Positive sequence modeling of grid forming (GFM) inverters and 100% inverter systems

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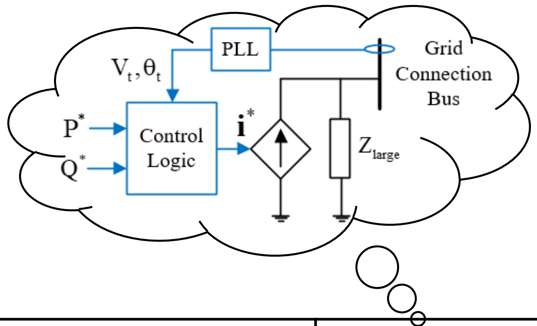
Few basics about various inverter mathematical models

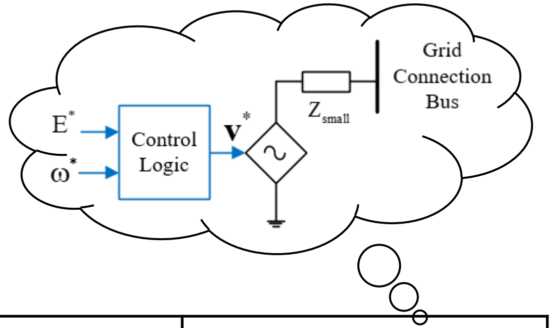
Generic model	Does not always imply	Bad model
User defined model from manufacturer	Does not always imply	Good model
RMS/Positive sequence model	Does not always imply	Bad model
Electromagnetic transient (EMT) model	Does not always imply	Good model

- 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

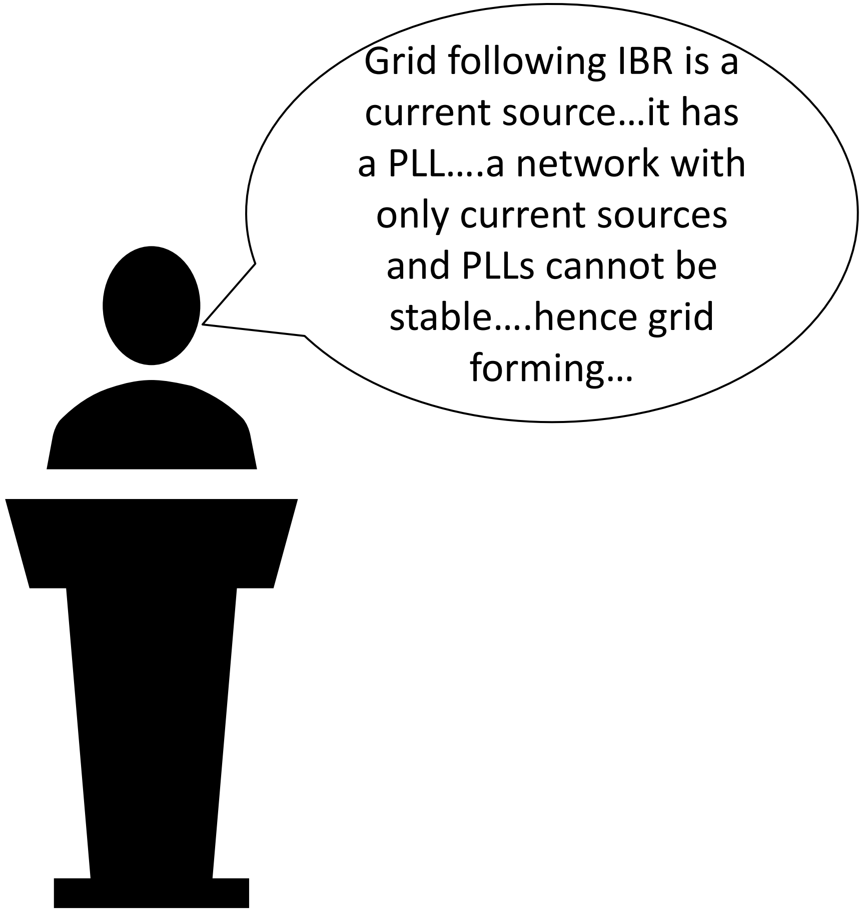
High level definition usually based on specific control design



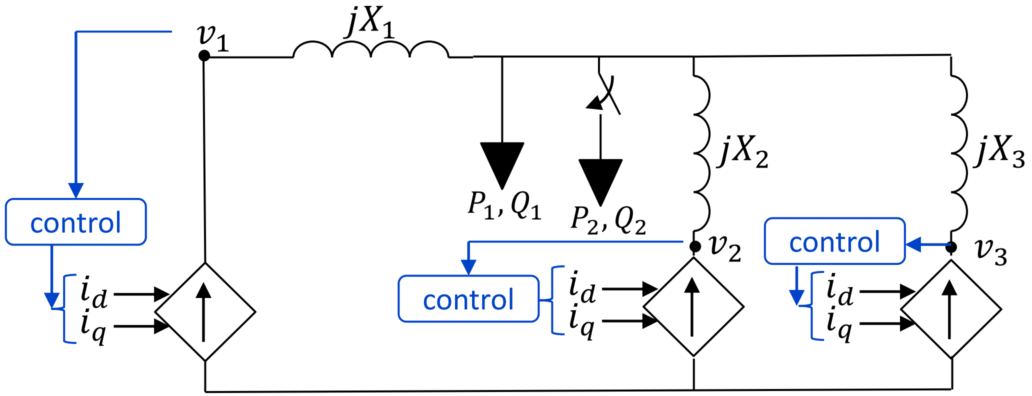


	Grid-following inverter	Grid-forming inverter
Basic control objectives	Deliver a specified amount of power to an energized grid	Set up grid voltage and frequency
Output quantity controlled	ac current magnitude and phase angle	ac voltage magnitude and frequency
Require a stiff and stable voltage at the 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

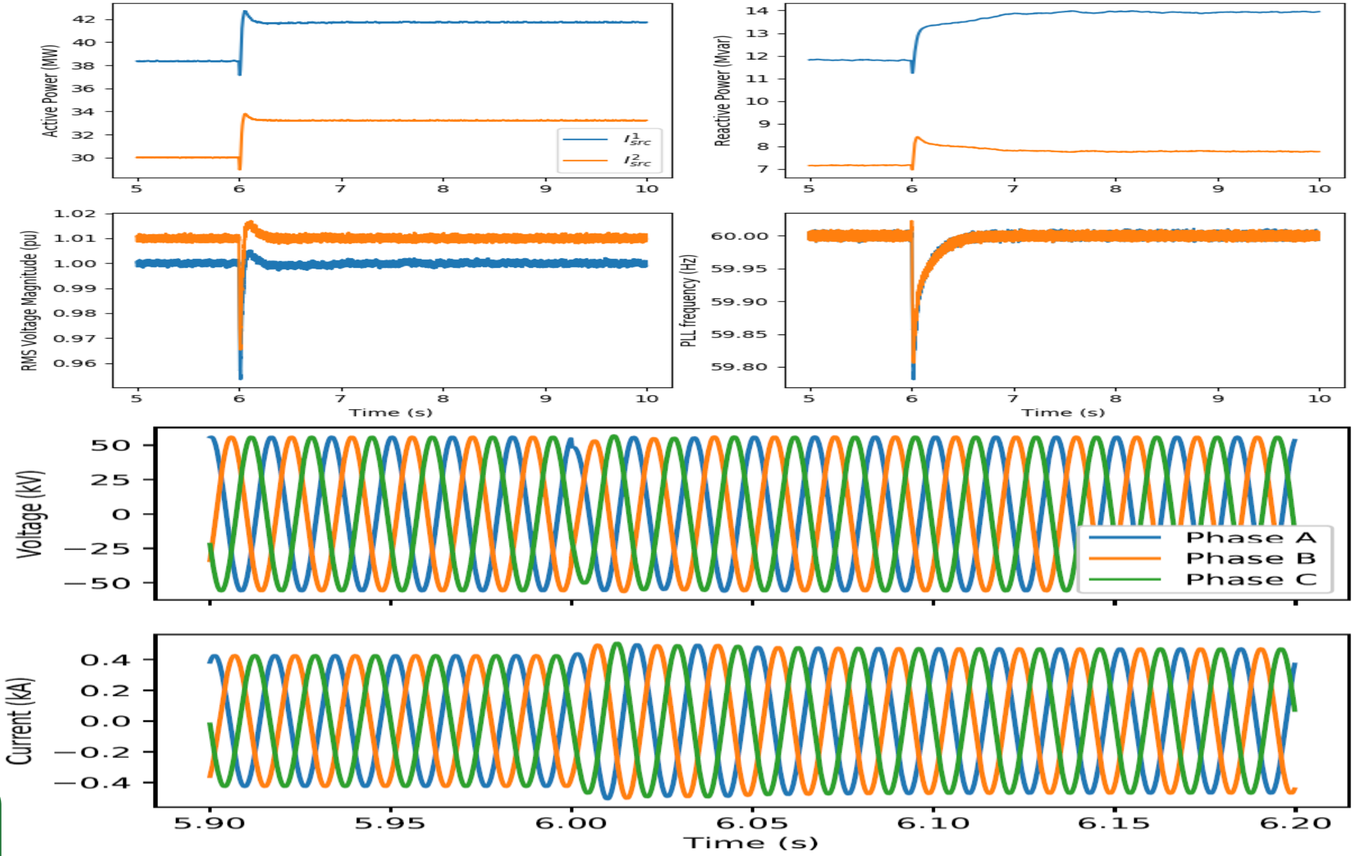


» Voltage levels in network decided by current and impedance

» 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

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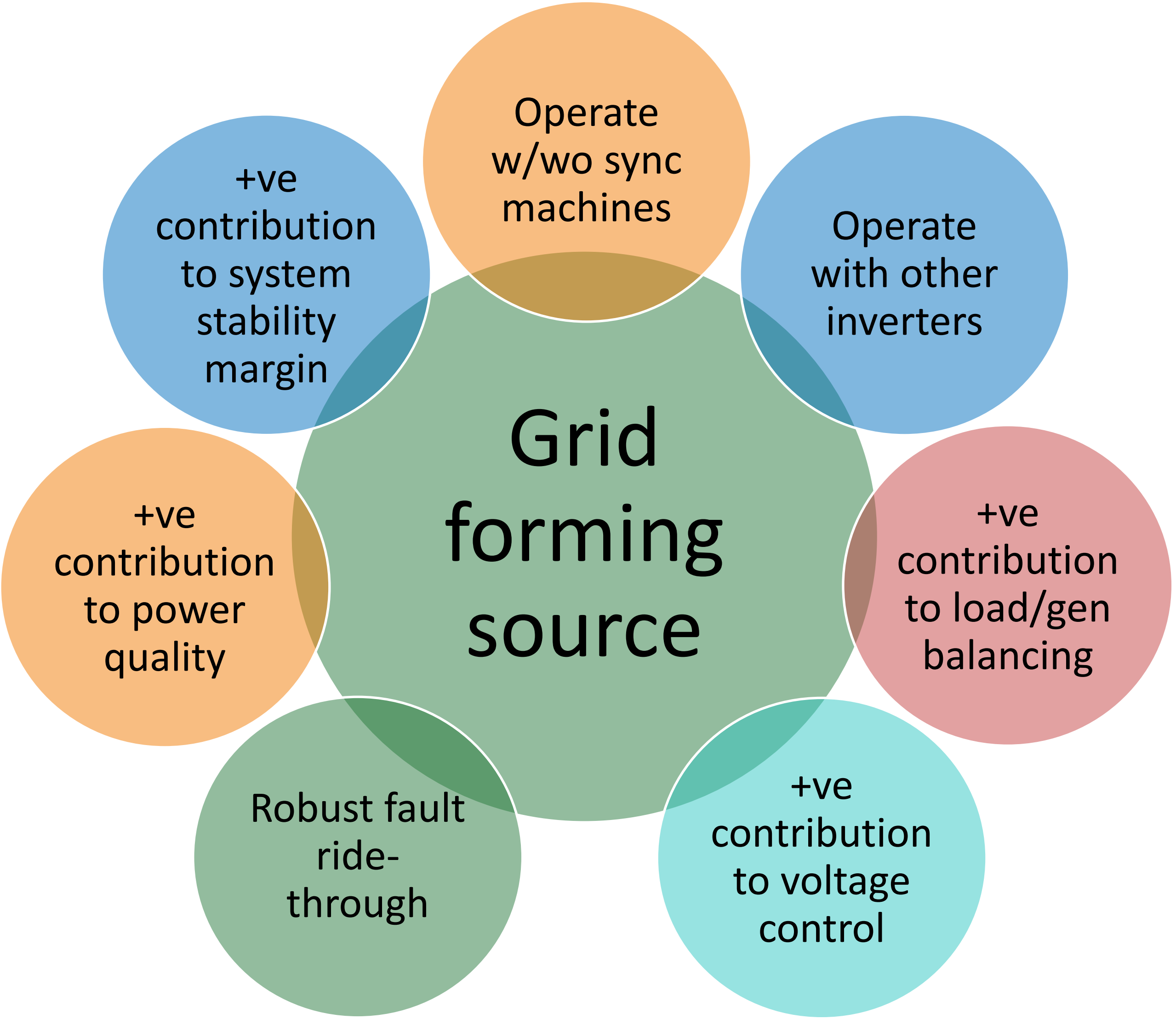
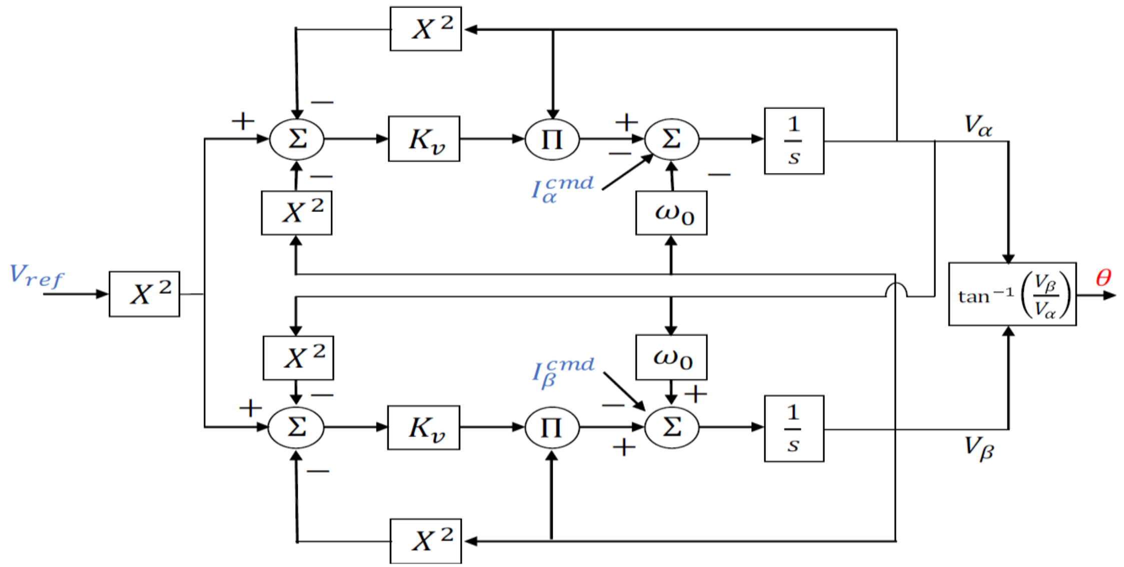
Performance requirement for grid forming source

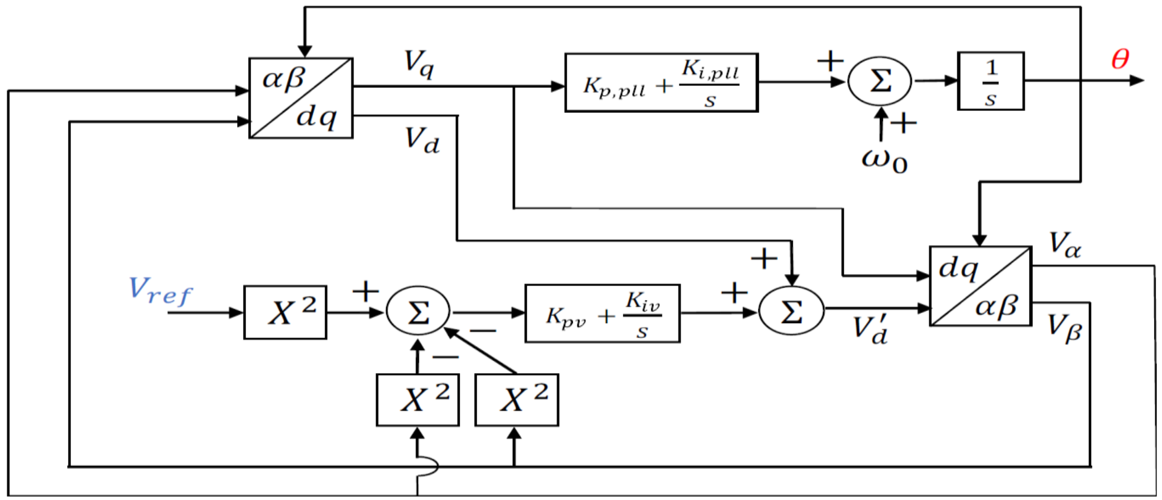


Presentations from Julia and Tim provide more details on service/performance-based outlook on GFM behavior

- 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

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





Virtual Oscillator

PLL – Voltage controlled oscillator

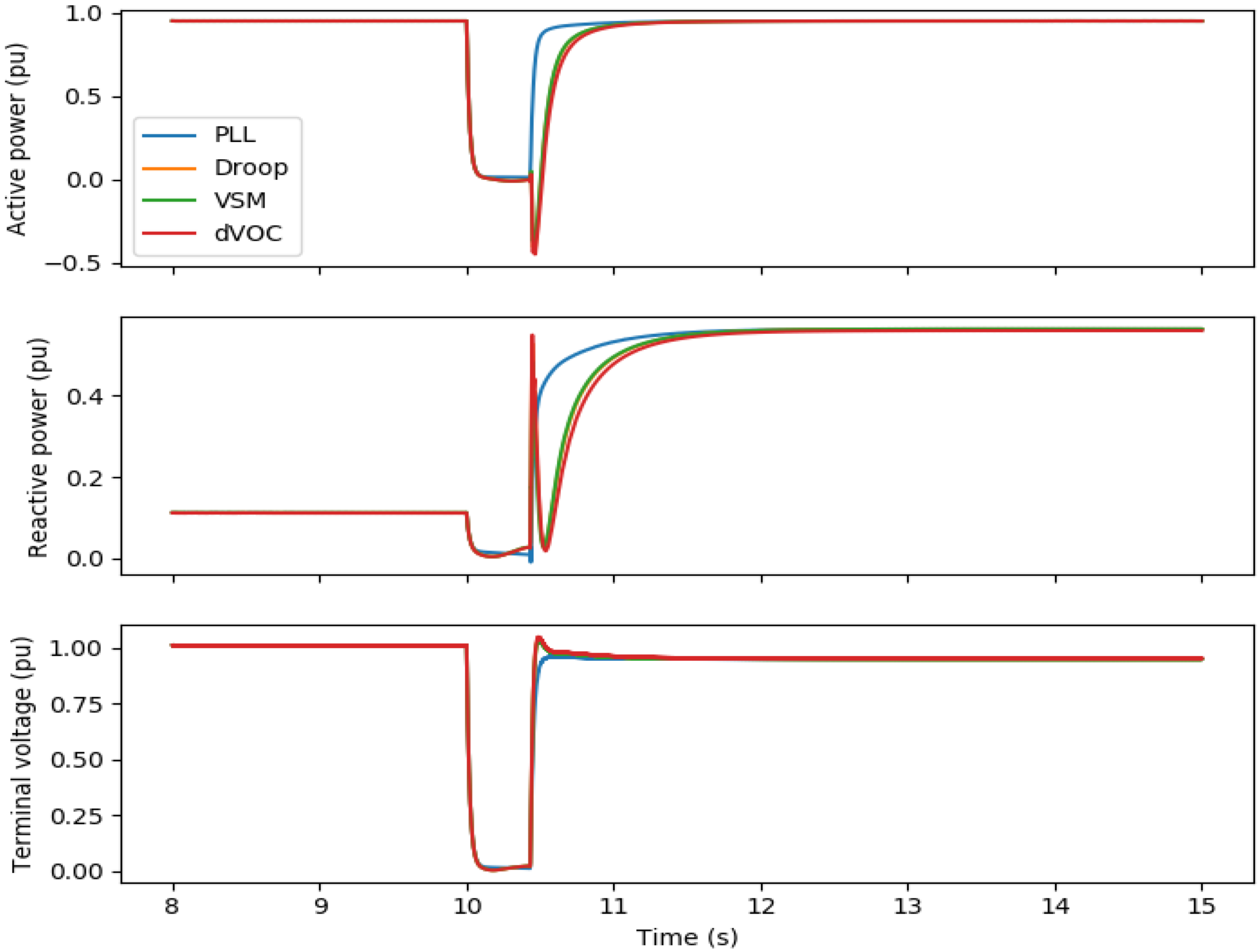
- » A virtual oscillator uses internal state variable feedback to generate a sine wave
- » A PLL with an additional voltage control loop uses external output variable feedback to generate a sine wave

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 GFM response in EMT domain for low short circuit conditions

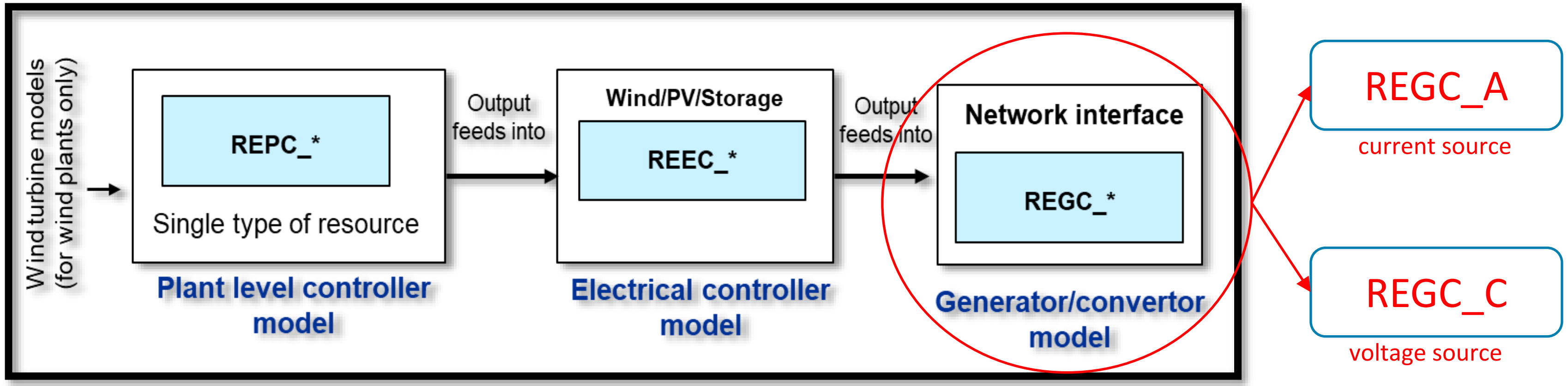
» Based on test specification in AEMO's Dynamic Model Acceptance Test Guideline (link)
  - Pre-fault SCR = 3.0
  - Post-fault SCR = 1.0
  - X/R ratio = 14
  - 3PHG fault at POI, Zf = 0.0, duration 0.43s

» Model controls not optimally tuned



How does this link to positive sequence models?

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

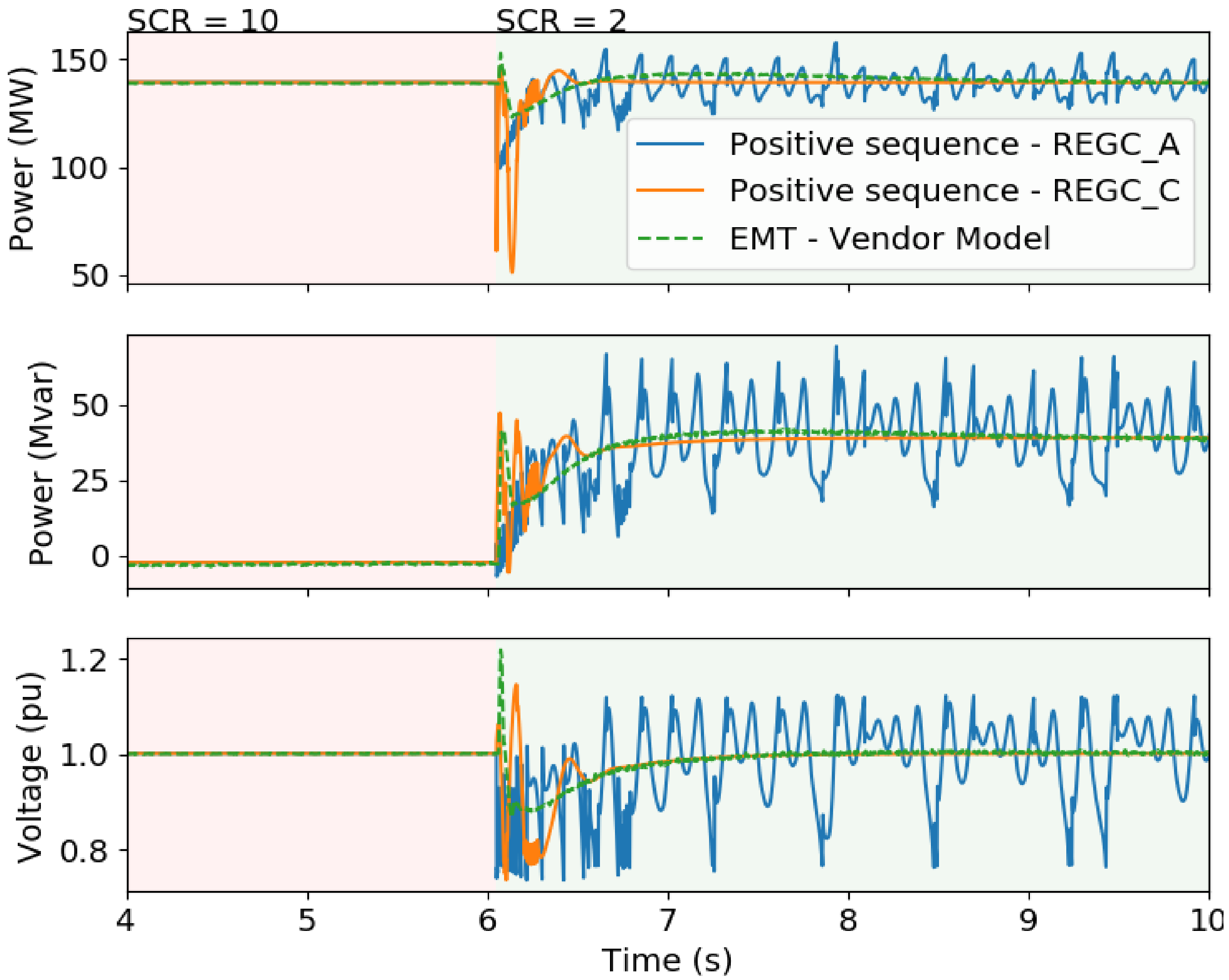


Generic models are vendor-agnostic models that do not necessarily represent the exact control algorithm of any particular IBR vendor. When appropriately parameterized, these models can subsequently provide the trend of dynamic behavior expected from IBR plants.

Model User Guide for Generic Renewable Energy System Models. EPRI, Palo Alto, CA: 2018. Product ID: 3002014083

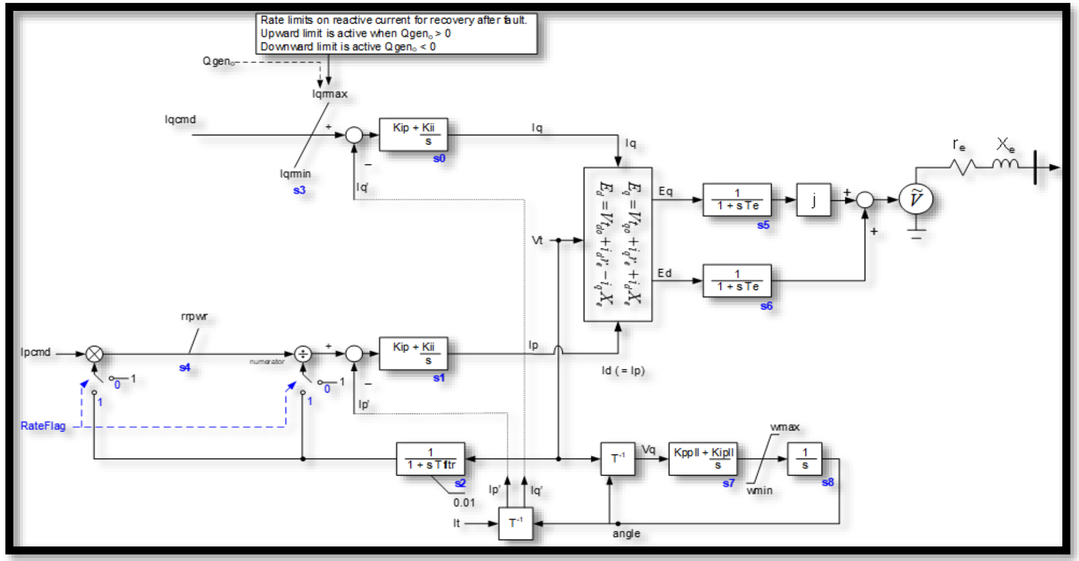
Existing REGC_A generic model

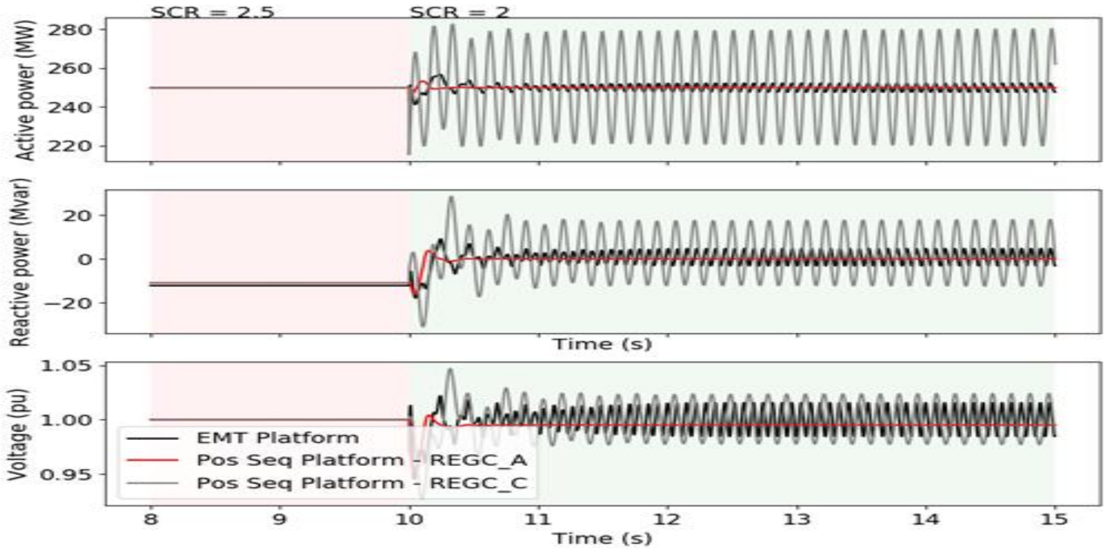
- Model represents a current source behavior
- In low short circuit scenarios, a current source model can encounter numerical robustness obstacles
- To overcome this obstacle and to get more granular representation of IBR dynamics:
  - REGC_B and REGC_C models developed

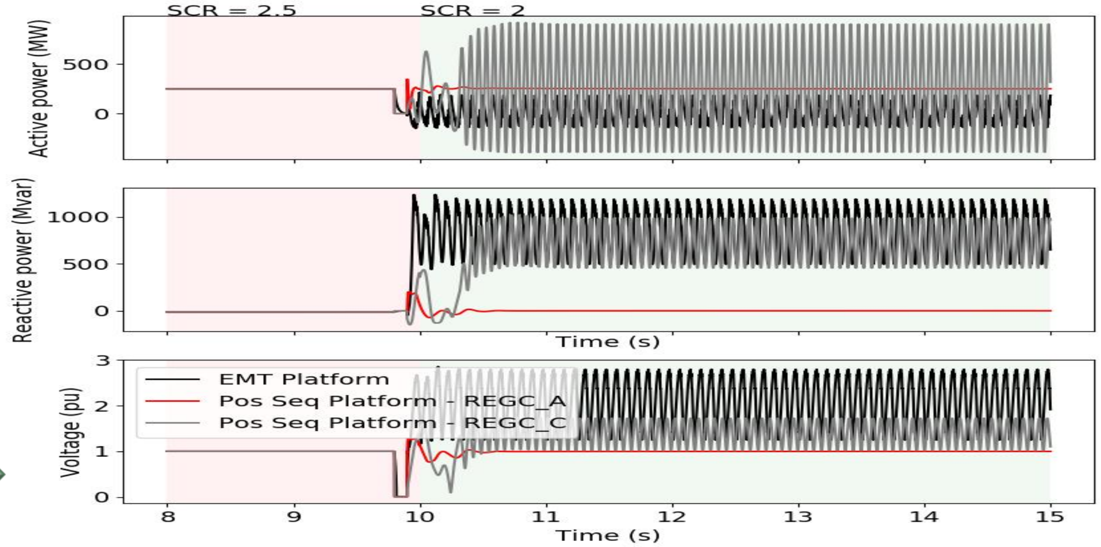


Deepak Ramasubramanian, Wenzong Wang, Pouyan Pourbeik, Evangelos Farantatos, Anish Gaikwad, Sachin Soni, and Vladimir Chadliev, “Positive Sequence Voltage Source Converter Mathematical Model for Use in Low Short Circuit Systems,” *IET Generation, Transmission & Distribution*, vol. 14, no. 1, pp. 87-97, Jan 2020

The REGC_C generic model





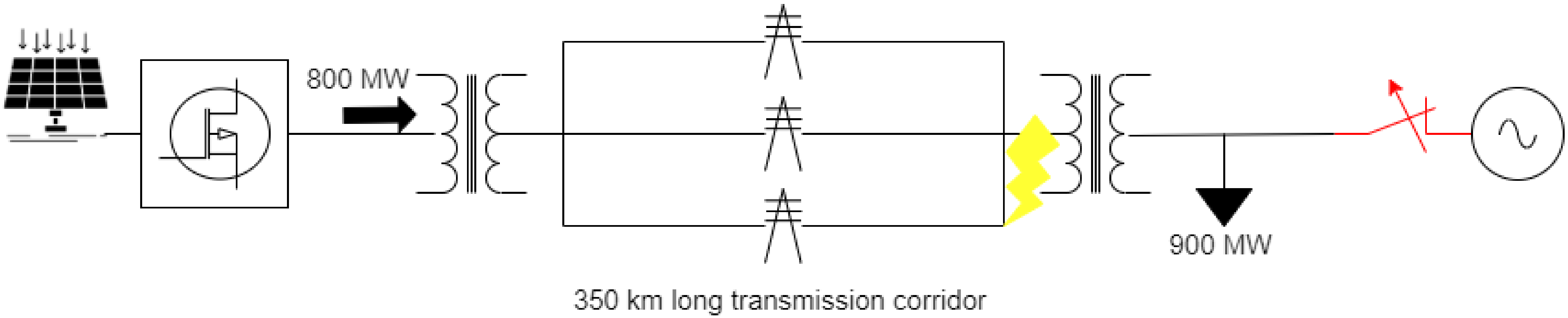


- Approximate representation of dynamic behavior of
  - inverter's inner current control loop.
  - Inverter's phase locked loop
- Current commands are translated into voltage reference commands behind an impedance

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

Deepak Ramasubramanian, Xiaoyu Wang, Sachin Goyal, Manjula Dewadasa, Yin Li, Robert J. O'Keefe, and Peter F. Mayer, "Parameterization of Generic Positive Sequence Models to Represent Behavior of Inverter Based Resources in Low Short Circuit Scenarios," *2022 Power Systems Computation Conference (PSCC)*, Porto, 2022, pp. 1-8 *[under review]*

Use of positive sequence REGC_C model to represent grid forming behavior



» Voltage at PV plant point of interconnection to be controlled

» Frequency control is implemented at device level

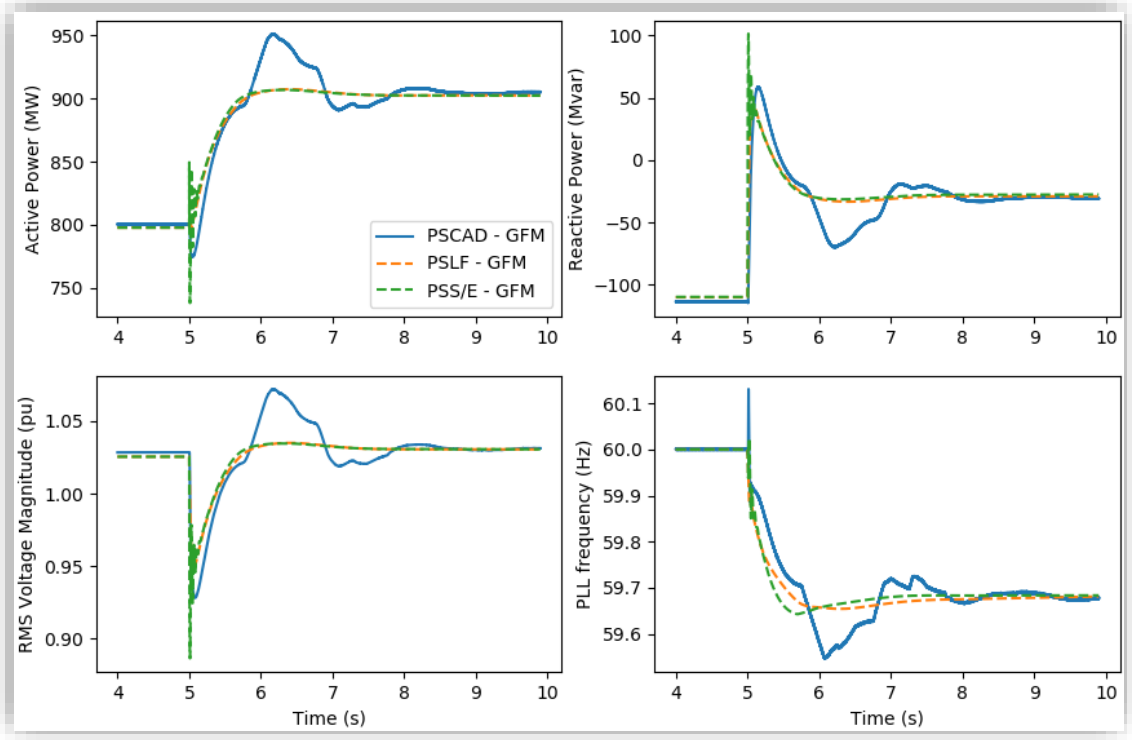
- 10pu/s ramp rate limit

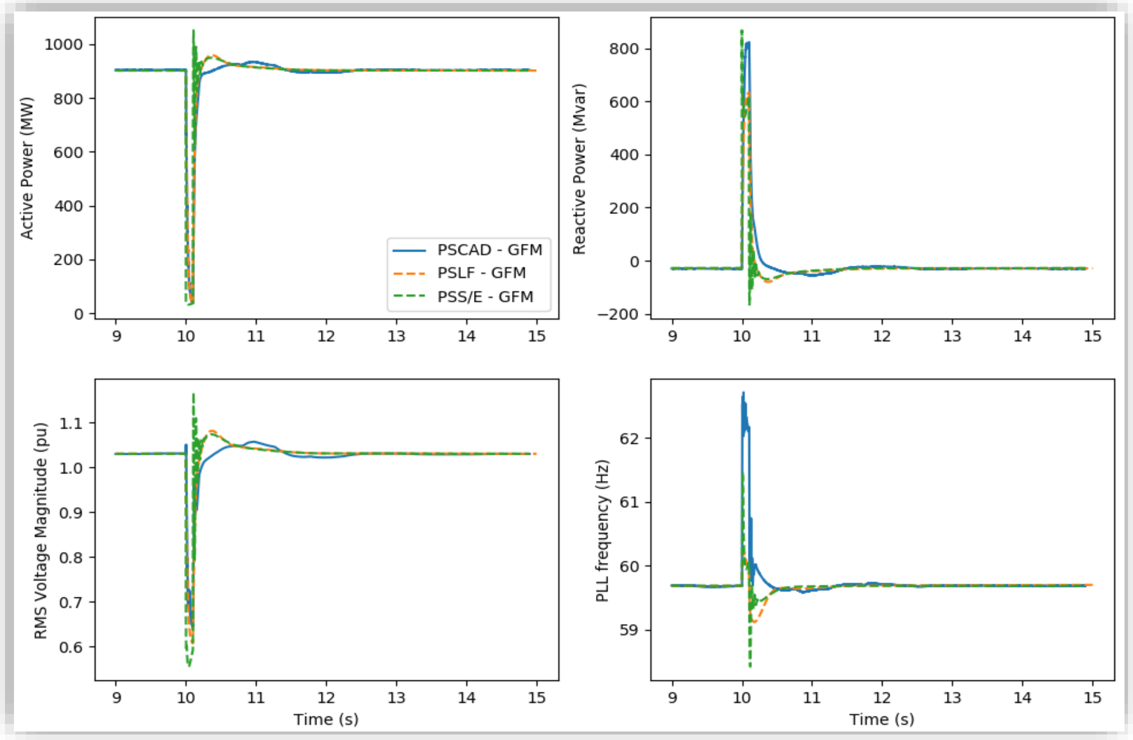
» Voltage control at inverter and plant level:

- 500ms sampling time – conservative
- 500ms dead time delay between plant and inverter

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

Use of REGC_C model to represent grid forming behavior



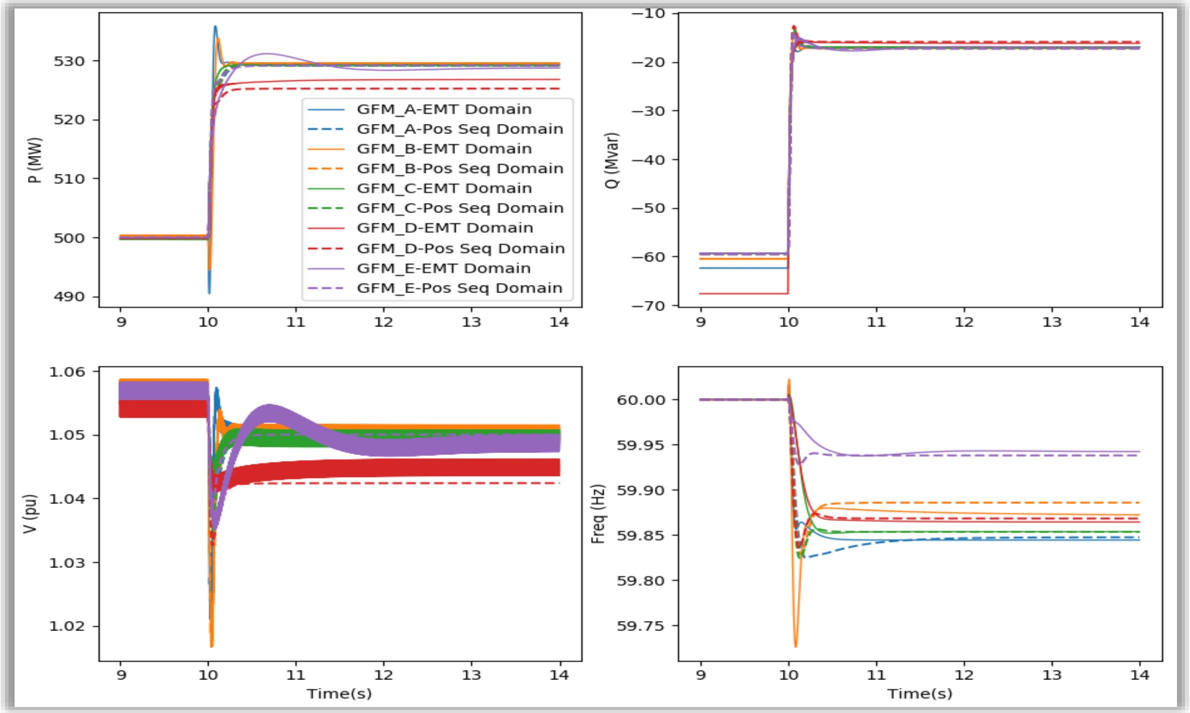


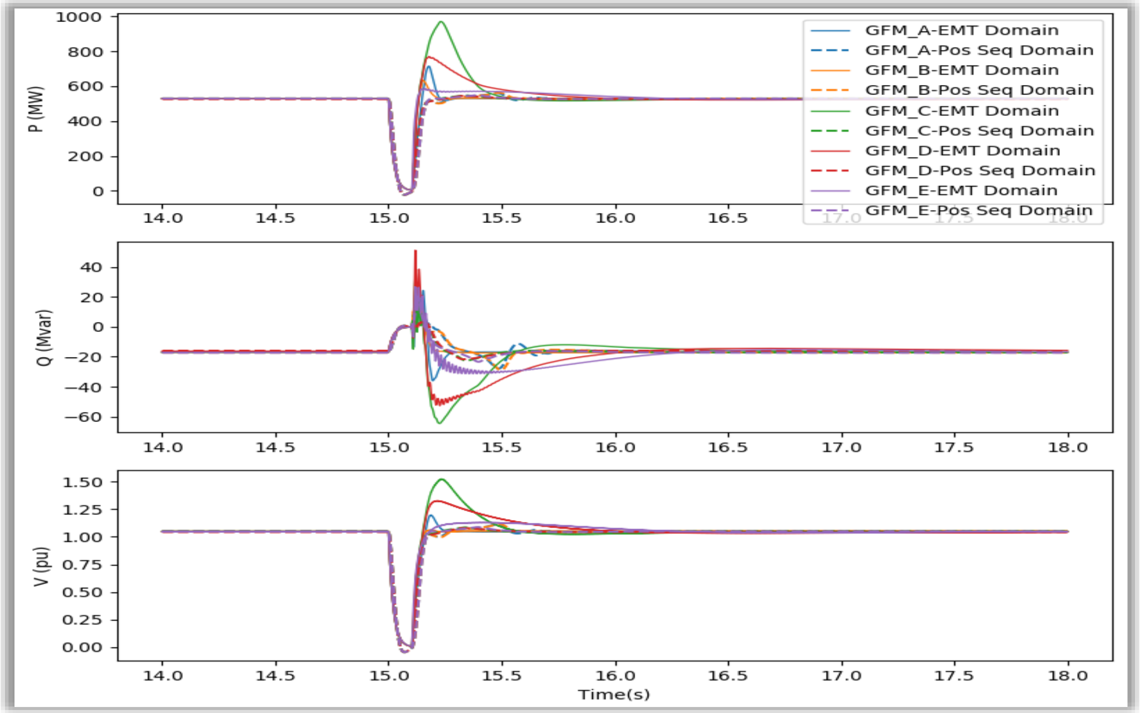
» Positive sequence response obtained using approved WECC generic models
  - REGC_C + REEC_D + REPC_A

» Models should be parameterized with diligence and thoroughness

EMT and Positive Sequence Domain Model of Grid Forming PV Plant (GFM-PV), EPRI, Palo Alto, CA, 2021, 3002021787 (link)

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

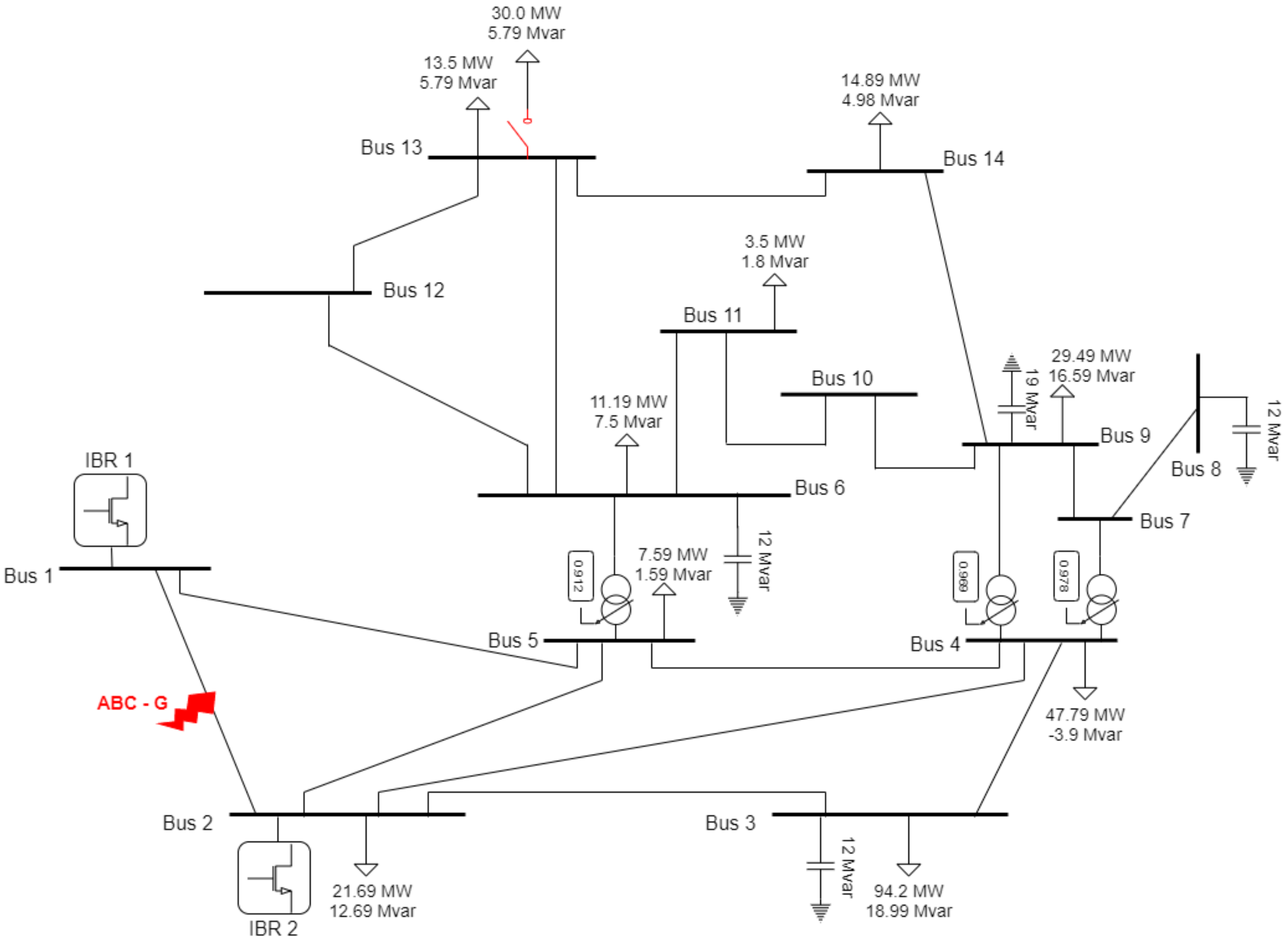
- Different GFM implementations, without additional tuning, can have different transient behavior
- Complete tuning of generic positive sequence model is yet to be completed
  - But results are encouraging!

Consider a larger network…

» Two IBR energy sources in one pocket of the network
  - Virtual oscillator control in EMT domain
  - WECC generic models in positive sequence domain

» Four shunt capacitors providing reactive power support

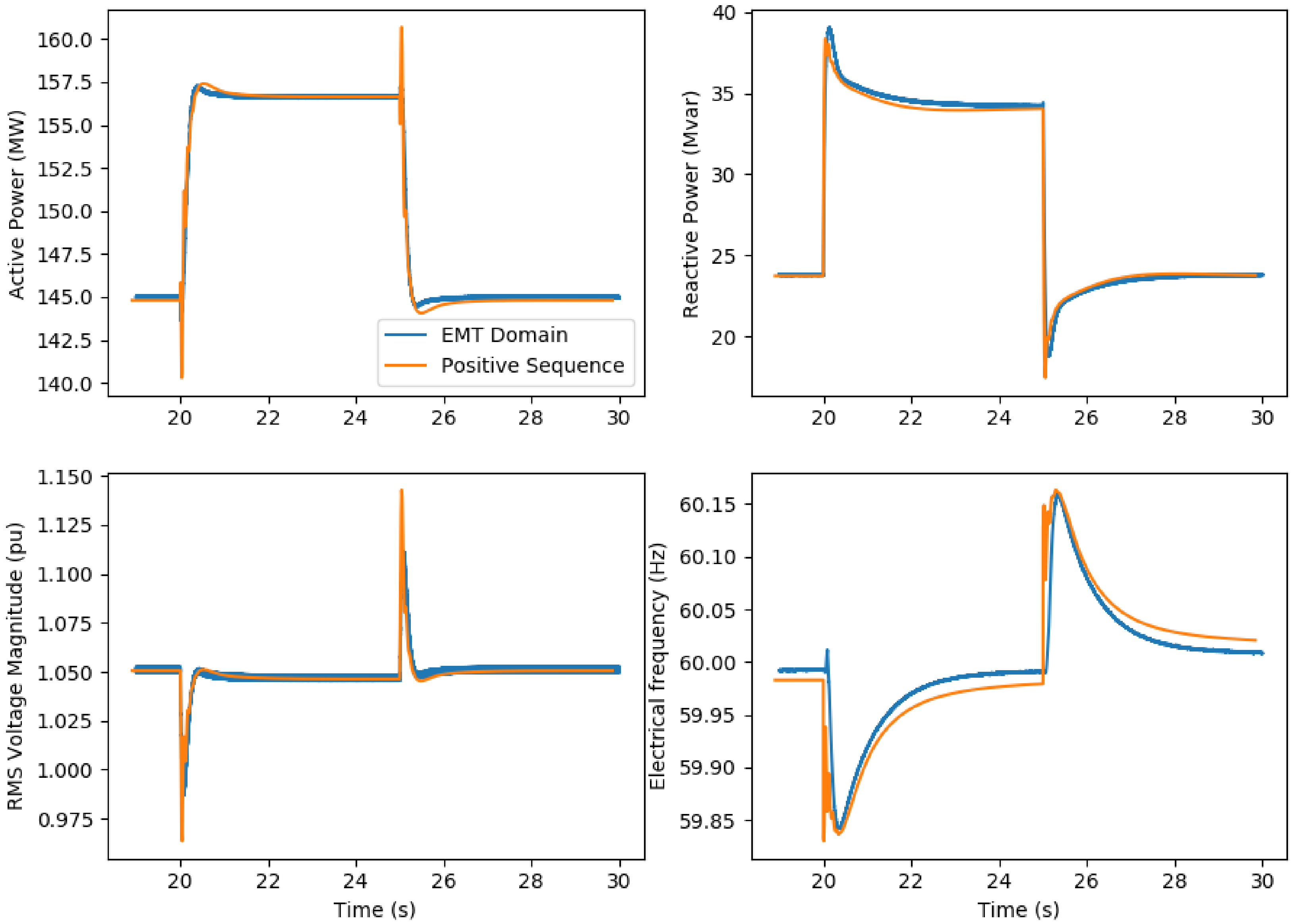
» Total load on the network approximately 250 MW



Load increase of 12% and subsequent decrease of 10%

» This flavor of virtual oscillator control can be represented by approved generic models

» Cannot stress enough the importance of parameterization



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

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

» Important to continue research efforts in this topic

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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

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Project Team is either receiving DOE funding and/or providing cost share

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