Deliverability of system stabilization services from inverter based resources

Sushrut Thakar, Stavros Konstantinopoulos, Deepak Ramasubramanian, EPRI

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    - The views expressed in the presentation **do not necessarily represent the views of the DOE or the U.S. Government.**

- References to material in this slides can be provided upon request

Introduction

- Changing needs and services for grids with the increased use of inverter-based resources (IBRs)
- What are the services IBRs can provide and fill these needs?
- Services from IBRs may be different from synchronous machines
- Focus here on services from IBRs within a short time scale, i.e. from a stability perspective
- What are the factors that may impact the deliverability of the services?

- Based on work performed by various EPRI staff as a part of different projects EPRI is involved in
- Valuable feedback, inputs and industry collaboration throughout these projects by different partners

Grid services from IBRs?

Fast & stable response to events

Help maintain voltage

Help maintain frequency

Robust fault ride through

Network benefits when devices work as a team

Blackstart capability

Network requires MVP

Services from IBRs: categories

Need of network	Service that IBR can provide
Synchronization	Synchronization torque/phase jump mitigation
	First swing mitigation
	Phase jump ride-through
	PLL Stability Support
Frequency Control	Frequency containment
	Inertial response/limiting RoCoF
	Frequency stabilization
	Frequency recovery
Voltage control	Voltage containment
	Mitigate voltage collapse
	Fault ride-through
	Mitigate unbalance and harmonics
Damping	Damp sub-synchronous oscillations (SSO)
	Damp super-synchronous oscillations
Protection	Detect and locate faults
Restoration	Black start
	Cold load pick up
	Island operation

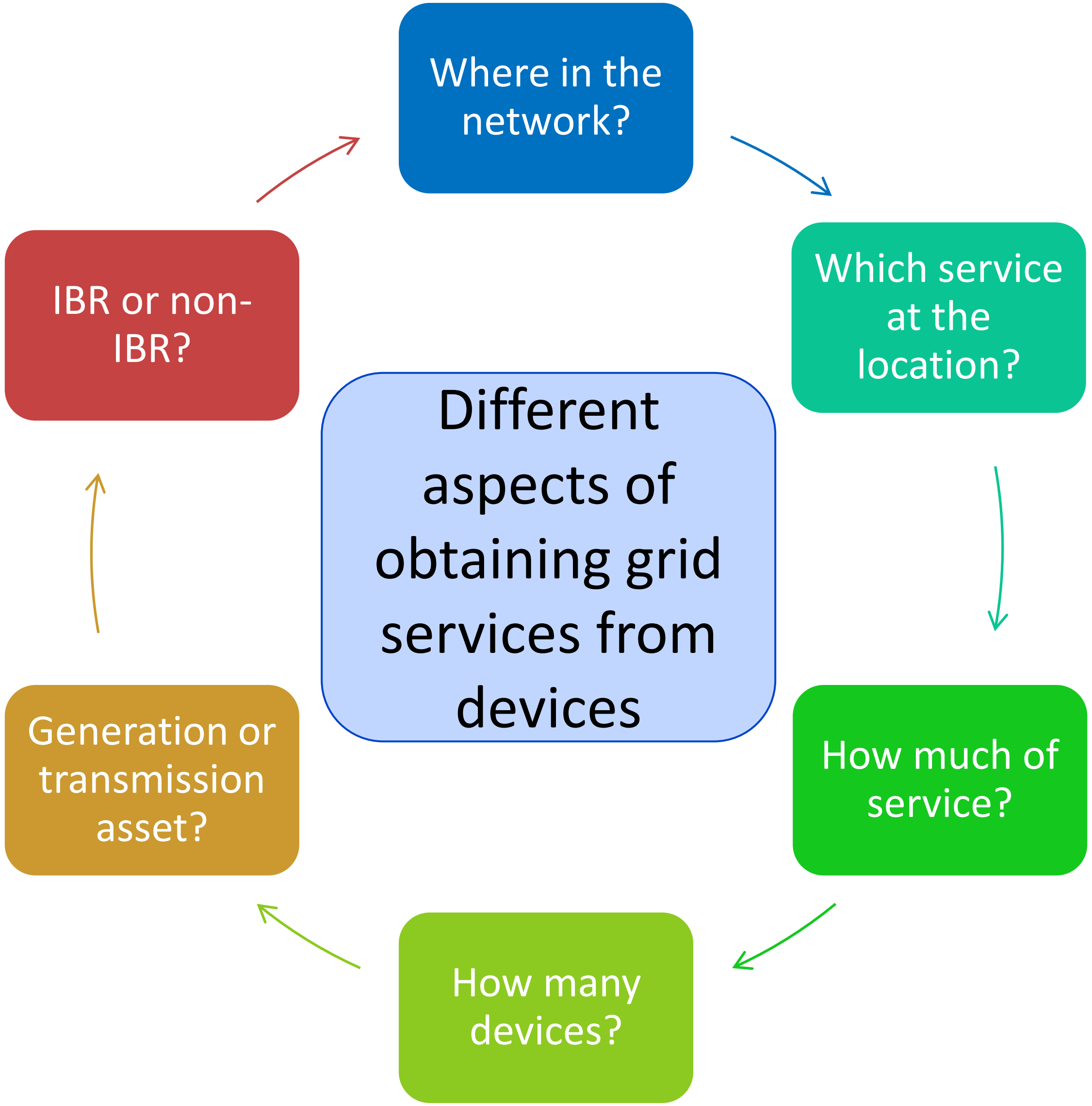
Table from [1]

Points to note:

- More than one service may be provided at a time
- Not every service is required at all points in time

[1] B. Chaudhuri, D. Ramasubramanian, J. Matevosyan, M. O'Malley, N. Miller, T. Green and X. Zhou, "Rebalancing Needs and Services for Future Grids: System Needs and Service Provisions With Increasing Shares of Inverter-Based Resources," in IEEE Power and Energy Magazine, vol. 22, no. 2, pp. 30-41, March-April 2024

Delivery of services from IBRs



- Capability - ability to perform (for example, whether the IBR has relevant functionality built-in)
- Delivery of services - may depend on other operational factors as well e.g. headroom, limits

Terminology for evolution of services from IBRs

Legacy IBR

- Injects active power at unity power factor
- Provides no grid support services

Conventional IBR

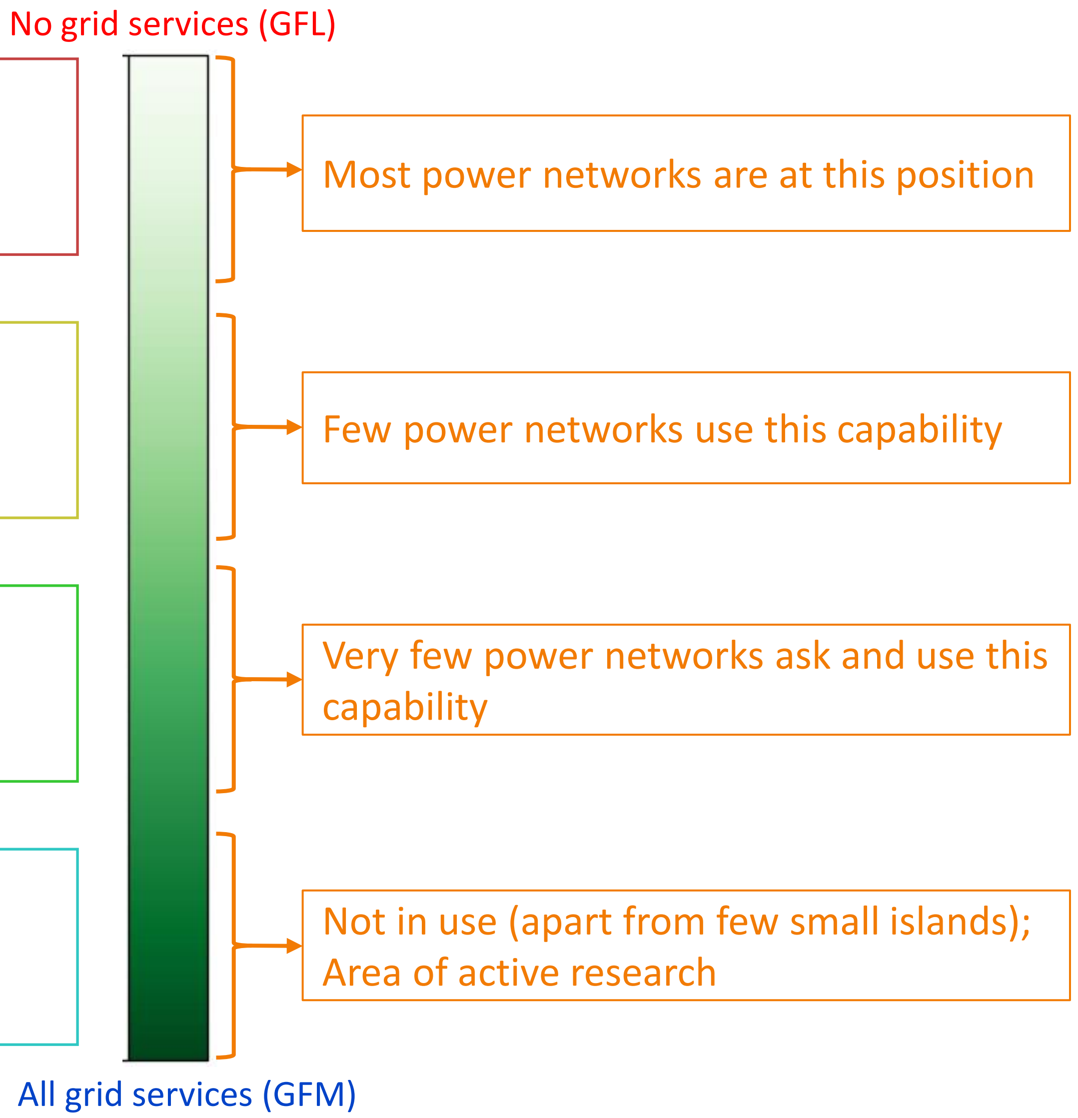
- Has capability to provide both frequency and voltage response
- Typically, full delivery of response over multiple seconds

Enhanced IBR

- Delivers full frequency and voltage response within 1s of event
- As a group, could survive loss of last synchronous machine

Future IBR

- Is capable of blackstart
- A single IBR could ride through extreme load-gen mismatch

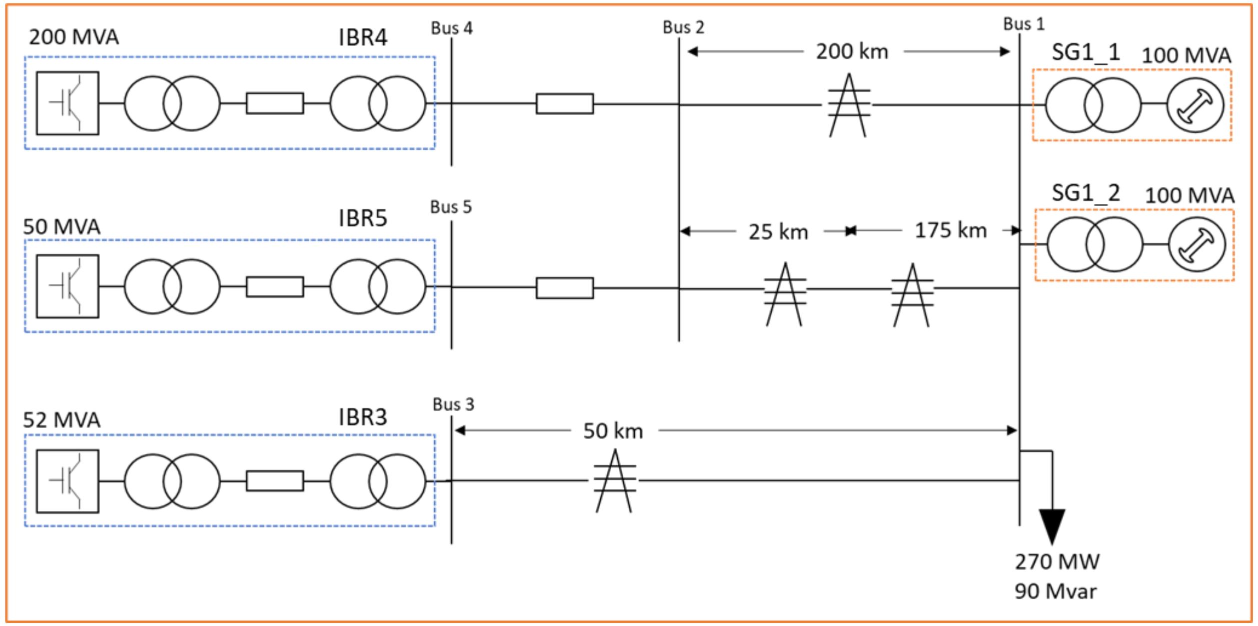


EPRI's discussions with inverter OEMs supports these minimal categories. Some OEMs desire future categories to be included based upon the capability that can be offered by their products

Stability services from new and existing IBRs – case studies

Microcosm network

- Represents a transmission network with 270 MW, 90 MVAr load cluster fed by two synchronous generators close to the load cluster and three IBRs (conventional response) far from the load cluster
- Potential weak grid conditions ➔trip of one/both synchronous generators results in unstable behavior
- Focus is on investigating voltage and/or frequency services provided by existing and new IBRs for contingencies involving loss of generation and synchronous machines

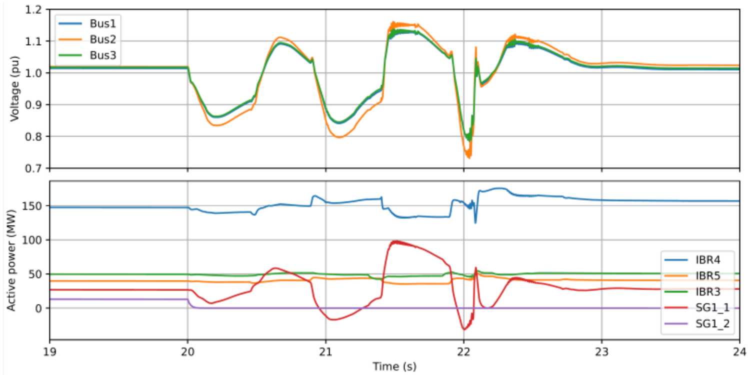


For more details:

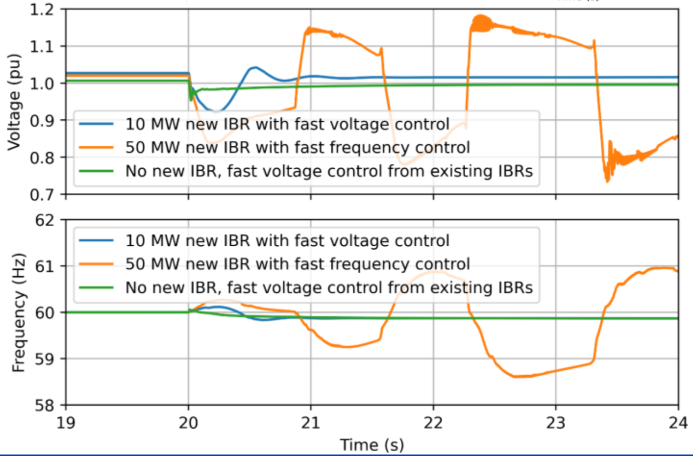
[2] System Services Task Force Report, Energy Systems Integration Group, Reston, VA, USA, 2024 (to be published)
[3] S. Thakar, D. Ramasubramanian, J. Matevosyan, F. Rajaei Najafabadi, and M. O’Malley, “System Services from Inverter Based Resources for Reliable Operation”, 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024

Trip of one synchronous generator

- Base network unstable for the contingency
- Additional services from new IBRs:
  - New IBR with fast frequency response still resulted in unstable behavior
  - However, new IBR with fast voltage response led to a stable operating point
  - In fact, fast voltage response from existing IBRs was also sufficient in ensuring a stable response



Base network



New IBR added with different services

For this disturbance, fast voltage response from existing IBRs is sufficient to ensure stable response

For more details:

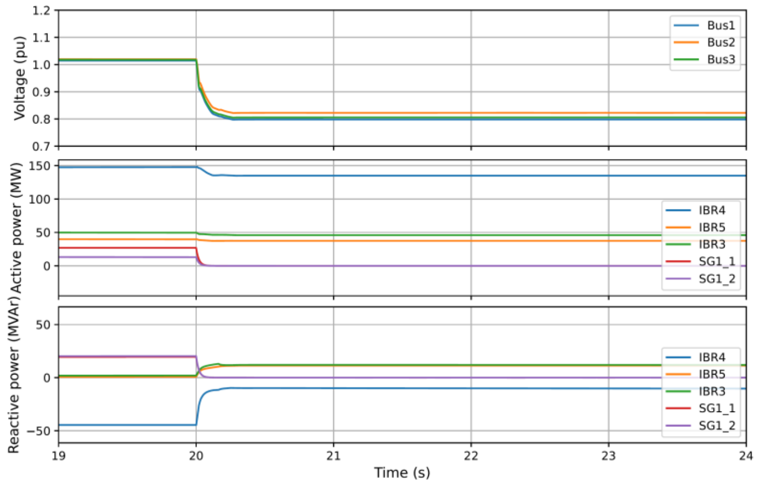
[2] System Services Task Force Report, Energy Systems Integration Group, Reston, VA, USA, 2024 (to be published)

[3] S. Thakar, D. Ramasubramanian, J. Matevosyan, F. Rajaei Najafabadi, and M. O'Malley, "System Services from Inverter Based Resources for Reliable Operation," 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024

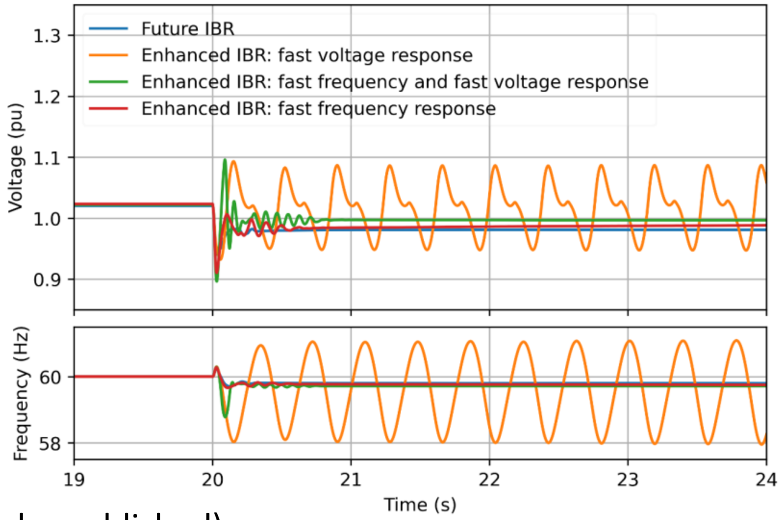
[4] C. Zhang, D. Ramasubramanian, P. Mitra and V. Singhvi, "Rapid Stability Screening Method for Fast Frequency Response from IBRs in Weakly Connected Areas," 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024

Trip of both synchronous generators

- 100% IBR penetration in the resultant system – viable operating point not achieved
- A viable operating point is still not achieved when existing IBRs have fast voltage control capability, or with just a new IBR with future capabilities
- Existing IBRs assumed to provide fast voltage response in conjunction with a new IBR:
  - When new IBR also provides just a fast voltage response – oscillatory behavior (fast response does not always imply a stable response)
  - When new IBR provides fast frequency response – stable and viable operating point reached
- Multiple services (voltage and frequency response) needed by the grid for surviving this disturbance



Base network



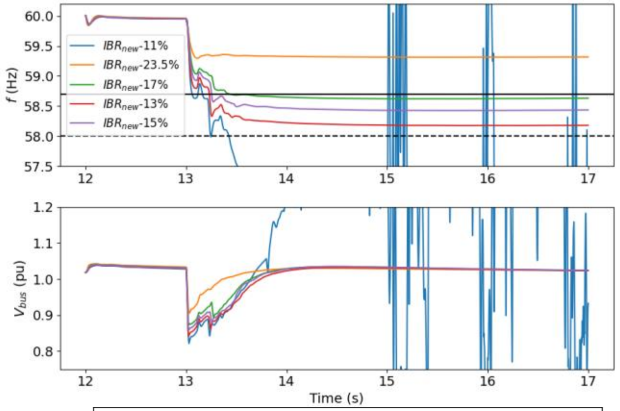
Existing IBRs provide fast voltage response, new IBRs with different services

For this disturbance, new IBR by itself may not be sufficient, needs to work with existing IBRs and provide voltage and frequency services

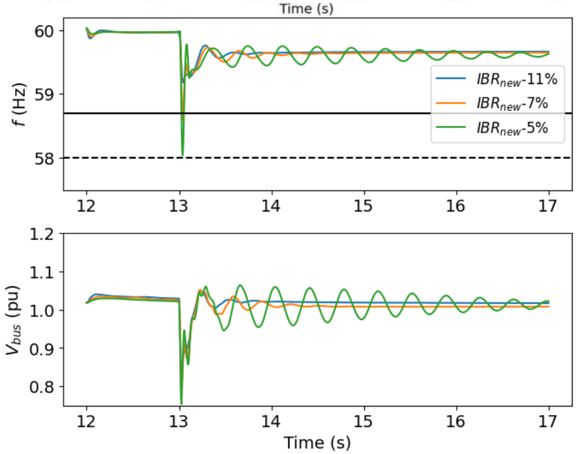
For more details:
[2] System Services Task Force Report, Energy Systems Integration Group, Reston, VA, USA, 2024 (to be published)
[3] S. Thakar, D. Ramasubramanian, J. Matevosyan, F. Rajaei Najafabadi, and M. O'Malley, "System Services from Inverter Based Resources for Reliable Operation," 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024
[4] C. Zhang, D. Ramasubramanian, P. Mitra and V. Singhvi, "Rapid Stability Screening Method for Fast Frequency Response from IBRs in Weakly Connected Areas," 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024

Trip of a synchronous condenser followed by trip of a solar PV unit in a real island system

- Island system fed entirely by IBRs, with 8.25 MVA PV, 8 MVA BESS and 3.25 MVA DERs installed
- Contingency requires ~25% new IBR with future capabilities to achieve stable response and avoid triggering UFLS
- The size of new IBR required for avoiding triggering UFLS and achieving a stable operating point reduced when existing IBRs share the burden of providing frequency response service



Existing IBRs provide only voltage response



Existing IBRs provide voltage and frequency response

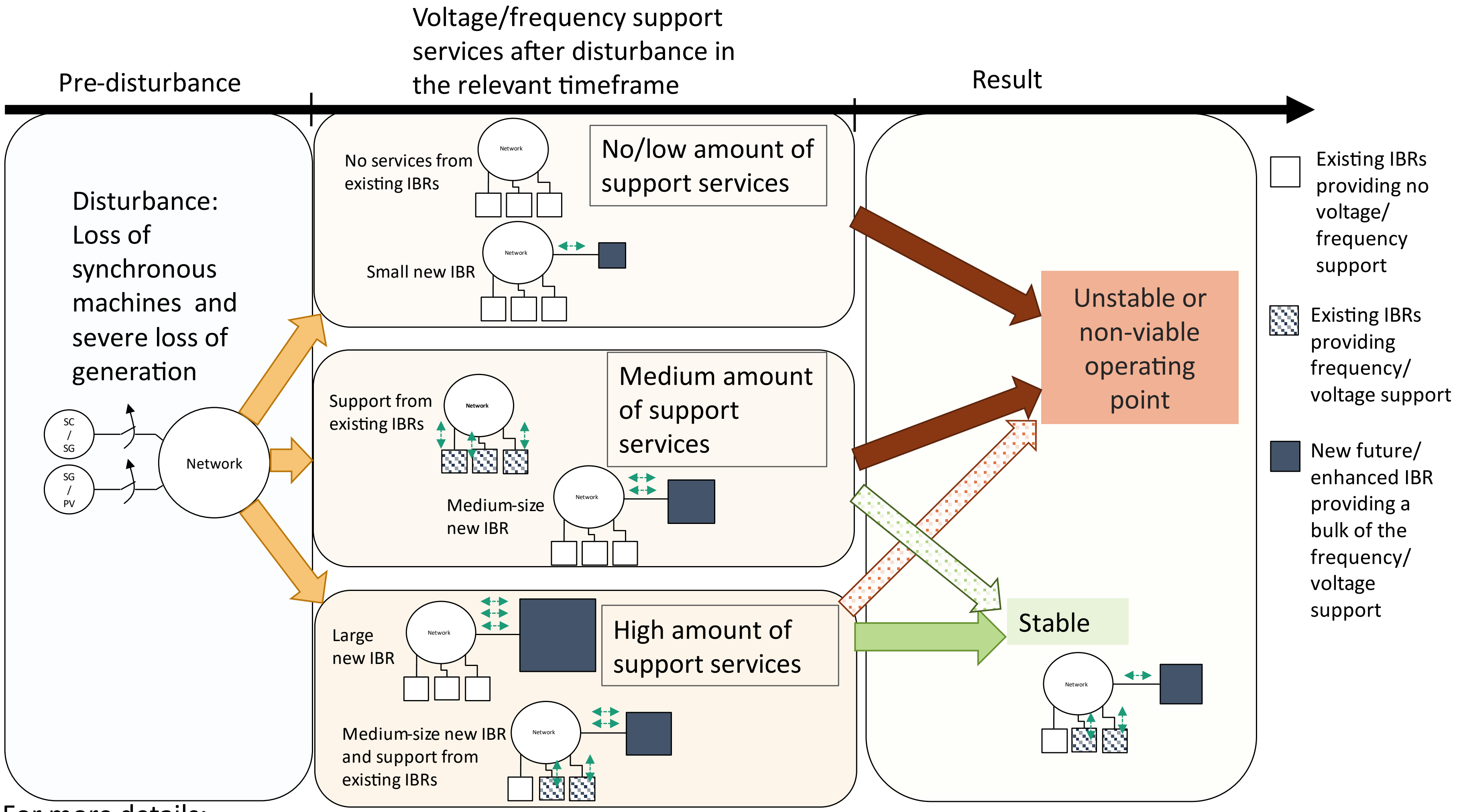
Frequency response provided by existing IBRs may reduce the burden on new IBRs to provide a larger portion of the response

For more details:

[2] System Services Task Force Report, Energy Systems Integration Group, Reston, VA, USA, 2024 (to be published)

[5] D. Ramasubramanian, S. Thakar and J. Matevosyan, “Unlocking Capability in Transmission Connected Inverters for Improved Reliability of Transmission Power Networks”, CIGRE Paris Session 2024, Paris, France, 2024

Key observations from the different case studies



Higher amount of services from existing IBRs utilizing the capabilities them and from new IBRs needed to maintain stability, but it depends on different factors

For more details:

[2] System Services Task Force Report, Energy Systems Integration Group, Reston, VA, USA, 2024 (to be published)

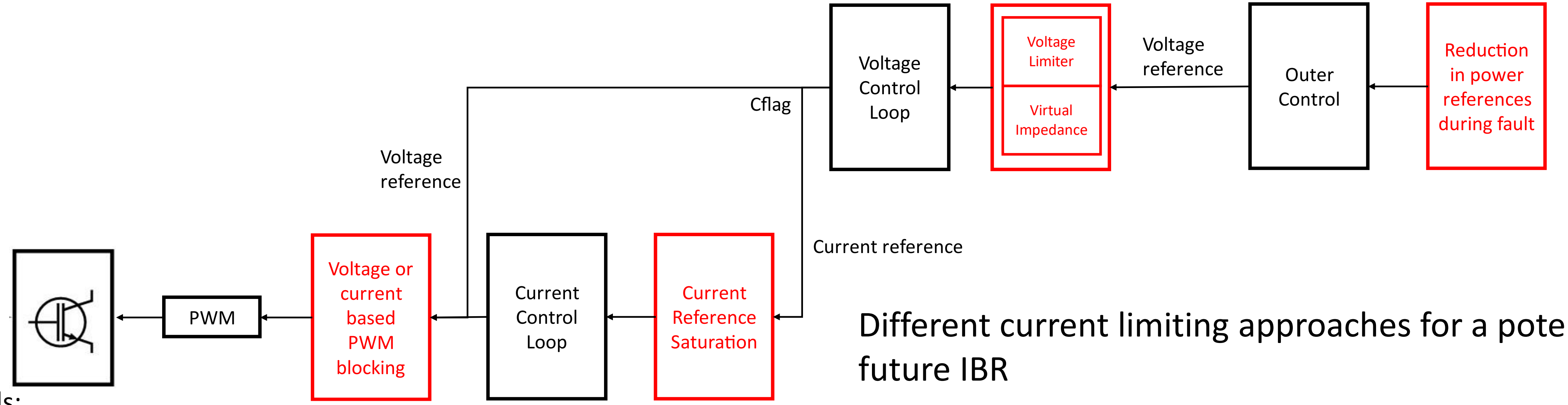
[3] S. Thakar, D. Ramasubramanian, J. Matevosyan, F. Rajaei Najafabadi, and M. O'Malley, "System Services from Inverter Based Resources for Reliable Operation," 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024

[5] D. Ramasubramanian, S. Thakar and J. Matevosyan, "Unlocking Capability in Transmission Connected Inverters for Improved Reliability of Transmission Power Networks", CIGRE Paris Session 2024, Paris, France, 2024

Impact of current limiting behavior of IBR

Different current limiting approaches may be implemented for future IBRs

- Different current limiting approaches may be implemented for enhanced/future IBRs – these may impact the IBR stability services and performance, and also need to be modeled accurately
- Multiple limits at different timescales are also possible – transient and steady state limits
- Other factors such as sequence extraction, PLL/frequency freezing, domain used for the controls/limits (abc,αβ,dq) may also impact the IBR response



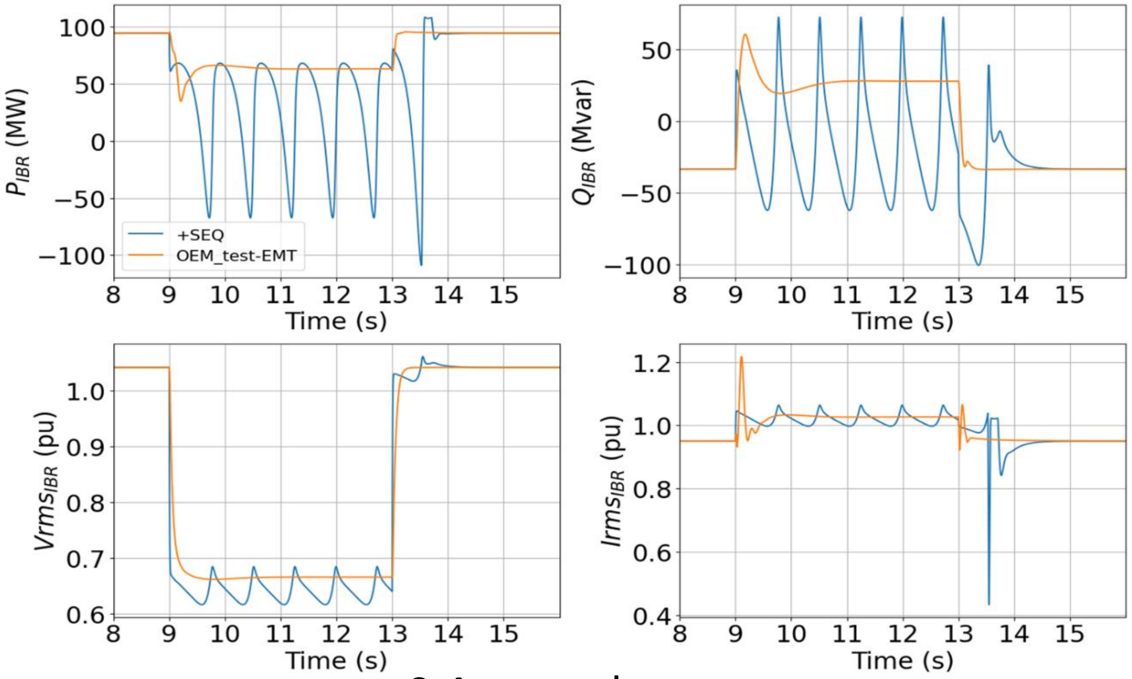
Different current limiting approaches for a potential future IBR

For more details:

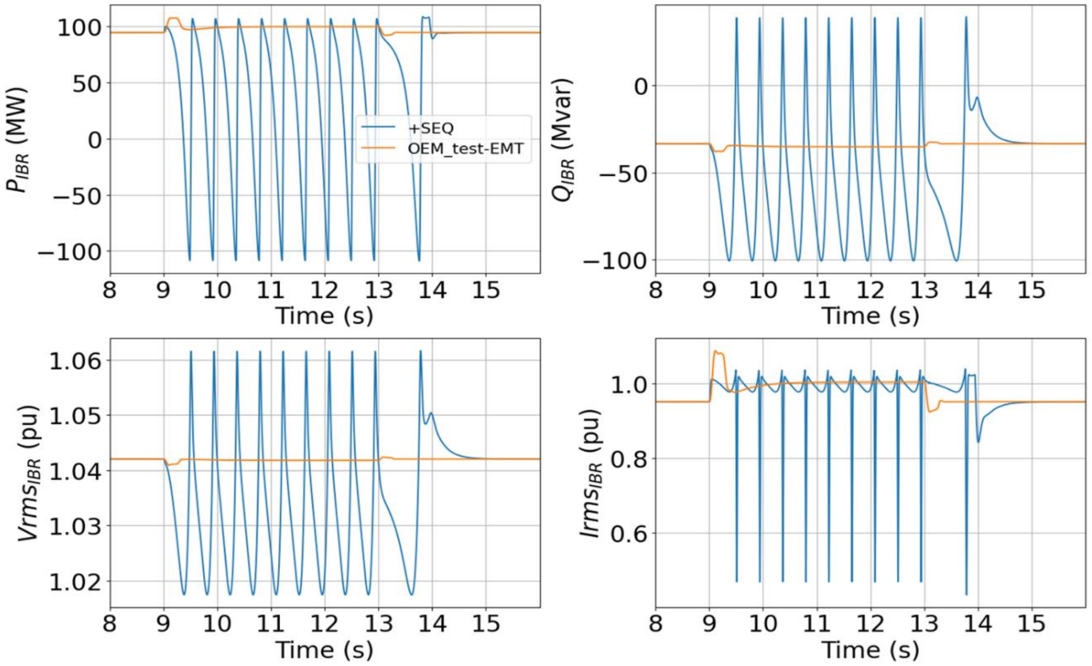
[6] Investigating the Fault Response of Grid Forming Inverter-Based Resources, EPRI, Palo Alto, CA: 2023. 3002027139 Available: link

Improvements to fault ride through behavior

- Positive sequence generic model compared against EMT OEM model, operating near the current limit



0.4 p.u. voltage step



1 Hz frequency step

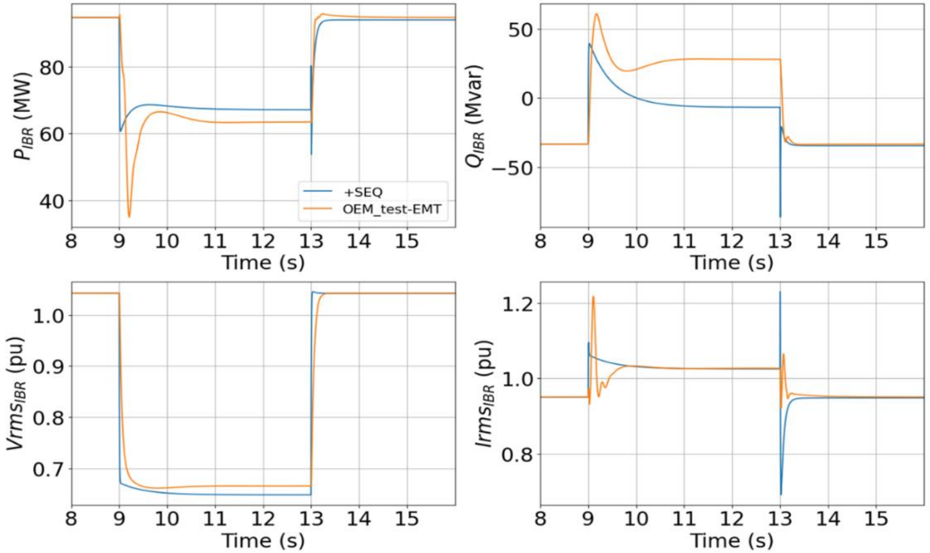
Too aggressive current limiting leading to oscillations – possible inaccurate assessment

For more details:

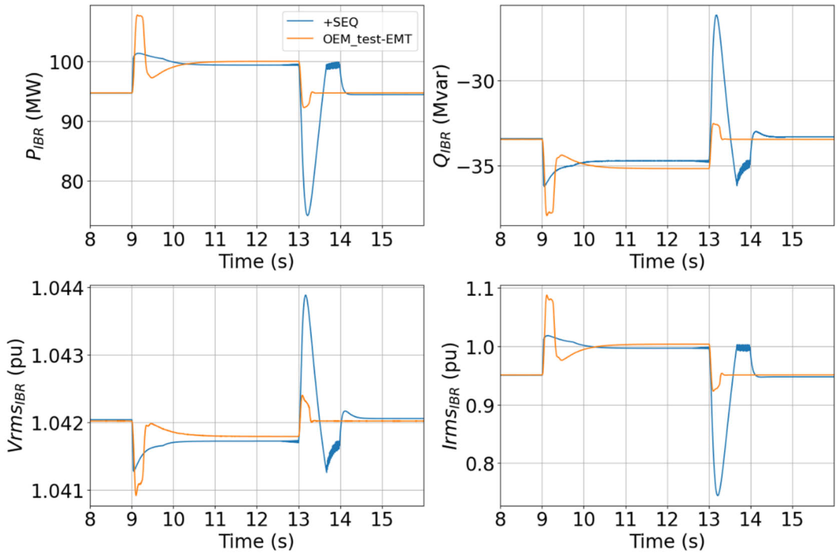
[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

Modified positive sequence model improves the response match with OEM model

- OEM model uses a different steady state limit – applied after a time constant
- Modified the generic positive sequence model by using different transient and steady state (applied after a set time period) limits



0.4 p.u. voltage step



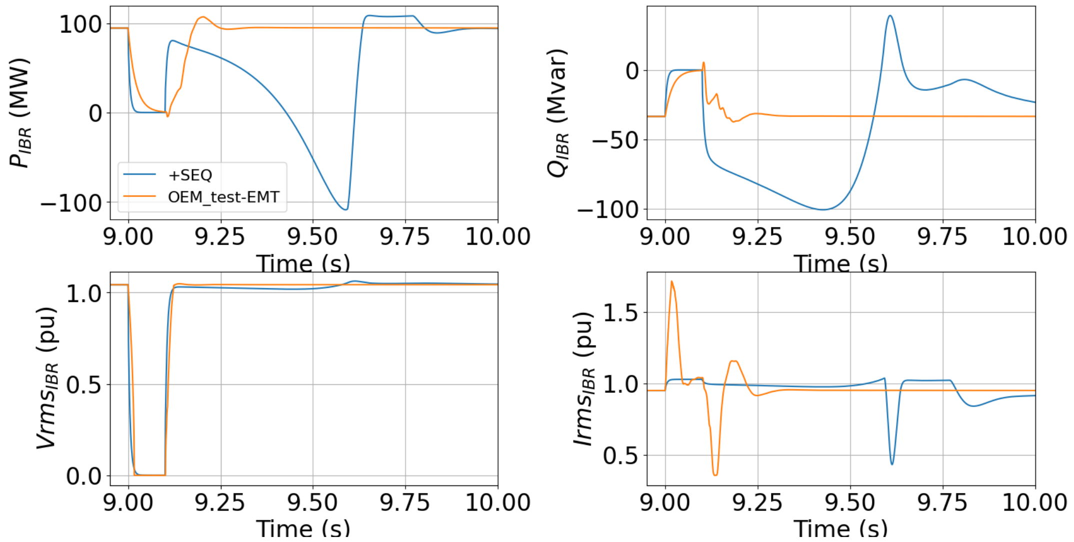
1 Hz frequency step

Modified model shows improved response against OEM model

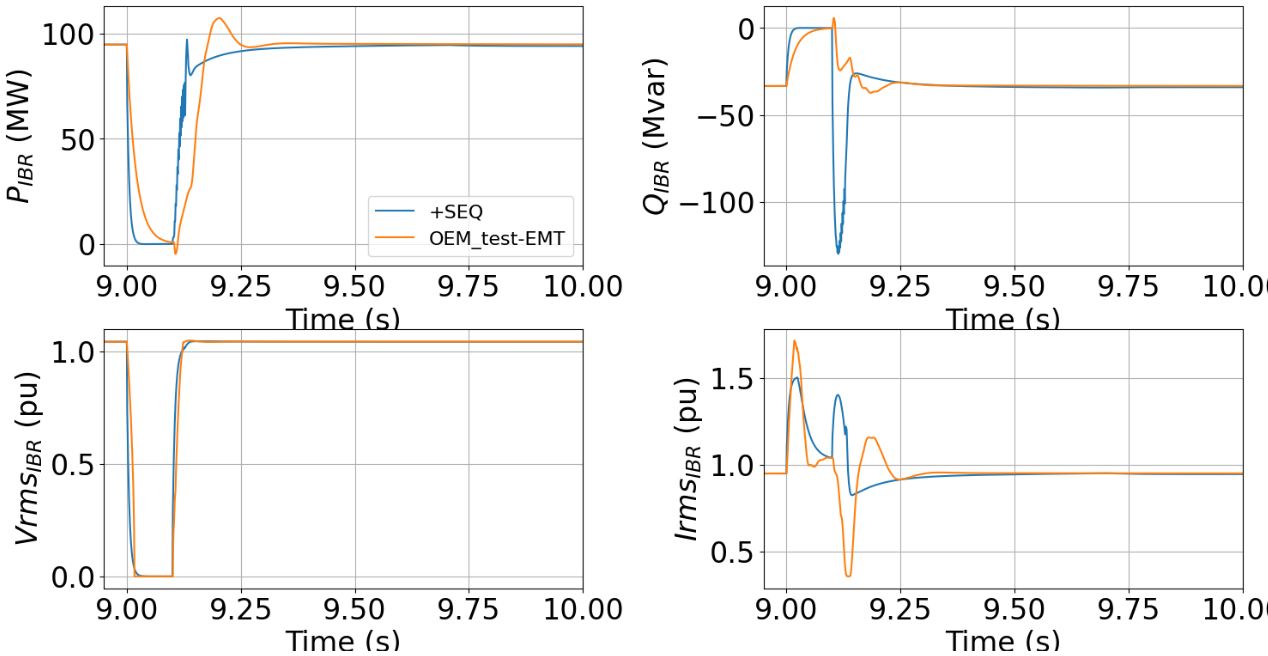
For more details:

[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

Modified positive sequence model shows improved response against OEM model – three phase fault



Original positive sequence model



Modified positive sequence model

Modified model shows improved response against OEM model

For more details:

[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

Impact of dc side on IBR performance

DC side modeling/including primary energy source

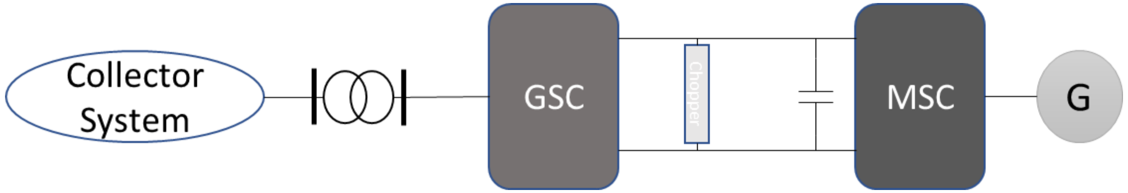
- DC link dynamics can in general impact small signal and transient behavior
- The DC link controls may be different depending on the resource –
  - WTG: high modeling requirement, explored a bit here
  - Battery plant – depends on standalone/hybrid operation? May also depend on SOC level
  - PV plant – MPPT or constant voltage DC operations
- Plant aggregation – does the aggregate plant respond similar to the detailed model

For more details:

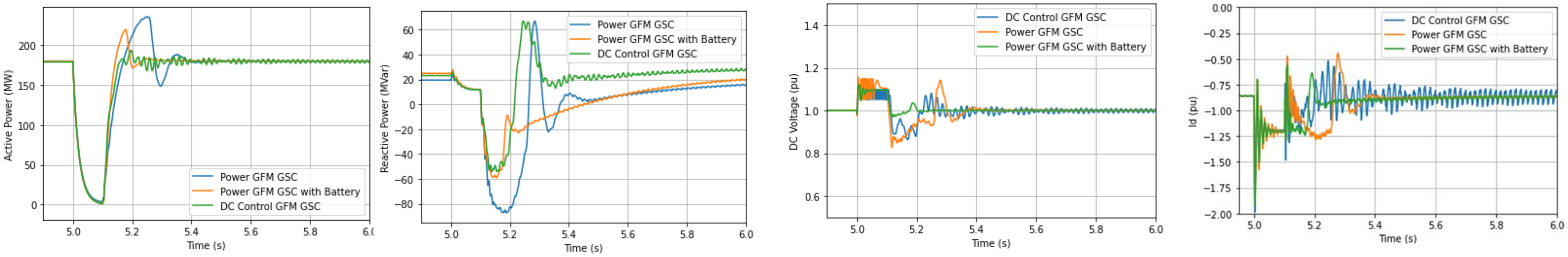
[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

Detailed modeling of Type 4 wind farm GFM controls

- A large number of Type 4 wind plant realizations exist
- Three control schemes:
  - GSC operates in droop active power control
  - GSC operates in DC voltage control supplemented by a frequency feedback to MSC
  - GSC operates in active power droop mode, MSC operates in active power control mode and the DC voltage is regulated by a battery.



Balanced fault



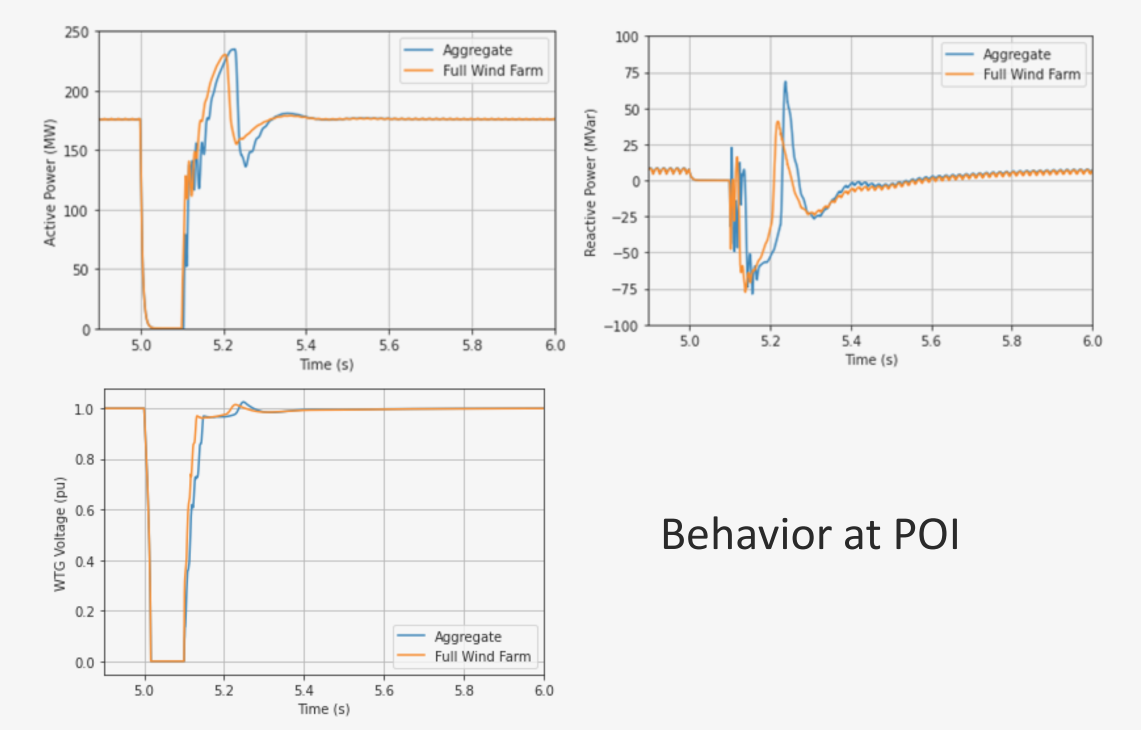
Different DC controls can lead to differences in behaviors, especially at the DC level

For more details:

[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

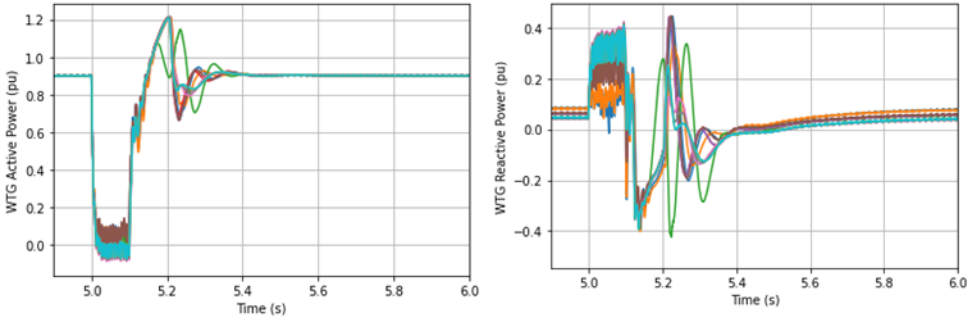
Behavior of aggregated vs detailed wind farm models

- Does an aggregate model accurately represent the behavior of the detailed model of a wind farm with future control capabilities?



Behavior at POI

Response of individual wind farms

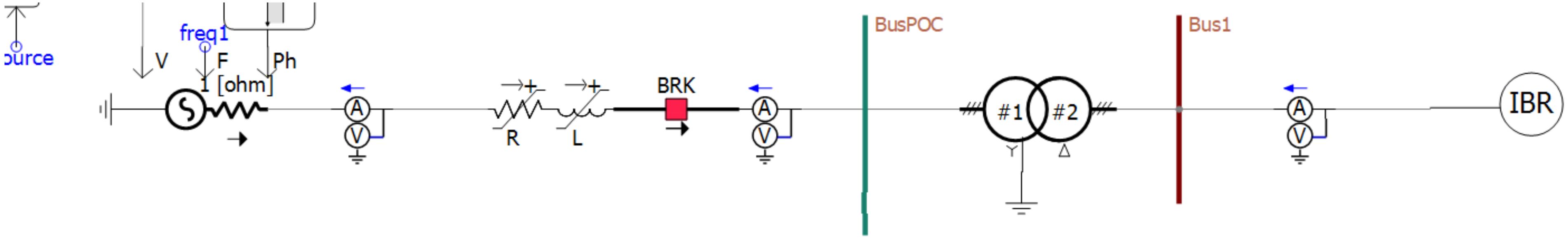


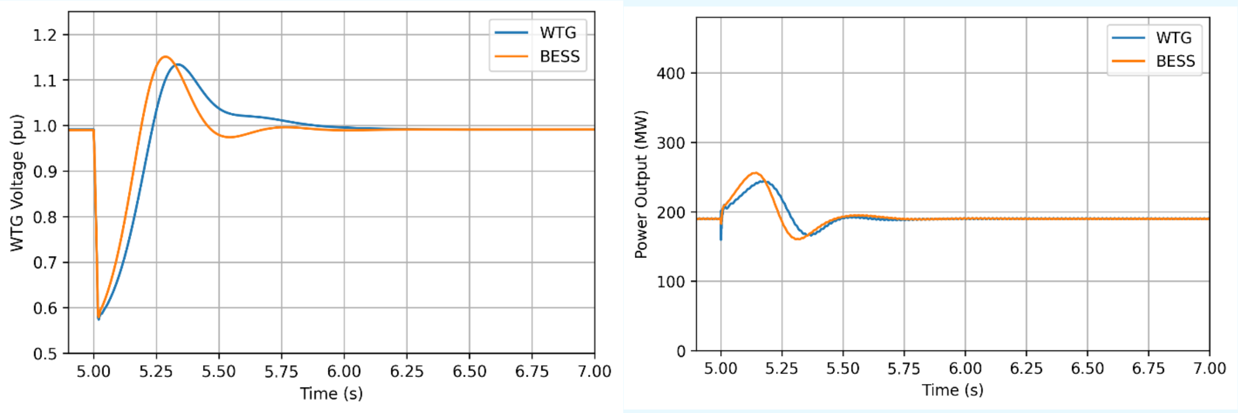
Some differences at the POI behavior if wind farm is modeled in detail, but there may be differences in how units respond

For more details:

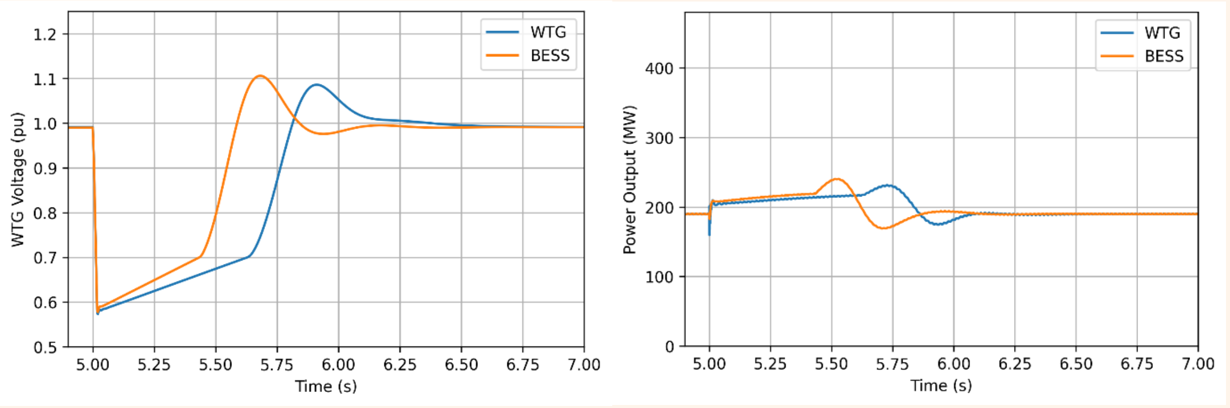
[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

Comparing Type 4 WTG and BESS GFM response – 40 degrees step in infinite bus, with and without FRT freezes





No FRT Freeze



FRT Freeze below 0.7 pu voltage

Modeling source/DC control and FRT dynamics may be important to accurately capture transients

Limits of RMS models

Limits of RMS models – small signal perspective

- Key differences in models:
  - Network dynamics excluded in RMS (fundamental frequency equivalent used)
  - Transformer saturation and inrush are excluded in RMS
  - Some of the faster loops excluded in RMS models
  - Different source representation from EMT (output of current control passed through a delay)
- Objectives of comparison:
  - Do the EMT and RMS models show similar response – time domain, frequency domain and small signal stability perspectives
  - Hence, EMT and RMS small signal models are compared here
  - Does this match/mismatch depend on the control parameters? Are there limits?

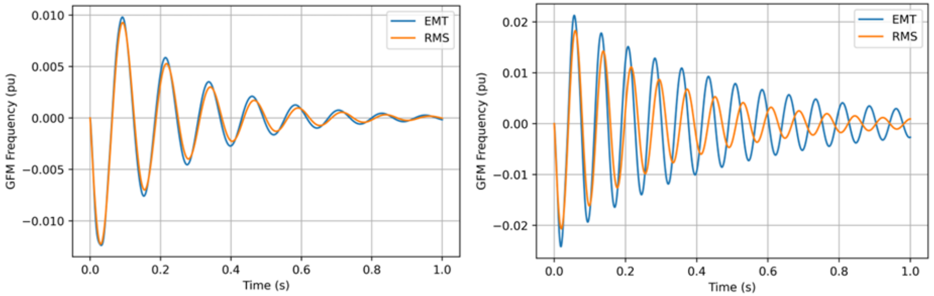
For more details:

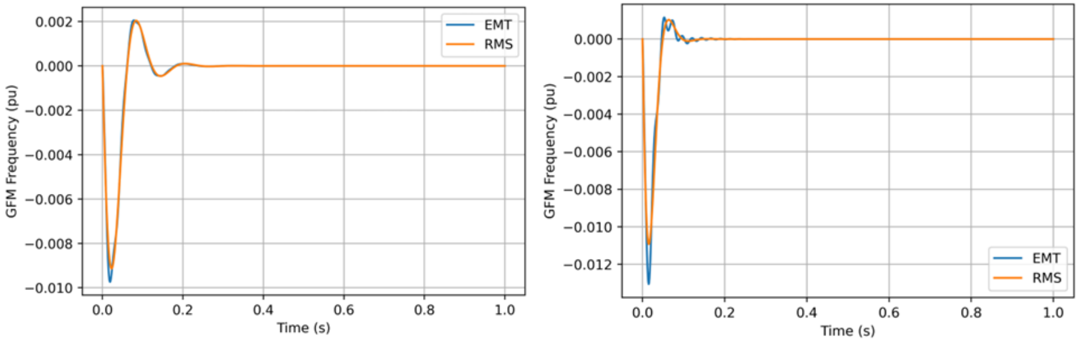
[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

[8] S. Konstantinopoulos and D. Ramasubramanian, “On the Limitations of RMS IBR Models: A Small-Signal Perspective,” 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024.

Limits of RMS models – time domain perspective

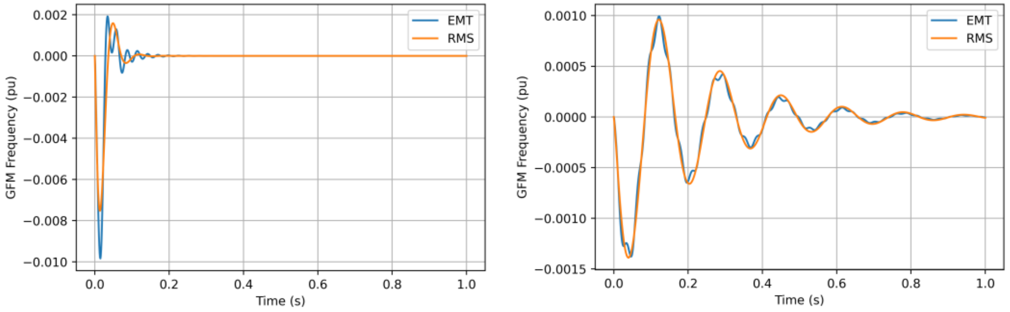
different power outputs – 180 MW left vs 50 MW right





Impact of decreasing droop time constant – 0.02s left vs 0.01s right: Interactions of swing mode with dynamics only captured by EMT model

Impact of increasing SCR – 10 left vs 30 right: Some poorly damped components may be missed in RMS models



RMS models may fail to capture some faster modes and may have a different response depending on various parameters

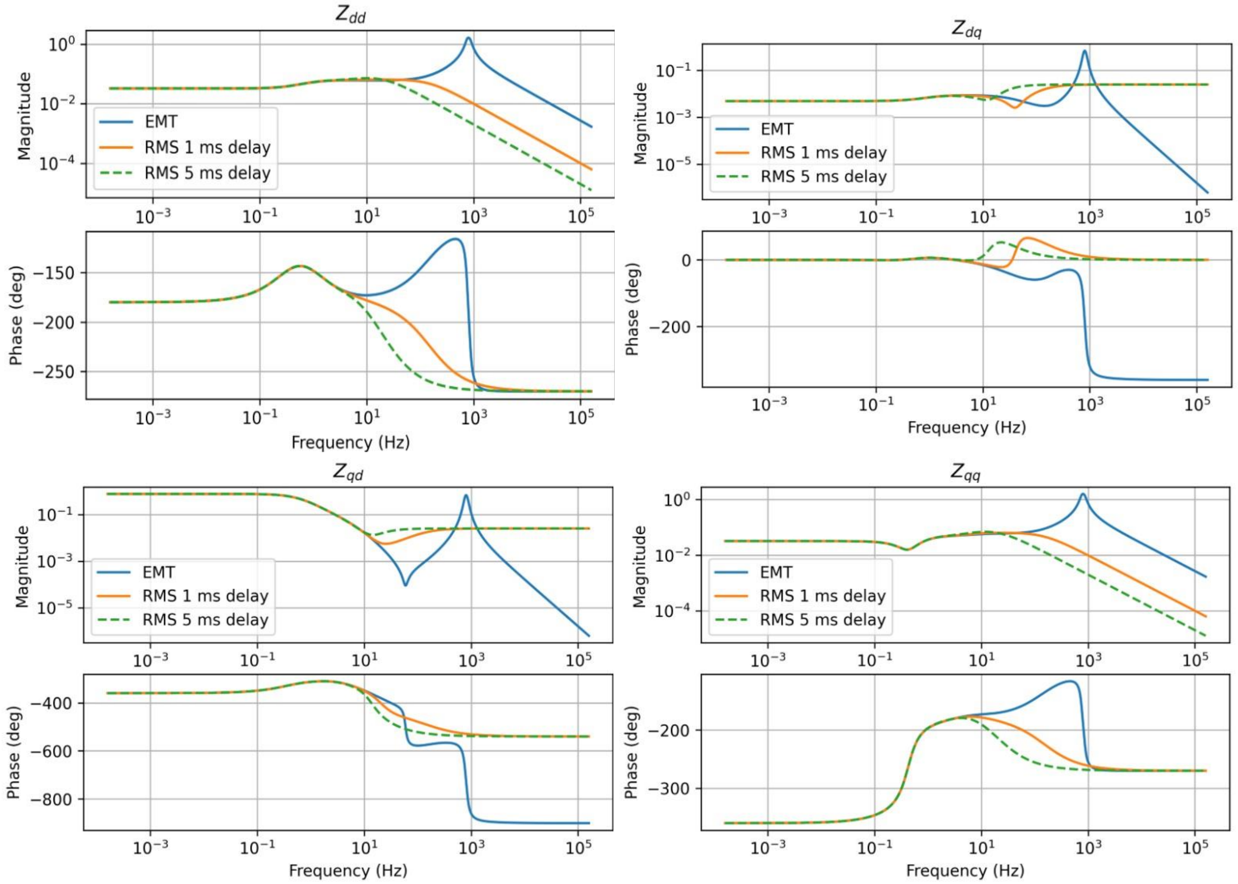
For more details:

[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

[8] S. Konstantinopoulos and D. Ramasubramanian, “On the Limitations of RMS IBR Models: A Small-Signal Perspective,” 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024.

Limits of RMS models – frequency response

- Here, Zdq implies transfer function between Id to Vq
- Good match up to 10 Hz
- If the models have adverse interactions outside that range, how would they perform?



Large differences in higher frequency range, depends on RMS voltage source delay

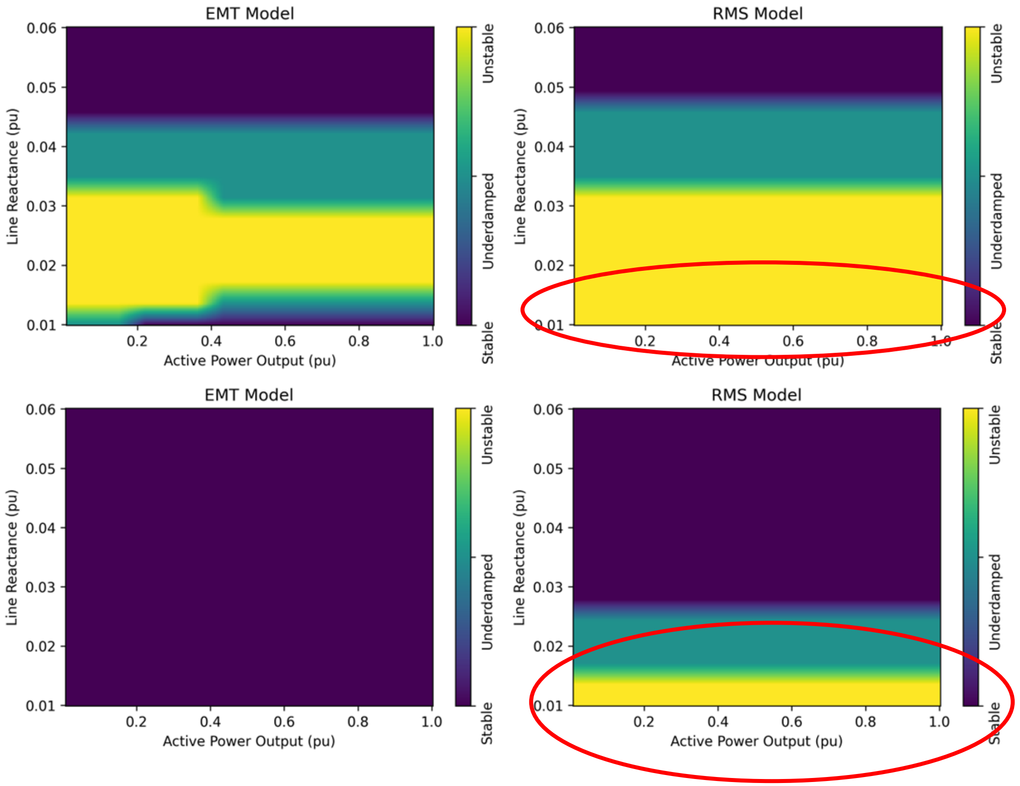
For more details:

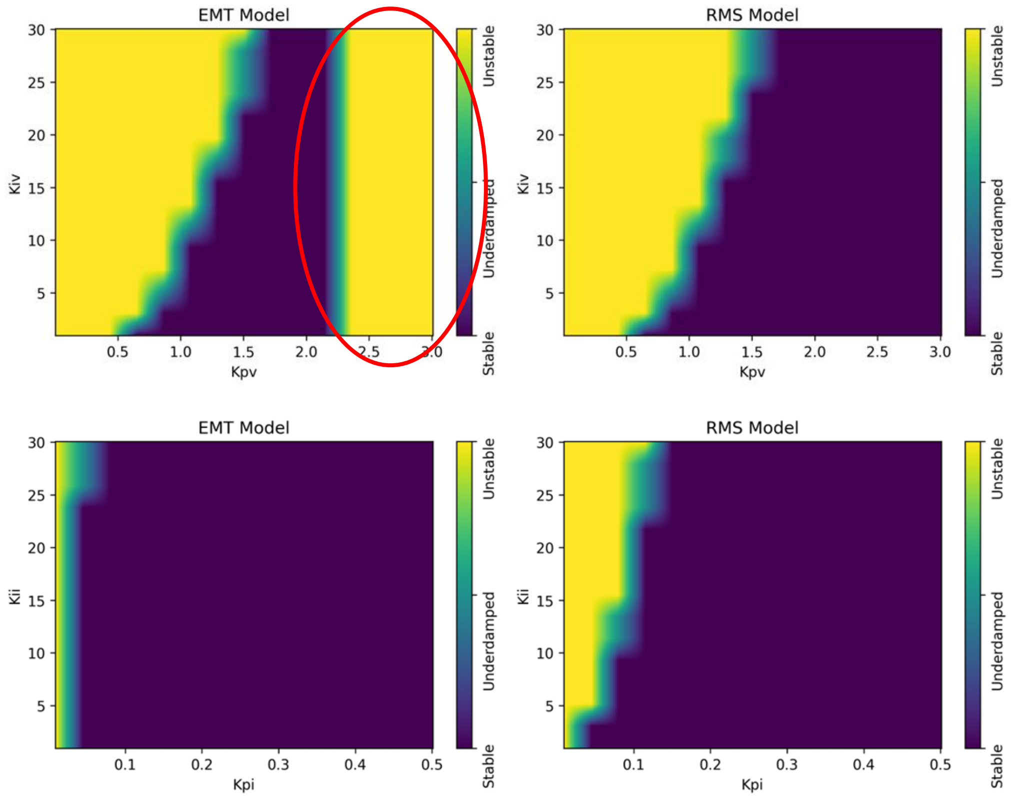
[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

[8] S. Konstantinopoulos and D. Ramasubramanian, “On the Limitations of RMS IBR Models: A Small-Signal Perspective,” 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024.

Small signal stability – different parameter sweeps

- IBR connected through a reactance to the infinite bus
- Some differences in stability in low reactance – RMS has a high frequency mode sensitive to the delay between current control output and VSC voltage
- For some control parameters, interaction involving GFM transducers unstable in EMT





Voltage controller gains varied

Current controller gains varied

For more details:

[7] EPRI UNIFI Consortium Work Progress: 2022 – 2023. EPRI, Palo Alto, CA: 2024. 3002030336. Available: link

[8] S. Konstantinopoulos and D. Ramasubramanian, “On the Limitations of RMS IBR Models: A Small-Signal Perspective,” 2024 IEEE Power & Energy Society General Meeting (PESGM), Seattle, WA, USA, 2024.

Summary

- Existing and new IBRs may provide different stability services to electrical grids
- Utilizing the capability of providing these services from existing IBRs may reduce the burden of needing to acquire these services from new IBRs
- Different nuances in IBR controls as well as primary sources may impact the IBR performance and may need to be considered
- Model accuracy may be important when assessing if a resource can deliver a particular service for a given case

Contact presenter and/or EPRI for more details regarding each case study including simulation models used for analysis

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