SAND2022-16253C

eGrid NZ 2022
Conference

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University of Auckland

PANEL DISCUSSION

"Grid Forming Inverter Integration and Validation"

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Power Electronics and Energy Conversion Systems

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SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Sandia National Laboratories

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E ZERO-CARBON ECONOMY

Organization

GRID 2022

unifi consortium

Leadership

Establish management & governance structure to support sustained US leadership in GFM tech

Develop/Update Interoperability Guidelines and Functional Requirements

Advisory Board

SETO + WETO + OE
Industry + Academia
ESIG + GPST

Thrusts

Research & Development

- Advance R&D for GFM technologies
- Ensure a coherent & comprehensive portfolio of solution sets
- Integrate & evaluate new capabilities, products, & processes

Demos & Commercialization

- Provide guidance & transition R&D to commercial products and applications
- Demonstrate solutions that showcase multi-vendor interoperability
- Bring together public+private entities

Outreach & Training

- Develop expertise, networks, & training
- Communication & dissemination strategies
- Engage community at all levels of supply chain
- Build awareness of issues, & create alignment amongst stakeholders

Areas

Research & Development		Demos & Commercialization		Outreach & Training	
Modeling & Simulation	Hardware	IP management	Domestic Products	Education	Workforce Development
Controls	Integration & Validation	Standards	Field Demonstration	Communicatio n	Events

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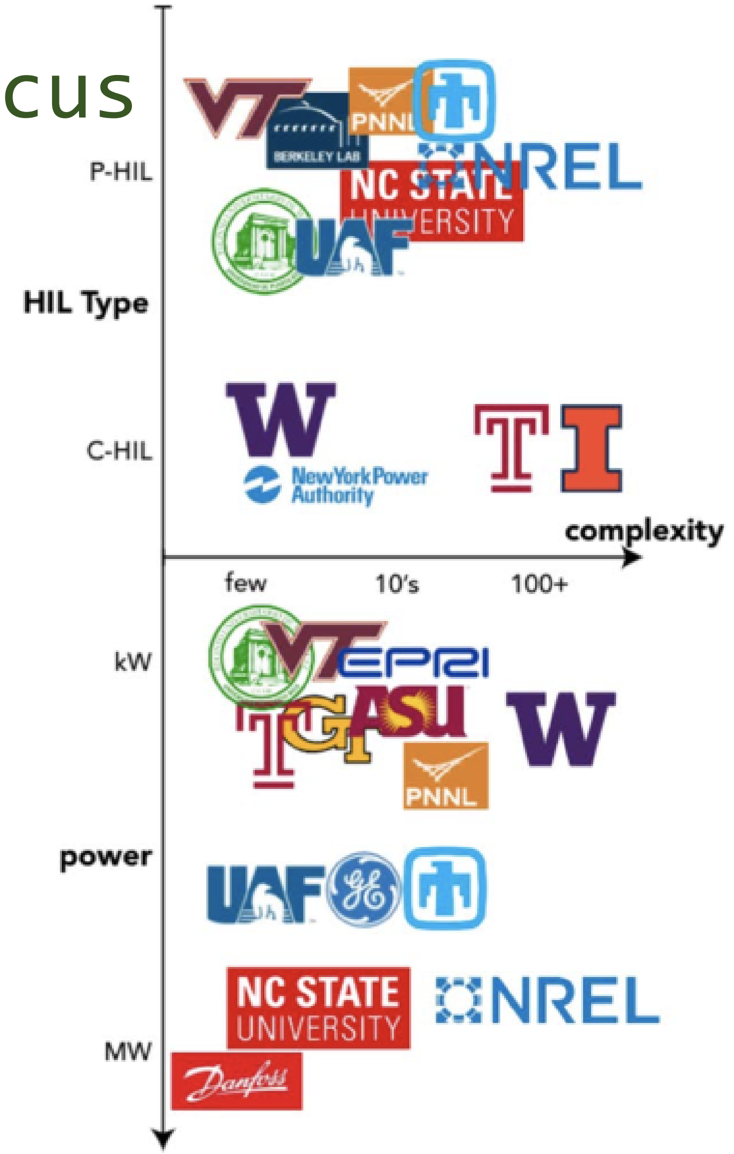
Integration and Validation – Focus

1. Evaluate the performance of GFM technologies at scale in representative integrated power system environments

2. Establish a conduit between the R&D areas and specific activities in the D&C Areas

3. Evaluate the *Interoperability Guidelines & Functional Requirements developed by the* consortium



I&V Thrusts

1. Validation infrastructure and IBR baseline characterization

2. Integration of GFM Technology into power systems

3. 1+MW Multi-vendor Experiment

Integration & Validation Area

1 MW Experiment – at NREL in Year 3

- Includes various physical sizes (250W-1MW)
- Three-phase, single-phase generation & loads
  - GFM, GFL, & synchronous machines
  - Comms interfaces (2030.5, SunSpec)
- Multiple source-side resources (PV, energy storage, wind (if possible))
- Coupled to PHIL to evaluate scales: 1MW microgrid to larger grids
- 50%, 75%, 90%, and 100% power contribution from GFM IBRs
- Network connections (LV and MV, overhead and conductors)
- Connections to multiple laboratories: integrated testing and validation approach to realize multiple 1MW demos

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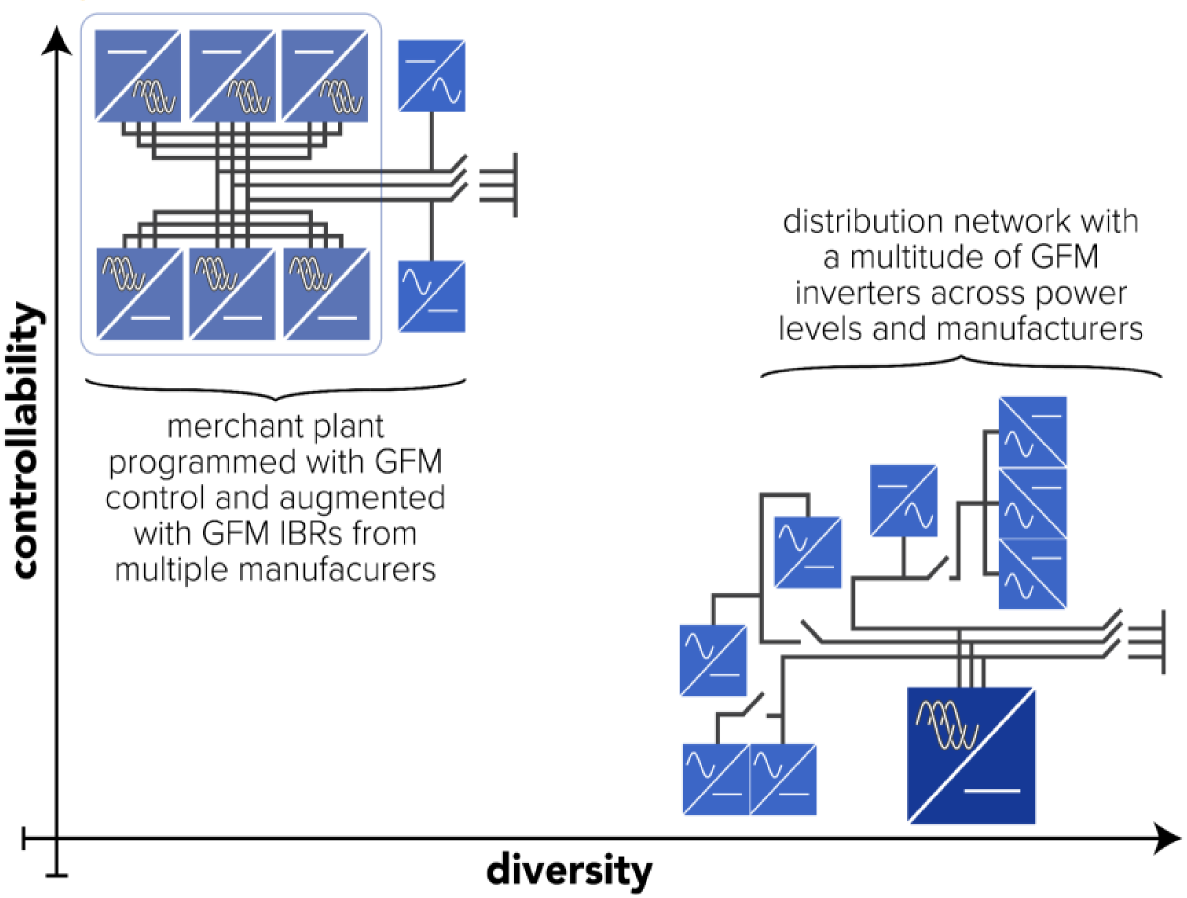
20+MW Demonstration

Large-scale Plant Integration

[Barilla Solar, TX]



Distribution Networks with high PV integration

[Chicago, IL]

[Oahu, HI]

- Examining a **range of possible sites** that trade off controllability and diversity of resources and IBR size
- Also looking for demonstrating much larger than 20MW sizes and at possibly **at multiple sites**
- Demonstrate a full range of GFM services and validate *Interoperability Guidelines & Functional Requirements*
- Would like to examine unique objectives if possible such as energy justice (collocate with underserved communities)

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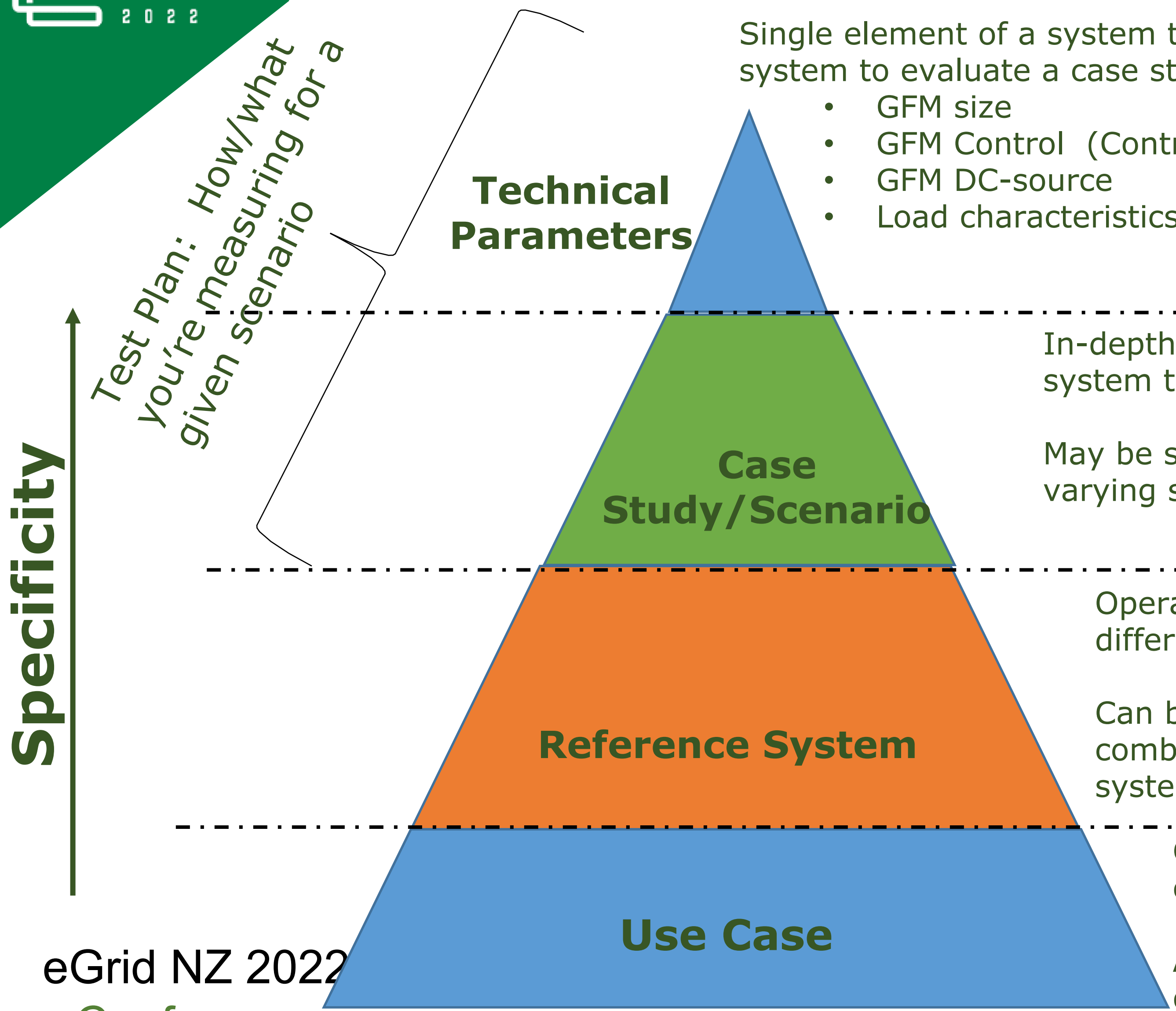
Hierarchical Categorization of GFM Use



Technical Parameters

Single element of a system that can be measured, varied, or incorporated into a reference system to evaluate a case study.

- GFM size
- GFM Control (Control type, droop offset/slope, etc)
- GFM DC-source
- Load characteristics (power factor, THD, machine/resistive/electronic composition)

Case Study/Scenario

In-depth investigation of specific phenomena or capability a reference system that can be further studied

May be several specific case studies for each use case, demonstrating the varying system configurations, challenges, and benefits.

Reference System

Operational systems (real or simulated) that can be evaluated for different scenarios/operation modes/asset mixes, etc.

Can be analyzed entirely simulated environment, in the lab with combination of physical hardware and simulation, or in a deployed system

Use Case

Concept in system analysis to broadly identify, clarify, and organize system requirements

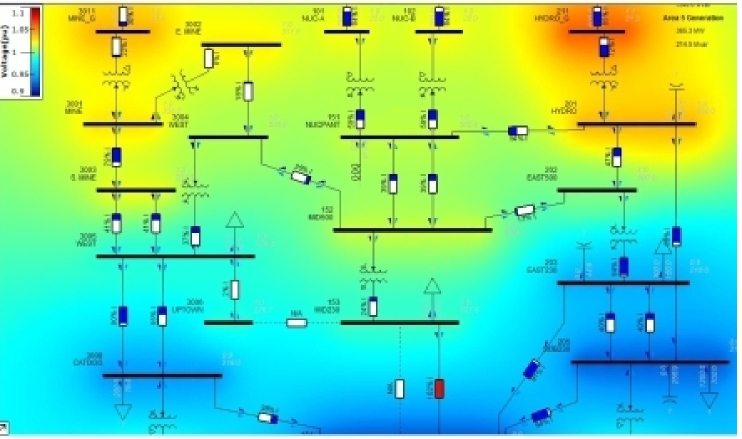
Apply innovations to systems to assess their value or to demonstrate their readiness for use by industry in commercially deployed systems.

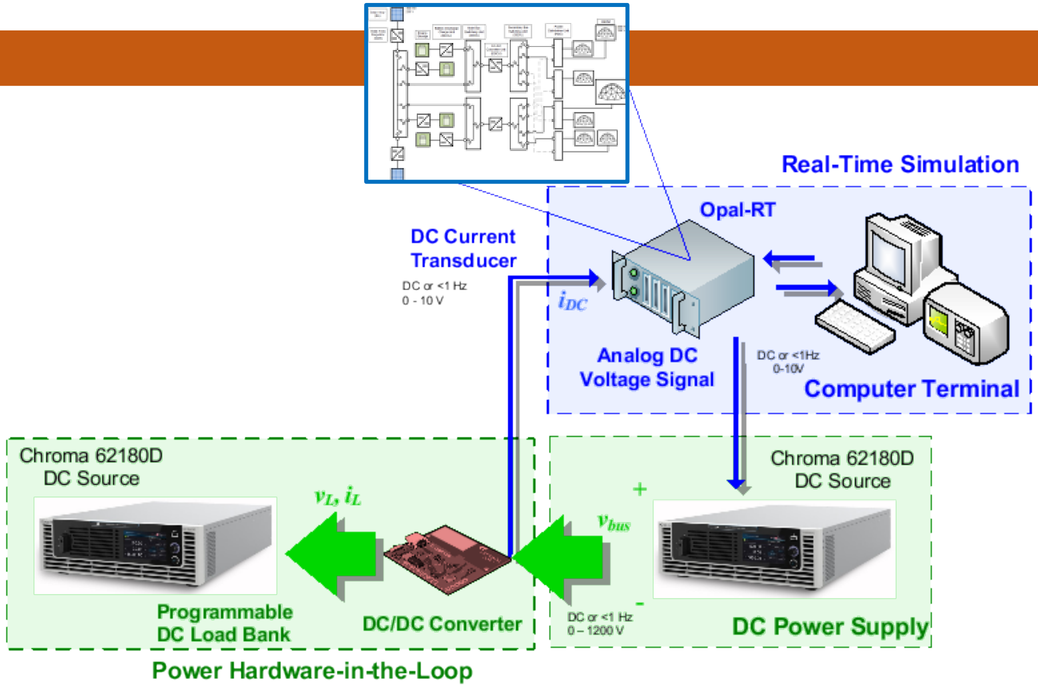
Hierarchical Categorization of GFM Use

Use Cases	Microgrid----	Island (isolated) Grid	Distribution Connected	Transmission connected
Reference Systems (linked to mod/sim software library)	• Banshee • Sheriff • Consortium for Electric Reliability Technology Solutions (CERTS) • 1MW Demo System	• Hawaiian Islands (Oahu, Kauai, Maui) • St. Mary's, AK • South Australia, AEMO • Culebra, PR	• IEEE test feeders (342-Node, 13-Node, 34-Node, 123-Node, 8500 system) • EPRI Ckt 5 • 20 MW Demo	• 1WECC System • IEEE systems (39 Bus, 14 Bus) • 2000 Bus Synthetic Texas System • Hydro Quebec System • Eastern Interconnect
Scenarios (linked to *Interoperability Guidelines and Functional Requirements*)	• Blackstart • Generation Loss/Load step • Fault (balance/unbalance) • Phase Imbalance (voltage/power) • Island/resynch. (control/uncontrolled) • Inductive Inrush/motor stall • Overload (load > generation) • DC-side Dynamics	• Blackstart • Generation Loss/Load step • Fault (balanced/unbalanced) • Phase Imbalance (voltage/power) • Multi-segment island/resynch • Overload (load > generation) • Inductive Inrush/motor stall • DC-side Dynamics	• Generation Loss/Load Step • Fault (distribution) • Phase Imbalance(voltage/power) • Loss of Utility • DC-side loss of generation • Inductive Inrush • Protection Coordination • Overload (load > generation) • Fault (Transmission)	• Generation Loss/Load Step • Fault (Distribution) • Blackstart • System oscillation/transient stability • Line Series Compensation • FACTs device interaction • Fault (Transmission) • Protection Coordination

Experimental Continuum

Flexibility





Pure Simulation
Extended system representation

Controller HIL
High fidelity control systems

Power HIL
High fidelity Unit Response

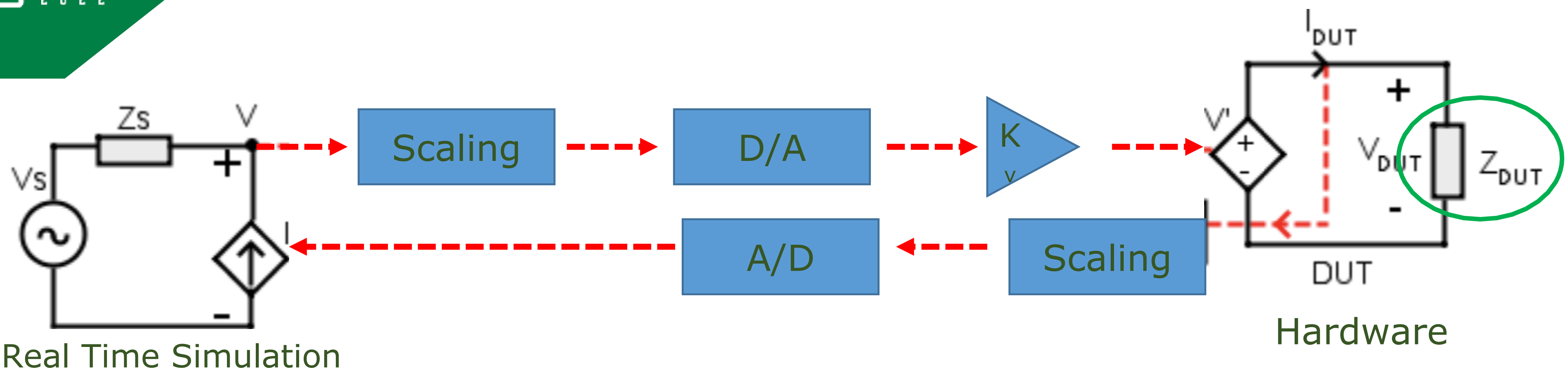
Pure Hardware
Nonlinear interactions

Fidelity

C/P HIL: Testing of external devices interfaced to a simulated system

- Simulations are normally **closed loop**
- DUT receives signals from the simulation and provides signals back to the simulation
- Mix of fidelity of response with flexibility of scenarios

Power Hardware in Loop of GFM-Ideal Transformer Method



The Ideal Transformer Method (ITM) is one of the most common PHIL setup
Simple to implement, Faster solve times, good stabilityx

Issue: GFM is not a ***pure load***, but a ***4 quadrant voltage source***

Warning: Direct connection of voltage sources is metastable

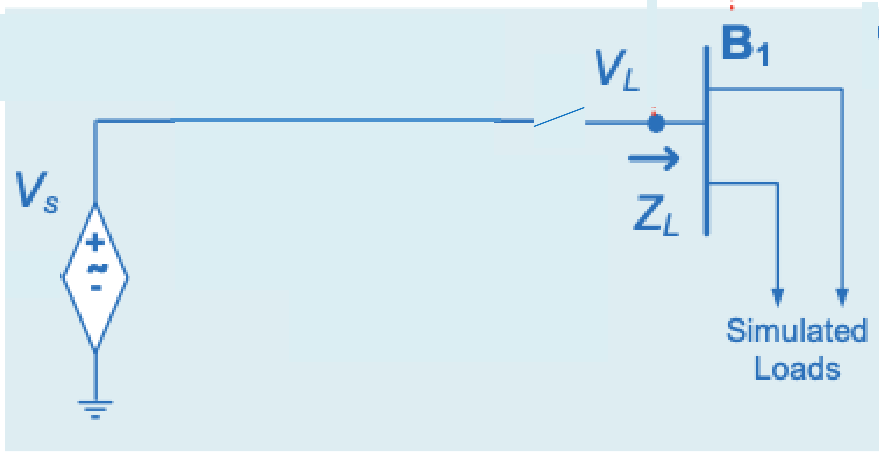
Can result in instability during simulation

Blackstart of GFM in HIL

Power System Simulation

In simulation

Real Time Simulator

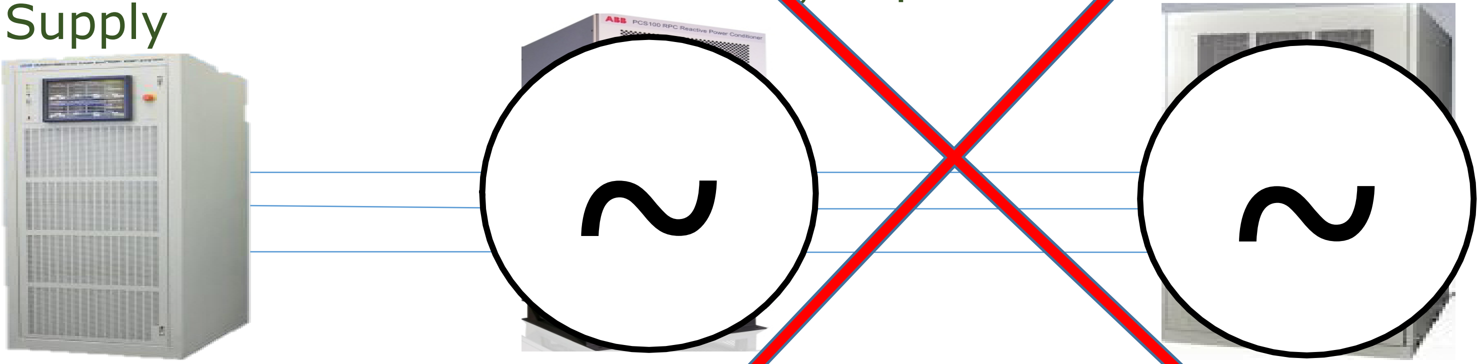


In laboratory

DC Power Supply

V_s =1pu

V_L =0



Same issue for isoch mode voltage sources

Device Under Test

AC Amplifier

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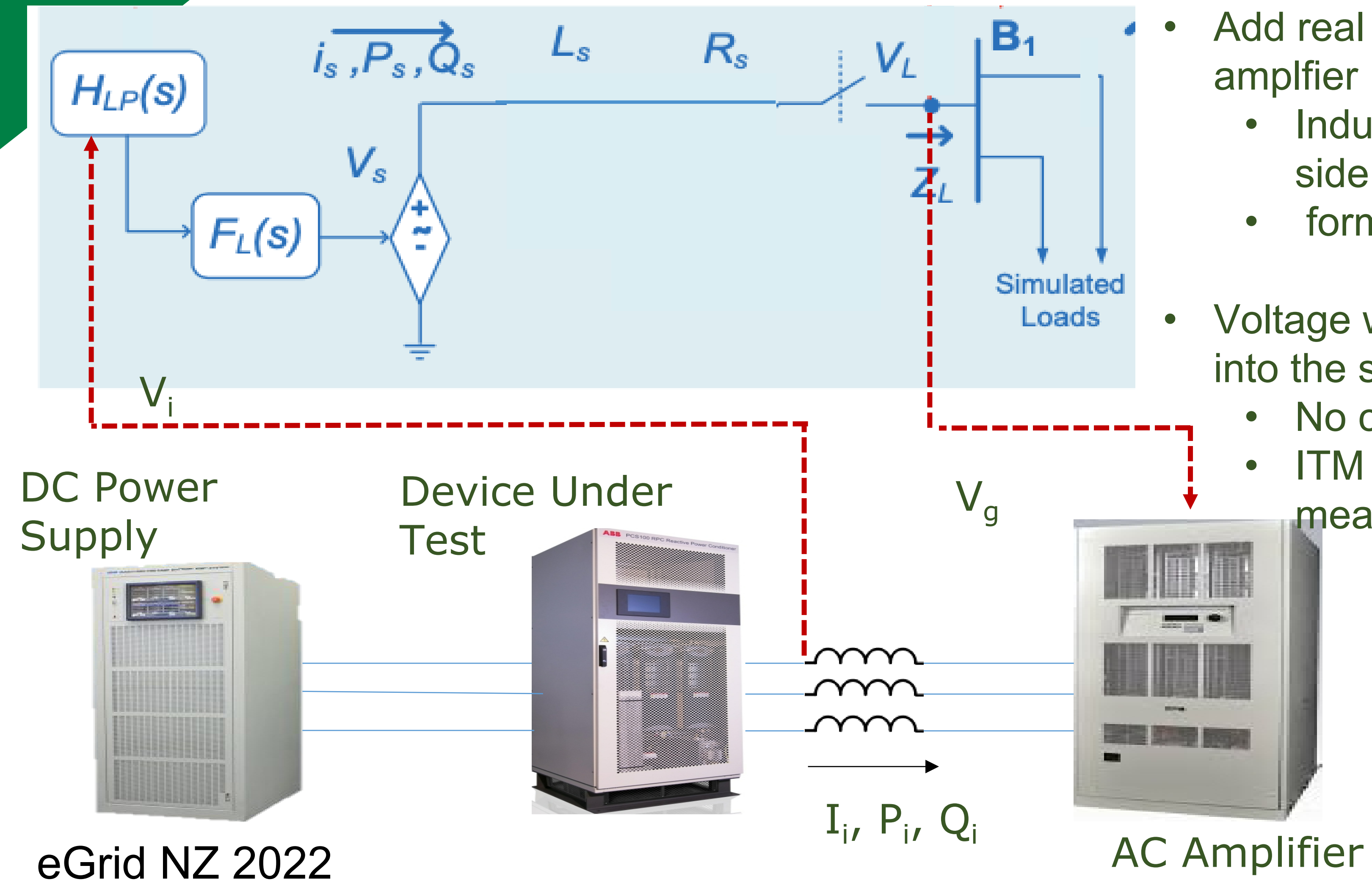
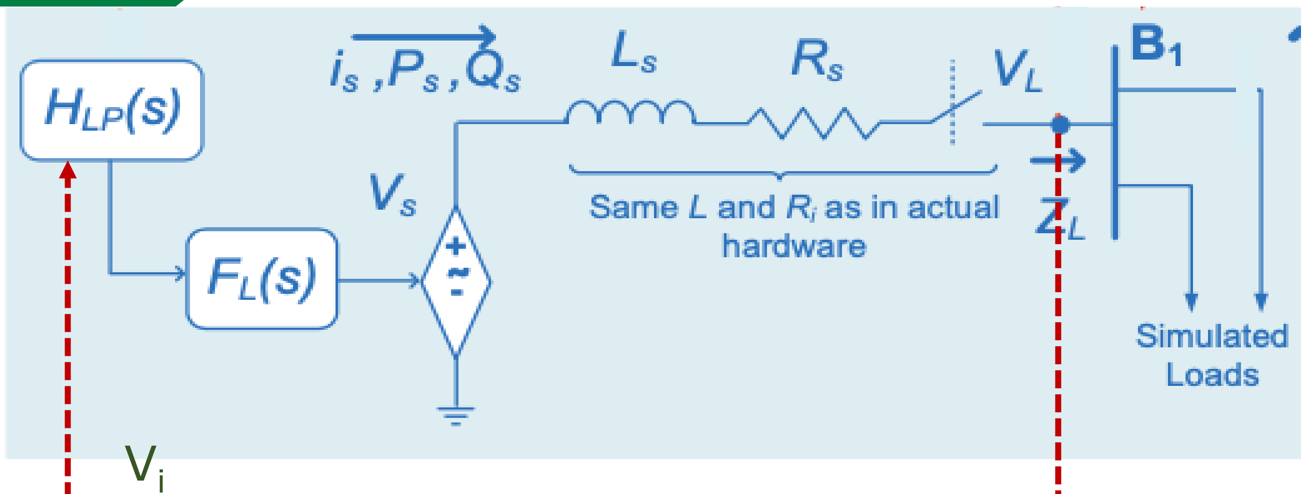
Blackstart of GFM in HIL

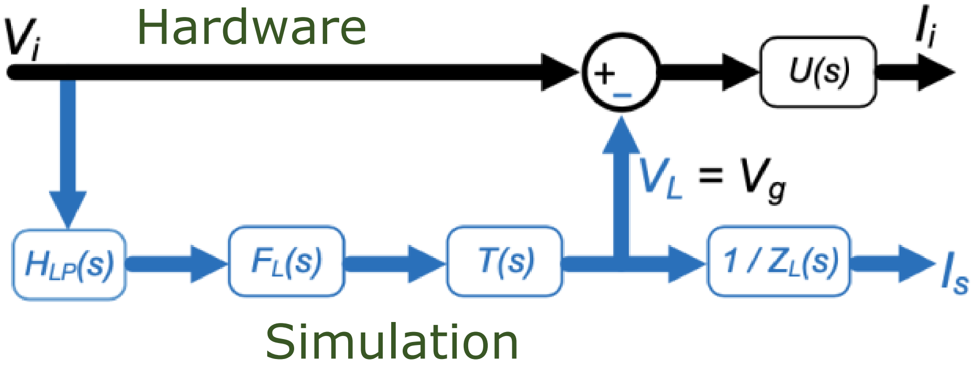


- Add real inductor in between GFM and AC amplfier
  - Inductor and total resistance in hardware side replicated inside the simulation
  - forming a digital twin
- Voltage waveform measured and then injected into the simulation/amplifier
  - No current monitoring
  - ITM uses 1 voltage measure and 1 current measure

Javier Hernandez-Alvidrez; Nicholas S. Gurule; Matthew J. Reno; Jack D. Flicker; Adam Summers; Abraham Ellis, Method to Interface Grid-Forming Inverters into Power Hardware in the Loop Setups, 2020 47th IEEE Photovoltaic Specialists Conference (PVSC).

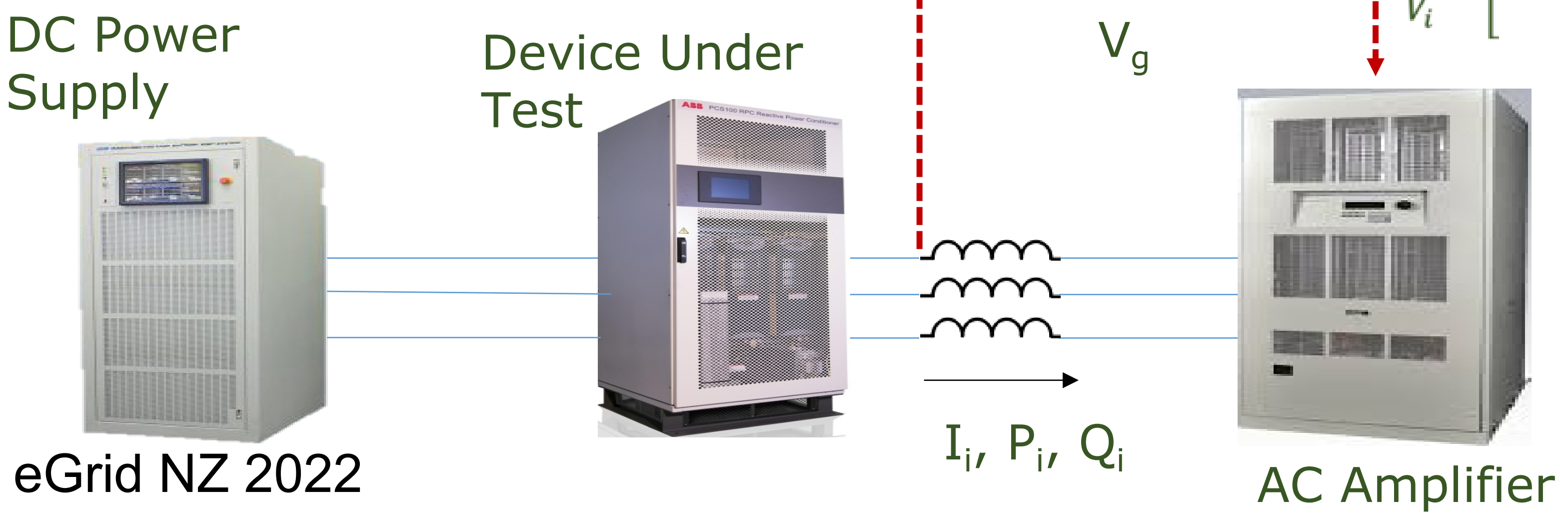
Blackstart of GFM in HIL





$$\frac{I_i}{V_i} = [1 - H_{LP}(s) \cdot F_{LP}(s) \cdot T(s)] \cdot U(s)$$

$$\frac{I_i}{V_i} = \left[1 - \left(\frac{\omega_c}{s+\omega_c}\right) \cdot \left[\frac{s+(p_1+\alpha)}{s+p_1}\right]\left[\frac{Z_L(s)}{sL_s+R_s+Z_L(s)}\right]\right] \cdot \frac{1}{sL_i+R_i}$$



$\omega_c, p_1, L_i, R_i > 0$ → all associated pole on LHS

→ Ensures stable behavior

So stability determined by zeros of:

$$sL_s + R_s + Z_L(s) = 0$$

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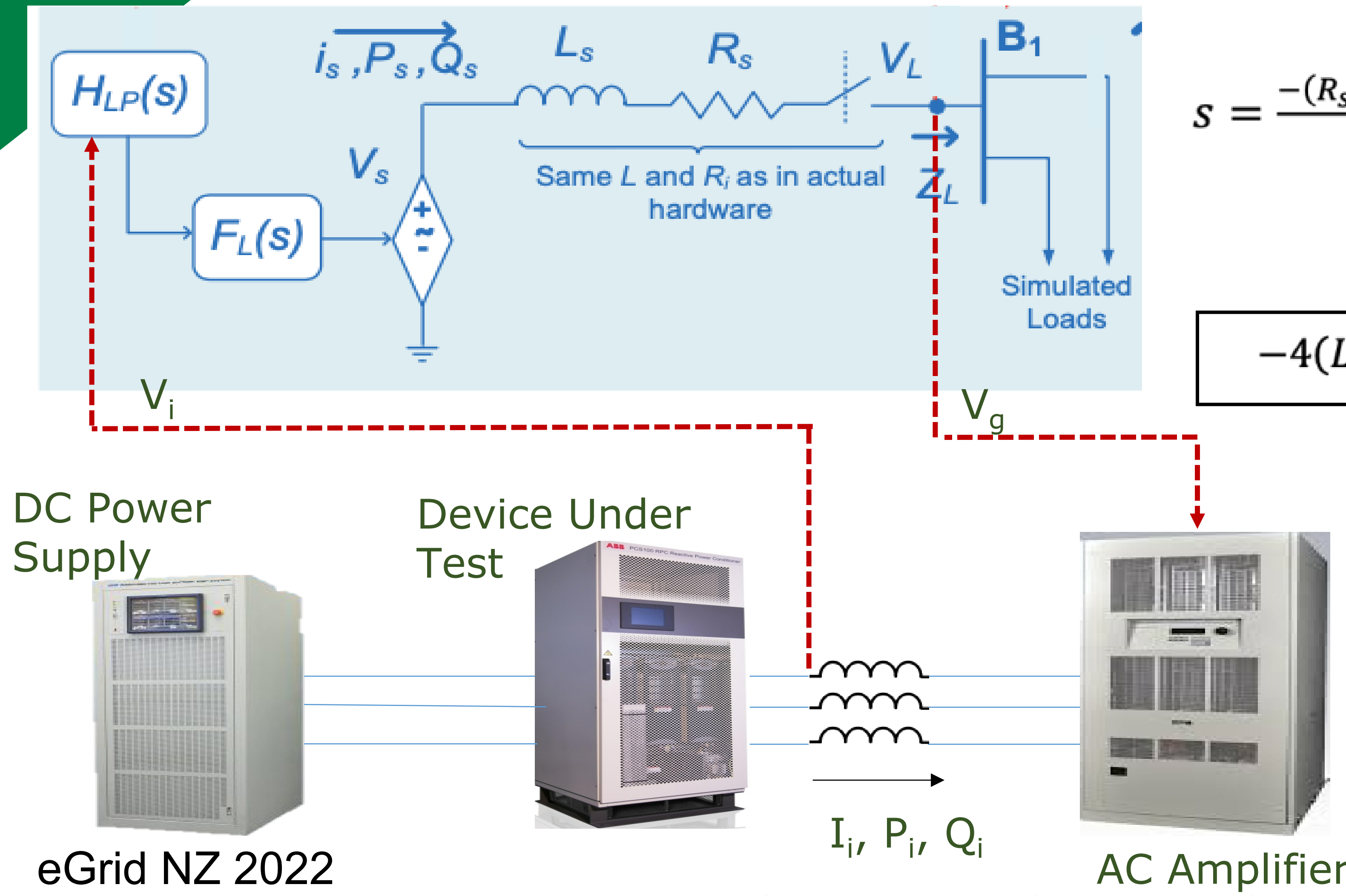

For RLC series case:

$$Z_L(s) = R_L + sL_L + \frac{1}{sC_L}$$

$$s = \frac{-(R_sC_L+R_LC_L) \pm \sqrt{(R_sC_L+R_LC_L)^2 - 4(L_sC_L+L_LC_L)}}{2(L_sC_L+L_LC_L)}$$

A lot of algebra later…

$-4(L_s + L_L) < 0$	Inequality to ensure stability…

Since L_s and L_L are real quantities… ***exponentially stable for all systems that can be represented by Series RLC circuit***

For the RLC parallel case, closed expression is more difficult → solve numerically

- Accuracy dictated by how well real inductance and resistance is represented in simulation (digital twin)
  - Issues with nonideal/nonlinear inductance/resistance

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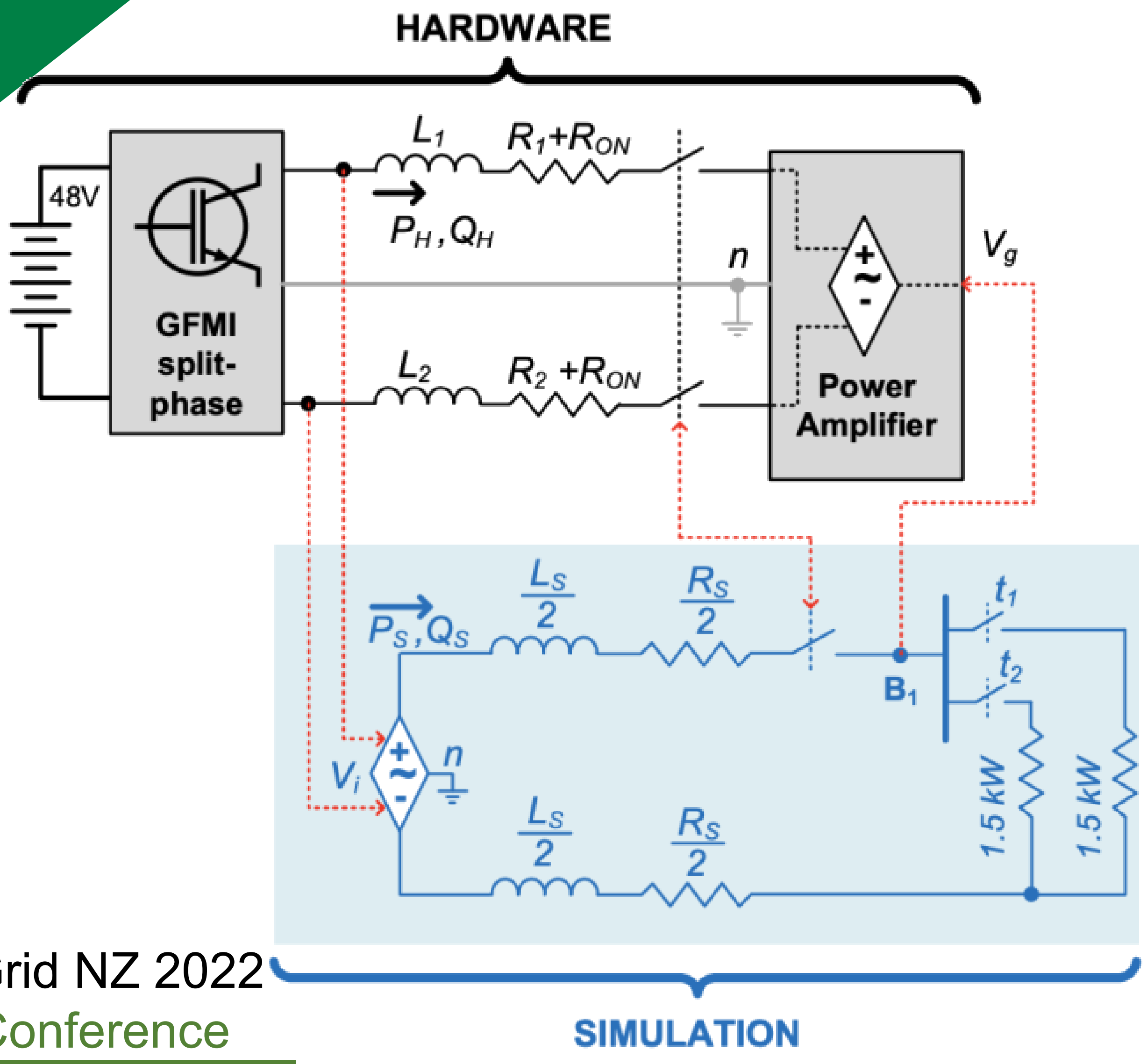

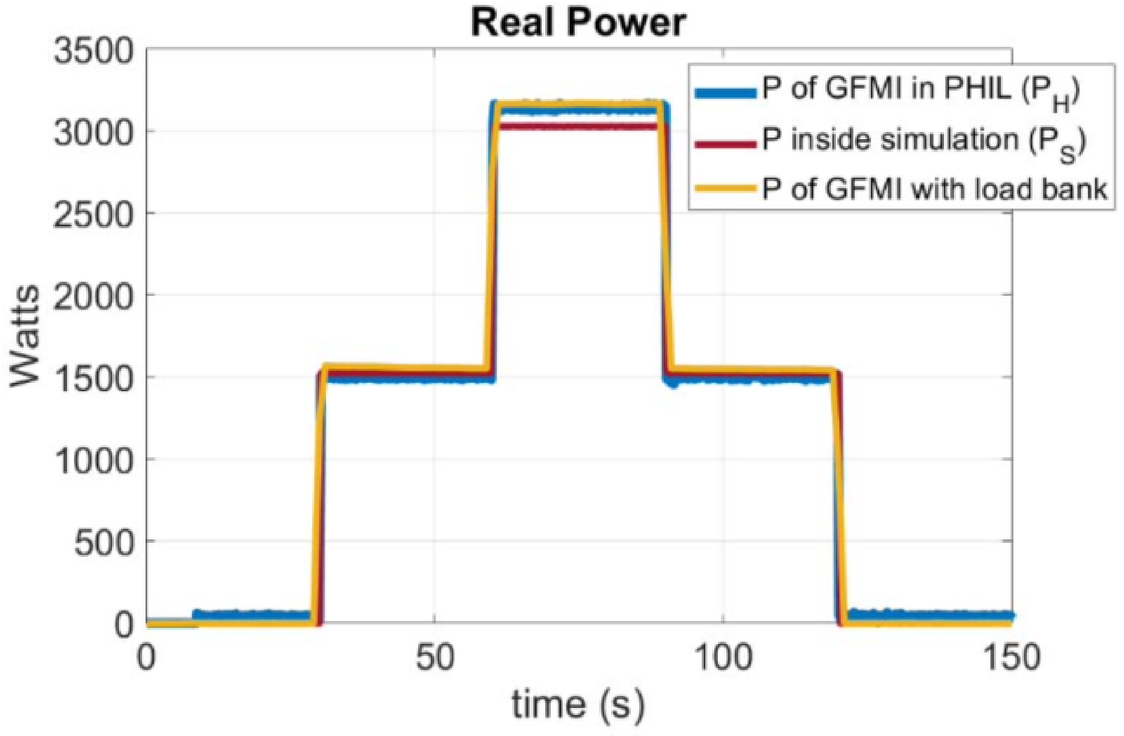

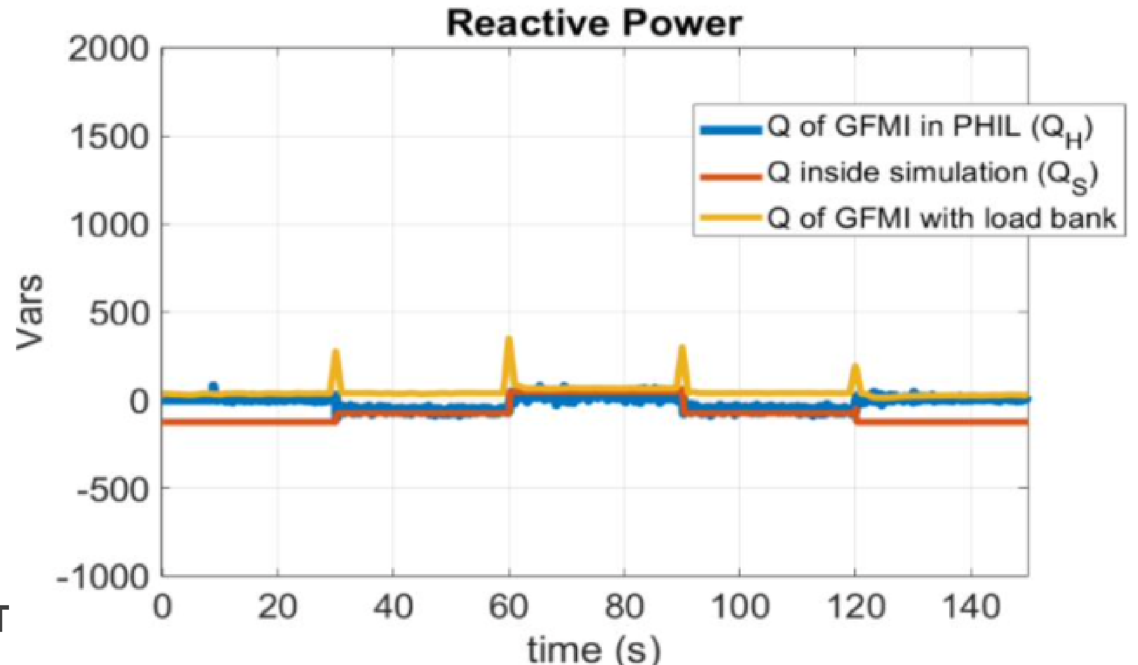

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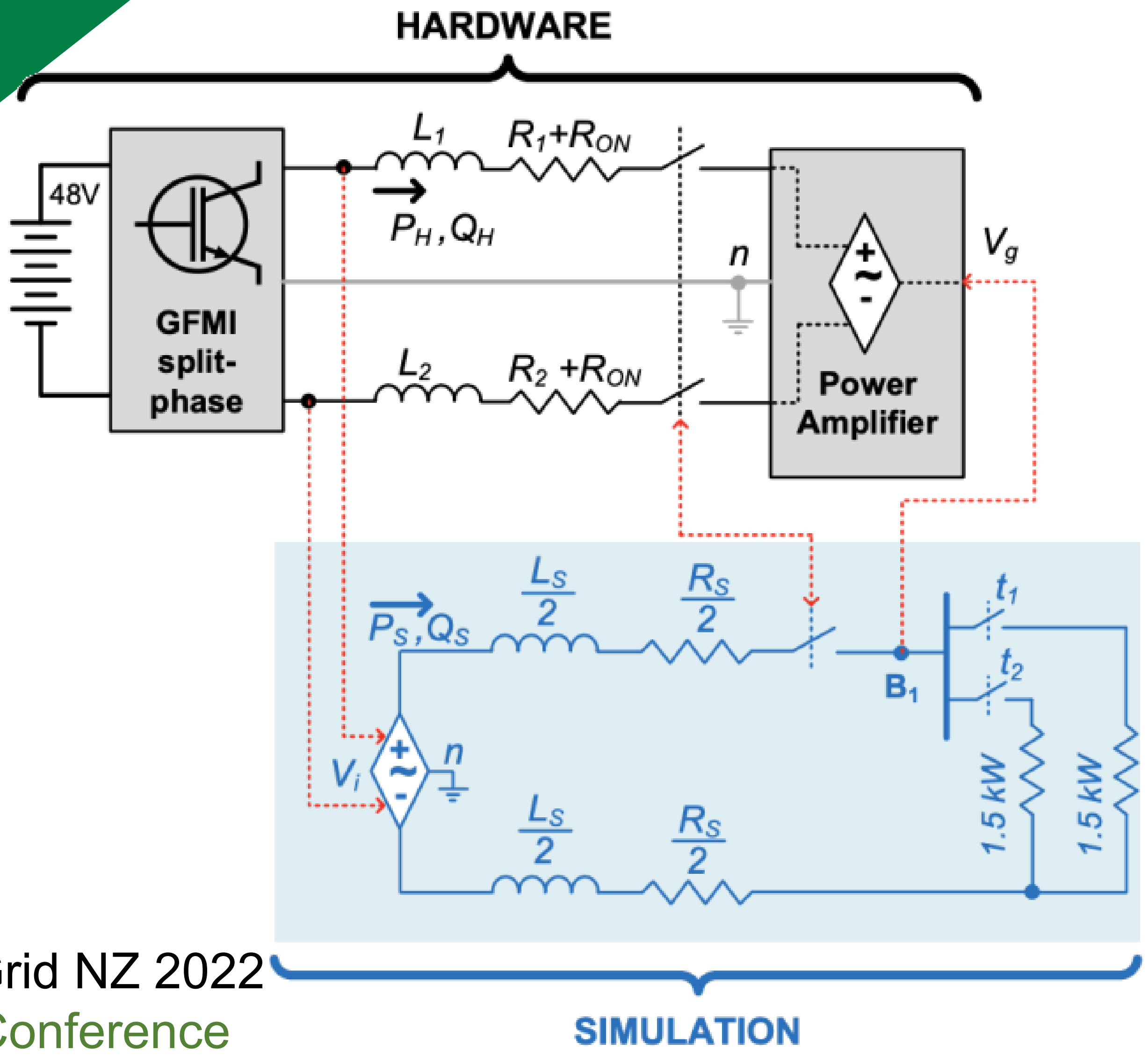
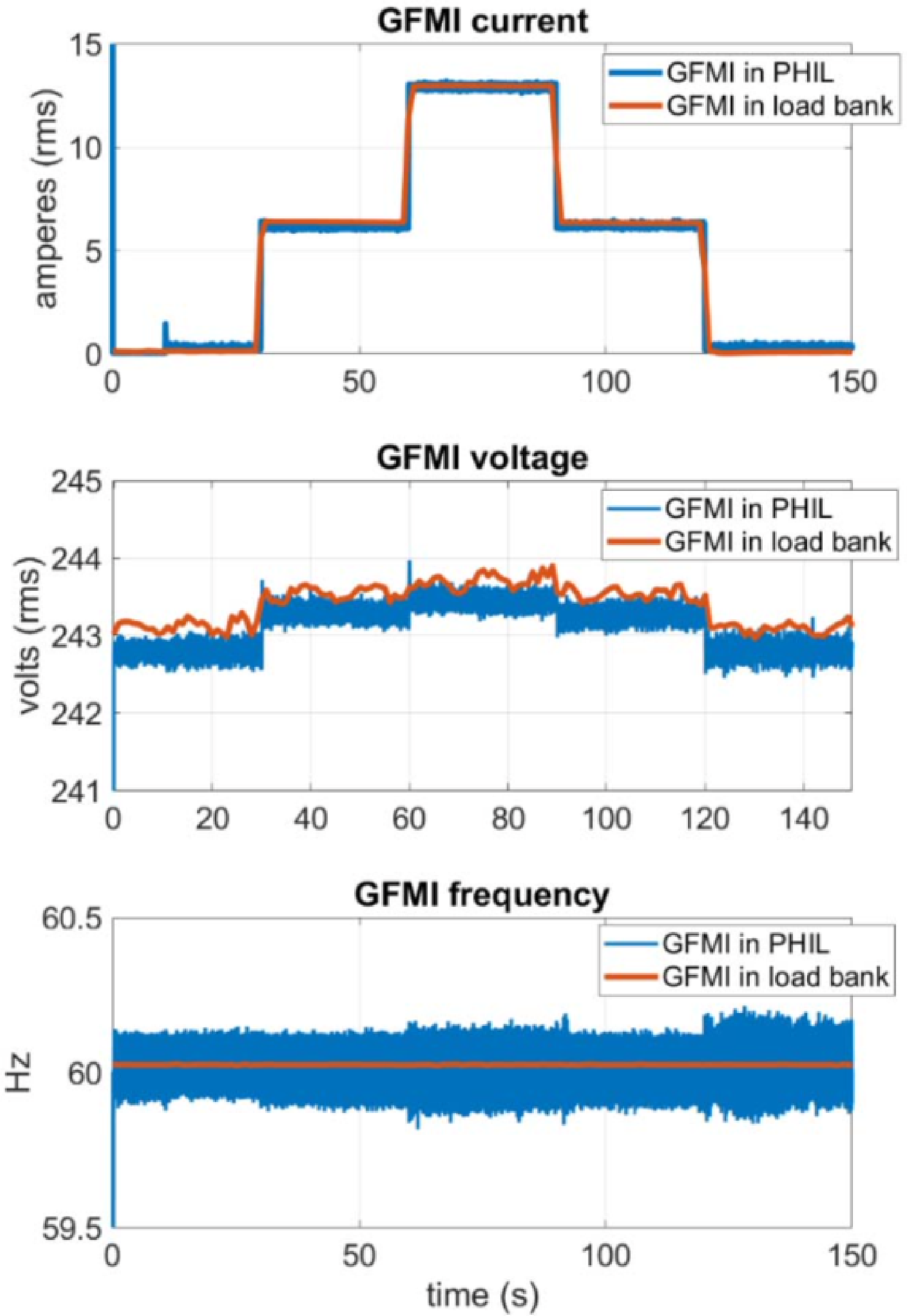
FUTURE ELECTRICITY ARCHIT

Blackstart of GFM in HIL





Future Work

Integration of GFM into power systems is a new a emerging area. HIL car
elucidate behavior of fielded systems

- Protection
  - Short circuit protection
  - Power flow and impedance changes during contingency events
  - Protection in the Loop
- Interoperability with other units
  - Diesel + GFM (significantly different time scales)
  - Multiple GFM (different control mechanisms)
- Black start and islanded operation