Modeling of grid forming (GFM) IBR and frequency response in a 100% IBR Grid

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Few basics about various inverter mathematical models

Generic model	Does not always imply	Bad model
User defined model from manufacturer	Does not always imply	Good model
RMS/Positive sequence model	Does not always imply	Bad model
Electromagnetic transient (EMT) model	Does not always imply	Good model

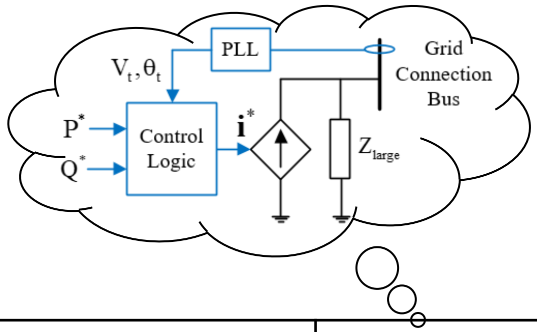
» All mathematical models have limitations

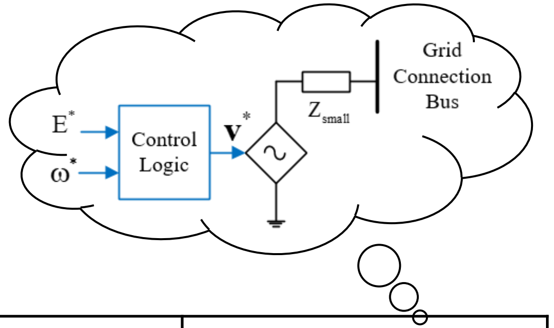
» When using mathematical models, few questions to be asked:

- Is this the appropriate type of model for the study that is to be done?
- Is the model being used in a correct manner?
- Are all relevant components/control loops, that matter for the study, modeled?
- Is the model appropriately parameterized?
- Are sufficient validation results of model behavior available?

What you may have heard regarding grid following (GFL) and grid forming (GFM) inverters

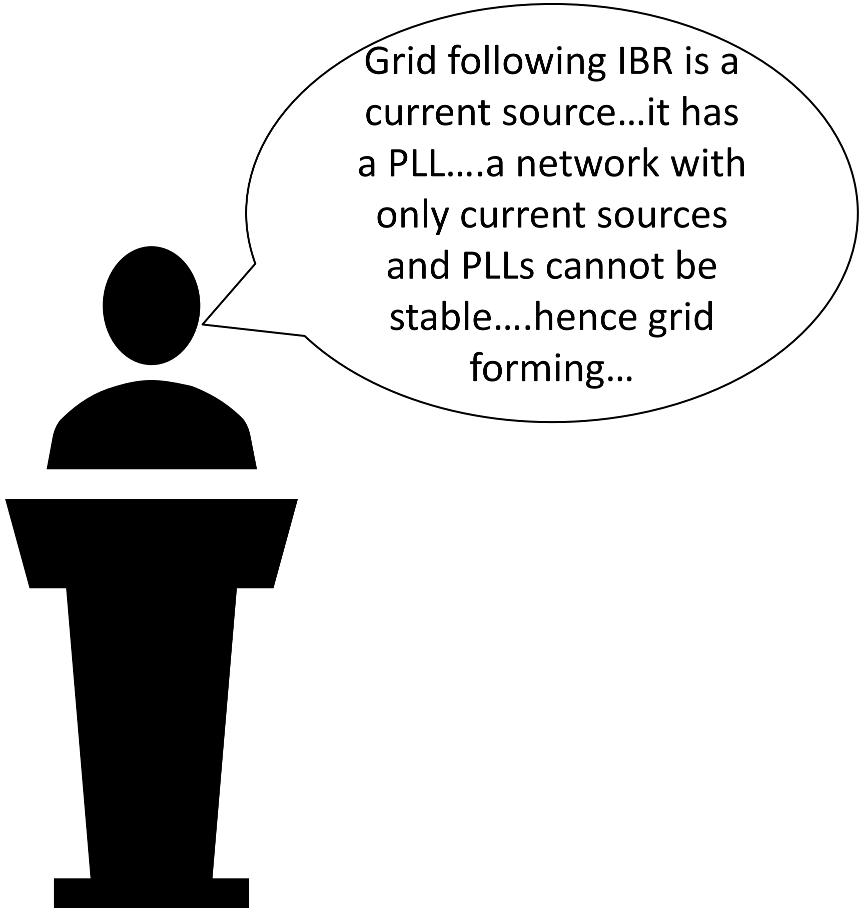
High level definition usually based on specific control design



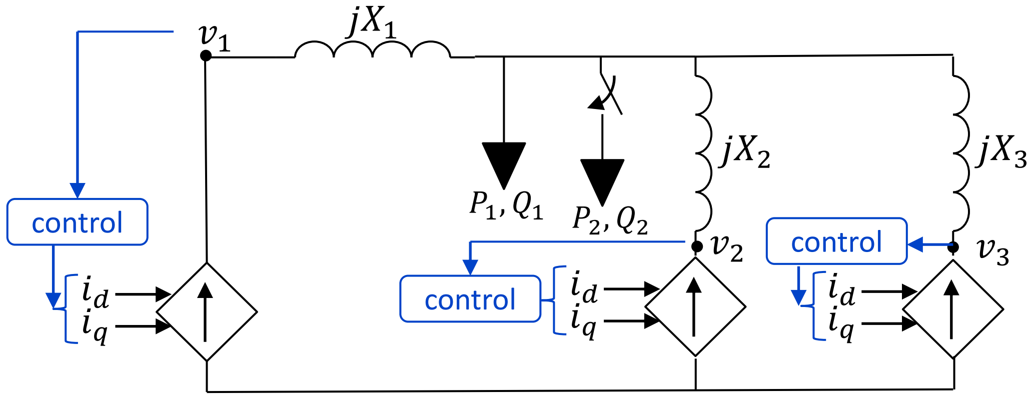


	Grid-following inverter	Grid-forming inverter
Basic control objectives	Deliver a specified amount of power to an energized grid	Set up grid voltage and frequency
Output quantity controlled	ac current magnitude and phase angle	ac voltage magnitude and frequency
Require a stiff and stable voltage at the terminal?	Yes	No
Control elements present	Compulsorily has a phase locked loop (PLL)	Compulsorily does not have a phase locked loop (PLL)

There are many nuances within each statement above that may blur the line between grid following and grid forming

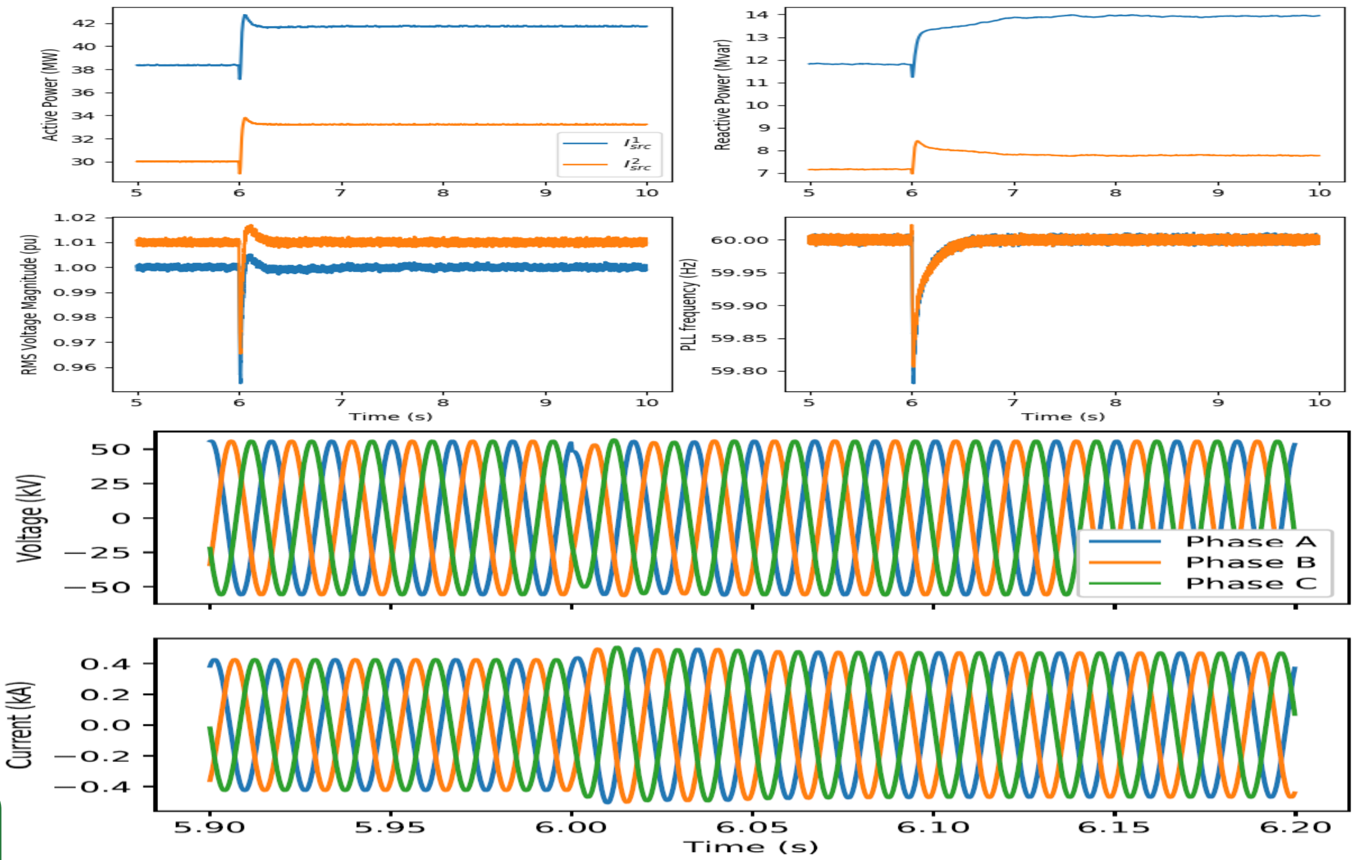


But Kirchhoff's Laws still apply in a 100% current source network



- 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



10% increase in constant power load

What does this have to do with grid forming behavior?

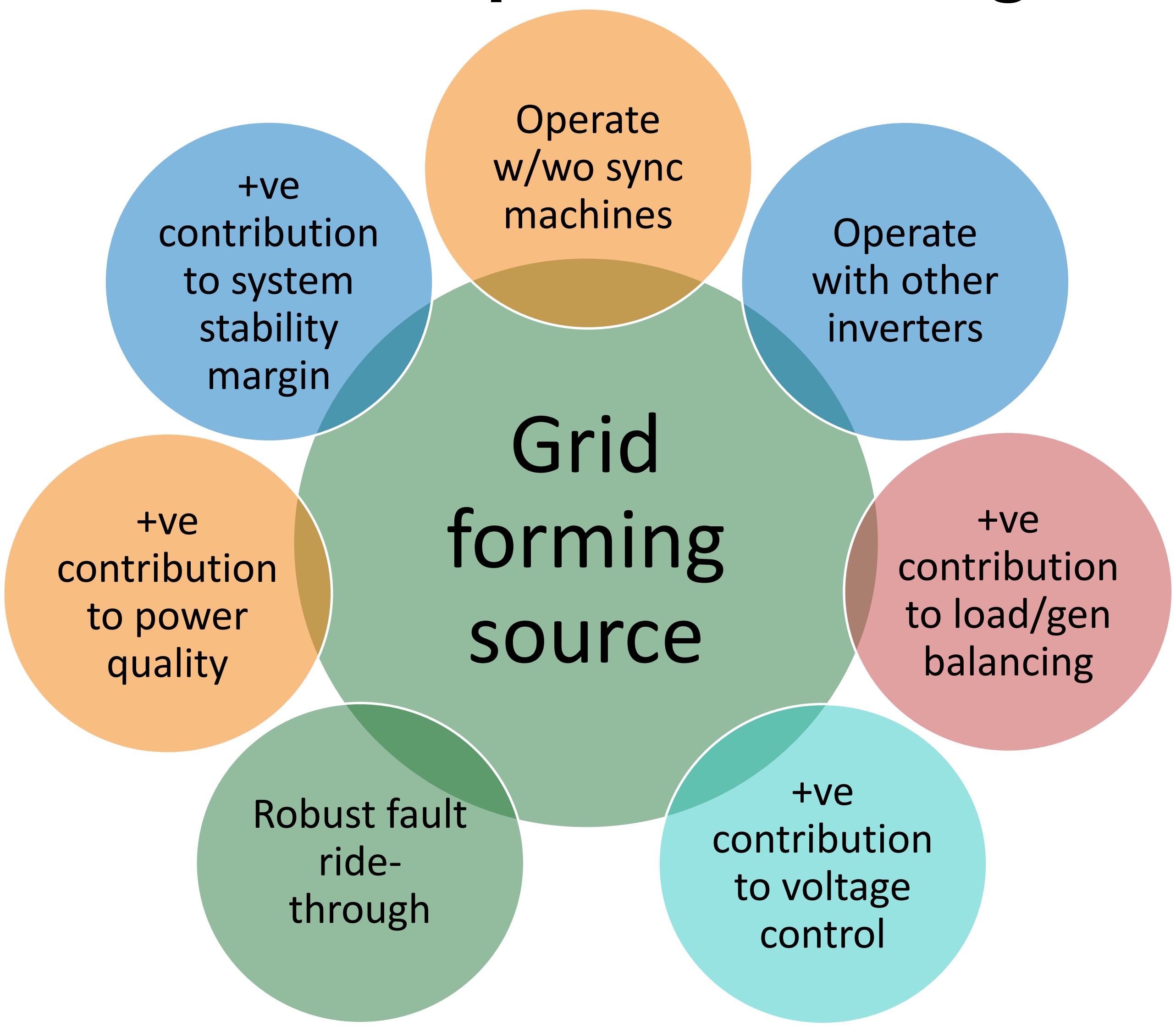
Defining grid forming behavior from system planner perspective

- Continued operation of 100% current source network is possible
  - System blackstart and restoration is a special operation scenario even today
- 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

» Inverter control with PLL can also be developed to work in weak or even 100% IBR grids
  - Provided the required services are delivered in a timely manner

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.*

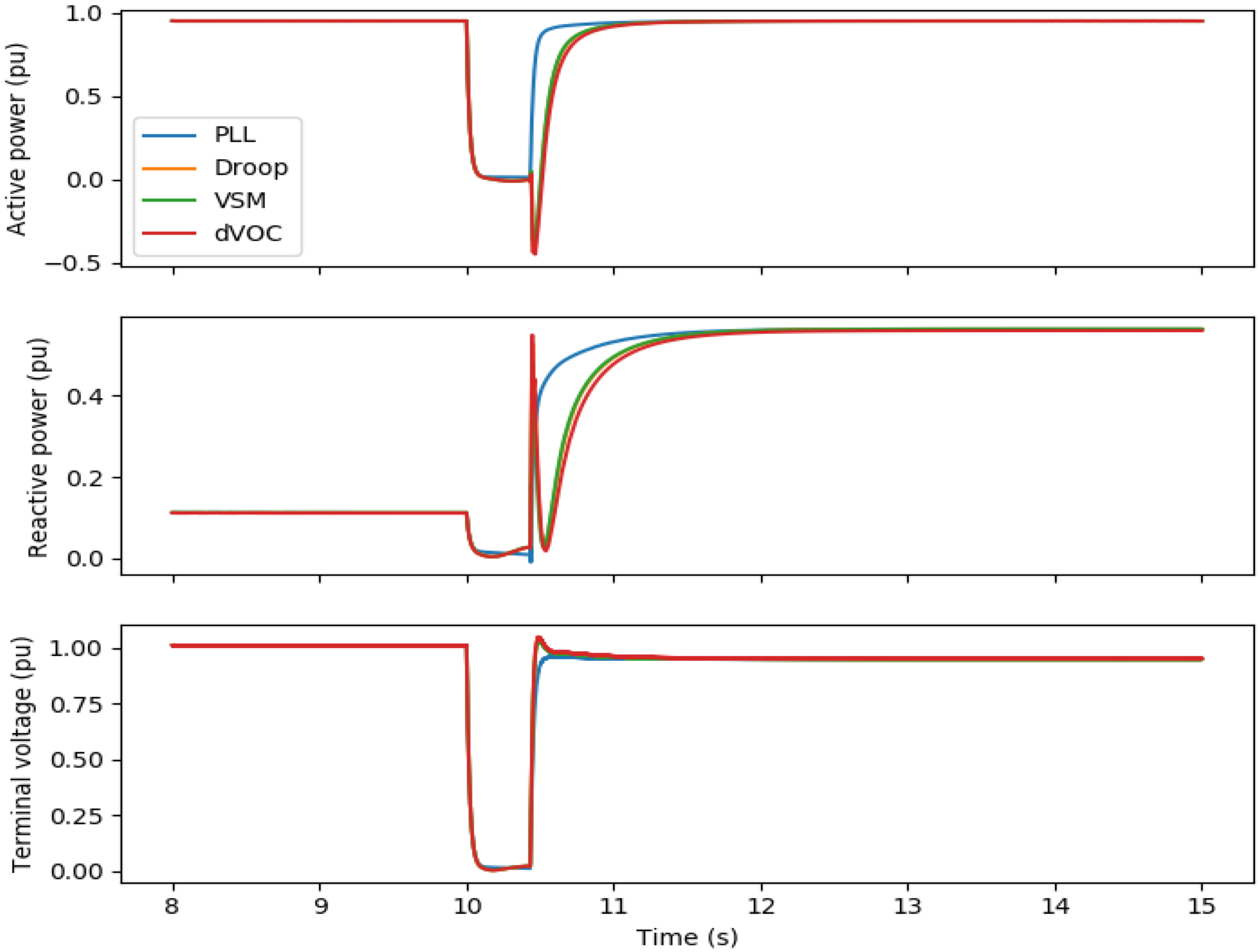
» *Few GFM sources* can also be designated as blackstart resources

Similar GFM response in EMT domain for low short circuit conditions

» Based on test specification in AEMO's Dynamic Model Acceptance Test Guideline (link)

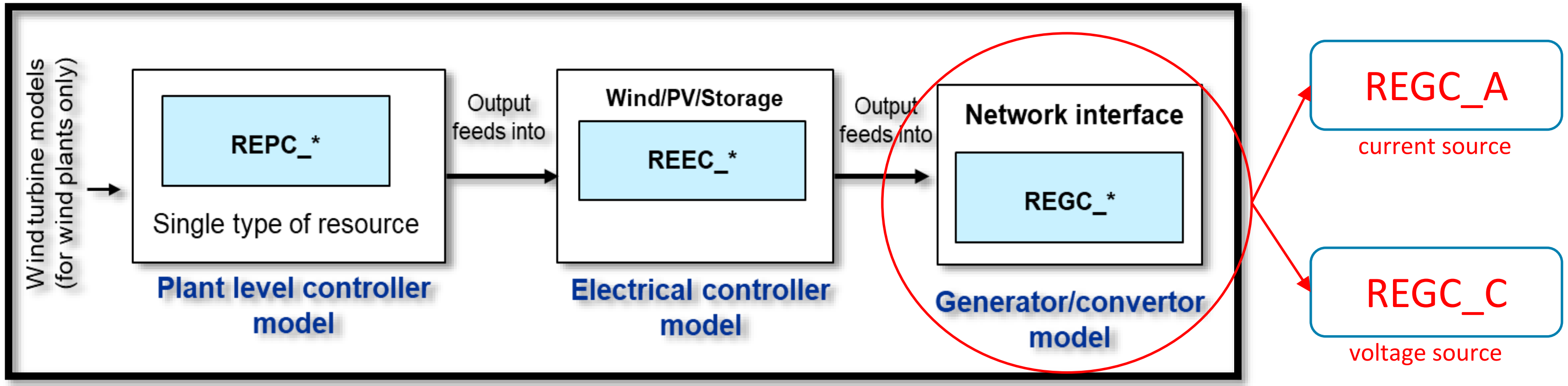
- Pre-fault SCR = 3.0
- Post-fault SCR = 1.0
- X/R ratio = 14
- 3PHG fault at POI, Zf = 0.0, duration 0.43s

» Model controls not optimally tuned



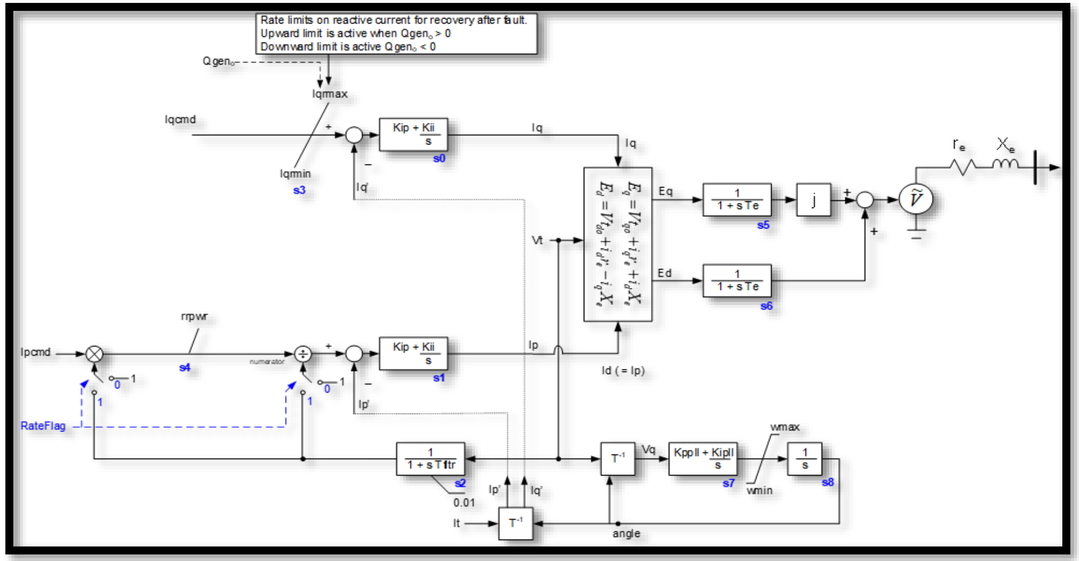
How does this link to positive sequence models?

Positive sequence generic models (a.k.a. WECC generic models)



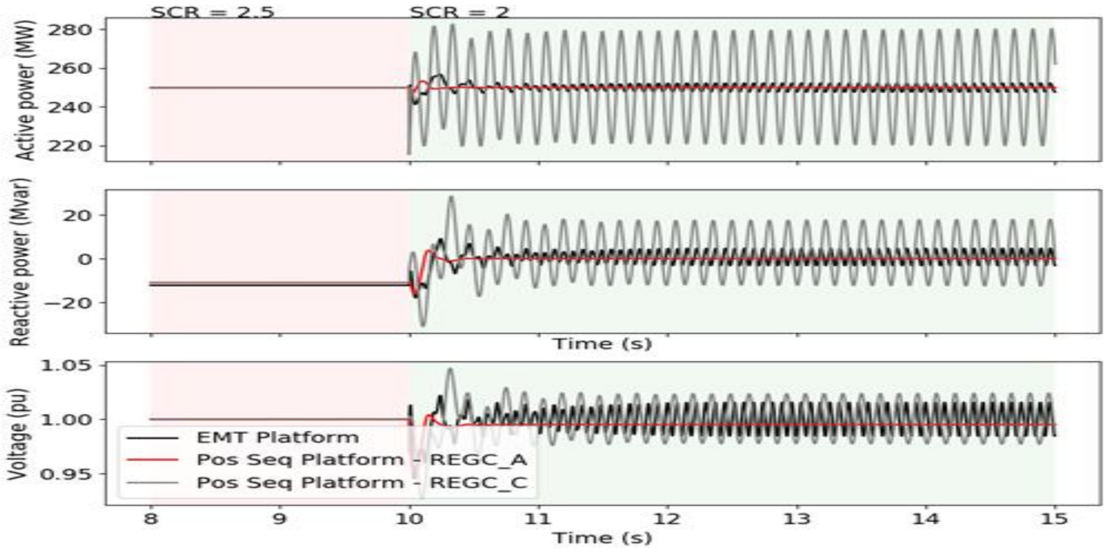
Generic models are vendor-agnostic models that do not necessarily represent the exact control algorithm of any particular IBR vendor. When appropriately parameterized, these models can subsequently provide the trend of dynamic behavior expected from IBR plants.

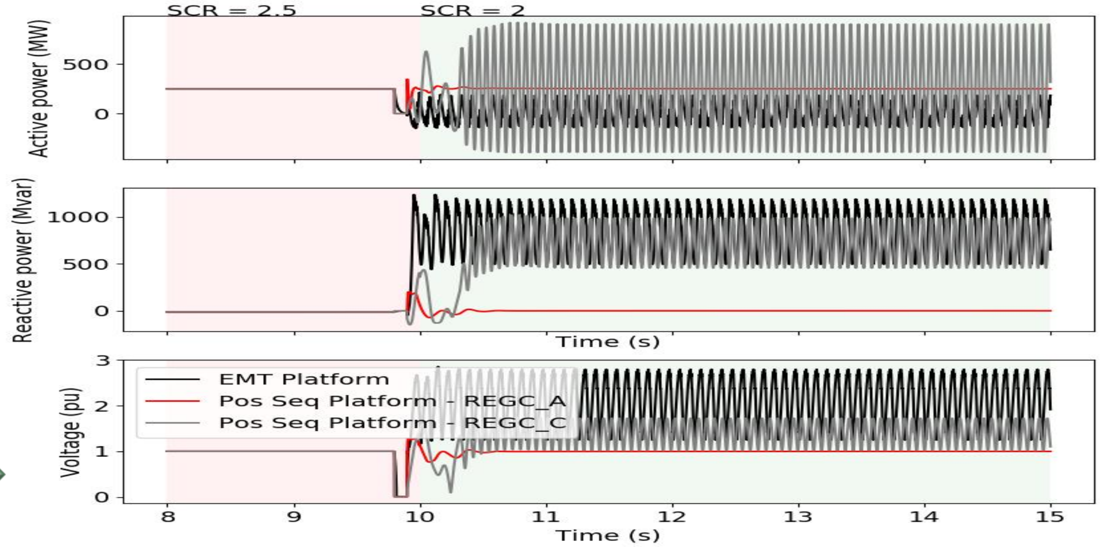
The REGC_C generic model



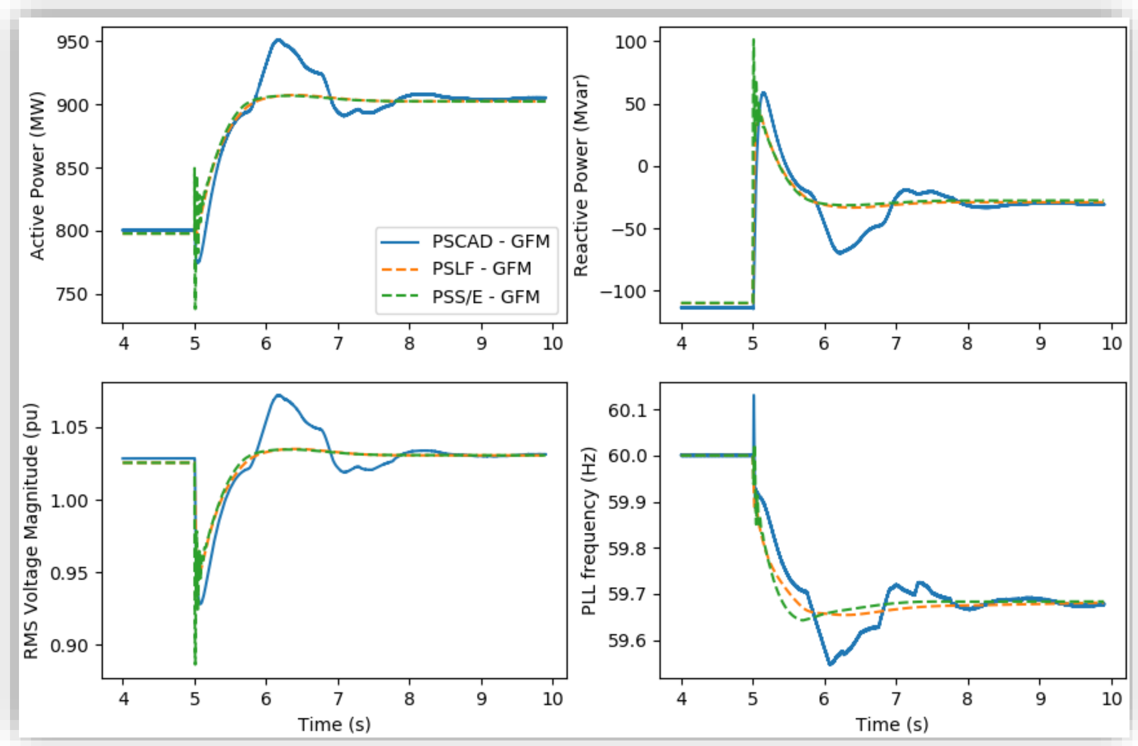
- Approximate representation of dynamic behavior of
  - inverter's inner current control loop.
  - Inverter's phase locked loop
- Current commands are translated into voltage reference commands behind an impedance

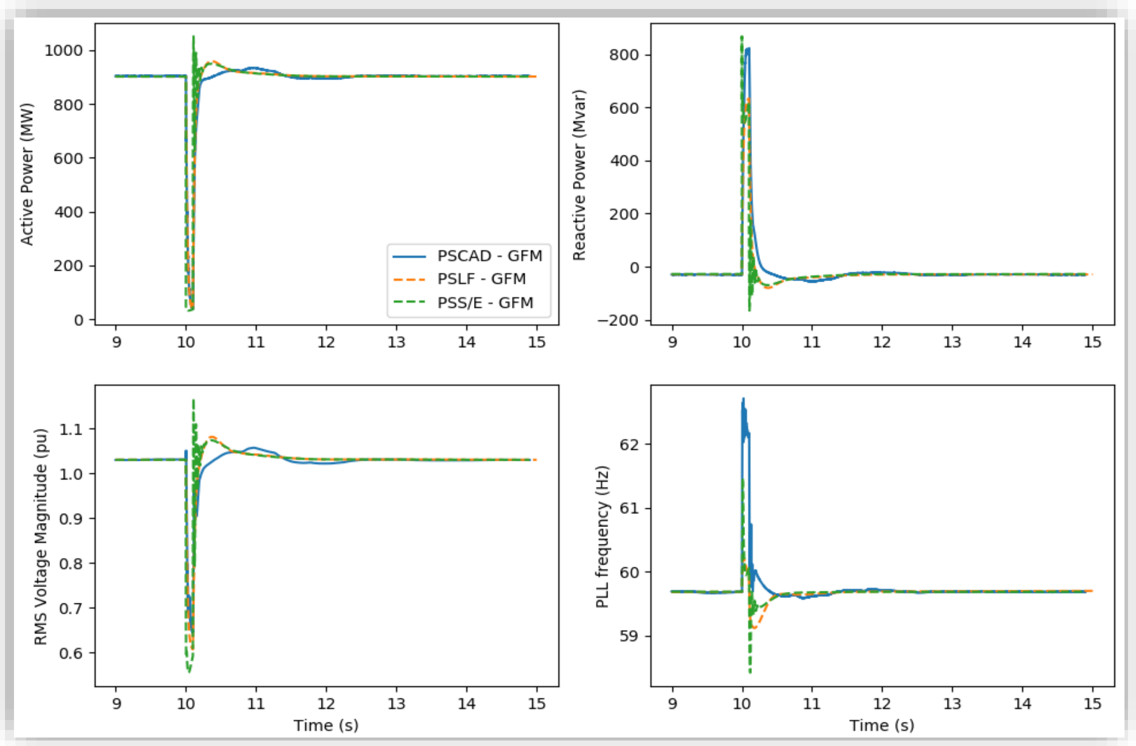
User defined positive sequence model from OEM was unable to show the oscillations





Use of REGC_C model to represent grid forming behavior

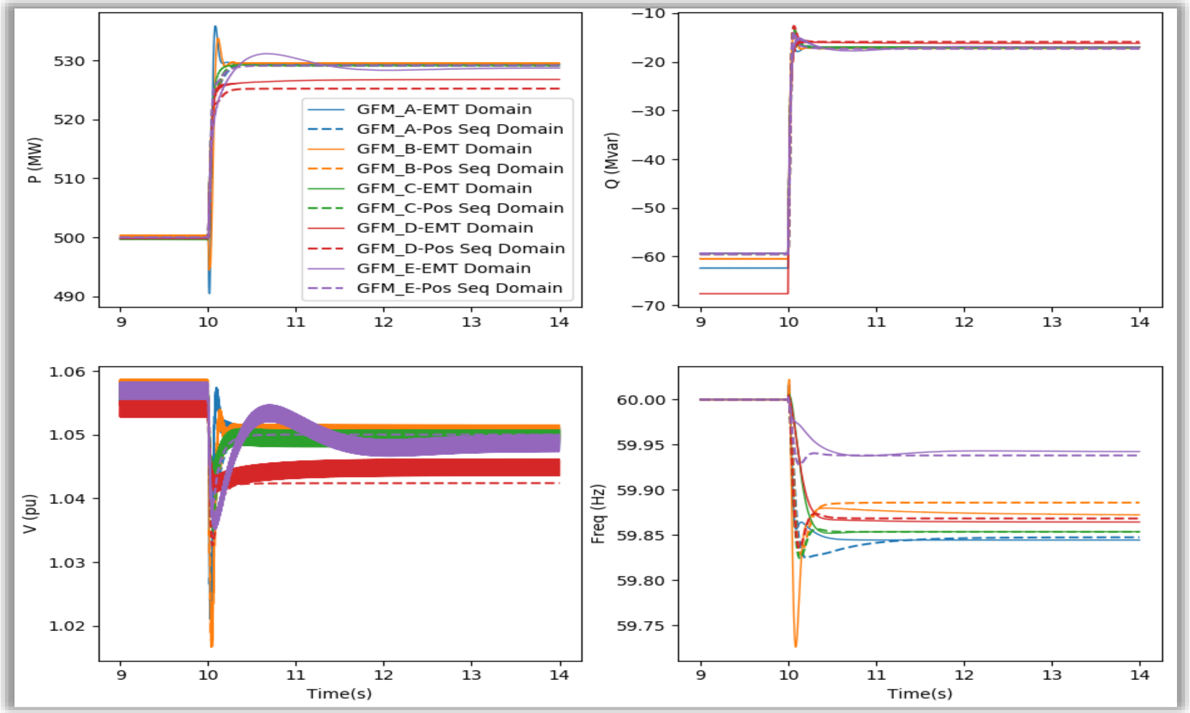


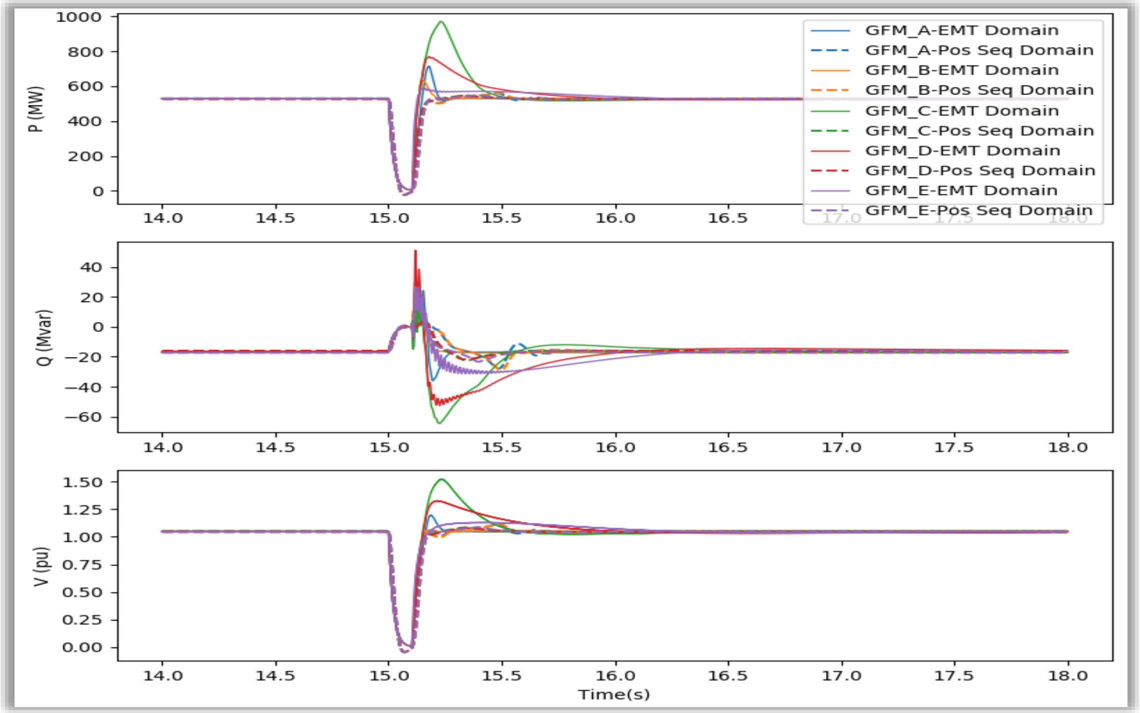


» Positive sequence response obtained using approved WECC generic models
  - REGC_C + REEC_D + REPC_A

» Models should be parameterized with diligence and thoroughness

Comparing REGC_C response across different EMT domain GFM implementations



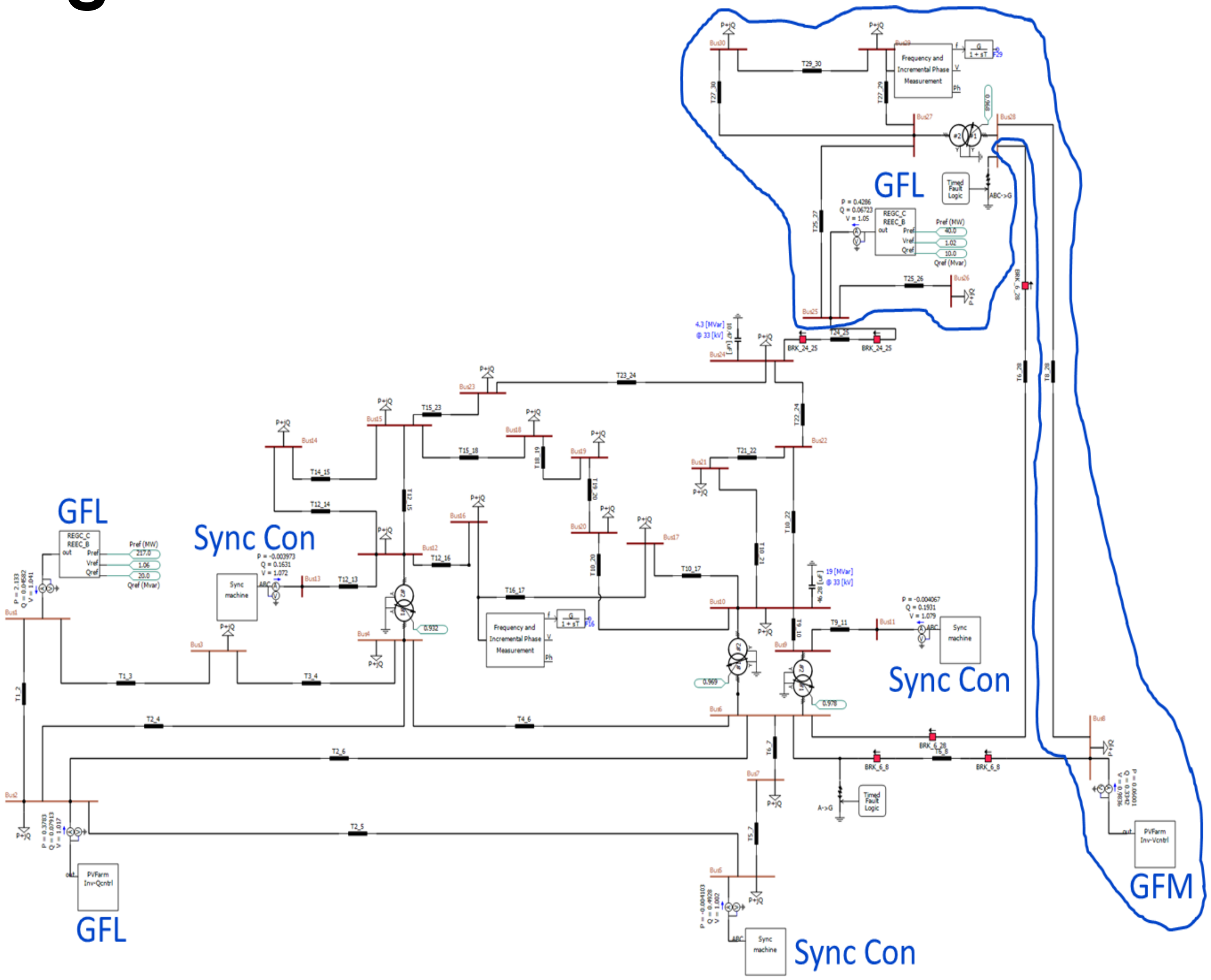


EMT domain GFM implementations include virtual oscillator based, droop based, PLL based, and unknown implementations

- Different GFM implementations, without additional tuning, can have different transient behavior
- Complete tuning of generic positive sequence model is yet to be completed
  - But results are encouraging!

Modeling system islanding with GFM IBR

- A portion of bulk power system is to be islanded
- System has mix of GFL, GFM, and synchronous machines
- Islanded section has
  - load of 46 MW
  - IBRs of 125 MVA capacity
- System simulated in EMT domain and positive sequence domain



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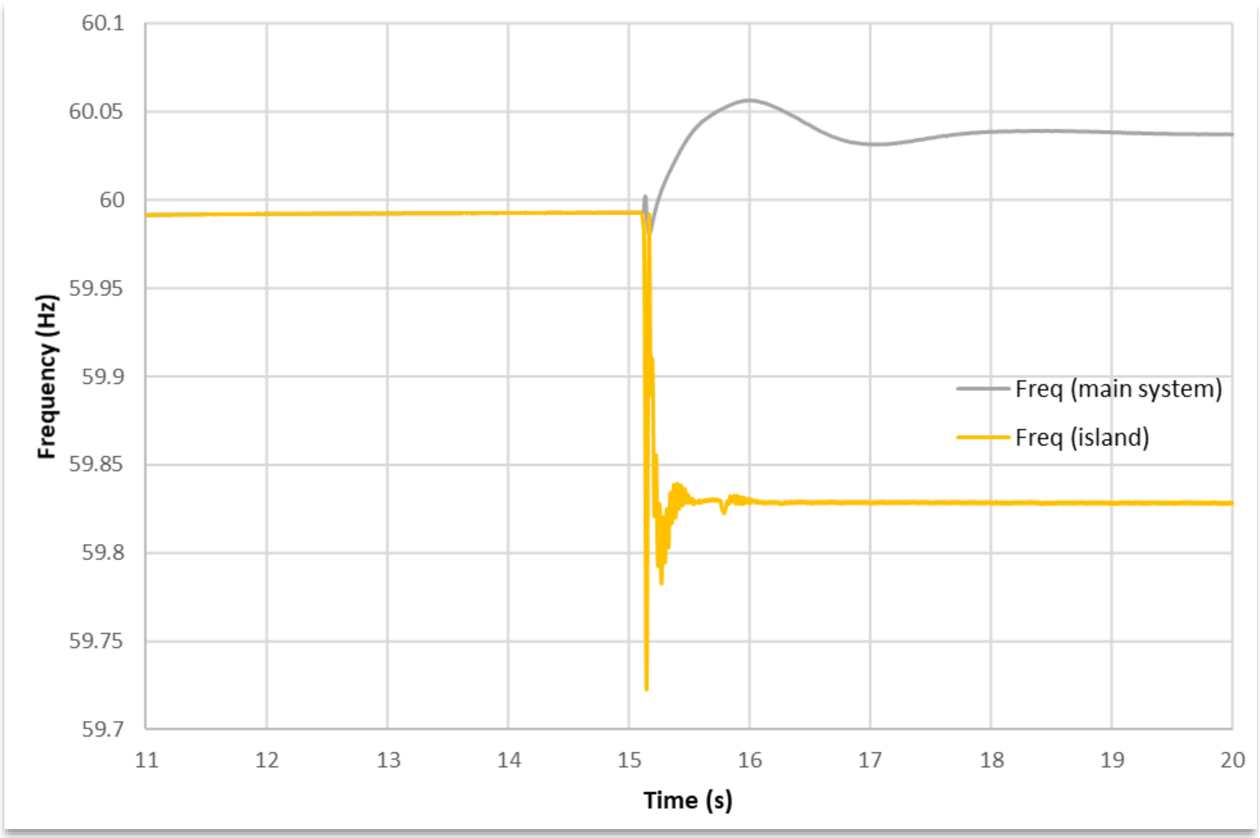
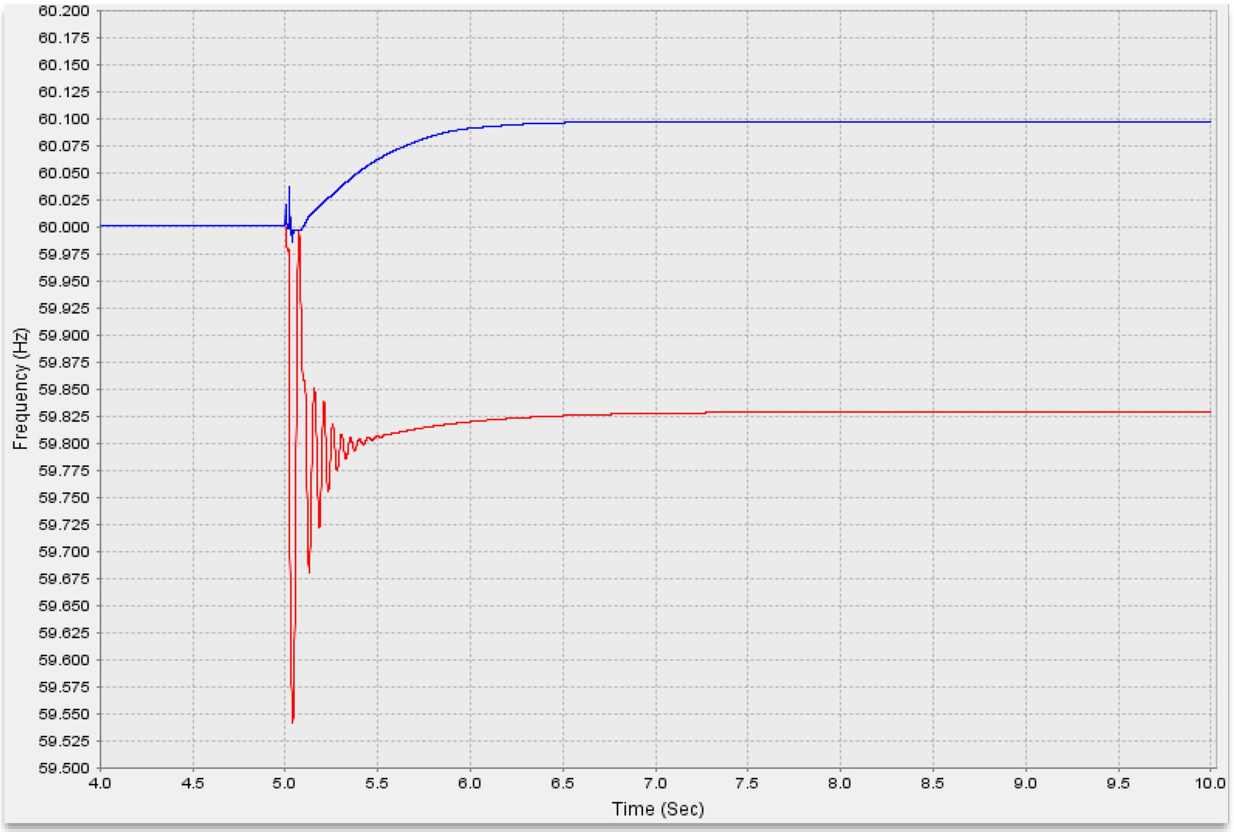
Frequency response upon island creation



EMT domain result



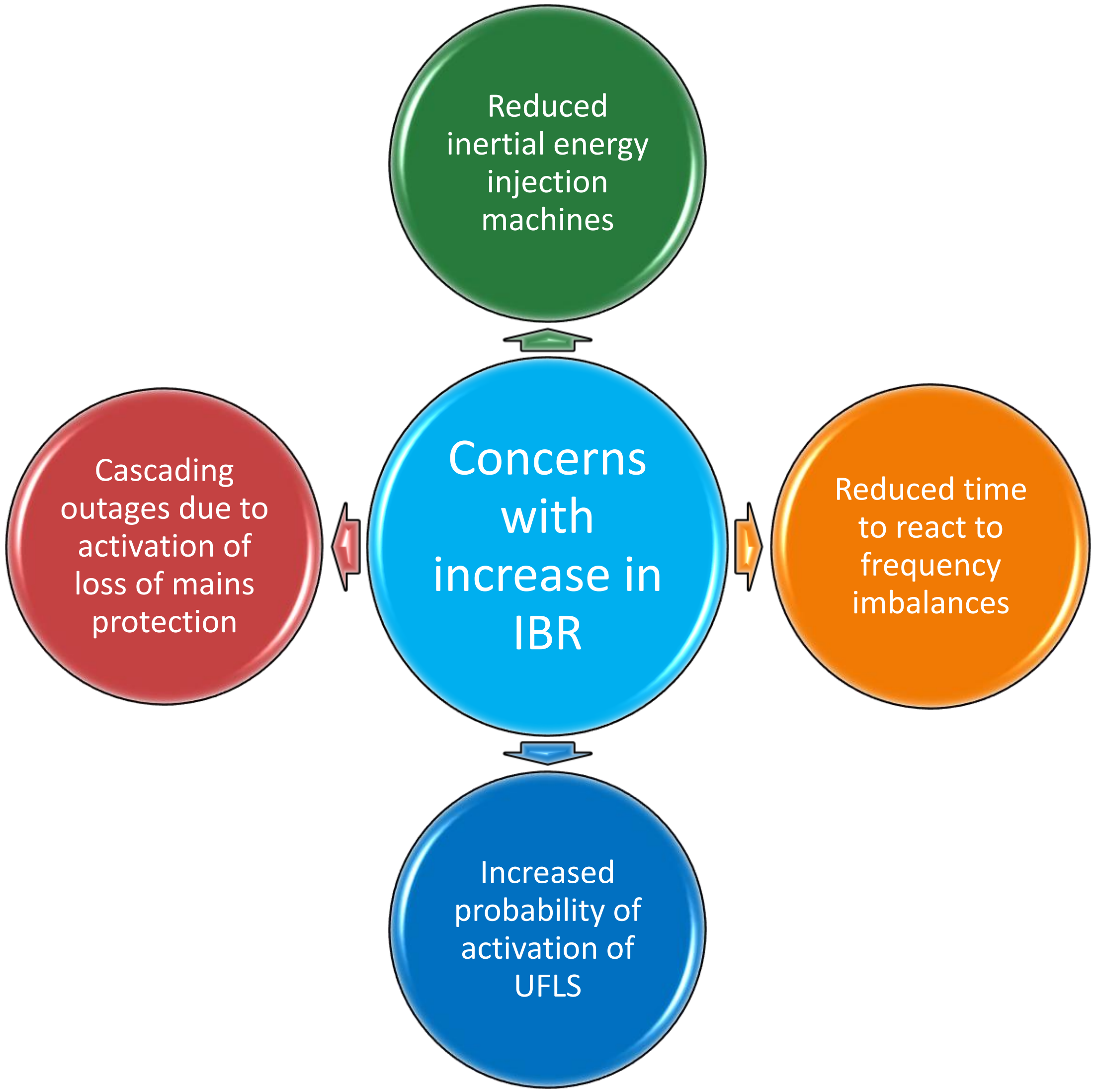
Positive sequence domain result

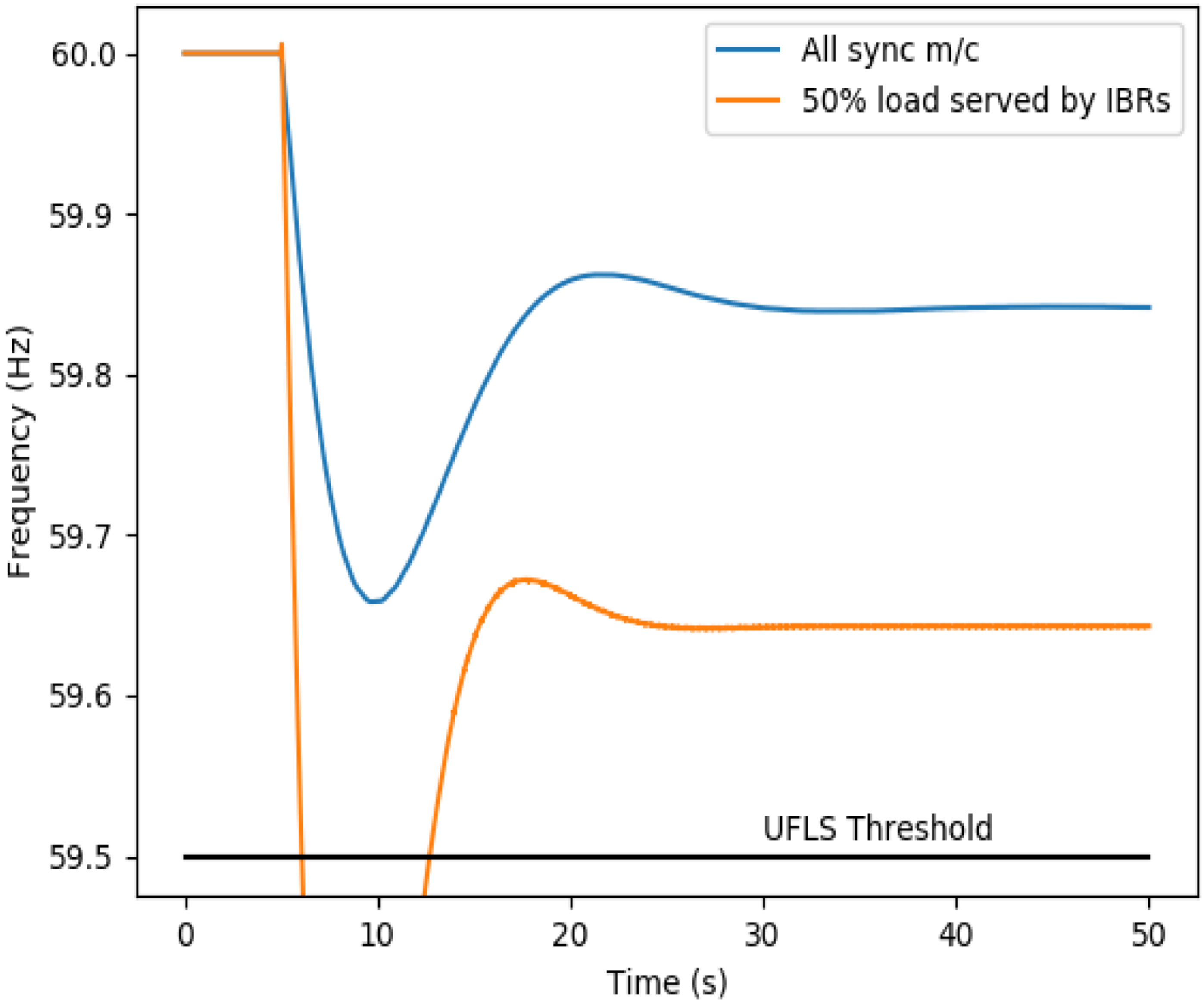
» Encouraging (not yet perfect!) results across both EMT domain and positive sequence domain

» WECC generic models can be first step for planning study with GFM IBRs

Now, how to assess adequacy of frequency response in a 100% IBR network?

IBRs and frequency response…



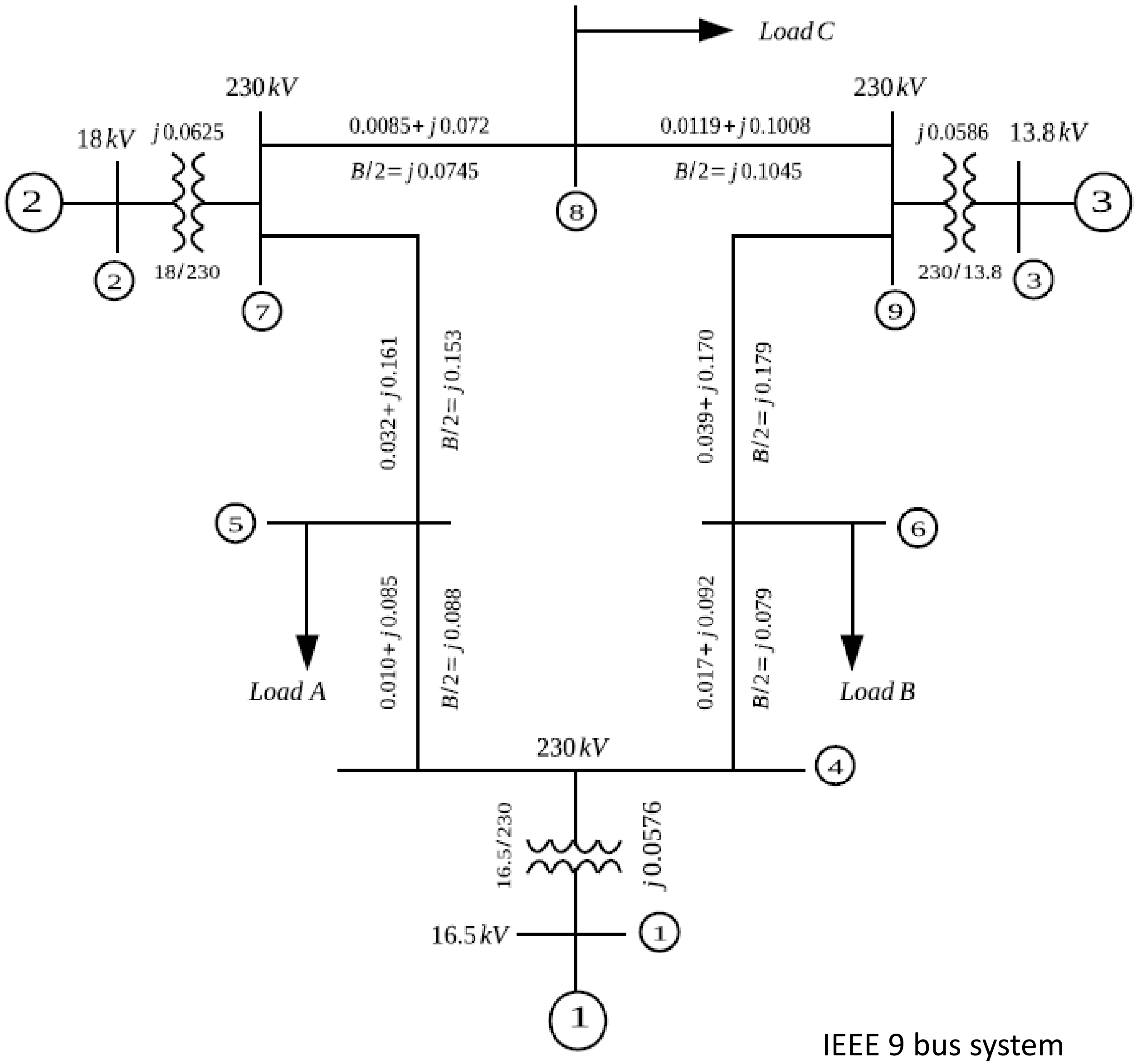


Frequency response in the bulk power system

» Sufficient spinning reserve is available on all sources

» Response for a 5% load increase is discussed

What would happen if IBRs replace the generation sources?

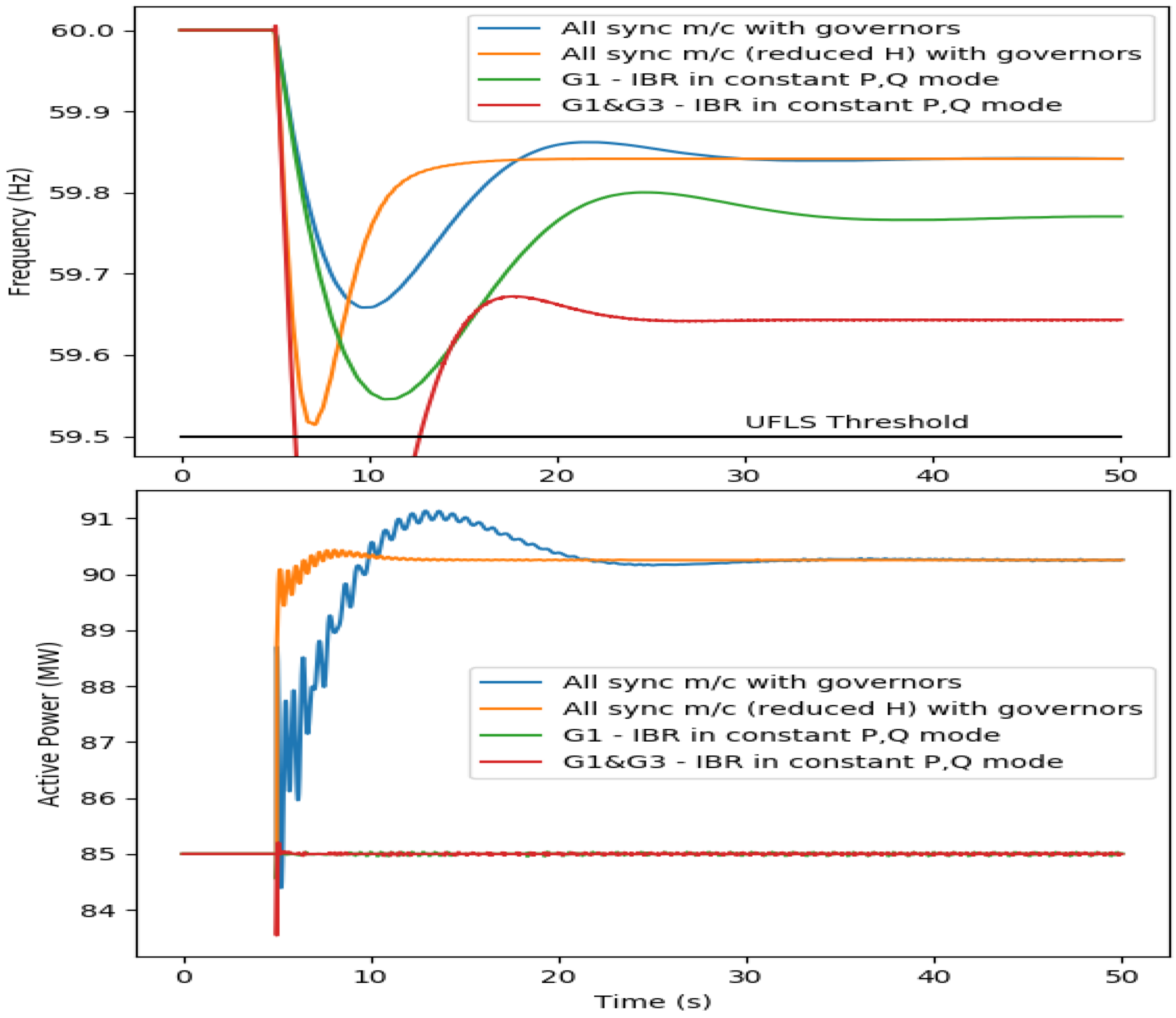


IEEE 9 bus system

Impact of replacing machines with IBR…

» Replacing synchronous machines with IBRs:
  - IBRs operate in constant P,Q mode
  - Similar RoCoF as with smaller synchronous machines
  - UFLS triggered because of fewer number of resources providing frequency response
    - Only G2 provides response

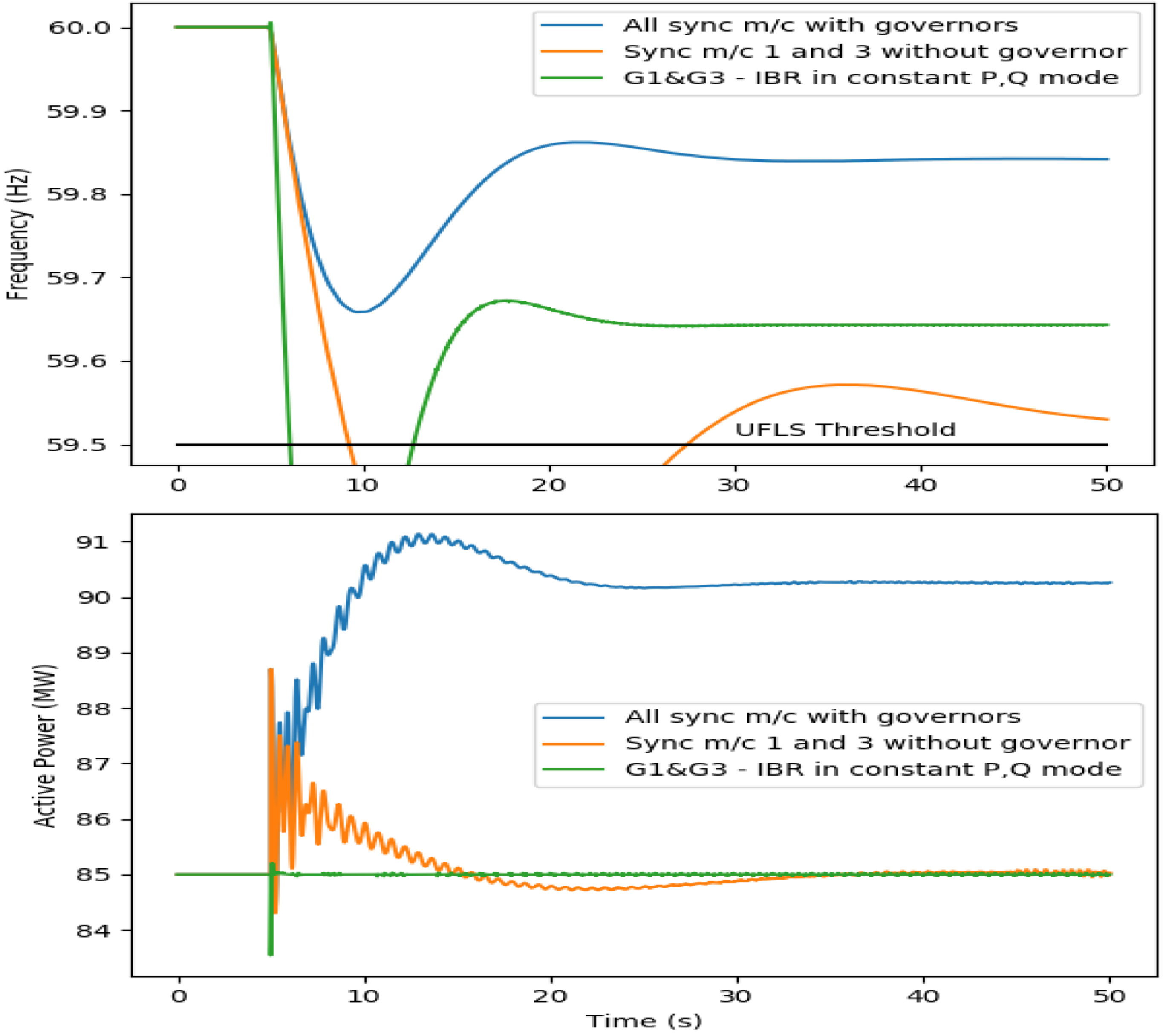
Is this because of IBRs or because of reduced amount of response?



Can it happen with synchronous machines too…?

» With all synchronous machines, governors on G1 and G3 are switched off:
  - UFLS triggered because of fewer number of resources providing frequency response
    - Again only G2 providing response

Number of resources providing response matters!

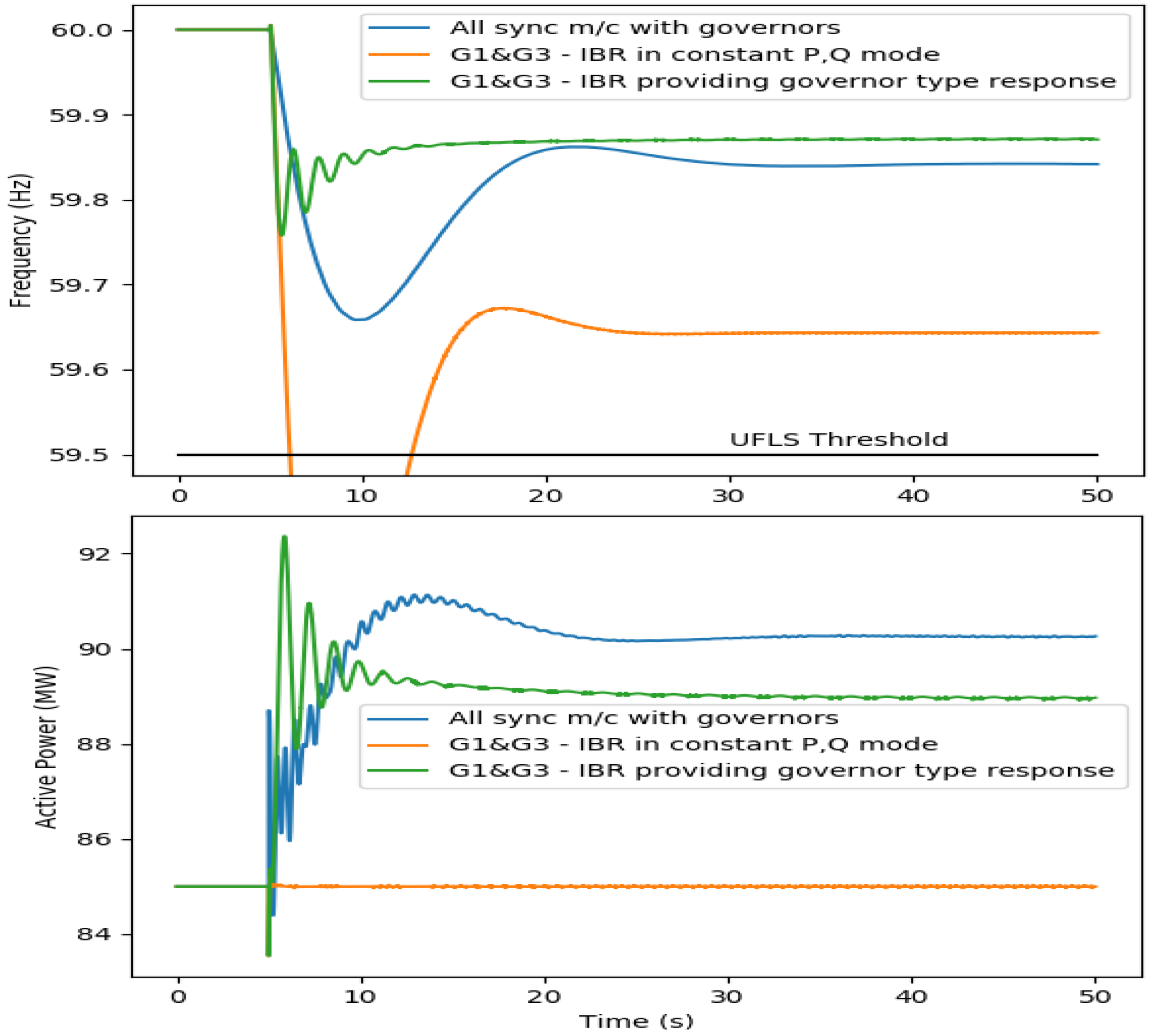


Can conventional IBRs provide frequency response…?

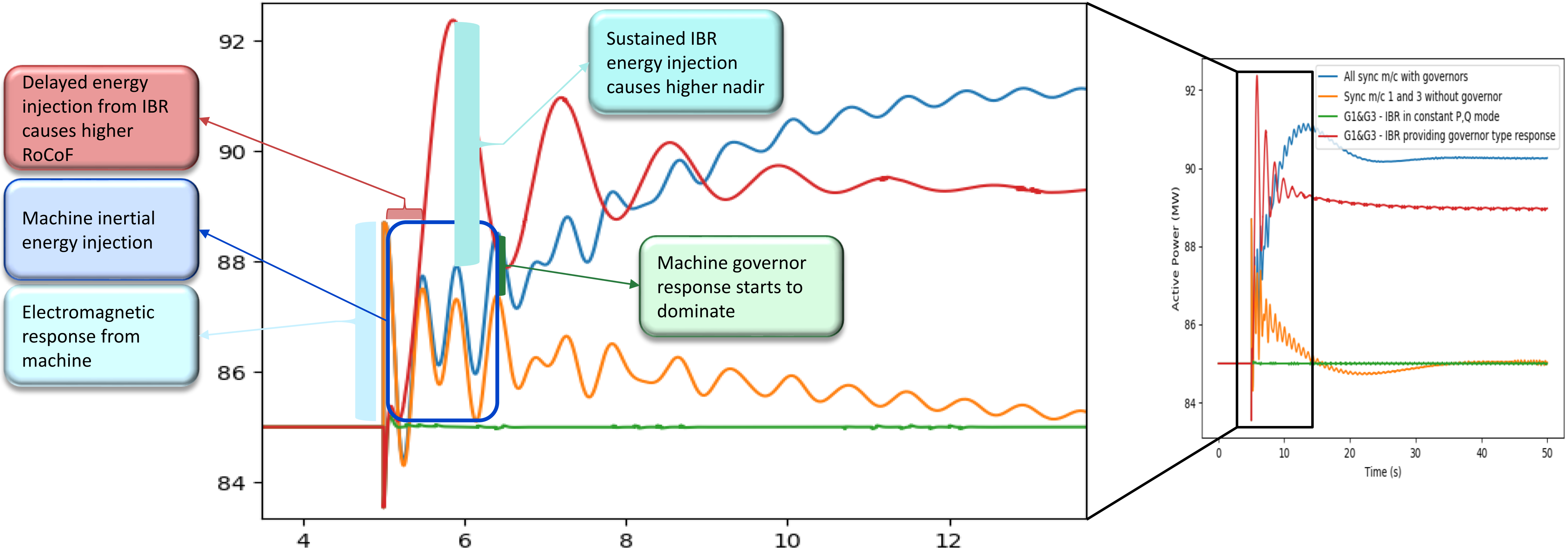
- » Both IBRs at G1 and G3 have governor – like capability enabled:
  - 750ms time lag in IBR control
  - Inherent fast primary response due to lack of mechanical components and low inertia
- » If IBR controls need a measure of electrical frequency, robust measurement techniques should be implemented

FERC Order 842 presently mandates this governor – like capability in IBRs

Provision of such a functionality can make an IBR grid forming?



Inertial energy injection from synchronous machine compared to energy injection from IBR



- IBR energy injection delayed by around 500ms
  - But subsequent continued energy injection from IBR results in higher nadir

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

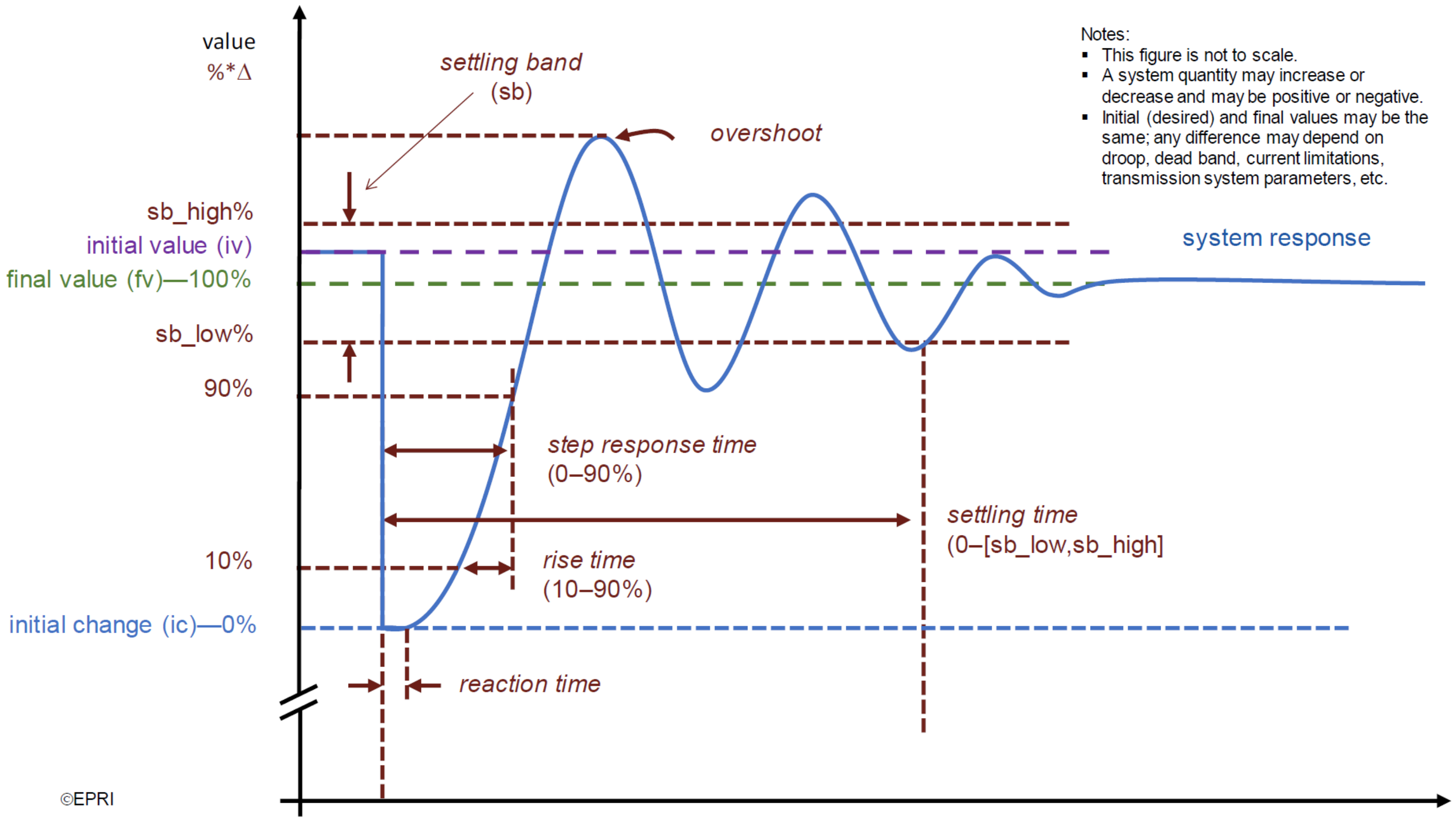


Figure 5(b) from Draft 5.1 of IEEE P2800 Draft Standard

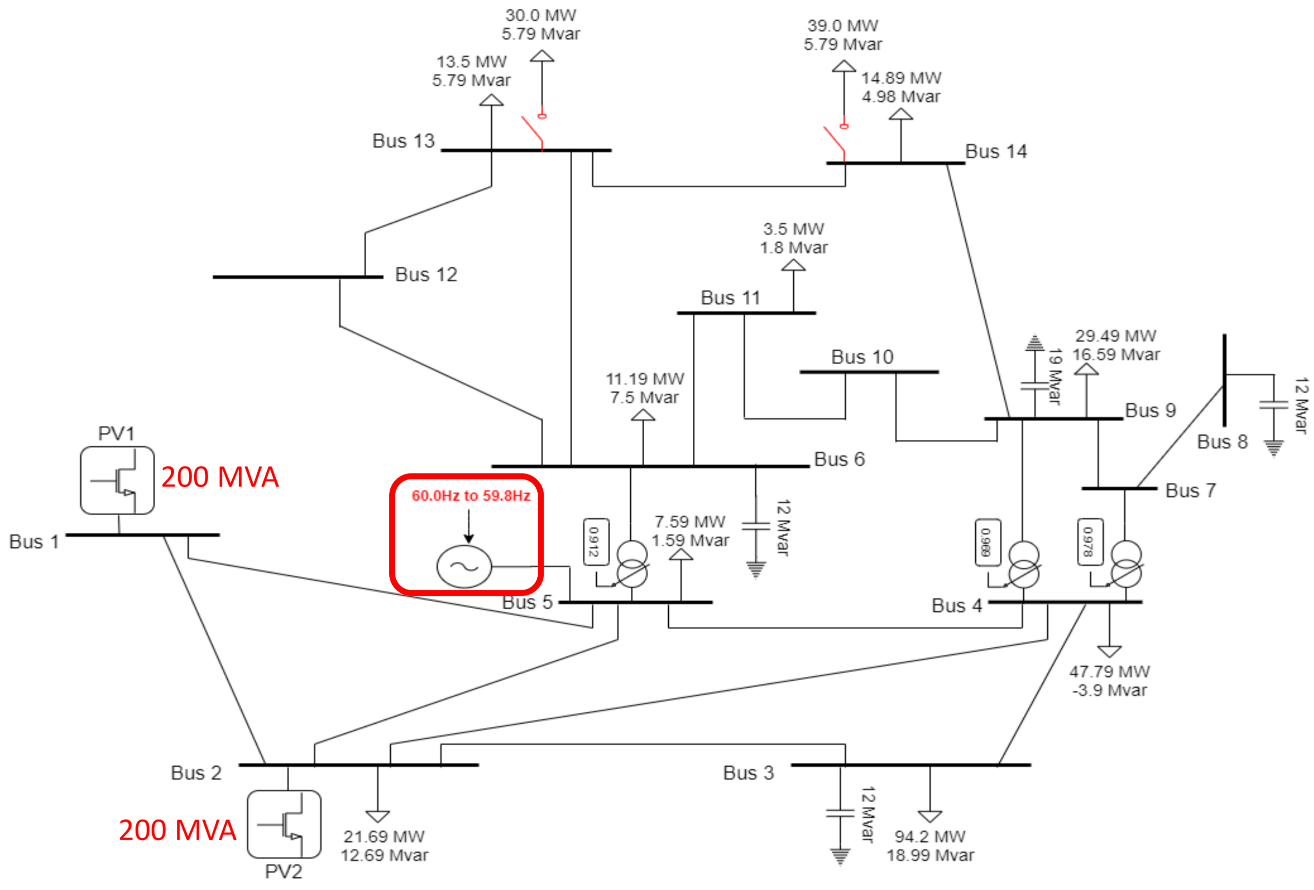
	Units	Default Value	Minimum	Maximum
Reaction time	seconds	0.50	0.20 (0.5 for WTG)	1
Rise time	seconds	4.0	2.0 (4.0 for WTG)	20
Settling time	seconds	10.0	10	30
Damping Ratio	% of Change	0.3	0.2	1.0
Settling band	% of Change	Max (2.5% of change or 0.5% of ICR)	1	5

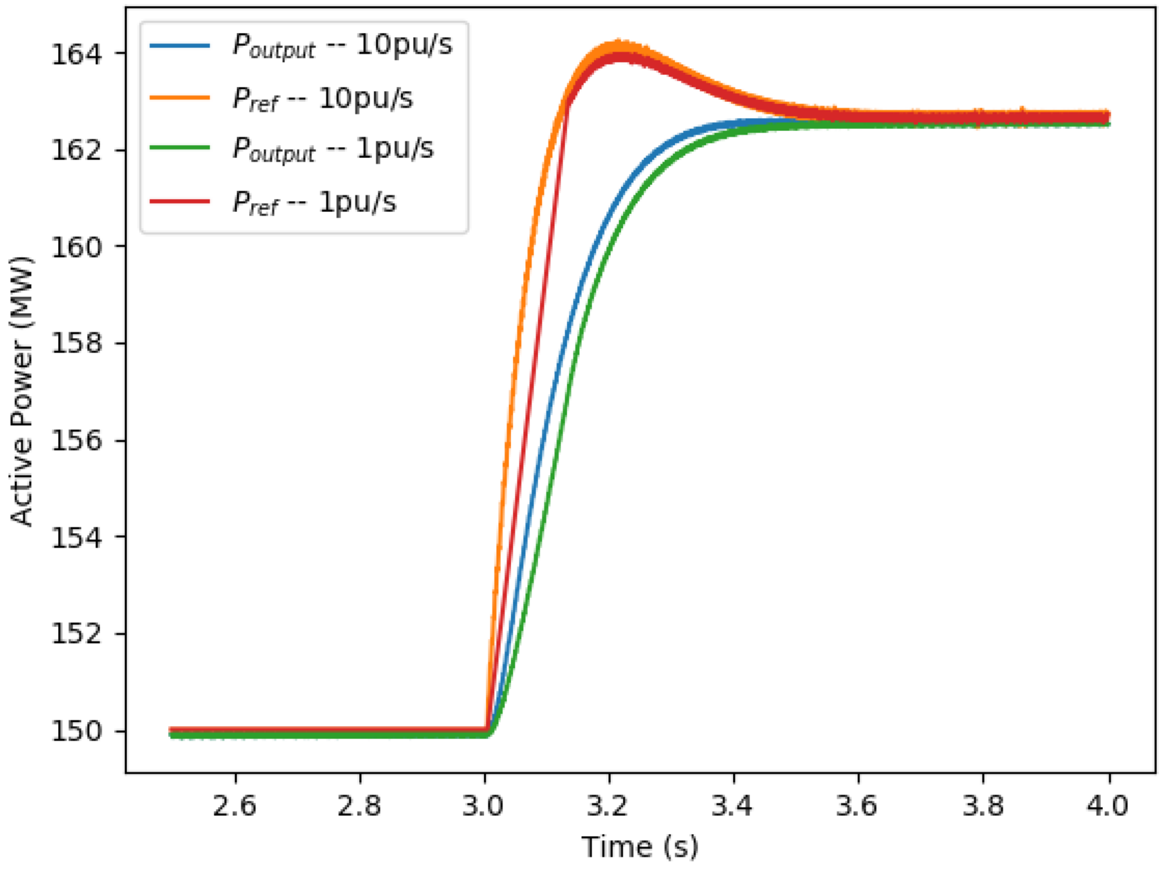
Table 10 from Draft 5.1 of IEEE P2800 Draft Standard

- Table 10 specifies minimum 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 ever 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

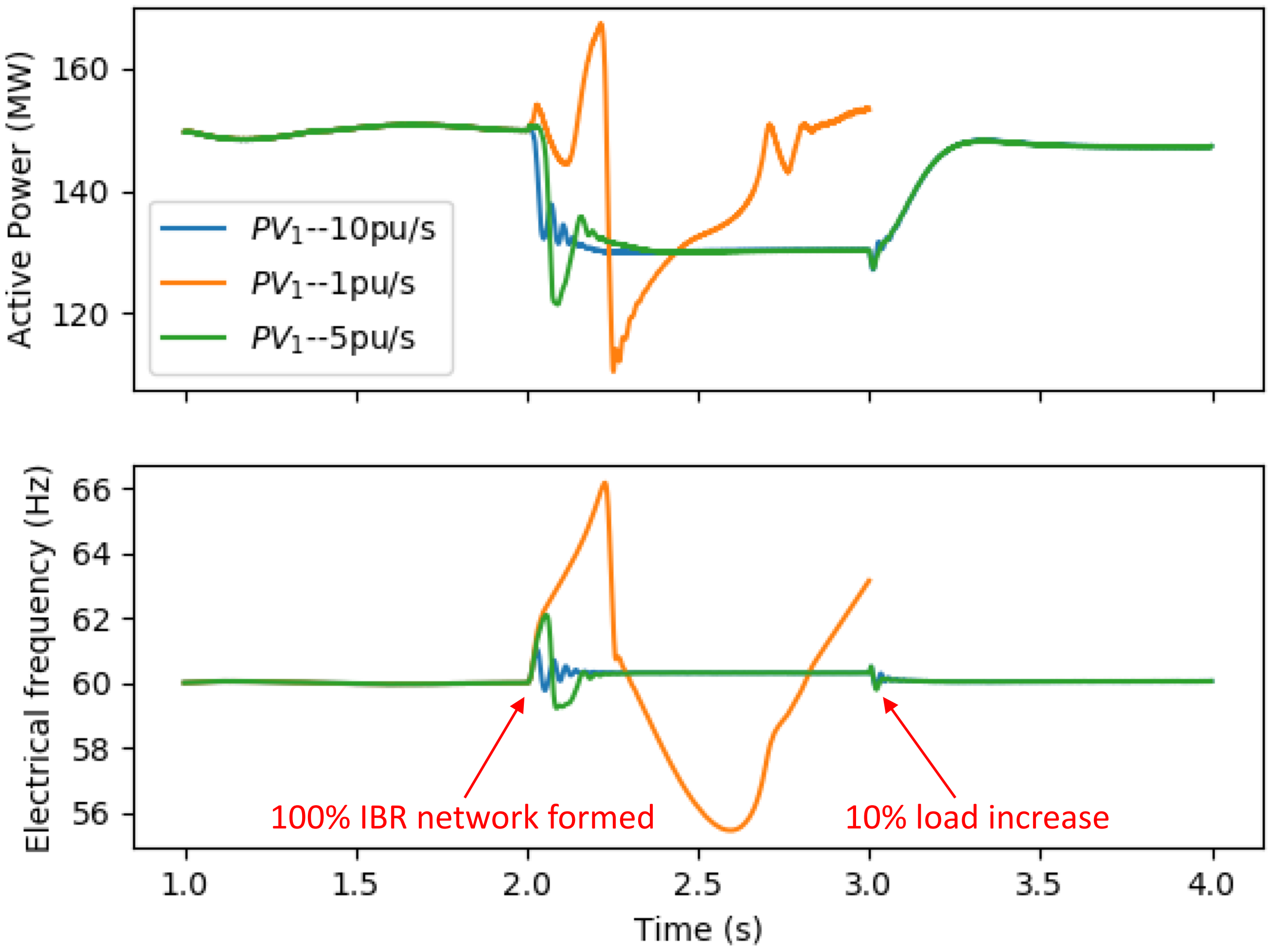
Lower ramp rates may not work in a 100% IBR system

» 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

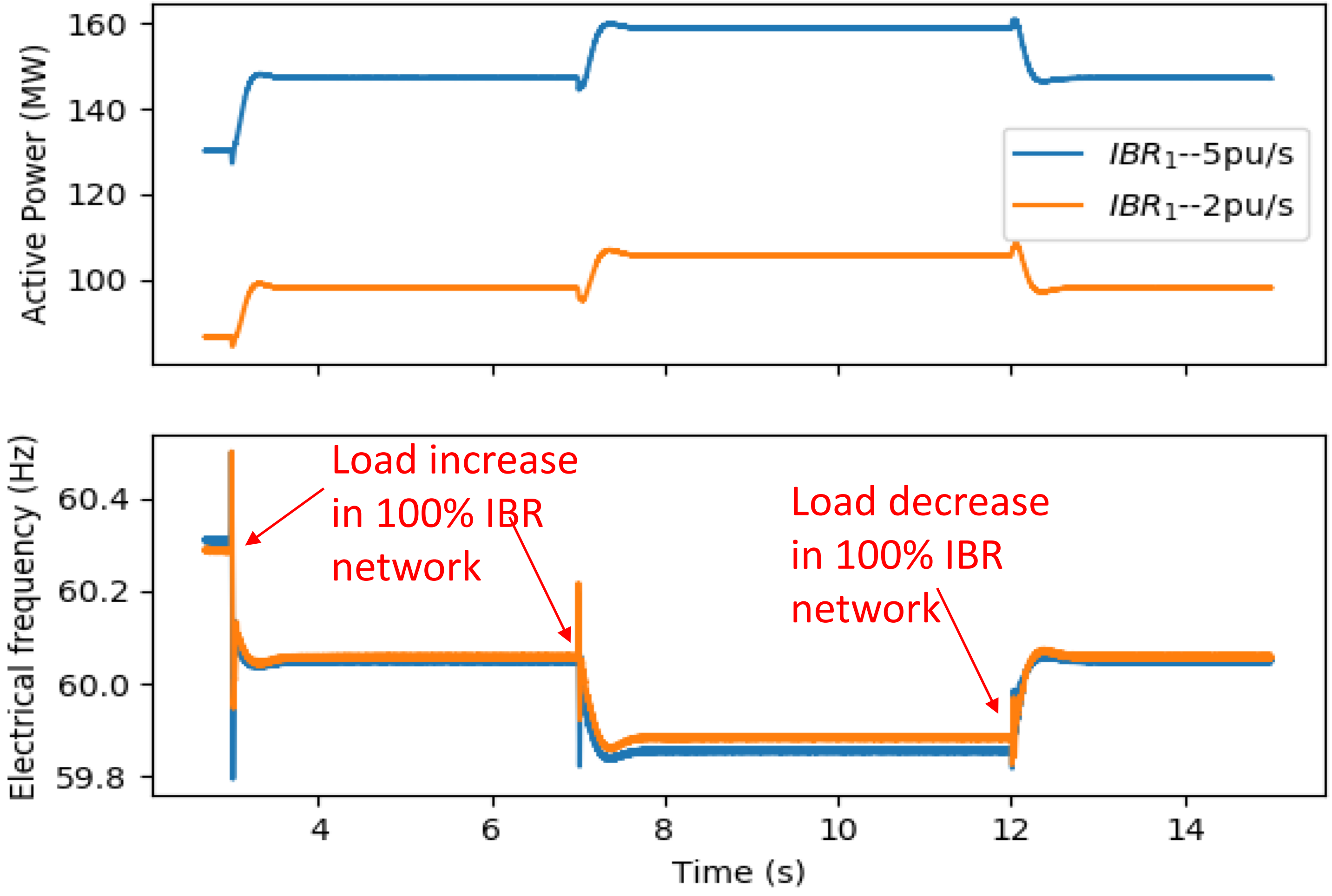


- 100% IBR network created at t=2.0s
- Load increase at t=3.0s

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

Summary

» To conduct future planning studies, availability of adequate simulation models in software library is important

» Any mathematical model, in any software domain, can be a bad model

» New generic positive sequence models parameterized with due diligence show promise in representing behavior of 100% IBR network

- Not intended to completely replace other detailed studies
- Rather, adds more tools in a system planner's toolkit to study high IBR systems

» Important to continue to work with OEMs to validate model behavior

» When evaluating frequency response of an IBR network, important to consider effect of ramp rate limit

» More IBR resources that provide frequency response, the better it will be for the system

Few references:

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- » Deepak Ramasubramanian, Wenzong Wang, Pouyan Pourbeik, Evangelos Farantatos, Anish Gaikwad, Sachin Soni, and Vladimir Chadliev, “Positive Sequence Voltage Source Converter Mathematical Model for Use in Low Short Circuit Systems,” IET Generation, Transmission & Distribution, vol. 14, no. 1, pp. 87-97, Jan 2020
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- » Deepak Ramasubramanian, “Importance of Considering Plant Ramp Rate Limits for Frequency Control in Zero Inertia Power Systems,” 2021 IEEE Green Technologies Conference (GreenTech), Denver, CO, USA, 2021, pp. 320-322
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- » Frequency Response Primer: A Review of Frequency Response with Increased Deployment of Variable Energy Resources, EPRI Palo Alto 2018 3002014361

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