Positive Sequence Generic Model for Grid Forming Technology (GFM)

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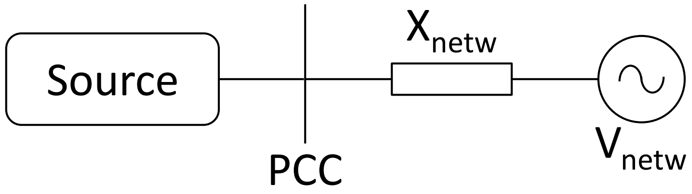
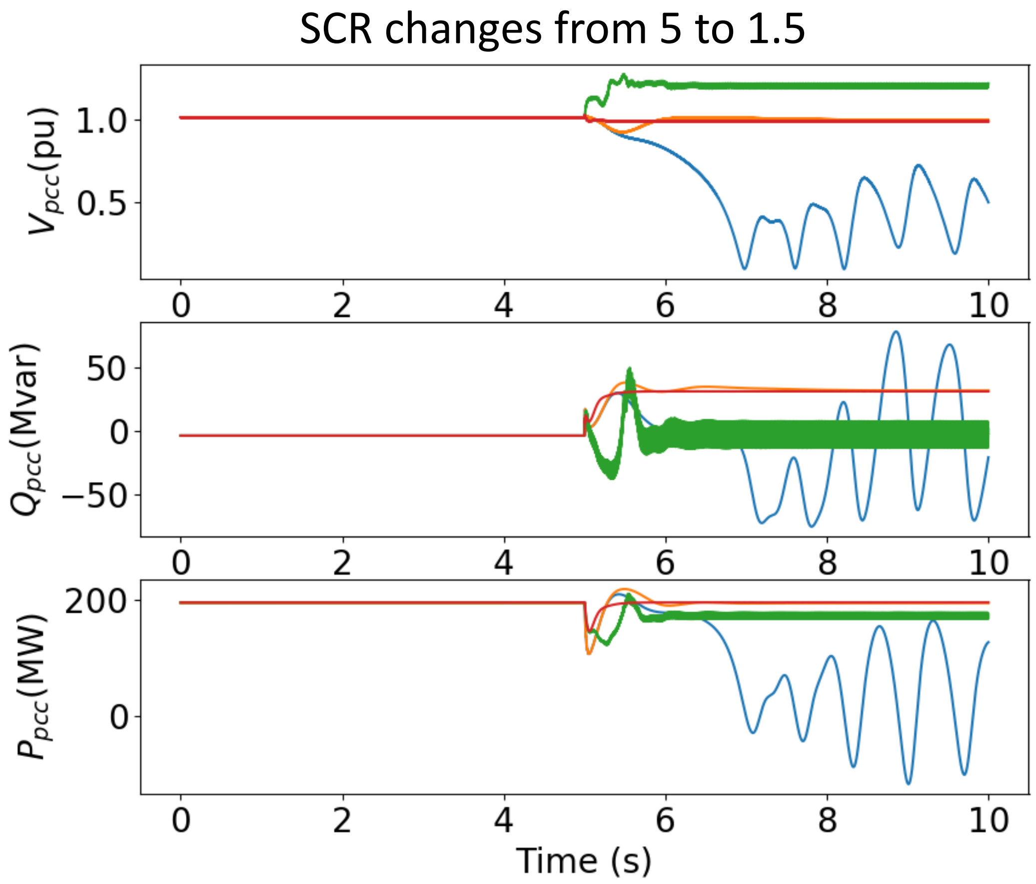
Few basics about various inverter mathematical models

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?
  - Nature of validation also important, e.g., field event data, or field test model.

Consider a source connected to an infinite bus

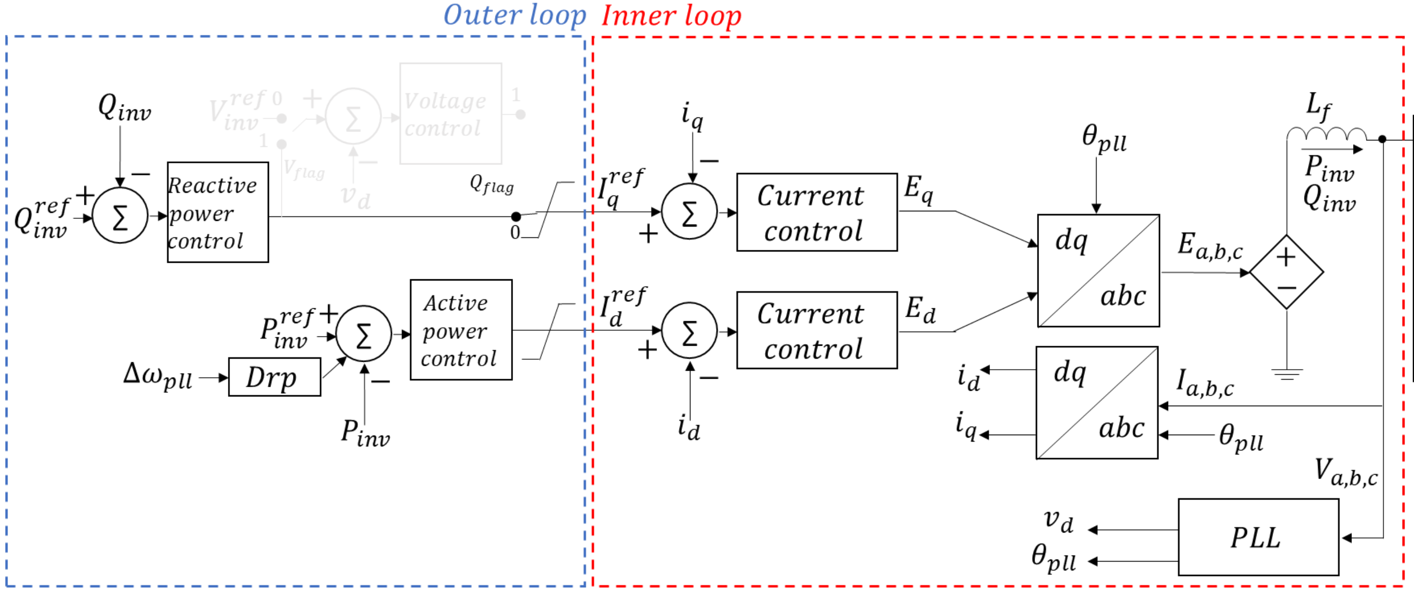


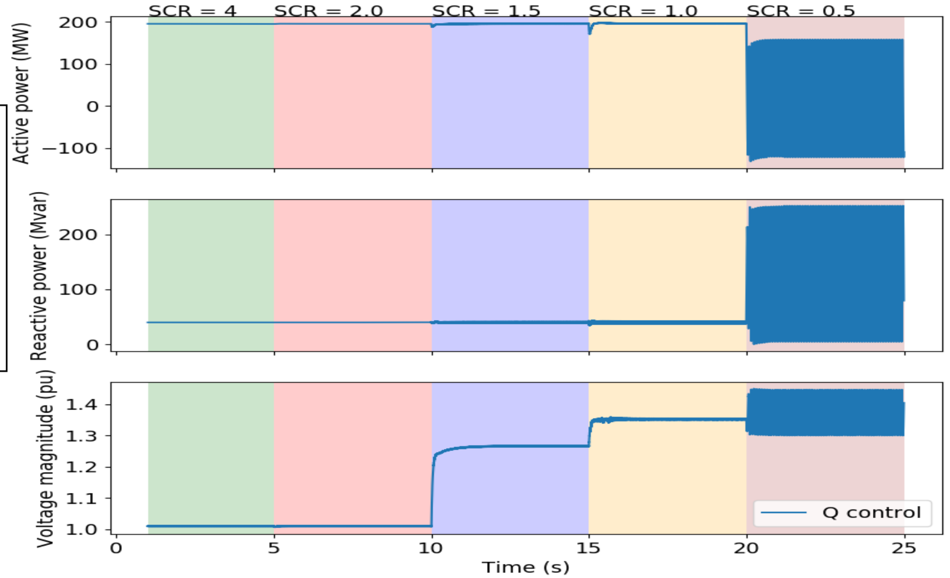


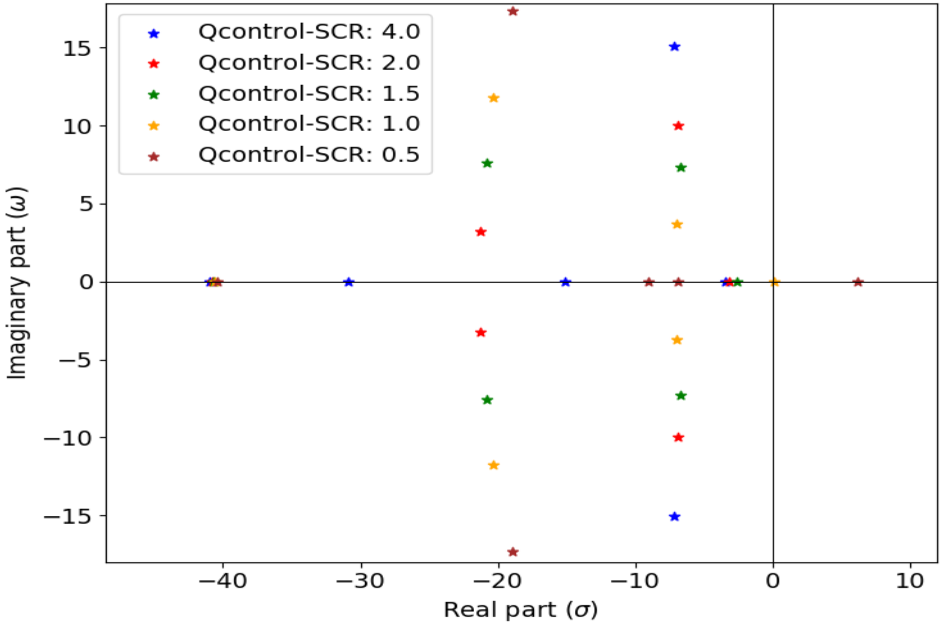
- A voltage behind impedance grid forming resource (synchronous machine) showcases similar level of instability for low SCR when attempting to control Q instead of V.
  - Blue – Synchronous machine with Q control
  - Green – PLL IBR with Q control
  - Orange – Synchronous machine with V control
  - Red – PLL IBR with V control

PLL and current source operation is potentially not the initiator of instability in an IBR in weak grid but rather Q control is the initiator

Fast inverter level reactive power level and SCR



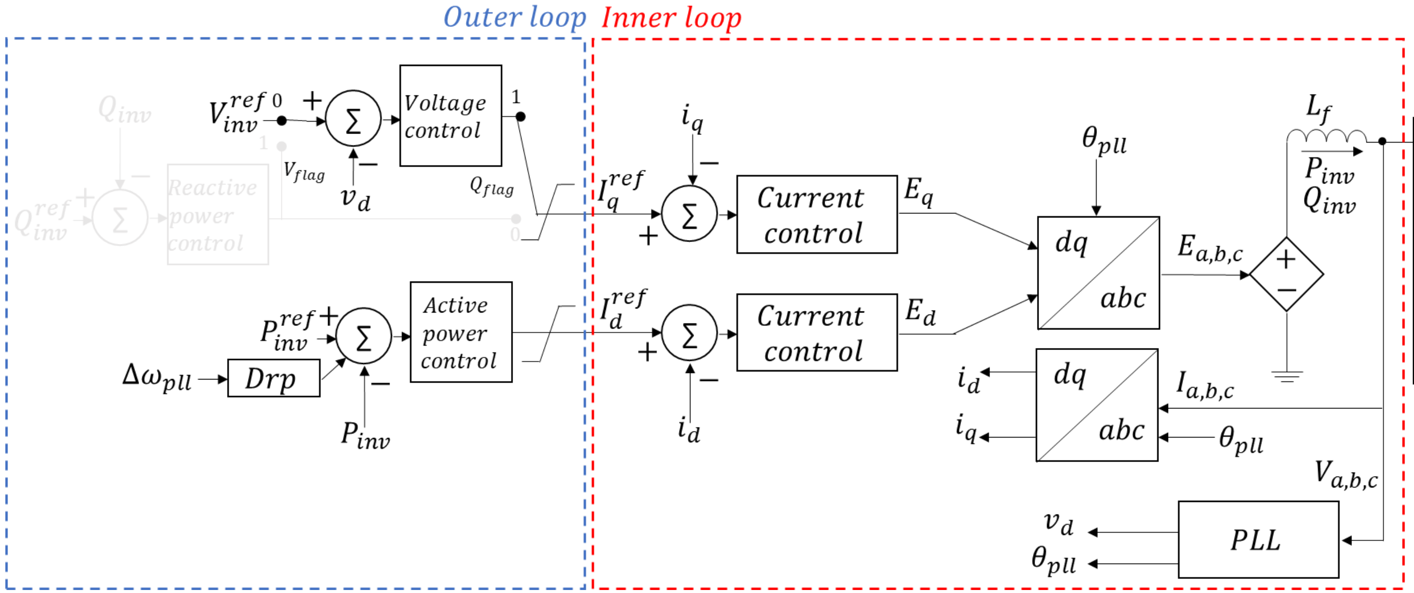


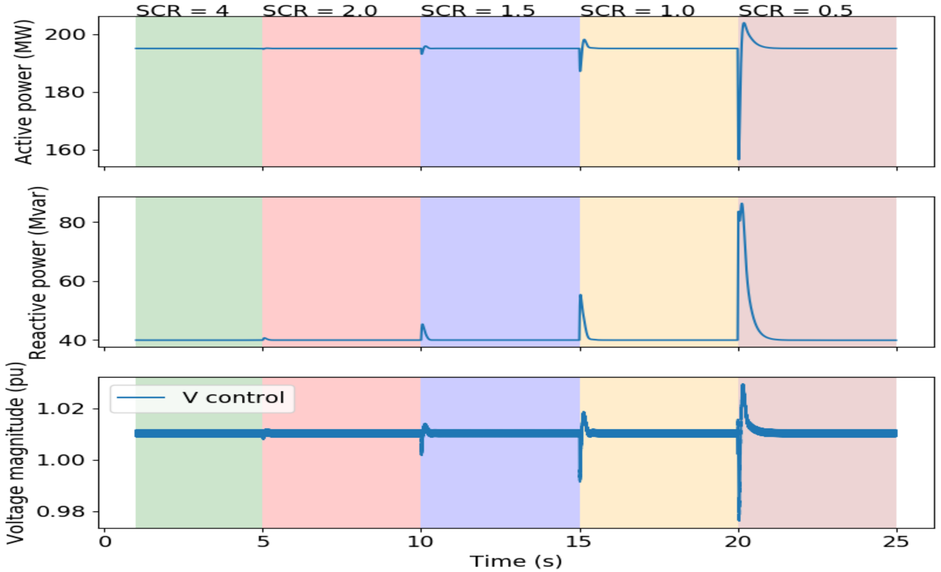


- Reduction in SCR below 2.0 results in instability
- Again, PLL and inner current control loop are not the sole elements responsible.

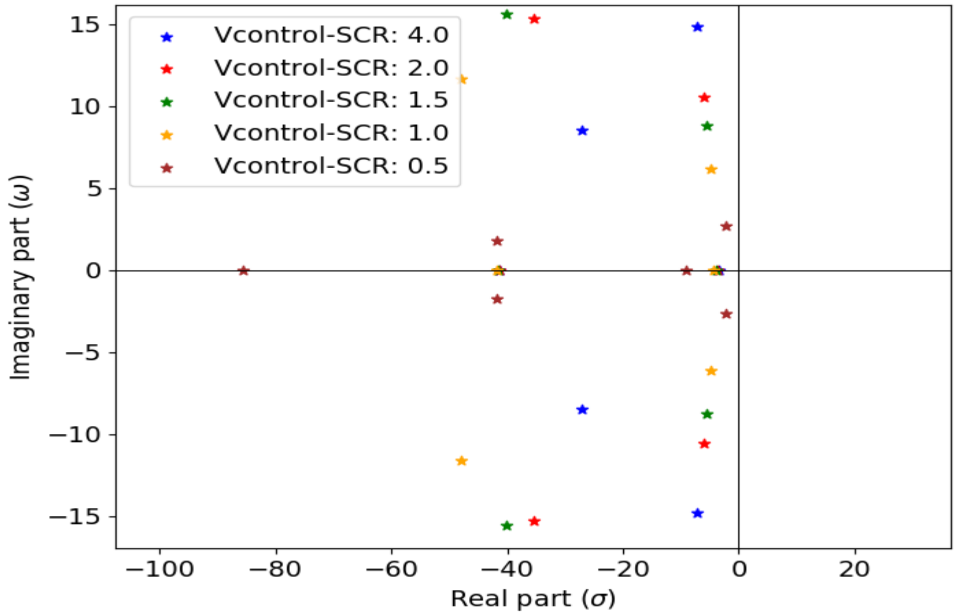
Deepak Ramasubramanian, Wes Baker, Julia Matevosyan, Siddharth Pant, and Sebastian Achilles, “Asking for Fast Terminal Voltage Control in Grid Following Plants Could Provide Benefits of Grid Forming Behavior,” *IET Generation, Transmission & Distribution*, early access [Link]

Switching to inverter level voltage control





- Keeping the PLL and current controller gains the same, switch to inverter level voltage control.
- From a small signal sense, the control is now stable even for SCR of 0.5!



Deepak Ramasubramanian, Wes Baker, Julia Matevosyan, Siddharth Pant, and Sebastian Achilles, “Asking for Fast Terminal Voltage Control in Grid Following Plants Could Provide Benefits of Grid Forming Behavior,” *IET Generation, Transmission & Distribution,* early access [Link]

A generic grid forming (GFM) model

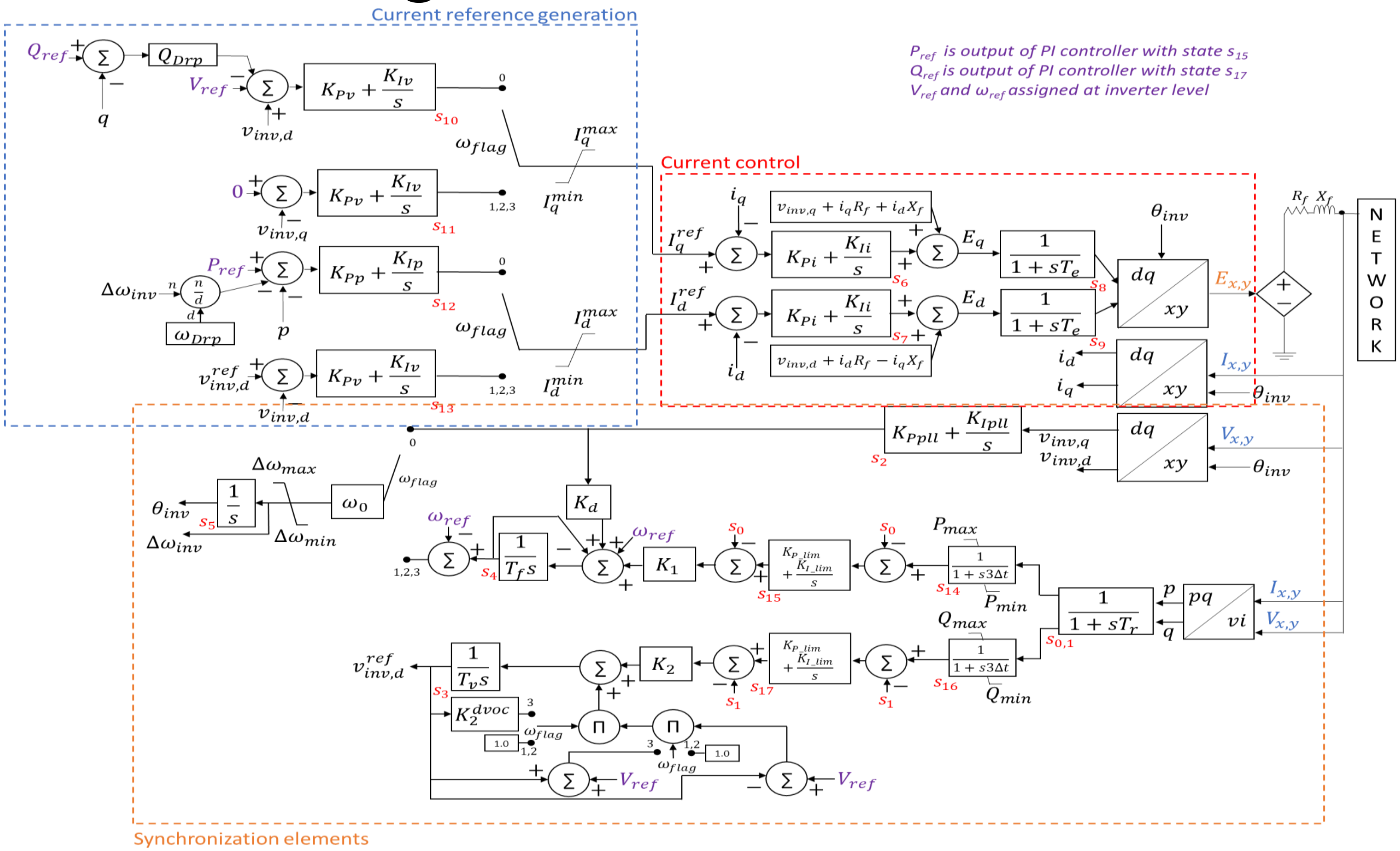
- Model developed through collaborative work across EPRI, University of Illinois Urbana-Champaign (UIUC), University of Washington (UW), and University of Minnesota (UM).

- In the context of this model, a grid forming (GFM) resource is defined as a resource that can transiently change its current injection to help control voltage and frequency.

- The generic model is structured to allow representation of four different GFM control methods:
  - Droop based GFM (Type – A Droop)
  - PLL based GFM (Type – B Droop)
  - Virtual synchronous machine (VSM) based GFM
  - Dispatchable virtual oscillator (dVOC) based GFM

- Model can be interfaced with existing generic plant controller models

Structure of generic model



- Choice of type of GFM model decided by value of ω_{flag}
  - 0 – Type B droop
  - 1 – Type A droop
  - 2 – VSM
  - 3 – dVOC
- Fault current limiting handled at network interface
- Power limits controlled at inverter level
- Can optionally also be controlled by existing plant controller generic models (REPC_*)
- Three equations represent synchronization elements

B. Johnson, T. Roberts, O. Ajala, A. D. Dominguez-Garcia, S. Dhople, D. Ramasubramanian, A. Tuohy, D. Divan, and B. Kroposki, "A Generic Primary-control Model for Grid-forming Inverters: Towards Interoperable Operation & Control," *2022 55th Hawaii International Conference on System Sciences (HICSS)*, Maui, HI, USA, 2022 [Link]

D. Ramasubramanian, "Differentiating between plant level and inverter level voltage control to bring about operation of 100% inverter-based resource grids," *Electric Power Systems Research*, vol. 205, no. 107739, Apr 2022 [Link]

Deepak Ramasubramanian, Wes Baker, Julia Matevosyan, Siddharth Pant, and Sebastian Achilles, "Asking for Fast Terminal Voltage Control in Grid Following Plants Could Provide Benefits of Grid Forming Behavior," *IET Generation, Transmission & Distribution,* early access [Link]

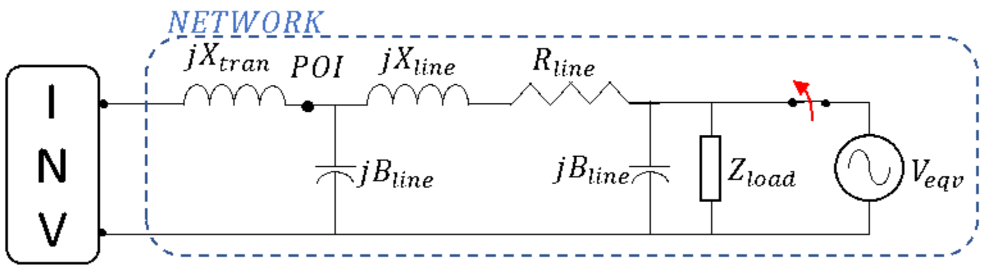
Comparison of number of parameters with existing 2nd generation WECC Renewable generic models

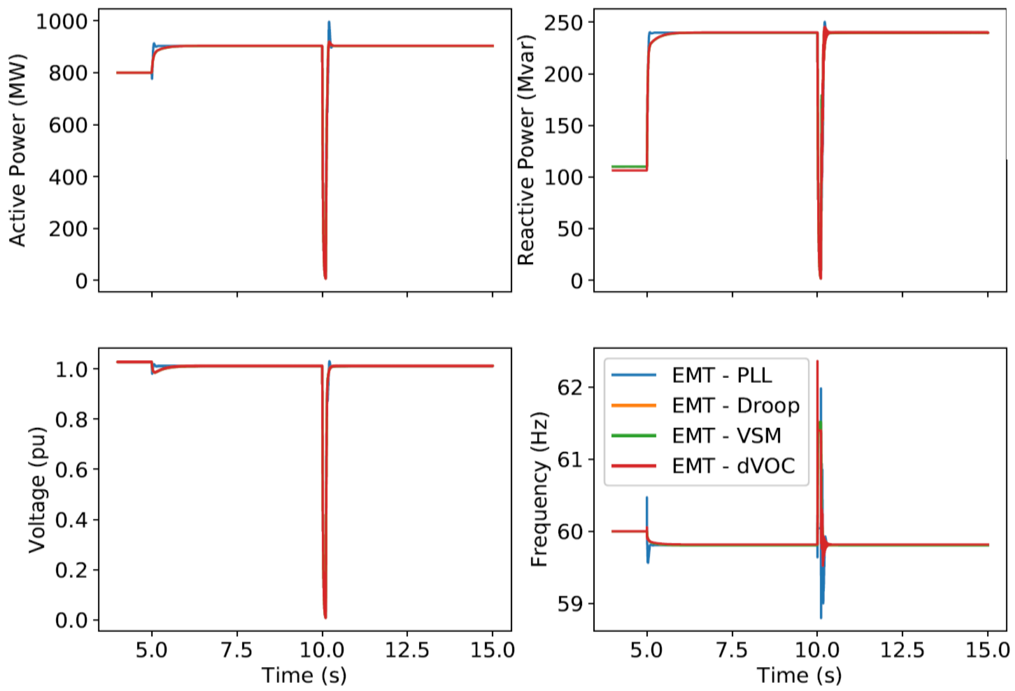
- 5 additional parameters compared to REGC_C[+]
  - One flag
  - Two droop coefficients
    - Also available in existing REEC models
  - Two parameters to represent VSM inertia and damping

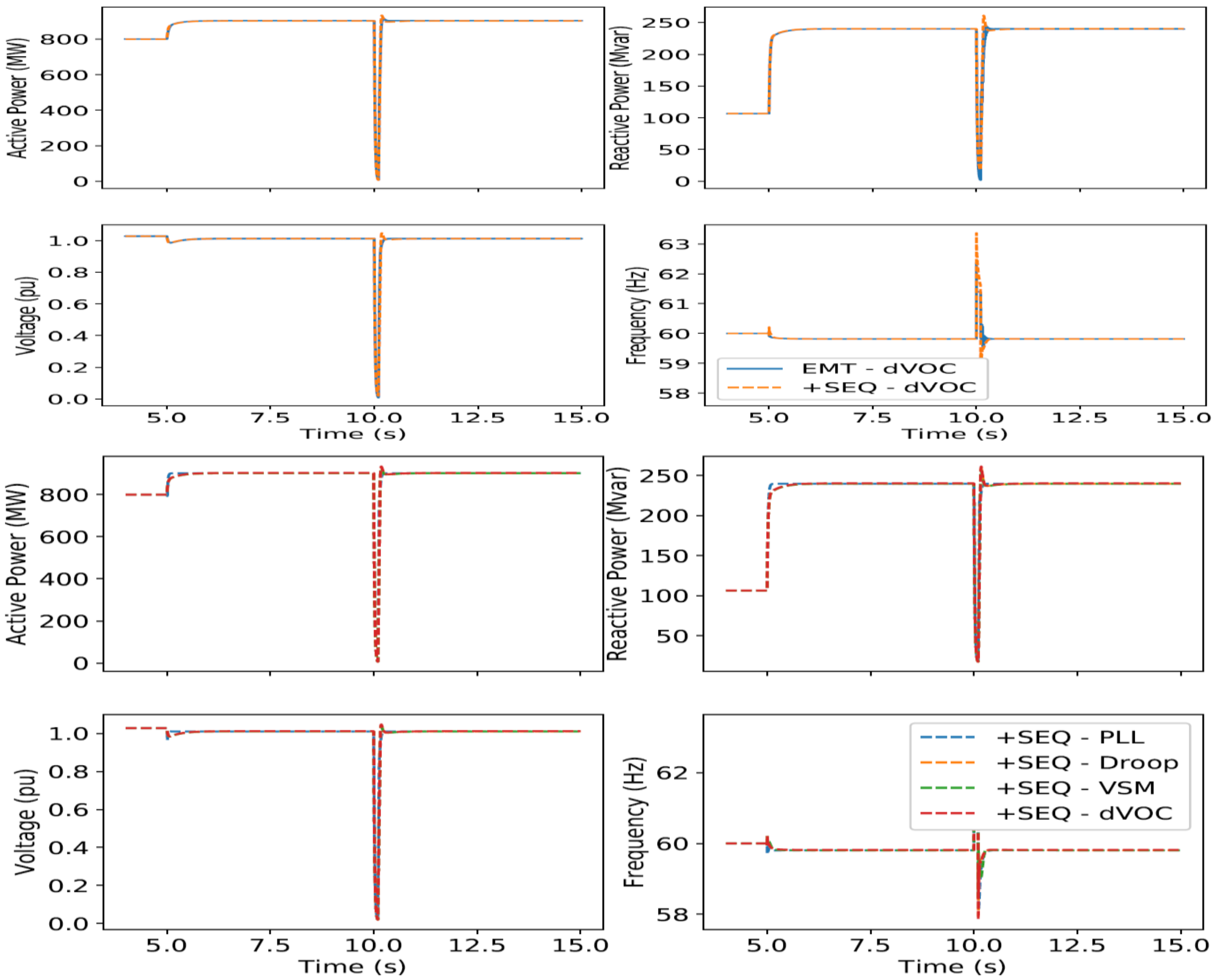
- Complete parameter list provided in EPRI memo to WECC MVS dated November 16th 2021. (link)

[+]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. [Link]

Benchmarking of model in SMIB – PSLF vs PSCAD



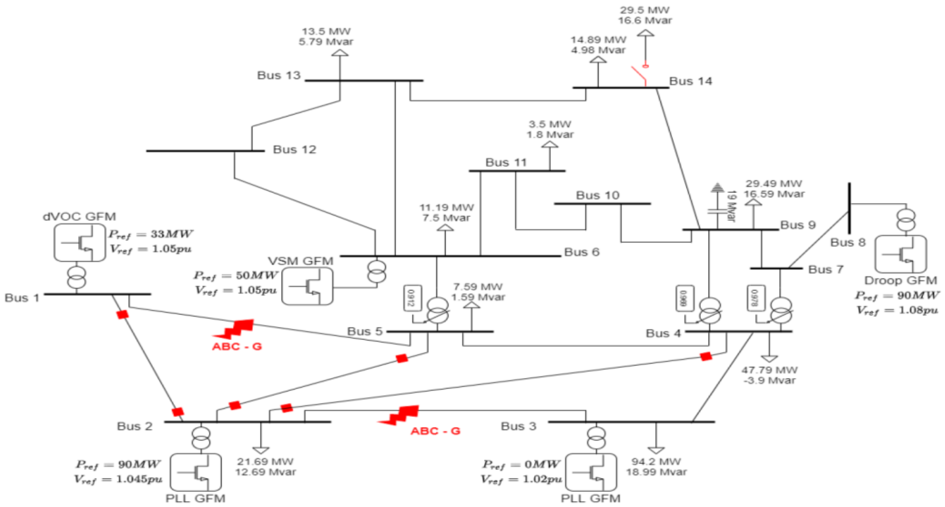


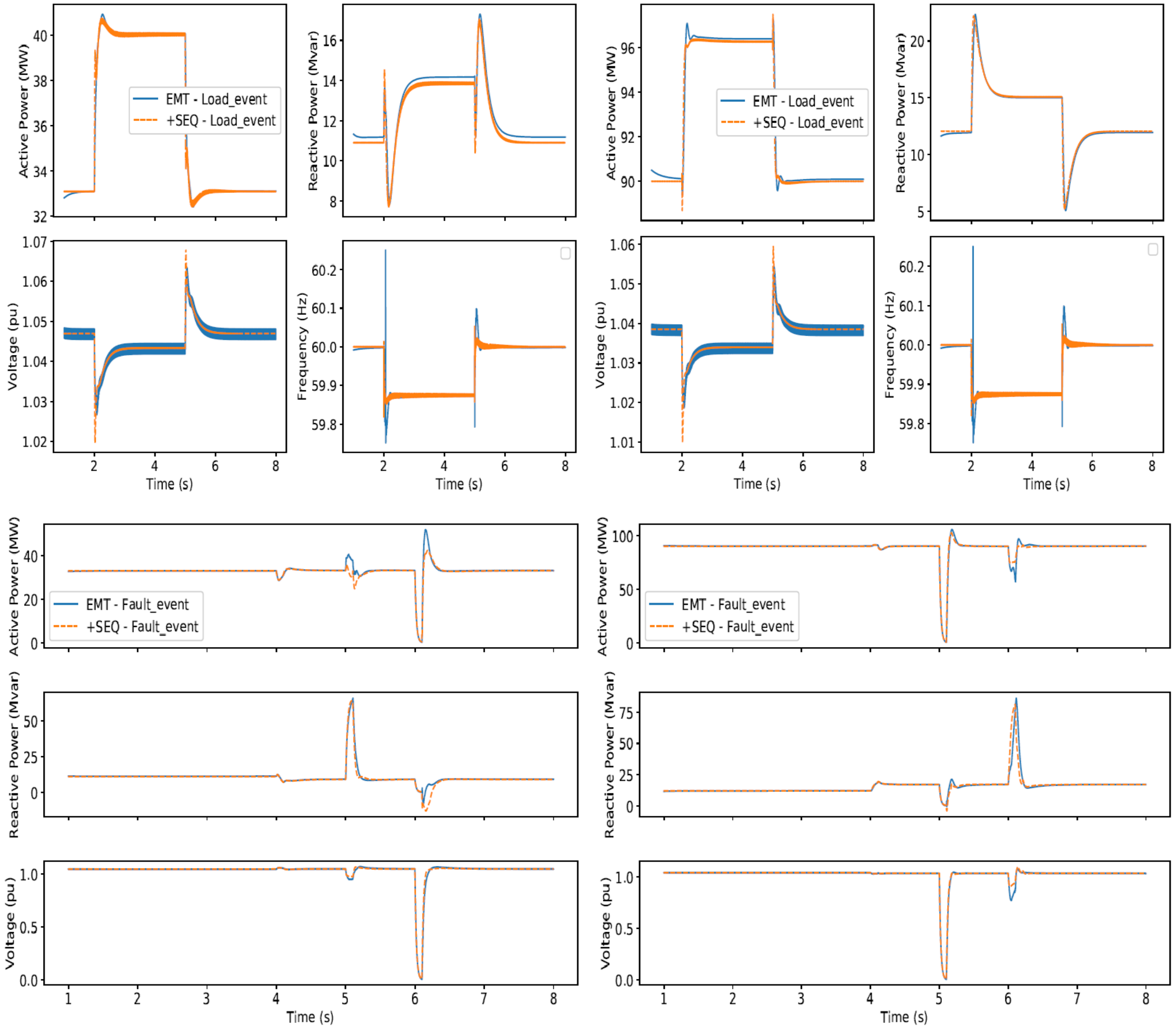


- Switch opened at t = 5s, three phase fault applied at POI at t=10s

EPRI memo to WECC MVS dated November 16th 2021. (link)

Benchmarking of model in IEEE 14 bus network – PSLF vs PSCAD





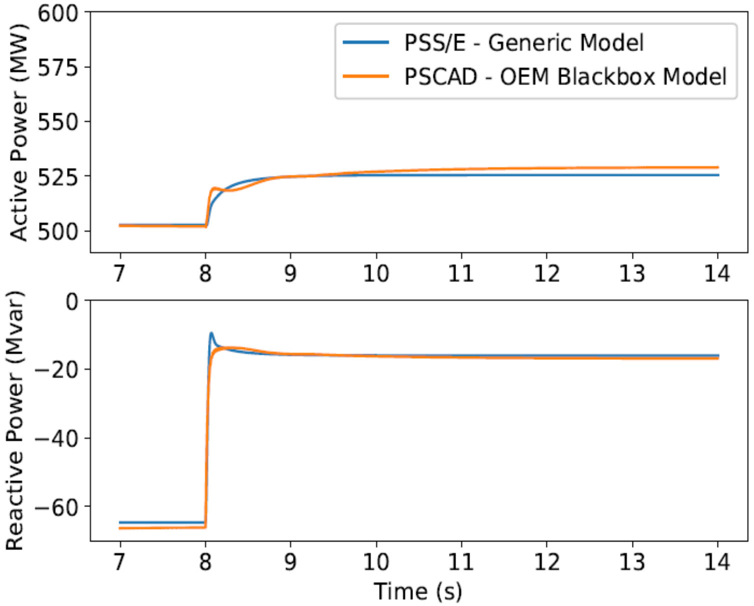
- Multiple instances of model in same network
- Load events and three phase fault events

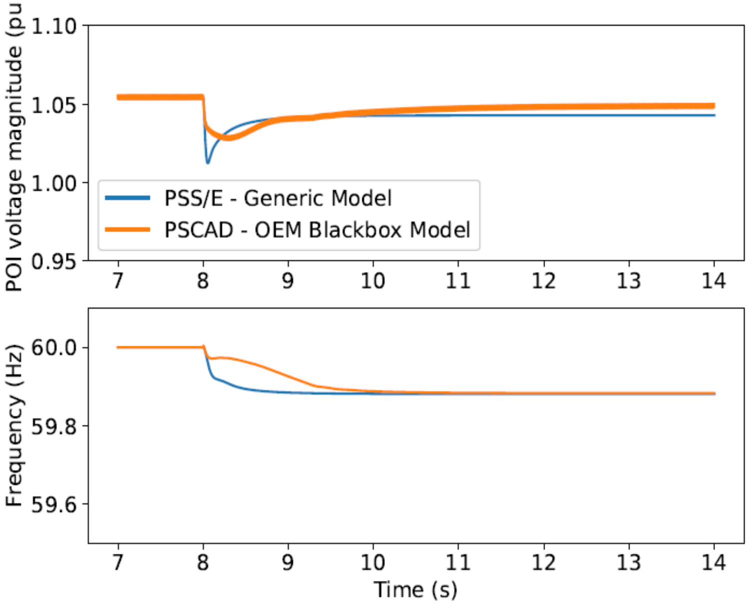
EPRI memo to WECC MVS dated November 16th 2021. [link]

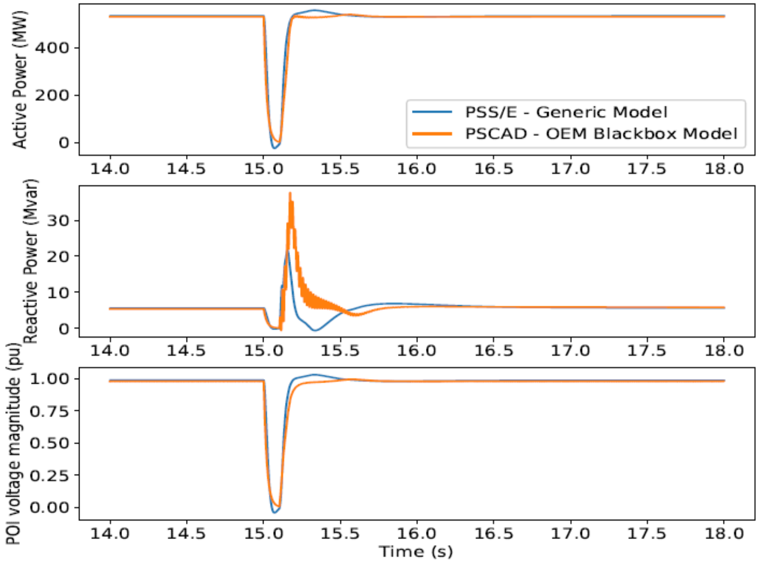
D. Ramasubramanian, P. Pourbeik, E. Farantatos and A. Gaikwad, "Simulation of 100% Inverter-Based Resource Grids With Positive Sequence Modeling," *IEEE Electrification Magazine*, vol. 9, no. 2, pp. 62-71, June 2021 [Link]

Comparison against OEM Blackbox model

- PLL based GFM mode used for this analysis as OEM may have a similar <u>operational</u> characteristic
  - Exact OEM control structure is not known due to black box nature of EMT model





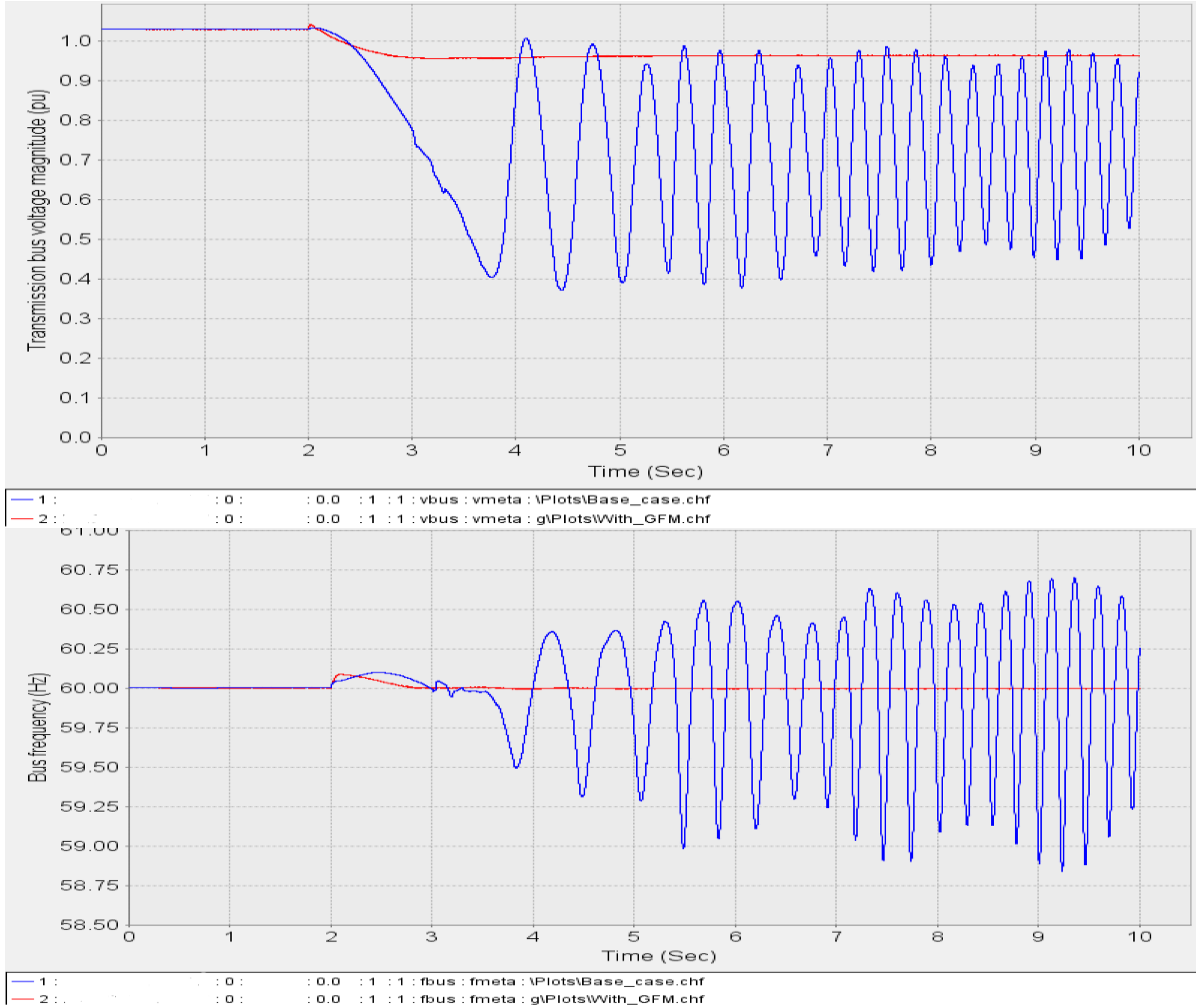


Deepak Ramasubramanian, "Generic Positive Sequence Representation of Grid Forming Behavior and its Application in an Island System Case Study," *2022 IEEE Power & Energy Society General Meeting (PES)*, Denver, CO, USA, 2022 [*accepted*]

NERC Inverter-Based Resource Performance Working Group, ``Reliability Guideline: Performance, Modeling, and Simulations of BPS Connected Battery Energy Storage Systems and Hybrid Power Plants," North American Electric Reliability Corporation, March 2021 [Link]

Robustness of model in WECC base case

- One entire area of WECC base case made 100% IBR
  - Both existing GFL models and proposed GFM models present
  - GFM modes assigned at random
- Extreme contingency applied by tripping 60% of area's tie lines
- Plot legend
  - Blue – base case with sync machines
  - Red – one entire area being 100% IBR



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Availability of model (to-date)

<table>
<tr><th colspan="3">Positive sequence/RMS balanced domain</th><th colspan="5">EMT domain[+,^]</th><th colspan="2">RMS unbalanced domain</th><th>Real-time domain</th></tr>
<tr><th>Siemens PTI PSS/E</th><th>GE – PSLF</th><th>DIgSILENT PowerFactory</th><th>PSCAD[+]</th><th>EMTP*</th><th>DIgSILENT PowerFactory</th><th>SIMULINK</th><th>PLECS</th><th>OpenDSS</th><th>DIgSILENT PowerFactory</th><th>RTDS/Opal-RT/RSCAD</th></tr>
<tr><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✗</td><td>✓</td><td>✗</td></tr>
<tr><td>Type A Droop
Type B Droop</td><td>Type A Droop
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VSM
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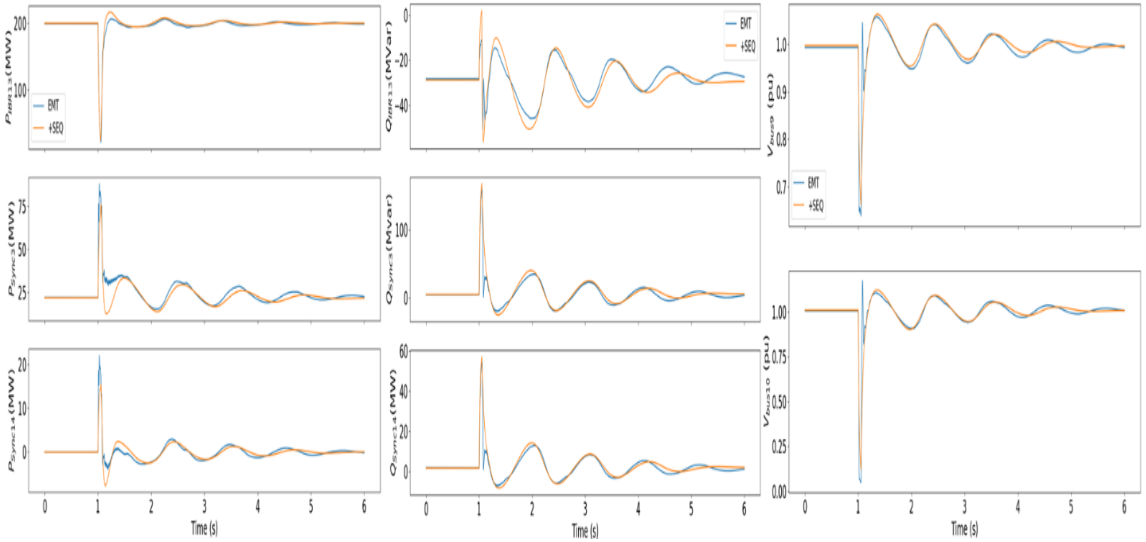
Type B Droop
VSM
dVOC</td><td>Type A Droop
VSM
dVOC</td><td></td><td>dVOC</td><td></td></tr>
</table>

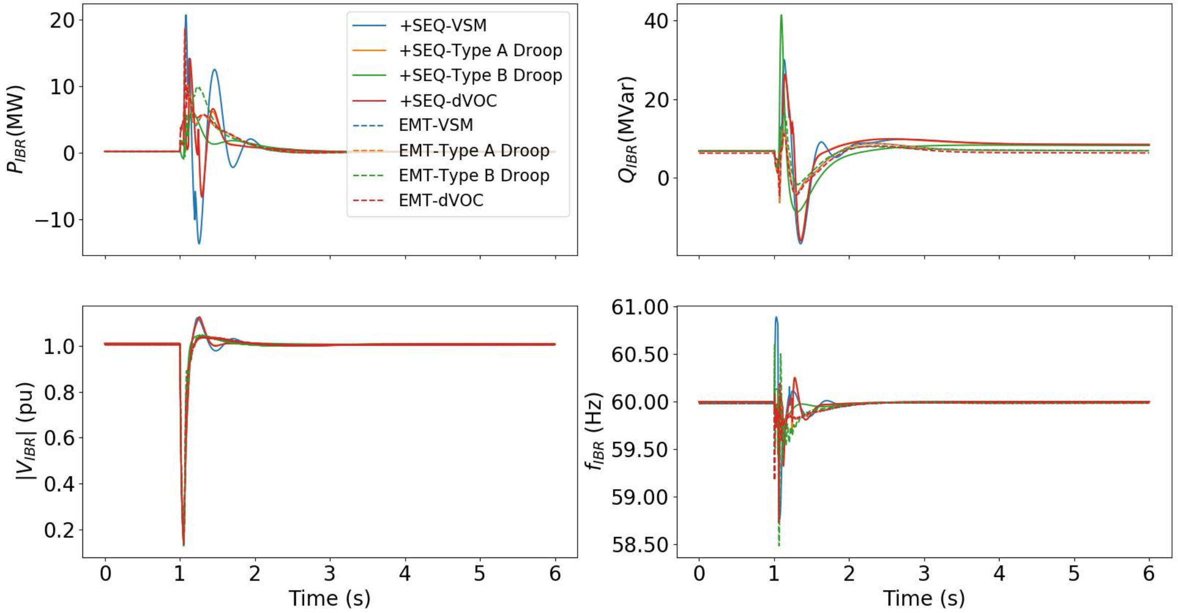
[*]implemented by software developer
[+]certain model versions also have negative sequence control implemented
[^]certain model versions are also implemented at switching level
[+]C-code based model in addition to GUI block-based model

- 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

Example use of positive sequence model



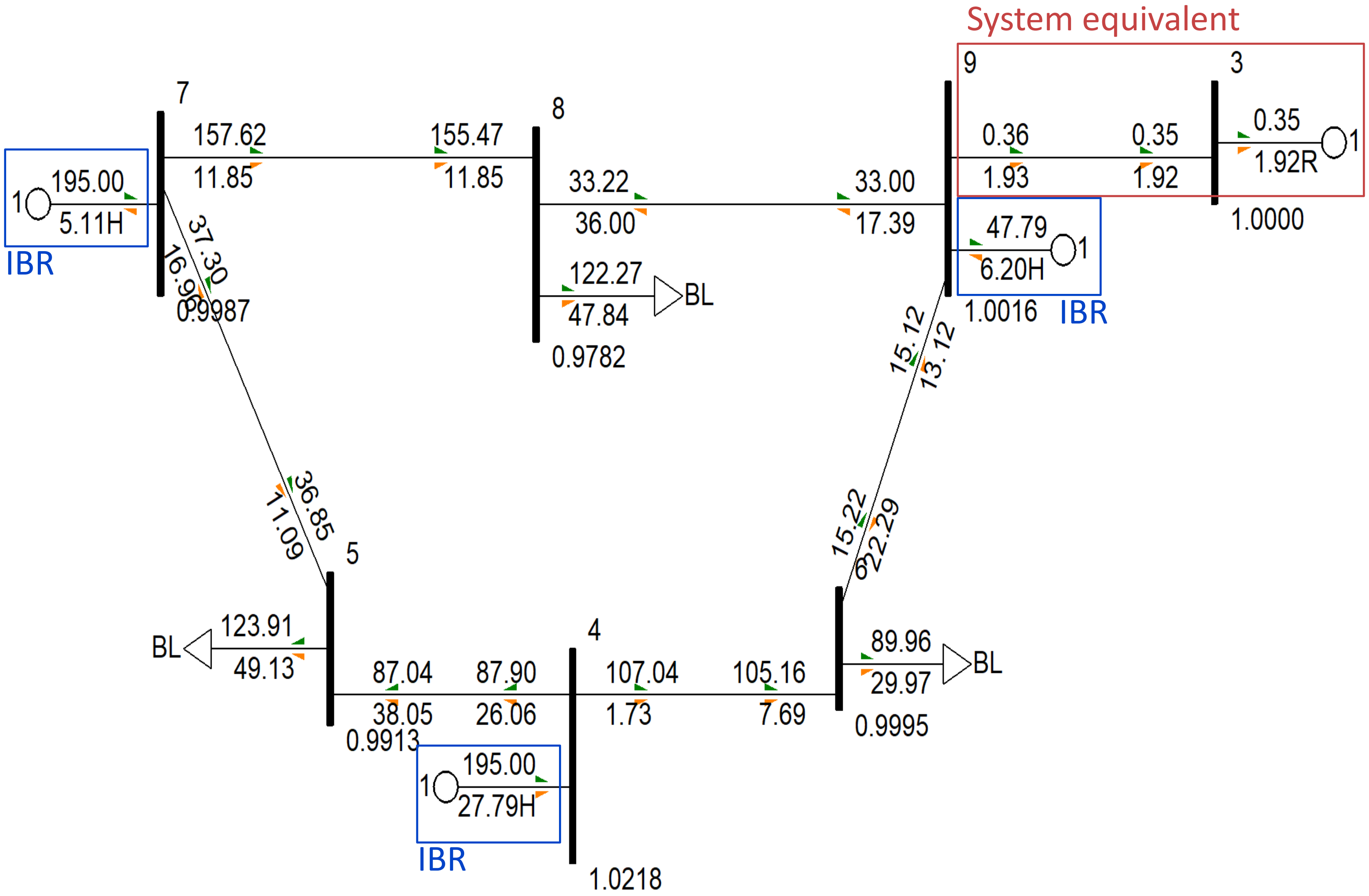
- Low damped oscillations observed in a system without grid forming inverters
  - Grid following and synchronous condensers present



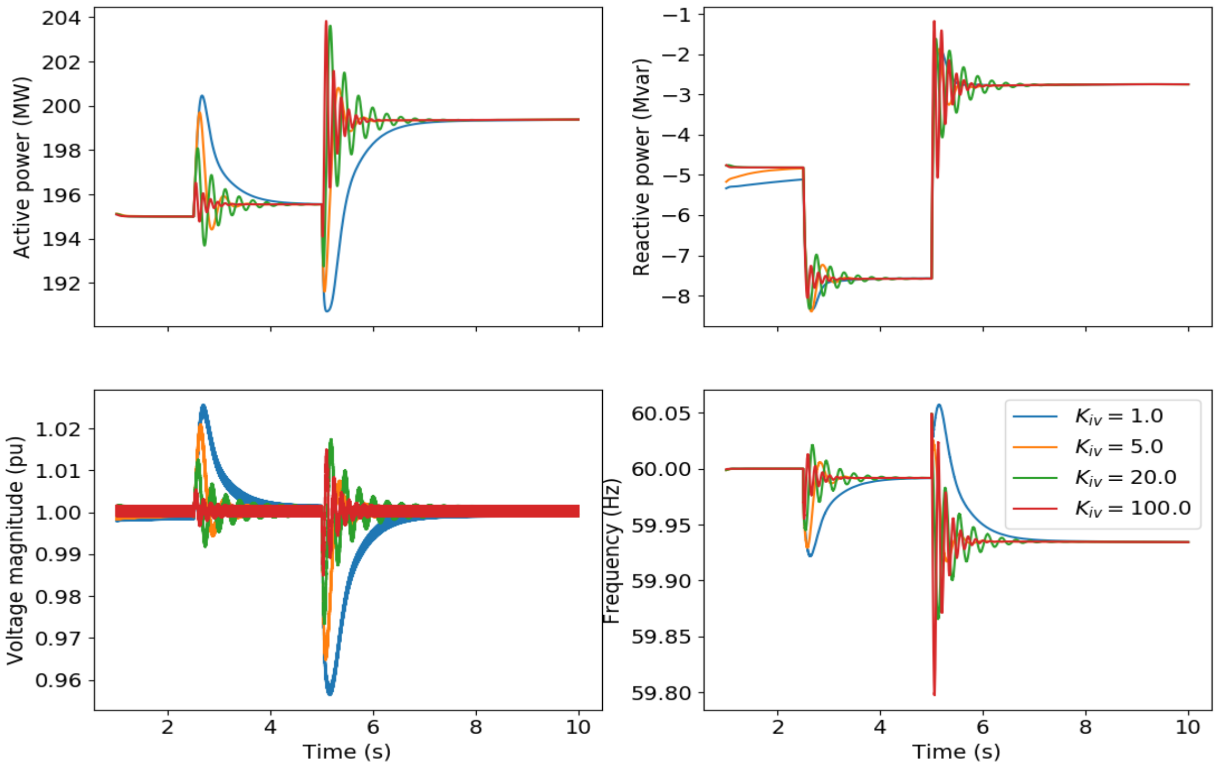
- Improved damping in the system with a grid forming resource added to the network
  - Similar damping characteristics across all four forms of GFM.

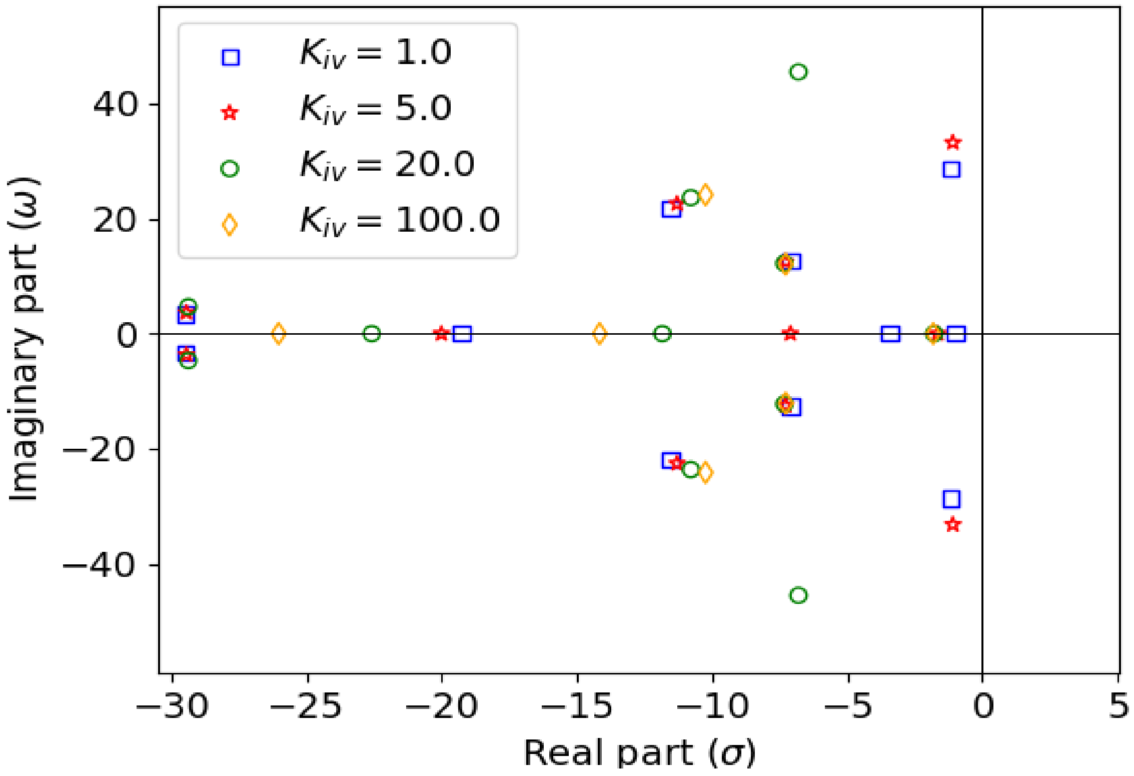
Use of this concept in larger power system planning

- Three legacy IBRs
  - Two IBRs with constant P and Q control
    - 200 MVA each
  - One IBR with constant I control
    - 50 MVA
- Power transfer to external network intentionally kept minimal



Effect of varying speed of voltage control of 200 MVA IBR at bus 7



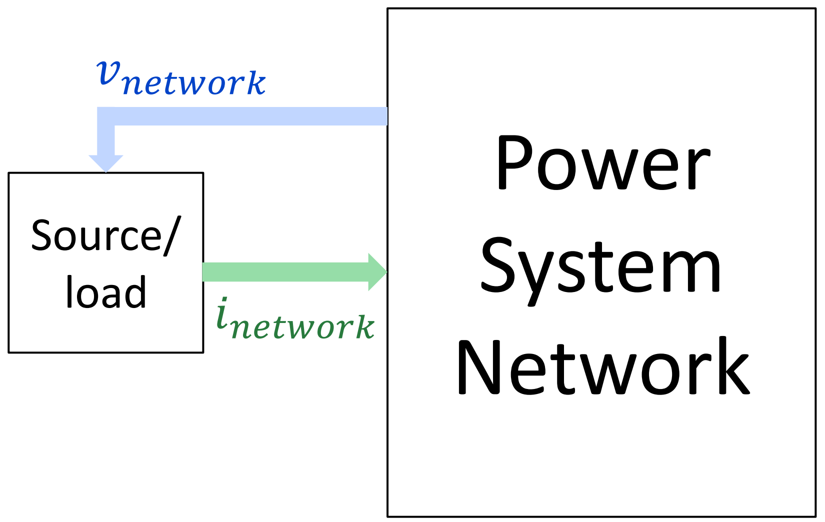


- Going towards less than 1s voltage control settling time results in improved stability.
- Further controller tuning can definitely improve damping.
- EPRI developed tools to identify eigen values for black box IBR models

Deepak Ramasubramanian, Wes Baker, Julia Matevosyan, Siddharth Pant, and Sebastian Achilles, "Asking for Fast Terminal Voltage Control in Grid Following Plants Could Provide Benefits of Grid Forming Behavior," *IET Generation, Transmission & Distribution,* early access [Link]

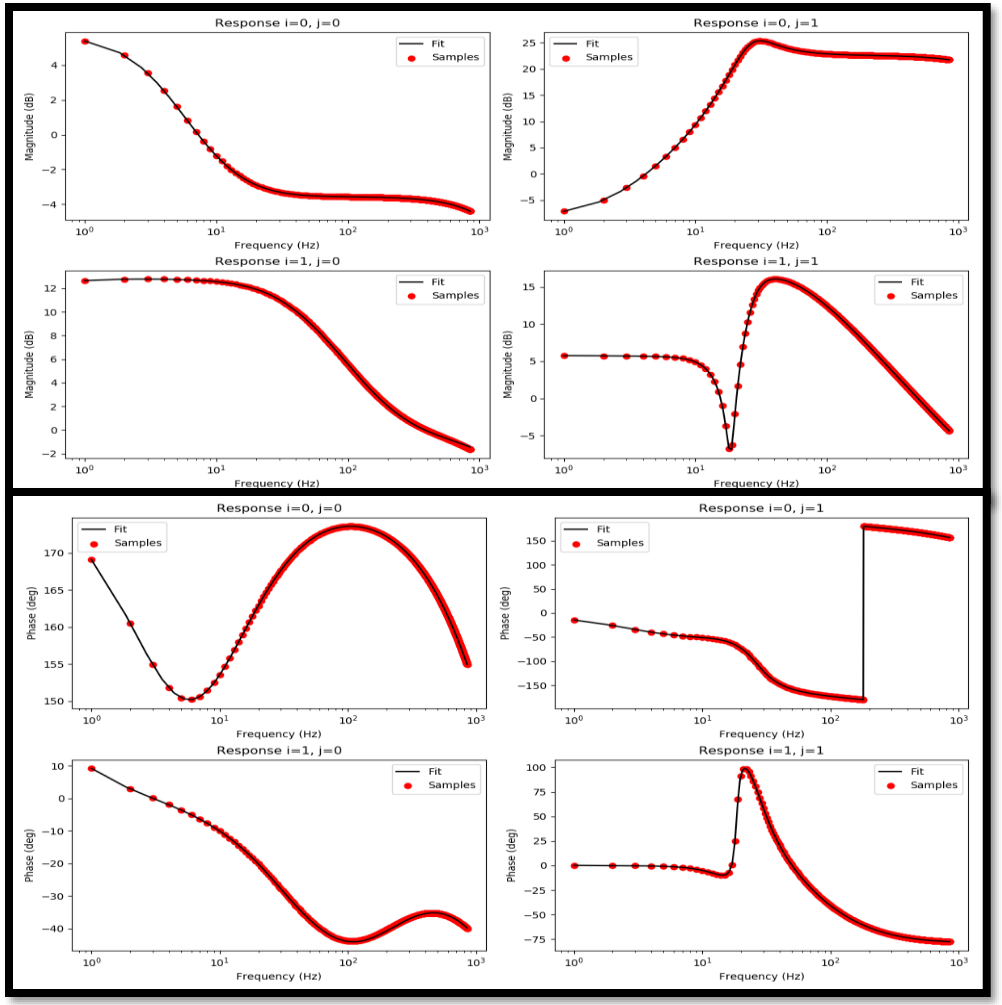
How can transmission planners use this approach?

- Small signal stability of a network depends on:
  - Power flow operating point
  - Dynamic behavior of individual elements at this operating point
  - System that connects the various elements together
- For large networks, it is efficient to adopt a modular structure
  - Each individual element is characterized as a 2 input – 2 output system
  - How to define the small signal dynamic behavior of each element?

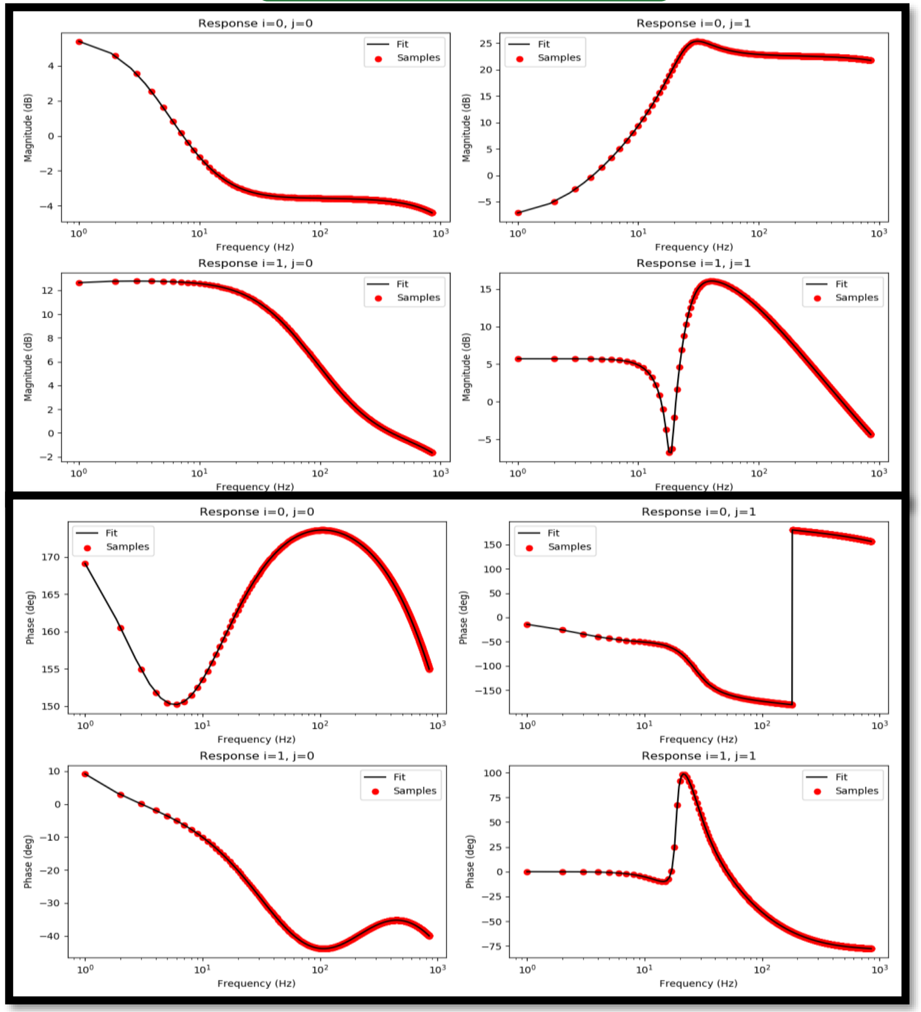


Vector fit of admittance scans from OEM

Fit with 7 states



Fit with 9 states



- State space representations are not unique
- Each transfer function can have infinite state space representations
  - Important to use minimal realization representation
- Admittance scans should be at appropriate operating point

Python: “Scikit-rf, An open-source Python package for RF and Microwave applications”, www.scikit-rf.org

Matlab: “Vector Fitting, A public domain Matlab routine”, https://www.sintef.no/projectweb/vectorfitting/

Small island power network with numerous IBRs

- Objectives
  - Can 100% IBR network be simulated in positive sequence domain?
  - Applicability of PLL based grid forming model to run a 100% IBR network
  - Compare response from synchronous condenser versus IBRs

- Three models used to set up grid forming IBR mode (using PSS®E terminology):
  - REGCCU Model
  - REECAU1 Model
    - Voltage control mode enabled
  - REPCAU1 Model
    - Voltage control mode enabled
    - Frequency control mode enabled

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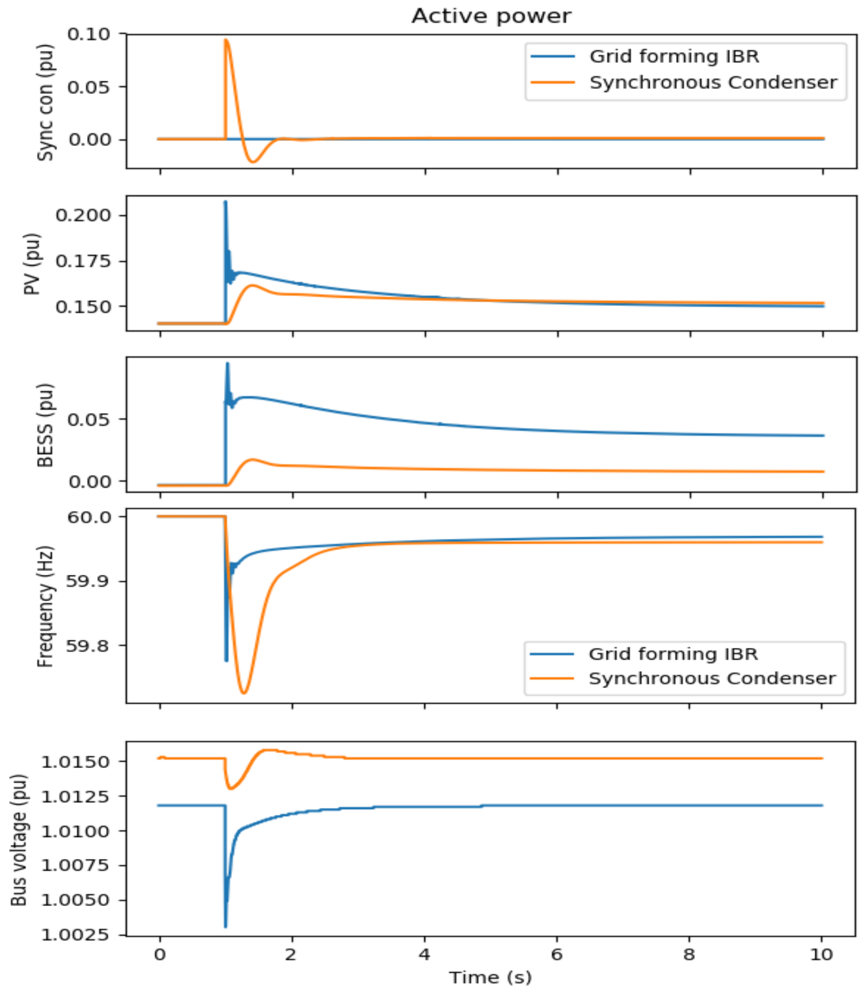
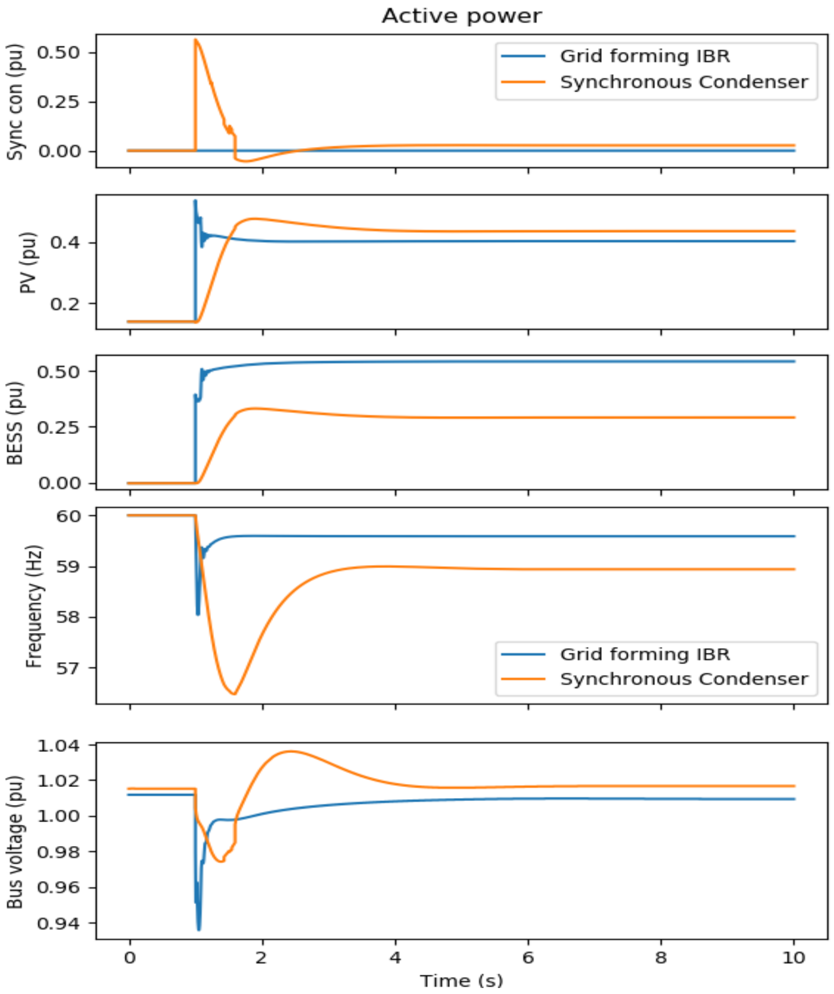
Generation trip scenarios to compare results

Routine generation trip



Extreme generation trip



- With synchronous condenser, PV and BESS operate in grid following mode
- Without condenser, they operate in grid forming mode
- IBR performance is superior compared to condenser
- Positive sequence results are numerically robust

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Summary

- Q control at inverter level is primary cause of instability in weak grids
  - Moving to V control can improve stability and even bring about grid forming behavior
- Preliminary version of generic positive sequence grid forming model developed to represent four types of grid forming control
- Model extensively tested and benchmarked across software domains and also against OEM black box EMT model
- Positive sequence grid forming models could be used to conduct planning studies and ascertain location, ratio and percentage of grid forming needed in a future system.

U.S. DEPARTMENT OF ENERGY

unifi is co-led by NREL, University of Washington, and EPRI

unifi consortium

universal interoperability for grid-forming inverters

Bringing the industry together to unify the integration and operation of inverter-based resources and synchronous machines

EPRI

Project Team

National Labs and Research Institutes

NREL Transforming ENERGY

EPRI

Sandia National Laboratories

PNNL

Berkeley Lab

Universities

NC STATE UNIVERSITY

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Hawaiian Electric

PG&E

Xcel ENERGY

MISO

Southern Company

New York Power Authority

ComEd

PGE

CAISO

PACIFICORP

ISO new england

unifi consortium

Examples of possible UNIFI Working Groups (WG)

will be determined as Area leads get organized

- UNIFI Specifications
  - Interoperability and Functional Requirements WG (defines interoperability, maintains rules, manages Core IP)
- Modeling and Simulation Area
  - Theoretical Innovations WG
  - GFM Model Interoperability WG
  - Use Case and Software Testbed WG
- Controls Area
  - Real-Time Control WG
  - System Level Stability WG
  - Cybersecure Controls WG
- Hardware Area
  - Open-source Code Development WG
  - Experiment Planning & Design WG
- Integration and Validation Area
  - Validation of UNIFI Specifications WG
  - 1MW Multi-vendor Experiment WG
- 20MW Demonstration Area
  - 20MW Demo Specifications WG
- Standards Area
  - Standards Coordination WG
- Education Area
  - K-12 Education WG
  - College Level Education WG
- Workforce Development Area
  - Seminar Series WG
  - Tutorials WG

Additional Industry Partners

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Consortia

Vendors

Software

System Operators

- Participation confirmed through Letters of Support
- Representative of potential (fee-paying) members, facility users, sponsors of directed R&D in later years

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