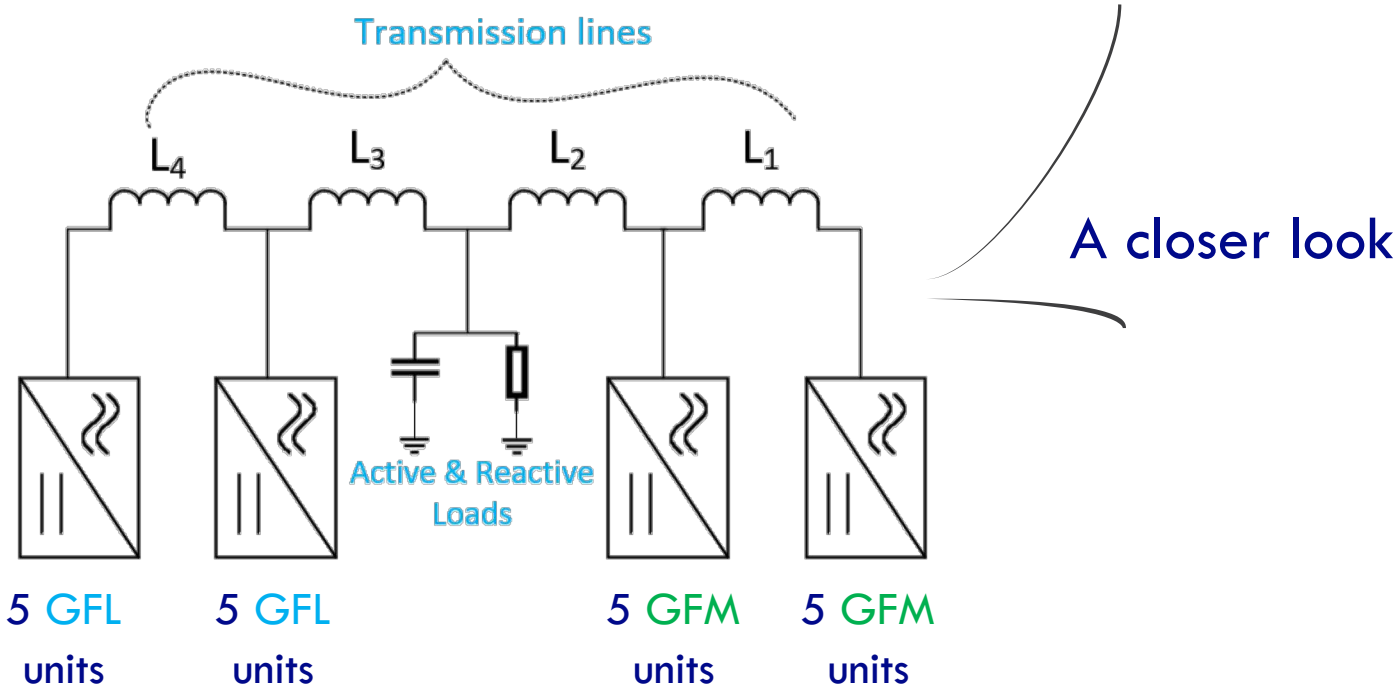
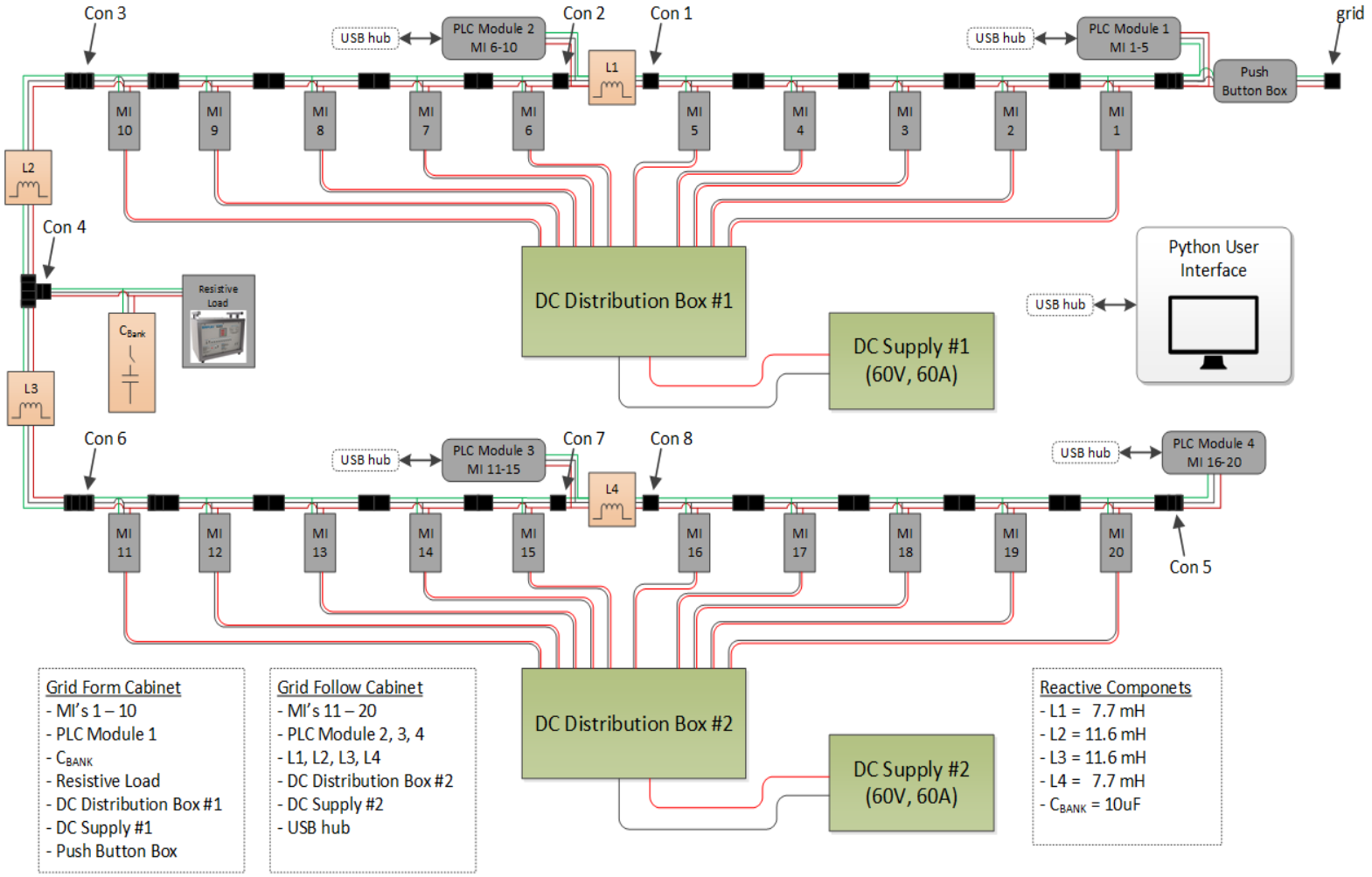
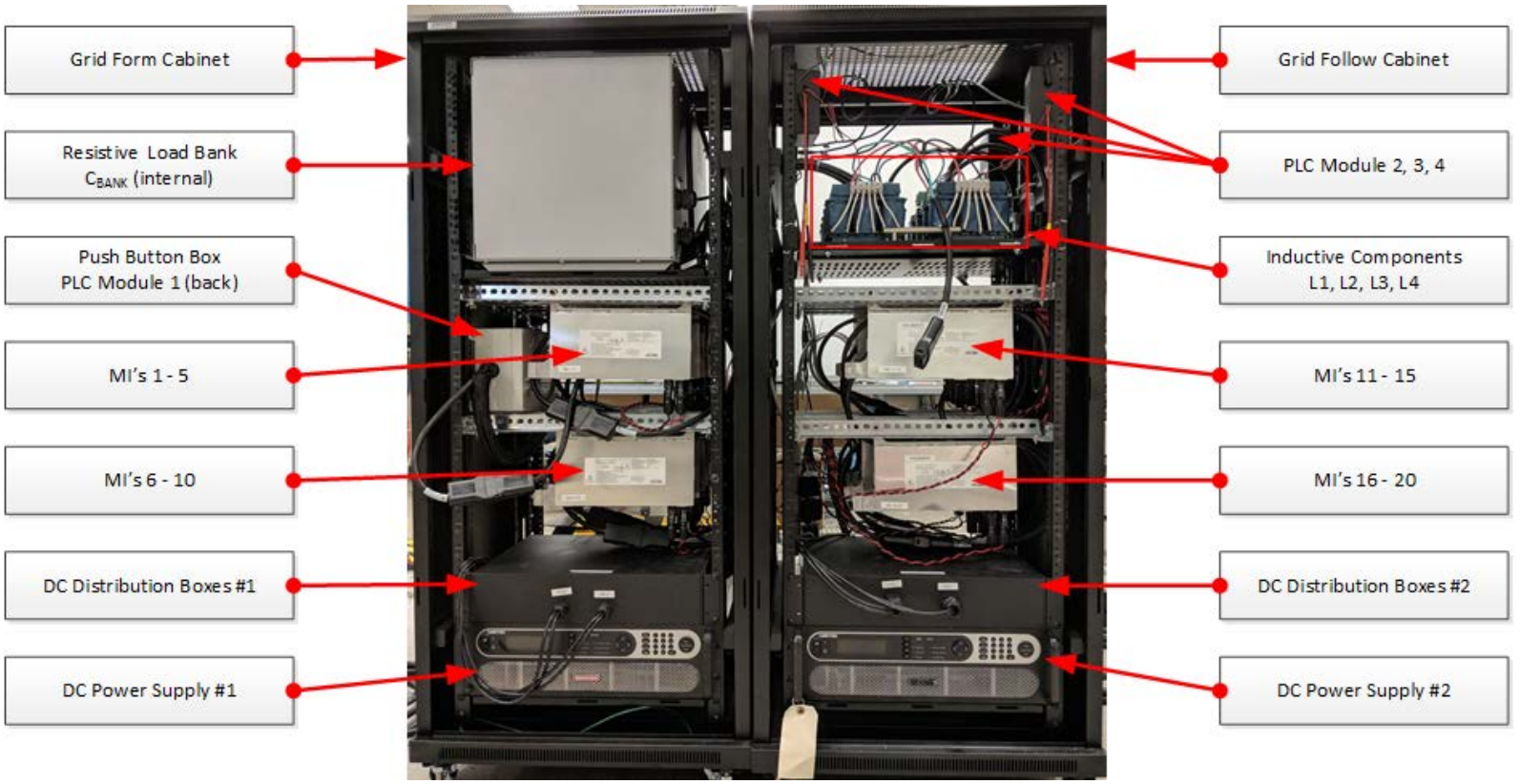


Network Details

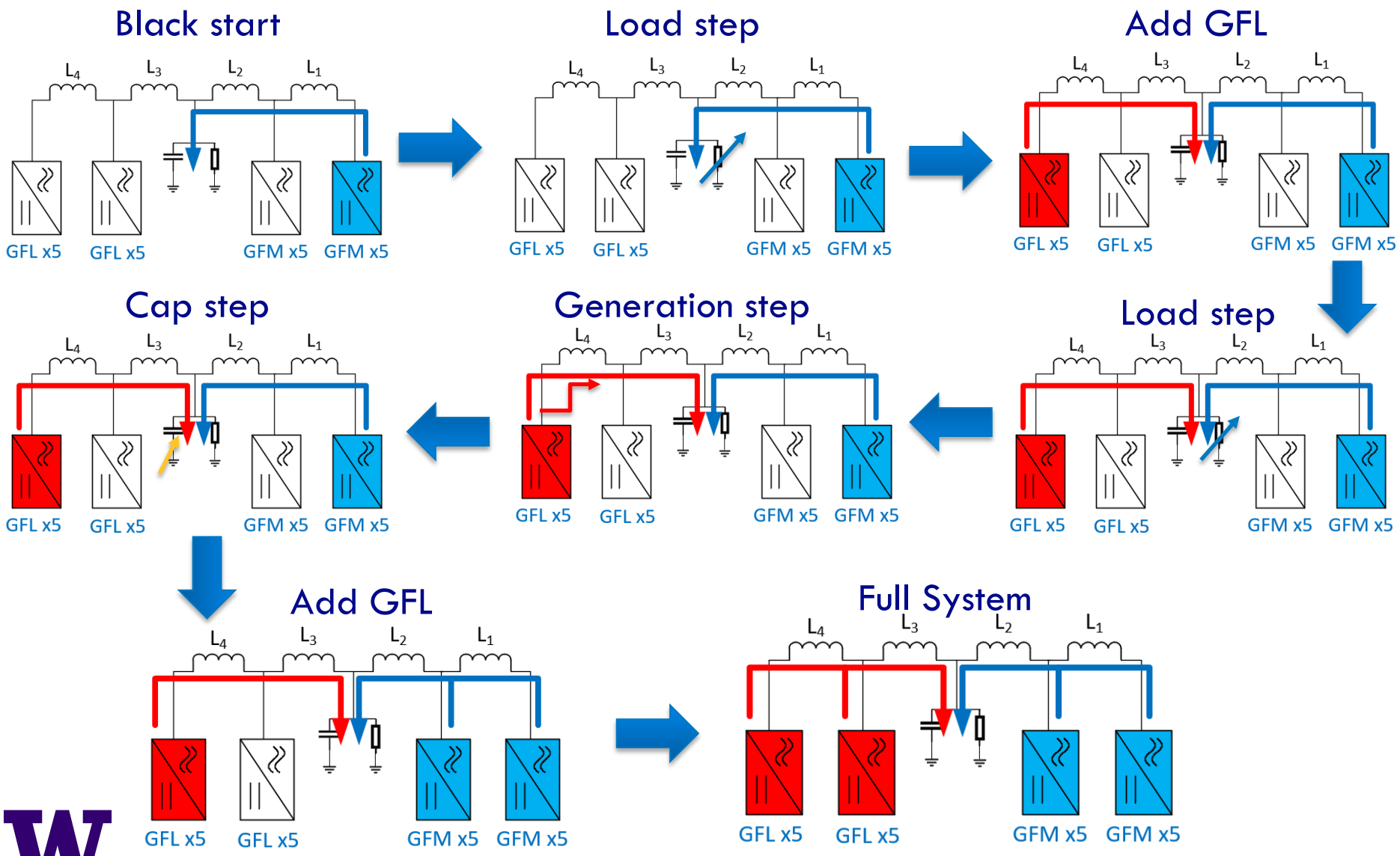


Realization

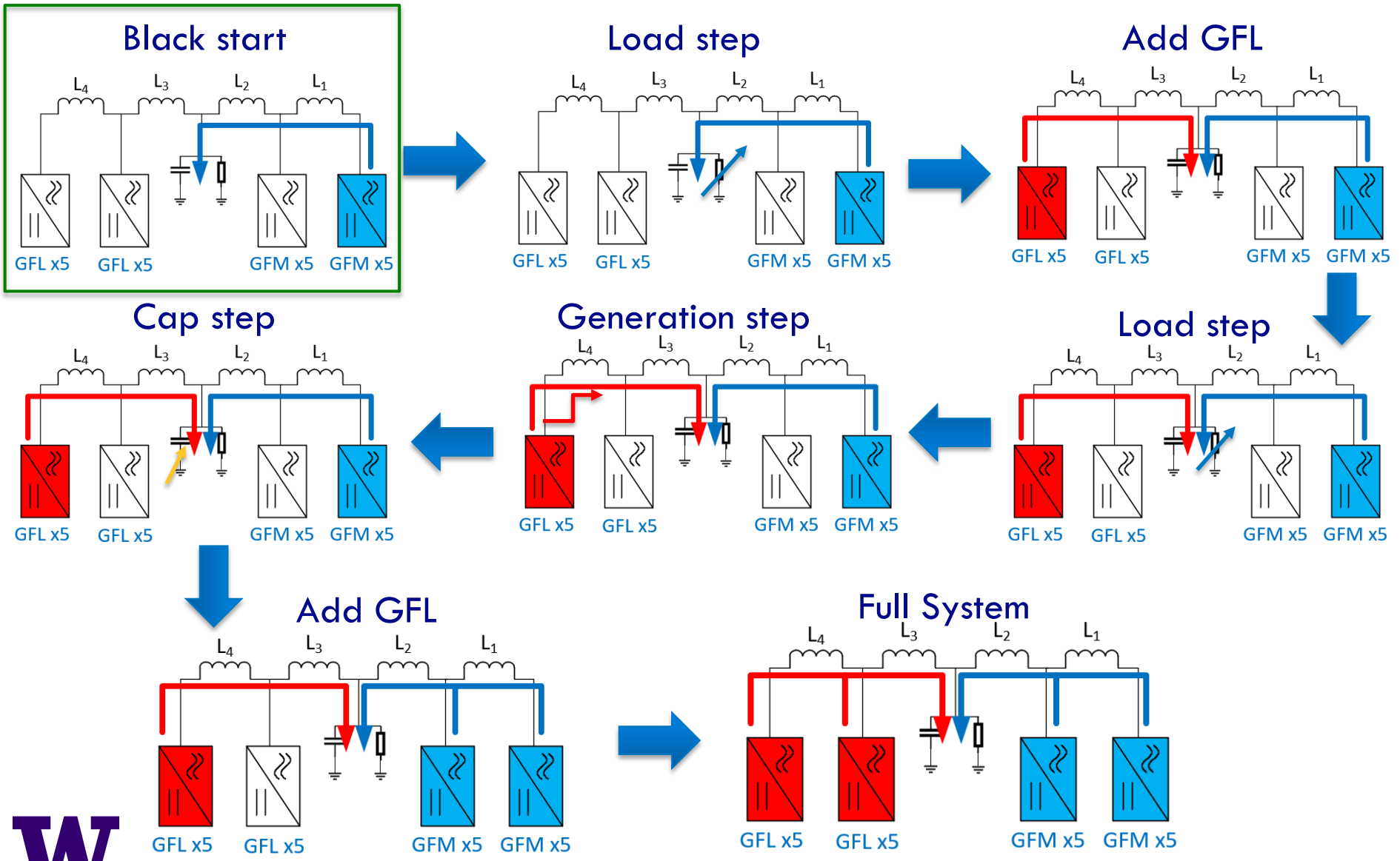


SunPower inverters with modified controls

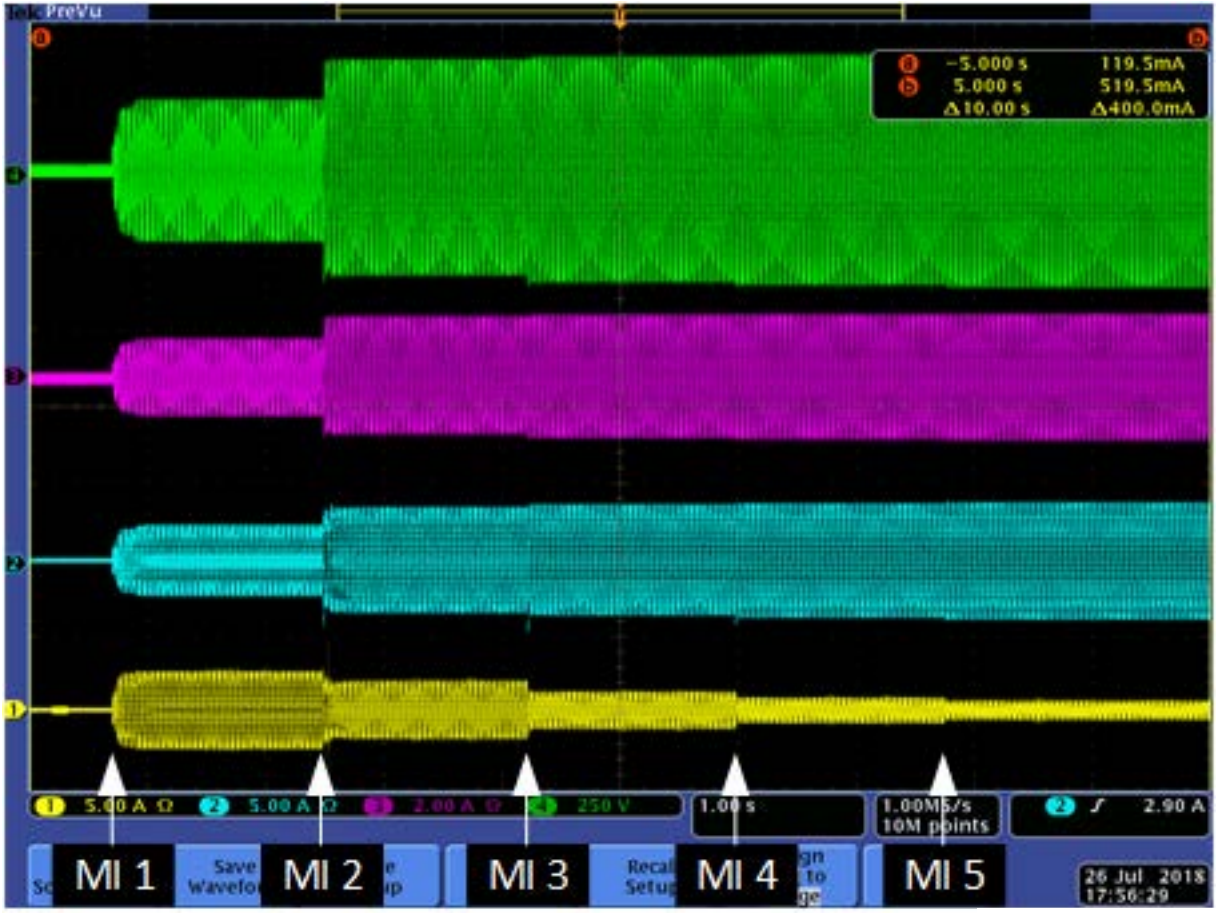
A Black-start to Full-system Sequence



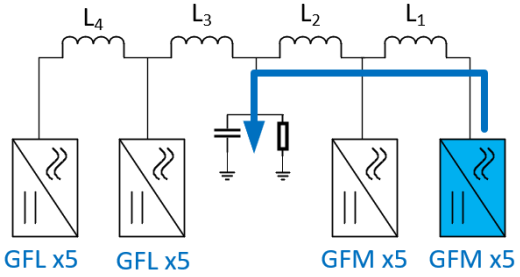
A Black-start to Full-system Sequence



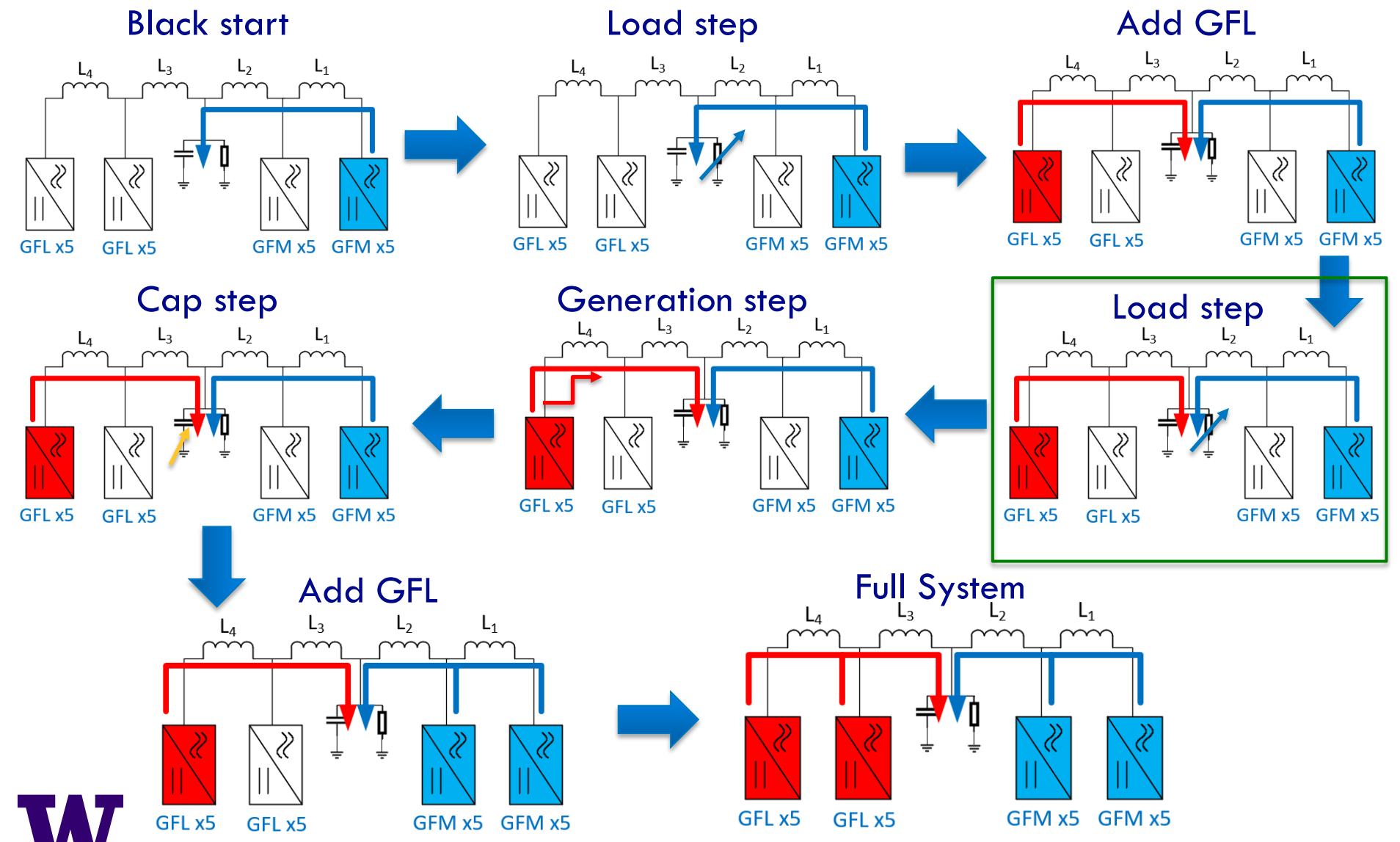
Step 1: Black-start



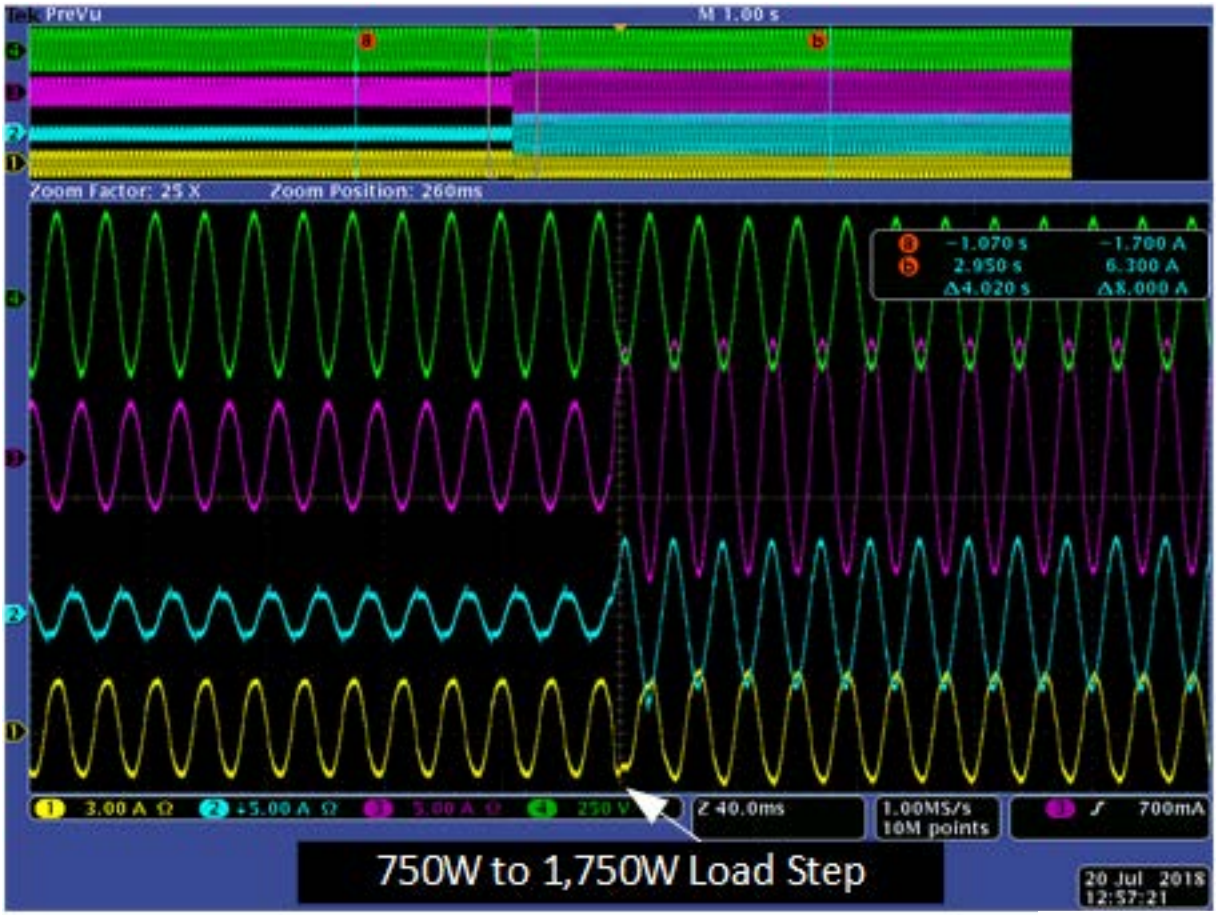
- Start with 250W load
- VOC units power share



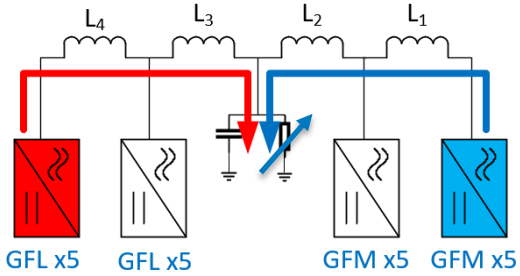
A Black-start to Full-system Sequence



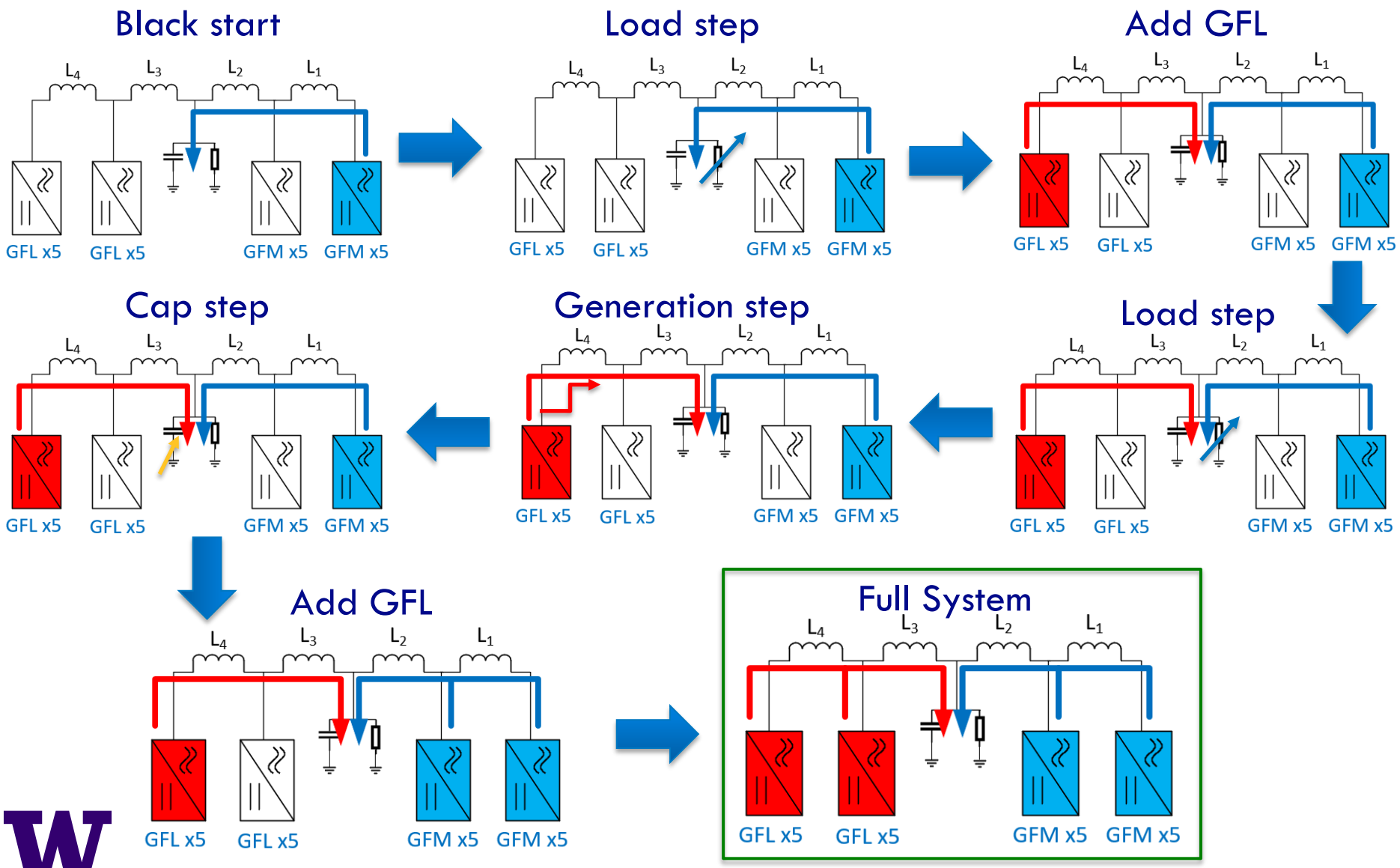
Step 4: Load Step with 10 Units



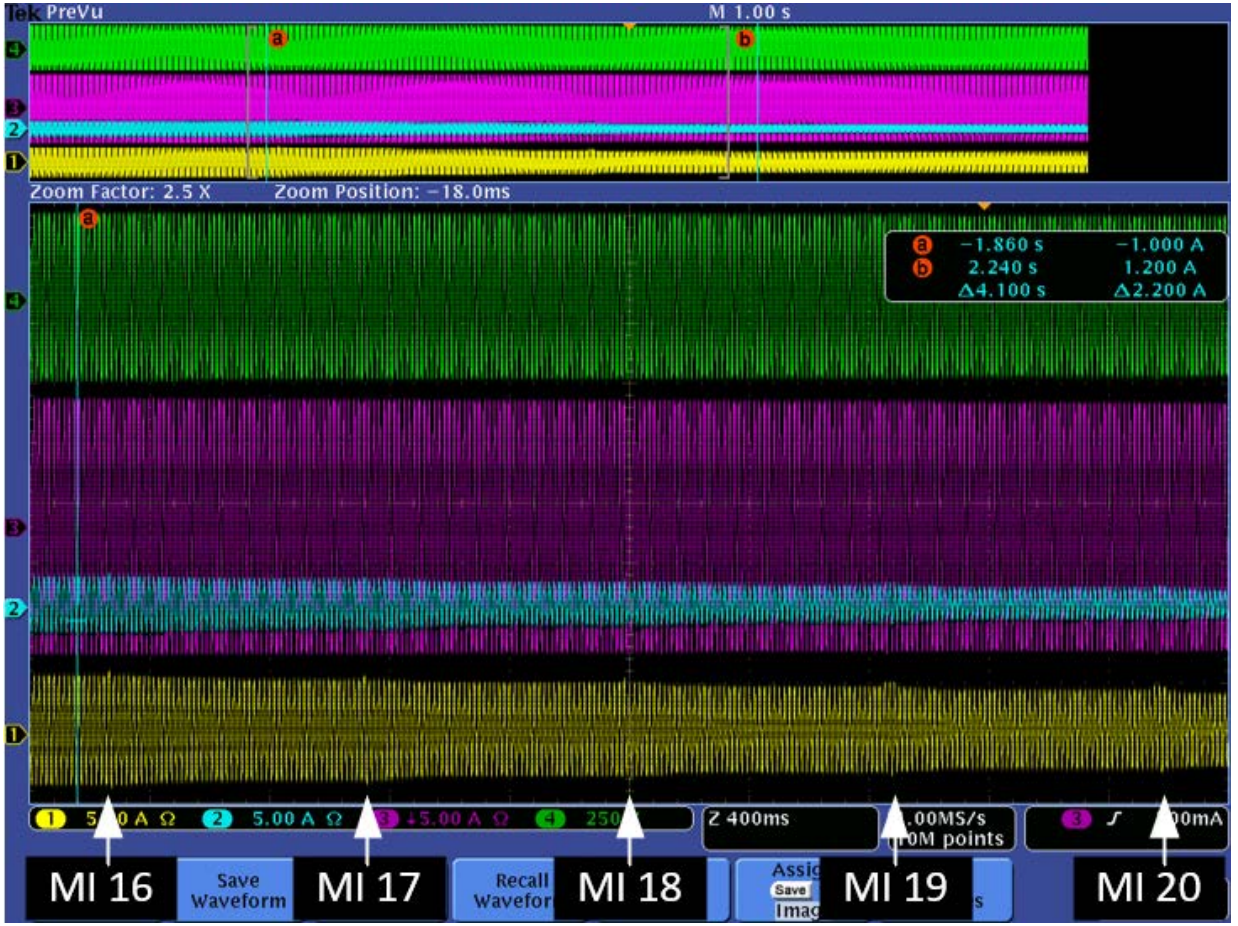
- GFL inverters share load step and regulate voltage
- GFM inverters generate 500 W



A Black-start to Full-system Sequence



Final Step: Turn on Last 5 GFLs



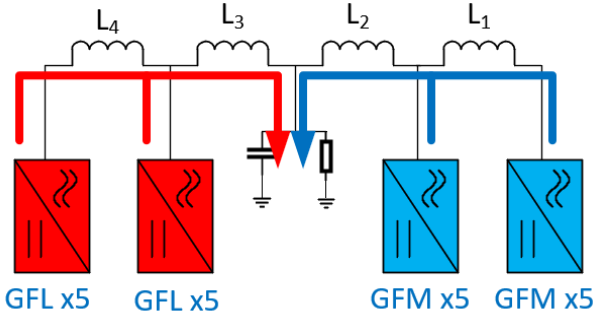
v_{load}

i_{load}

$i_{\text{line},1}$

$i_{\text{line},2}$

- Last 5 units turn on sequentially at 250 W output
- System robust to load/generation fluctuations

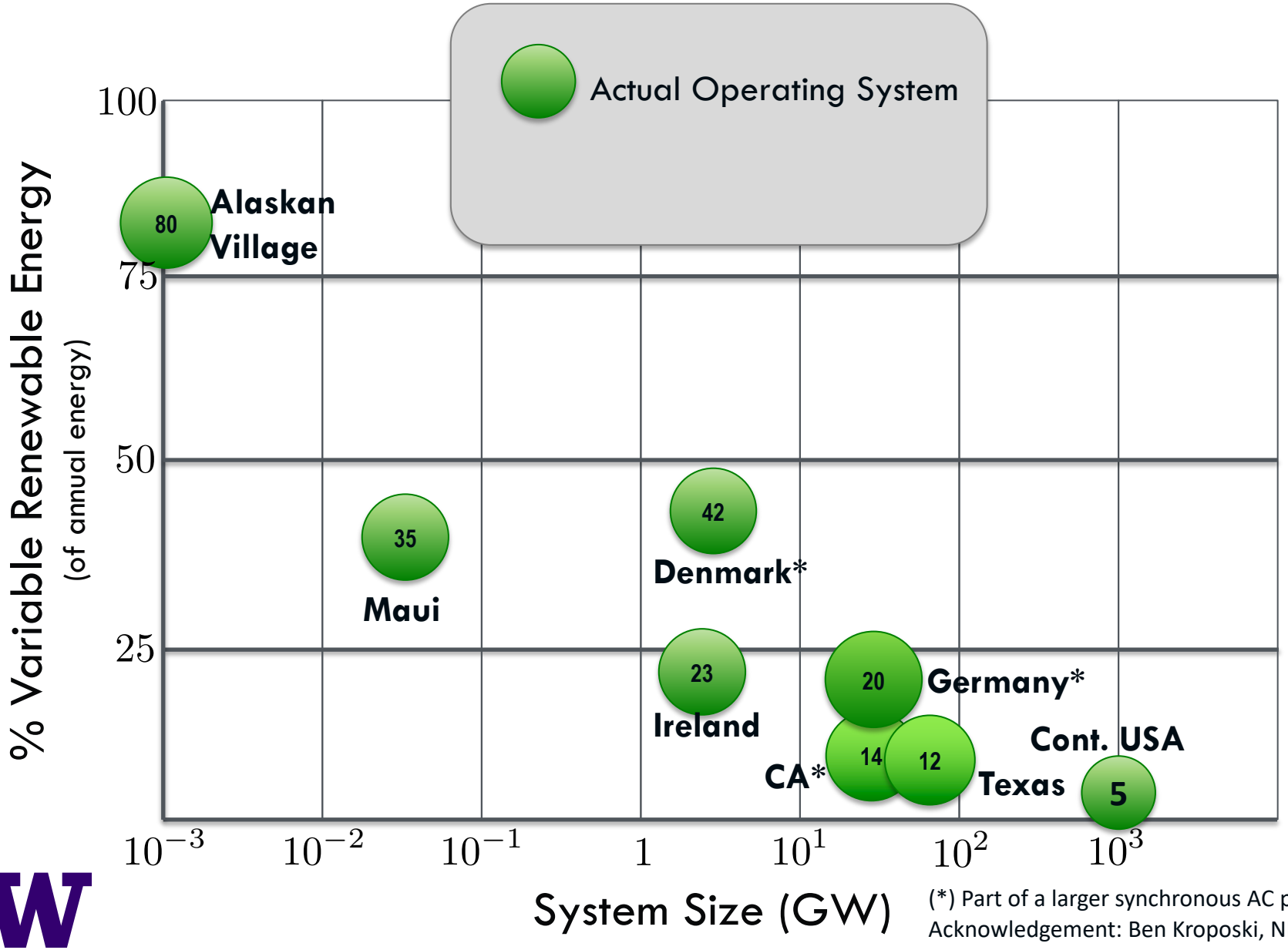


Thanks for your attention!

Brian Johnson

Contact: brianbj@uw.edu

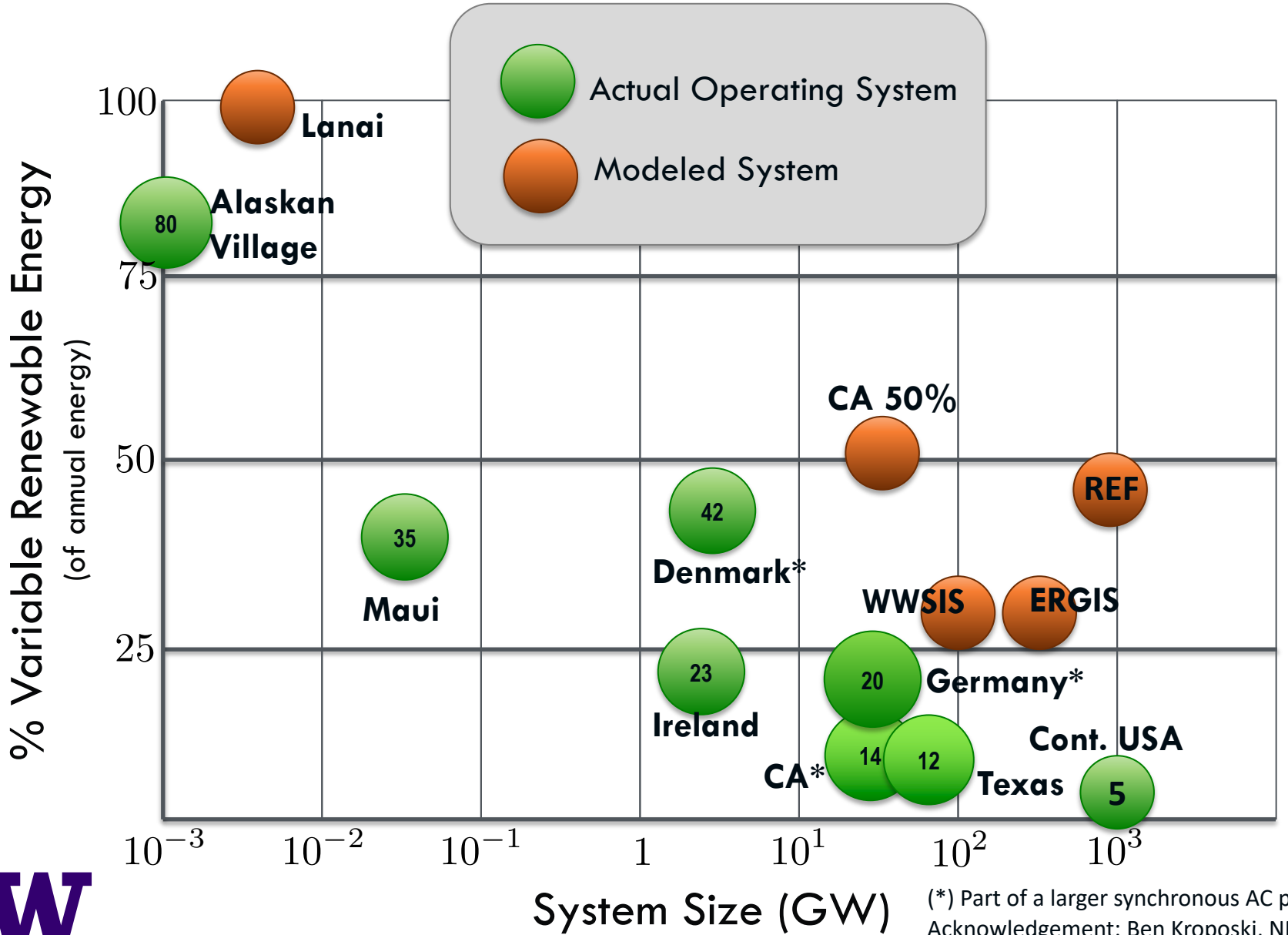
Transforming the Grid at a Scale That Matters



(*) Part of a larger synchronous AC power system

Acknowledgement: Ben Kroposki, NREL

Transforming the Grid at a Scale That Matters



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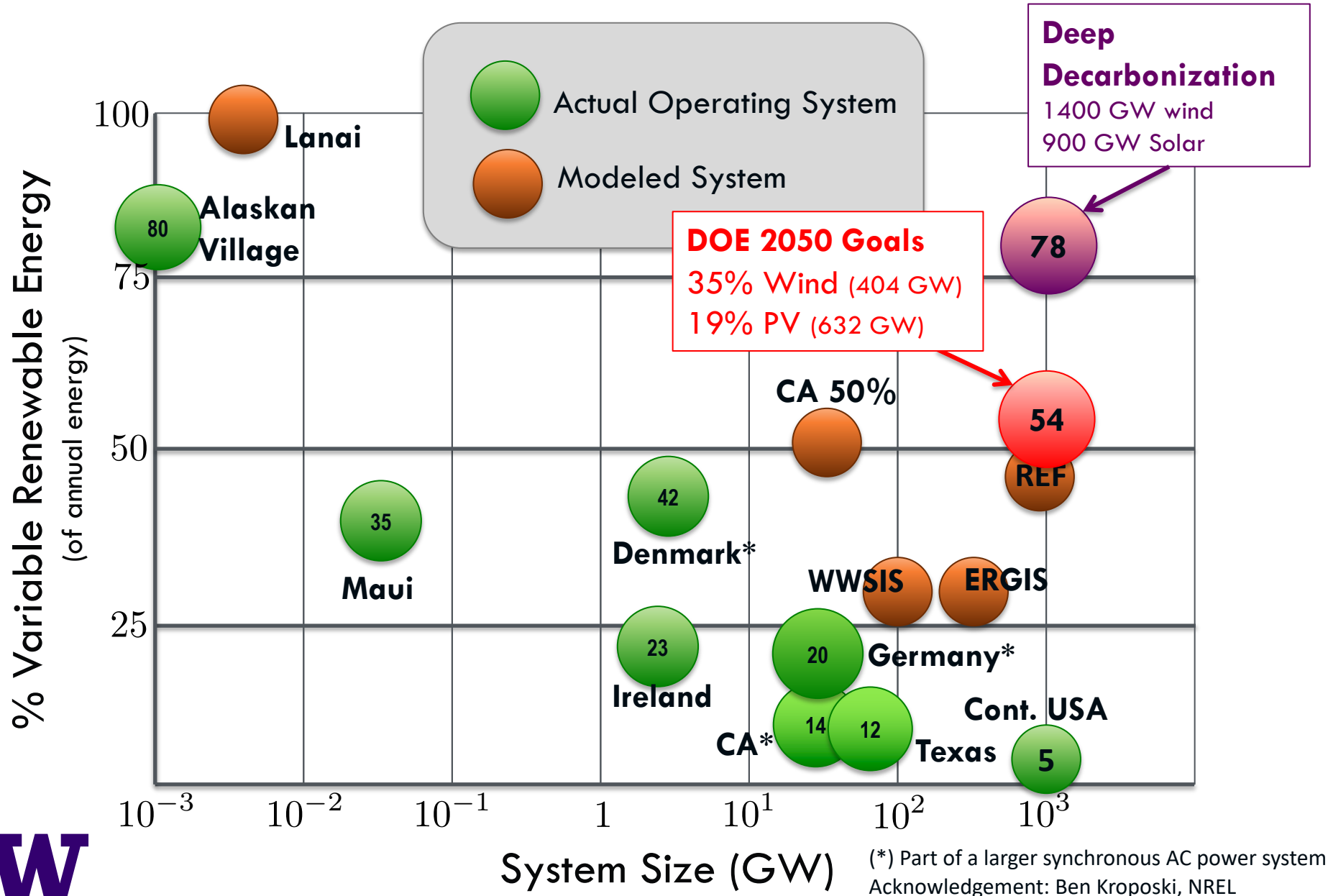
Transforming the Grid at a Scale That Matters



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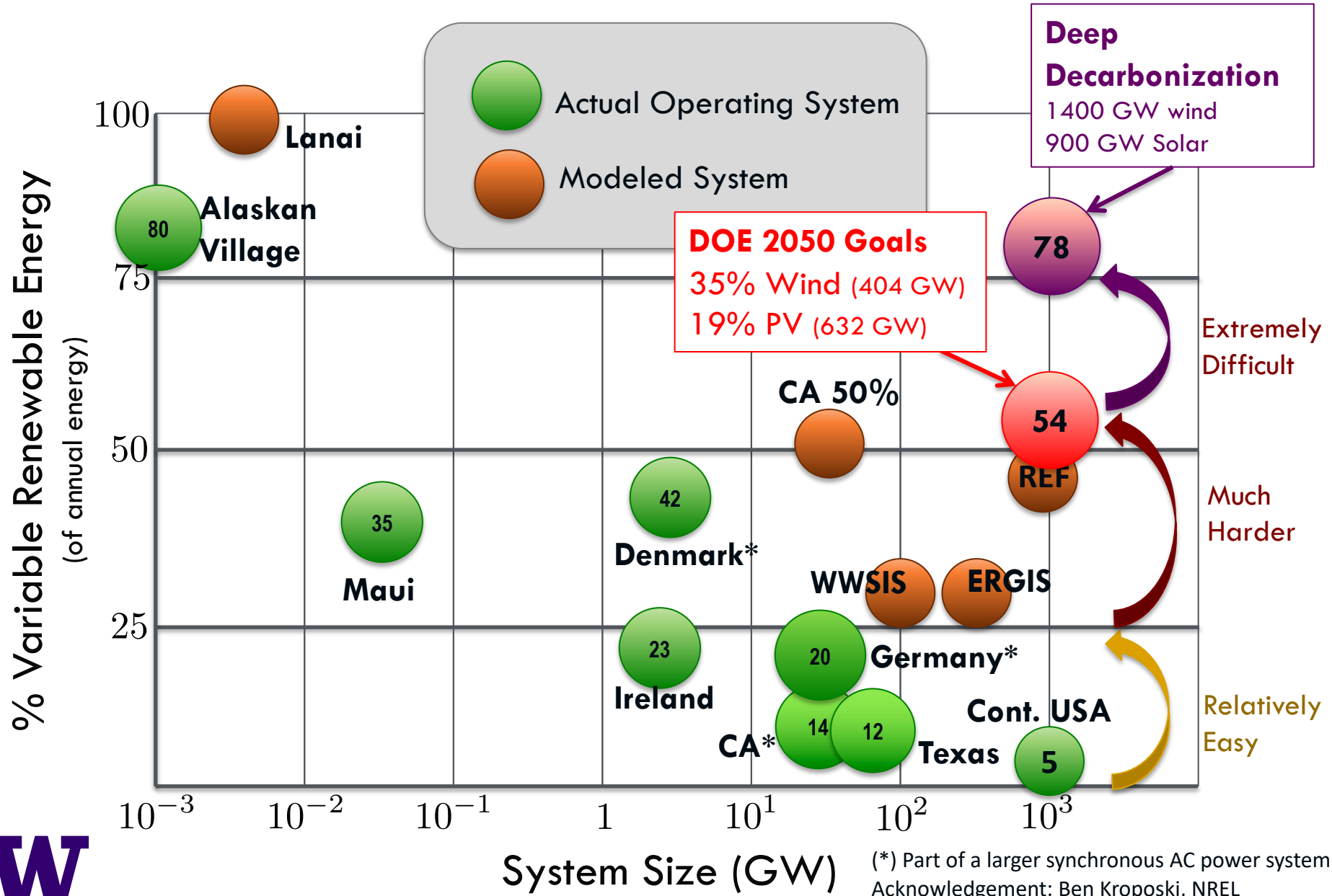
Transforming the Grid at a Scale That Matters



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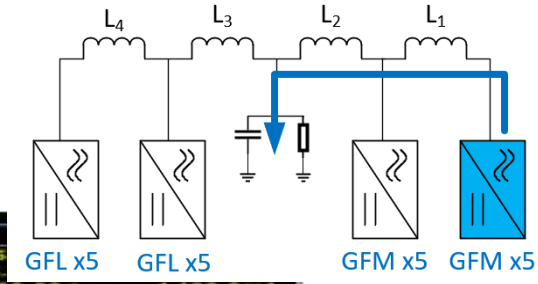
Demo Step 1: Black-start

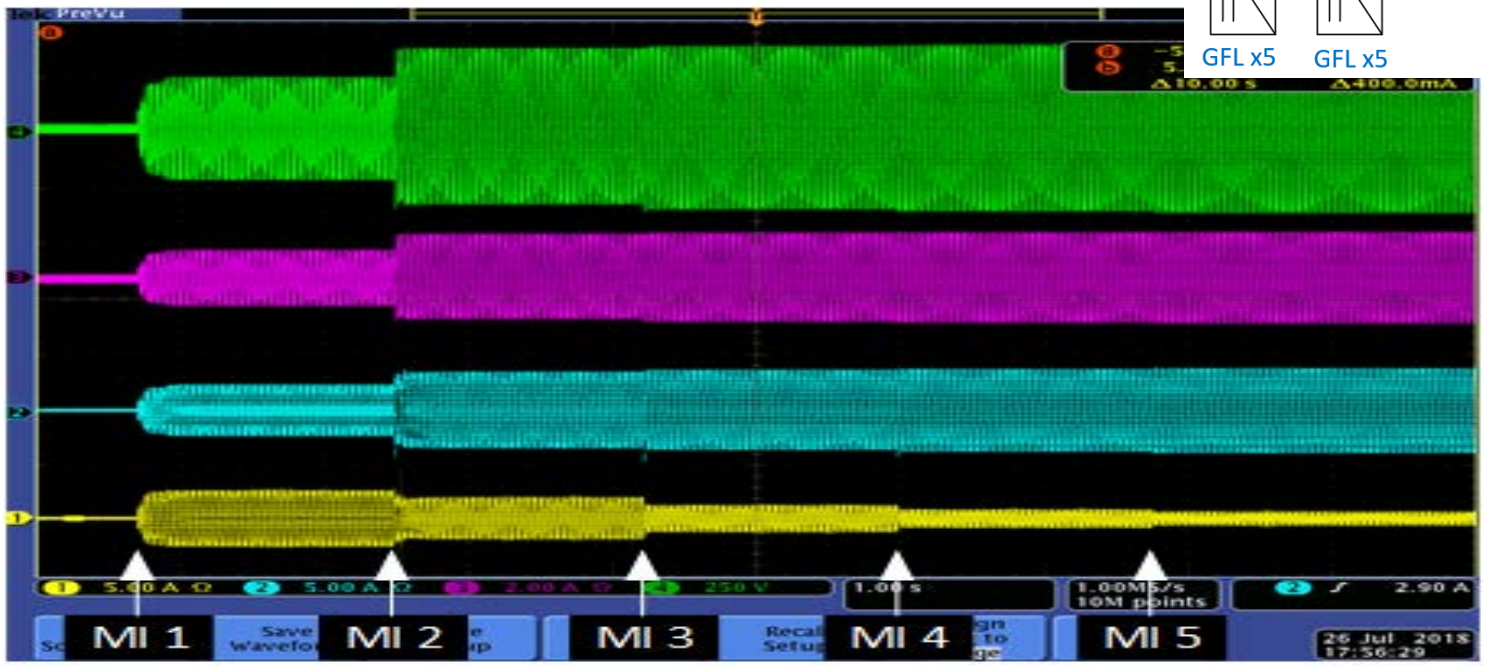


V_{Load}

i_{Load}

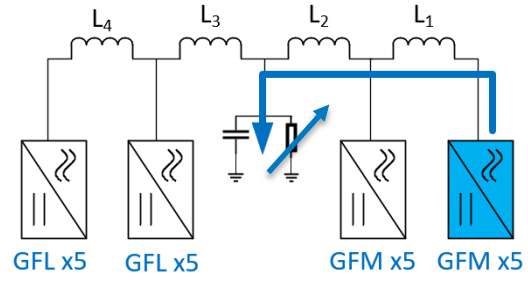
i_{L1}

i_{MI1}



- Successful Black Start by Grid Forming Inverters under 250W condition
  - ✓ Black Start
  - ✓ Dynamic Load Sharing

Demo: Step 2



V_{Load}

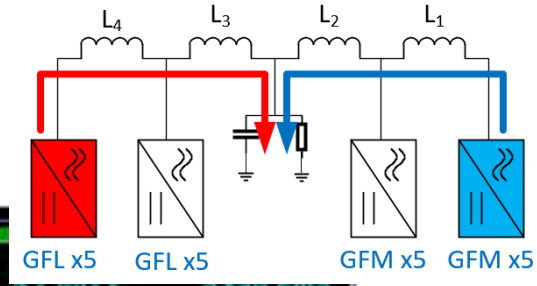
i_{Load}

i_{L1}

i_{L3}

- Load transient from 250W to 750W with five inverters sharing the load
  - ✓ Dynamic Load Sharing
  - ✓ Transient Voltage Regulation

Demo: Step 3

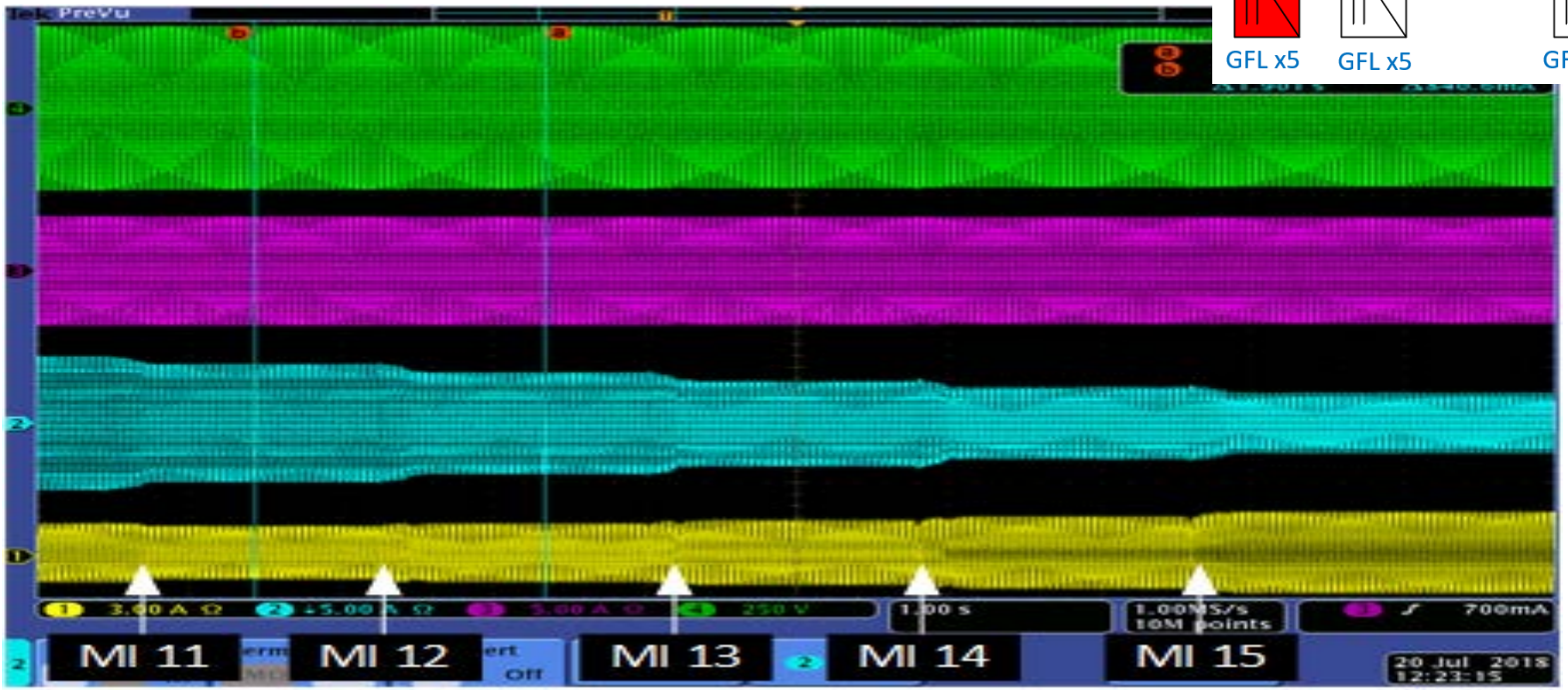


V_{Load}

i_{Load}

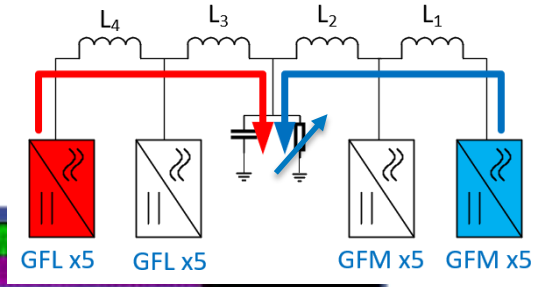
i_{L1}

i_{L3}



- 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

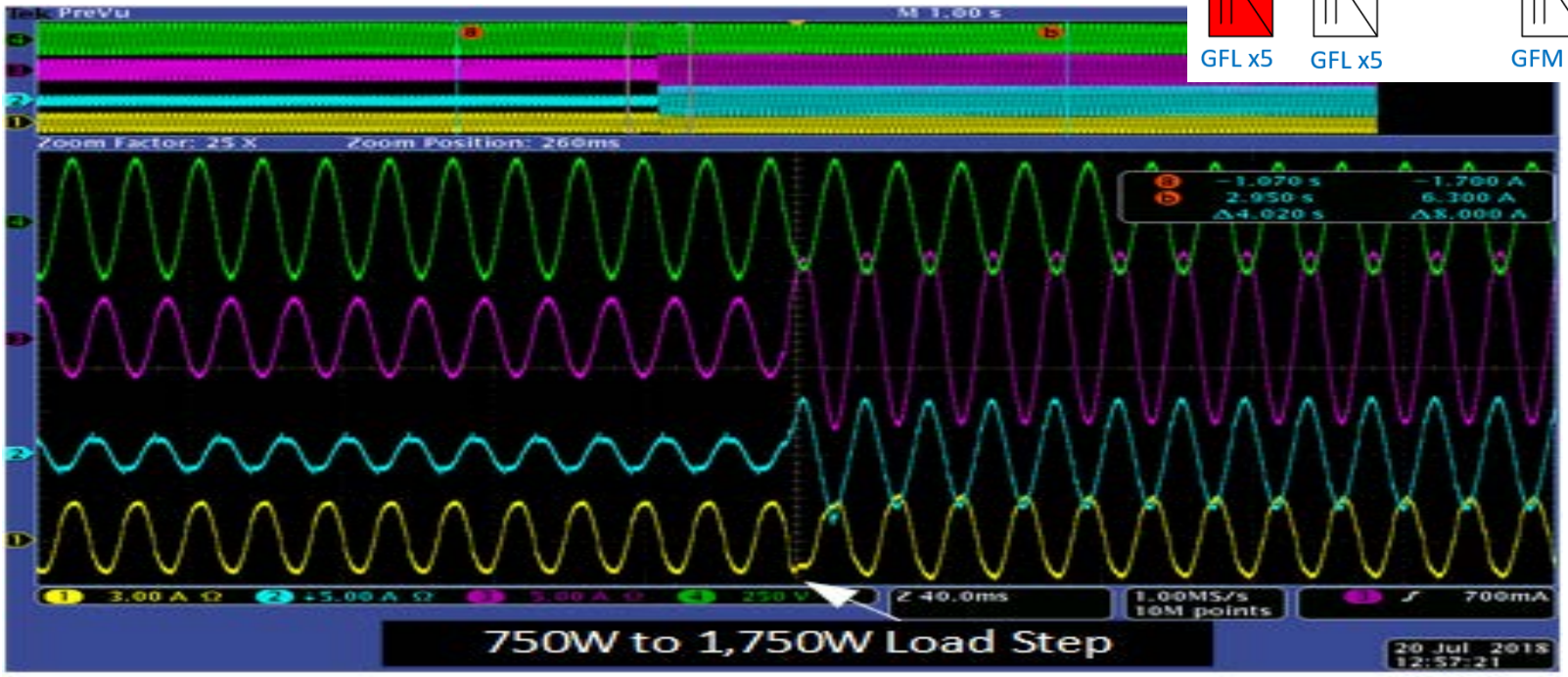


V_{Load}

i_{Load}

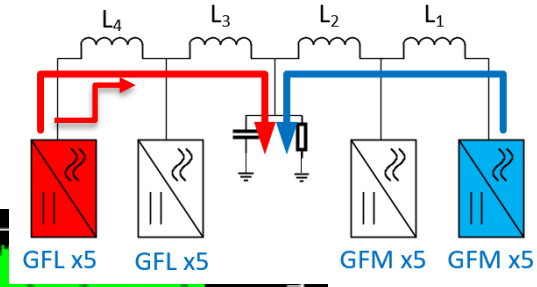
i_{L1}

i_{L3}



- 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

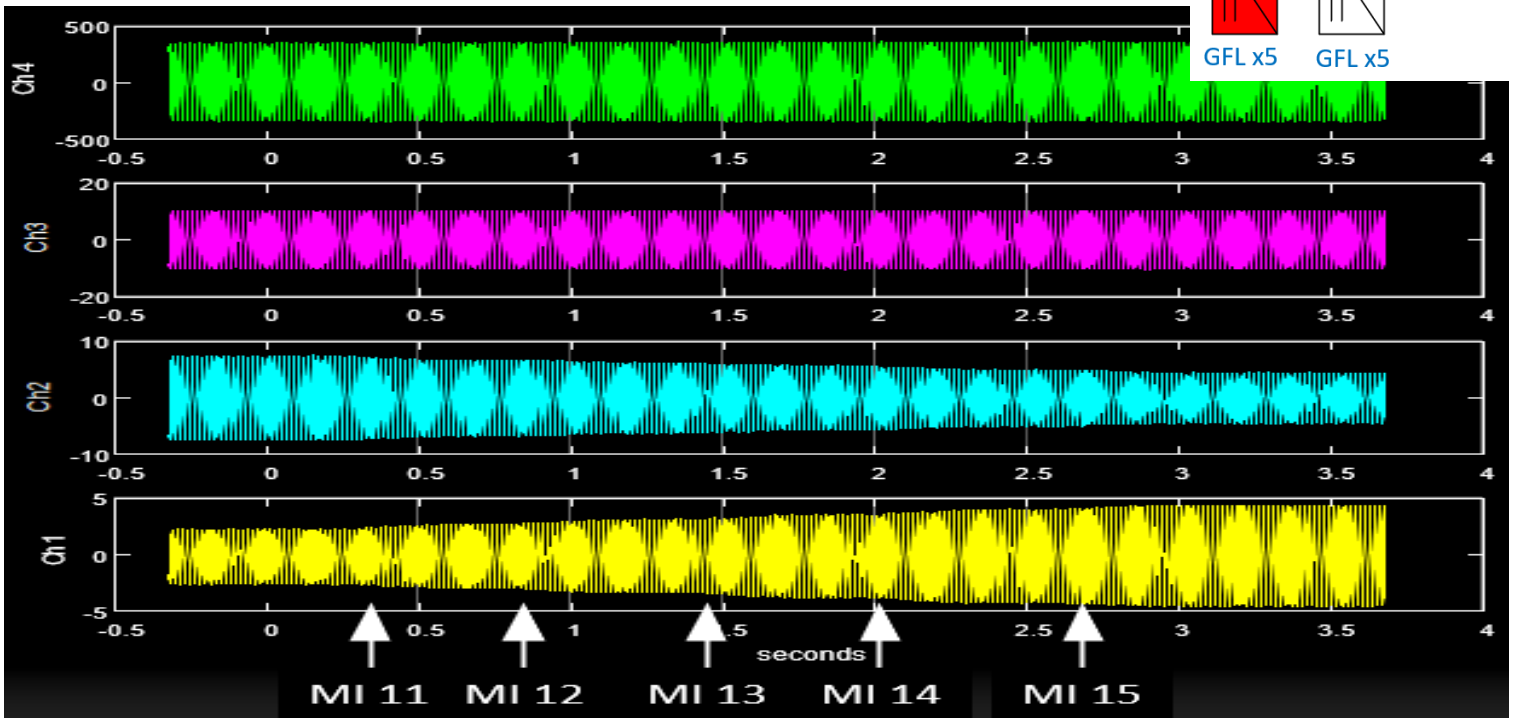


V_{Load}

i_{Load}

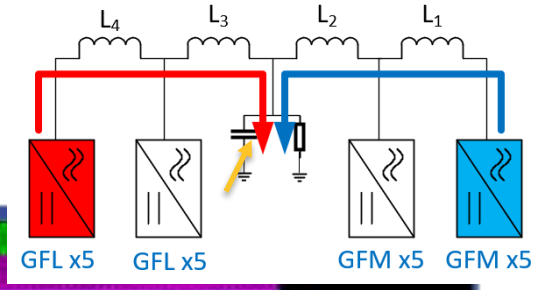
i_{L1}

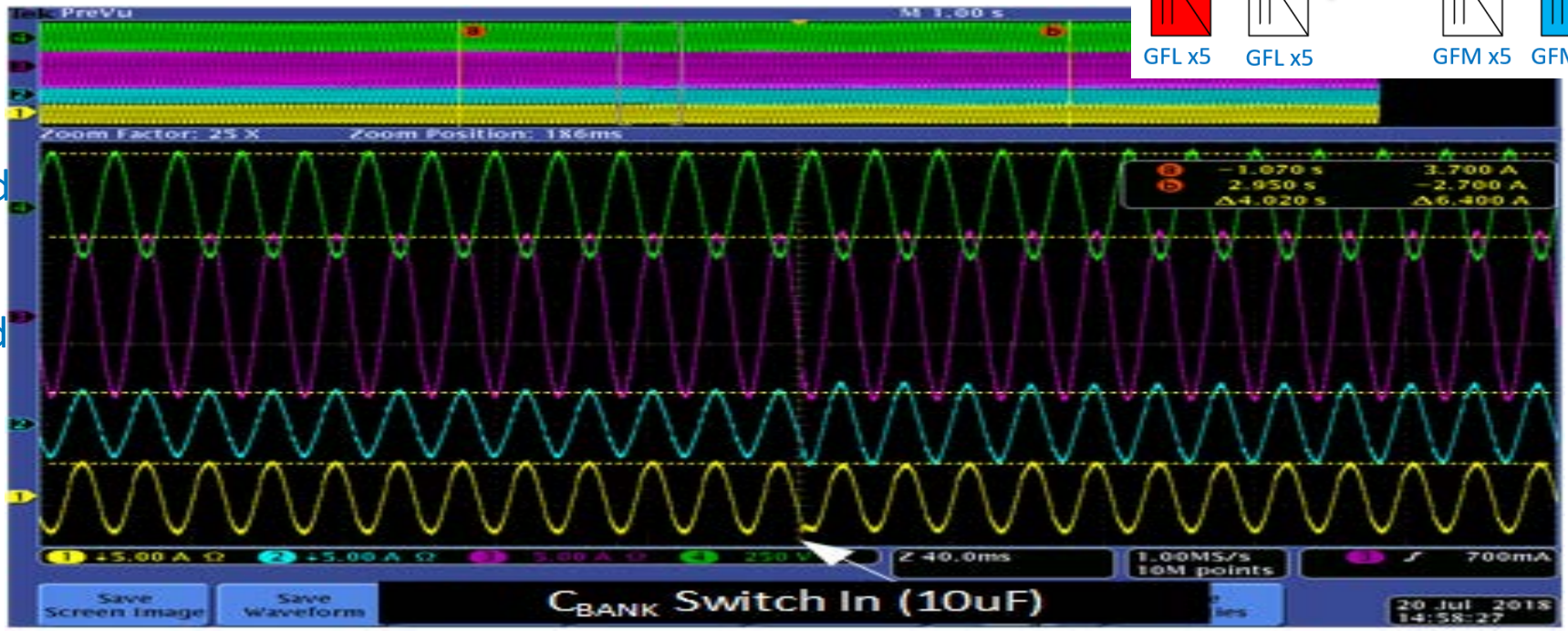
i_{L3}



- GFL Inverter Power Gen Increase to 200W
  - ✓ Grid Voltage Regulated by GFM MIs

Demo: Step 6





V_{Load}

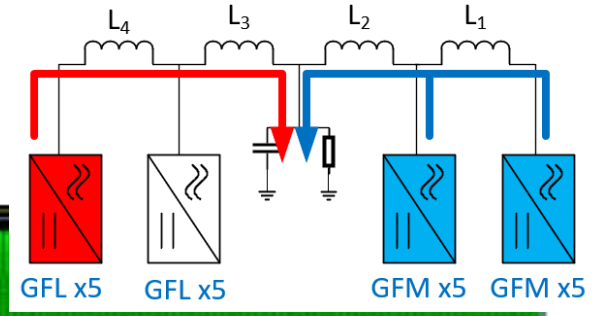
i_{Load}

i_{L1}

i_{L3}

- 10uF Capacitive Load Turn on (Load Voltage Compensation Simulation)
  - ✓ Reactive Power Transient Covered By GFM

Demo: Step 7

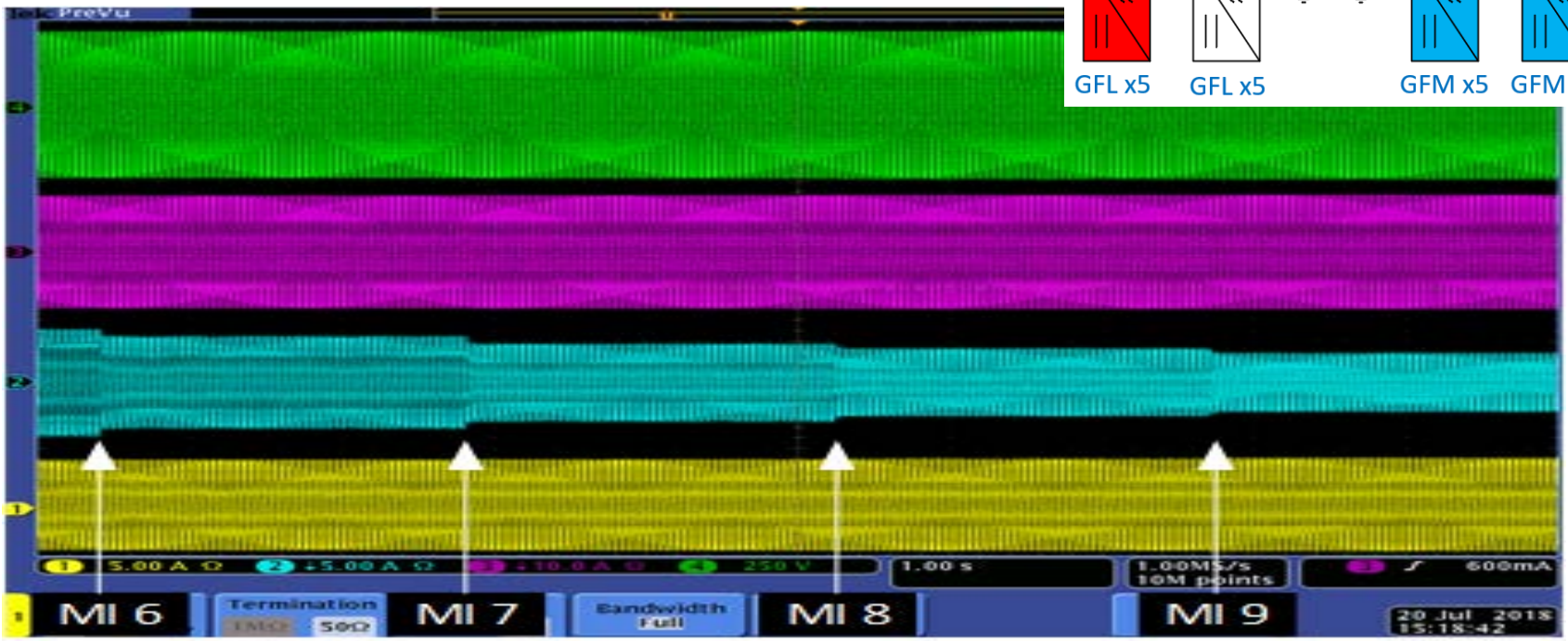


V_{Load}

i_{Load}

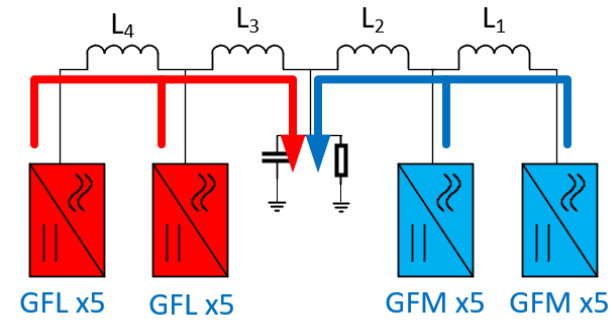
i_{L1}

i_{L2}



- GFM Inverters 6-10 Turned on to join
  - ✓ Successful Synchronization between GFM Inverters + Load Sharing

Demo: Step 8

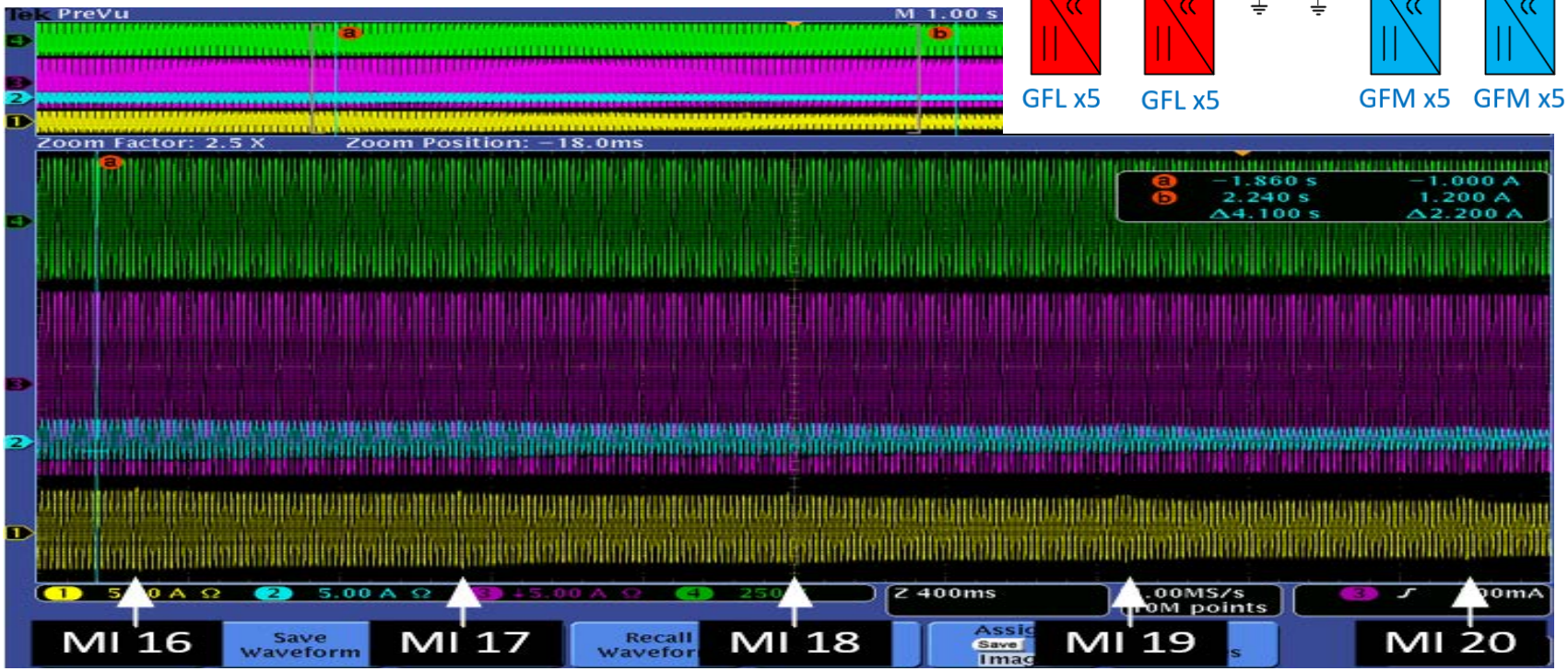


V_{Load}

i_{Load}

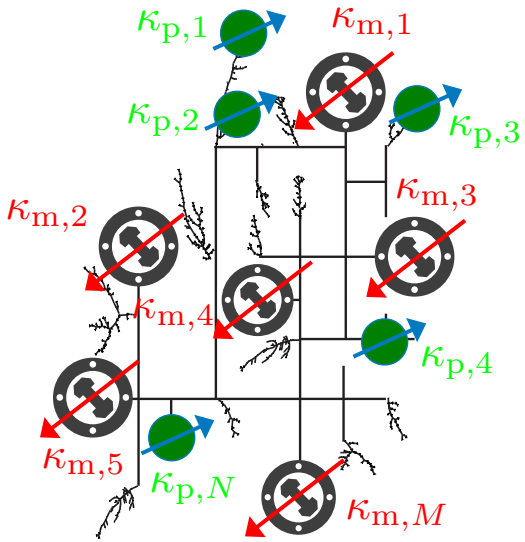
i_{L1}

i_{L2}



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

Framework for Multi-Machine Multi-Inverter System



Network algebra: $I = YV$

Machine & inverter dynamics: $\dot{x} = f(x, u)$

$$\text{inverter penetration} := \frac{\bar{P}_{\mathrm{i}}}{(\bar{P}_{\mathrm{i}} + \bar{P}_{\mathrm{m}})}$$

- Start with zero inverter penetration $\kappa_{\mathrm{m}} = \text{nominal}, \kappa_{\mathrm{p}} = 0$

1. Solve power flow to obtain machine/inverter terminal variables
2. Compute machine/inverter equilibrium states $\dot{x}^* = f(x^*, u) = 0$
   - Linearize, compute eigenvalues $\lambda \in \mathbb{C}^{|x|}$, assess stability
   - Increment κ_{p} or replace machine with inverter of equal rating