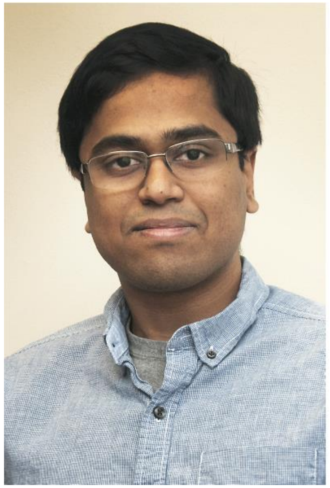
“Tipping Point” Analysis for Coupled Inverter-Machine Systems

Yashen Lin
National Renewable Energy Laboratory
PV Systems Symposium, May 16

Acknowledgement

Brian Johnson

Univ. of Washington



Sairaj Dhople

Univ. of Minnesota

Patrick Chapman

SunPower

Gabsu Seo

NREL

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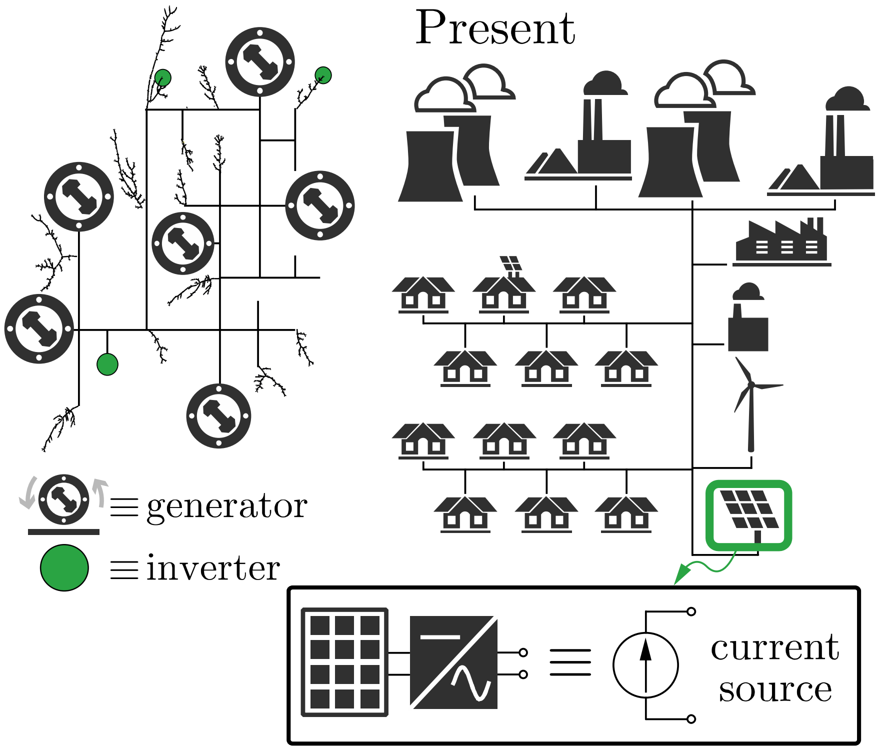
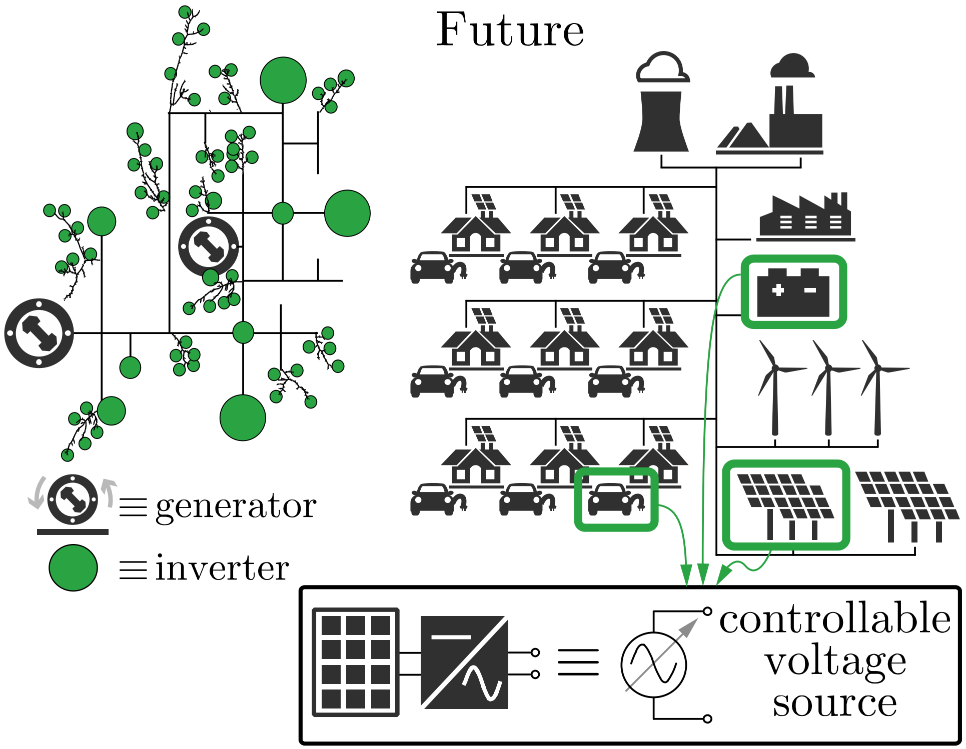
Motivation



Grid-following
controls

→



To next-generation
grid-forming controls

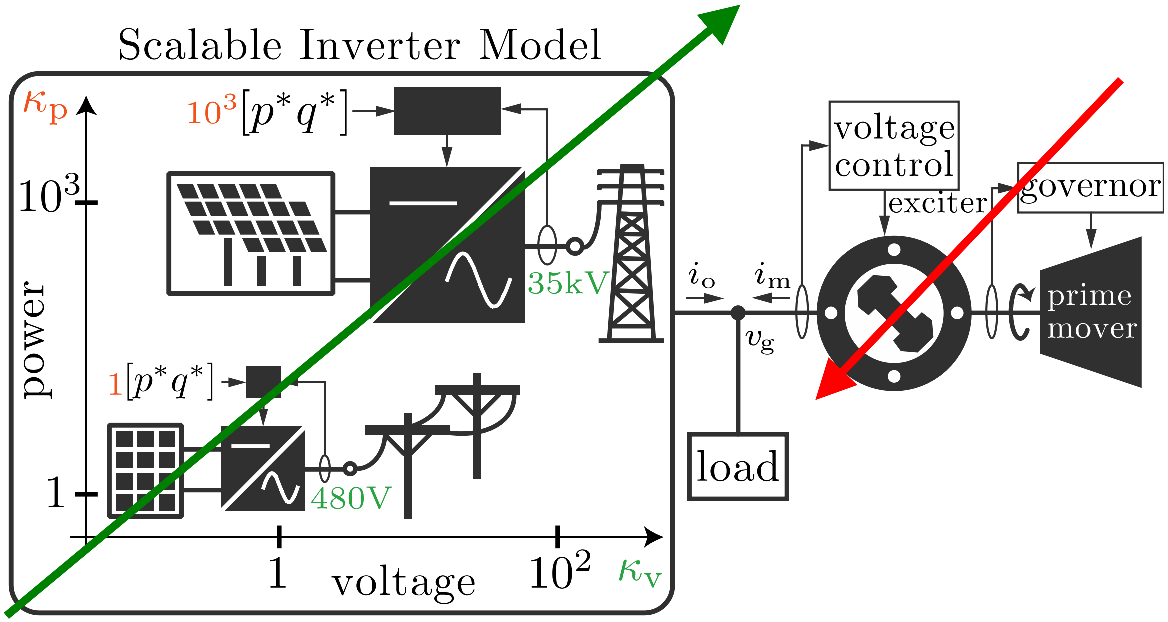
Content

1. "Tipping point" analysis
   - Small-signal stability of coupled inverter-machine systems

2. Inverter-dominant microgrid testbed
   - Grid-forming and grid-following

Tipping point analysis

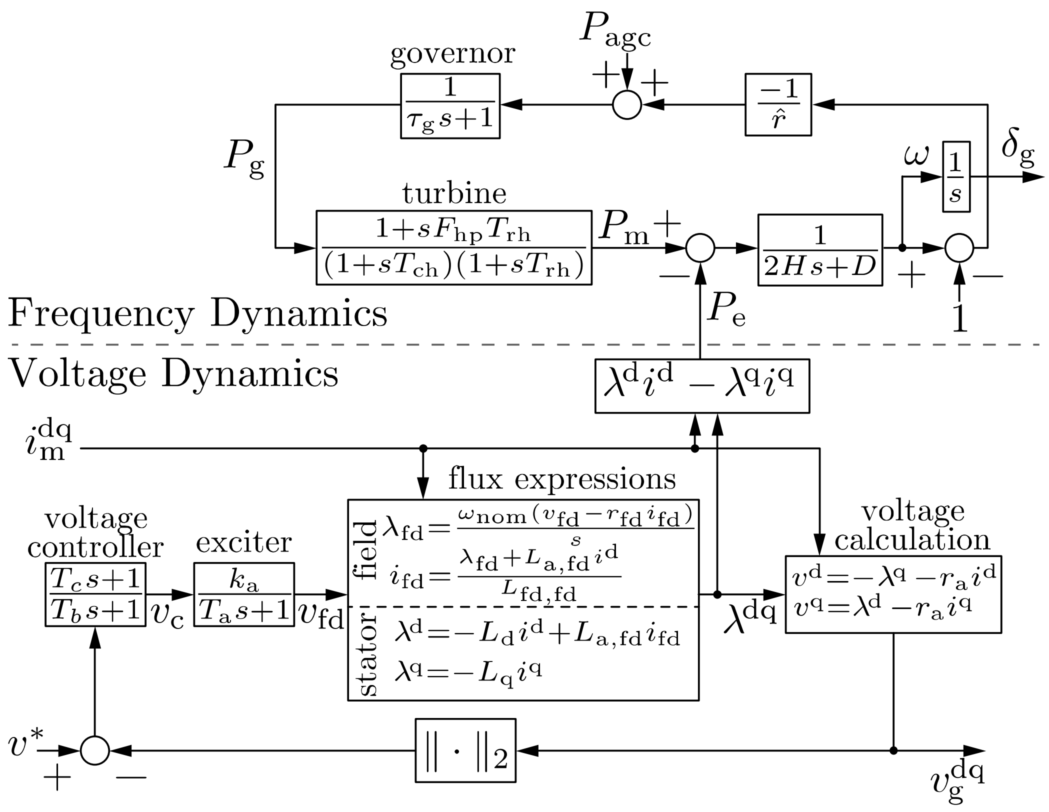
- **A fundamental question:** What happens as the ratio of inverter/machine ratings increases?
- A simple illustrative example system:



- Adjust the ratings of the inverter and machine to represent different inverter penetration level.

Model description: synchronous machine

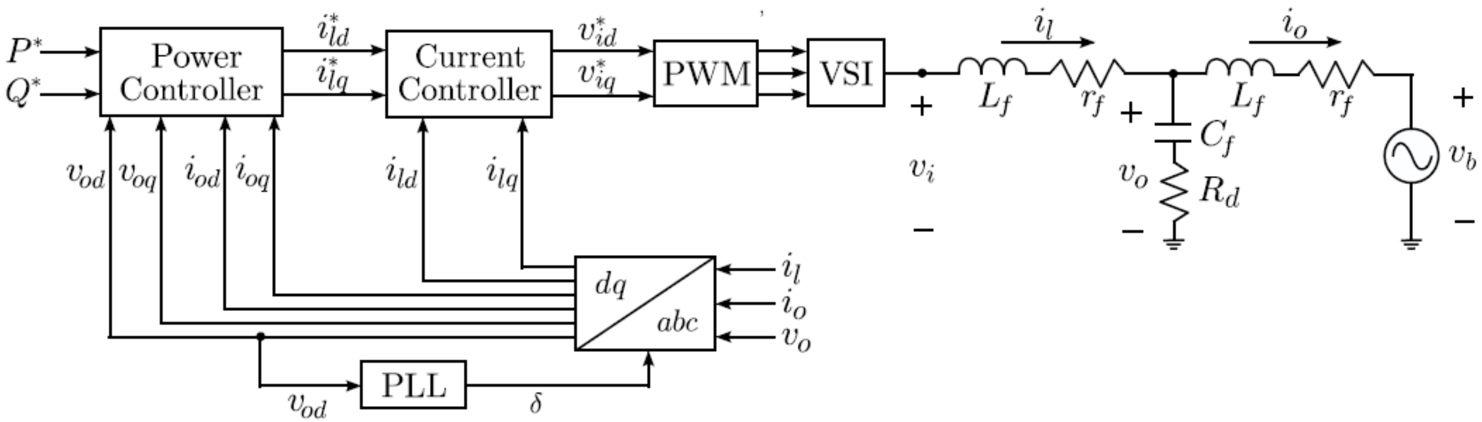
- Standard machine model [1]:



[1] Kundur, Prabha, Neal J. Balu, and Mark G. Lauby. Power system stability and control. Vol. 7. New York: McGraw-hill, 1994.

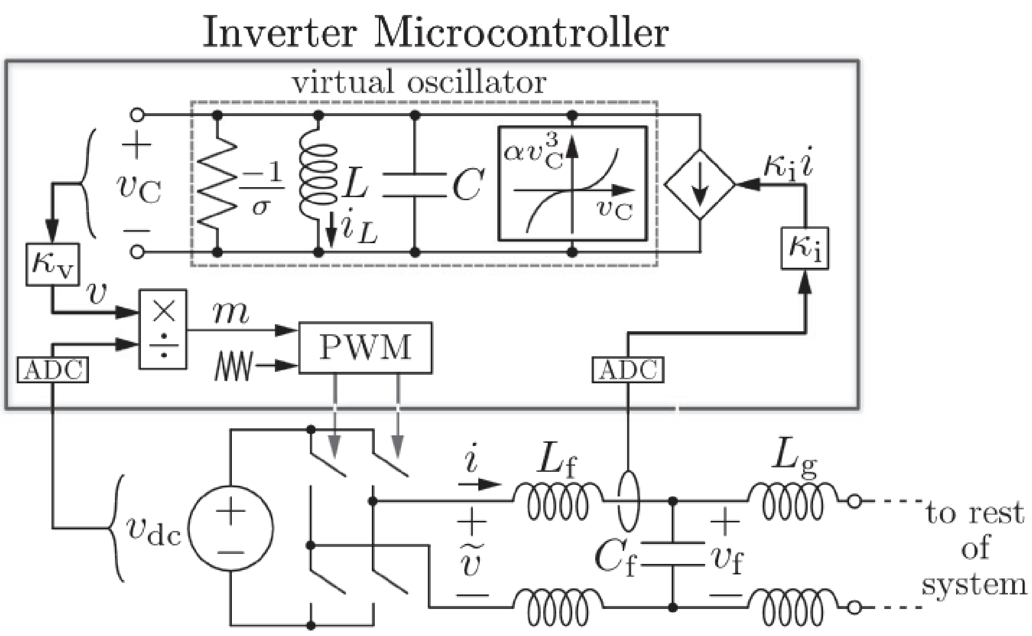
Model description: inverter

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



Grid-following inverter control

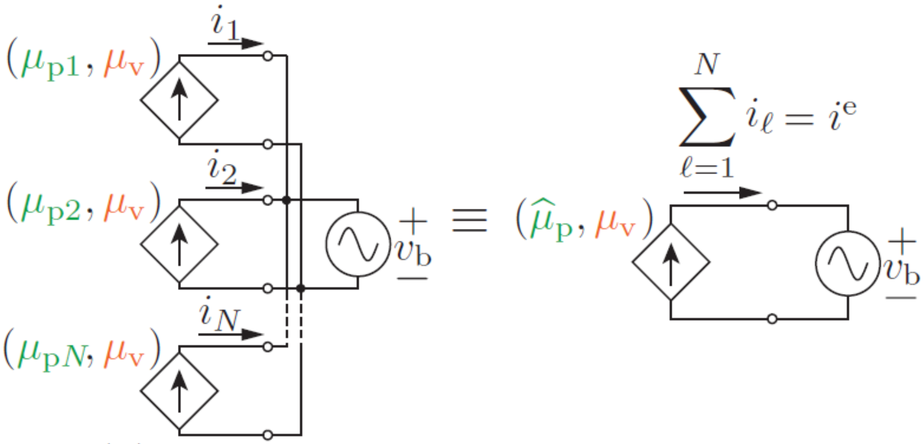
Model description: inverter



Grid-following inverter control: virtual oscillator controller (VOC)

Model aggregation

- 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.

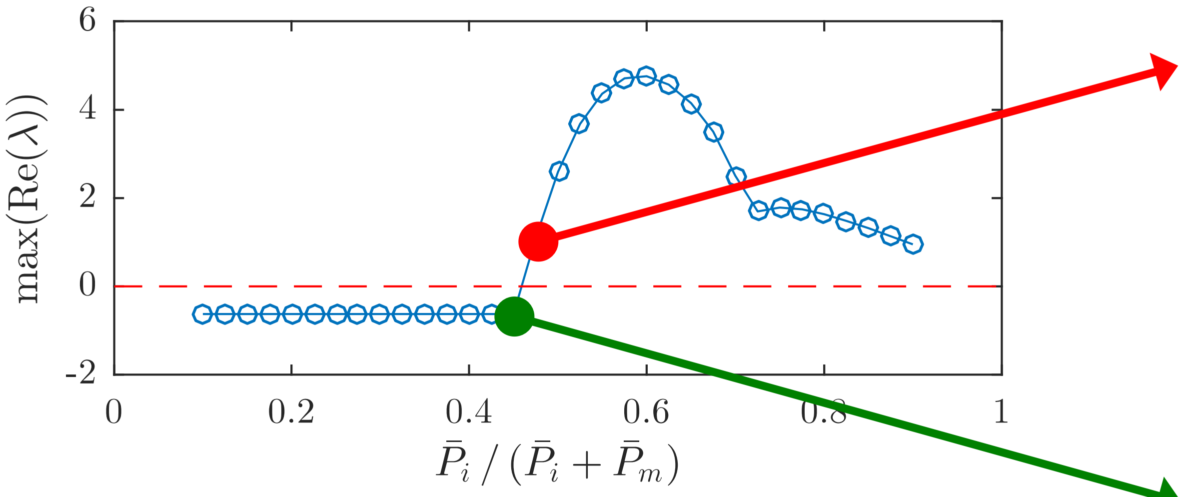


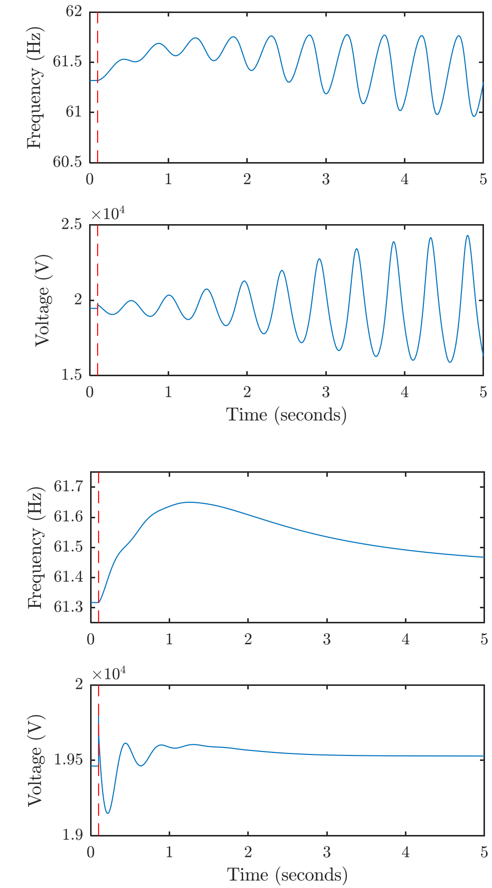
[1] Purba, Victor, et al. "Reduced-order Aggregate Model for Parallel-connected Single-phase Inverters." IEEE Transactions on Energy Conversion (2018).

[2] Khan, M. M. S., et al. "A Reduced-Order Aggregated Model for Parallel Inverter Systems with Virtual Oscillator Control." COMPEL 2018.

Results for grid-following case

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

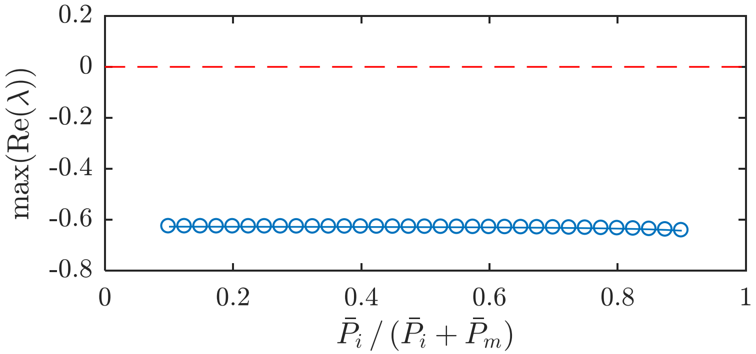




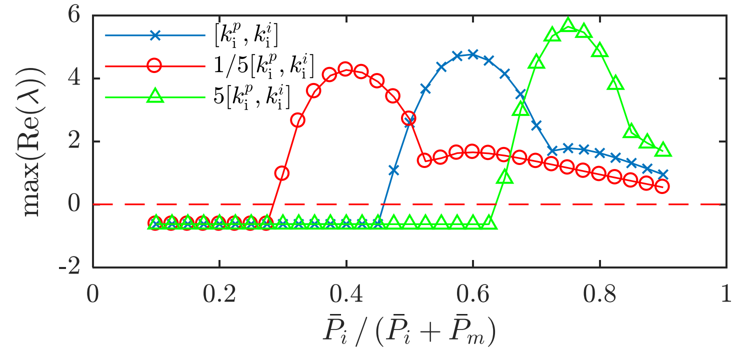
[1] Y. Lin, B. Johnson, V. Purba, S. Dhople, V. Gevorgian, “Stability Assessment of a System Comprising a Single Machine and Inverter with Scalable Ratings,” North American Power Symposium, 2017.

Sensitivity analysis

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



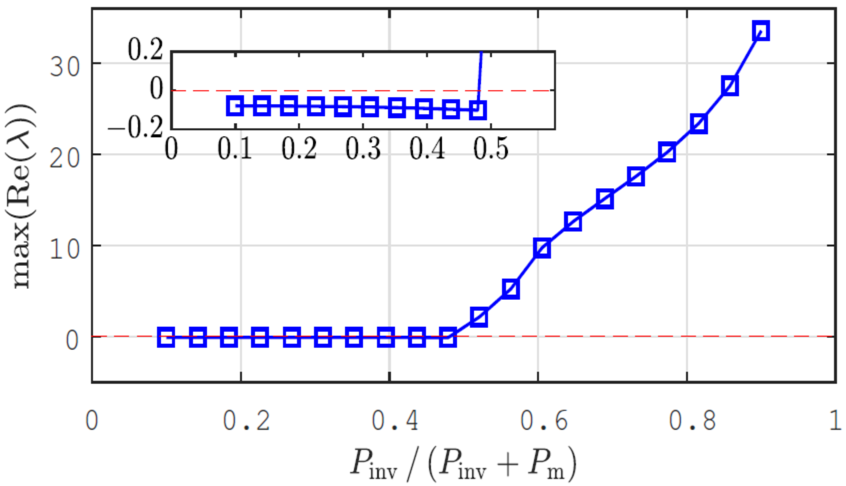
Bypass AVR and excitation



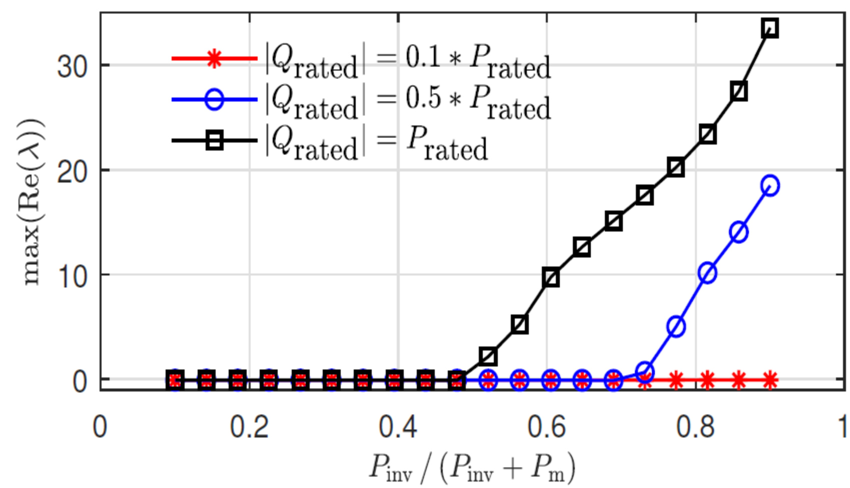
Different current controller gain

Results for grid-forming case

- 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



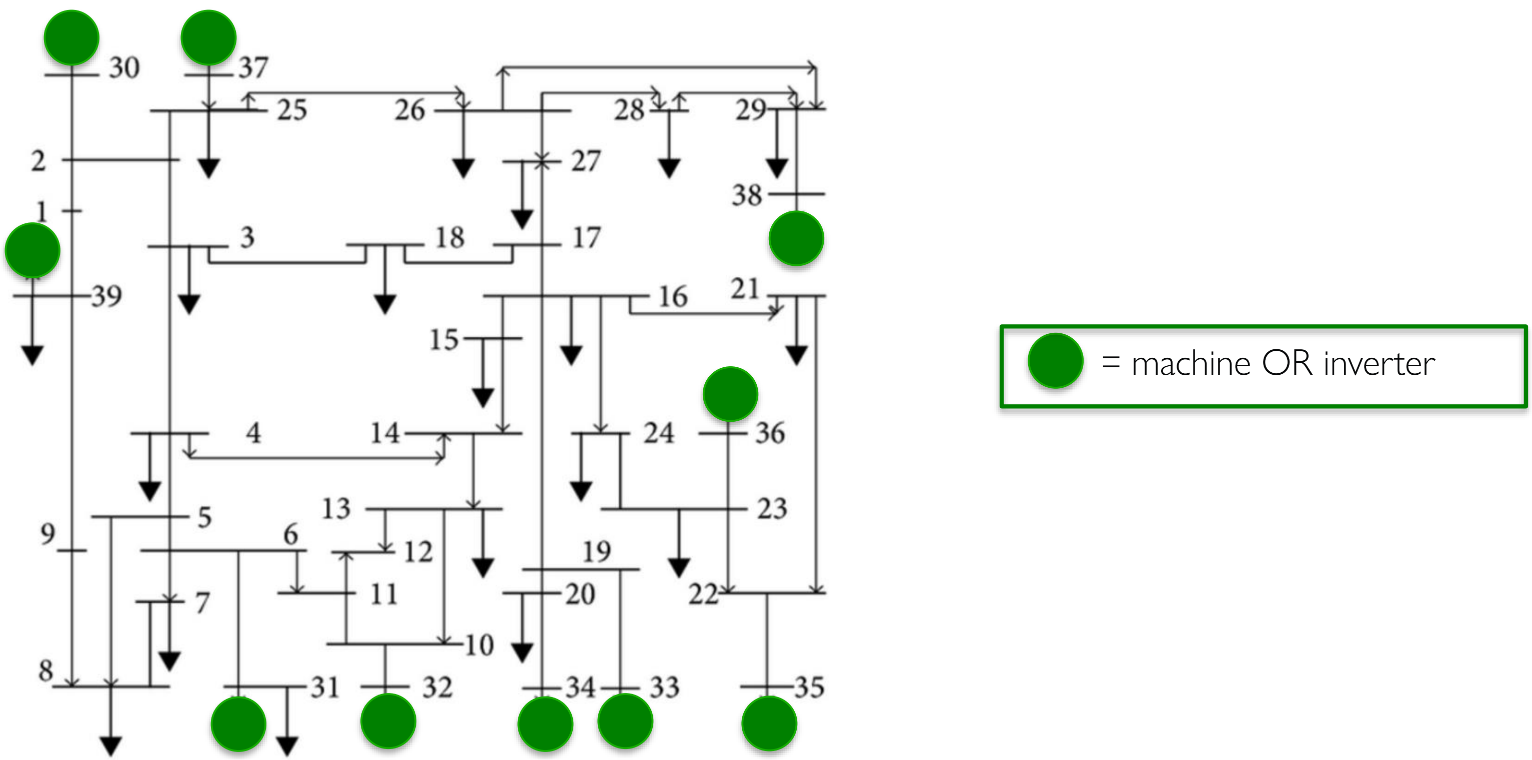
Default case



Different reactive droop slope

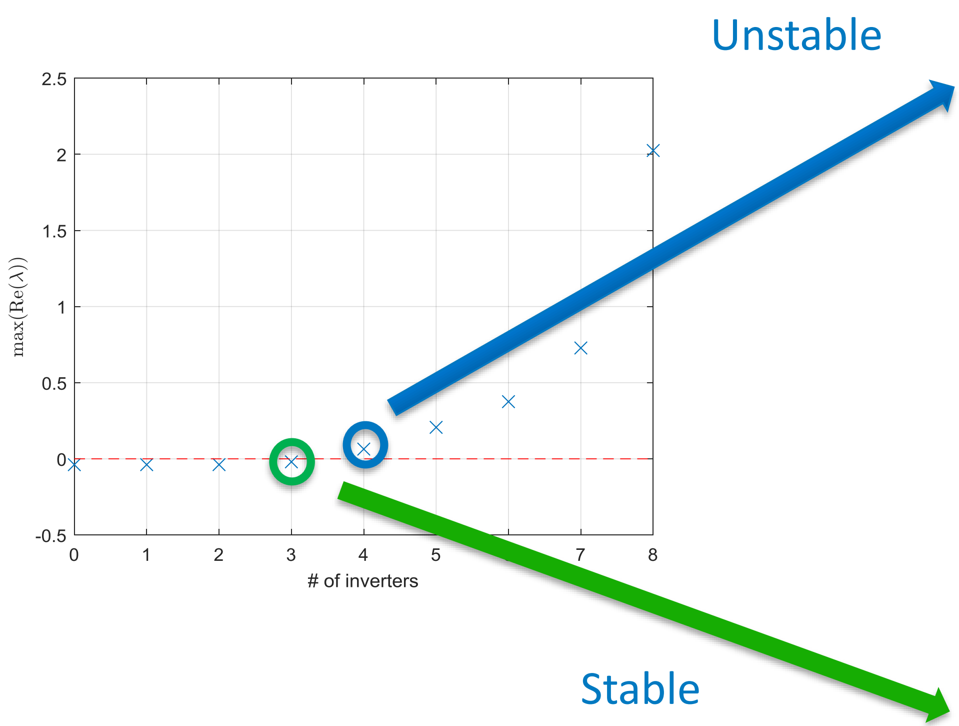
Multi-machine multi-inverter case

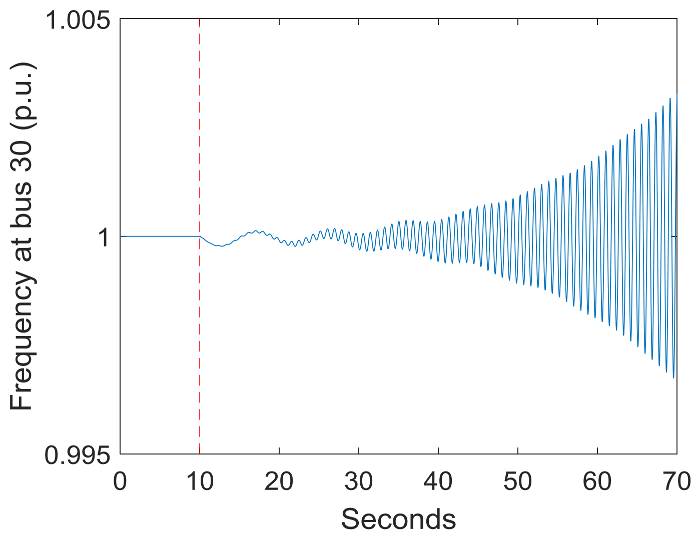
- IEEE 39-bus test system resembles the New England system.
- There are 10 generator/inverter buses.
- Approach: Sweep penetration level by replacing machine one-at-a-time with inverter of identical rating.

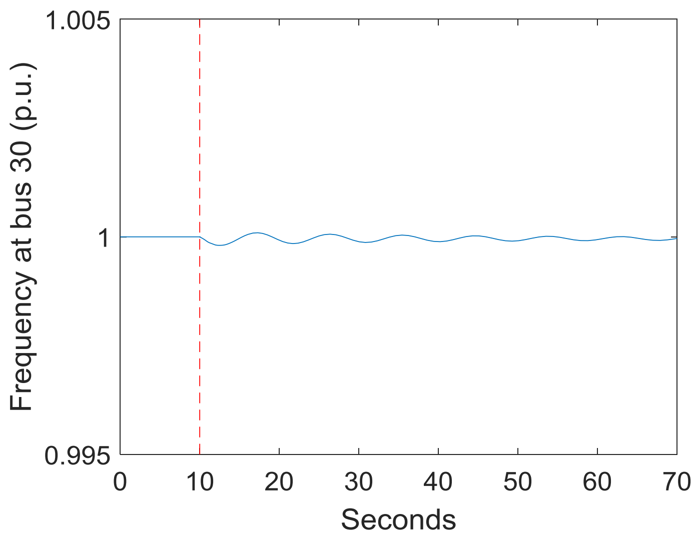


Multi-machine multi-inverter case

- 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.

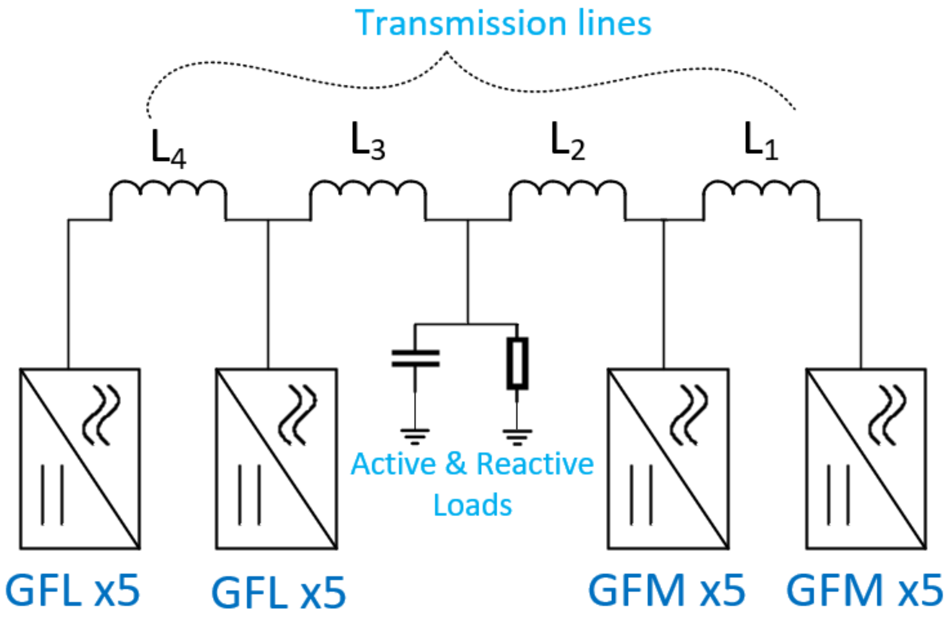
- The “tipping point” where the system becomes unstable depends on system parameters.

- Grid-forming inverter can potentially improve the stability of the system.

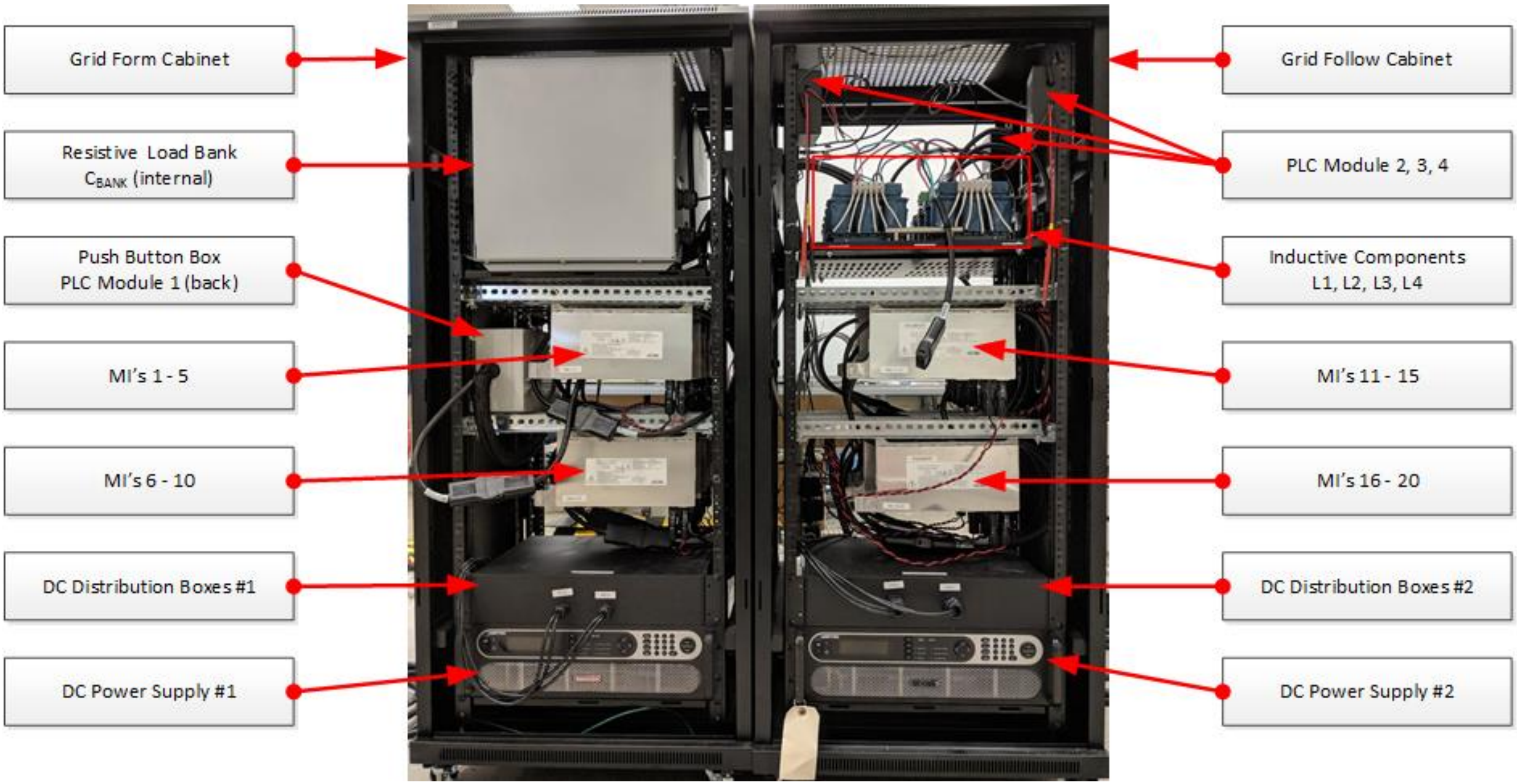
Inverter-dominant microgrid testbed

Inverter-dominant microgrid testbed

- Micro-inverter from SunPower (320 W, 240 Vrms)
- 10 grid-forming inverter + 10 Grid-following controlled inverter



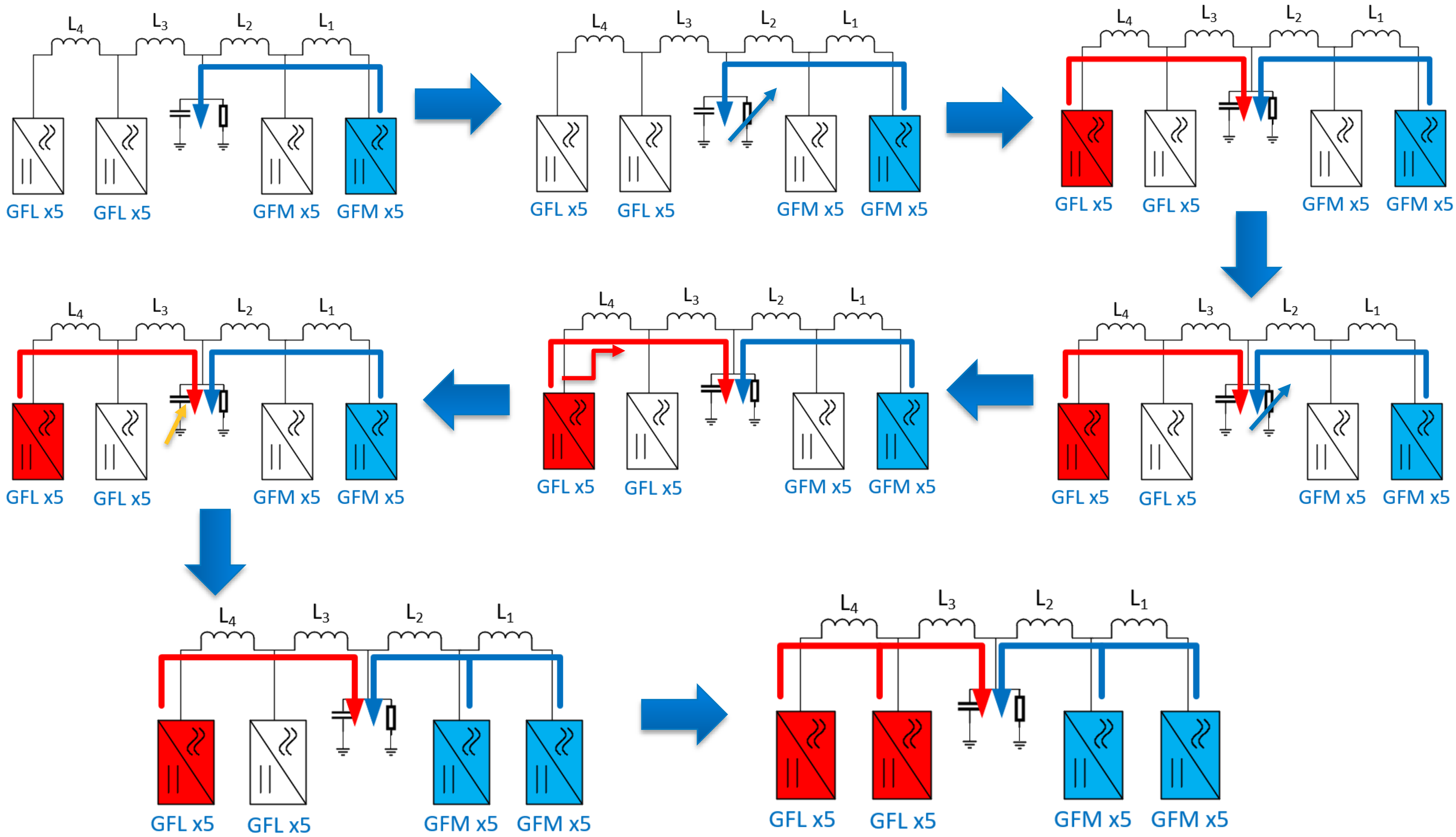
Inverter-dominant microgrid testbed



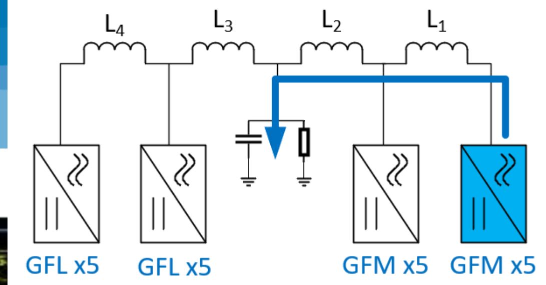
Test procedure

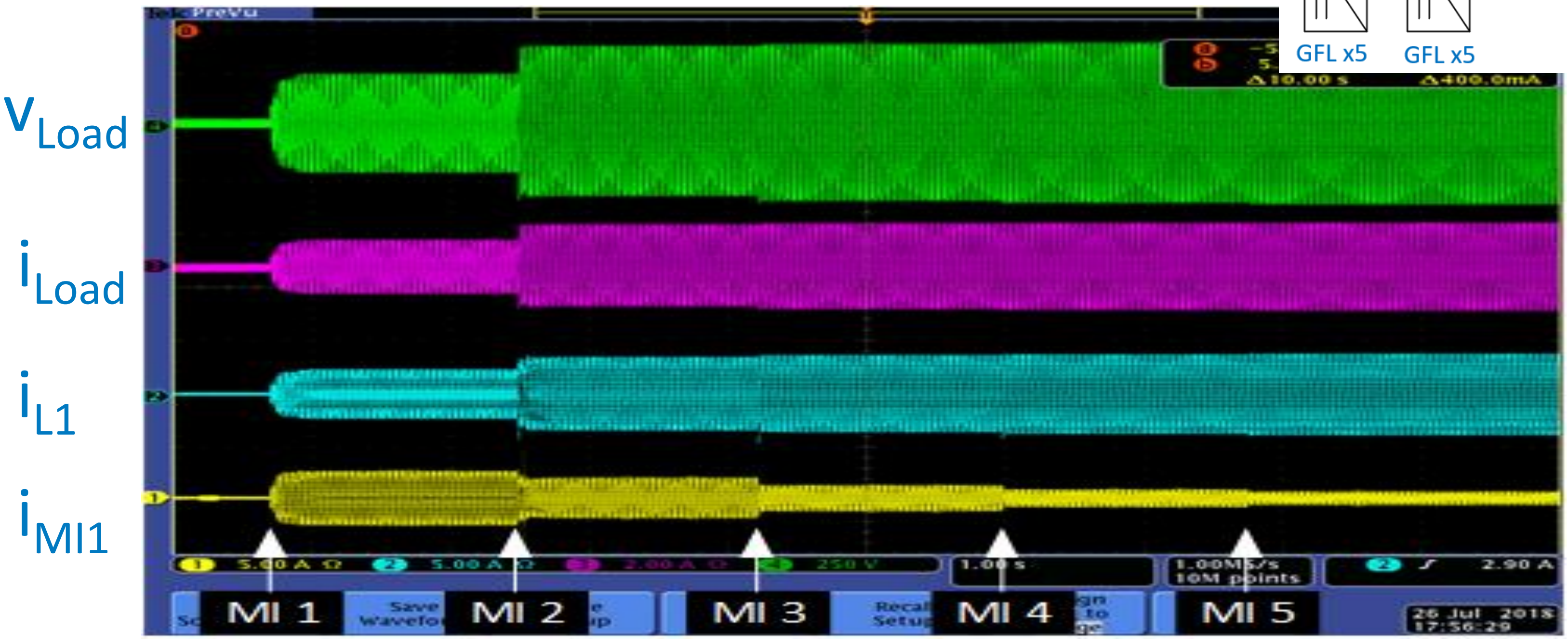
- Demonstrate feasibility of heterogeneous system with VOC & Grid-following inverters:
  - Black start with VOC inverters and load sharing
  - Cooperation with grid-following inverters
  - Load transients: resistive load and reactive load

Test procedure



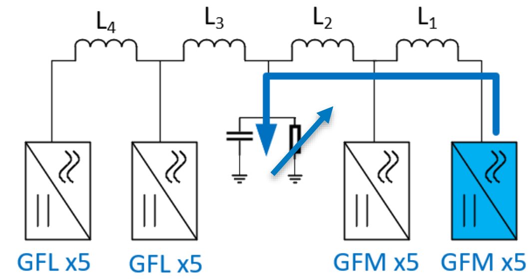
Step 1: black start

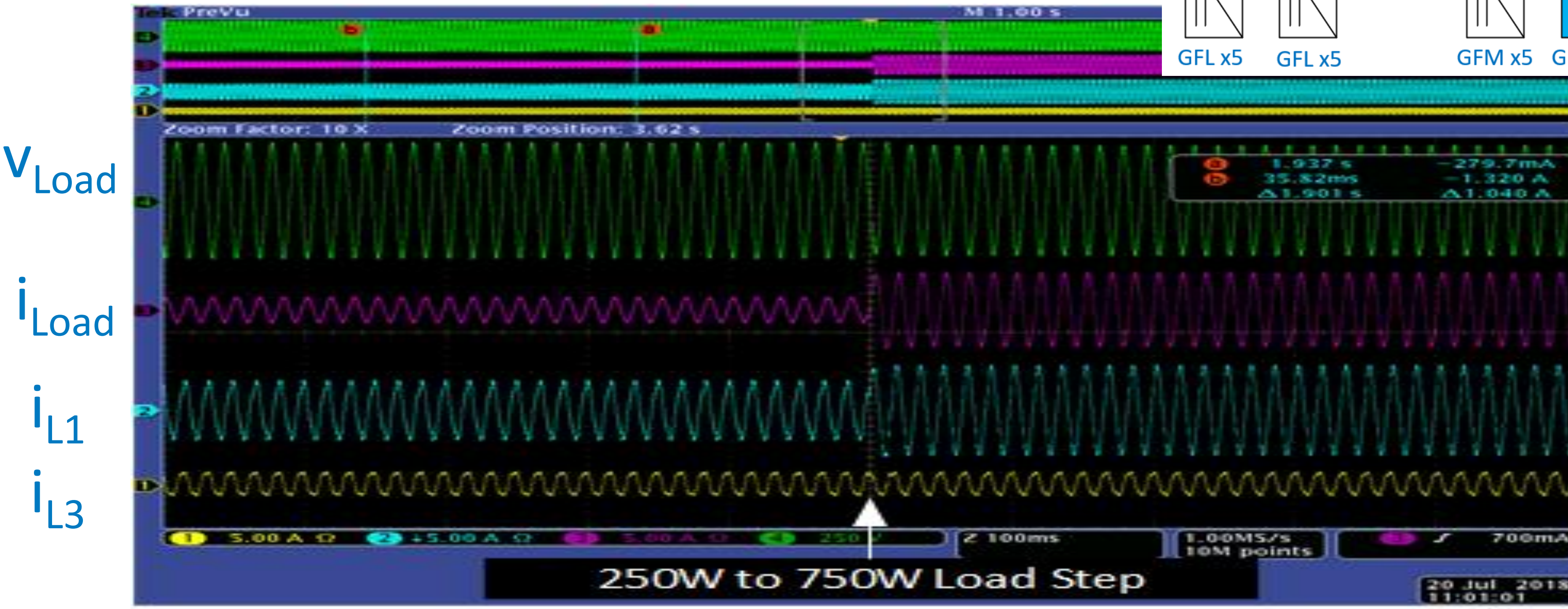




- Successful Black Start by Grid Forming Inverters under 250W condition
  - Black Start
  - Dynamic Load Sharing

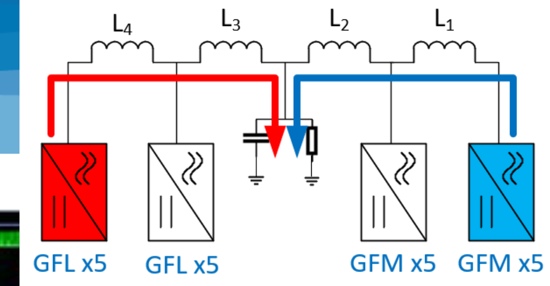
Step 2: load step change

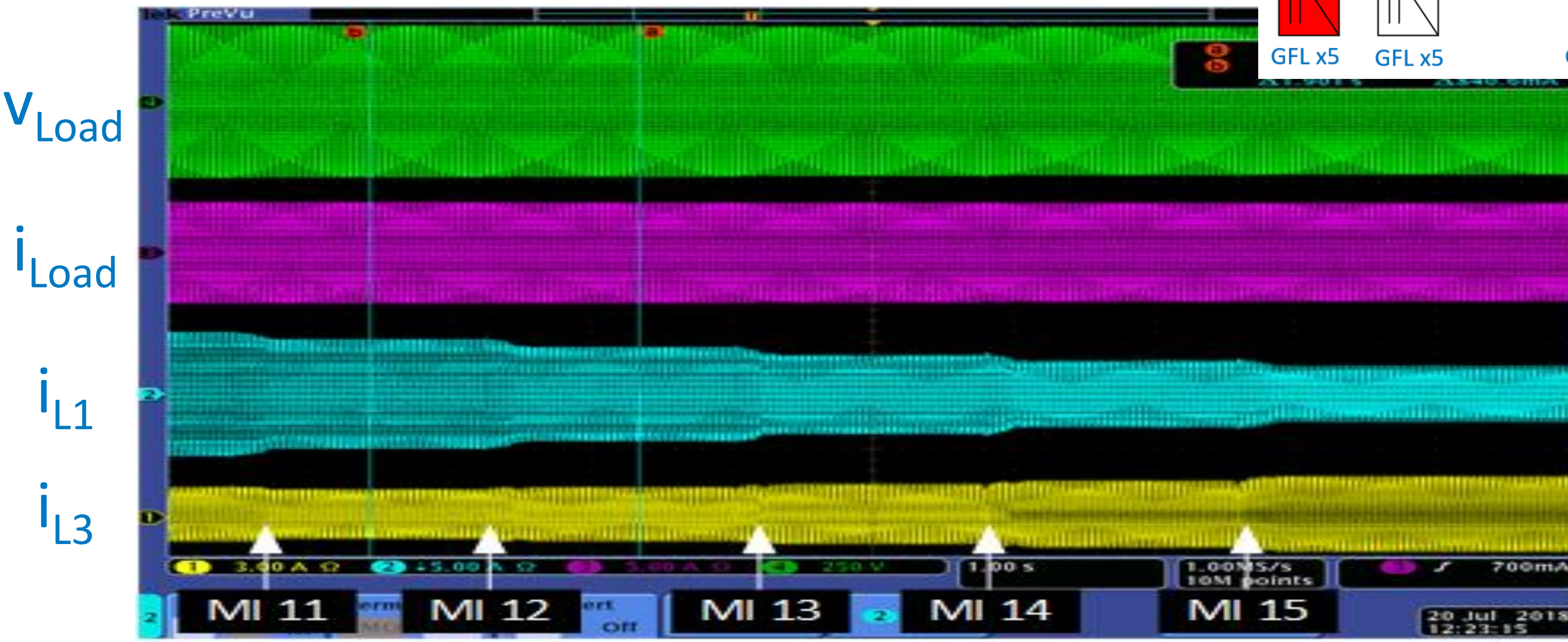




- Load transient from 250W to 750W with five inverters sharing the load
  - Dynamic Load Sharing
  - Transient Voltage Regulation

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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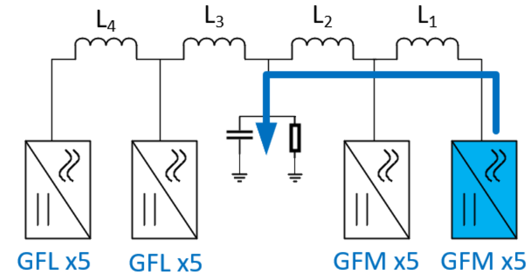
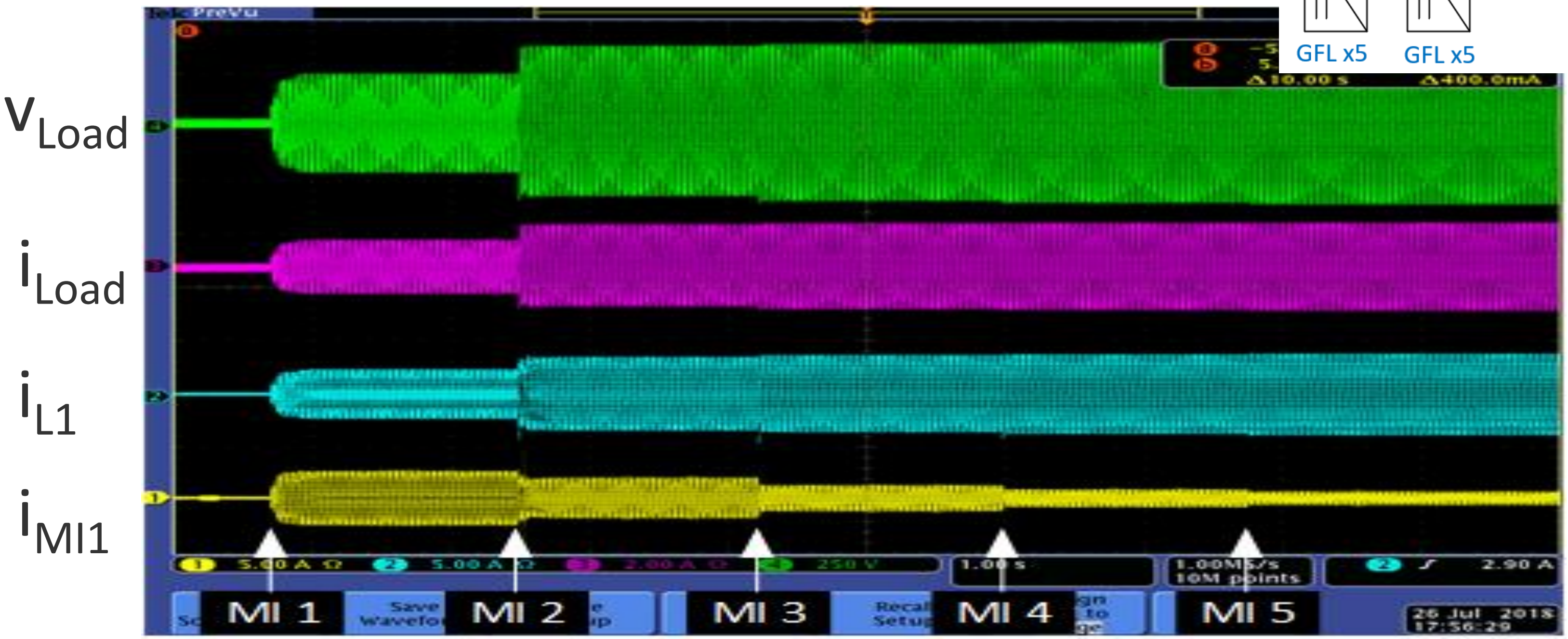
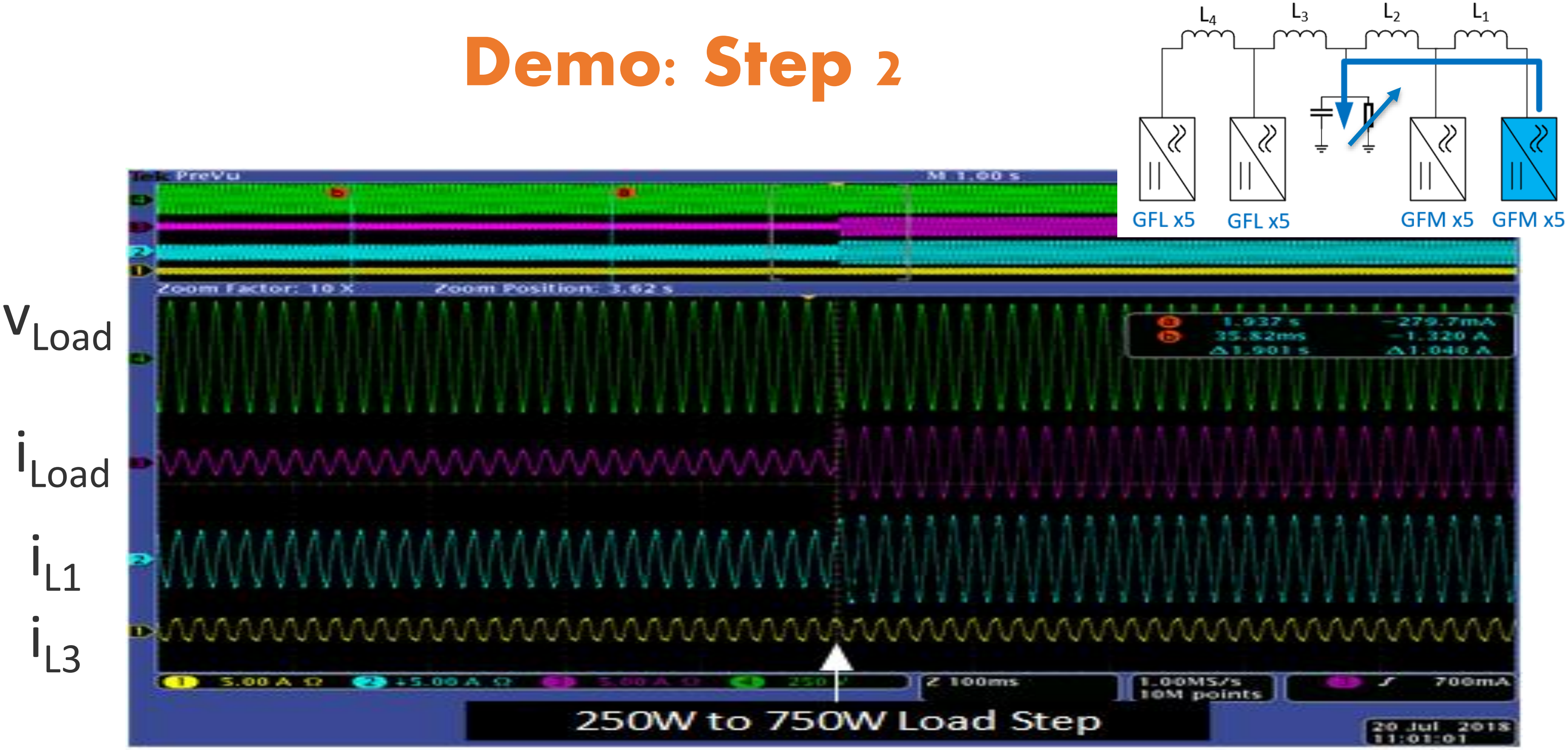
Demo: Step 1





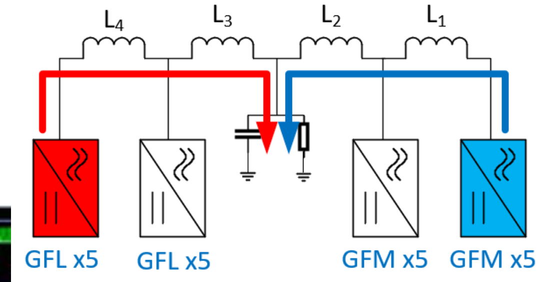
- Successful Black Start by Grid Forming Inverters under 250W condition
  - ✓ Black Start
  - ✓ Dynamic Load Sharing

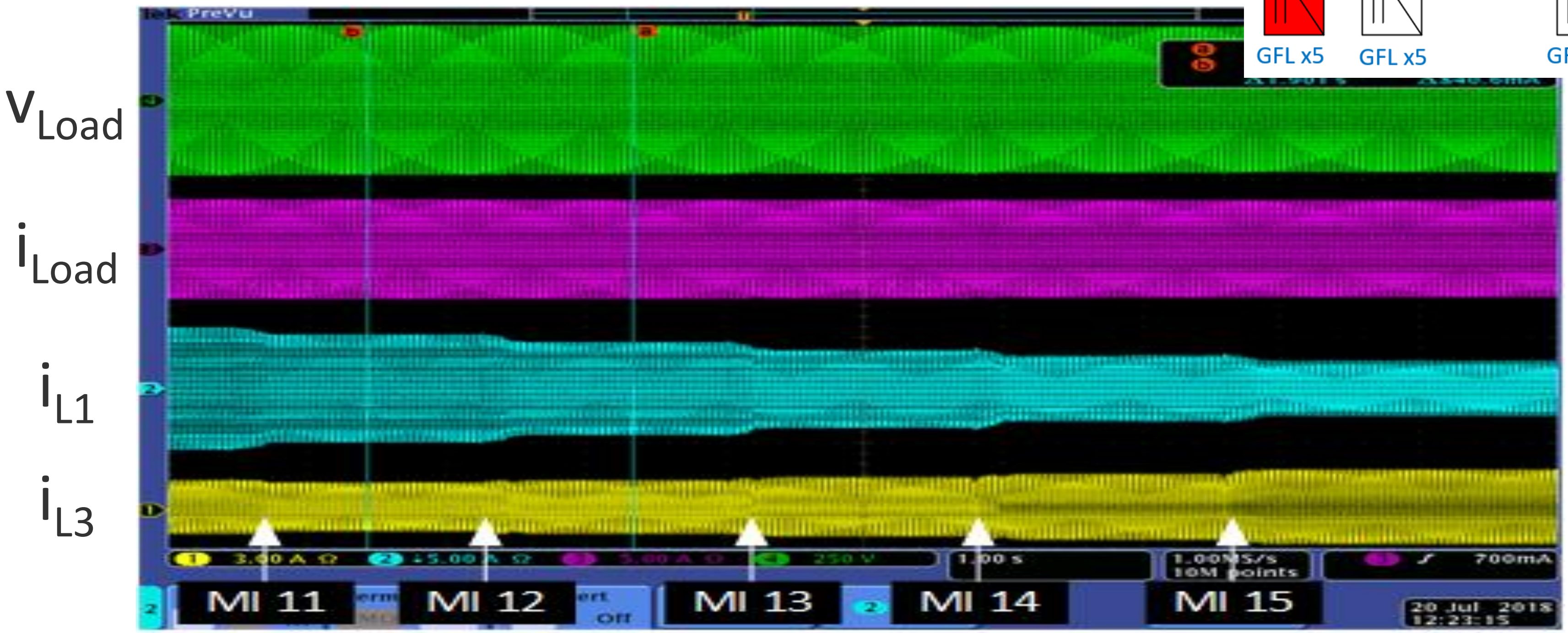
Demo: Step 2



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

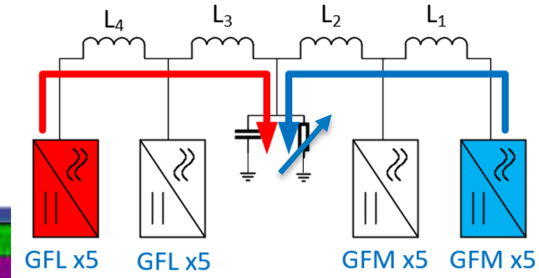
Demo: Step 3





- 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

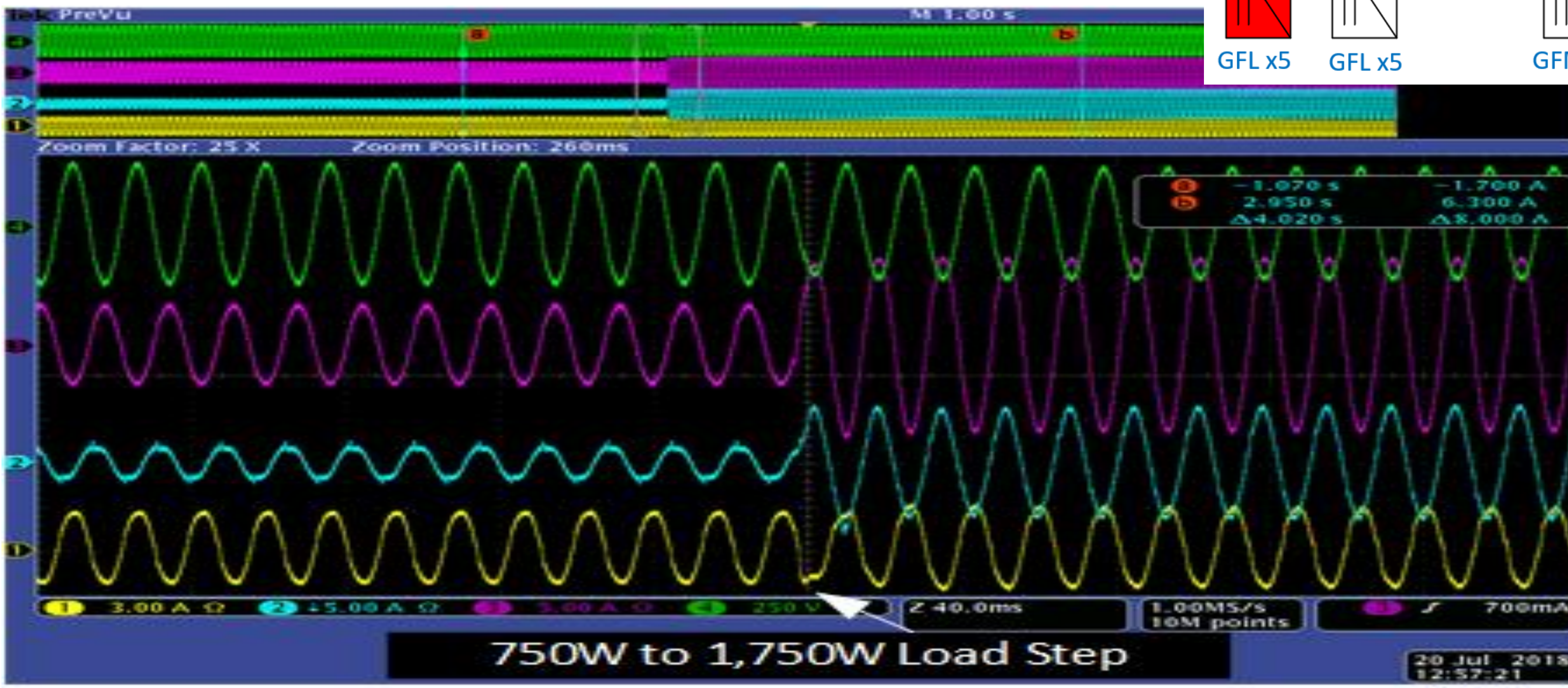


V_{Load}

i_{Load}

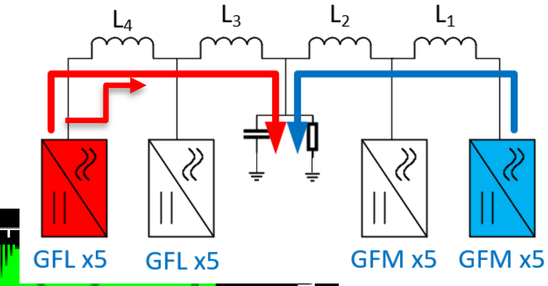
i_{L1}

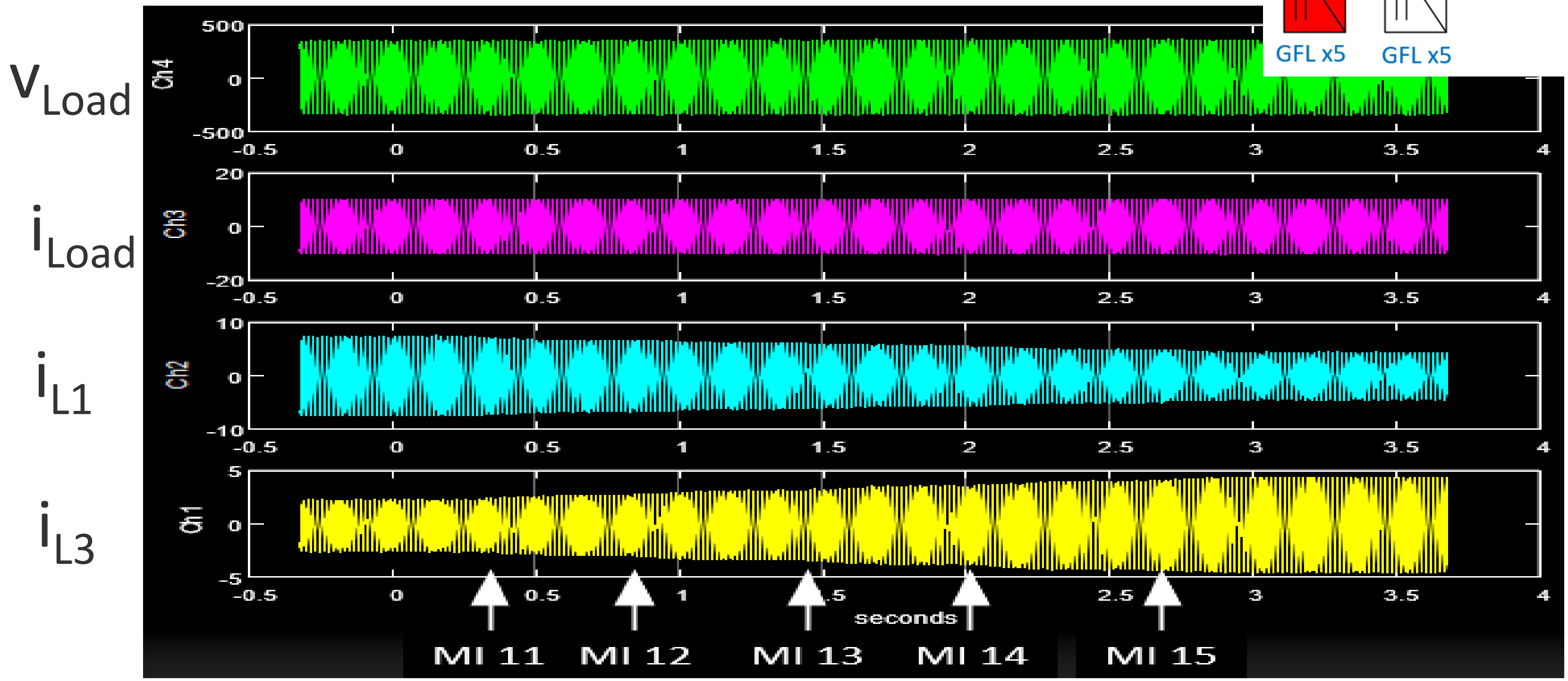
i_{L3}



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

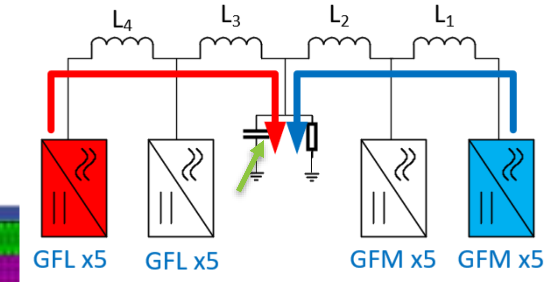
Demo: Step 5

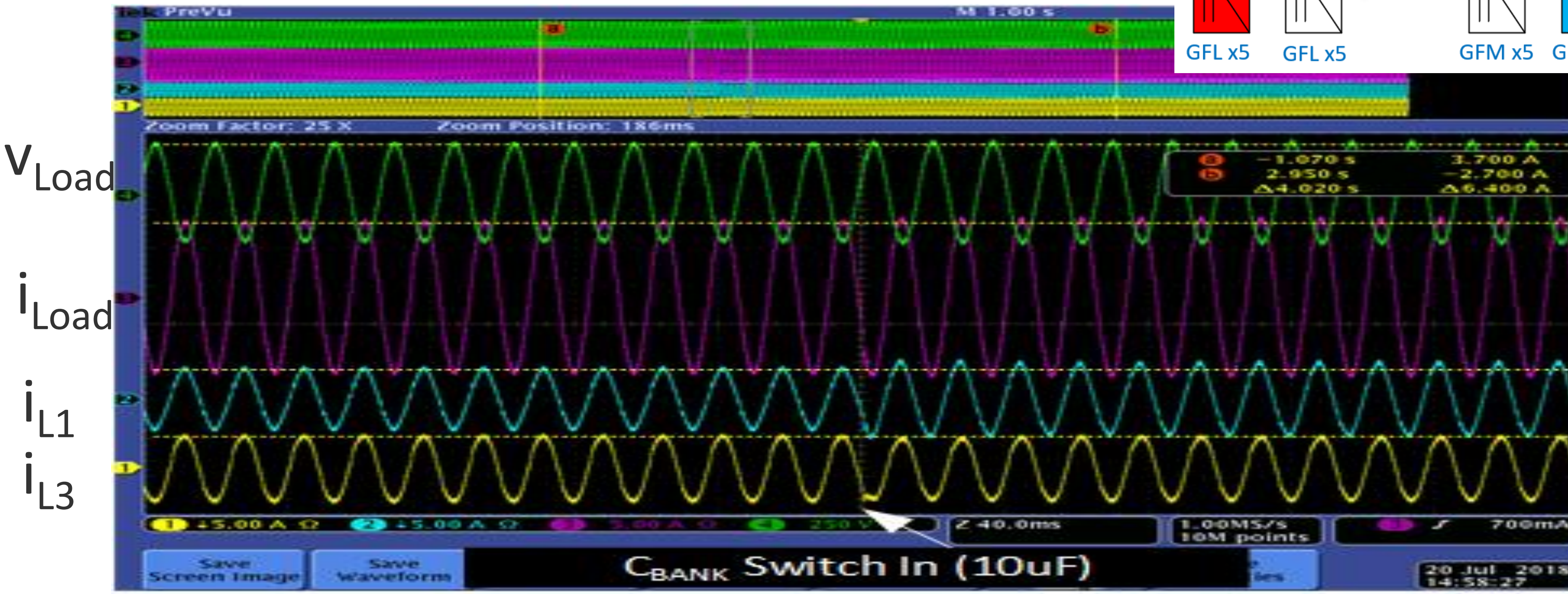




- GFL Inverter Power Gen Increase to 200W
  - ✓ Grid Voltage Regulated by GFM MIs

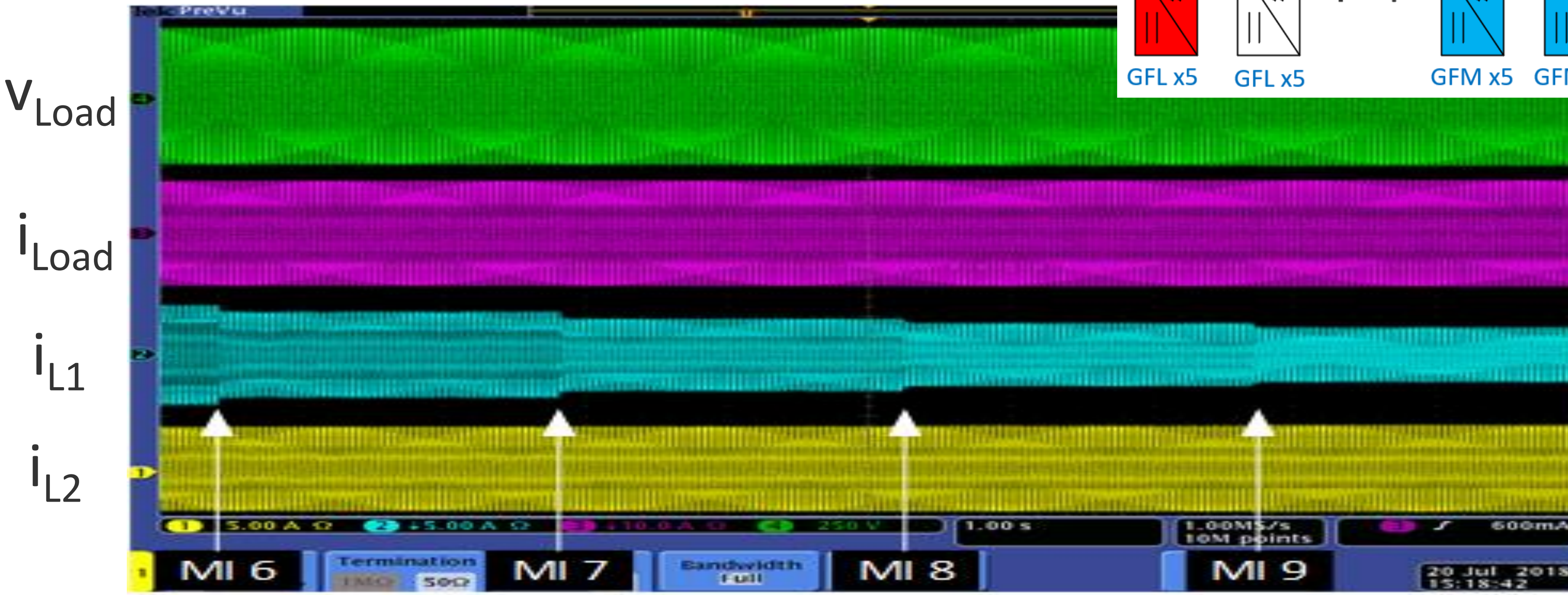
Demo: Step 6

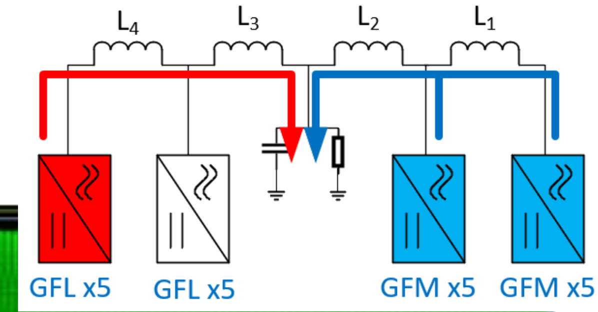




- 10uF Capacitive Load Turn on (Load Voltage Compensation Simulation)
  - ✓ Reactive Power Transient Covered By GFM

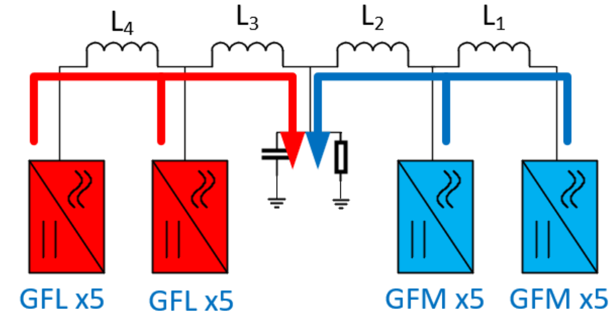
Demo: Step 7

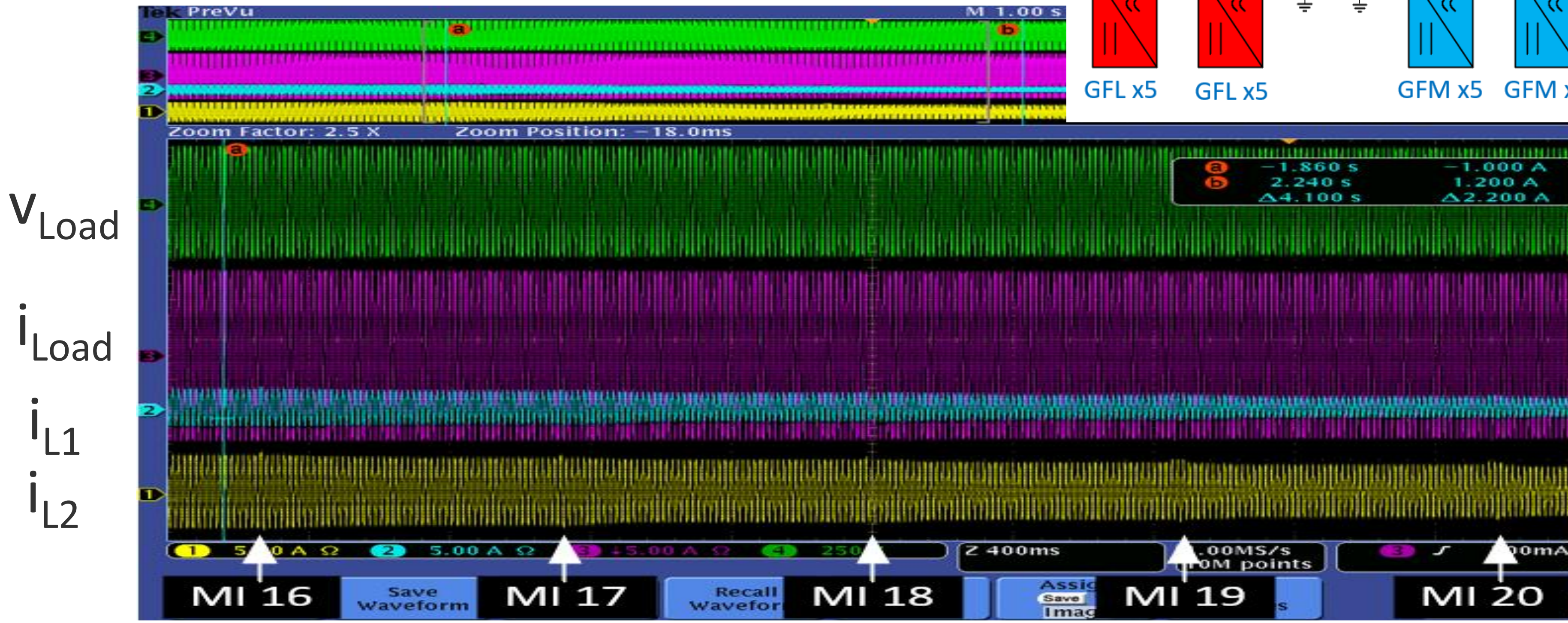




- GFM Inverters 6-10 Turned on to join
  - ✓ Successful Synchronization between GFM Inverters + Load Sharing

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.