NC STATE UNIVERSITY

FREEDM SYSTEMS CENTER

Research Symposium 2023

Interoperability for Grid -Forming Inverters

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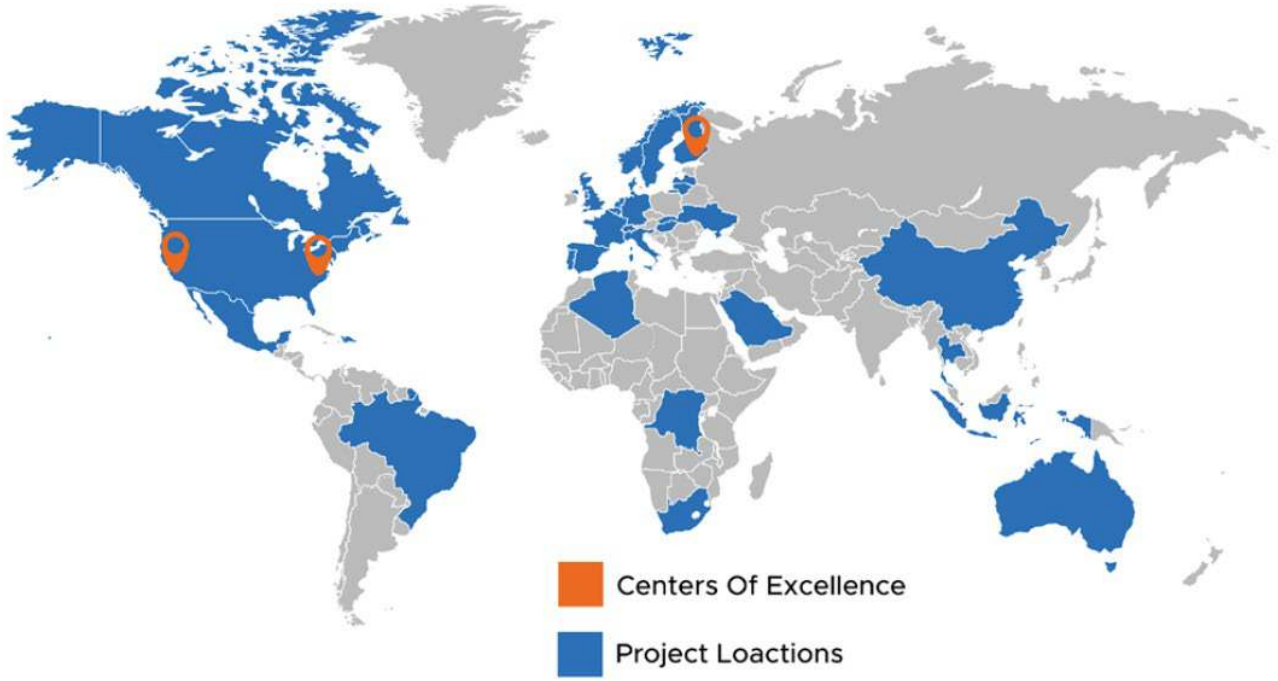
Outline

- UNIFI Consortium
- Grid-Following (GFL) vs Grid-Forming (GFM) Controls
  - Different Ways to Provide Grid-Support
- Why GFM?
- Ideal GFM Fault Ride-Through (FRT) Behavior
- Recent Advances (FREEDM Research)
  - Structure Preserving GFM FRT Control
  - UNIFI Software-in-the-Loop (SIL) Wrapper Library
  - UNIFI GFM Code (C) Library

Developing Utility Scale Inverters @EPC Power Corp

- Founded in 2010, fully in-house development
- Utility-scale inverters (1.5kV DC, 1.5-6MW)
- In-house manufacturing; capacity > 4GW/year
- Certified grid-Following & full grid-Forming capable



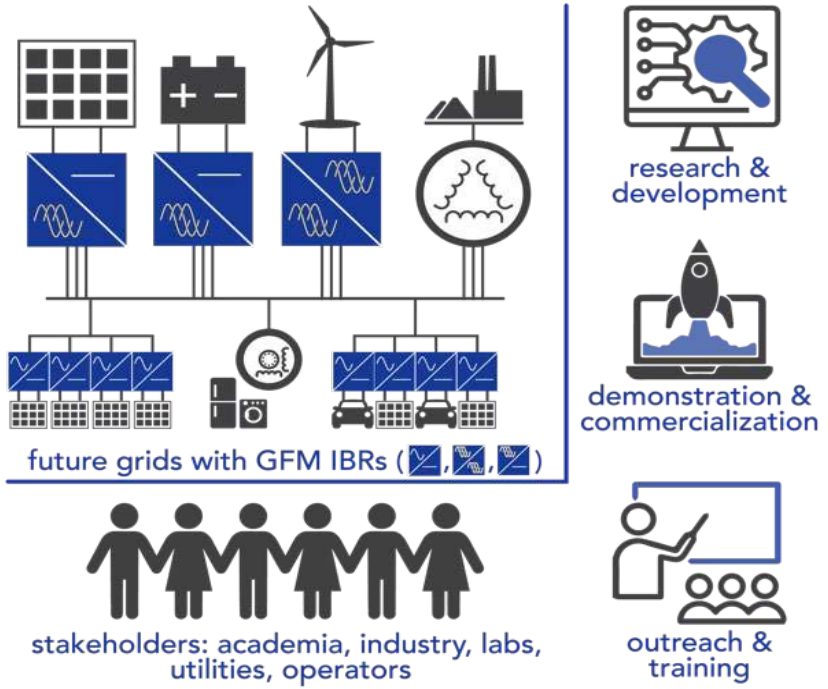
- Installed base in currently 35 countries
- Four locations
  - San-Diego, CA (sales, manufacturing, R&D, admin)
  - Helsinki, Finland (sales, R&D, customer support)
  - Greenville, SC (sales, manufacturing, R&D, admin)
  - Durham, NC (R&D, admin)

UNIFI Consortium

Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium

Mission: Bringing the industry together to **unify** the integration and operation of inverter-based resources and synchronous machines

DOE funding for first 5 years; self-sustaining through membership afterwards



- Research & Development
- Demonstration & Commercialization
- Outreach & Training

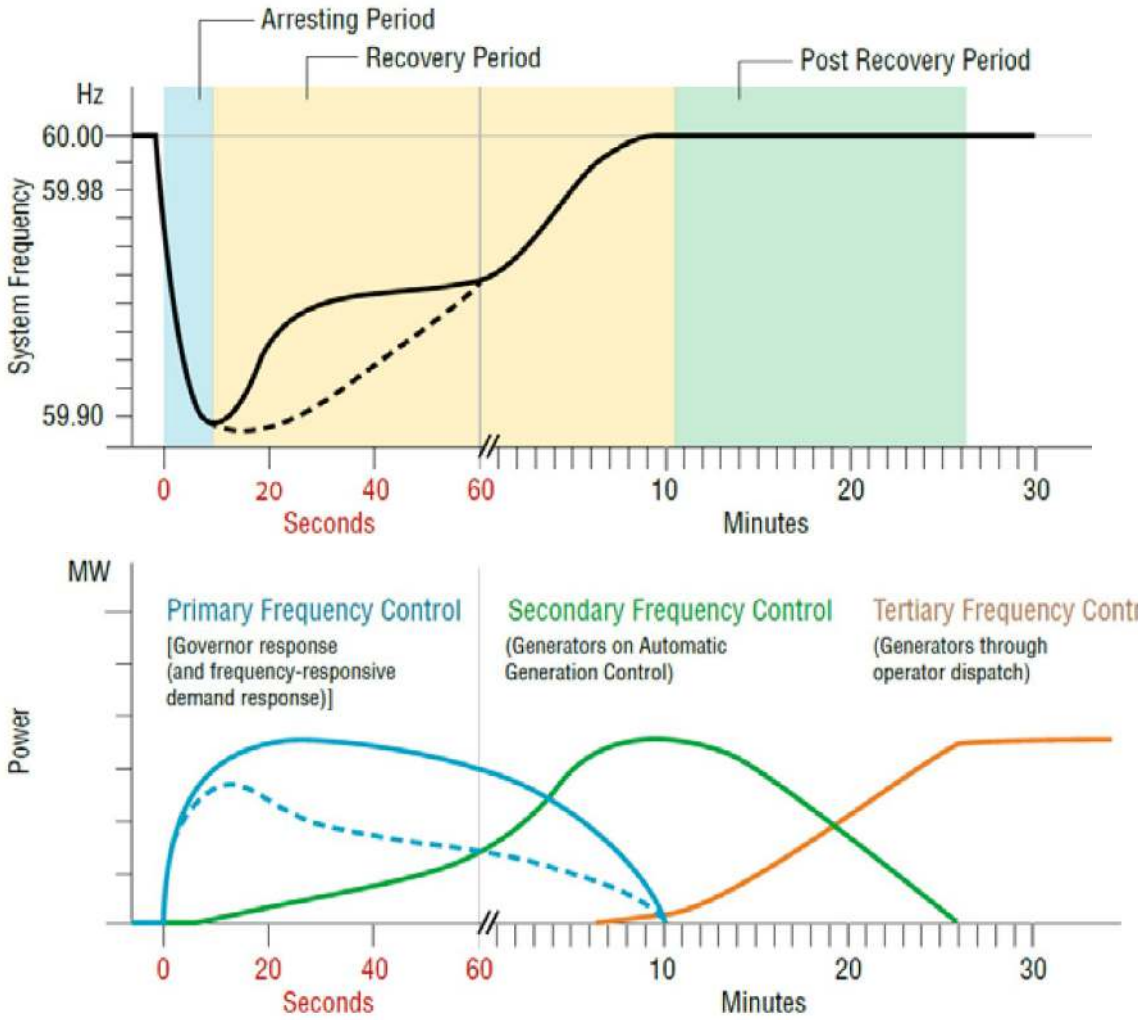
Goals

- Set of vendor- and technology-agnostic **UNIFI Grid -Forming (GFM) Specifications** to standardize performance and benchmark capabilities
- Foster collaboration between inverter manufacturers and system operators
- Fill technology gaps, such as fault ride-through, protection coordination

Grid-Support

- Frequency support
  - Inertial support
  - Frequency response
    - Fast freq. response (FFR)
    - Primary, secondary, & tertiary freq. response (PFR, SFR, TFR)
- Voltage support
  - Reactive-power support (Volt-Var)
  - Unbalance mitigation - negative sequence reactive power/current injection

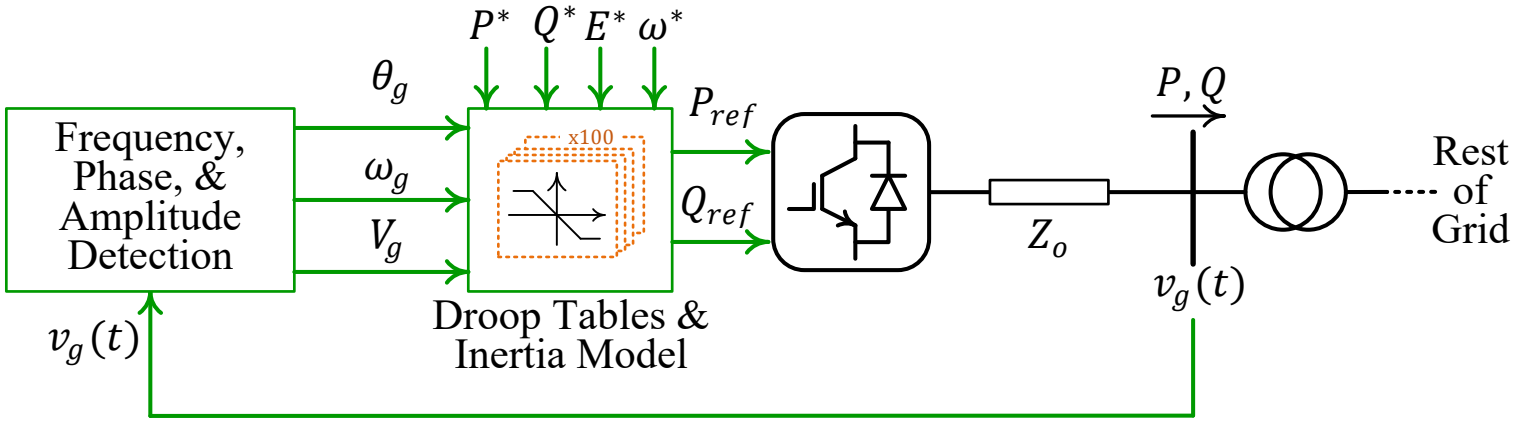
Grid-following (GFL) inverters capable of all of the above!



Source: Lawrence Berkeley National Laboratory[1]

[1] *2018 LBNL Frequency Control Requirements for Reliable Interconnection Frequency Response*, https://emp.lbl.gov/publications/frequency -control-requirements

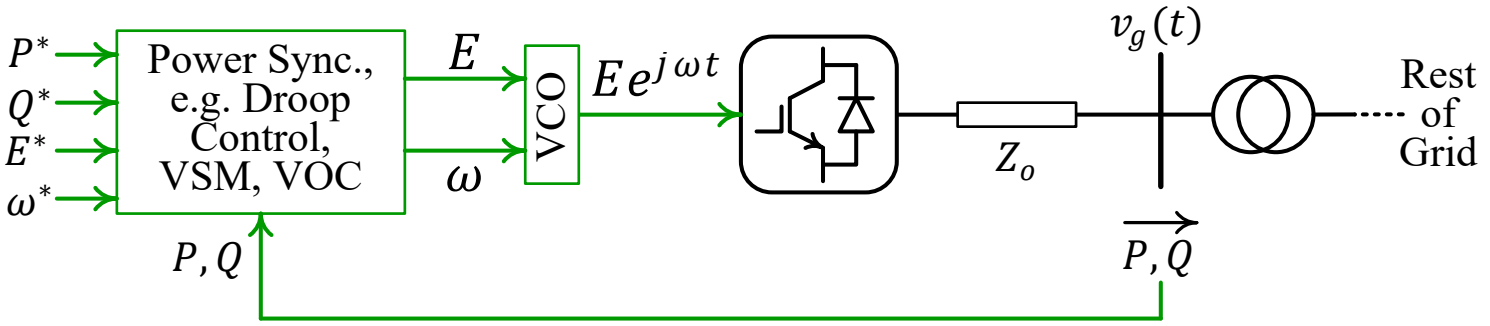
Grid-Following vs Grid-Forming Controls



Grid-following (GFL) IBR

- Needs to detect the terminal voltage phase & frequency- **voltage based synchronization**
- Droop-tables & inertia/ machine model to generate dynamic power references

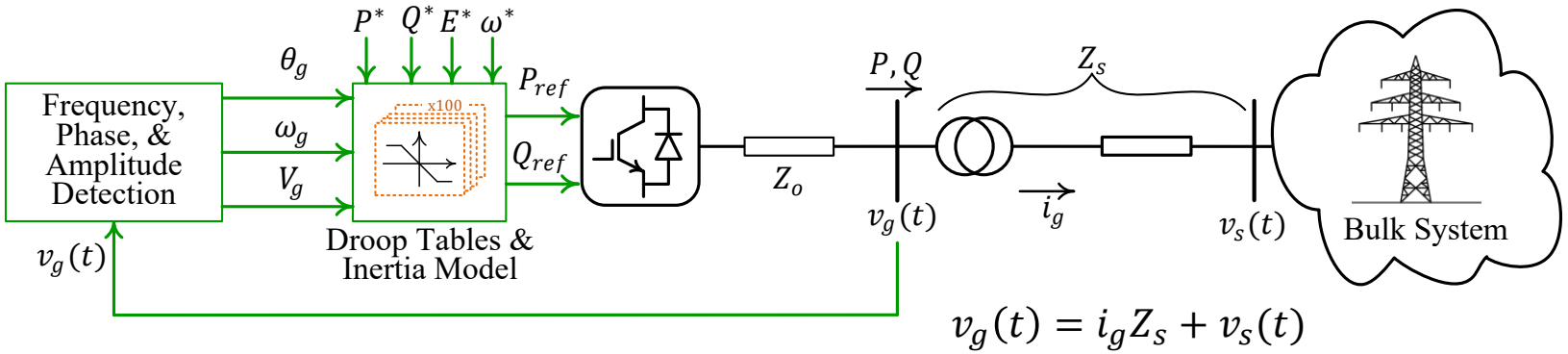
- Self-defines frequency and reference phase using output power feedback – **power-synchronization**
- Droop dynamics/ inertial response inherent in synchronizing mechanism



Grid-forming (GFM) IBR

Almost indistinguishable droop response attainable by GFL IBRs for perturbation **at the terminal.**

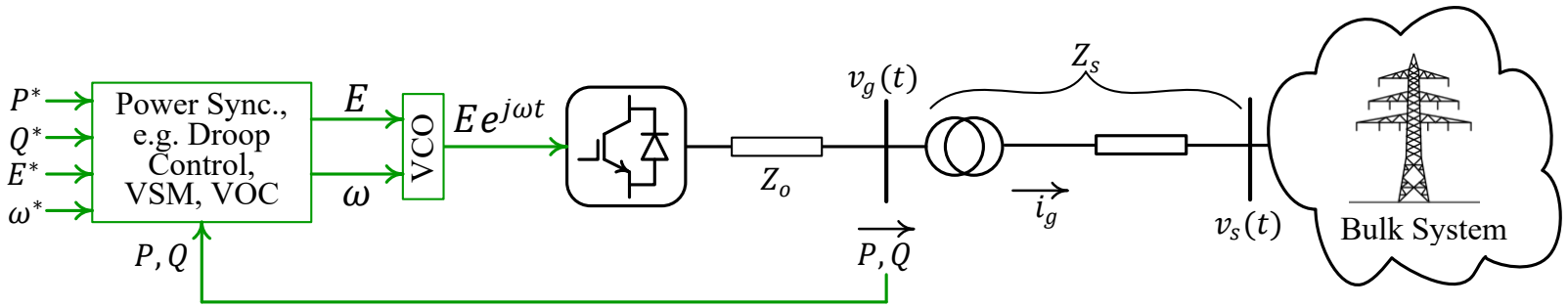
Where GFL vs GFM Matters



$$v_g(t) = i_g Z_s + v_s(t)$$

- **Weak interconnection:** $v_{g(t)}$ heavily affected by own injection (i_g); $v_g(t)$desensitized to network dynamics
- **Heavy IBR penetration** : low-inertia → faster frequency dynamics

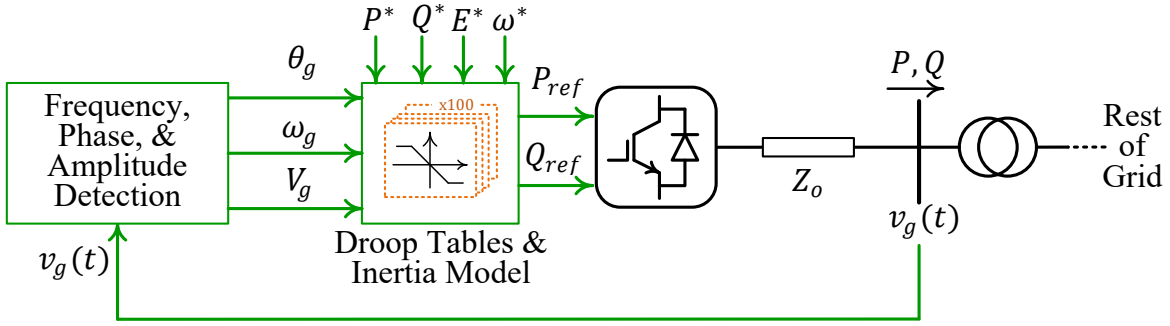
- How to define/ detect frequency of terminal voltage $v_g(t)$ under fast transient?
- GFL droop/ inertial response not well-defined during rapid frequency changes/ large contingency events

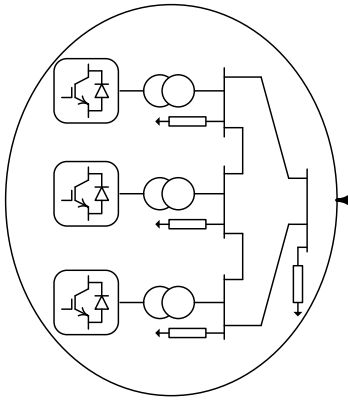


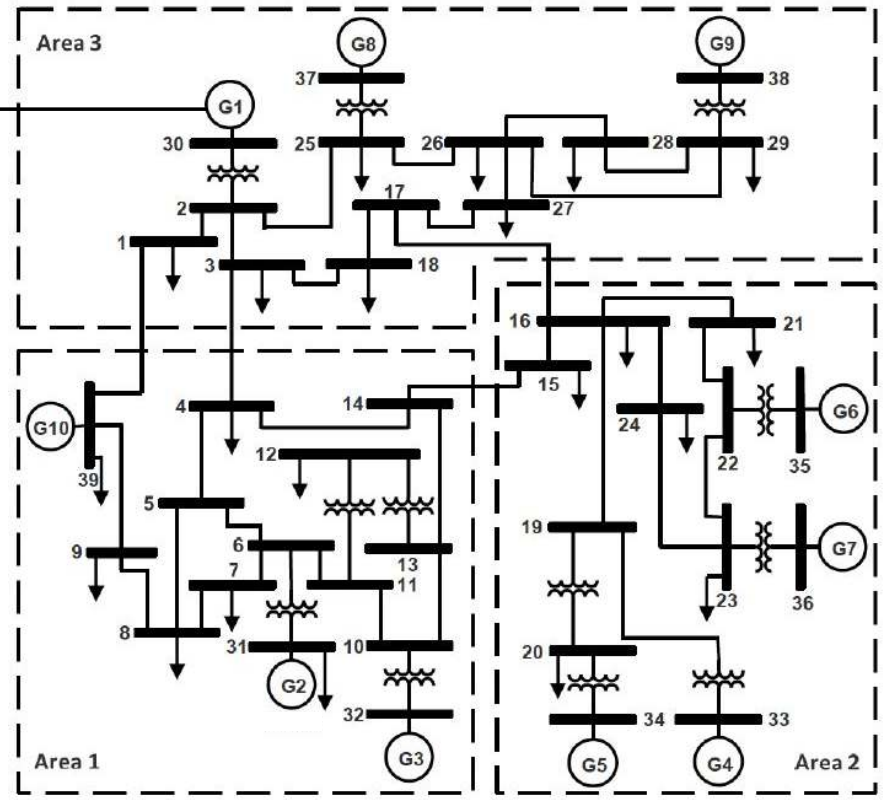
- Output power well defined instantaneously regardless of interconnection strength and/ or penetration

- GFL "retroactively" responds to "detected frequency" in response to contingency event
- GFM "inherently" slows down/ speeds up "internal frequency" in response to changes in output power

Large Scale Modeling

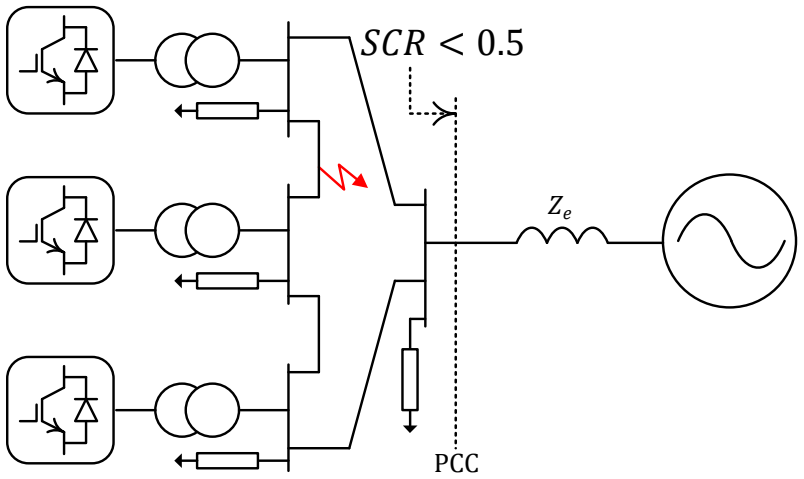


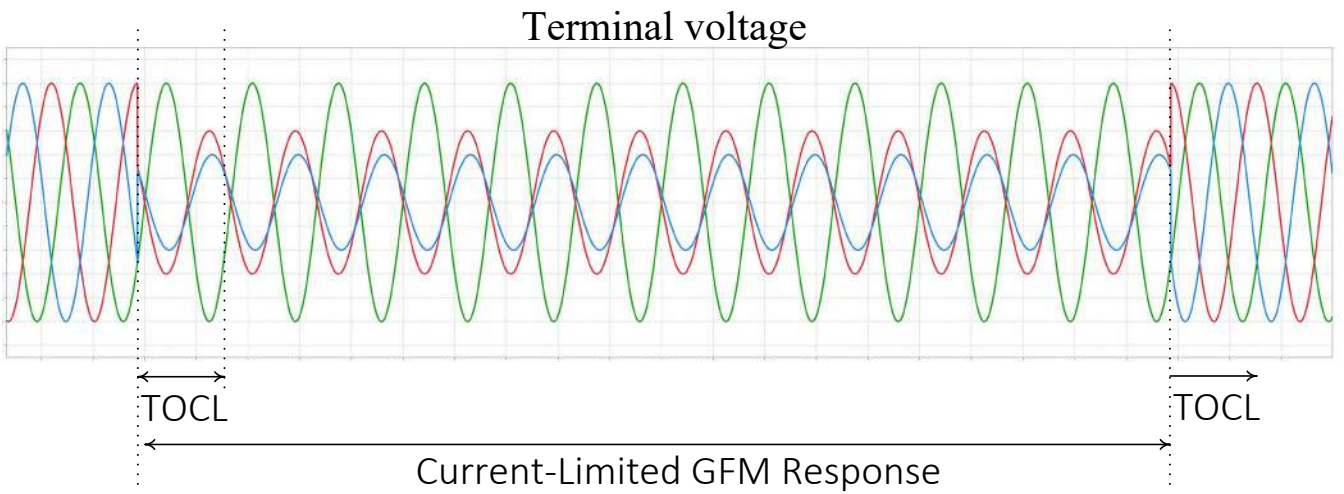




- A GFL inverter may have thousands of parameters defining droop tables/ inertial response for various operating conditions
- Large scale modelling exceedingly challenging
- Well-defined, simple, and repeatable response desired
- Ideal case - structure-preserving dynamic/ control response under all conditions

Wish List for Fault -Ride-Through (FRT)

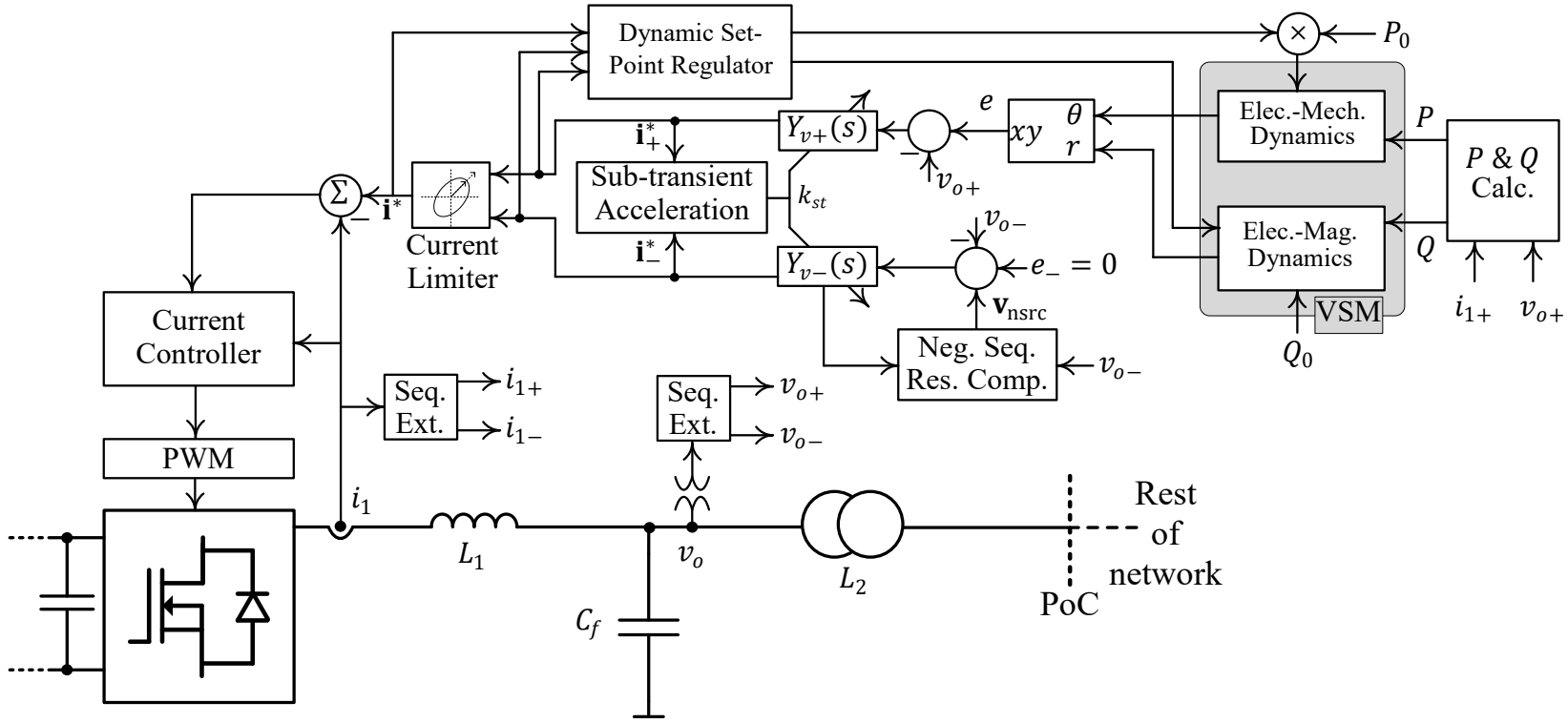




- **Transient over-current limiting (TOCL)** : IBR does not trip due to transient over-current at fault instant and at fault clearing instant; critical under phase-jumps
- **Current-limited primary GFM response** : $P - f$ and $Q - V$ responses, retained under IBR's maximum current capacity constraint
- **Real and reactive loads shared 'equitably'** : preferably a byproduct of primary GFM response. Network load includes fault currents in both negative- and positive-sequences; should be shared by IBRs
- **Structure-Preserving Control** : No controller parameter/ mode change required based on detection of fault and/ or fault clearance

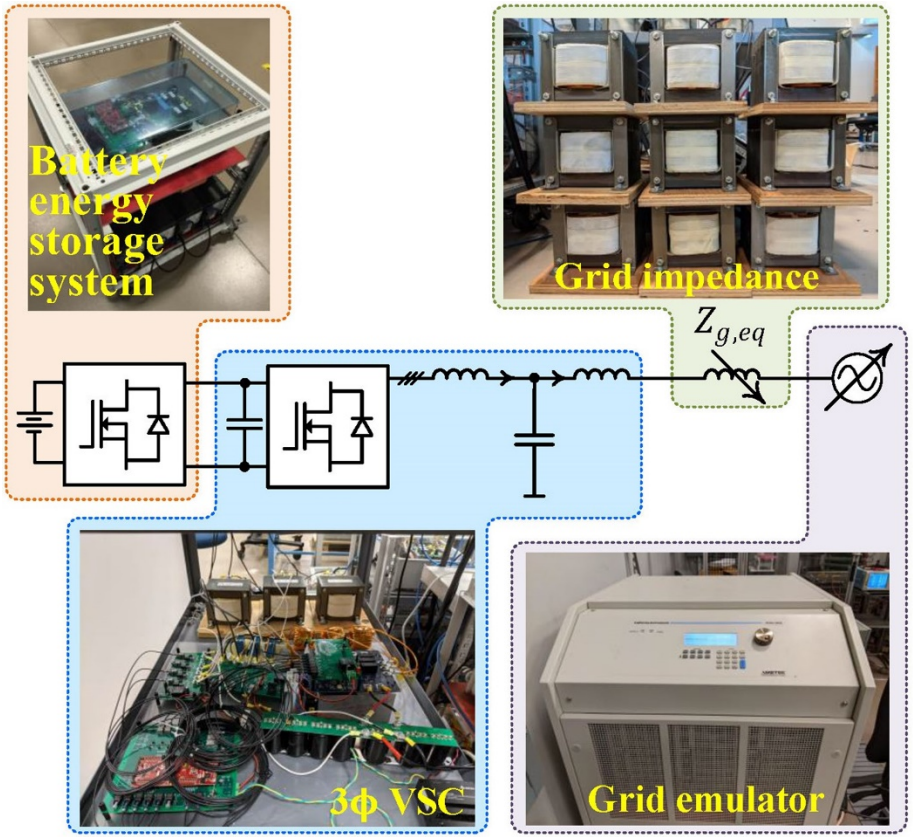
Structure-Preserving FRT Controller[2]

- Preserves control-structure under symmetric and asymmetric faults
- Retains grid-forming nature (power-frequency droop response) under fault
- Appears as a passive impedance to negative sequence, similar to a synchronous generator

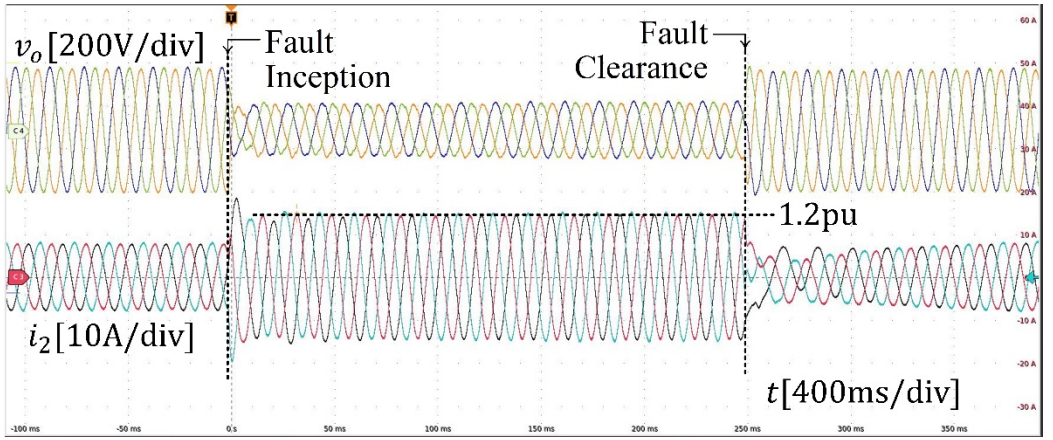


[2] M. A. Awal, M. R. K. Rachi, H. Yu, S. Schroder, J. Dannehl, and I. Husain, "Grid-Forming Nature Retaining Fault Ride-Through Control," 2023 IEEE Applied Power Electronics Conference (APEC), Orlando, FL, USA, 2023.

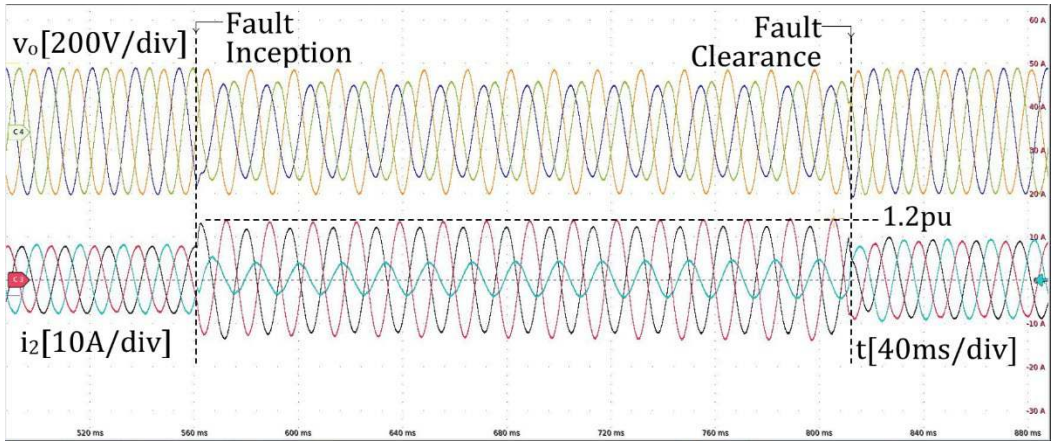
Structure-Preserving FRT Controller[2]



Experimental setup



Response to a three-phase symmetrical fault

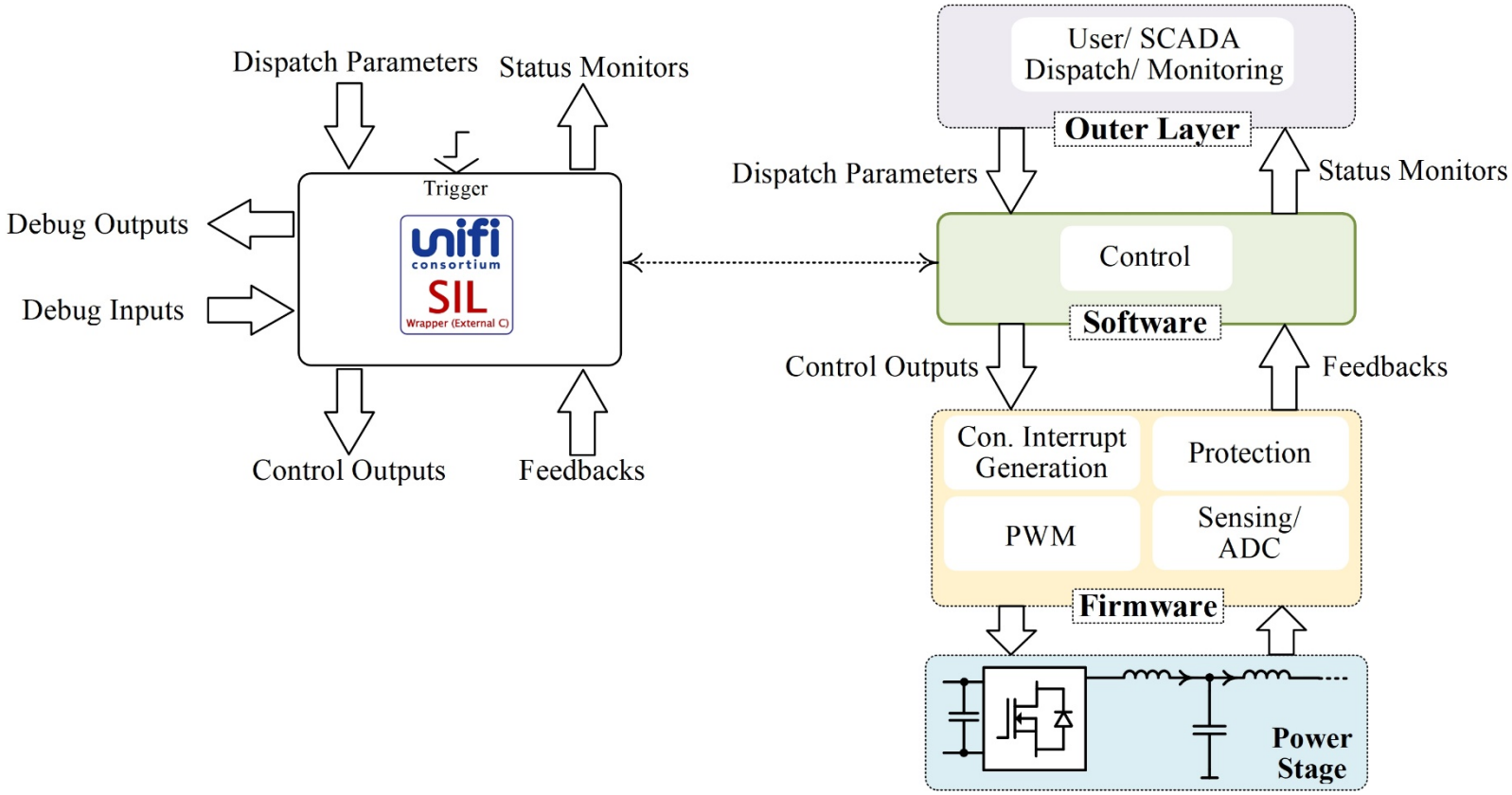


Response to a single-phase fault

Check out our student poster for further details!

UNIFI Software-in-the-Loop (SIL) Wrapper

- A library toolbox for MATLAB-Simulink environment
- Wraps embedded-C code base for power electronics converters and systems
- Rapid control development
- Multi-institutional collaboration through black-box software/ model sharing

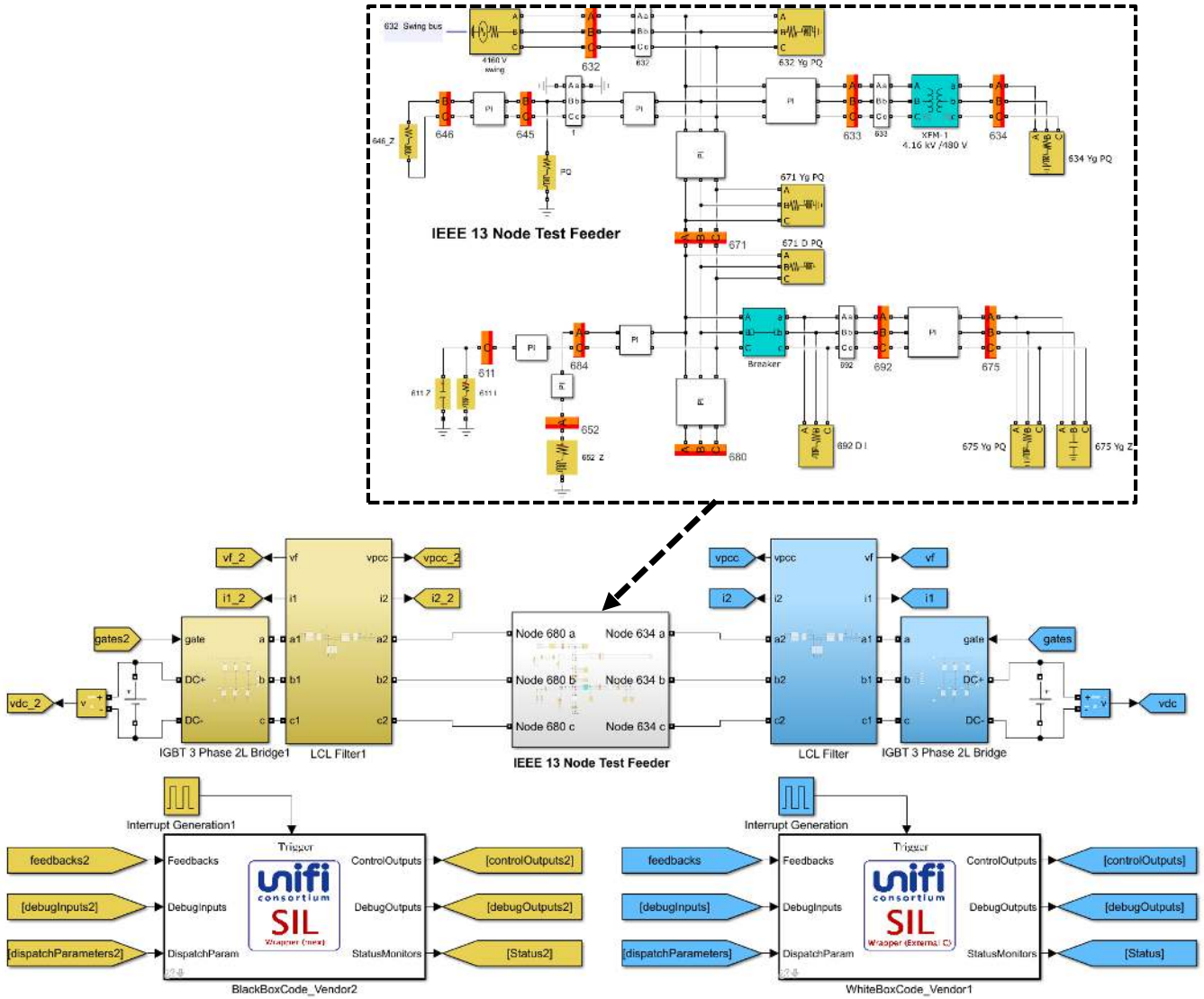


UNIFI SIL wrapper tool -chain

UNIFI Software-in-the-Loop (SIL) Wrapper

- Rapid control development
- Network-level EMT simulation using original software of an IBR
- Black-box model sharing enables simulation consisting of IBRs from multiple vendors

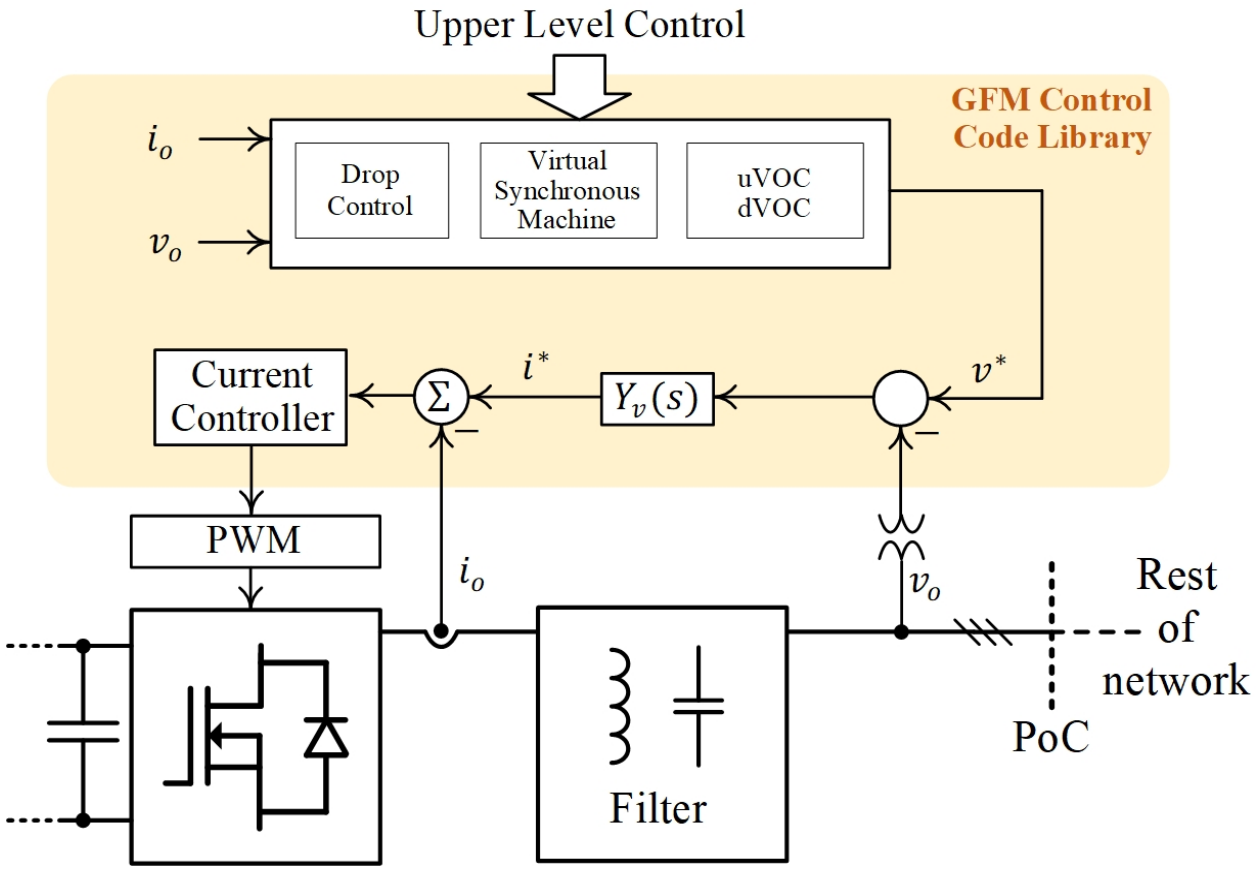
Check out our student poster for further details!



UNIFI GFM Control Library – C

- A GFM control software library – written in C
- Uses floating-point arithmetic
- Portable across control hardware platforms, e.g., TI DSPs, ST microcontrollers, Xilinx SoC
- Synchronizing control options (selected at compile time through compiler flags)
  - Droop control
  - Virtual synchronous machine (VSM) control
  - Oscillator based control
    - uVOC
    - dVOC

Check out our student poster for further details!



Functional view of GFM Control Library – C

Contributors

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Thank You!
Questions and/comments are welcome!