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Multiple Inverter Microgrid Experimental Fault Testing

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Introduction

- Inverter based resources (IBR) have low overcurrent capability
  - Photovoltaic inverters usually have less than 1.25 p.u. of current capability
  - Energy storage inverters have less than 3.00 p.u. of capability
- Traditional fault protection utilizes overcurrent detection
  - IBRs cannot sufficiently provide fault current to trip protection devices unless there is a very large generation to load ratio
- Other options for fault detection are needed for systems with high penetration of IBRs, or 100% IBR microgrids
  - Negative- and zero-sequence current detection can be used for unbalanced faults
- Grid-forming inverters (GFMIs) can provide negative- and zero-sequence current depending on control scheme
- Common grid-following inverters (GFLIs) used for PV systems only provide positive-sequence current
  - Other methods are needed to support the system during a fault

Background

- GFMIs are not a technology, but how they are utilized has changed over the years
  - Initially developed for standalone systems, no synchronizing scheme
  - Now they are used for grid support and for microgrid applications
- PV inverter penetration is increasing, but GFLIs are not a perfect system
  - Require a voltage and frequency reference
  - Must meet copious requirements for grid interconnection standards
    - Modern standards require voltage and frequency ride throughs and Grid Support Functions (GSFs) that are a valuable assets for grid stability
  - Are commonly used for intermittent resources
  - High penetration reduce inertia of a system
- GFMIs with proper control schemes can mimic synchronous machines
  - Provide balanced and unbalanced load support
  - Can emulate inertia for grid stability
  - Still current-limited when compared to synchronous machines

Experimental Setup

- Equipment Under Test
  - 100 kW GFMI (energy storage inverter w/ Virtual Synchronous Machine (VSM) control)
  - 24 kW GFLI (PV inverter)
- DC Sources
  - NH Research 9300 100 kW Battery Emulator
  - Ametek TerraSAS 100 kW PV Simulator
    - Set to 1.15 p.u. of GFLI rated power
- Load Bank
  - 0-150kW delta configuration resistive load
- Fault
  - 150kW single phase load (approximately 0.5 ohm)
- Bus Separation
  - 1mH series inductor bank
    - Emulating approximately 500m of line length.

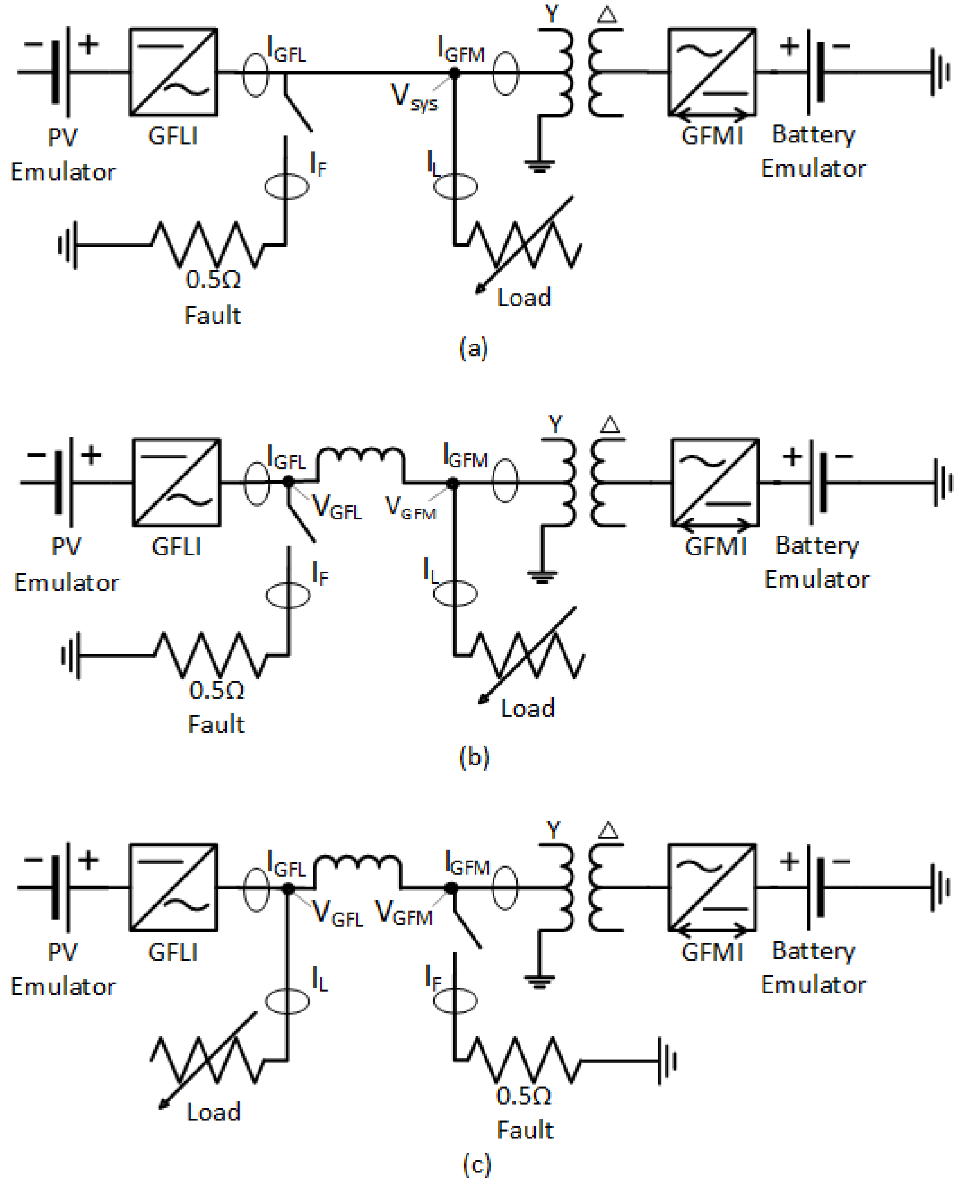

Fig. 1: Experimental Lab Test Configurations, Single Bus Fault (a), GFLI Side Fault (b), and GFMI Side Fault (C)

Baseline Testing

- GFMI subjected to 150kW single phase load
  - 4.5 p.u. of line rating
  - No additional load
  - GFLI removed from system
- All three phase voltages affected
- Inverter provided negative-sequence current, transformer provided zero-sequence current
- Voltage drop on Phase A to 0.536 p.u.
- Fault current of 2.462 p.u. of GFMI line current rating

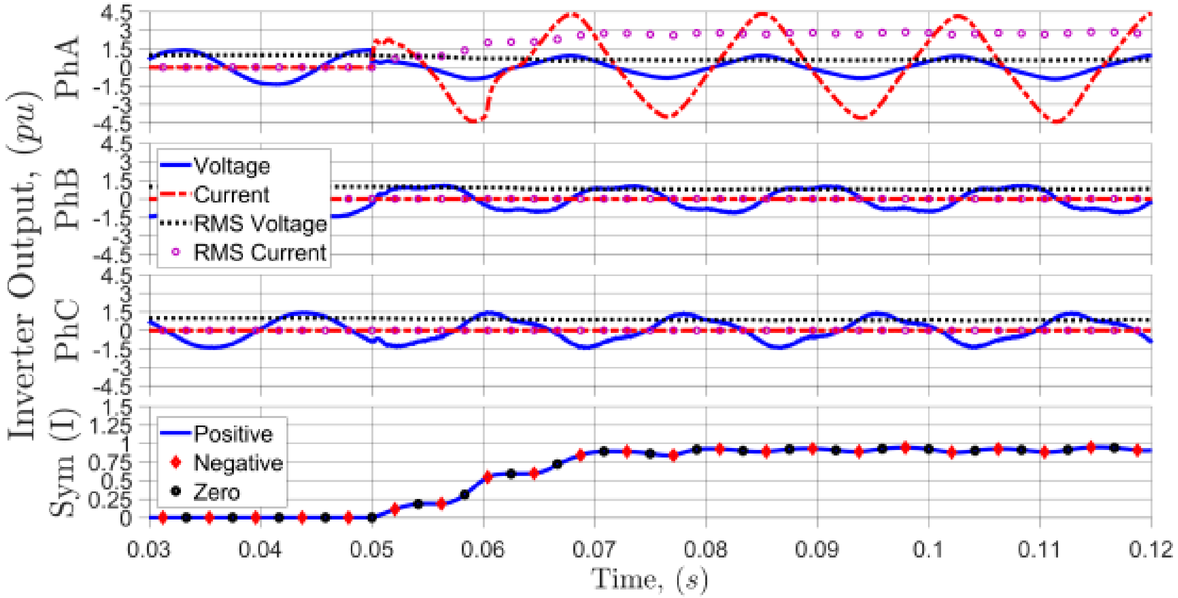

Fig. 3: GFMI Subjected to 150kW Single Line Fault

Single Bus Configuration, GSF Disabled

- GFLI added to the test system
  - 24 kW balanced resistive load added to system to compensate for GFLI generation
- GFLI initially went into momentary cessation during the fault
  - GFMI had to support fault and load
  - System voltage reduced to 0.511 p.u.
- GFLI parameters adjusted to ensure device will not go into momentary cessation
- After rerunning test
  - Voltage of 0.563 p.u. and a total fault current of 2.588 p.u. of GFMI rated current
    - GFMI provided 2.501 p.u. of fault current
    - GFLI supported full load and part of fault (0.36 p.u. of its rated line current)
  - Current oscillation seen from GFLI
    - Reactive power seen even though GSF are disabled
    - Due to Phase-Locked Loop cannot maintain synchronization

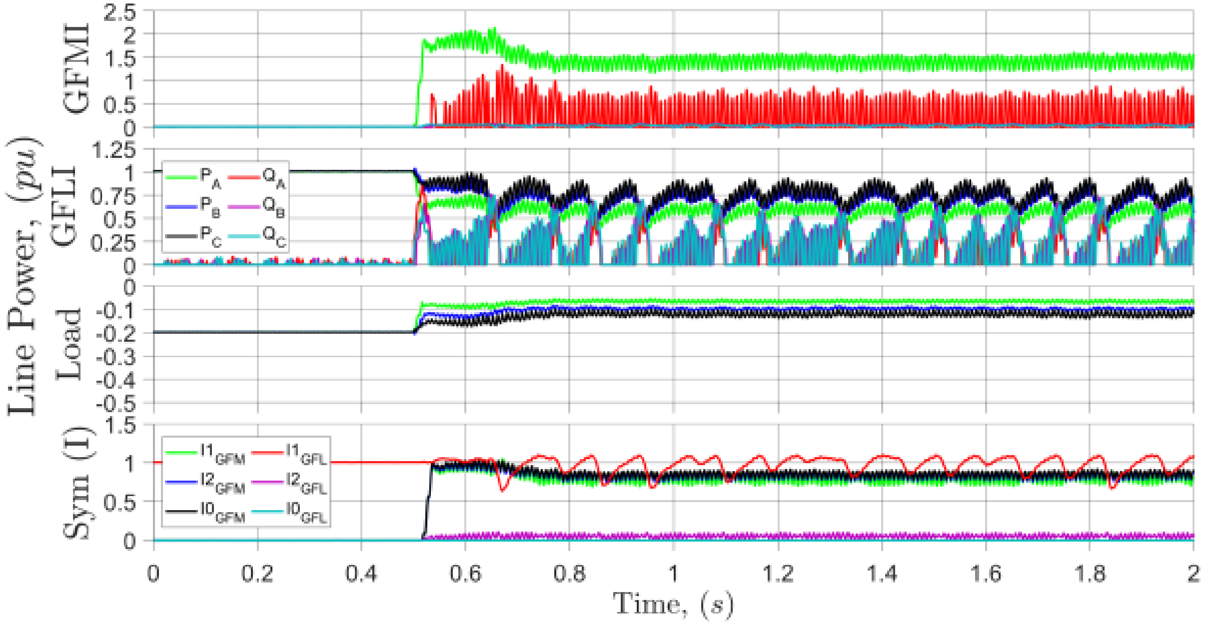

Fig. 5: Configuration A, GSF Disabled, 24kW Load, IBR, Load Power and Sequence Current Injections

Single Bus Configuration, GSF Disabled Continued

- Resistive load increased to 49kW
  - 24 kW for GFLI production
  - 25 kW for 25% of GFMI rating
- System voltage was reduced to 0.481 p.u. following the fault
- Total fault current of 2.329 p.u. of GFMI rated line current
  - GFMI supplied 2.307 p.u.
  - Most of load provided by GFLI

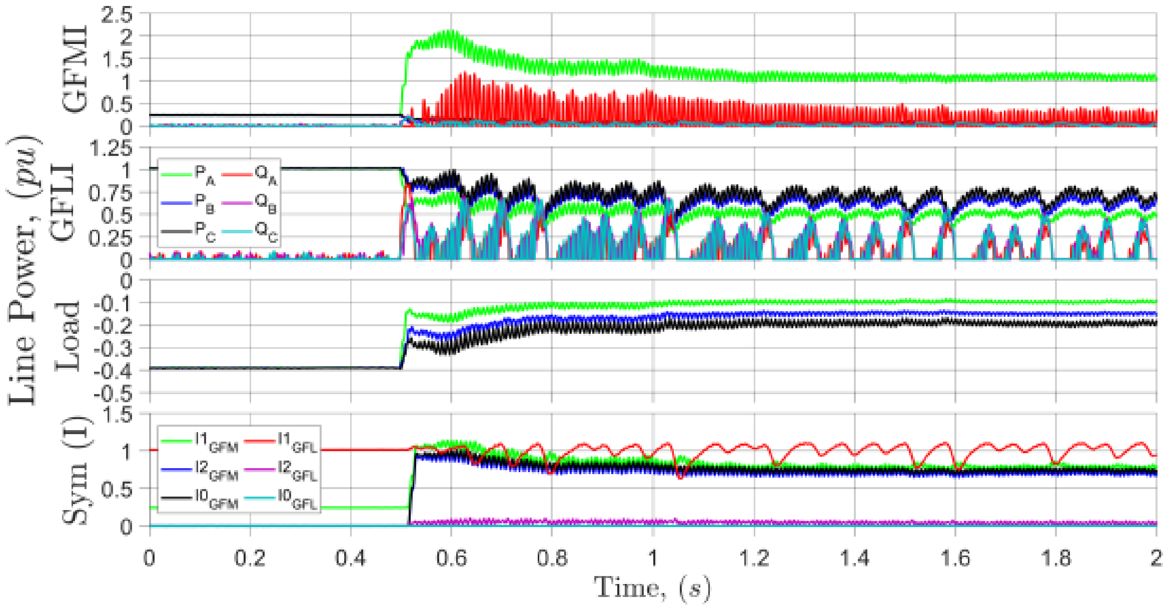

Fig. 6: Configuration A, GSF Disabled, 49kW Load, IBR, Load Power and Sequence Current Injections

Single Bus Configuration, GSF Enabled

- VV and FW enabled in GFLI
  - First test performed with FW profile with pre-disturbance power of 24 kW
- Immediately after fault onset, inverter response is very similar
- VV begins to function within 250ms
- System voltage was 6.5% (of nominal) greater than test w/o GSFs
- Total fault current of 2.545 p.u. of GFMI rated line current - Fully supported by the GFMI
- GFMI also covered small portion of load
- Reactive power of GFLI still increasing following removal of fault
  - GFLI inevitable tripped due to over-voltage event
  - Slow VV response time was set
- VV is supporting system voltage during fault

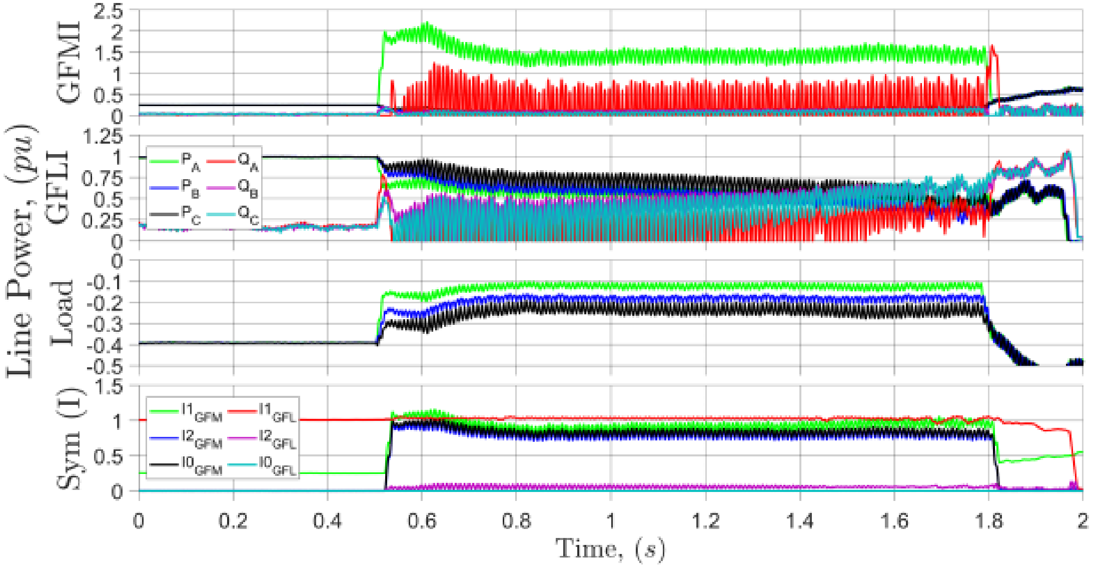

Fig. 7: Configuration A, GSF Enabled, 49kW Load, IBR, Load Power and Sequence Current Injections

GFLI Side Fault Configuration, GSF Disabled

- IBRs split by series line inductance
  - Load placed on GFMI bus
  - Fault placed on GFLI bus
- Total fault current of 1.958 p.u. of GFMI line rating observed
  - GFMI bus comparable to single bus, GSF disabled test
  - GFLI bus was over 6% lower than GFMI bus
- Still observing consistent dynamics of the fault inverters
- Little to no load supported by GFMI

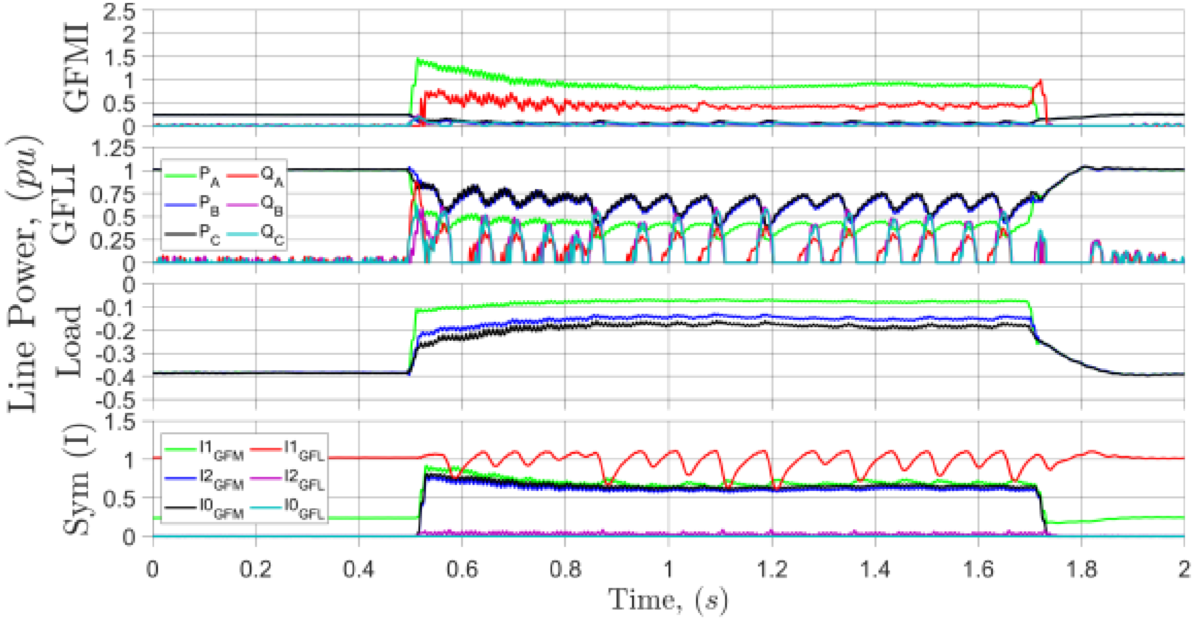

Fig. 8: Configuration B, GSF Disabled, 49kW Load, IBR, Load Power and Sequence Current Injections

GFLI Side Fault Configuration, GSF Enabled

- VV and FW enabled in GFLI
  - Test only performed with FW profile with pre-disturbance power of 24 kW
- Voltage increase of 6% seen on both buses
- 2.238 p.u. of GFMI rated line current was seen for total fault current
  - Better bus voltages and fault current
  - Still lower GFLI bus voltage than single bus case
- GFMI supported load as GFLI real power was decreased by VV function
- Having fault away from primary source or voltage source is not ideal for system support

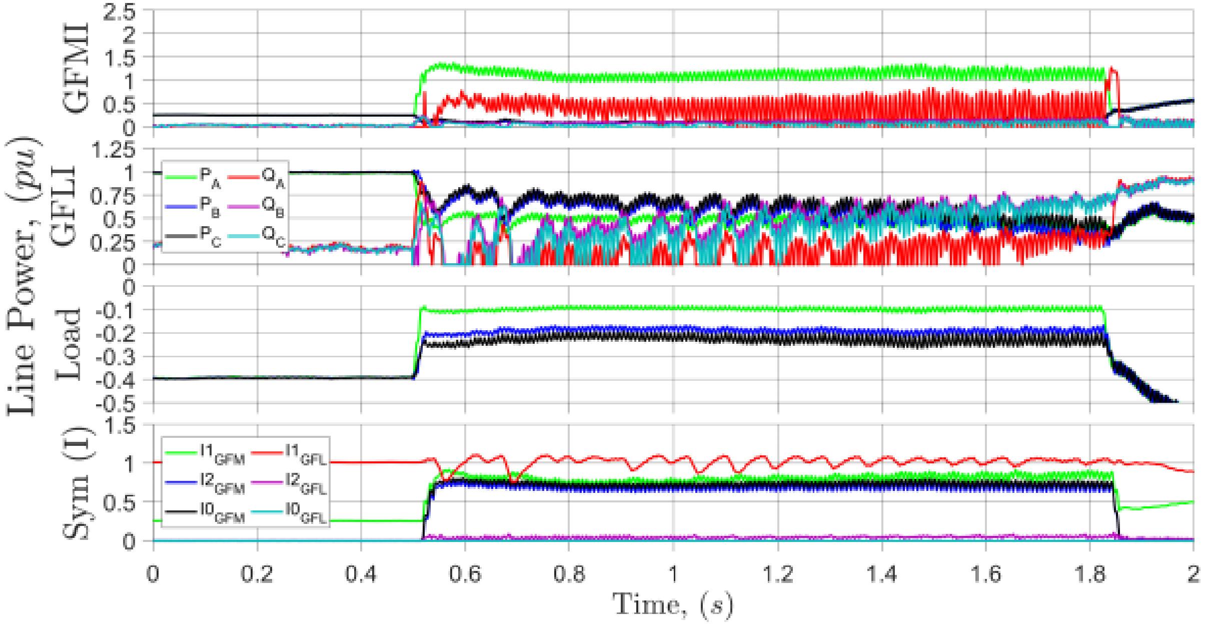

Fig. 9: Configuration B, GSF Enabled, 49kW Load, IBR, Load Power and Sequence Current Injections

GFMI Side Fault Configuration, GSF Disabled

- Load and fault locations were reversed
  - Fault now on GFMI bus
- 3.5-4.5% increase in voltage from single bus, GSF disabled test
  - Voltage drop along line length was minimal, around 1% lower in GFLI bus
- Total fault current of 2.404 p.u. of rated GFMI line current
- Still very little load being supported by GFMI

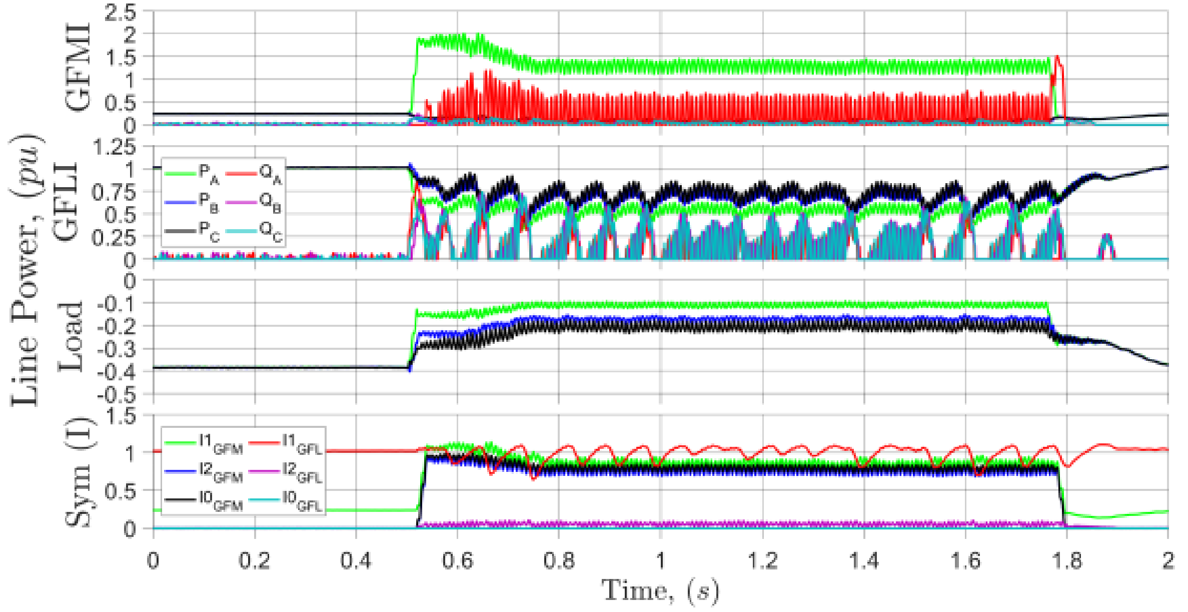

Fig. 10: Configuration C, GSF Disabled, 49kW Load, IBR, Load Power and Sequence Current Injections

GFMI Side Fault Configuration, GSF Enabled

- VV and FW enabled in GFLI
  - Test only performed with FW profile with pre-disturbance power of 24 kW
- 1.5-4.5% increase in voltage was seen on the two buses
  - GFLI side was now around 1.0-1.5% greater than the GFMI bus
  - Highest average bus voltage (other than 24 kW load test)
- Total fault current of 2.497 p.u. of GFMI rated line power
- Current being supplied to load from GFMI
  - Still had high bus voltages even though current flow through inductors

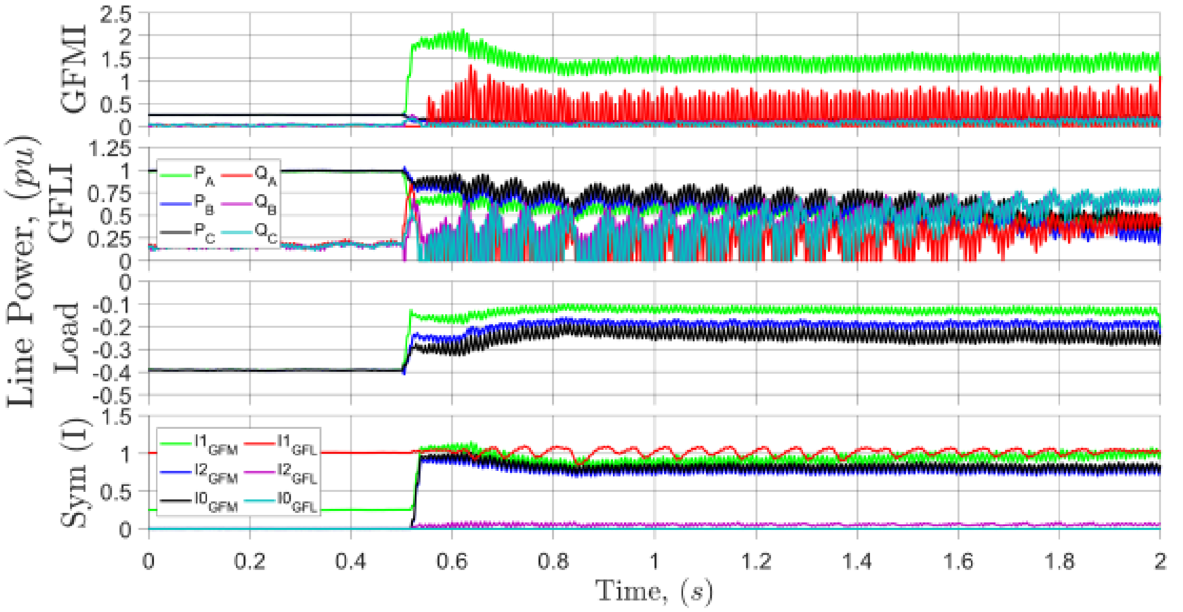

Fig. 11: Configuration C, GSF Enabled, 49kW Load, IBR, Load Power and Sequence Current Injections

Conclusion

- Different technologies have unique responses to faults due to their physics and controls
  - It is important to understand these differences
- GFLIs with GSFs can help support the system during a fault
  - If the fault is near the GFLI or far away from the primary source, having GSFs enabled (specifically VV) is more important than the GFLI supporting the load.
- Ensuring that GFLIs do not go into momentary cessation is crucial to support the system, and not rely on only grid-forming devices
- Fault recovery is additionally important
  - Too aggressive or slow of a response can lead to over voltage or frequency events and cause GFLIs to trip putting all the load on GFMIs
  - IBR response times and settings are vital to both fault support and recovery

Thank You