Grid Forming Inverters

Tutorial

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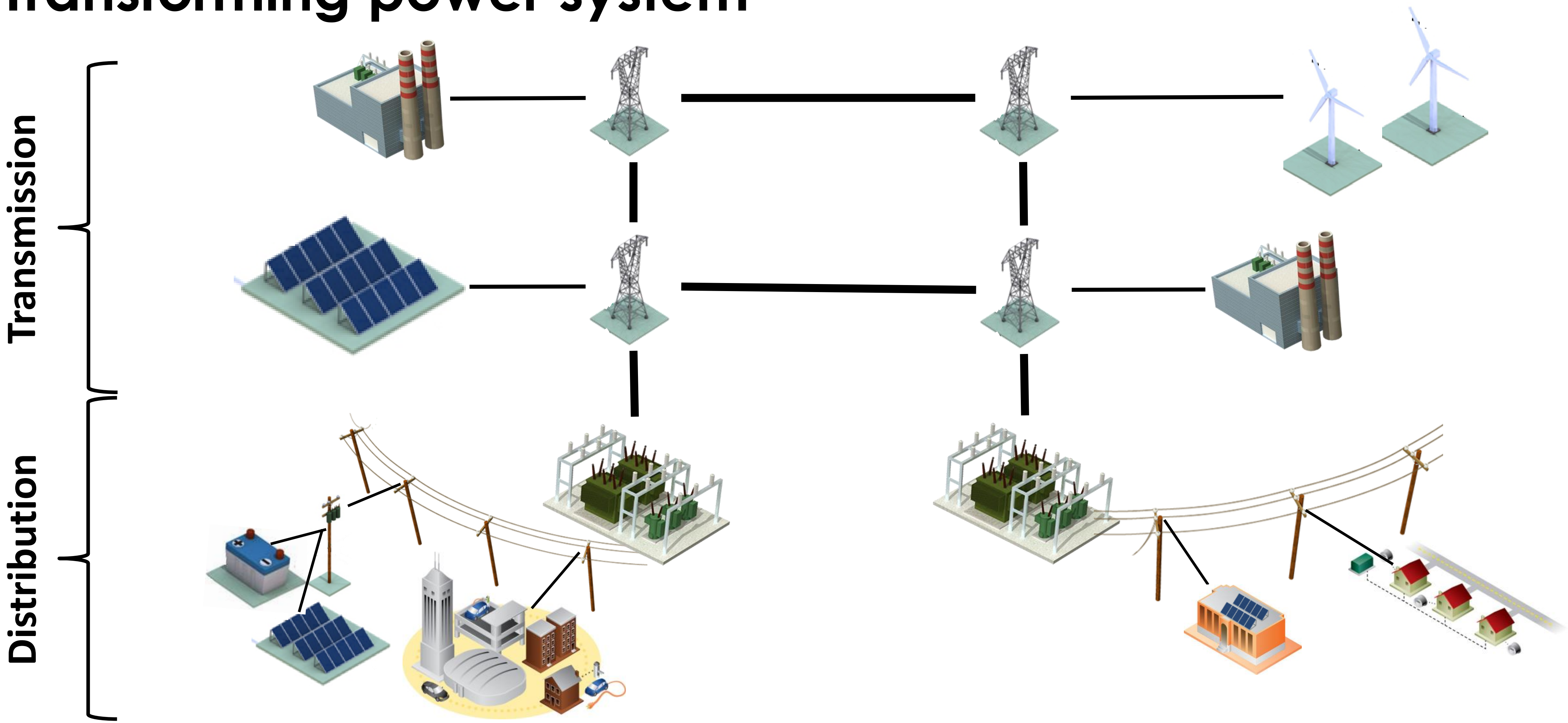
Agenda

- Introduction
- Definition of grid-forming (GFM) inverters
- Survey of a few GFM control methods
- Use cases of GFM inverters in distribution and transmission grid
- Break (15 min)
- GFM inverter performance requirements in microgrid
- Design considerations for GFM generation plants
- Planning a transmission network with GFM
- Summary

Introduction

Transforming power system

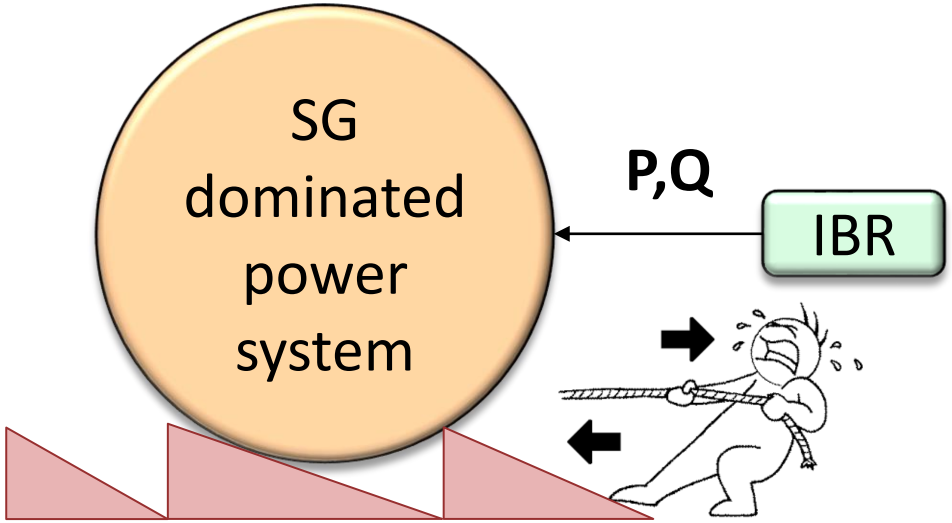


Central synchronous generators (SGs) are being replaced by transmission and distribution connected inverter-based resources (IBR), primarily wind and solar PV.

Evolving system needs expected from Inverter Based Resources (IBRs)

Power system	System needs from IBR
Past: SG dominated system	Unity power factor, minimal fault ride-through …
Present: Increased penetration of IBRs	Automatic voltage control, frequency response, V/F ride-through …
Future: IBR dominated system	Without relying on SGs, provide the above services and more (fast frequency response, maintain system stability…)

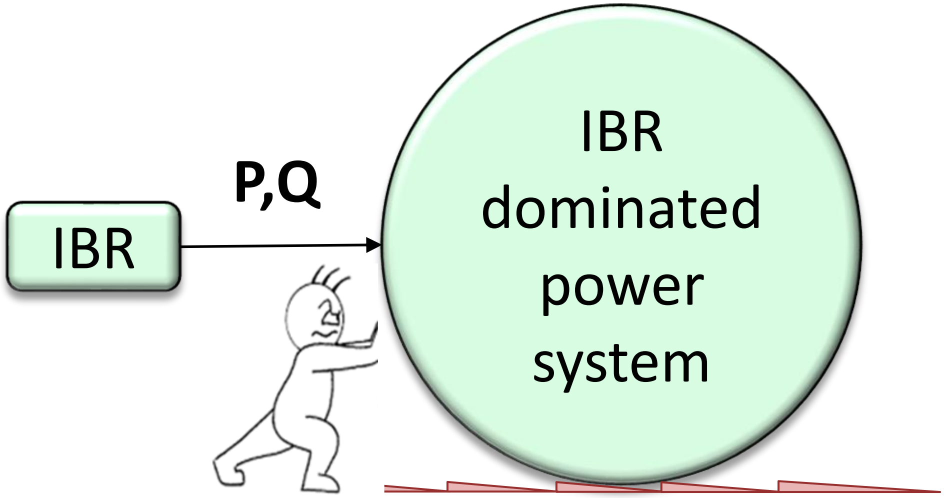
Challenges for IBRs to provide future grid services



- Majority of today's IBR control is designed to work in a stiff system
  - Changes in IBR injected current do not 'move' the stiff system
  - Changes in system cause IBR to 'move' in tandem

- This behavior has recently been labeled as grid following (GFL)

Challenges for IBRs to provide future grid services (cont'd)



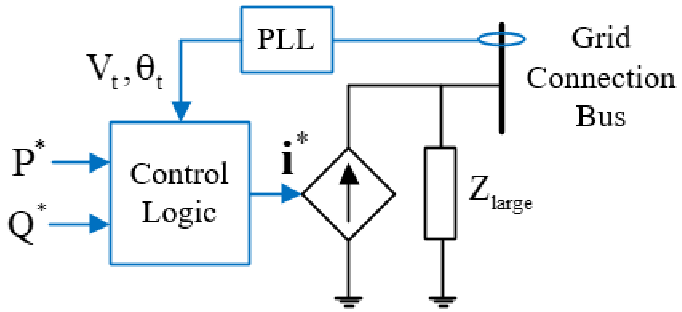
- In IBR dominated power system:
  - Increased elasticity in the grid
  - Changes in IBR injected current will 'move' the system
  - This movement in system will itself cause IBR to 'move' in tandem
- This increased interaction is to be stabilized for IBR to deliver expected needs

Could grid forming (GFM) IBRs be the solution to provide services in an inverter dominated grid?

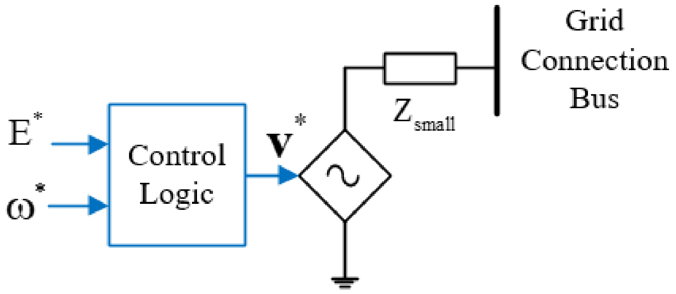
Definition of Grid-Forming Inverters

You may have heard this regarding grid following (GFL) and grid forming (GFM) inverters

High level definition based on specific control design



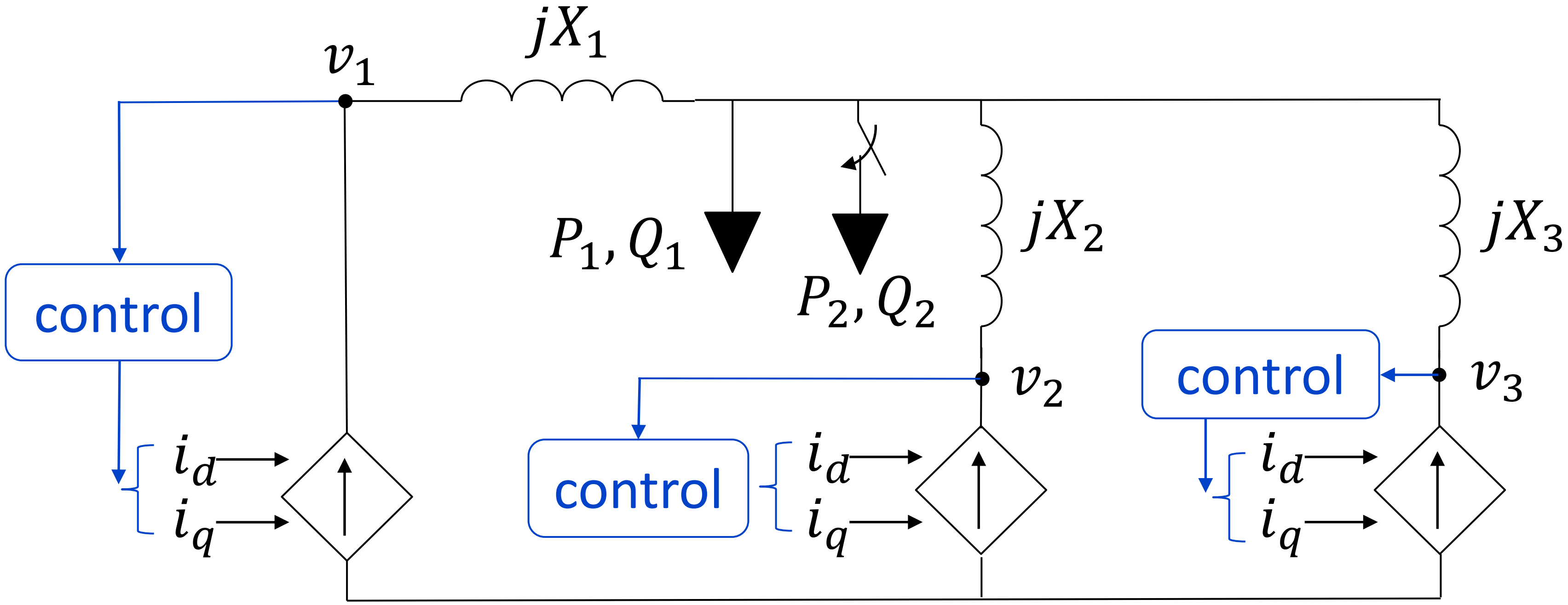
Grid-following inverter



Grid-forming inverter

Grid following IBR is a current source…it has a PLL….a network with only current sources and PLLs cannot be stable….hence grid forming…

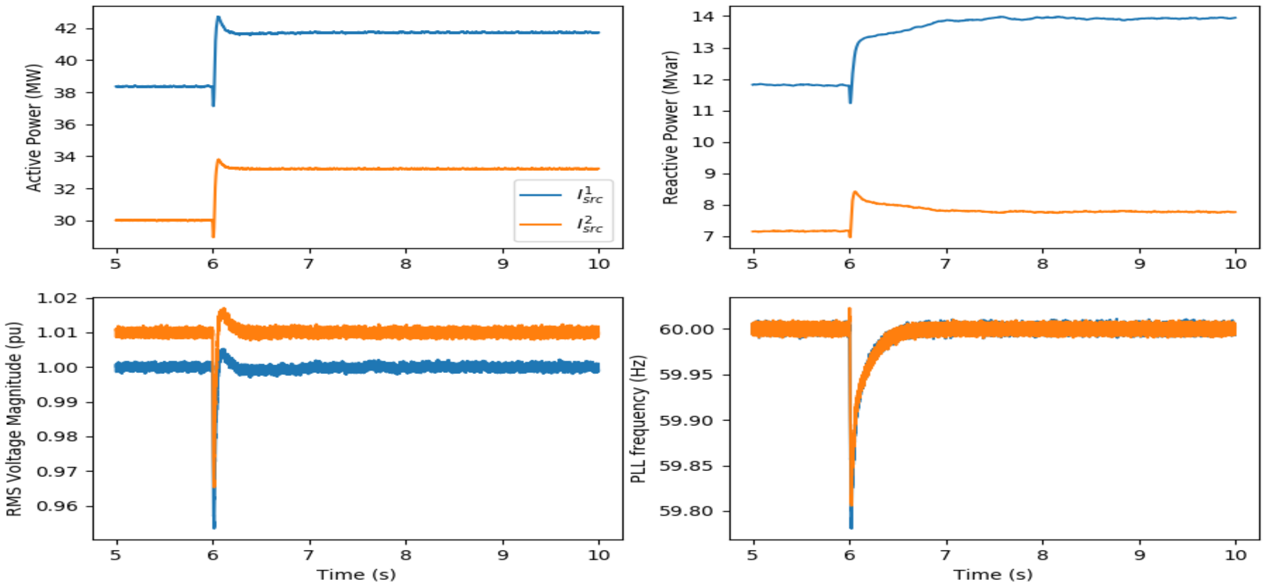
But Kirchhoff's Laws still apply in a 100% current source network

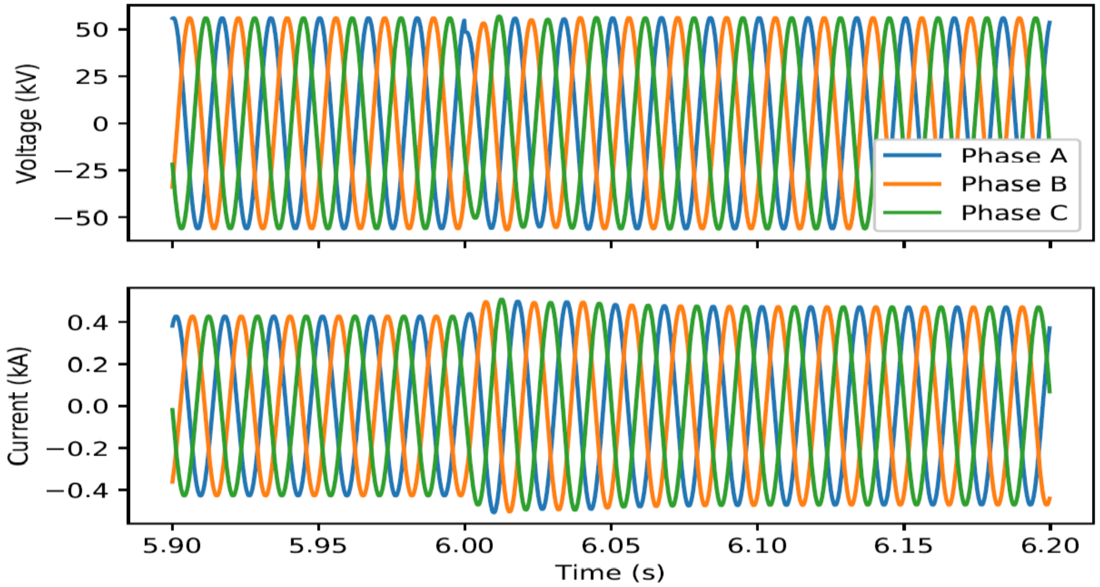


- Voltage levels in network decided by current and impedance
- Network will collapse if i_d and i_q do not change when load changes
- But from circuit theory, this network has a stable/viable solution

Values of injected current to be controlled in a timely manner for network to be stable

But Kirchhoff’s Laws still apply in a 100% current source network (cont’d)





10% increase in constant power load

What does this have to do with grid forming behavior?

Demo

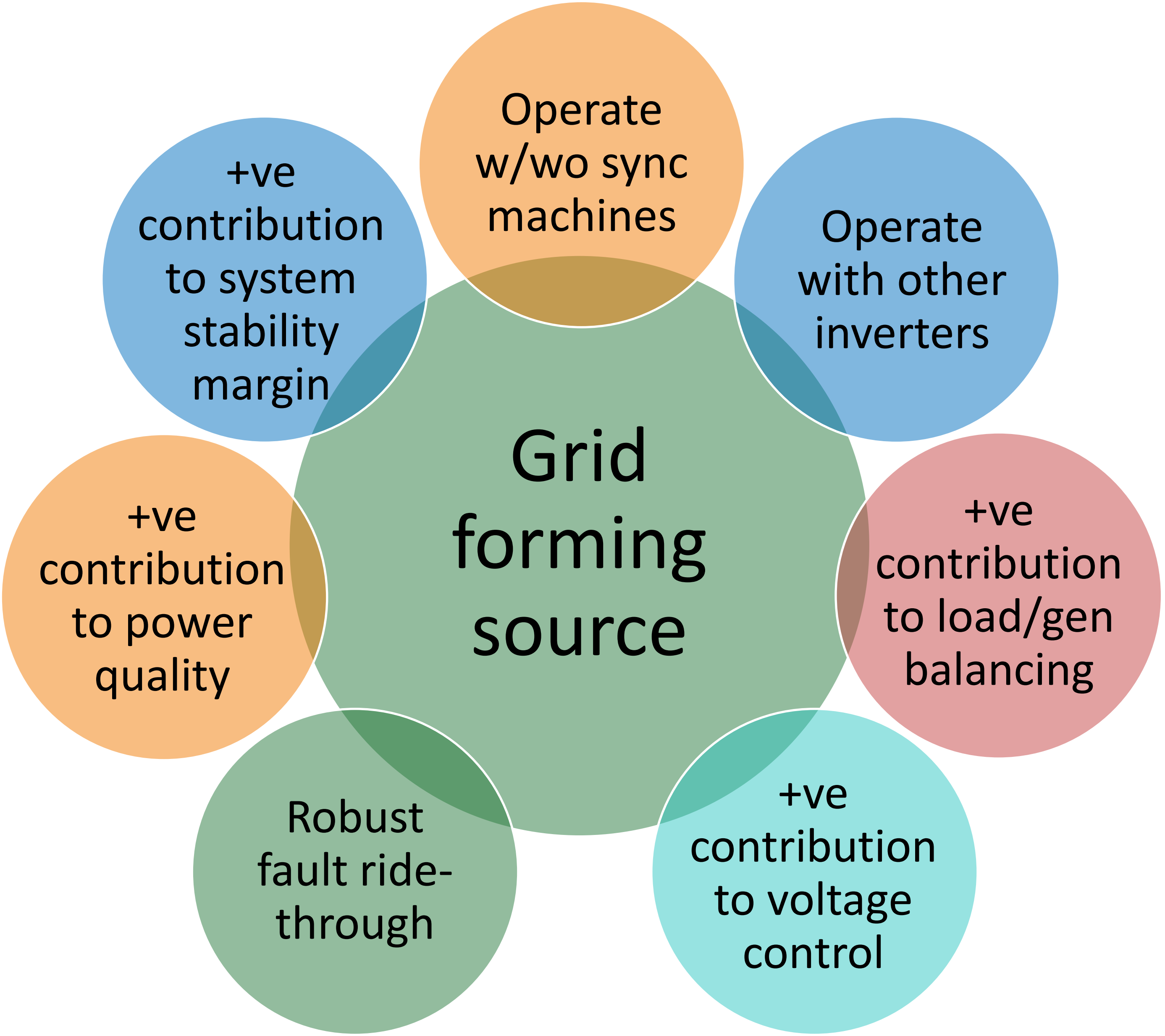
- Let’s look at few demo cases in simulation

Defining grid forming behavior from system planner perspective

- Continued operation of 100% current source network is possible
- Today's inverter may have issues operating in weak grid simply because the control is designed and tuned for strong grid operation
  - PLL is just part of the control architecture to obtain synchronization
  - It is not the sole cause of instability in weak grids
- This does not mean inverter control with PLL cannot be developed to work in weak or even 100% IBR grids

Can be beneficial to define grid forming using a performance based approach

Performance requirement for grid forming source



- GFM inverter can be defined based on its capability and the grid services it provides.
- These services should be provided while *meeting standard acceptable metrics* associated with reliability, security, and stability of the power system and *within equipment limits.*
- *Few GFM sources* can also be designated as blackstart resources

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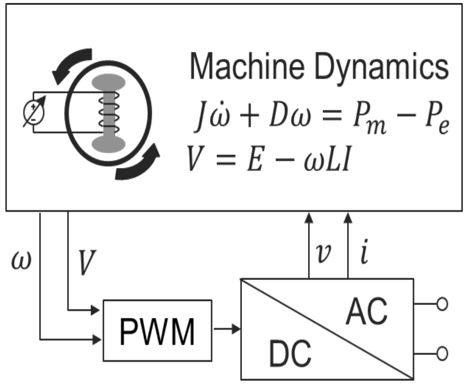
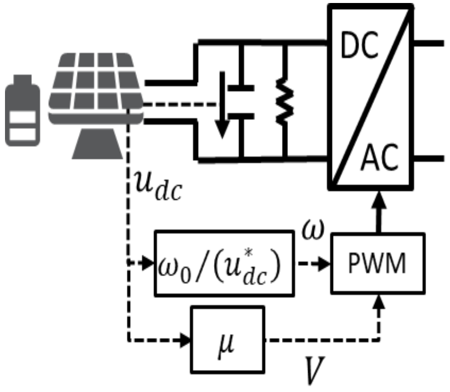
Survey of a few GFM Control Methods

Example GFM inverter controls from the literature

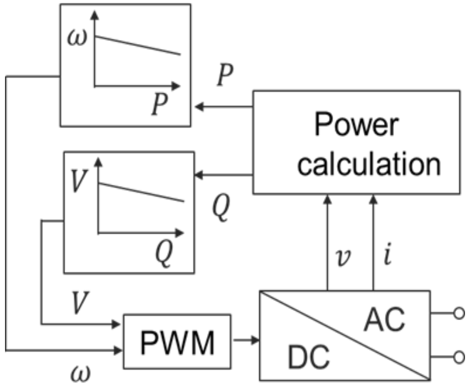
Virtual synchronous machine [1]



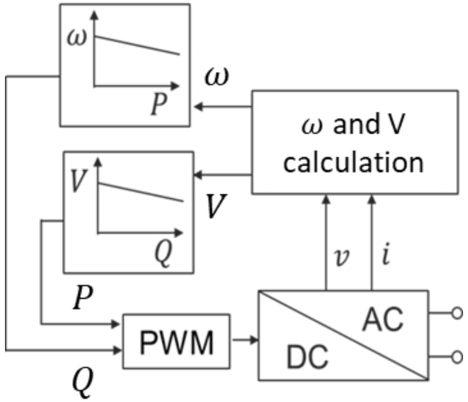
Matching control [2]



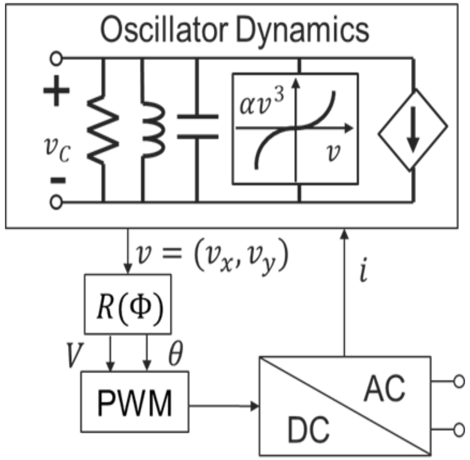
Droop based control [3]



FERC Orders 842 and 827 based control [4]



Virtual oscillator control [5]



Emulate Synchronous Machine Dynamic Behavior (Virtual synchronous machine, Matching control)

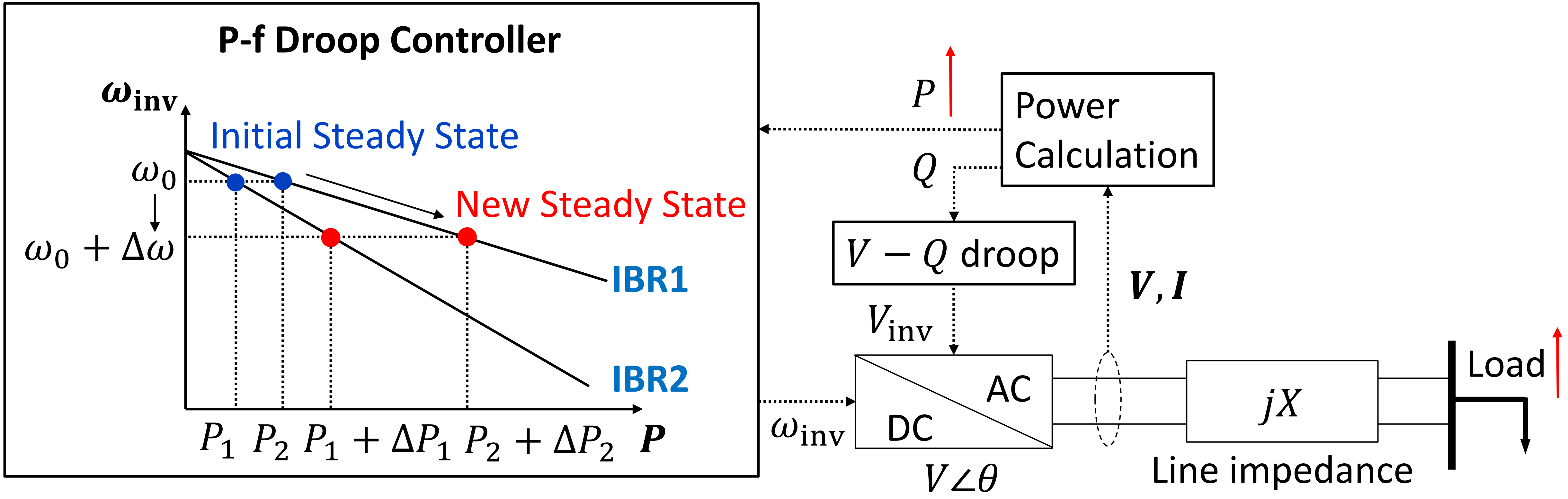
P-f and Q-V Droop (Droop based control, FERC Orders 842 and 827 based control)

Nonlinear Control (Virtual oscillator control)

Phasor-Domain Controller

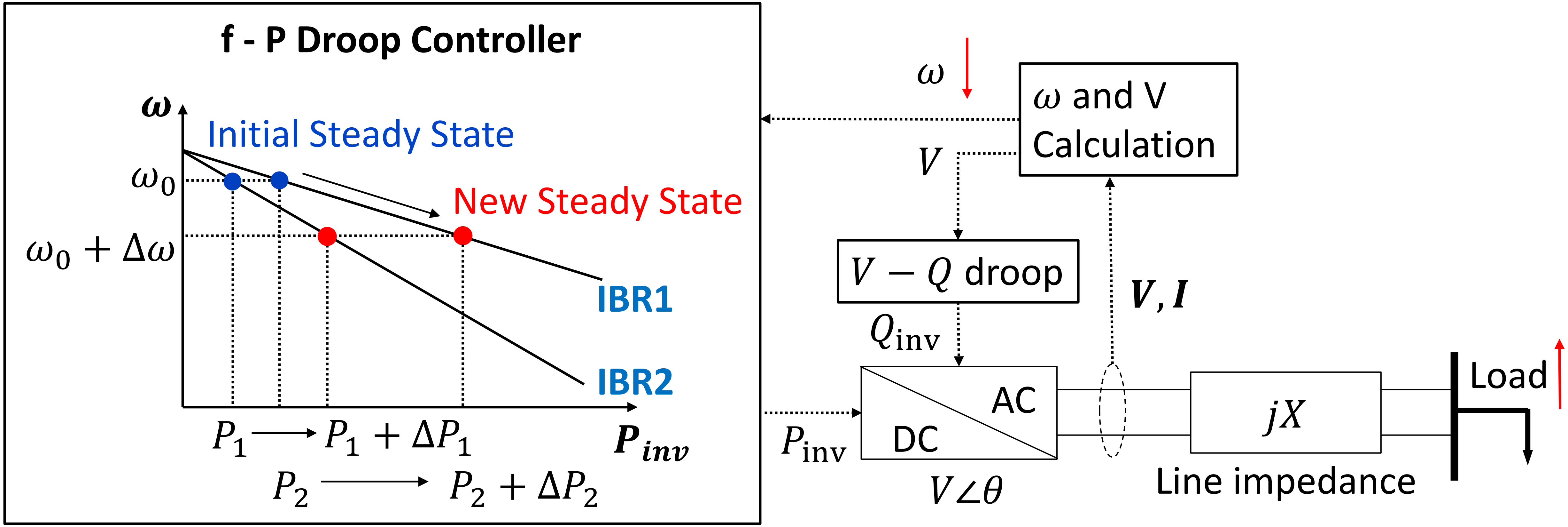
Time-Domain Controller (Faster Dynamics)

Operation principle of droop control



Load change is shared by IBRs with P-f droop

Operation principle of FERC order 842 and 827 control



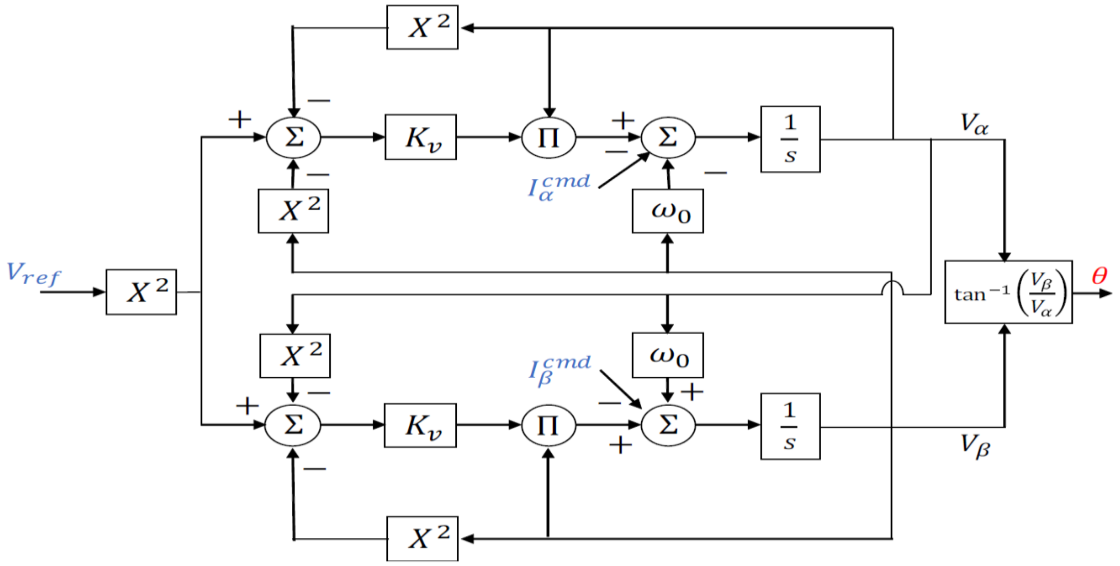
Load change is shared by IBRs with f-P droop

Let us stop for a moment here…

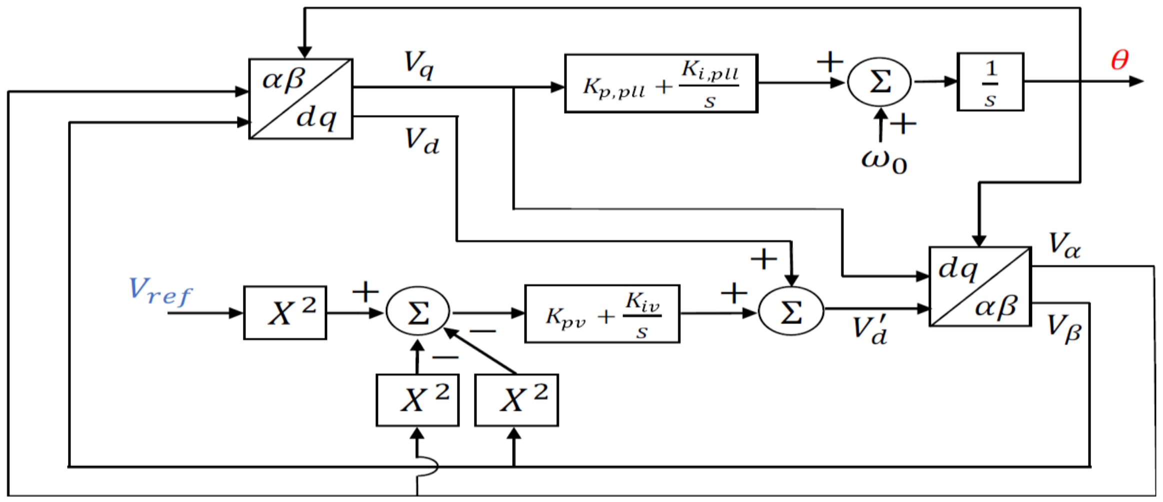
- Keeping our focus on the initial transient and subsequent dynamic time frame (60s after a disturbance)
- Traditional grid following (GFL) inverter resources
  - Both P_{inv}^{ref} and Q_{inv}^{ref} are constant
- Intermediate grid following inverter resources
  - $P_{inv}^{ref}(\omega_{pll})$ but Q_{inv}^{ref} is constant
  - Frequency support is 'slow' and at the plant level
- Possibility of grid forming behavior (?)
  - Both $P_{inv}^{ref}(\omega)$ and $Q_{inv}^{ref}(|V|)$ are varying based on system conditions
  - Both controls are 'fast' and implemented at the inverter level

How can this concept help when developing control agnostic requirements for future inverters?

Conceptual similarities between operation of PLL and other grid forming control techniques



Virtual Oscillator



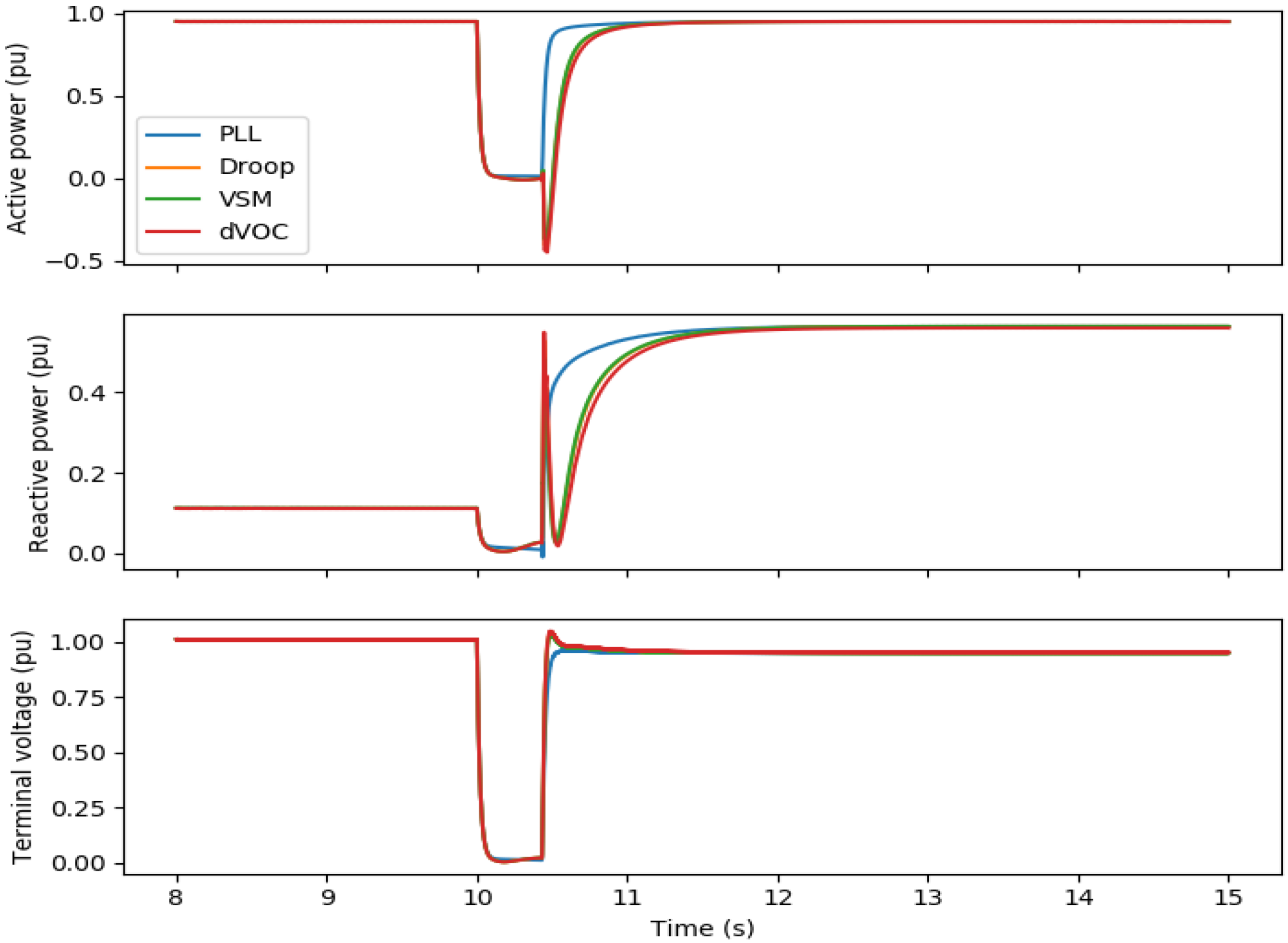
PLL – Voltage controlled oscillator

- A virtual oscillator uses internal state variable feedback to generate a sine wave
- A PLL with an additional voltage control loop uses external output variable feedback to generate a sine wave

Deepak Ramasubramanian and Evangelos Farantatos, "Representation of Grid Forming Virtual Oscillator Controller Dynamics with WECC Generic Models," 2021 *IEEE PES General Meeting*, Washington D.C. USA, July 2021

Similar response in EMT domain across four GFM types for low short circuit conditions

- System conditions
  - Pre-fault SCR = 3.0
  - Post-fault SCR = 1.0
  - X/R ratio = 14
  - 3PHG fault at POI, Zf = 0.0, duration 0.43s
- Model controls not optimally tuned



Structural similarity exists between different control mechanisms

Summary

- There are numerous ways of controlling an IBR to achieve the same desired result
  - Newer forms of control continue to be proposed and developed

- From a system planner perspective, it could be more beneficial to define desired IBR performance rather than specific form of IBR control topology

Use Cases of GFM Inverters in Distribution and Transmission Grid

Existing and potential application of grid forming inverters

- In the near term, GFM inverters are primarily considered in
  - Inverter-based microgrid design
  - Transmission systems with low fault current and rotational inertia
- In the future, thousands of GFM inverters may be deployed in both transmission and distribution grids to support reliable operation with low grid strength
- Stable and reliable coordination between numerous GFM inverters, and with other devices in grid-connected mode, is a major challenge

Few examples of GFM installations in utility-level microgrids

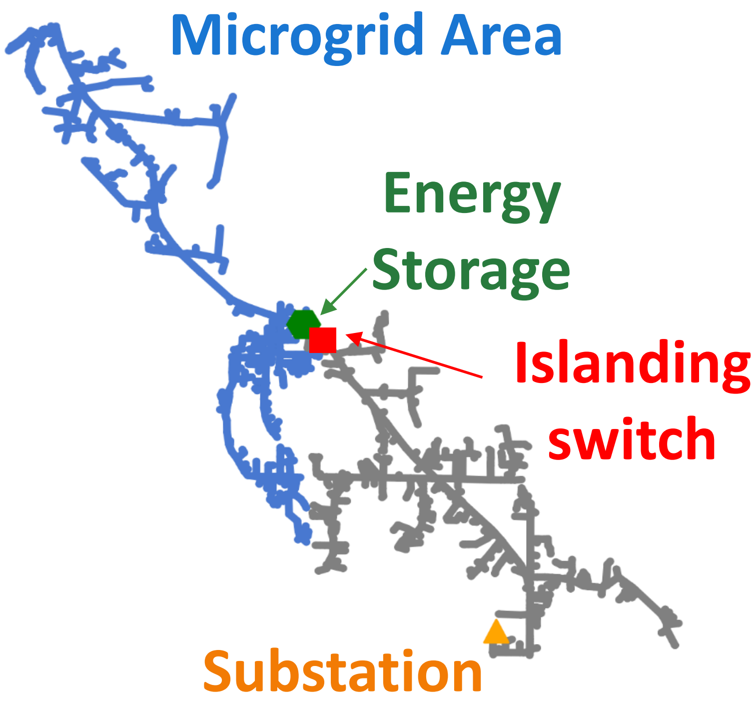


Illustration of a utility-level microgrid containing a section of a distribution feeder

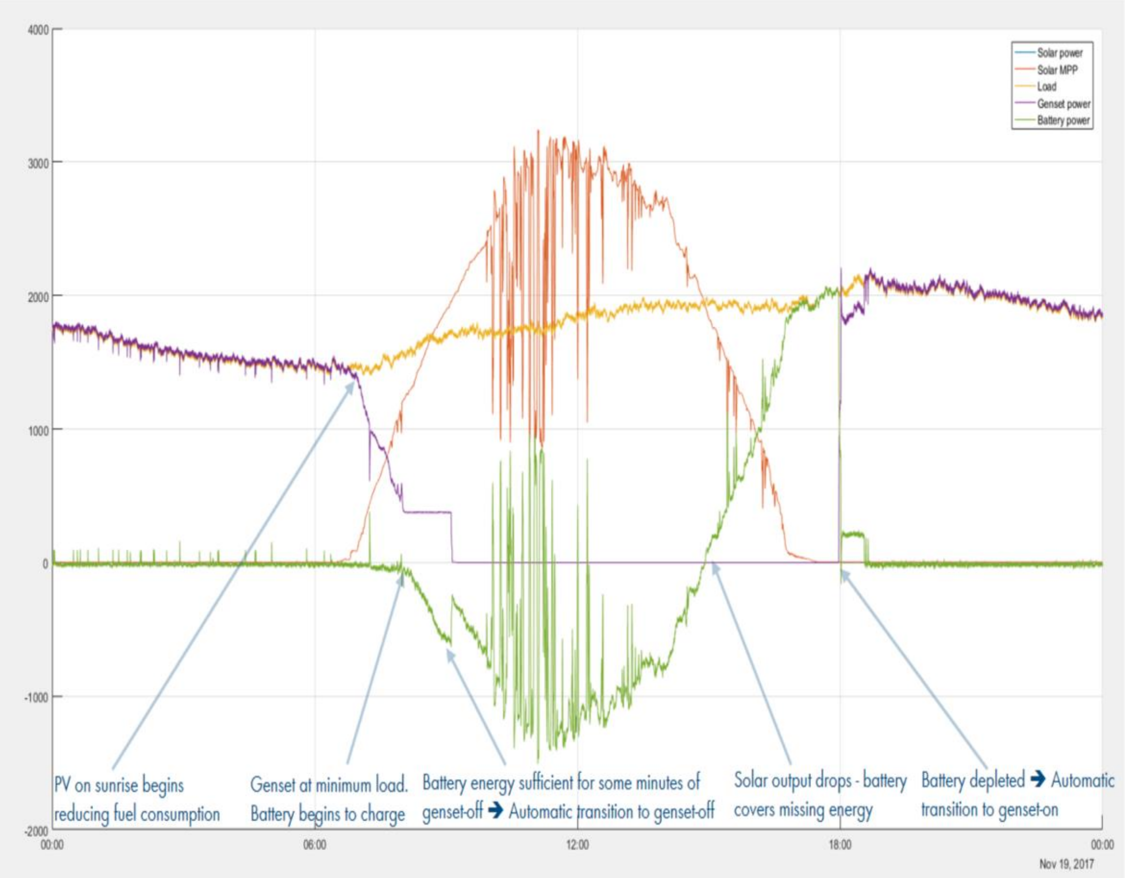
- BESS with GFM capability has been deployed in a growing number of inverter-based microgrids
- Micanopy microgrid, FL
  - Section of a MV feeder with 8.25 MW BESS to support the town of Micanopy and nearby neighbors during grid outage
  - Source: https://news.duke-energy.com/releases/duke-energy-florida-announces-three-new-battery-storage-sites-including-special-needs-shelter-and-first-pairing-with-utility-solar

Few examples of GFM installations in utility-level microgrids (cont'd)

- National Grid microgrid, NY (in process)
  - BESS requirements are 20 MW, 40 MWh, 75 MVA short circuit current
  - The system includes 5 substations, 46 kV sub-transmission line, and 10 feeders, which can separate to form an island supplied by the battery
  - Source: https://www.nationalgridus.com/media/pdfs/bulk-energy-storage-request-for-proposals/appendix-e-locations-usecases.pdf
- Waterton microgrid, AB (in process)
  - Section of a MV feeder with a 1.6 MW, 5.2 MWh BESS and a 200 kW PV site at different locations
  - Source: https://www.pc.gc.ca/en/pn-np/ab/waterton/visit/infrastructure/solaire-solar

Few examples of GFM installations around the world

- BESS in St. Eustatius Island
  - 2.3 MW peak load, 100% (Solar + storage) operation mode during daytime
  - Diesel free daytime electricity supply
    - Savings of 1.7 million liters of diesel fuel / yr
  - Load distribution across several parallel GFM units (no communication)
  - Seamless and immediate load transfer after simultaneous loss of all gensets at peak load
  - Source: https://www.sma-sunny.com/en/st-eustatius-100-solar-power-in-the-caribbean/



More examples available at: Julia Matevosyan, "Survey of Grid-Forming Inverter Applications," G-PST/ESIG Webinar Series, June 2020 (link)

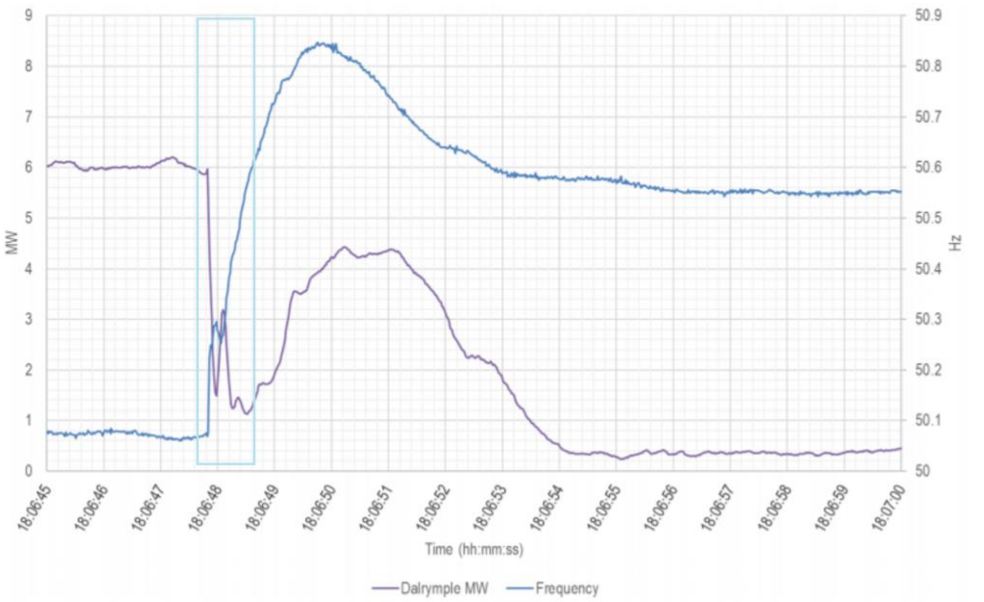
Few examples of GFM installations around the world (cont’d)

- Dersalloch Wind Farm in Scotland
  - 69 MW of wind turbines operated in GFM mode for 6 weeks
    - Virtual synchronous machine mode used
  - Wind farm responded to both large underfrequency events and phase steps.
  - Island operation (7 MW load) and blackstart capability of wind turbines to energize wind farm and re-synchronize with the grid
  - Source: https://renewablesnow.com/news/scottishpower-completes-black-start-project-using-69-mw-wind-farm-719904/

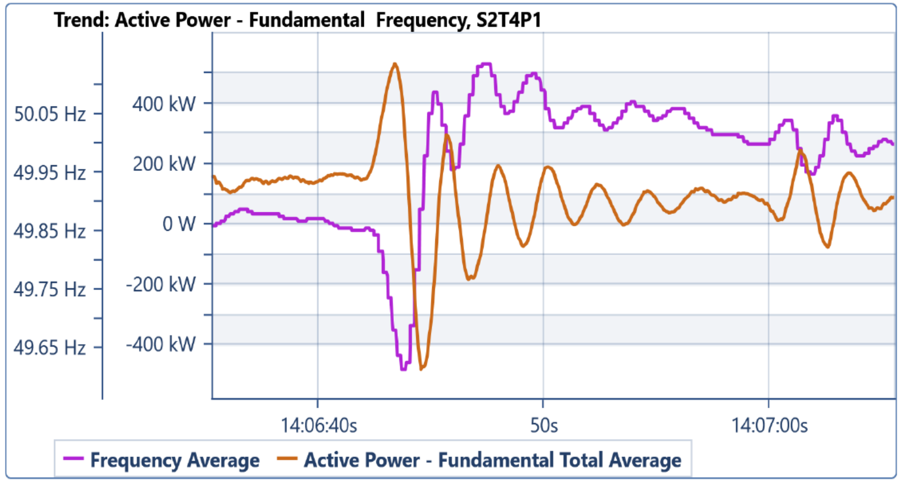
More examples available at: Julia Matevosyan, “Survey of Grid-Forming Inverter Applications,” G-PST/ESIG Webinar Series, June 2020 (link)

Few examples of GFM installations around the world (cont'd)

- Dalrymple BESS in South Australia
  - 30 MVA and 8 MWh battery connected close to 91 MW wind farm and 8 MW load
  - In first six months of operation, reduced loss of supply in area from 8 hours to 30 min
  - Source: https://go.hitachi-powergrids.com/grid-forming-webinar-2020



- Hornsdale BESS in South Australia
  - 150 MW/ 194 MWh BESS co-located with wind farm
  - Recently in 2020, provided response during a large grid disconnection event
  - Source: https://arena.gov.au/knowledge-bank/presentation-arena-insights-webinar-advanced-inverters/



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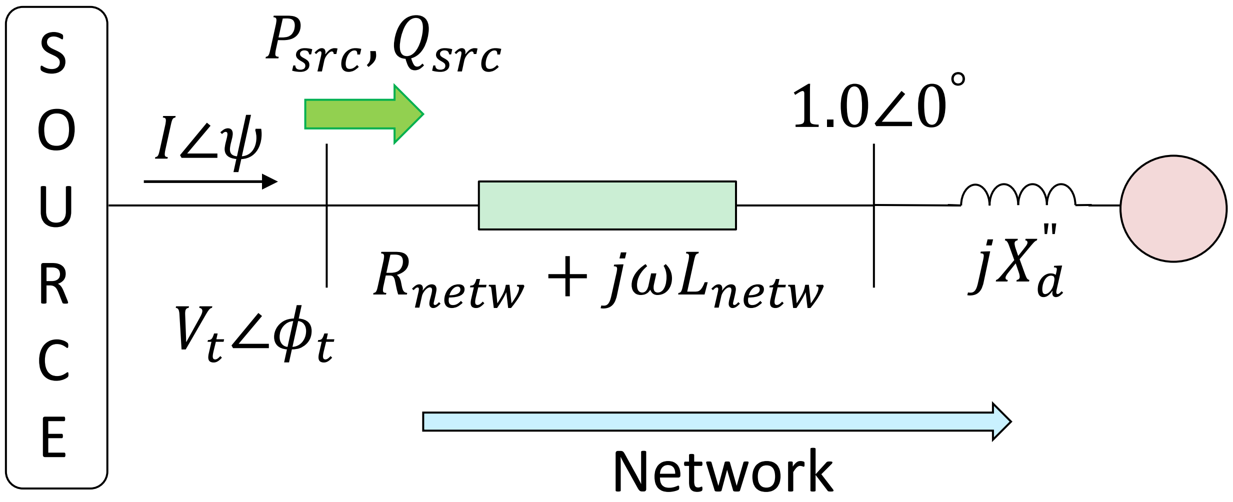
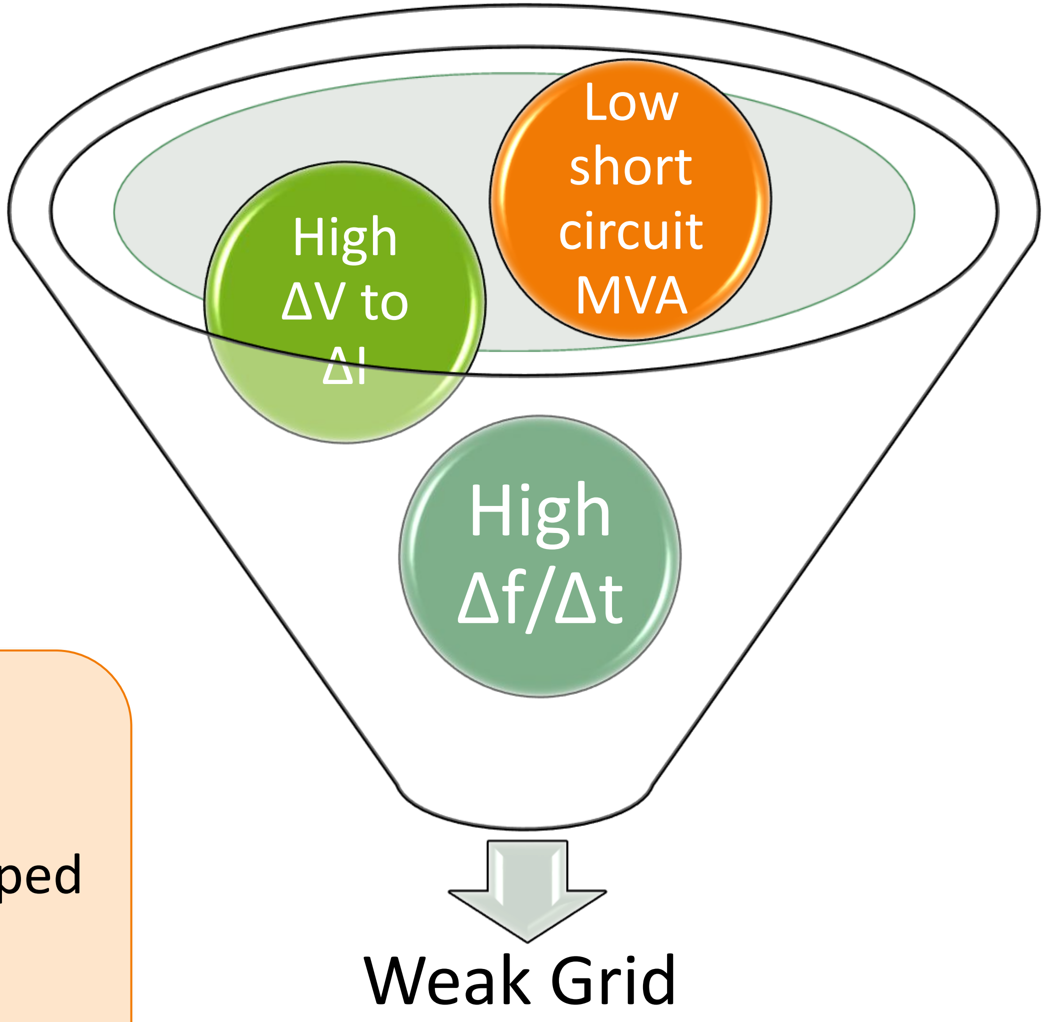
Defining, evaluating, and stability in weak grids

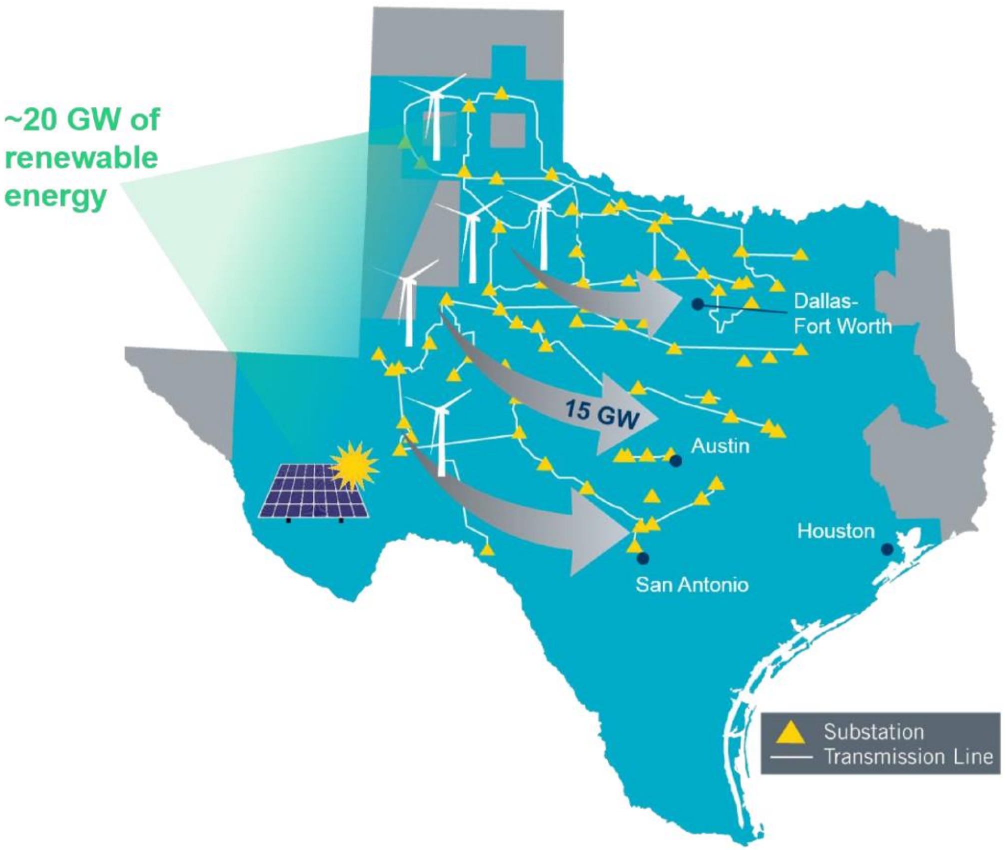


↑ L_{netw} → ↑ ΔV_t to ΔI

- Previously studied in context of synchronous machines connected through long lines
  - Power System Stabilizers (PSS) subsequently developed
- Similar approach can be utilized for future IBRs
  - Through power oscillation dampers (POD)



Reality of reduced grid strength and inverter operation



- Operational issues and control instability of IBRs connected to weak transmission grids have been reported by several transmission system operators around the world, (e.g. ERCOT*, AEMO).
- **This is one of the key drivers for looking into GFM inverters in the transmission system.**
- Similar challenges may also occur in the distribution grid.

*Figure source: Dynamic Stability Assessment of High Penetration of Renewable Generation in the ERCOT Grid

Few combinations of options for mitigation

Strengthen the transmission system to increase short circuit strength

Caveat: There could be significant constraints to build more lines

Re-tune the fast control loops to recognize a low short circuit condition

Caveat: May not provide desired performance under all conditions

Re-imagine IBR controls to introduce additional flexibility in operation

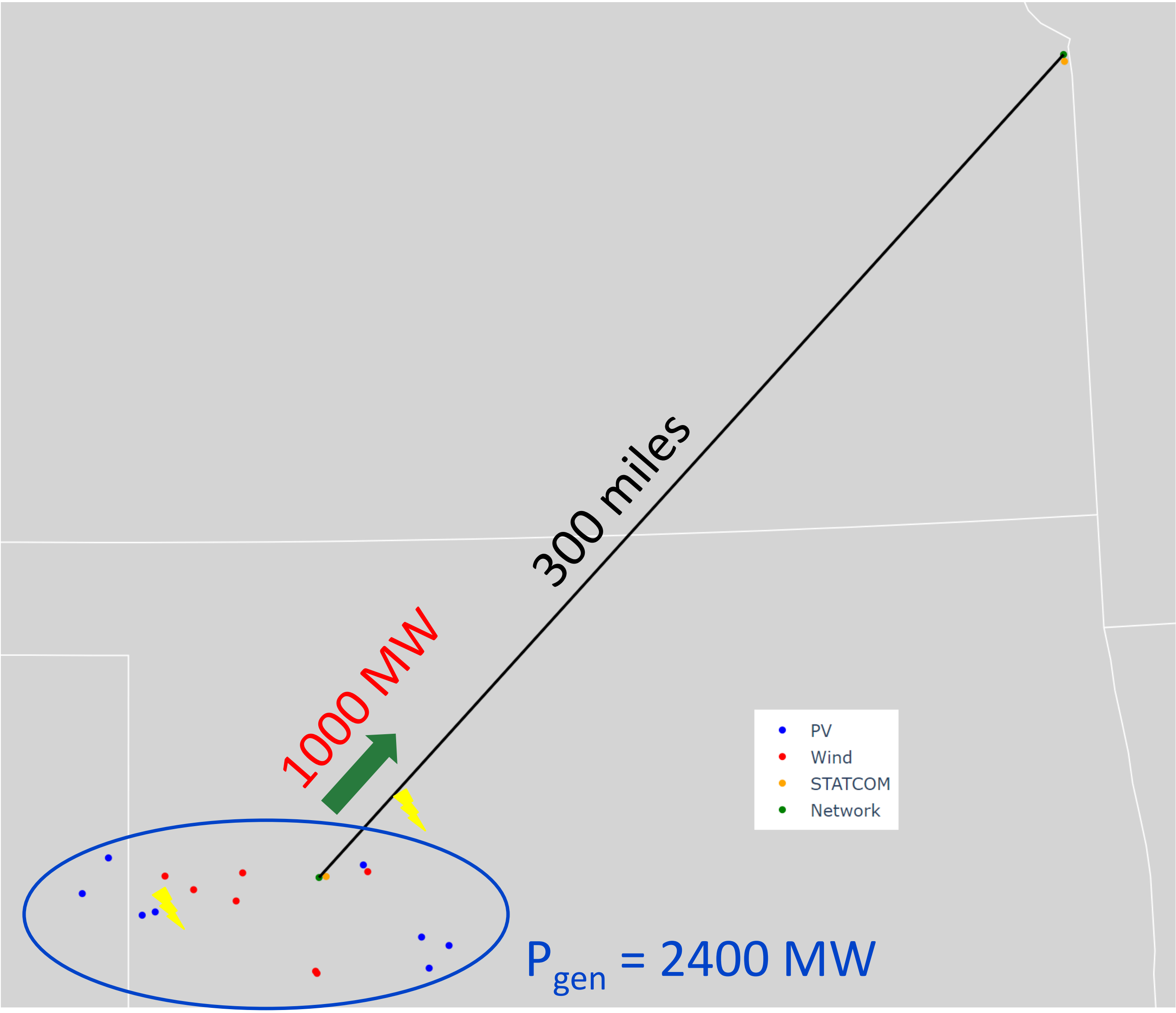
Caveat: May require standardization to ensure consistent performance

Addition of synchronous condensers

Caveat: There could be techno – economic constraints

Example use case in weak transmission network

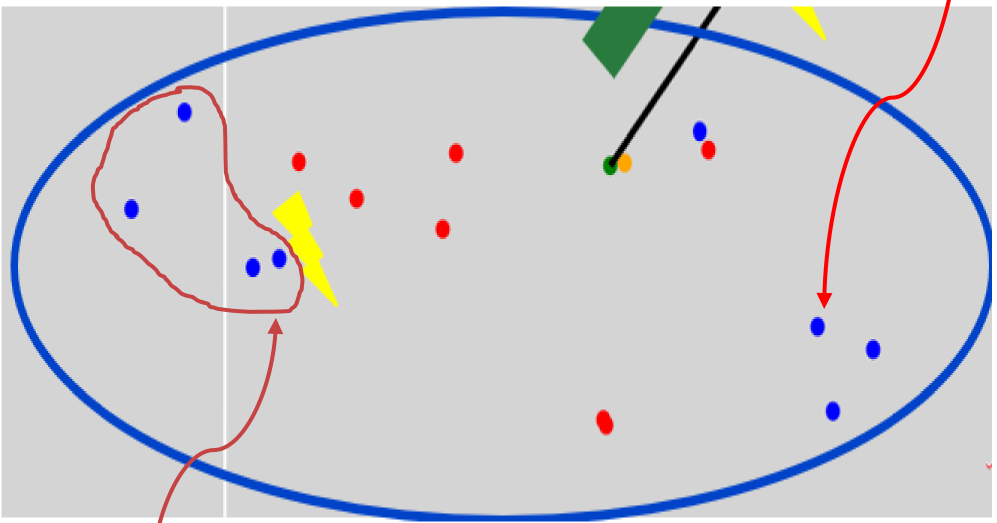
- Wind plant connections are real
- Local network connections (165 buses, 111 branches) are real
- PV plant connections are fictitious
- 300-mile 345kV corridor is fictitious but possible
- No synchronous generator present
- All load is static I-Z
  - 1100 MW in local network



Scenario setup

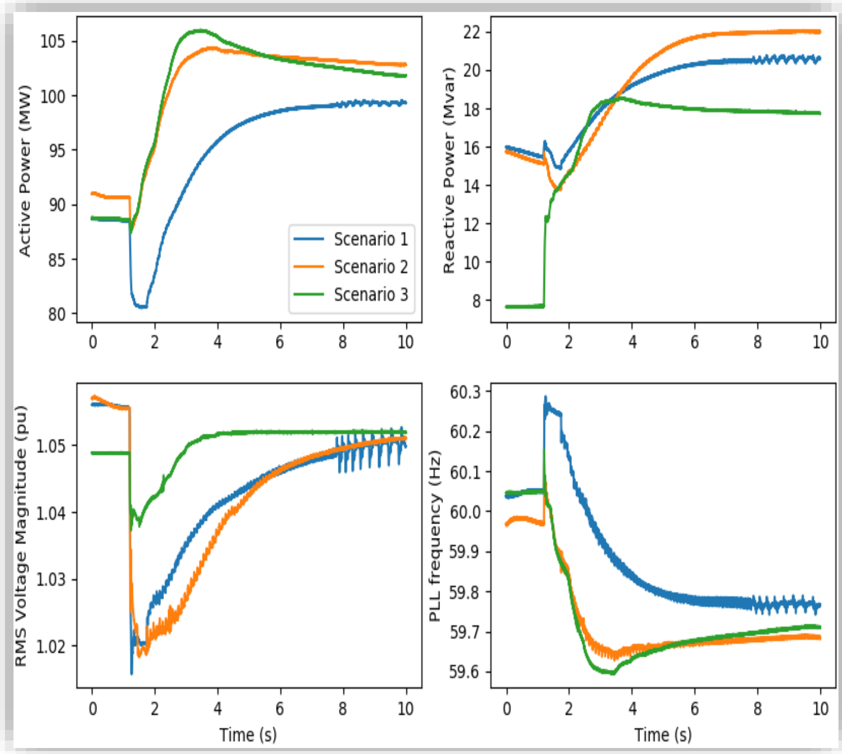
- All wind plants operate on maximum power transfer
  - No plant controller for wind plants
- Regarding PV plants, all have local frequency control
  - Scenario 1:
    - 1 out of 8 PV plants are grid forming
  - Scenario 2:
    - 4 out of 8 PV plants are grid forming
  - Scenario 3:
    - 8 out of 8 PV plants are grid forming

Scenario 1 PV with local V control

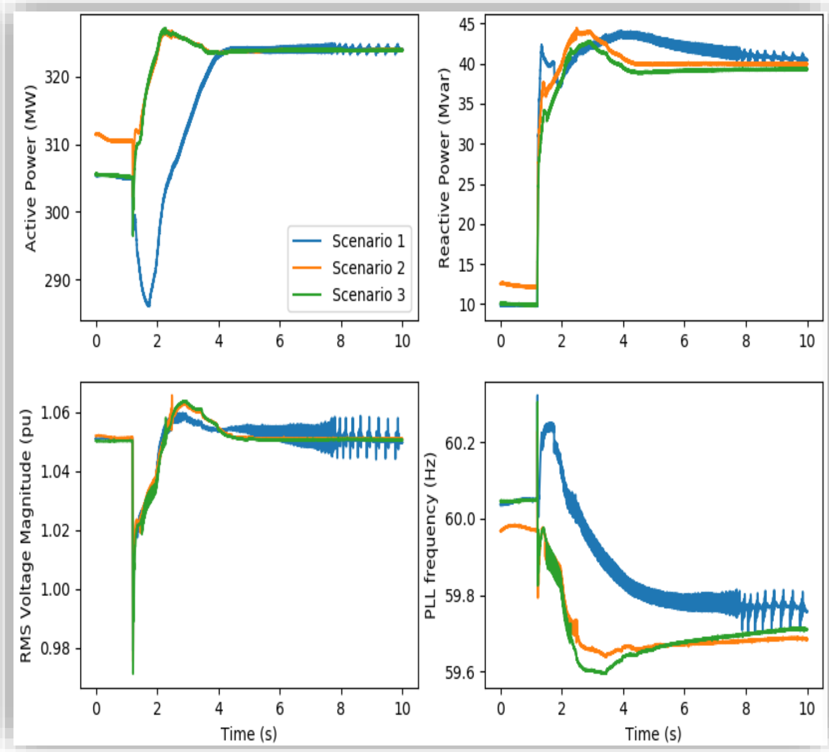


Scenario 2 PV with plant V control

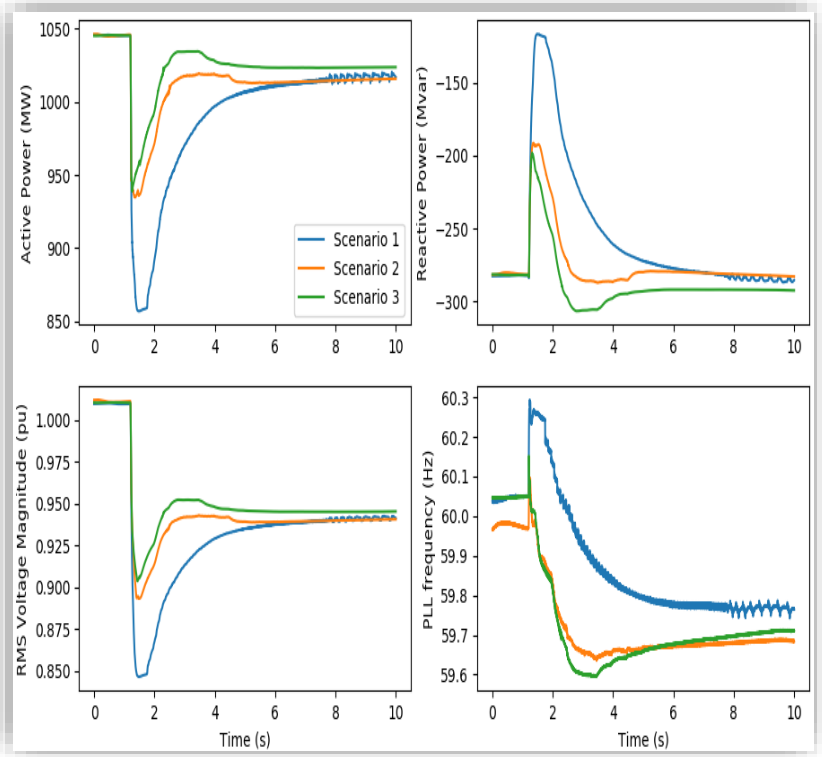
Load increase of 7.0% in local network



Response of PV plant 1



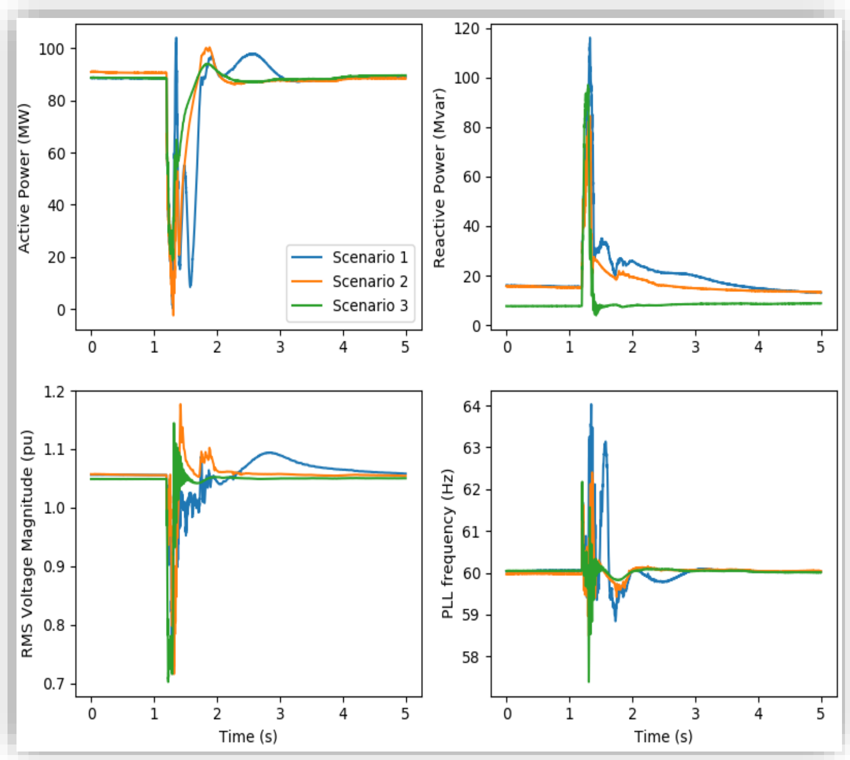
Response of PV plant 3



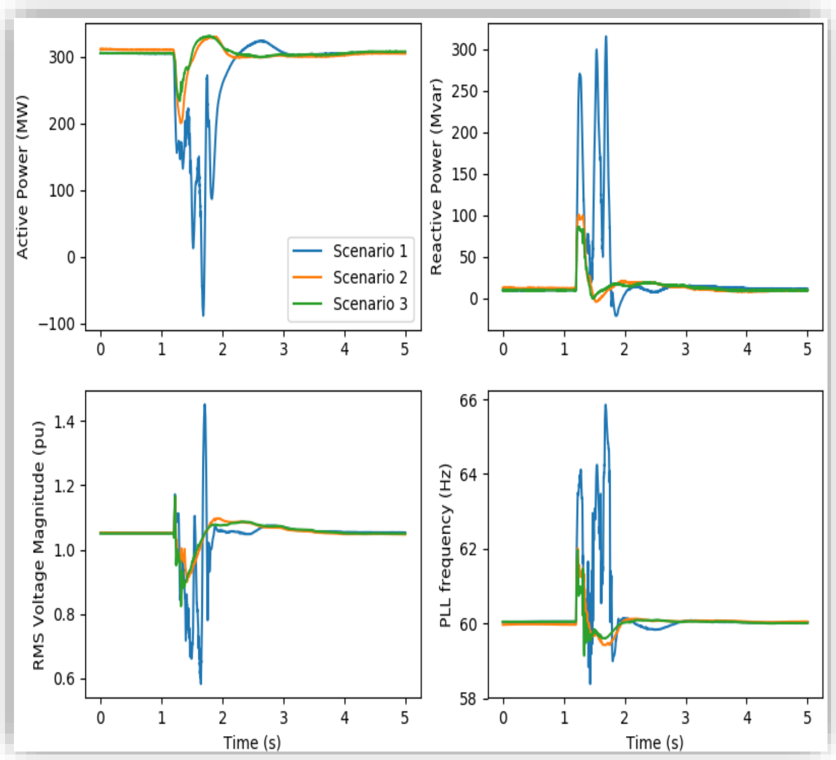
Response at sending end of 300 mile

- Additional PV plants in grid forming control (Scenario 2) improves frequency response of network

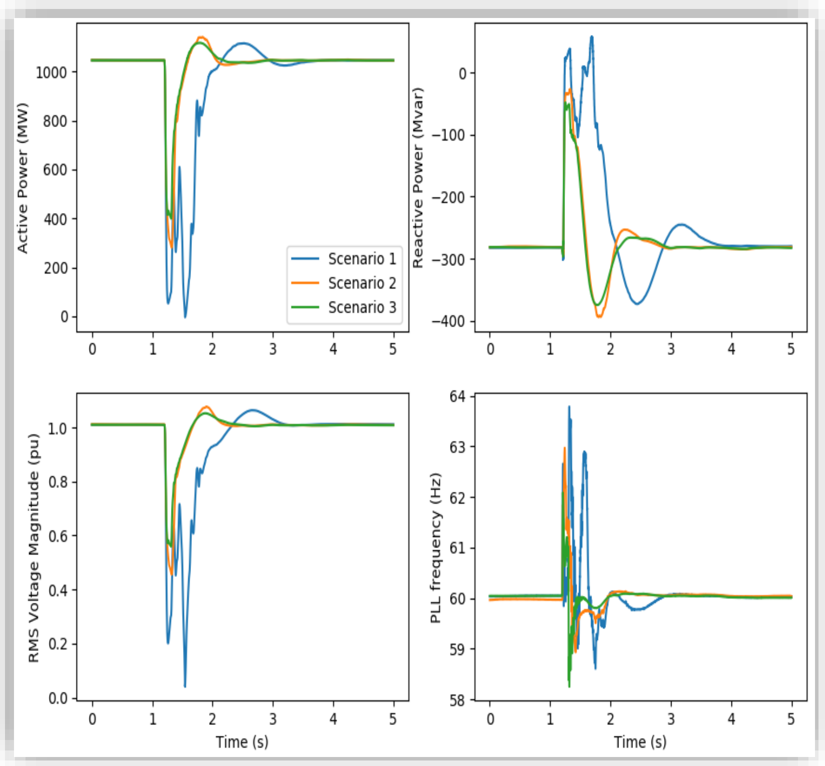
Three phase solid fault in local network



Response of PV plant 1



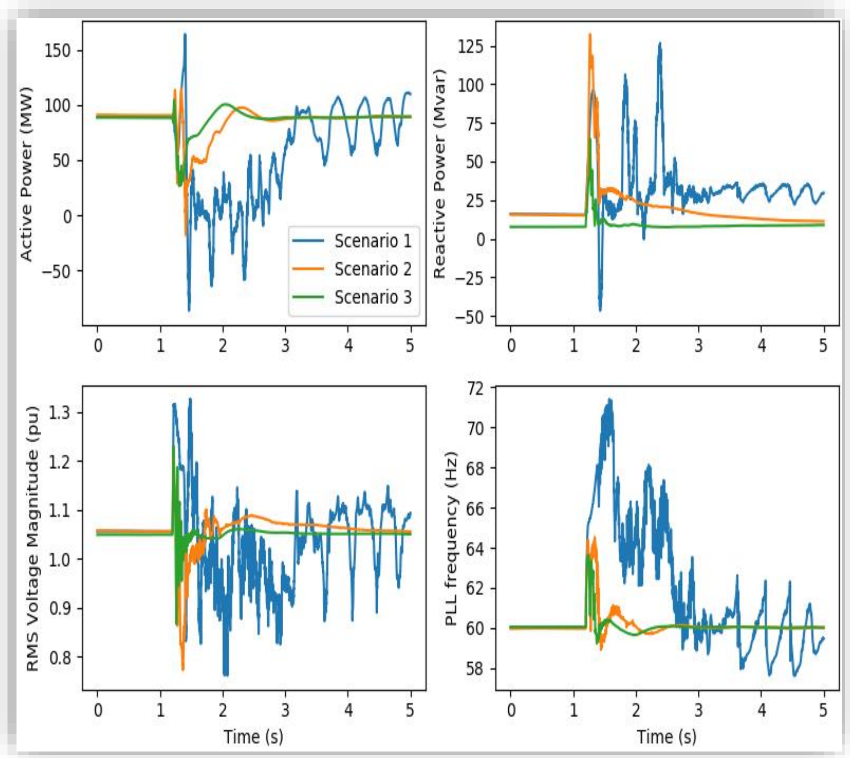
Response of PV plant 3



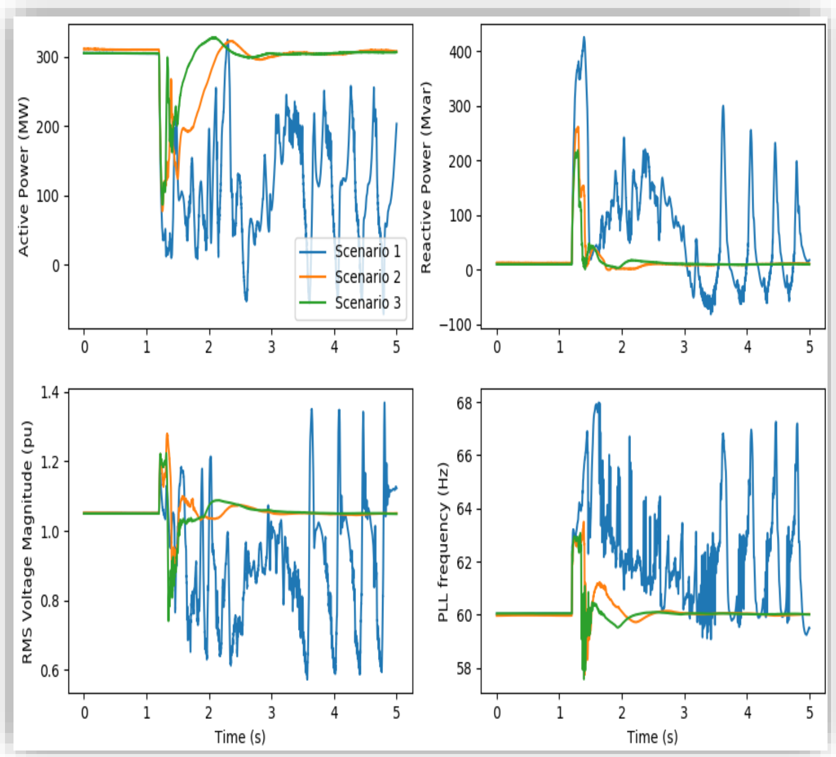
Response at sending end of 300 mile

- Increased amount of grid forming from PV plants brings about improved fault ride through

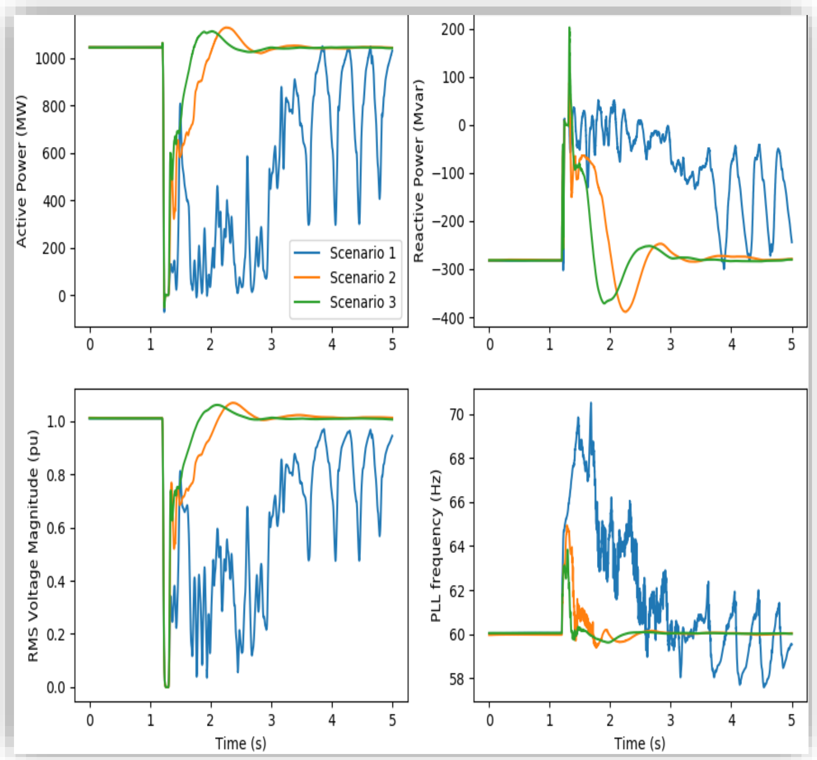
Three phase solid fault at near end of 300-mile corridor



Response of PV plant 1



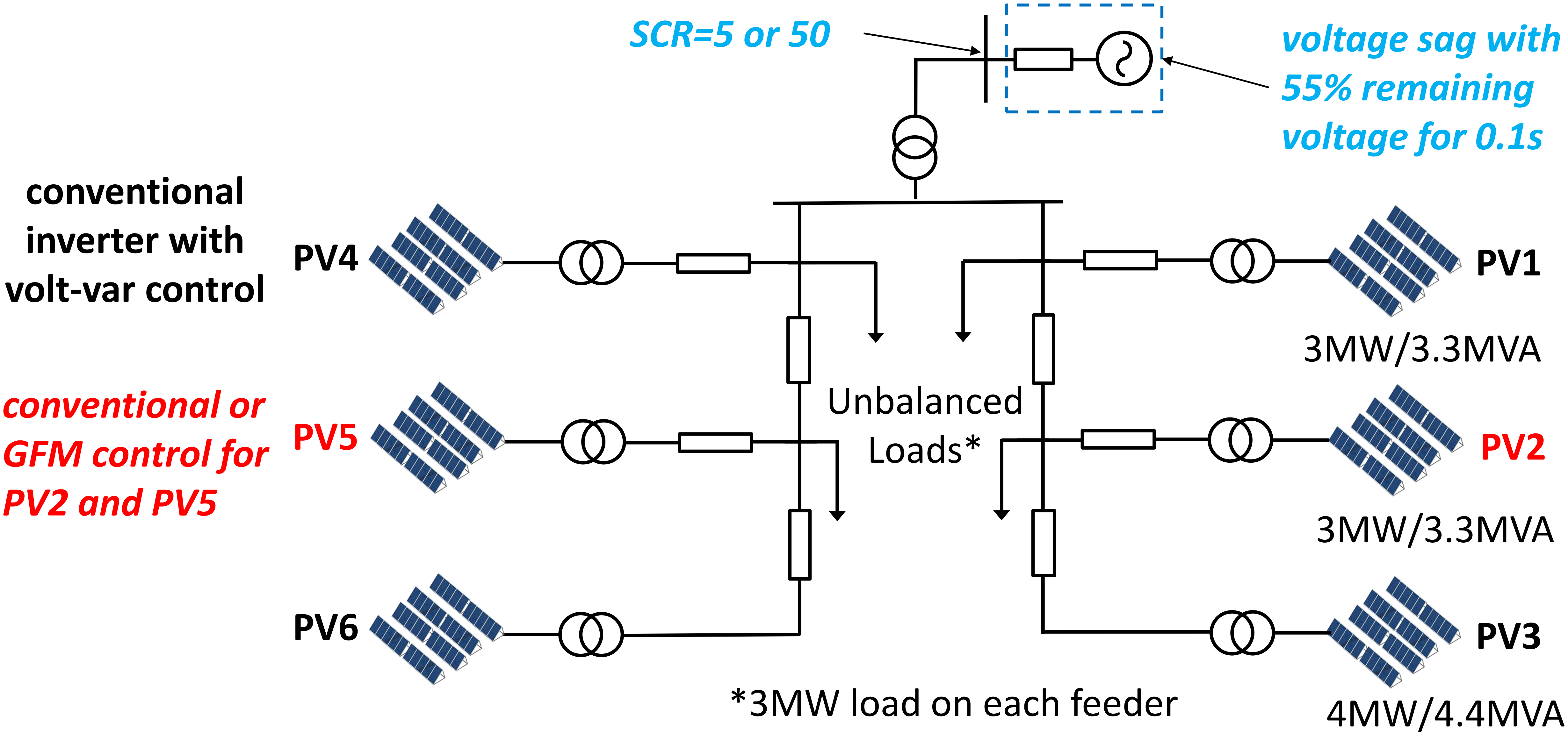
Response of PV plant 3



Response at sending end of 300 mile

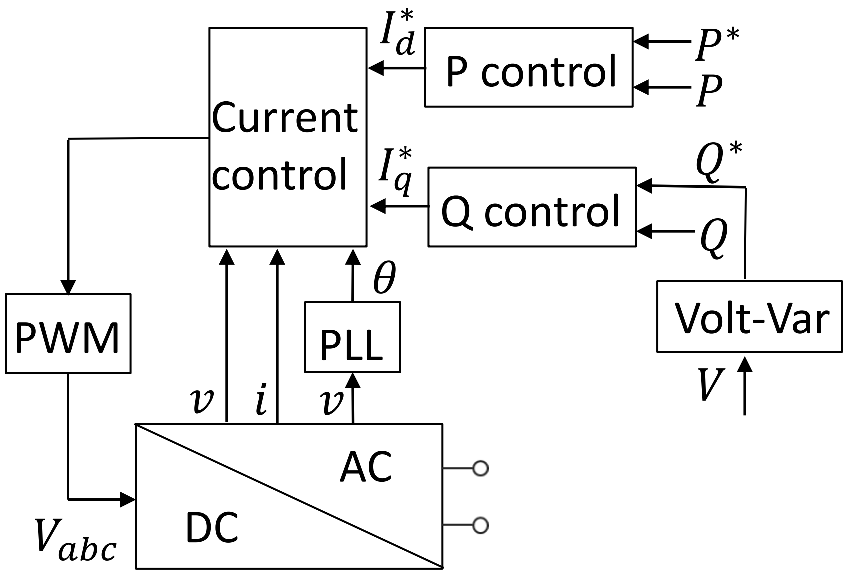
- Increased benefit with more grid forming IBR plants

Potential use case in weak distribution network

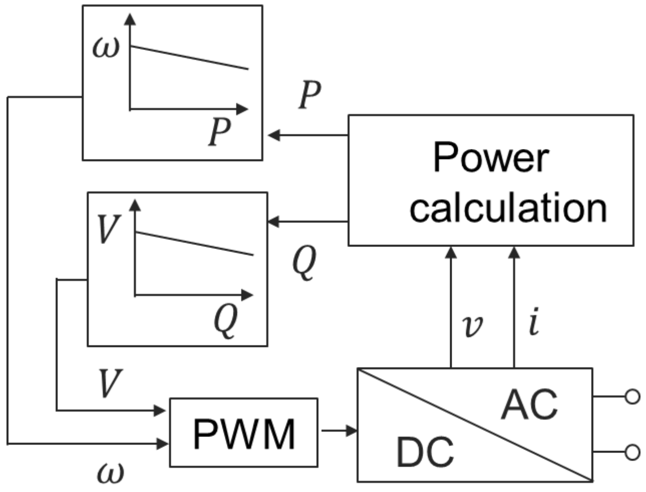


Different inverter controls considered

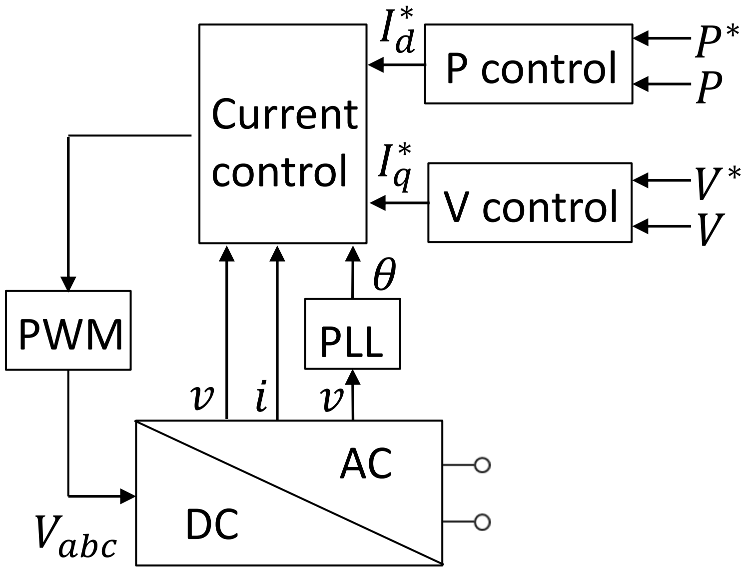
Two forms of GFM inverter control compared for improved system behavior



Conventional inverter control with volt-var

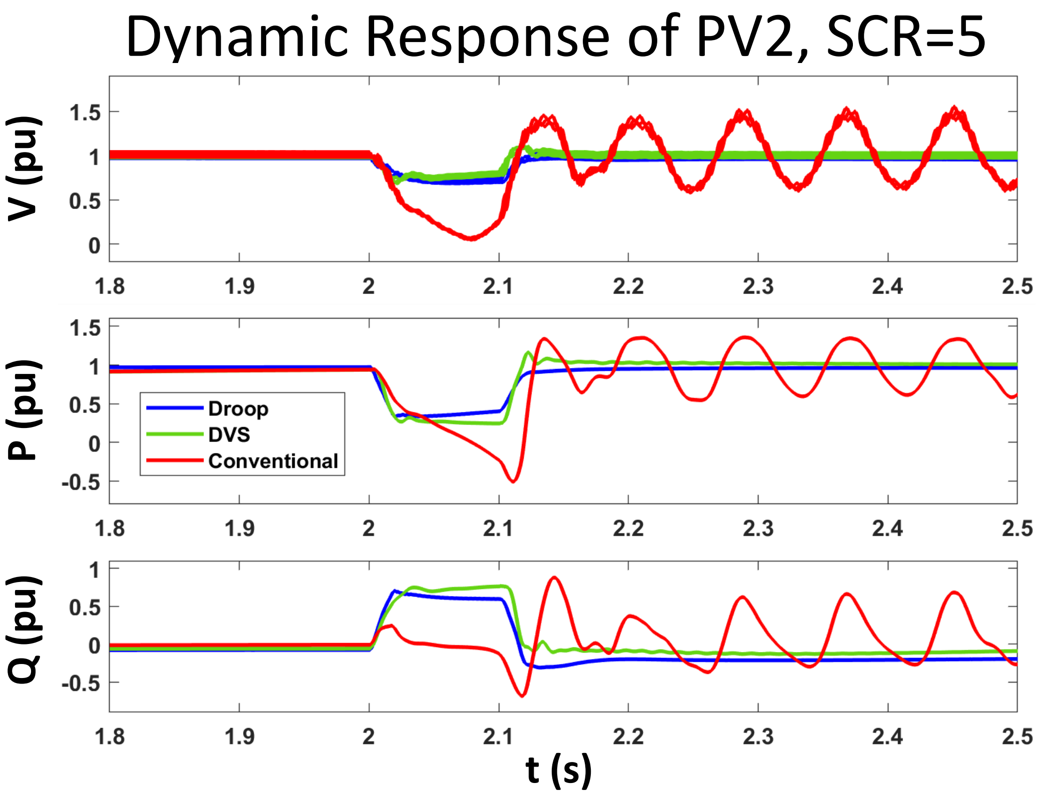


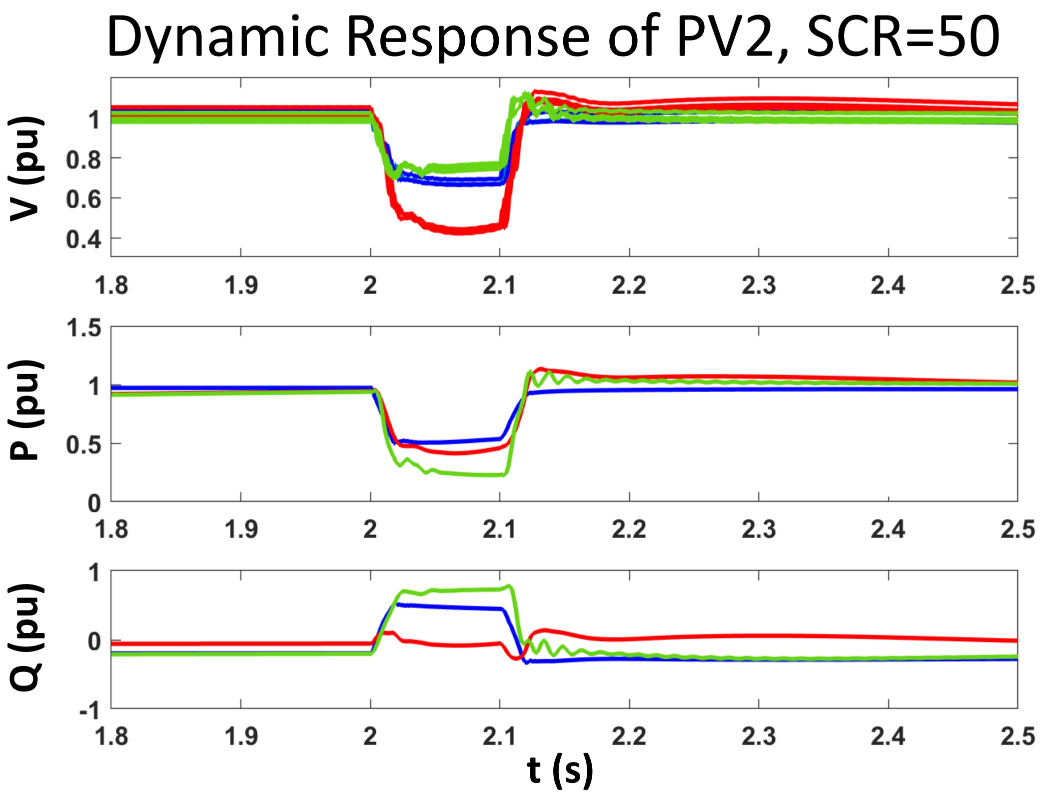
Droop-based inverter control



Inverter control with fast reactive current injection (labeled as DVS)

Performance comparison – conventional, DVS and droop





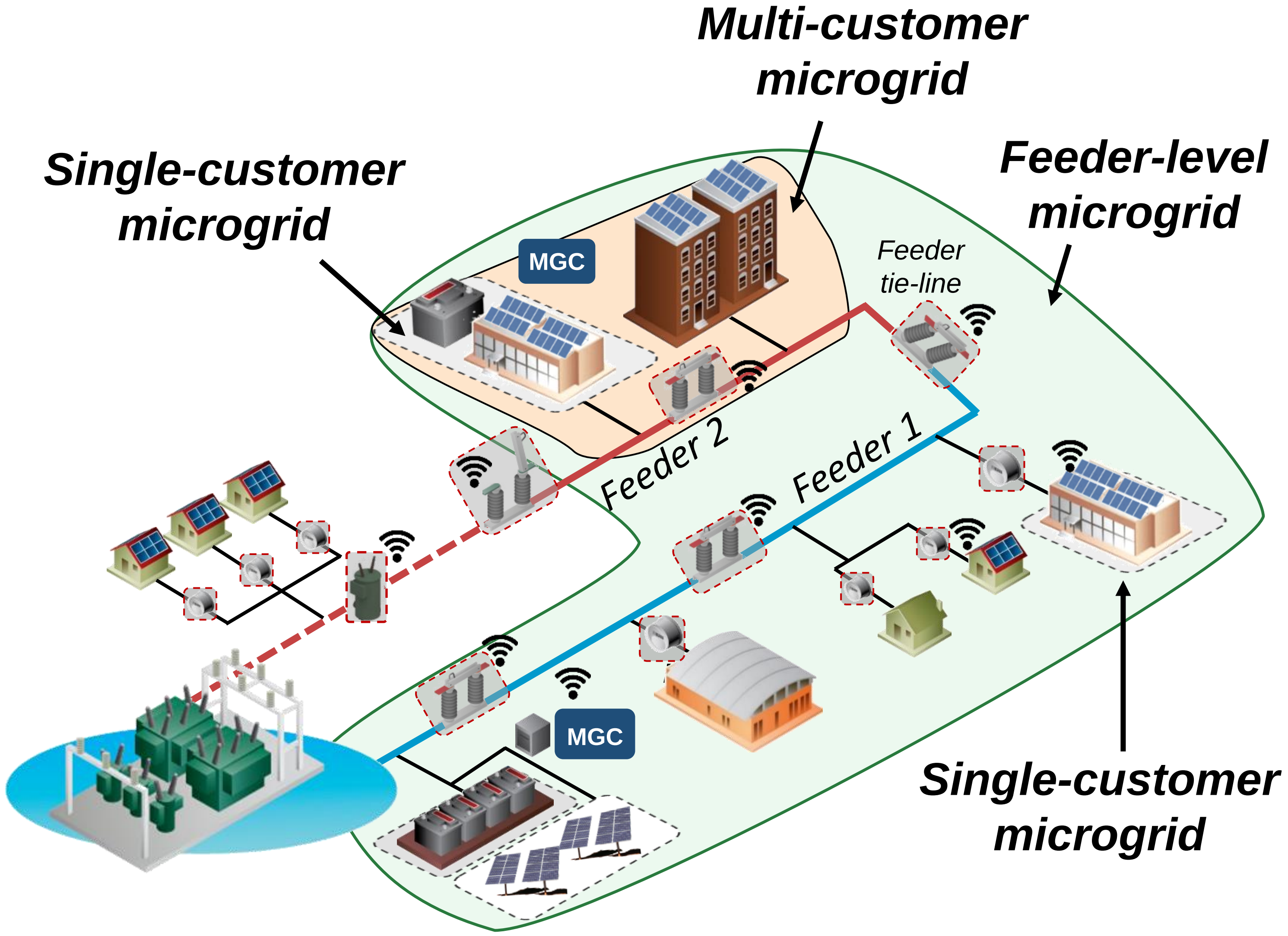
- DVS and droop-based control can both stabilize the inverters following the fault ride-through
- By using DVS or droop-based control for two PV plants, all the six PV plants in the system are stabilized

15 minutes

Performance Requirements for GFM Inverter in Microgrid Applications

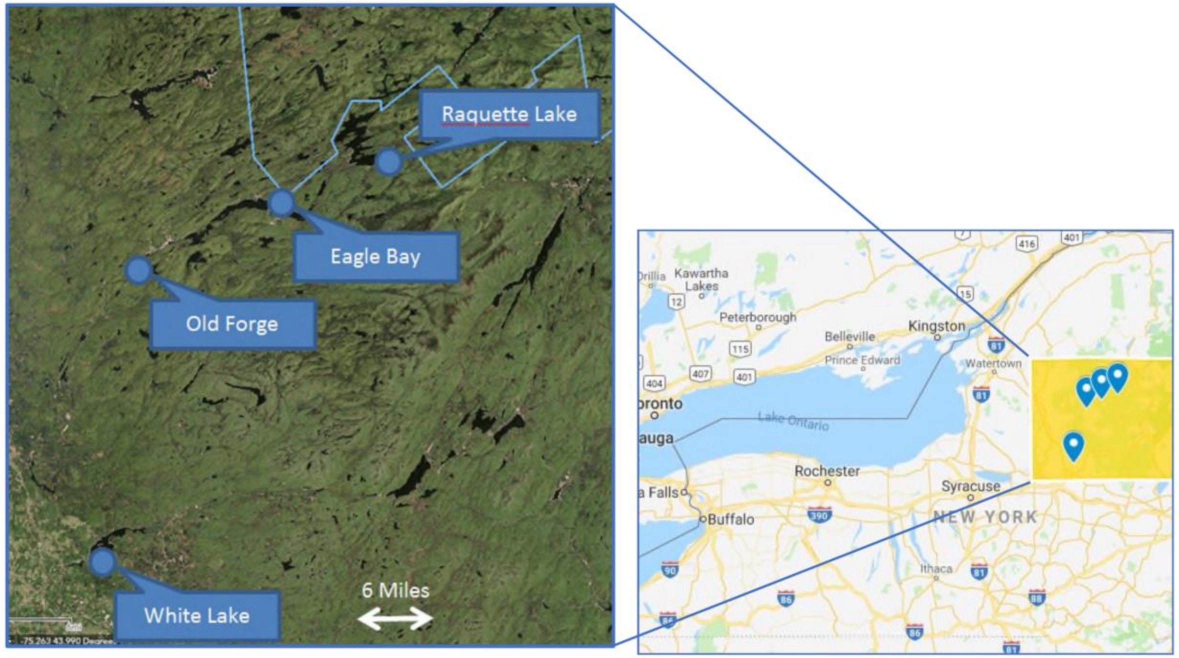
Utility-level microgrid and the system level performance requirements

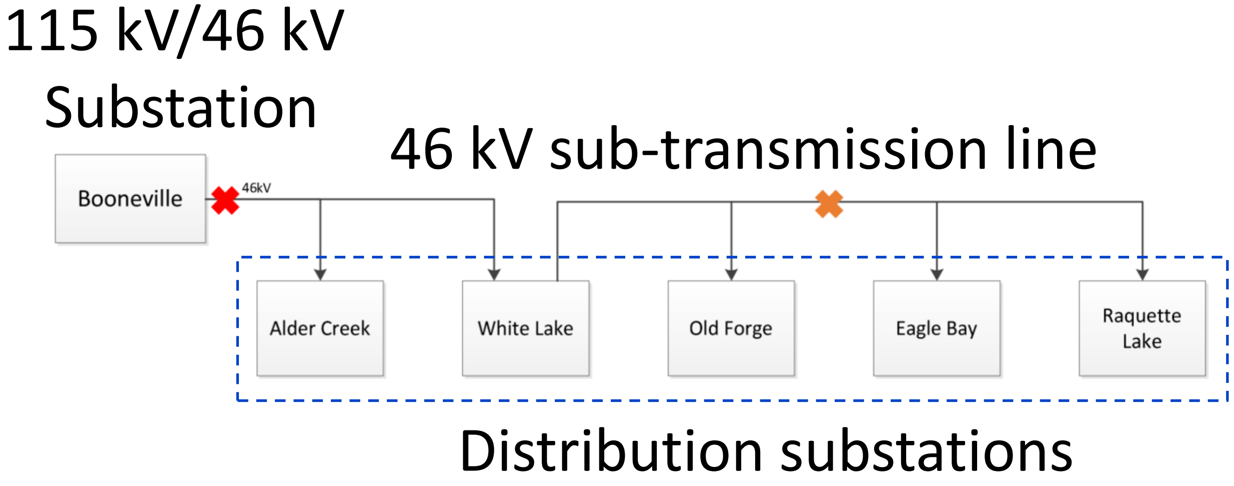
- Utility-level microgrid involves utility medium voltage feeder and loads/generations at different locations
- To ensure adequate power quality and reliability, a utility-scale microgrid must satisfy some **system level performance criteria** such as proper voltage and frequency regulation within certain ranges



Example microgrid project

- National Grid microgrid, NY (in process)
- BESS specifications are 20 MW, 40 MWh, **75 MVA short circuit current**
- The system includes 5 substations, 46 kV sub-transmission line, and 10 feeders, which can separate to form an island supplied by the battery





Source: https://www.nationalgridus.com/media/pdfs/bulk-energy-storage-request-for-proposals/appendix-e-locations-usecases.pdf

BESS GFM requirements in the example project

- The proposed energy storage system and associated Storage Management System will be required to support this microgrid operation, including:
  - Black-start capability;
  - Voltage and frequency regulation of the island (grid-forming);
  - Four-quadrant inverter capable of providing full leading and lagging power factor sufficient to support the reactive loads and manage voltage within the Company’s limits;
  - Sufficient fault current for fault detection for all possible fault types and locations, coordination, cold load pickup, and in-rush currents; and
  - Phase balancing

Source: https://www.nationalgridus.com/media/pdfs/bulk-energy-storage-request-for-proposals/appendix-e-locations-usecases.pdf

An industry acceptable method of defining the functions and performance requirements for GFM inverters in microgrid is presently lacking

GFM performance requirements needed

- Reactive power capability
- Steady state and dynamic voltage and frequency requirement
- Requirement on voltage harmonics
- Frequency and voltage ride-through
- Required behavior under ride-through condition
- Short-term overload/overcurrent capability
- Black start capability
- Grounding of the GFM plant

… …

The GFM requirements to be presented are results of ongoing EPRI research. Further studies and industry review are needed to improve the requirements

Performance Requirements for Grid Forming Inverter Based Power Plant in Microgrid Applications: First Edition. EPRI, Palo Alto, CA: 2021. 3002020571

Microgrid steady state voltage requirements

- The steady state voltage of any phase should be within a specific range (e.g., ANSI C84.1 range A) across the feeder
- The steady state voltage range should be designed considering load characteristics in the microgrid

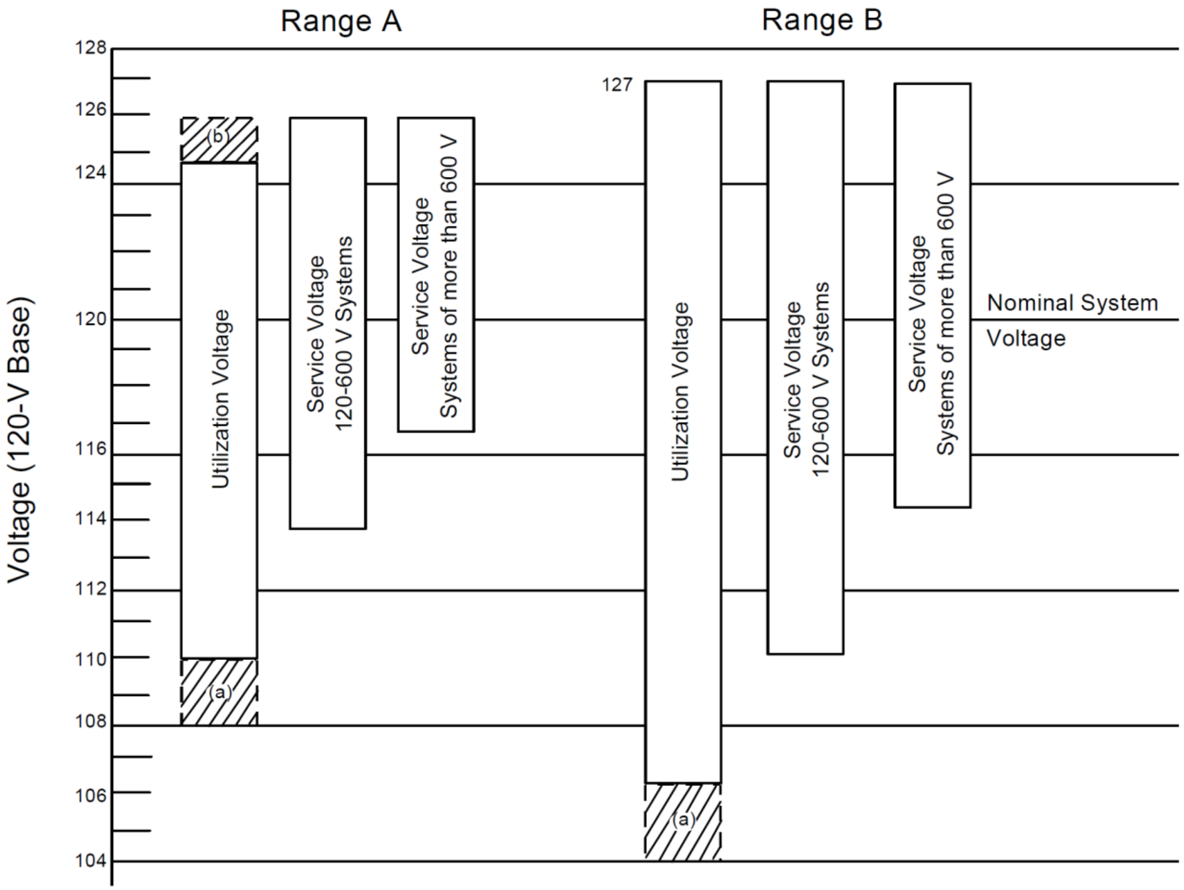


Figure 1. Voltage Ranges, ANSI C84.1

Microgrid steady state voltage requirements (cont'd)

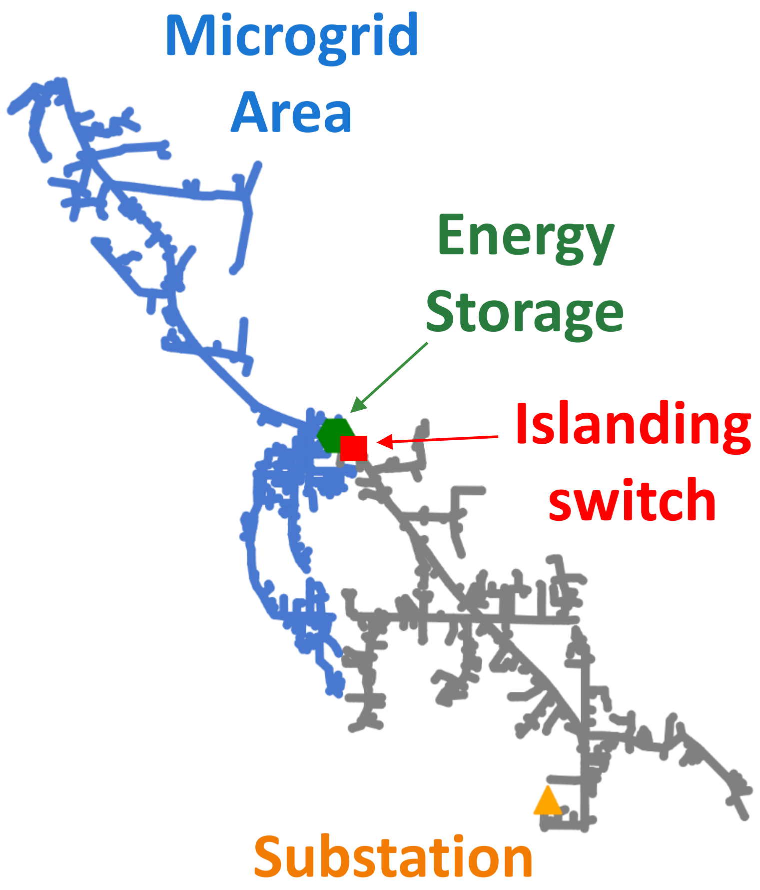
- Load unbalance in a microgrid can lead to voltage unbalance/imbalance even during normal steady state operation
- Voltage unbalance should be restrained to prevent damage or derating of three-phase induction motor loads
- ANSI C84.1 recommends that the maximum voltage unbalance to 3%

$$voltage\ unbalance = \frac{max\ deviation\ from\ average\ V}{average\ voltage} \times 100\%$$

- IEC 61000-3-x recommends that the voltage unbalance factor (VUF) should be less than 2%

$$VUF = \frac{|V_2|}{|V_1|} \times 100\%$$

Deriving GFM requirements from microgrid requirements
— study based on a real-world microgrid circuit



- Peak load of the microgrid is around 3000 kW with an average power factor of 0.88
- An energy storage site with 8250 kVA is the only power source inside the microgrid
- The microgrid circuit is modeled in PSCAD with constant impedance load
- The circuit was reduced (from 1973 nodes to 52 nodes) and converted from an original model in CYME

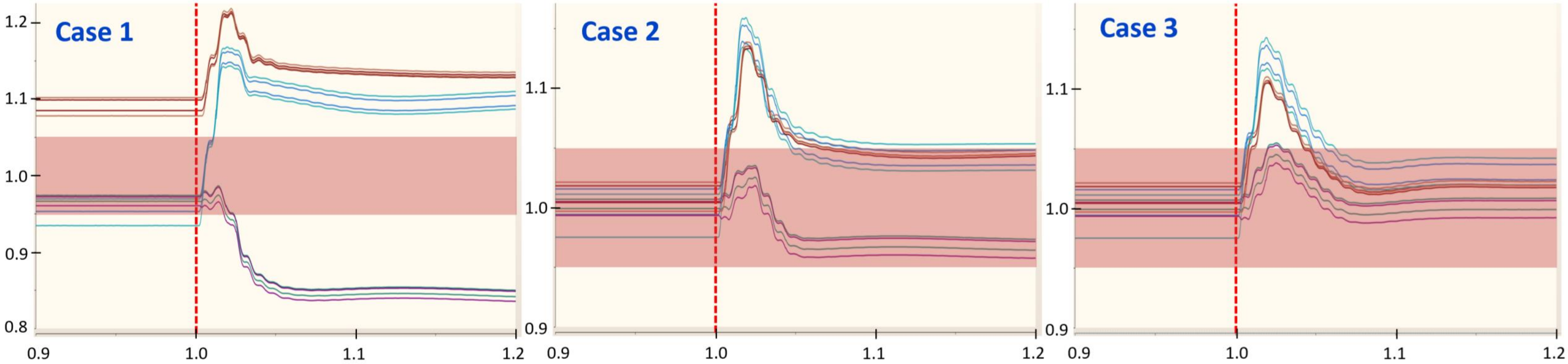
Case studies on GFM negative sequence voltage control

Case #	Negative Sequence Control Objective	Negative Sequence Current Capability
1	Regulate negative sequence current to zero	None
2	Regulate negative sequence voltage at RPA to zero	0.05 pu
3	Regulate negative sequence voltage at RPA to zero	0.1 pu

- The goal is to investigate the need for negative sequence voltage control from GFM inverter and the required negative sequence current capability in the particular microgrid
- The microgrid is initially operating at the peak load condition. At t=1s, a section of the feeder is disconnected from the microgrid to simulate a load drop event

Voltage magnitude across the MV feeder

Phase voltage magnitudes at different feeder locations (pu)



Time(s)

- Voltage unbalance reduces as the GFM inverter regulates the negative sequence voltage with higher negative sequence current capability

Voltage magnitude across the MV feeder (cont'd)

Analysis Case #	Negative Sequence Current Capability	Highest Feeder Voltage Unbalance per ANSI Definition	
		Before load drop	After load drop
1	None	9.11%	19.14%
2	0.05 pu	2.48%	6.21%
3	0.1 pu	2.48%	2.52%

- Voltage unbalance reduces as the GFM inverter regulates the negative sequence voltage with higher negative sequence current capability

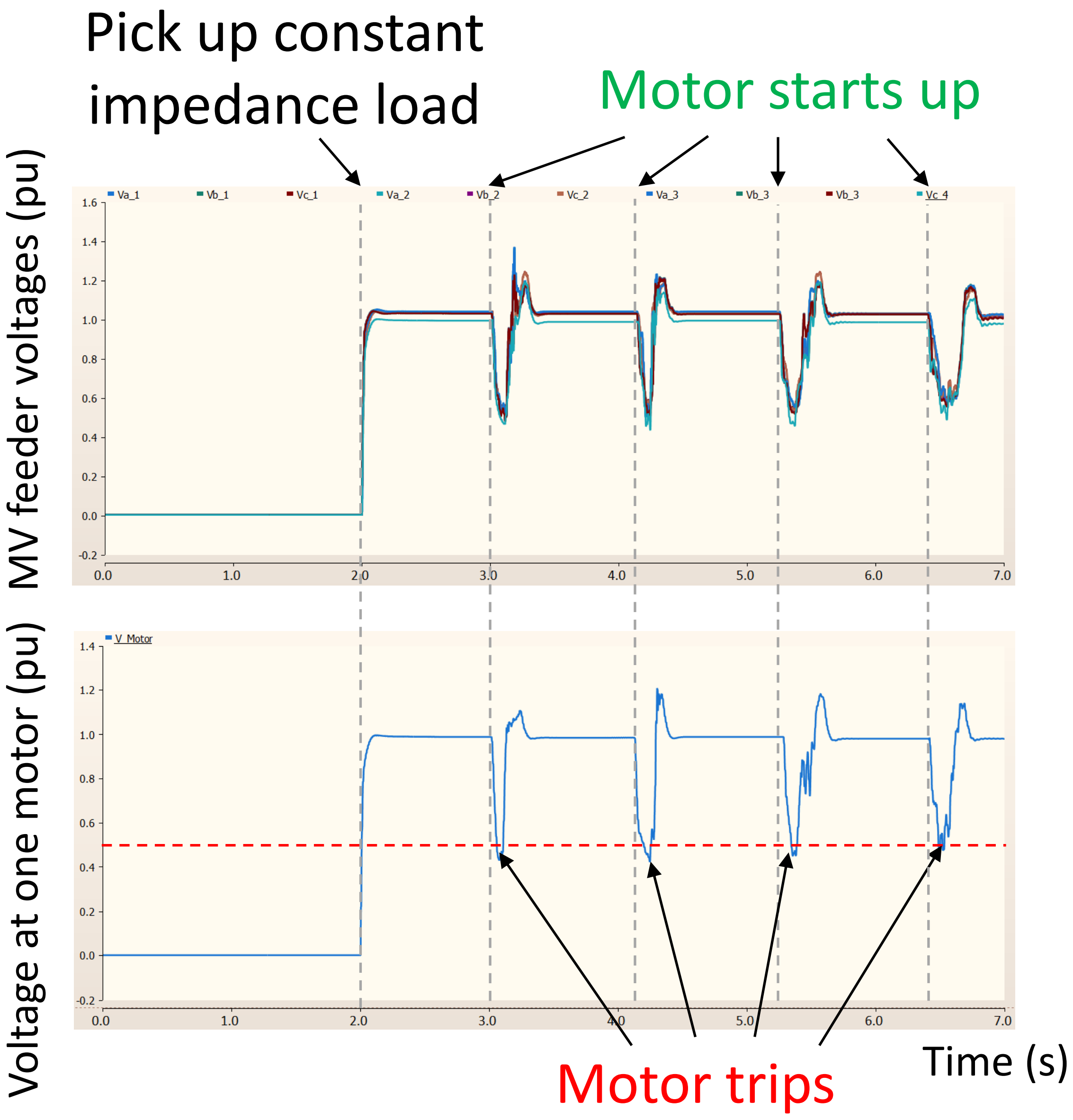
Steady state voltage requirement

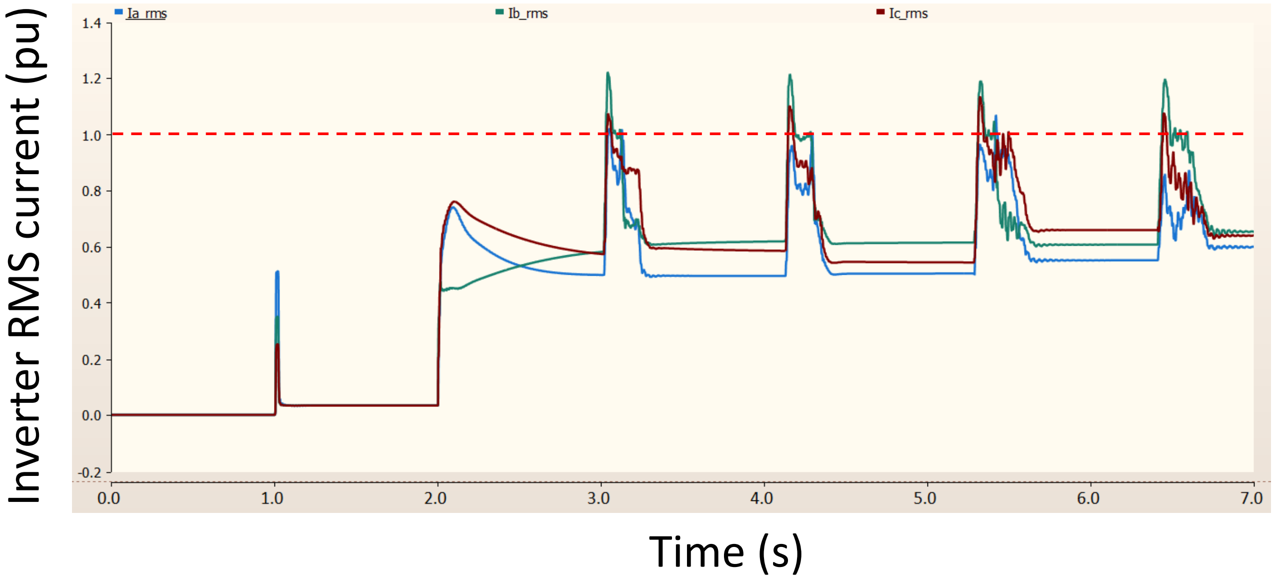
- A GFM power plant should be able to regulate its RPA voltage to be within ANSI C84.1 range A (or other ranges as appropriate for the load inside the microgrid), when the GFM plant output is within its power and current capability
- A GFM power plant should maintain balanced voltage at its RPA when it operates within the negative sequence current capability and total current capability
- Negative sequence current capability should be greater than a certain value which should be defined based on loading condition and possible contingency scenarios of the microgrid under consideration

Black start of a system with inverters – A grid forming service

- A cranking path should be identified for system restoration
- The first black start resource needs to form the voltage and frequency
  - It should be capable of providing transformer in-rush current
  - It should be capable of handling line charging currents
  - It should be capable of handling induction motor starting currents and power
- A GFM IBR can be this first black start resource
  - Not all GFM IBRs need to be capable of providing such services

Impact of induction motor load on microgrid black start

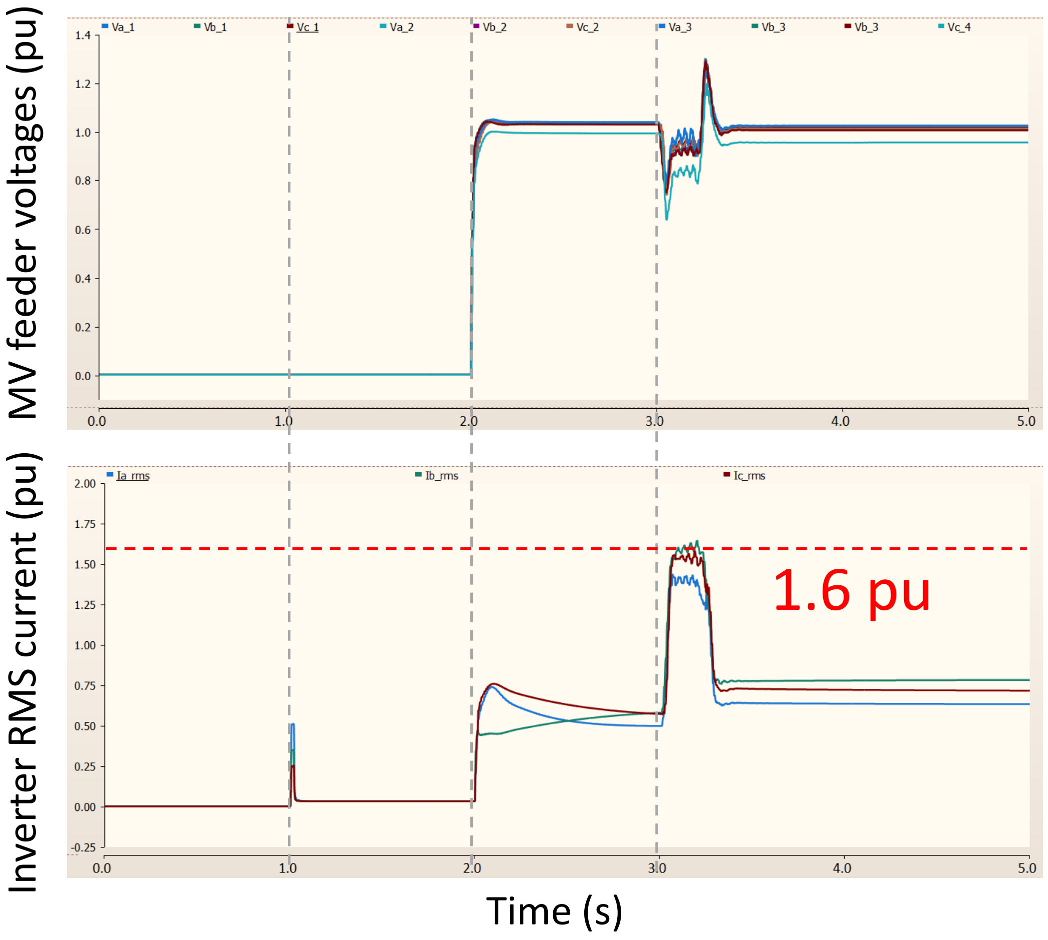


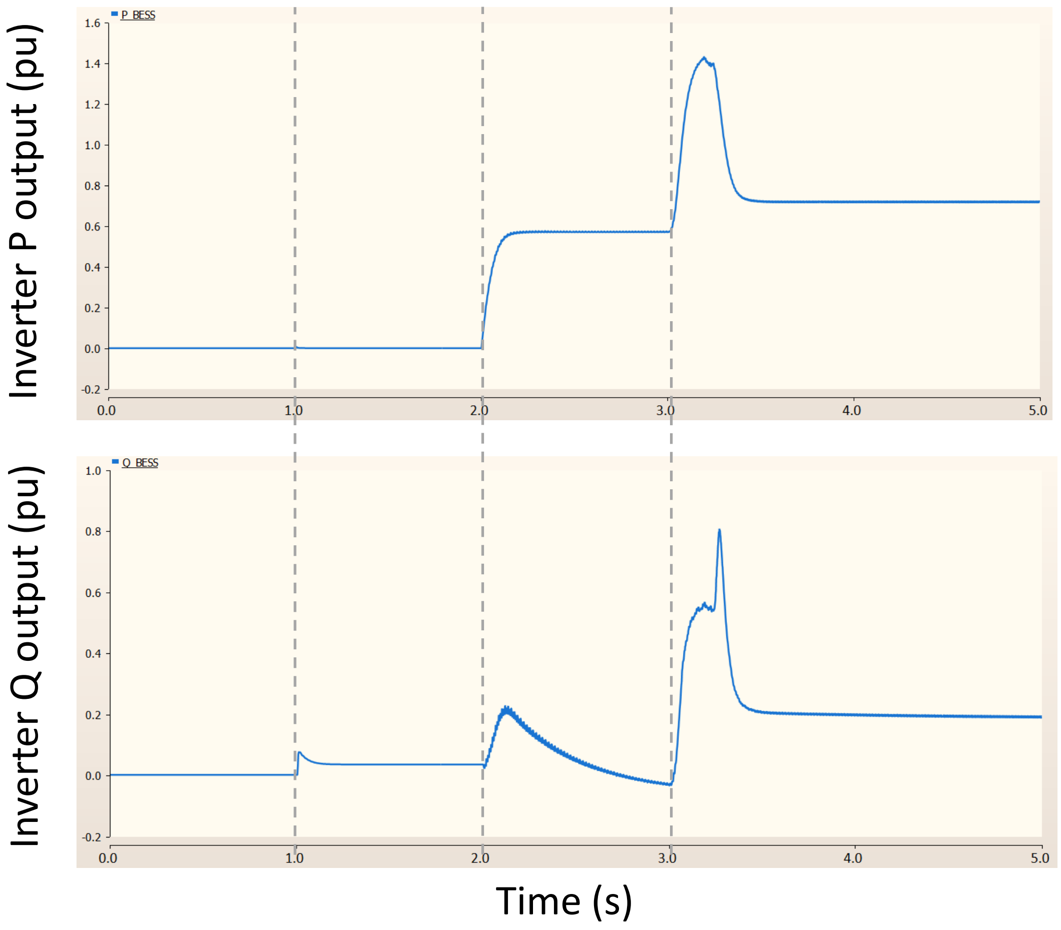


- Since motor start requires much higher active and reactive power than its normal rating, the GFM inverter cannot provide the high temporary overload when its current is capped at 1pu, resulting in motor start up failure

Higher short-term power rating from the GFM plant

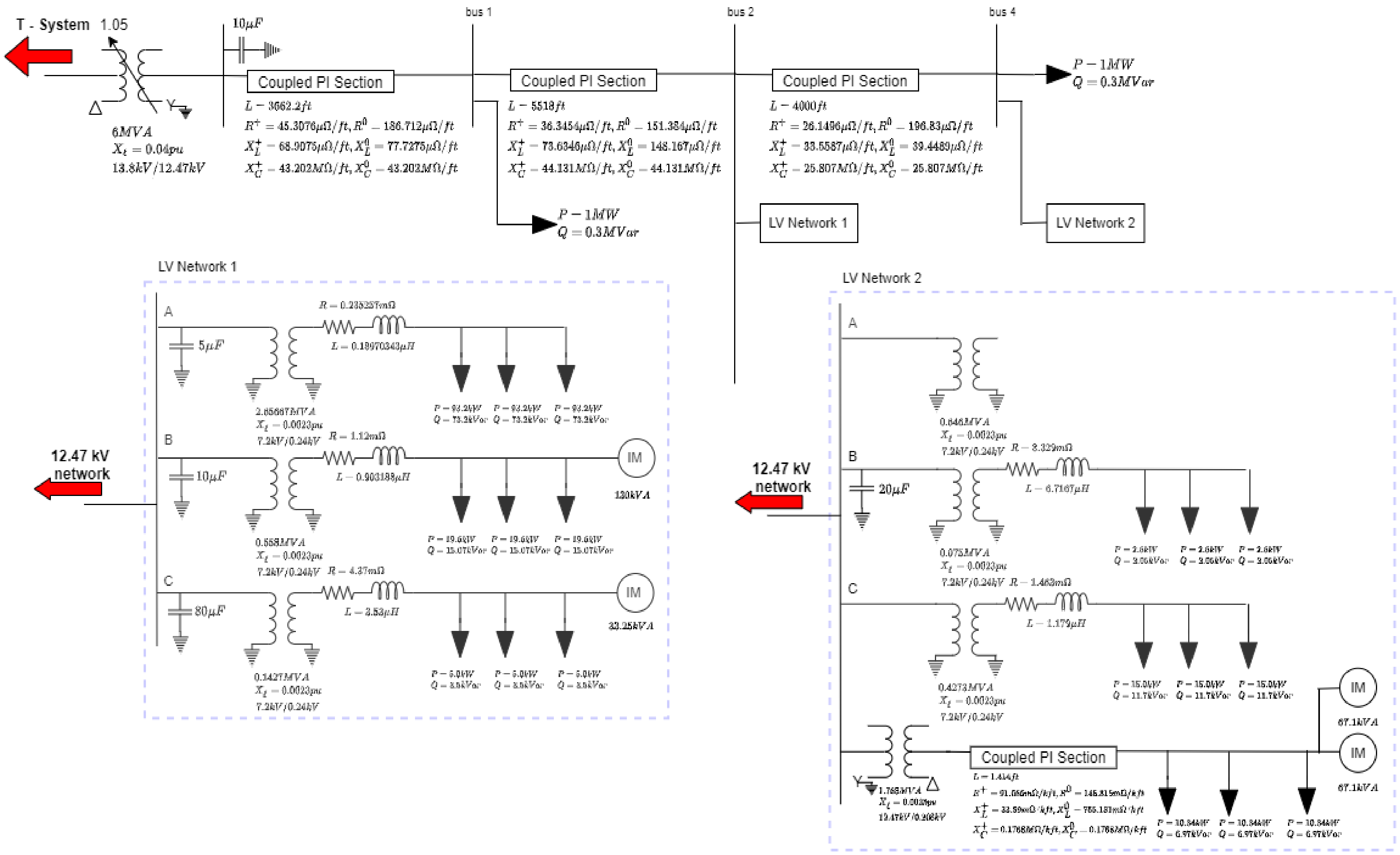
- For the studied scenario, if the GFM plant has short-term power rating that is 1.6 times higher than the continuous rating for 1s, it can black start the microgrid with the induction motor loads successfully





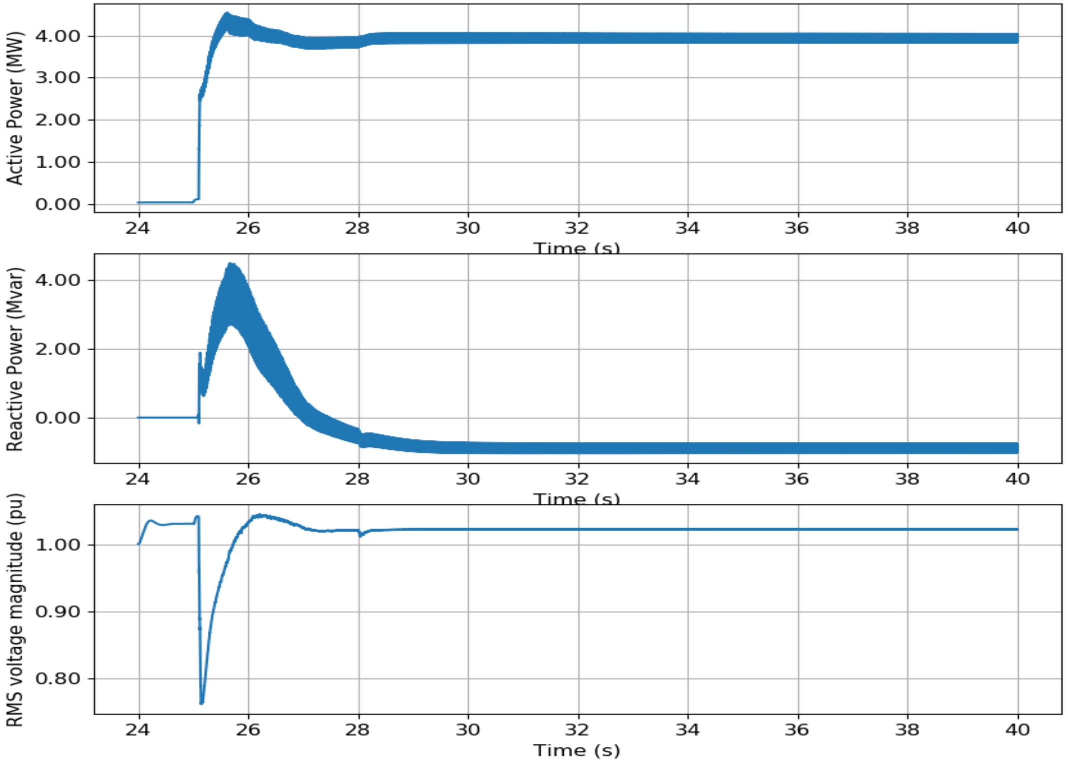
EPRI

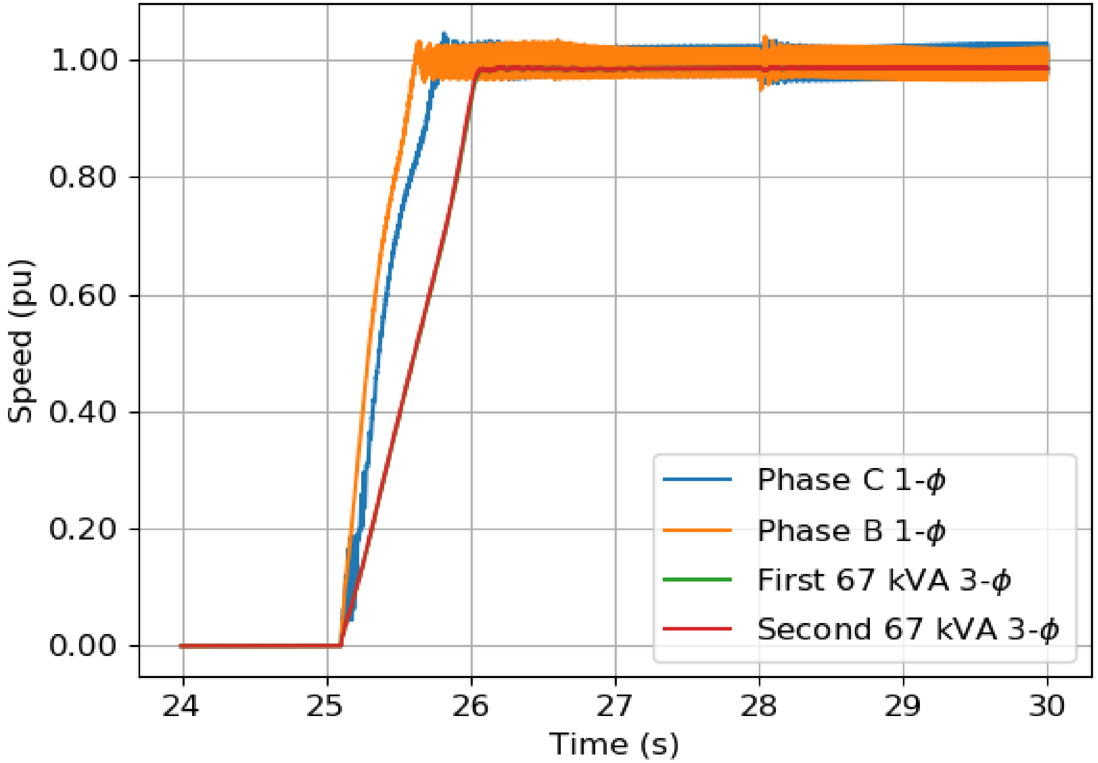
Possibility of load control interaction during blackstart



- A reduced real distribution feeder with path to critical load
- Both single phase and three phase induction motors present
- Radial transmission network with GFM inverter

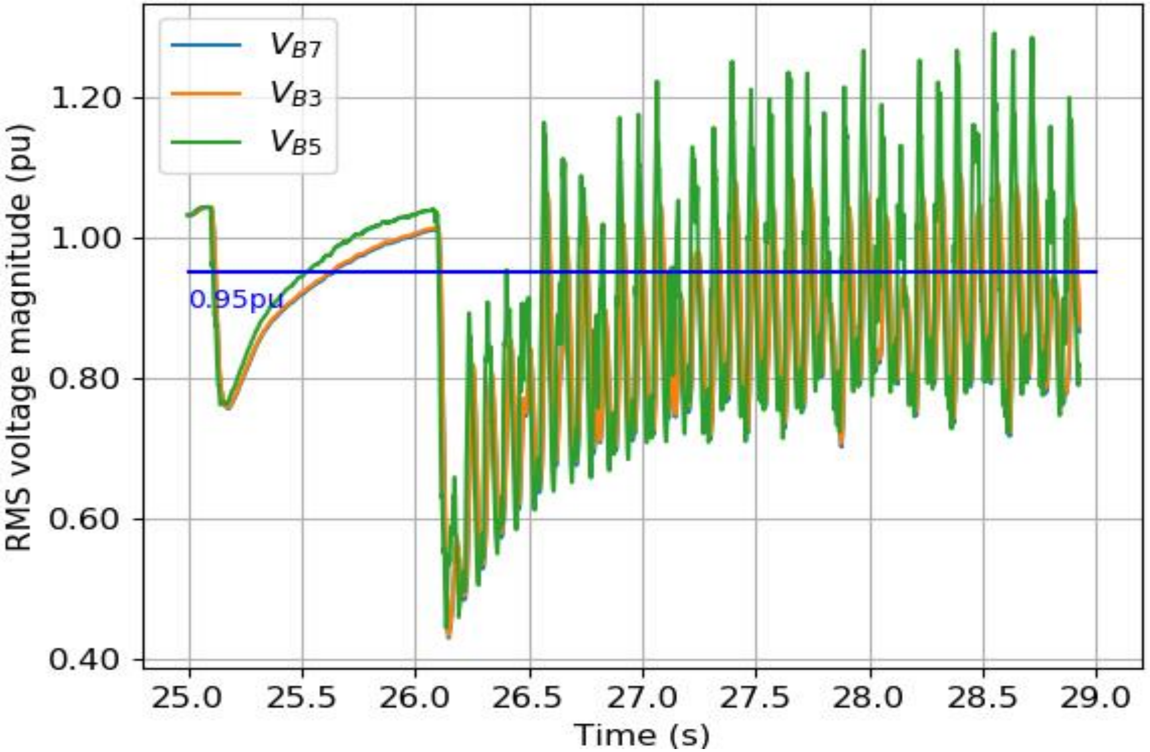
Load consumed by distribution feeder from transmission network

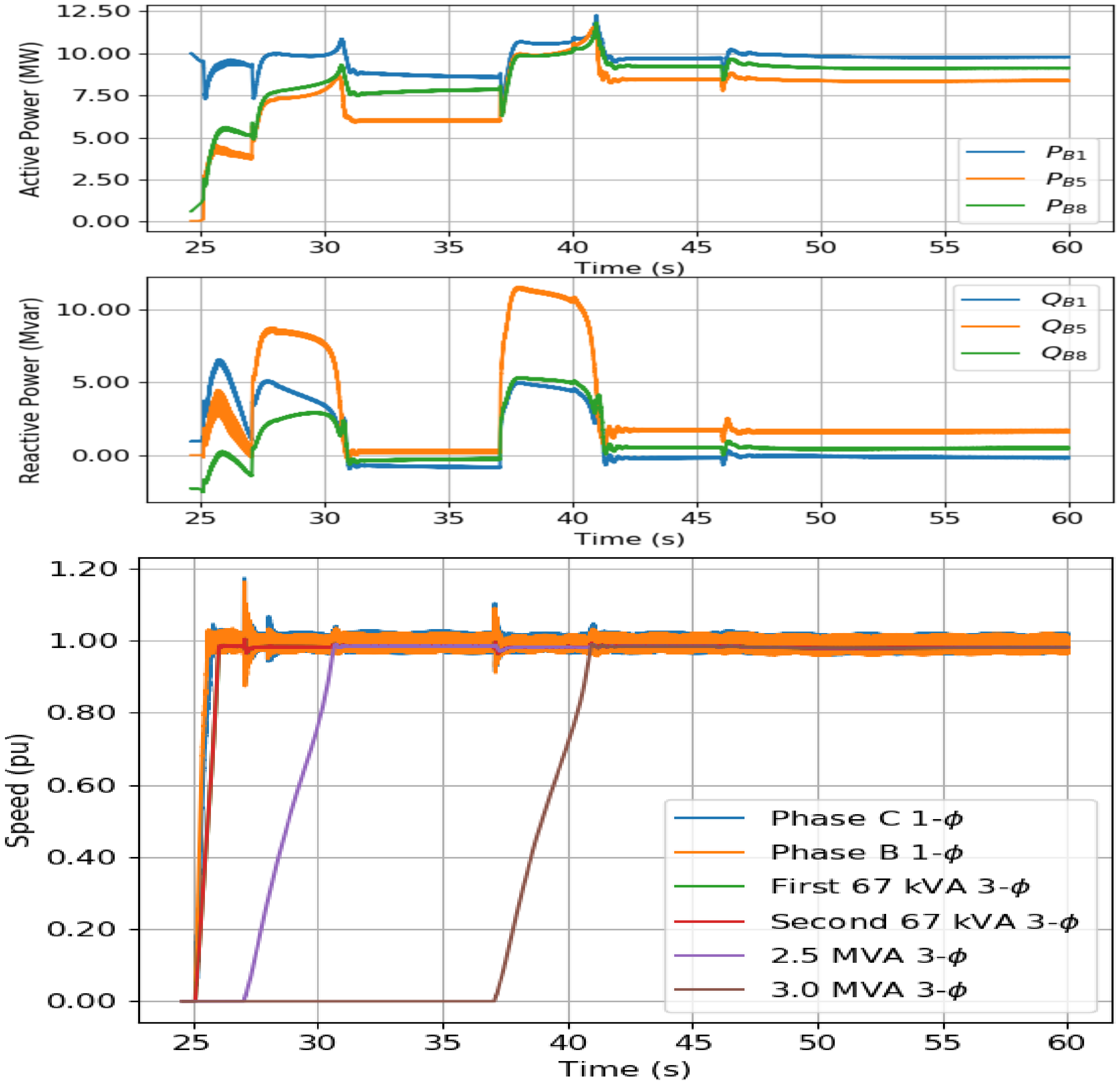




- Load on the feeder is unbalanced and GFM IBR control loops need to have negative sequence voltage control

Control interactions between large motor soft-start scheme and single-phase induction motors





- Distribution feeder energized as cold load pick-up
- Control interactions when three phase motor tries soft start
  - Solved by carrying out staggered start of three phase induction motors

GFM plant requirement to black start a microgrid with high percentage of motor loads

- The GFM plant should be able to black start itself, including the local auxiliary load and establish an open circuit voltage at the plant RPA without the utility grid
- If the GFM inverter and the dc source are not sufficiently oversized to provide the inrush current and motor start up power, short-term current and power capability should be required. The amount of short-term current and power rating required depends on the load characteristics and black start sequence

Design Considerations for GFM Generation Plants

Can all types of energy sources be used for grid forming behavior?

- Providing grid forming behavior can be impacted by natural characteristics of battery technology, solar, and wind sources

- While voltage/reactive power response is handled solely by the inverter, active power response depends on availability of energy behind the inverter

- Care should be taken to consider these limitations while requiring frequency response from grid forming devices

What does present draft IEEE P2800 standard say about primary frequency response?

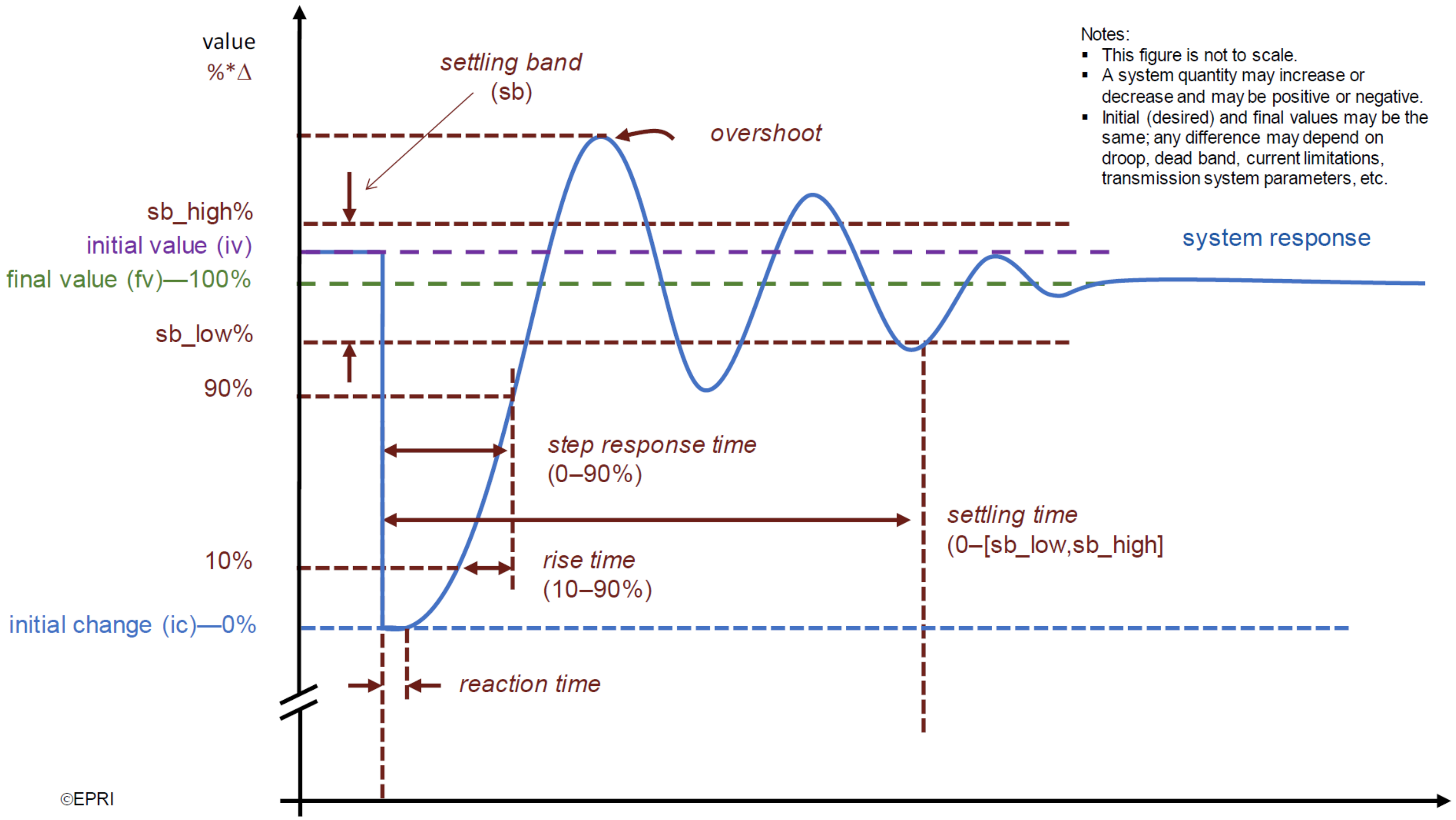


Figure 5(b) from Draft 5.1 of IEEE P2800 Draft Standard

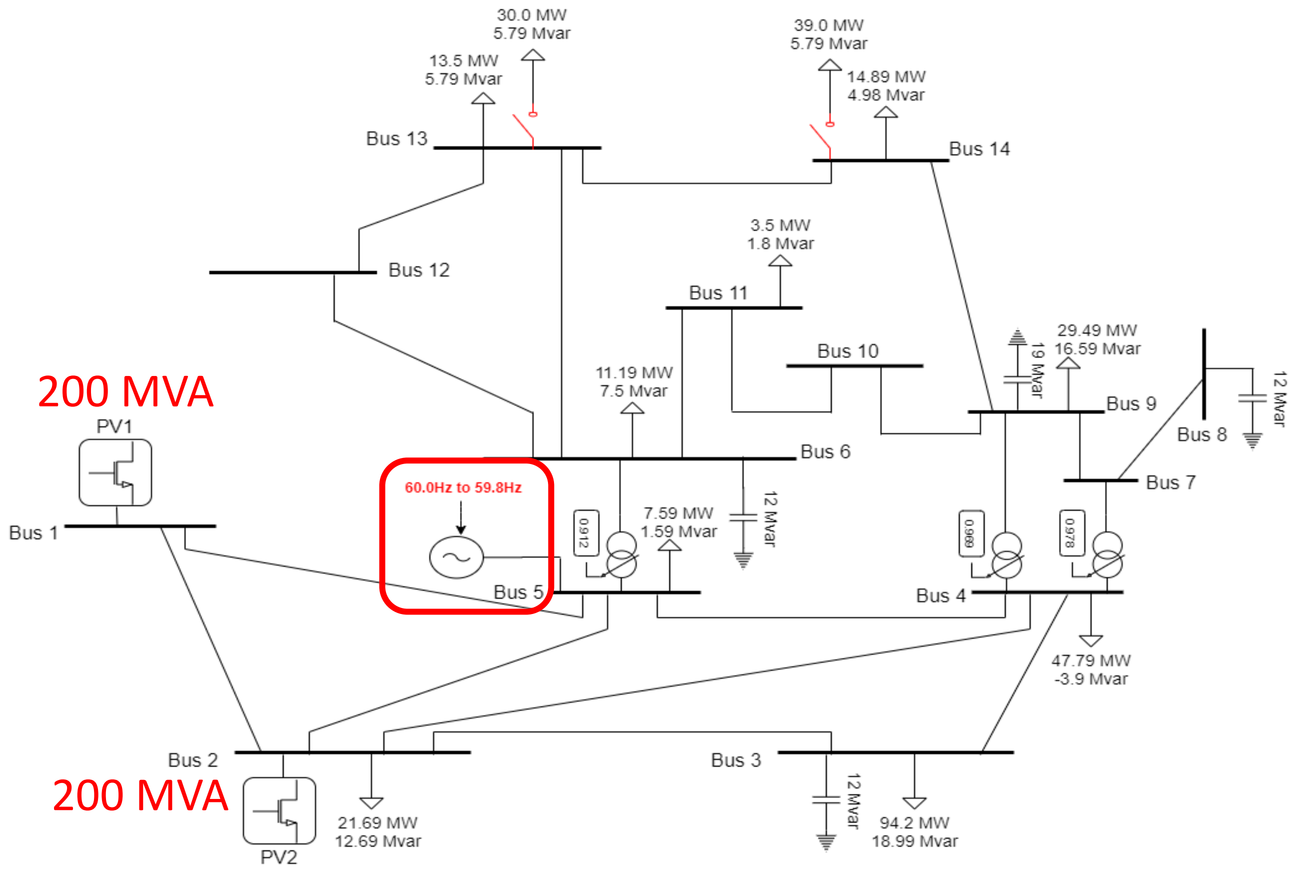
	Units	Default Value	Minimum	Maximum
Reaction time	seconds	0.50	0.20 (0.5 for WTG)	1
Rise time	seconds	4.0	2.0 (4.0 for WTG)	20
Settling time	seconds	10.0	10	30
Damping Ratio	% of Change	0.3	0.2	1.0
Settling band	% of Change	Max (2.5% of change or 0.5% of ICR)	1	5

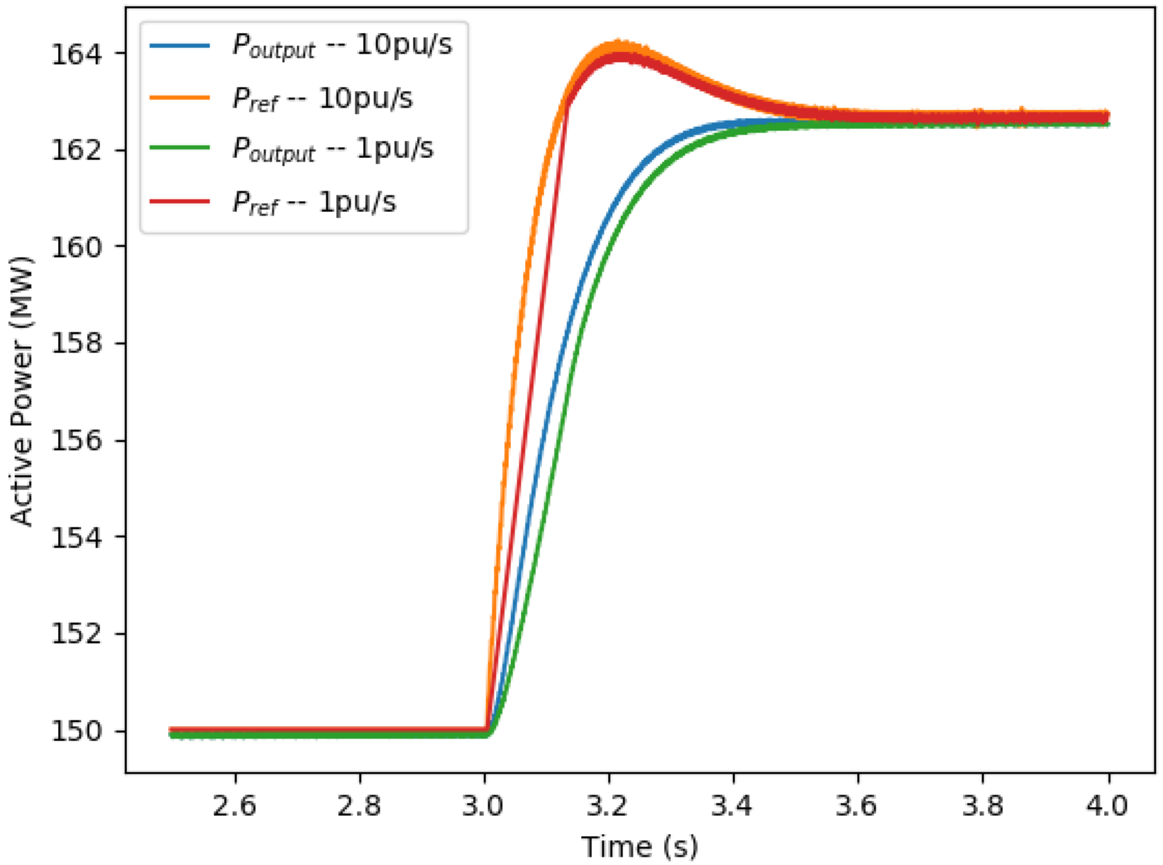
Table 10 from Draft 5.1 of IEEE P2800 Draft Standard

- Table 10 specifies <u>minimum</u> capability to be met
- Change in IBR plant power output may not be required to be greater than maximum ramp rate of plant
  - Should be as fast as technically feasible
- 15mHz - 36mHz deadband with 2% - 5% droop

Will this capability be sufficient for 100% IBR grids?

Example: Two PV plants in an existing strong network





- Each 200 MVA PV plant is a full switching model[1]
- Frequency control with 17mHz dead band and 5% droop at inverter level
- Comparison with 1pu/s and 10pu/s ramp rate on active power command

Both ramp rates meet requirements mentioned in IEEE P2800 Draft Standard

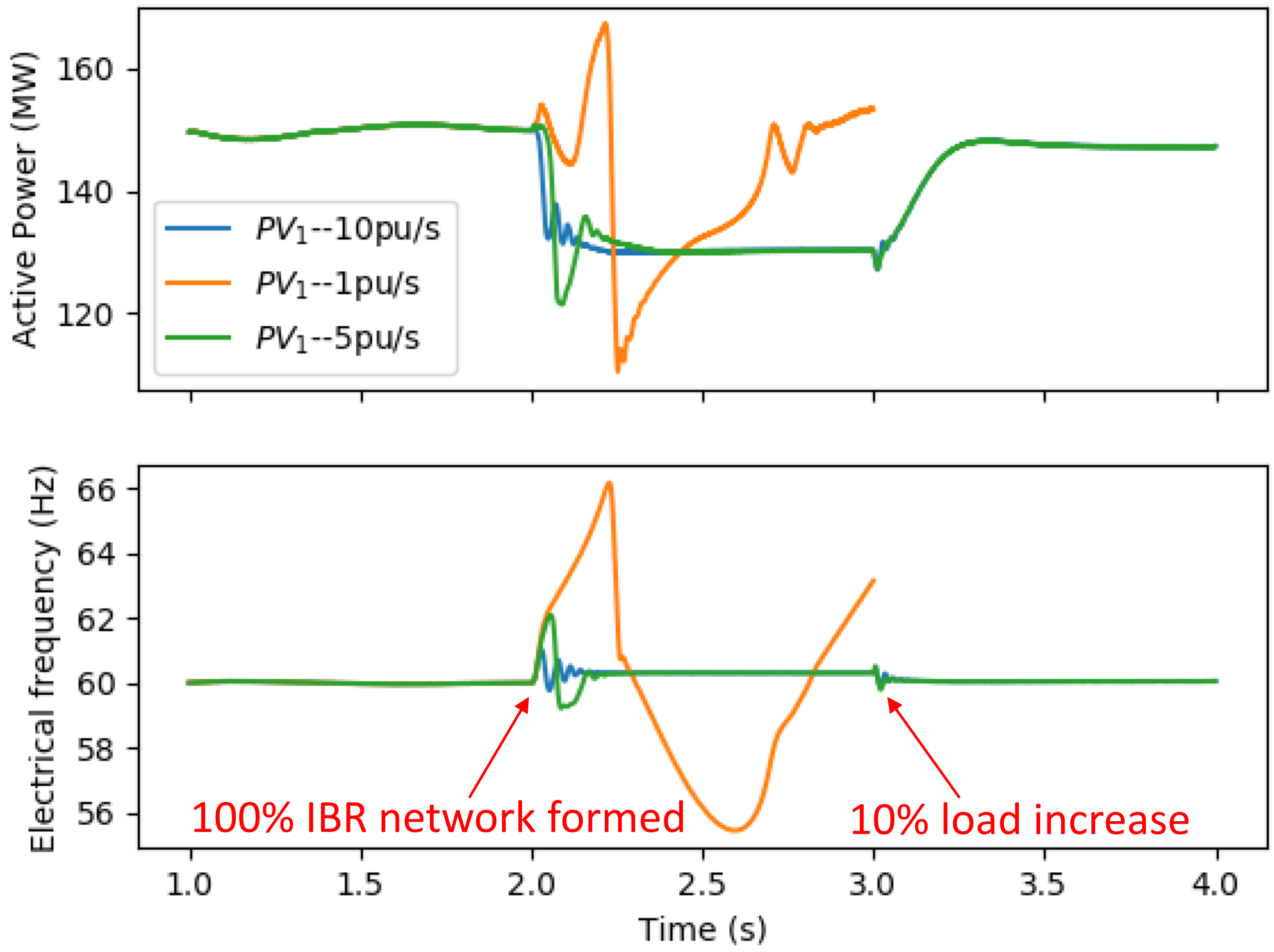
[1]https://www.pscad.com/knowledge-base/article/521

Lower ramp rates may not work in a 100% IBR system

- A low inertia power network needs fast injection of current to mitigate imbalances
- Suitable choice of ramp rate limit can bring about a stable response

Maximum ramp rate influenced by source behind the inverter

Batteries can tolerate higher ramp rates as opposed to wind turbines

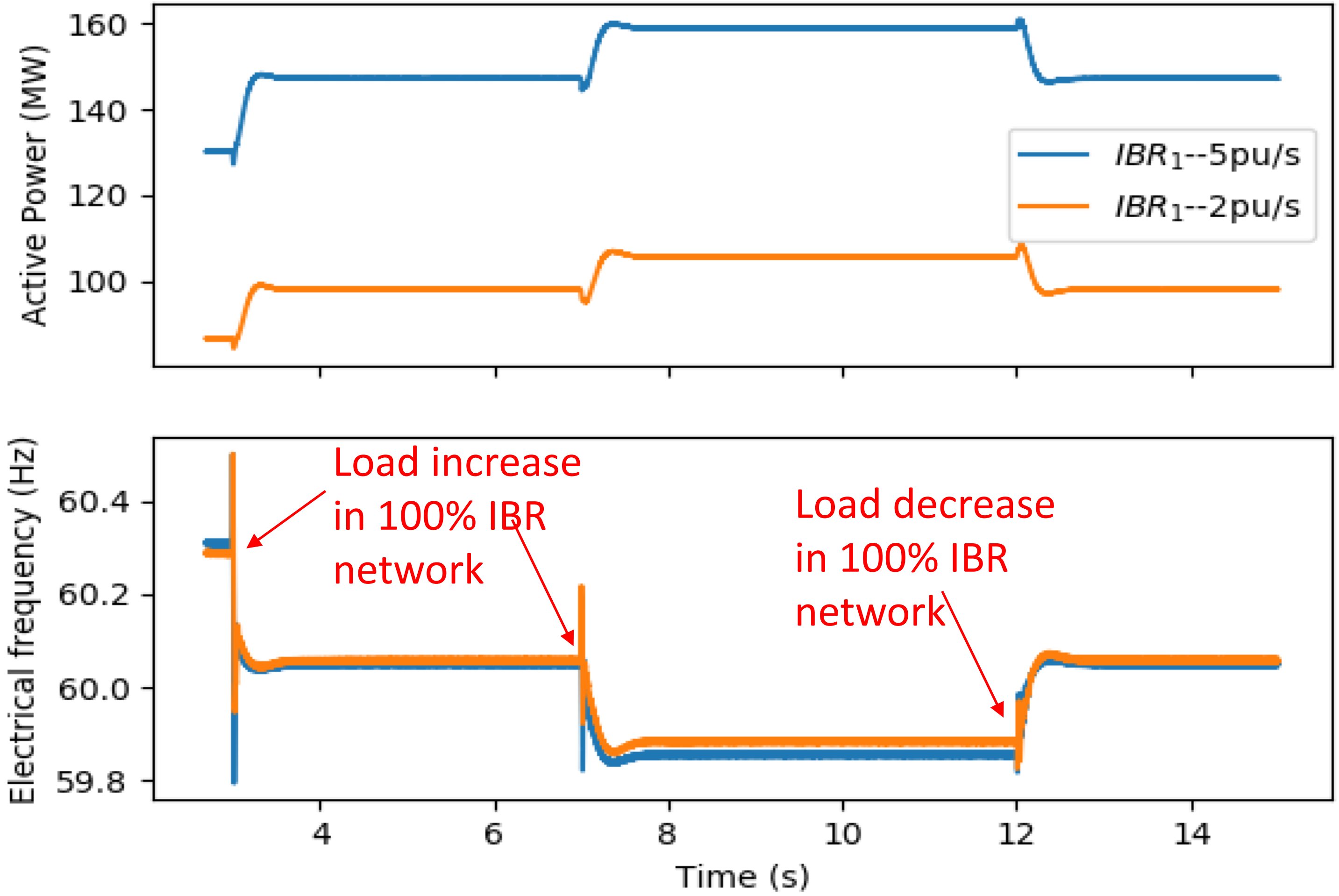


- 100% IBR network created at t=2.0s
- Load increase at t=3.0s

Lower ramp rate requires more responsive resources

- Possible to obtain stable frequency control in a 100% IBR network, with lower ramp rates
- Requires more resources to share the change in energy burden
- Any form of IBR device/control can have inherent ramp rate limits

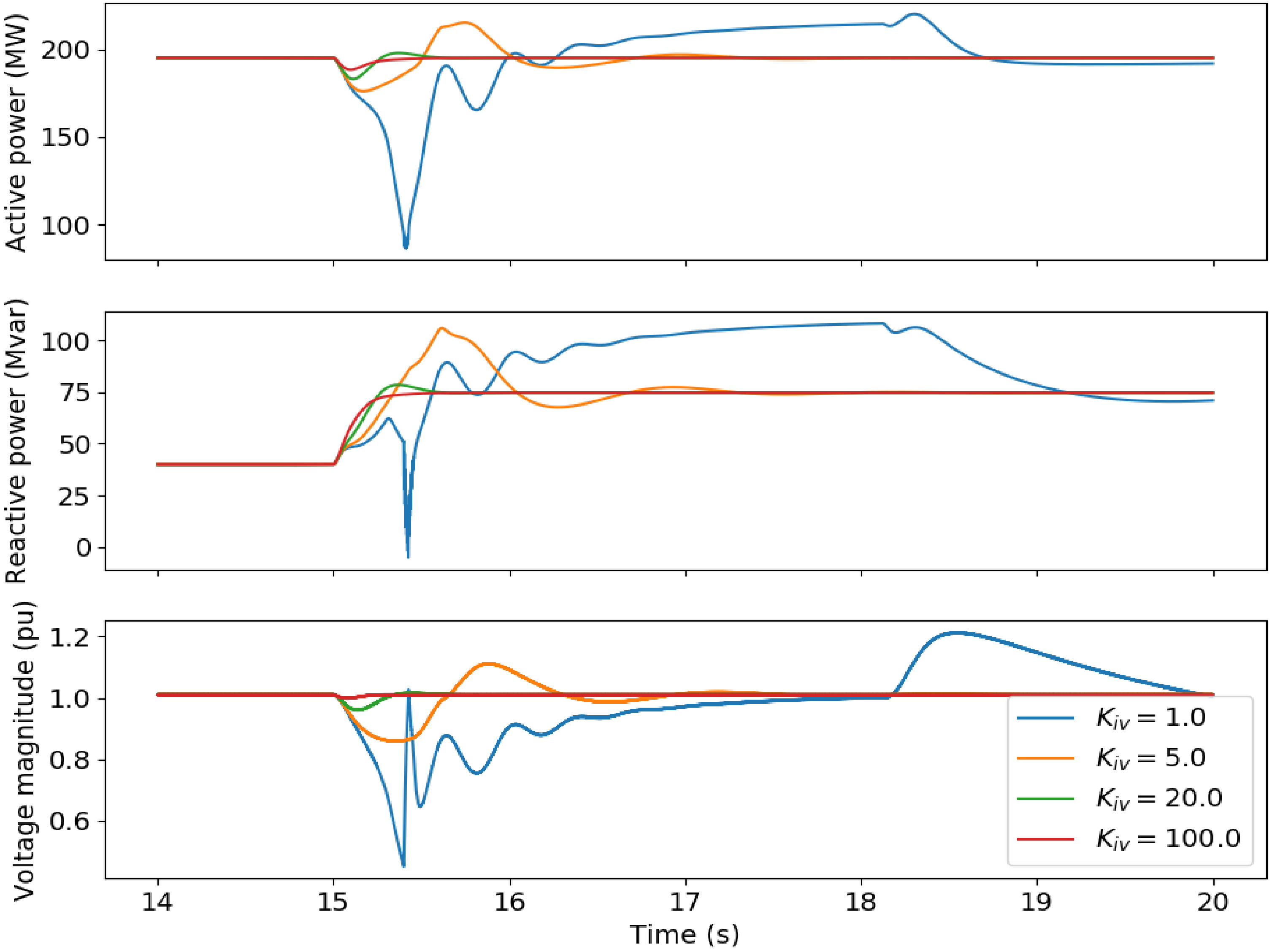
Important to recognize this if newer IBRs have to additionally support older IBRs



5pu/s – Two PV plants of 200 MVA each
2pu/s – Three PV plants of 100 MVA each

How fast should inverter level voltage control be?

- Lowest value of maximum step response time from draft IEEE P2800 is 1.0s
- Results on the right shown with SCR of 1.0, and a step reduction in grid voltage of 0.1pu
- To achieve grid forming behavior, potentially a faster voltage control loop may be required at the inverter level
  - With maximum step response time of less than 1.0s
  - Although the response with settling time of 3.0 may potentially also be sufficient



Determination of grid forming inverter capacity

- Similar behavior across multiple grid forming control structures allows for development of generic characteristics/models

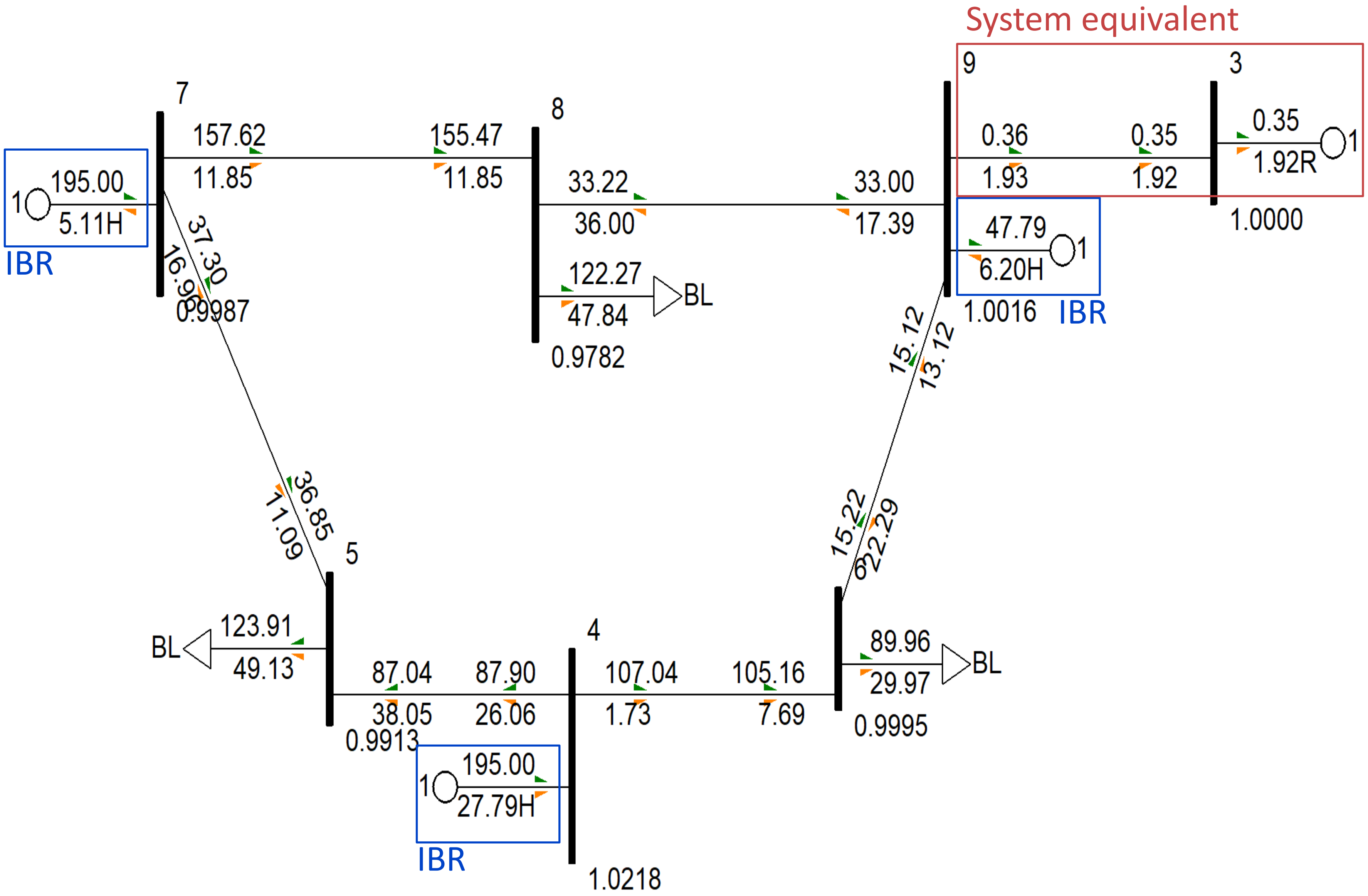
- These generic models in-turn allow for determination of grid forming capacity in future grids

- Both time domain and small signal stability concerns can exist

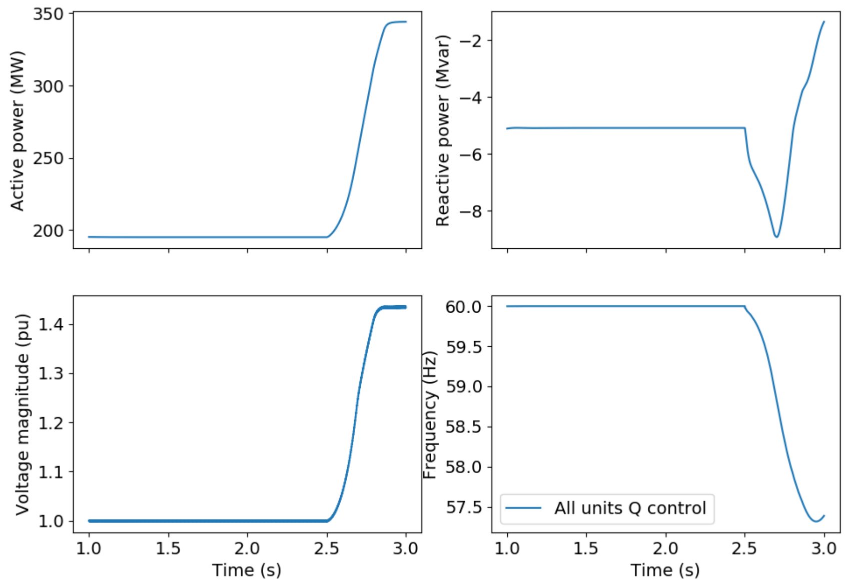
- Size of required grid forming inverters is not readily intuitive

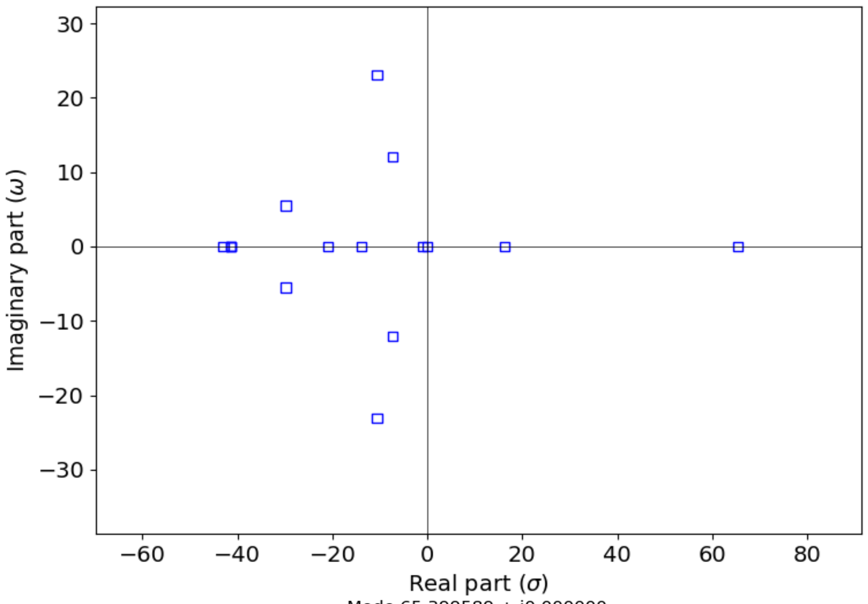
Consider an example network

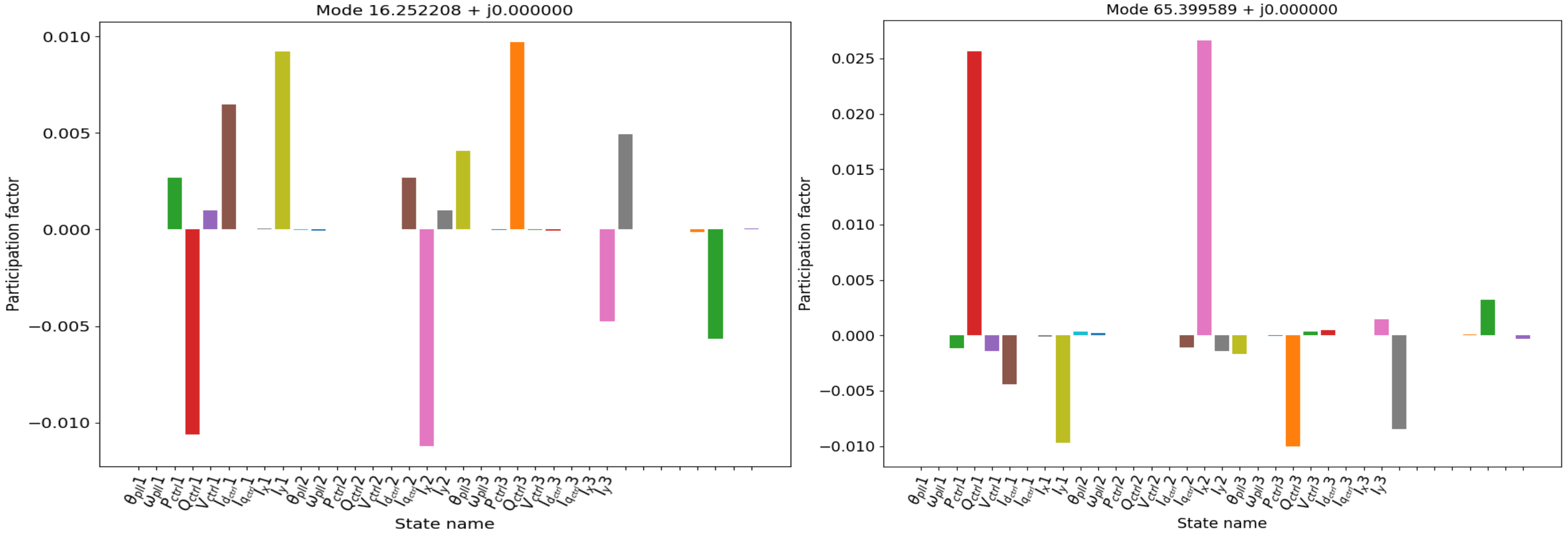
- Three legacy IBRs
  - Two IBRs with GFL P/Q control
    - 200 MVA each
  - One IBR with GFL current control
    - 50 MVA
- Power transfer to external network intentionally kept minimal



When all IBRs are grid following

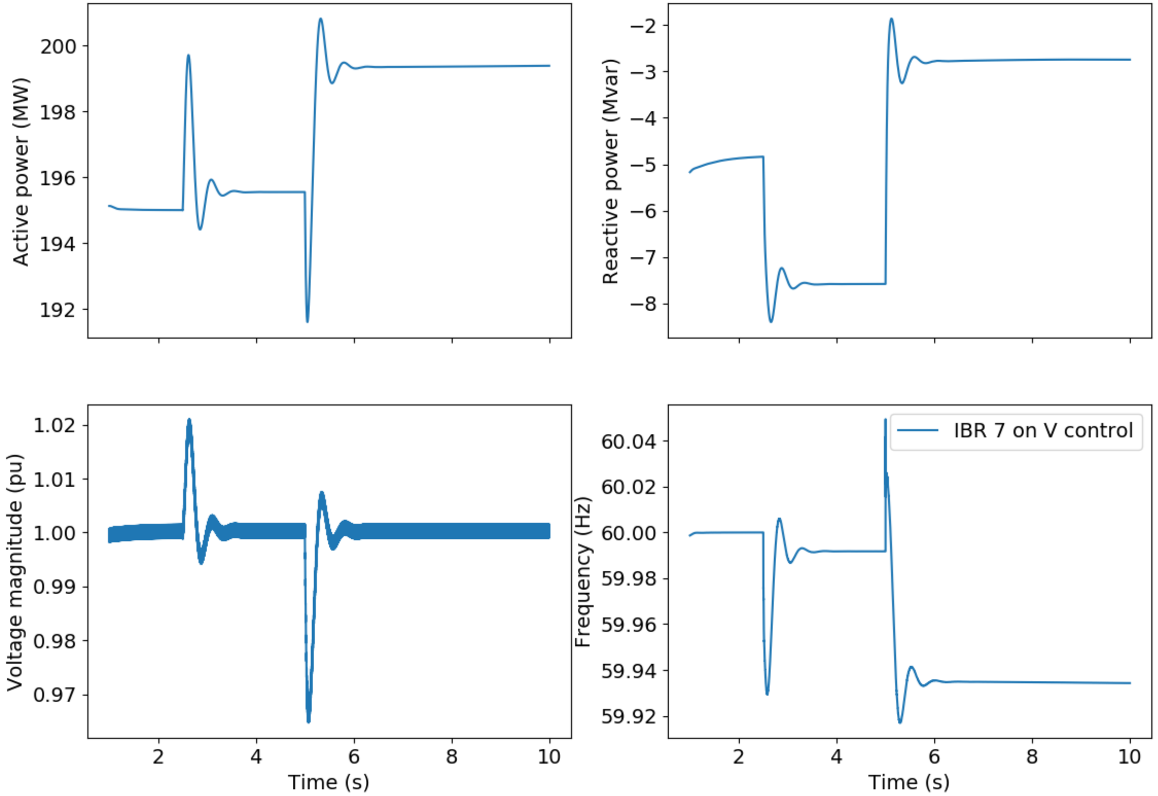


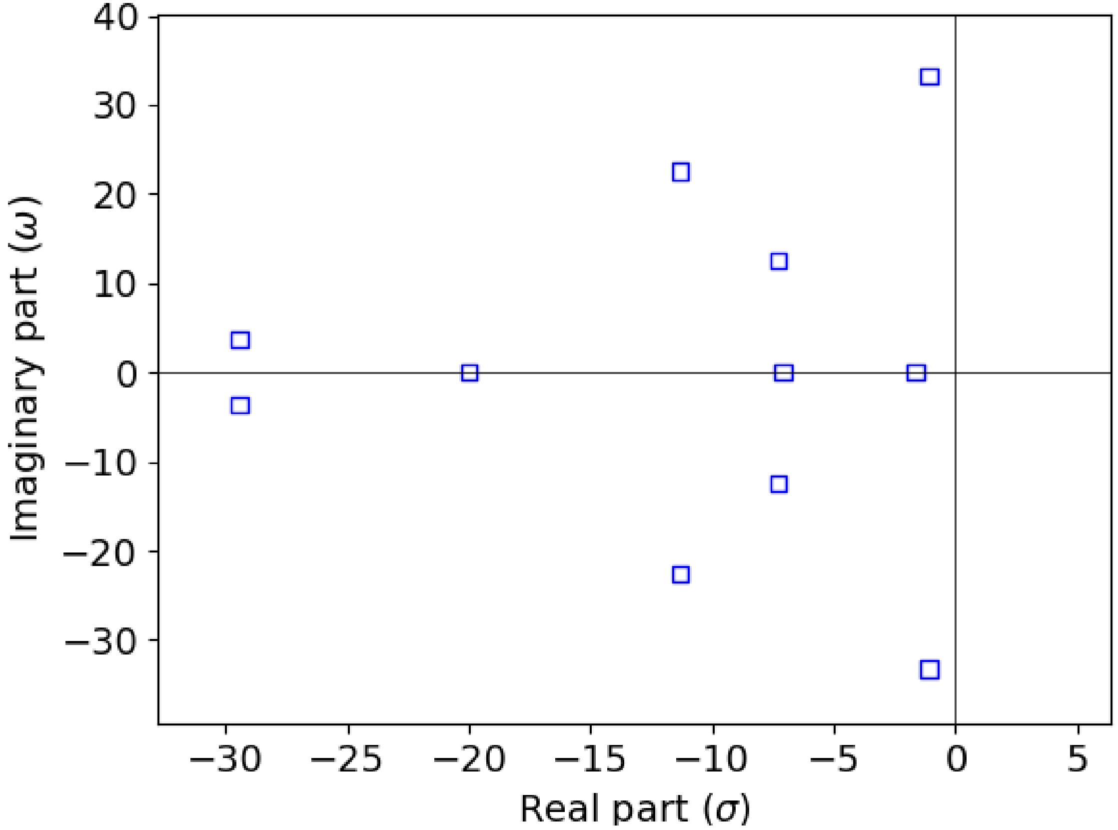




- Trip of system equivalent at t=2.5s
- Two unstable modes observed
- Large participation of Q-control loop in each unstable mode

When one 200 MVA IBR is transformed to GFM control

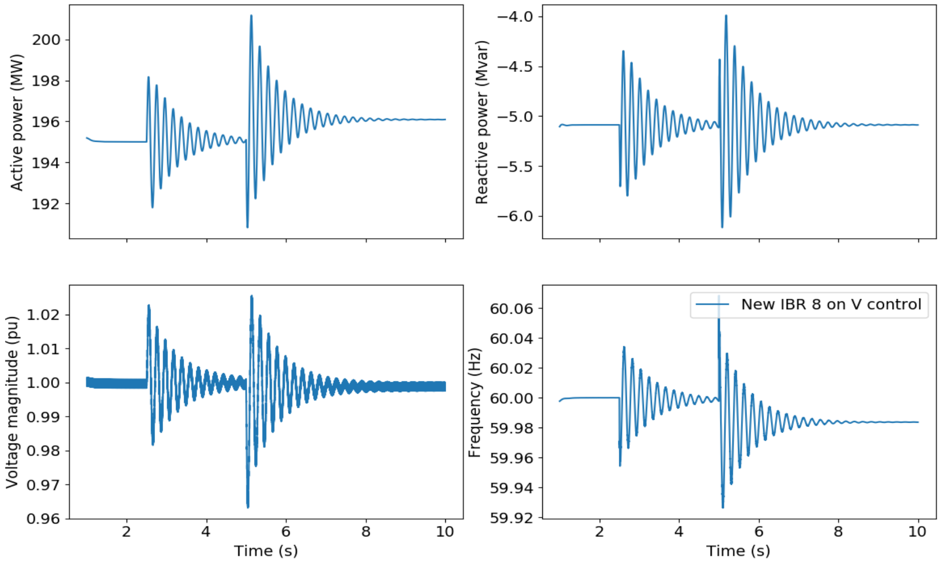


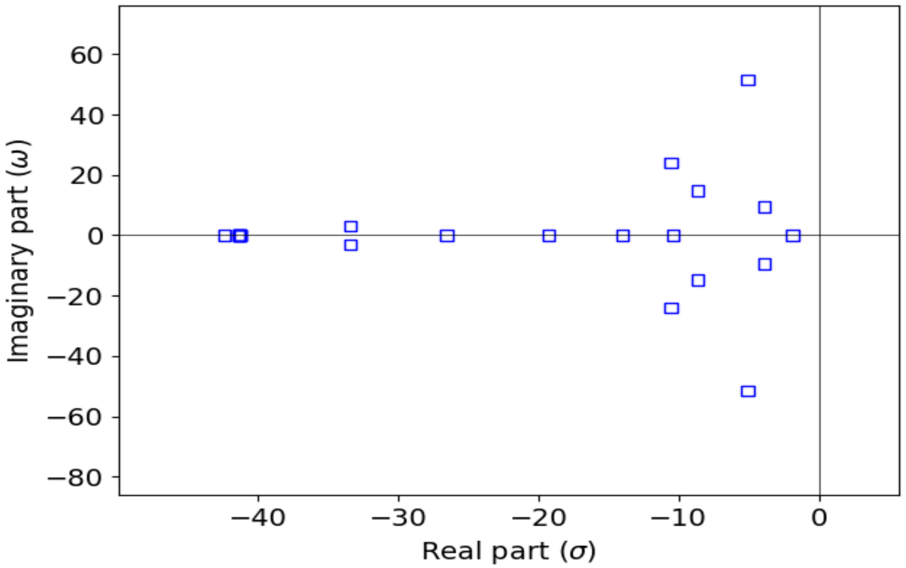


- Maximum settling time for performance of voltage control is 3.0s.
  - Within the specifications of draft IEEE P2800 standard!

- Robust performance immediately delivered
  - For grid islanding at t = 2.5s
  - Subsequent load increase at t = 5.0s

Suppose no scope to change existing inverters from GFL to GFM





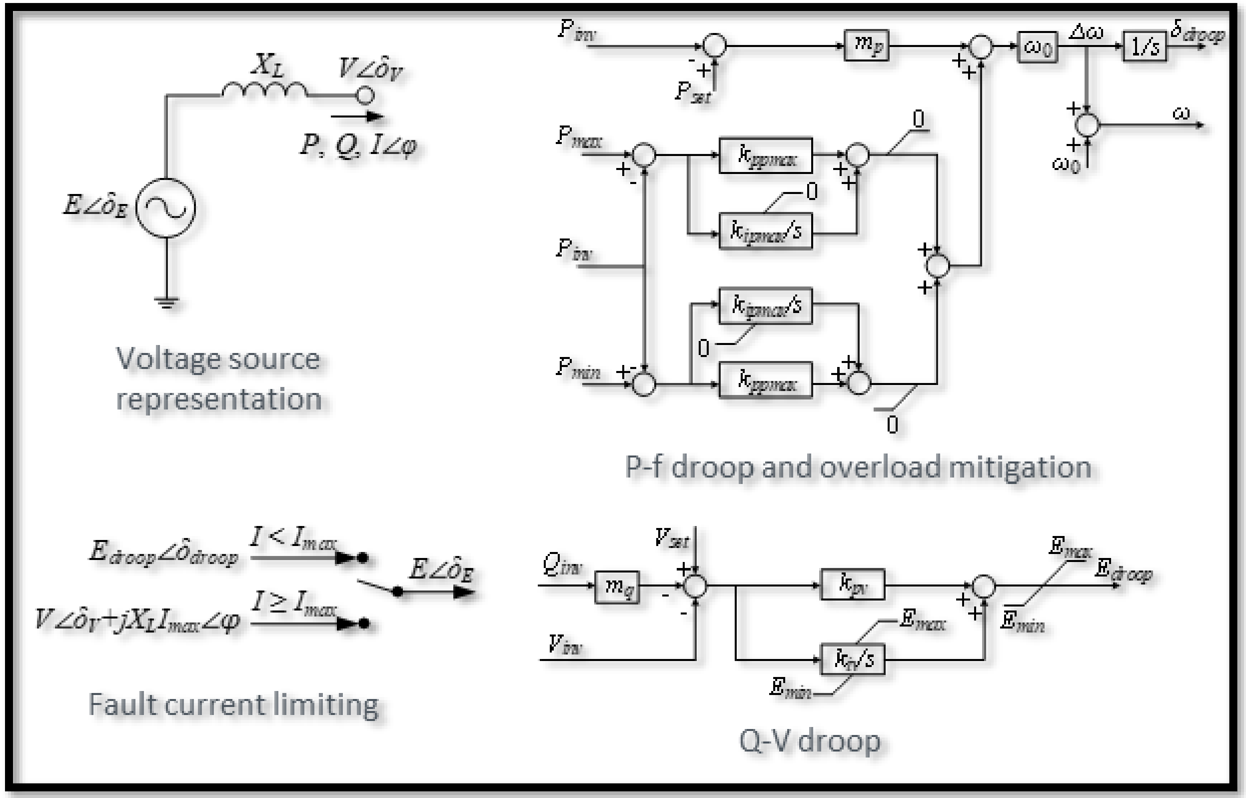
- A new 150 MVA inverter is required to maintain stability

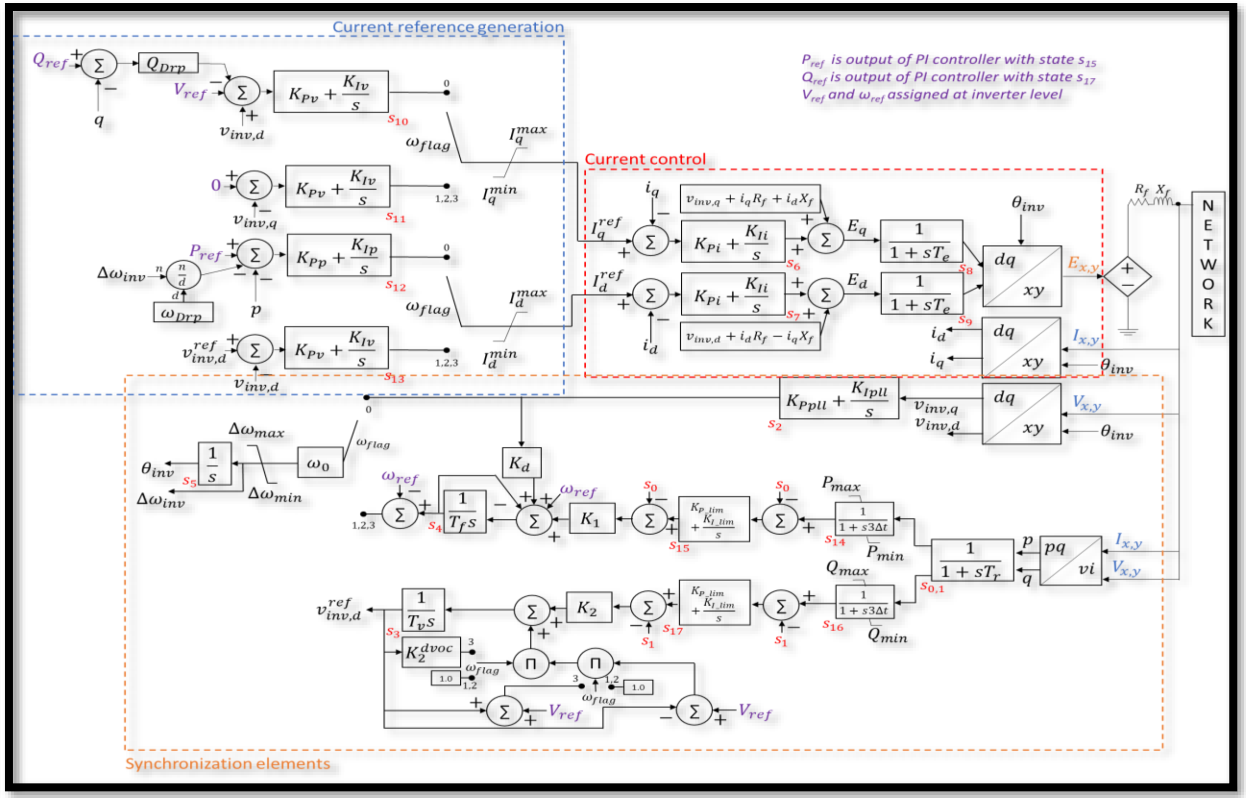
- Installation of new/additional equipment could have economic considerations

Planning a Transmission Network with GFM

Generic positive sequence models to aid in carrying out a study

- Single-loop and multi-loop structures allow for representation of wide variety of GFM behavior





1. https://www.wecc.org/Reliability/Model%20Specification%20of%20Droop-Controlled%20Grid-Forming%20Inverters_PNNL.pdf
2. https://www.wecc.org/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/Memo%20on%20Proposal%20for%20Generic%20GFM%20Model_v2.pdf&action=default&DefaultItemOpen=1

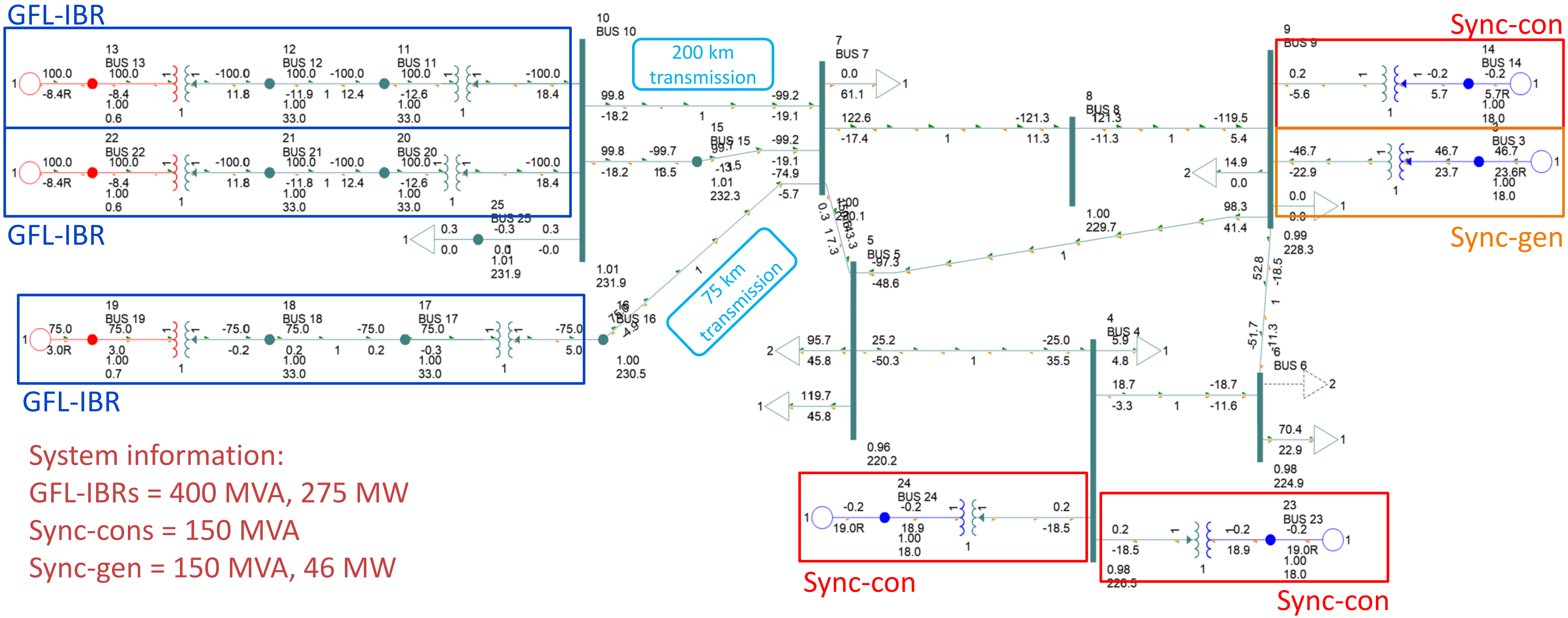
Availability of model (to-date)

Positive sequence/RMS balanced domain			EMT domain[+,^]					RMS unbalanced domain		Real-time domain
Siemens PTI PSS/E	**GE – PSLF**	**DIgSILENT PowerFactory**	**PSCAD[+]**	**EMTP[*]**	**DIgSILENT PowerFactory**	**SIMULINK**	**PLECS**	**OpenDSS**	**DIgSILENT PowerFactory**	**RTDS/Opal-RT/RSCAD**
✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×
Type A Droop Type B Droop	Type A Droop Type B Droop VSM dVOC	dVOC	Type A Droop Type B Droop VSM dVOC				Type A Droop VSM dVOC		dVOC	

[*]implemented by software developer
[+]certain model versions also have negative sequence control implemented
[^]certain model versions are also implemented at switching level
[+]C-code based model in addition to GUI block-based model

- Examples studies where models can be used:
  - Evaluate size of grid forming device required to be connected
  - Evaluate percentage of resources to be grid forming
  - Ascertain location on system where grid forming maybe beneficial

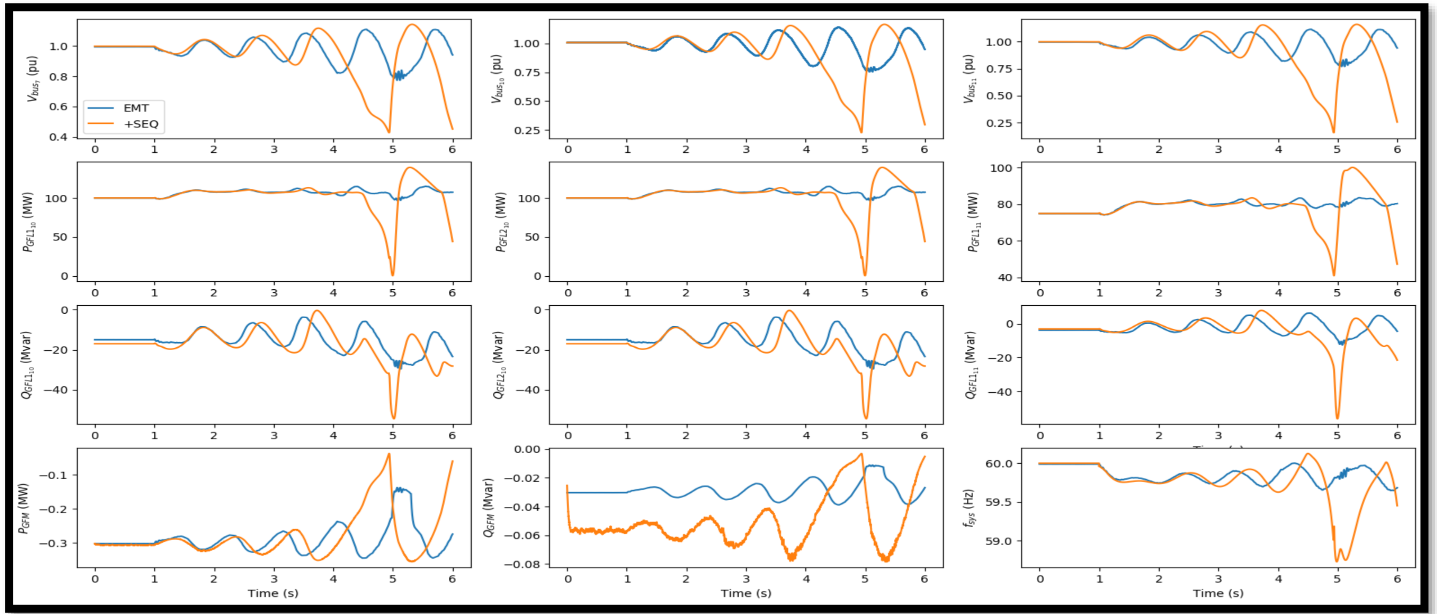
Locating and sizing of grid forming resources using generic models

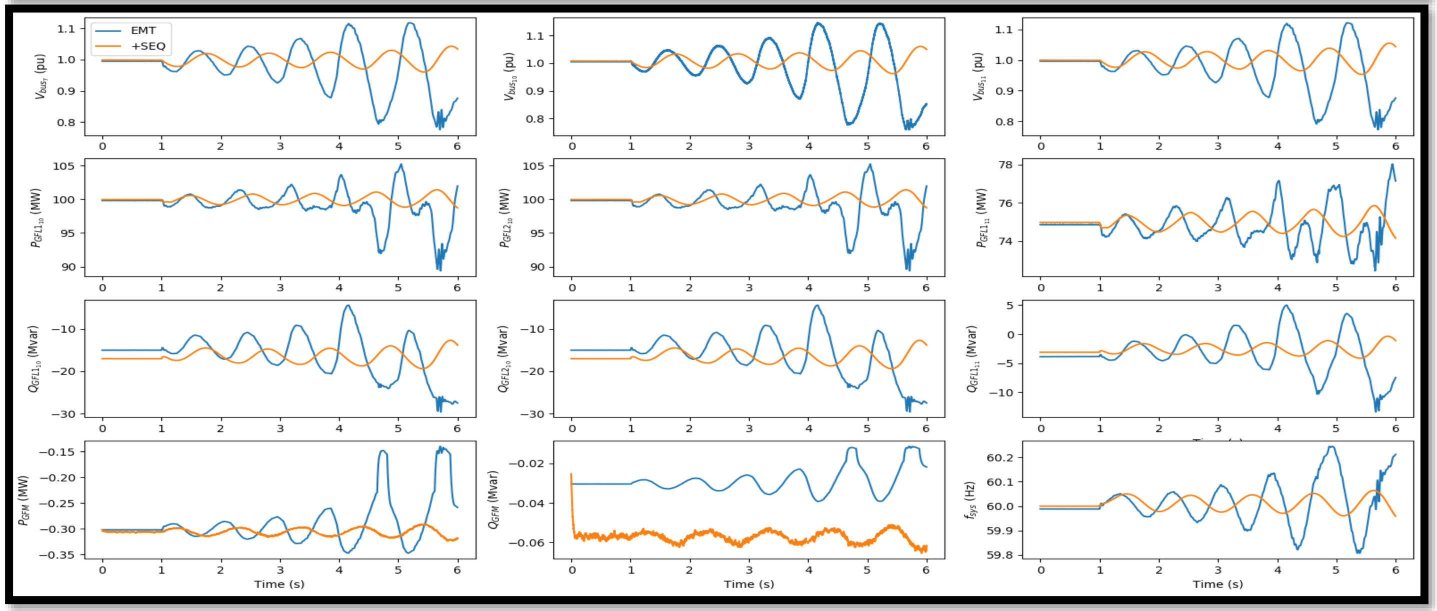


System information:
GFL-IBRs = 400 MVA, 275 MW
Sync-cons = 150 MVA
Sync-gen = 150 MVA, 46 MW

- Study objective: To allow retirement of synchronous condensers and generator from the load centers, where to place a GFM device and what should be its rating?

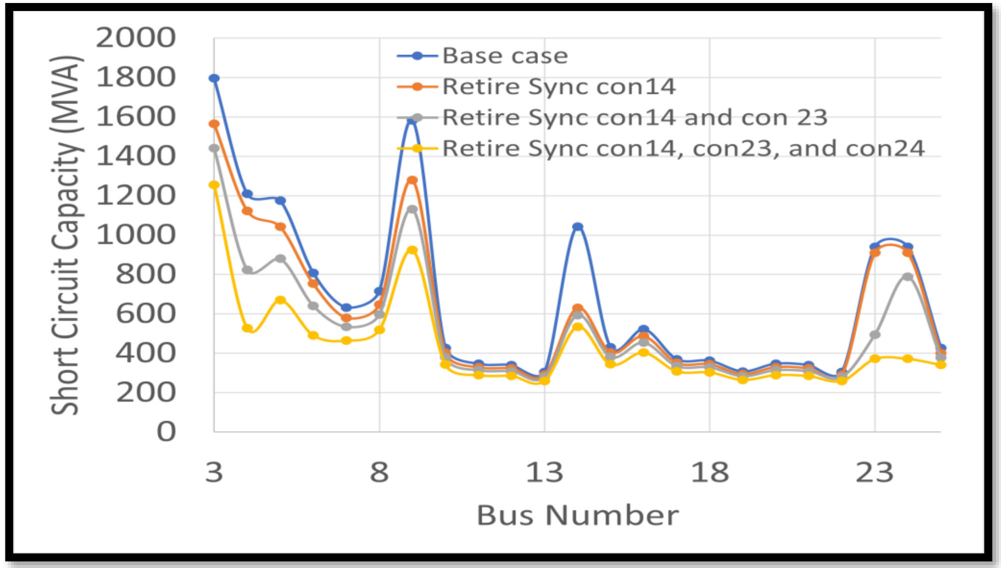
Locating and sizing of grid forming resources

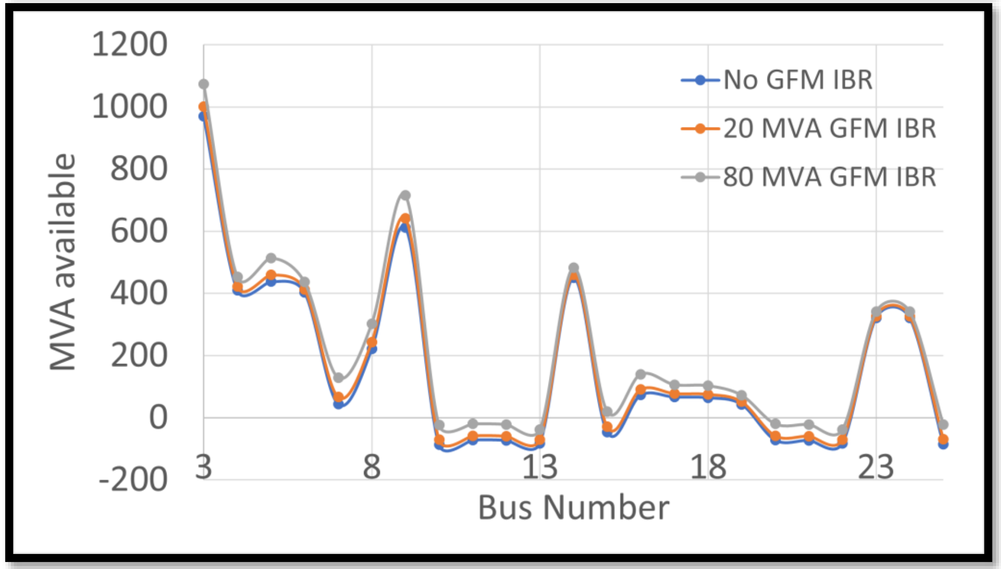


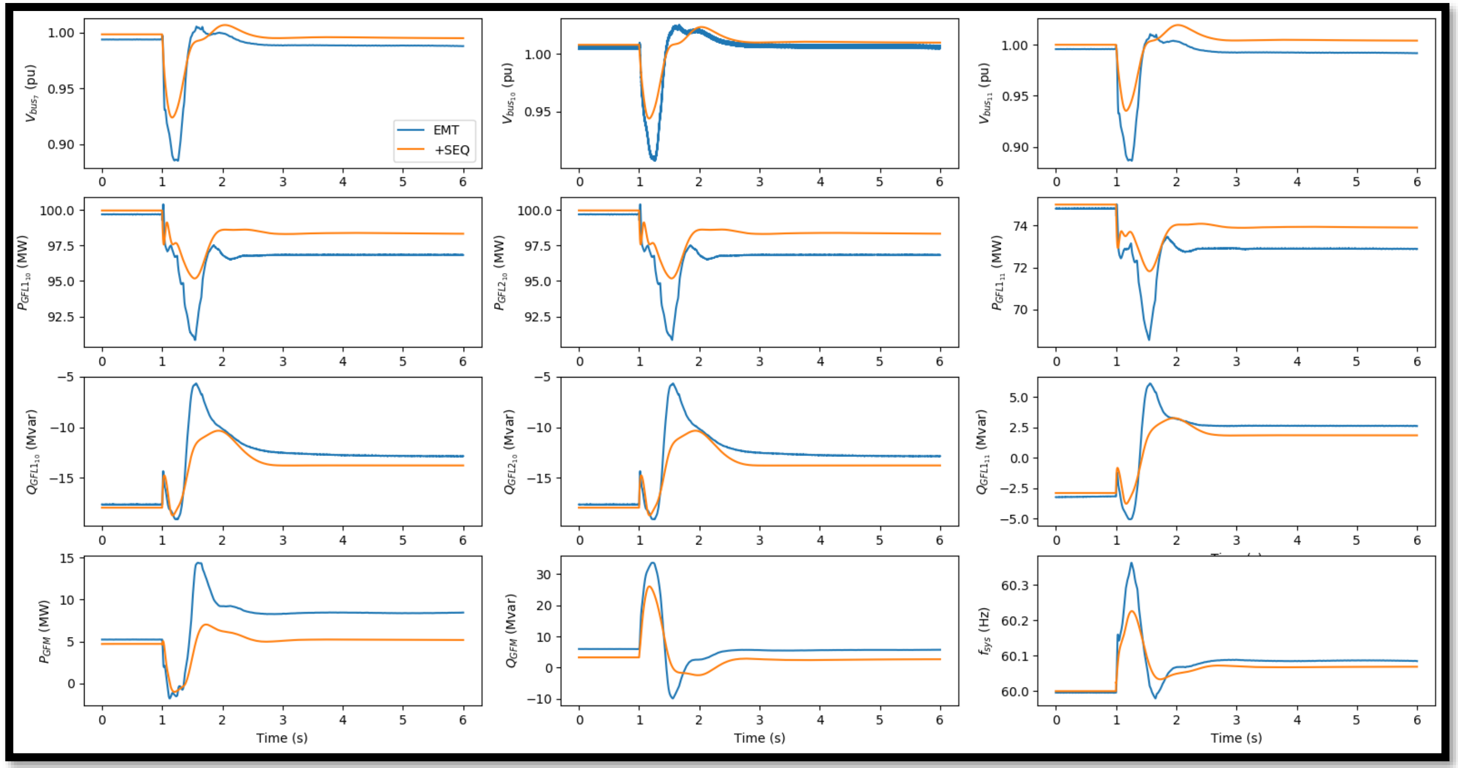


- Events shown:
  - Top: Load increase 10%
  - Bottom: Trip of one sync-con
- Even with synchronous resources (without power system stabilizers) system is on verge of instability
  - diligently parameterized models across both simulation domains

Locating and sizing of grid forming resources







- Determined size and location of GFM using steady metrics of short circuit strength and remaining MVA available
- Trip of all 150 MVA of sync-con could be stabilized with 80 MVA of GFM

[REF] Deepak Ramasubramanian, “Location and Sizing of Grid Forming Devices in Islanded Networks,” *[under review]*

What does all this imply?

Toward technology-agnostic requirements for GFM capabilities

- Instead of focusing on how GFM control can be implemented and which type of GFM control should be used, the ultimate goal is to set up technology-agnostic performance requirements and ensure the grid has enough GFM capability to support its reliable operation
- However, incorporating new and perhaps different types of GFM control could change the overall system dynamic behavior and alter the failure mode of the system
- Understanding the dynamics and stability limit with parallel operation of multiple GFM (different types) and GFL inverters is required in order to set up the requirements
- Development of good GFM models along with appropriate parameterization techniques is crucial for being able to formulate and verify performance requirements

GFM may not be a “Silver Bullet”

- Even though GFM control provides improvements on inverter stability and dynamic performance in weak grid operations, it is not a single/unique magical solution
- GFM is simply another way to control the sinusoidal voltage output of the inverter
- Physical limits of the inverter and the system still apply
- Like every other control, GFM control have stability limits beyond which synchronization with the grid can be lost or other types of instability can occur.

References

[1] J. Liu, Y. Miura, H. Bevrani and T. Ise, "Enhanced Virtual Synchronous Generator Control for Parallel Inverters in Microgrids," in IEEE Transactions on Smart Grid, vol. 8, no. 5, pp. 2268-2277, Sept. 2017, doi: 10.1109/TSG.2016.2521405.

[2] C. Arghir and F. Dörfler, "The Electronic Realization of Synchronous Machines: Model Matching, Angle Tracking, and Energy Shaping Techniques," in IEEE Transactions on Power Electronics, vol. 35, no. 4, pp. 4398-4410, April 2020, doi: 10.1109/TPEL.2019.2939710.

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