Modeling and Control of Grid Forming Inverters for Large System Studies

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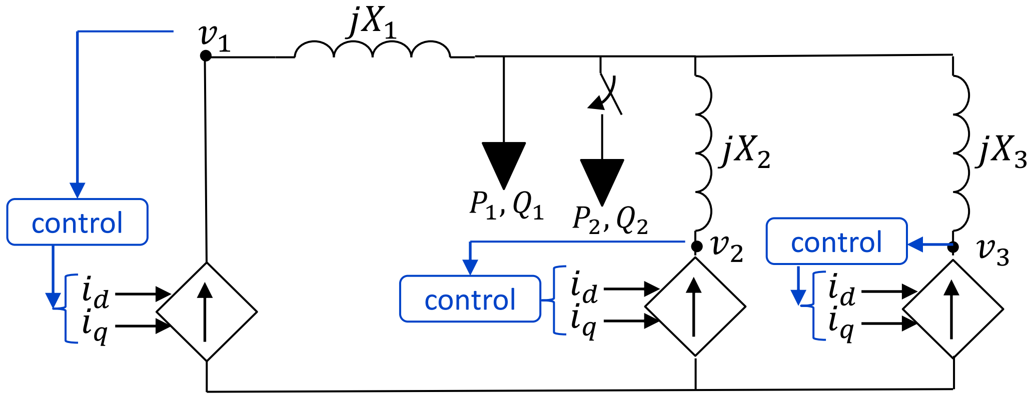
Few basics about various inverter mathematical models

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

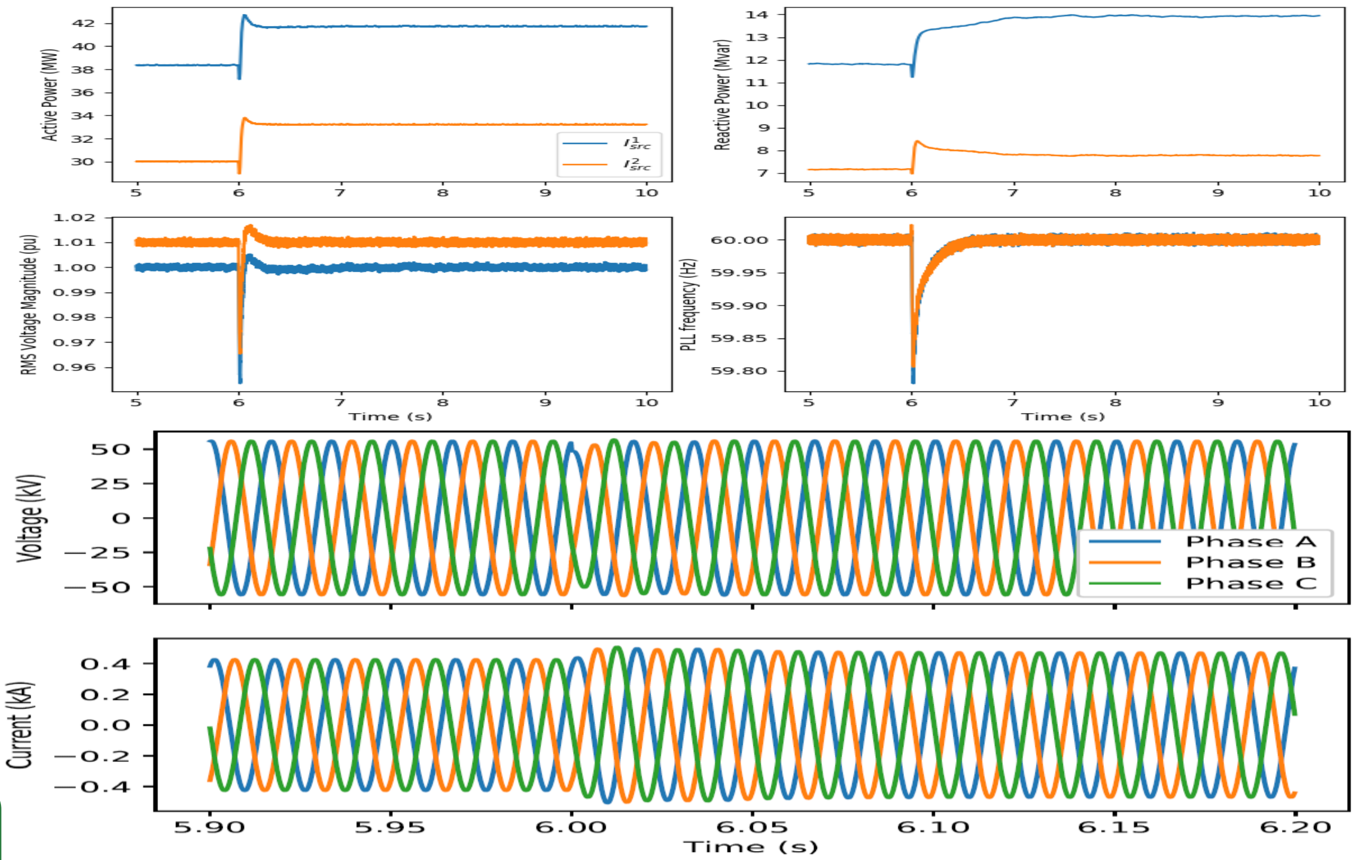
- All mathematical models have limitations
- When using mathematical models, few questions to be asked:
  - Is this the appropriate type of model for the study that is to be done?
  - Is the model being used in a correct manner?
  - Are all relevant components/control loops, that matter for the study, modeled?
  - Is the model appropriately parameterized?
  - Are sufficient validation results of model behavior available?

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

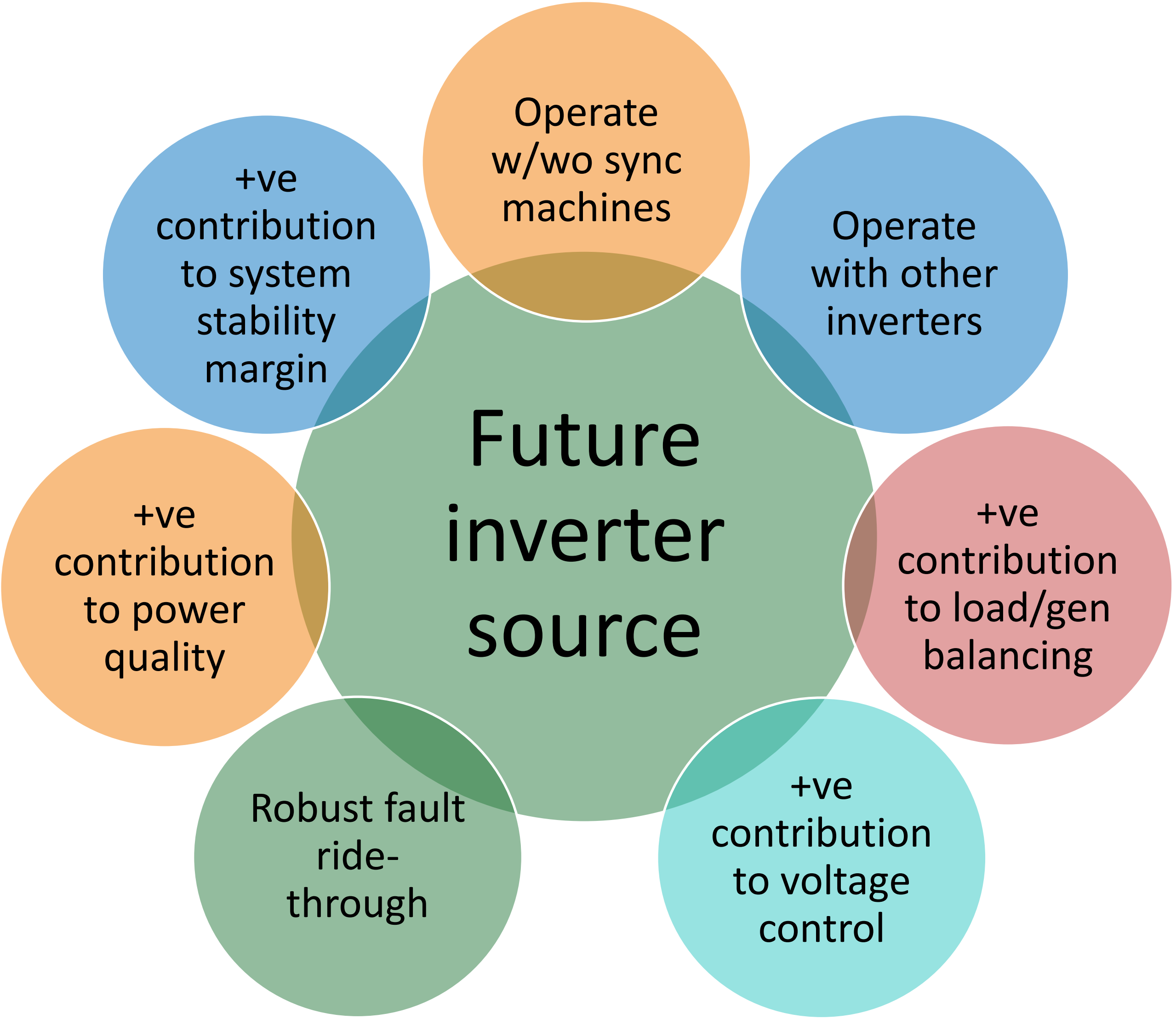
What does this have to do with grid forming behavior?

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

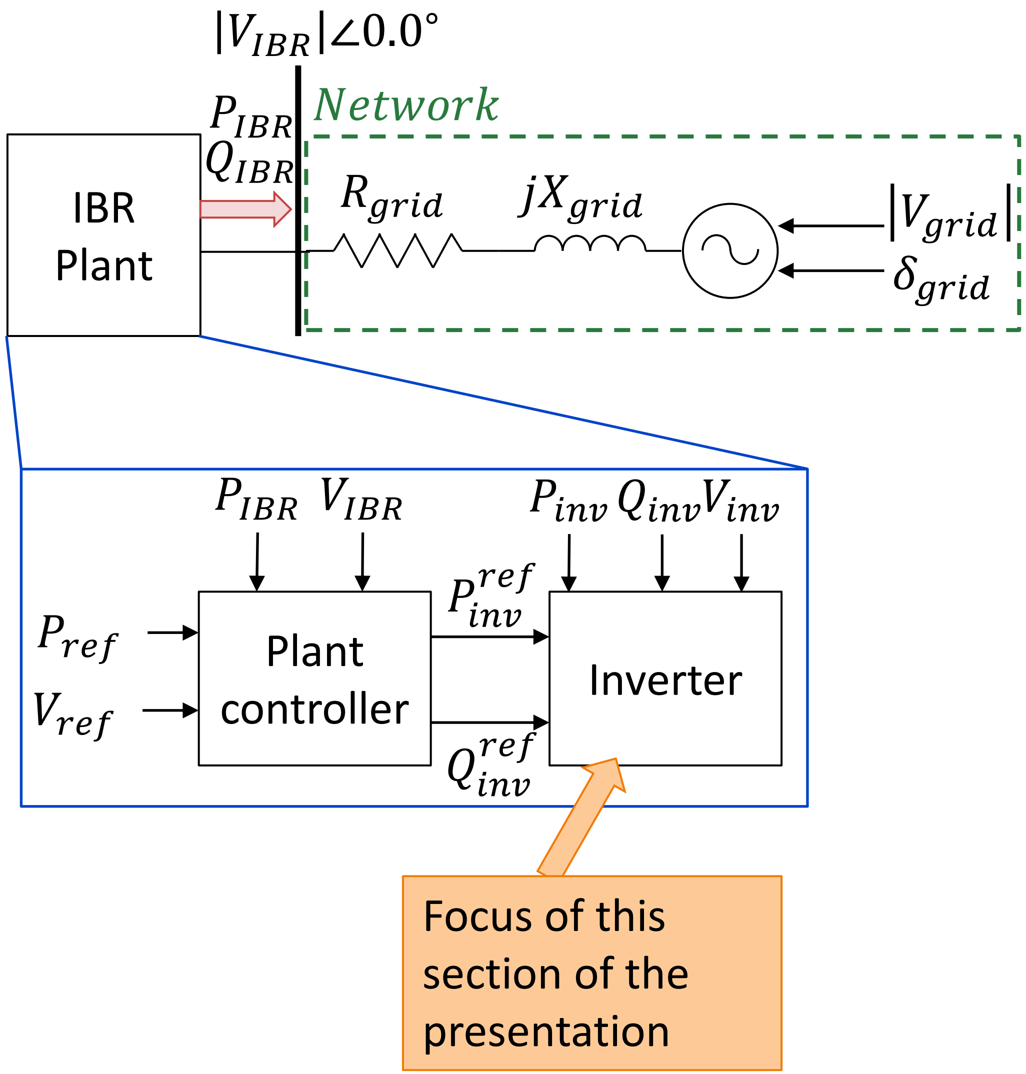
Performance requirement from a future inverter



- A future 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 inverter sources* can also be designated as blackstart resources

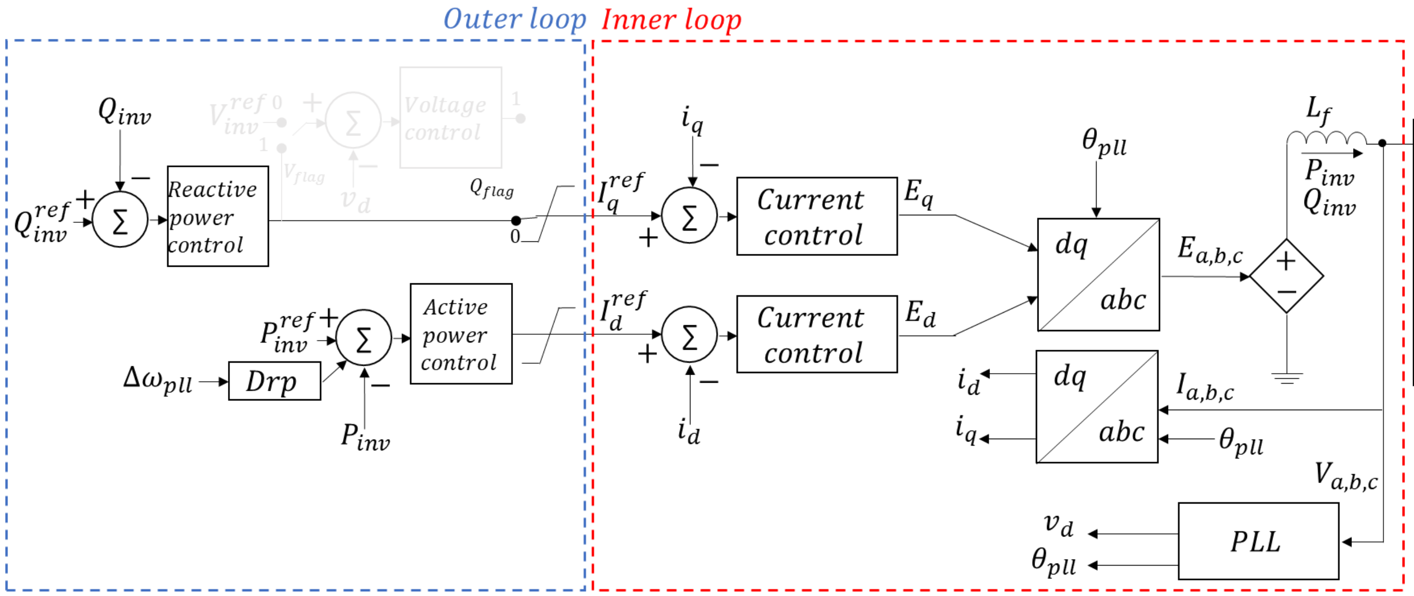
Can we obtain this behavior in a generic manner?

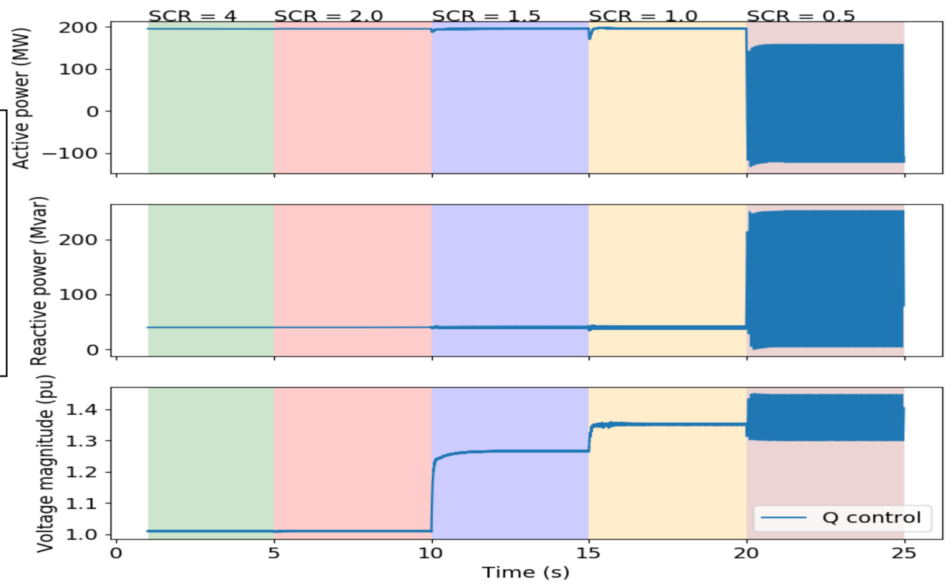
Single IBR connected to network equivalent

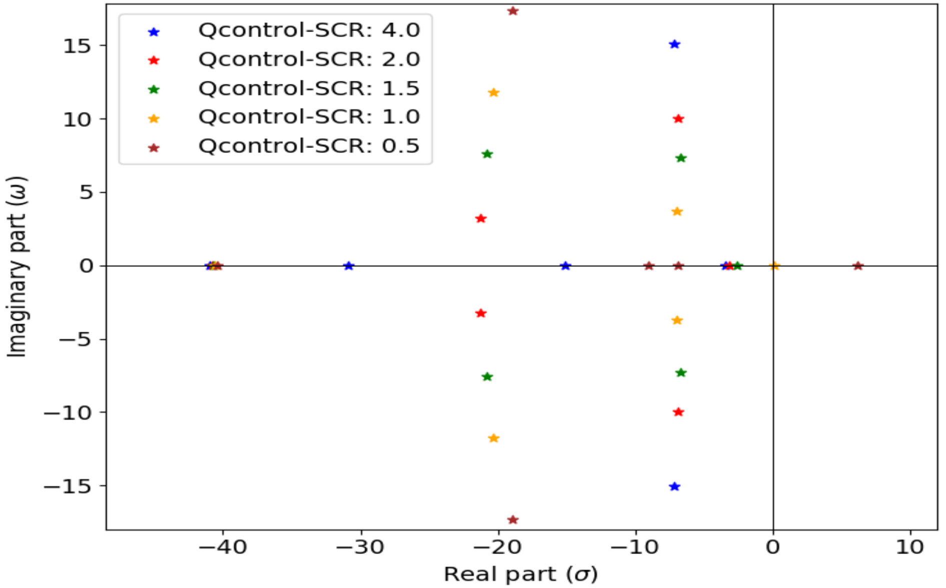


- With a fixed value of P_{IBR}, Q_{IBR} and $|V_{IBR}|$, and
- For a given value of SCR and X_{grid}/R_{grid}:
  - Evaluate values of X_{grid}, R_{grid}, $|V_{grid}|$, and δ_{grid}
- Conventional IBR plants have:
  - plant level active power and voltage magnitude control
  - inverter level active power and reactive power control

Fast inverter level reactive power level and SCR variation



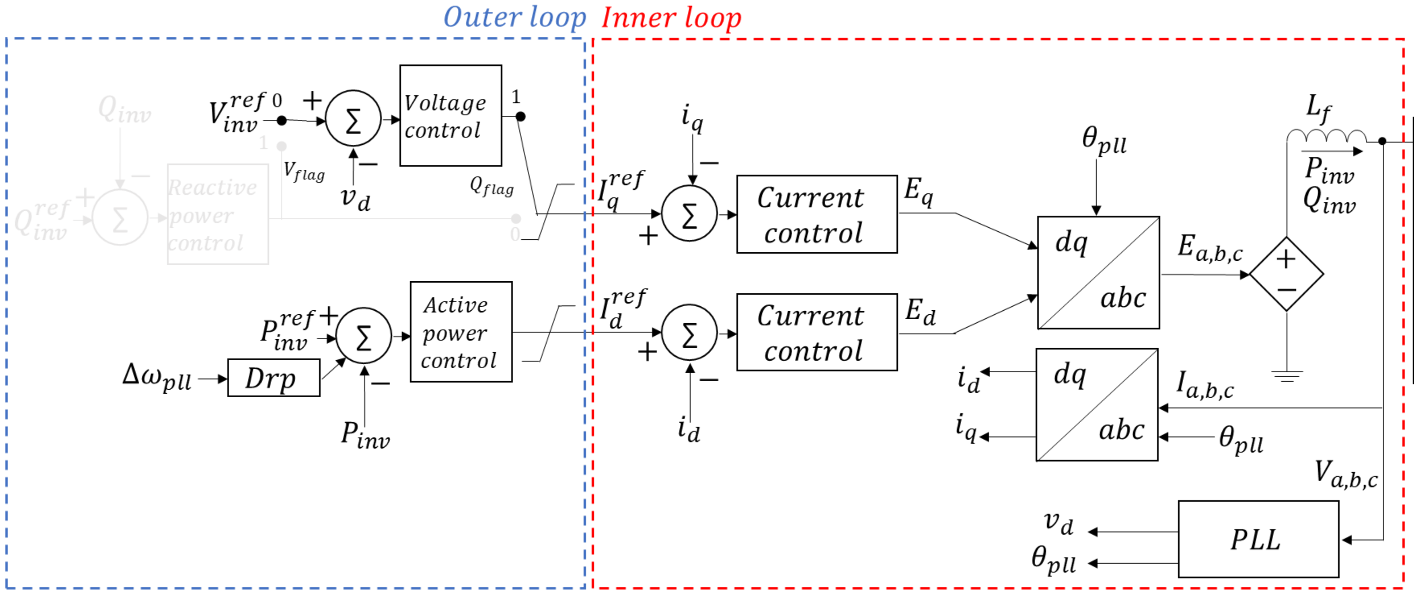




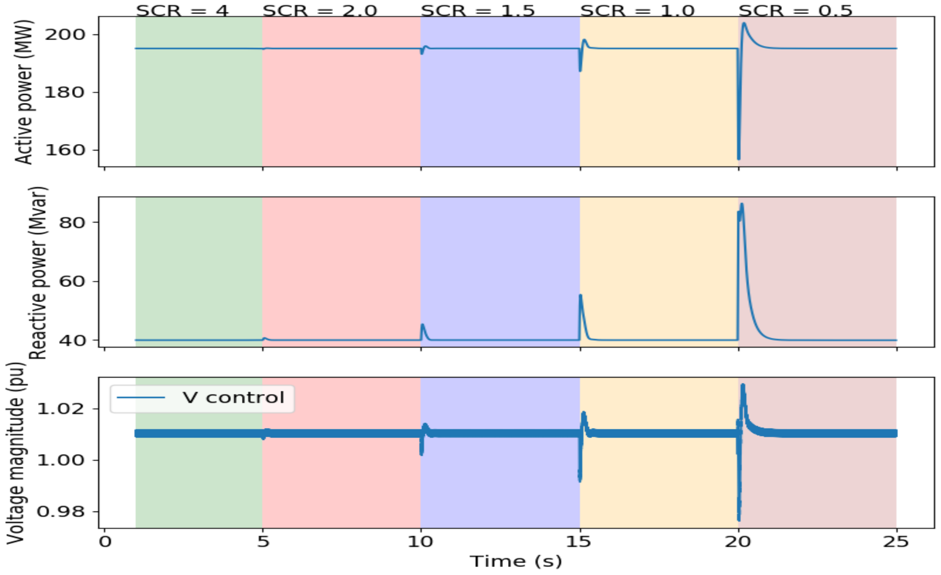
- Reduction in SCR below 2.0 results in instability
- However, PLL and inner current control loop are not the sole elements responsible for instability.

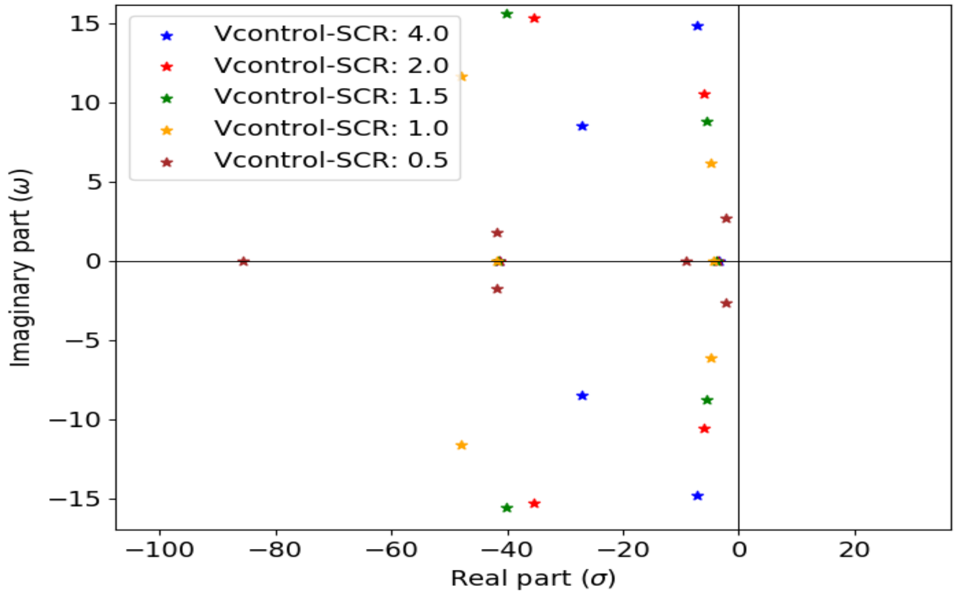
Deepak Ramasubramanian, Wes Baker, Julia Matevosyan, Siddharth Pant, and Sebastian Achilles, "Asking for Fast Terminal Voltage Control in Grid Following Plants Could Provide Benefits of Grid Forming Behavior," *IET Generation, Transmission & Distribution,* early access [Link]

Switching to inverter level voltage control

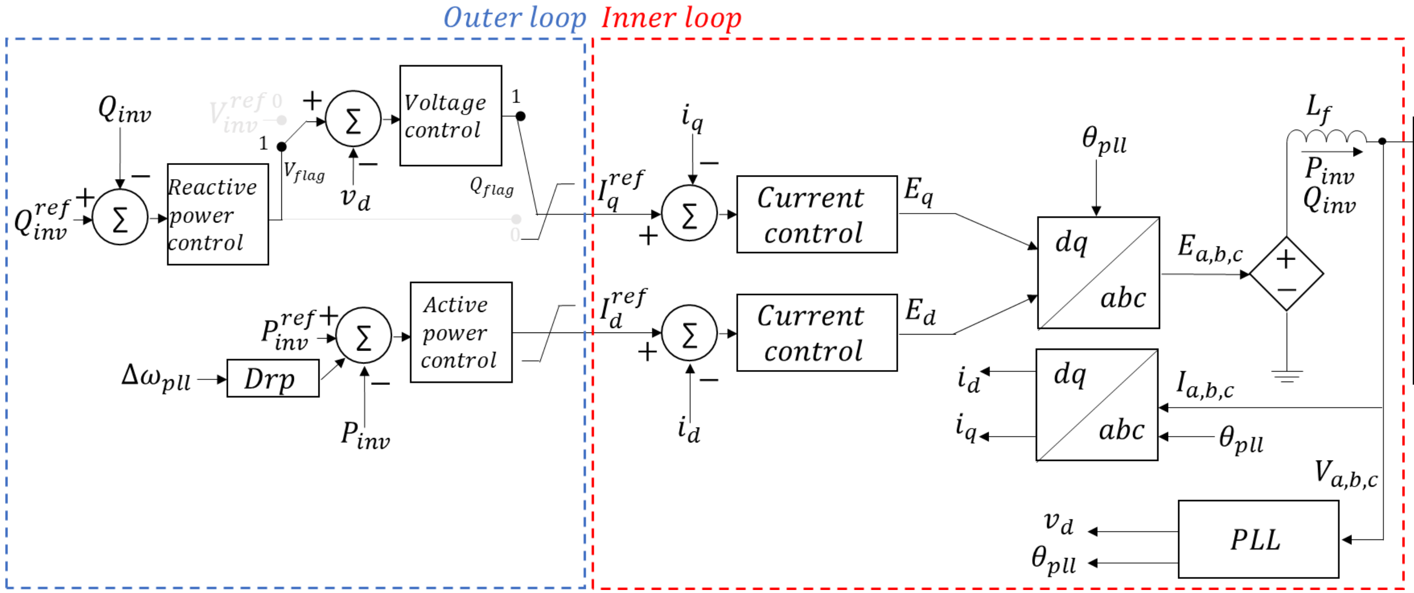


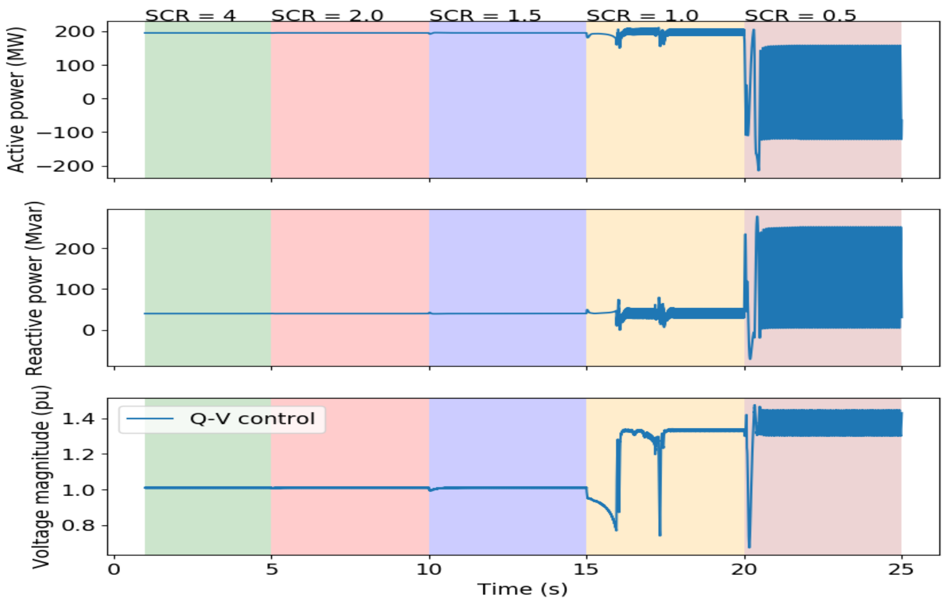
- Keeping the PLL and current controller gains the same, switch to inverter level voltage control.
- From a small signal sense, the control is now stable even for SCR of 0.5!

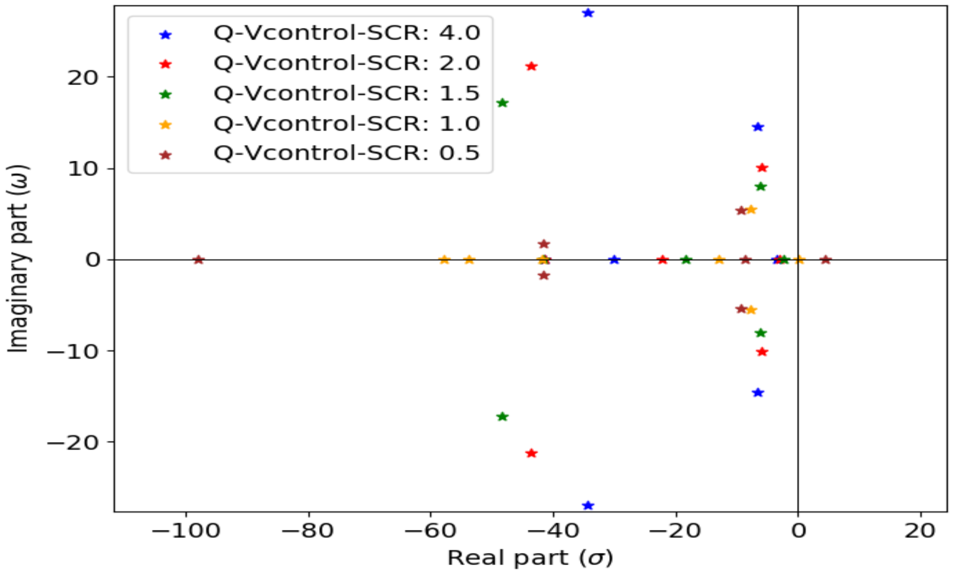




So, would inverter level coordinated Q-V control work?

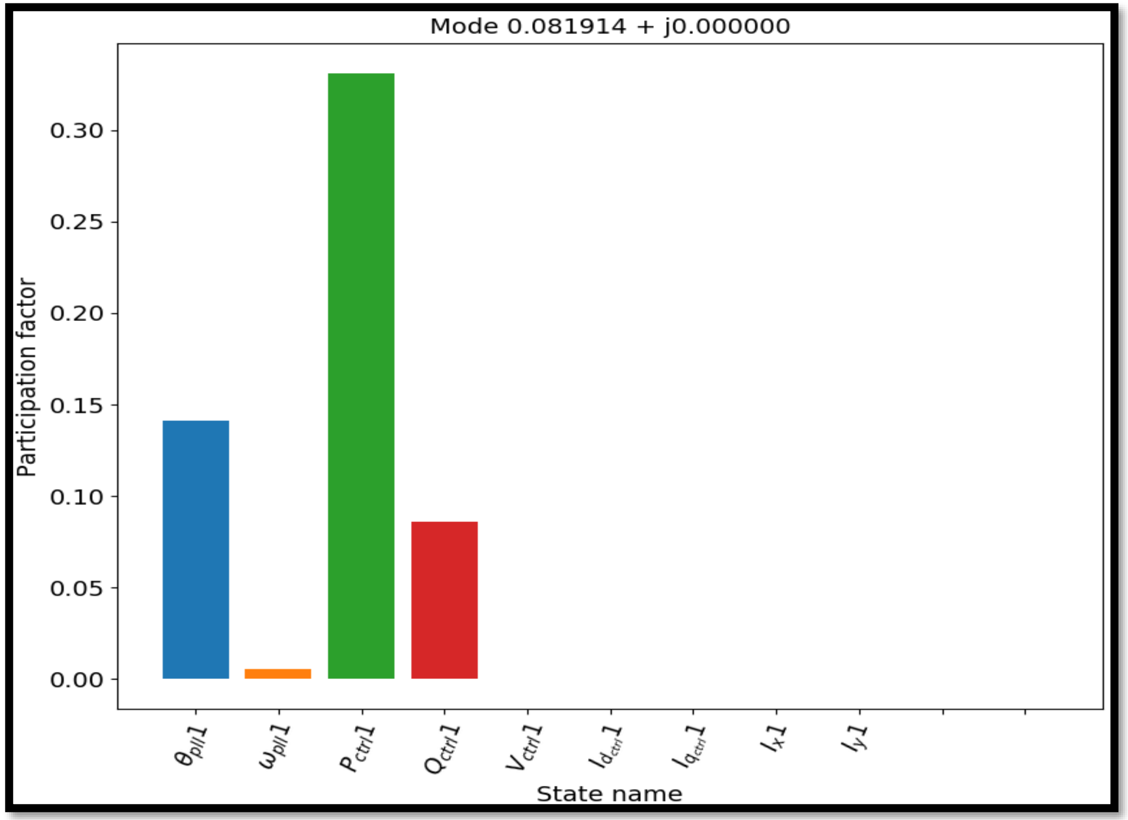




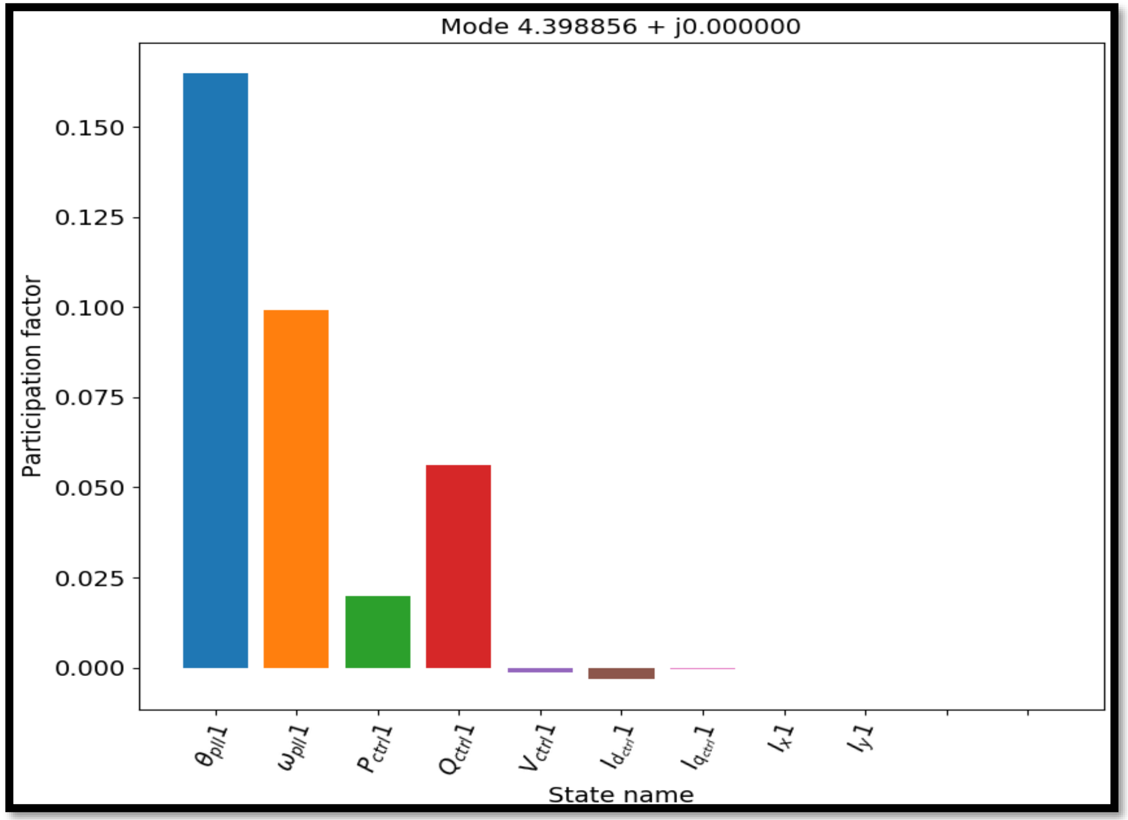


- There is only a marginal increase in stability with now SCR 1.5 also being stable
- Why is this behavior different from having voltage control only?

Participation factors reveal influence of reactive power controller in coordinated Q-V control



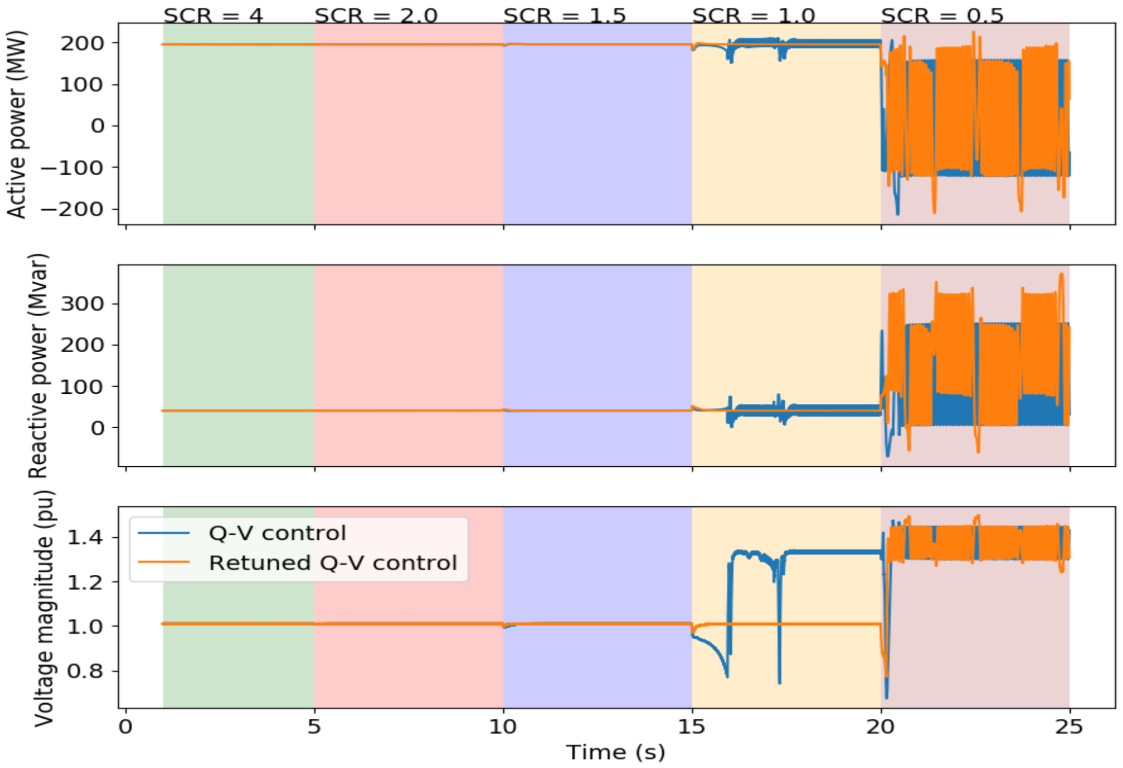
SCR = 1.0

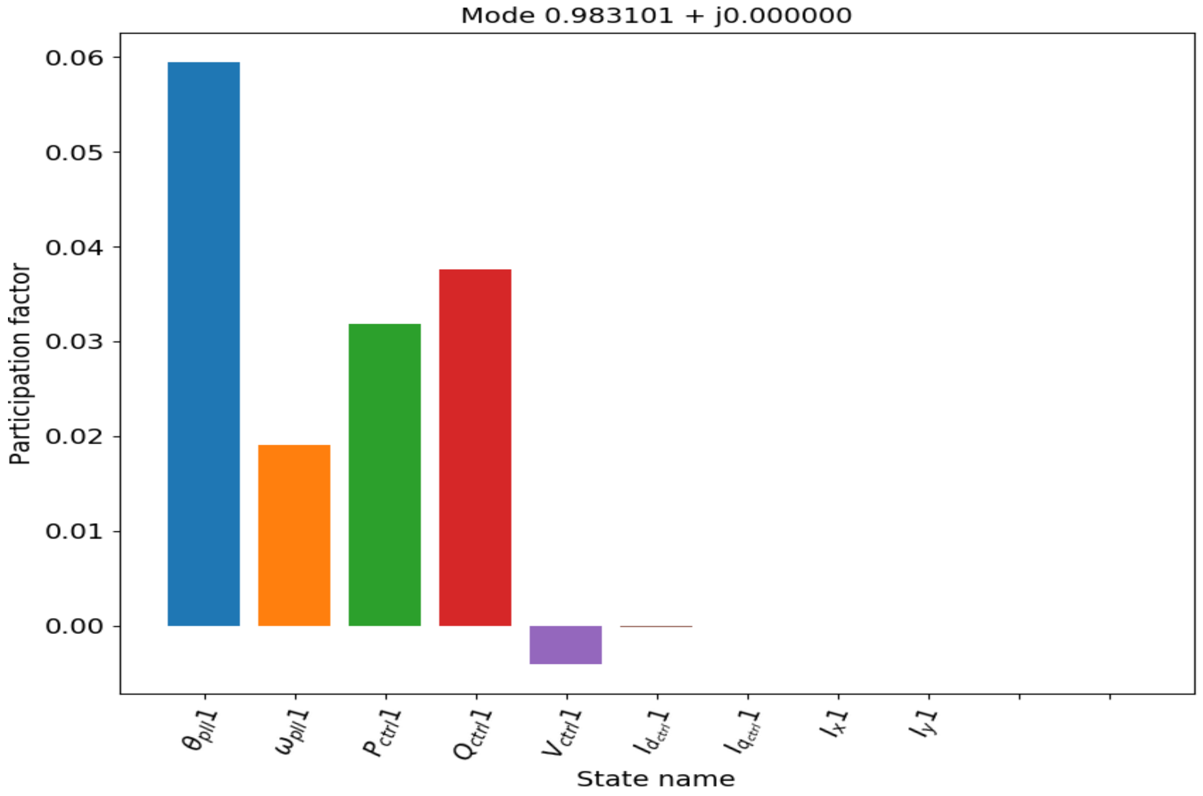


SCR = 0.5

- At both values of SCR, in addition to PLL states, reactive power and active power controllers plays a role.

Slowing down reactive power controller in coordinated Q-V control





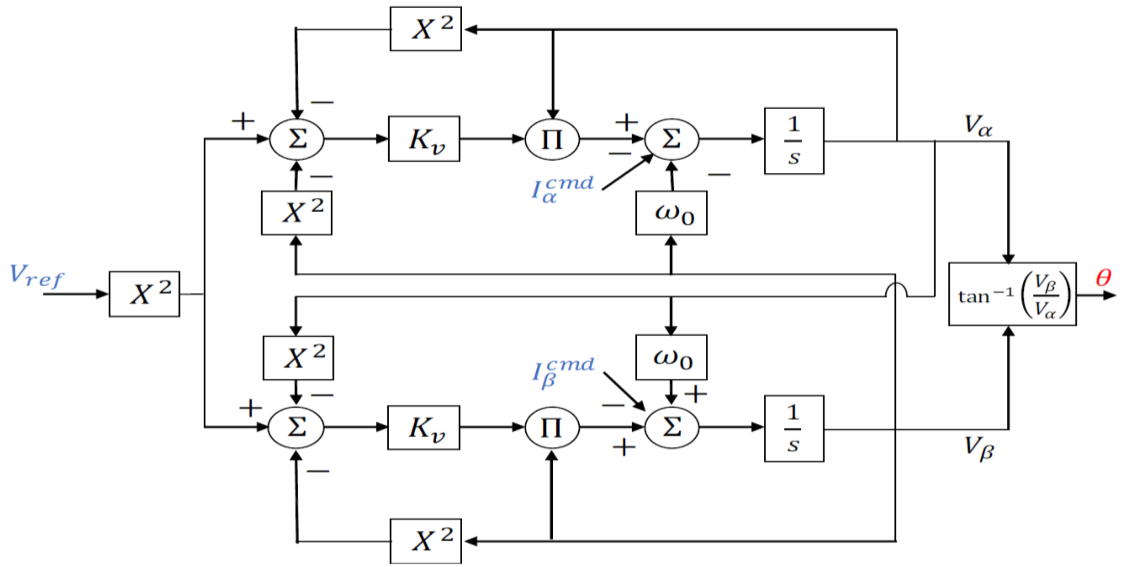
- Reducing time constant of reactive power controller makes the system stable for SCR = 1.0
- But the reactive control loop still plays a role at lower SCR values
  - Any further slowing down of reactive control loop = removing the control loop entirely

Let us stop for a moment here…

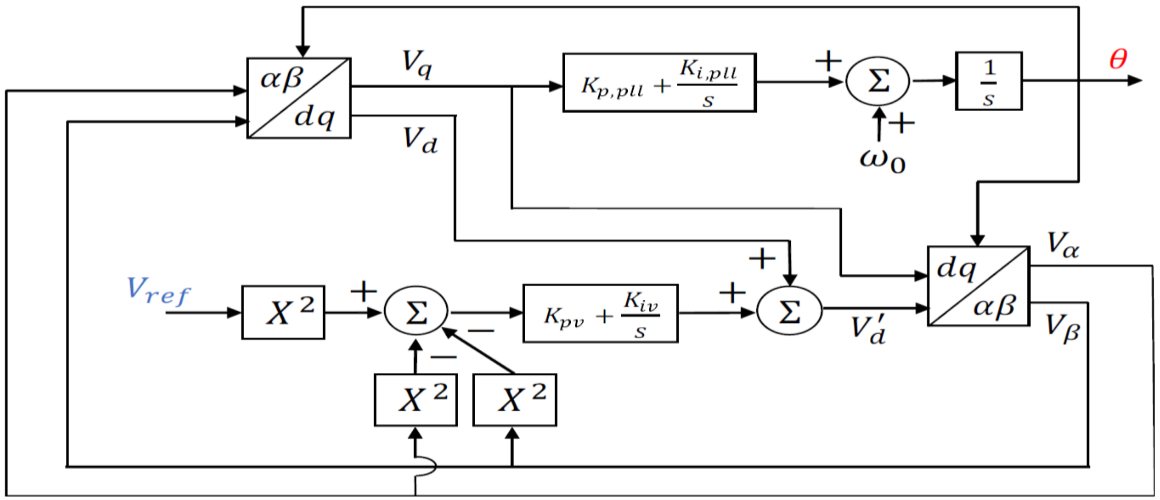
- Keeping our focus on the transient/dynamic time frame (60s after a disturbance)
- Traditional grid following (GFL) inverter resources
  - Both P_{inv}^{ref} and Q_{inv}^{ref} are constant
- Intermediate grid following inverter resources
  - $P_{inv}^{ref}(\omega_{pll})$ but Q_{inv}^{ref} is constant
  - 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 models for future inverters?

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



Virtual Oscillator

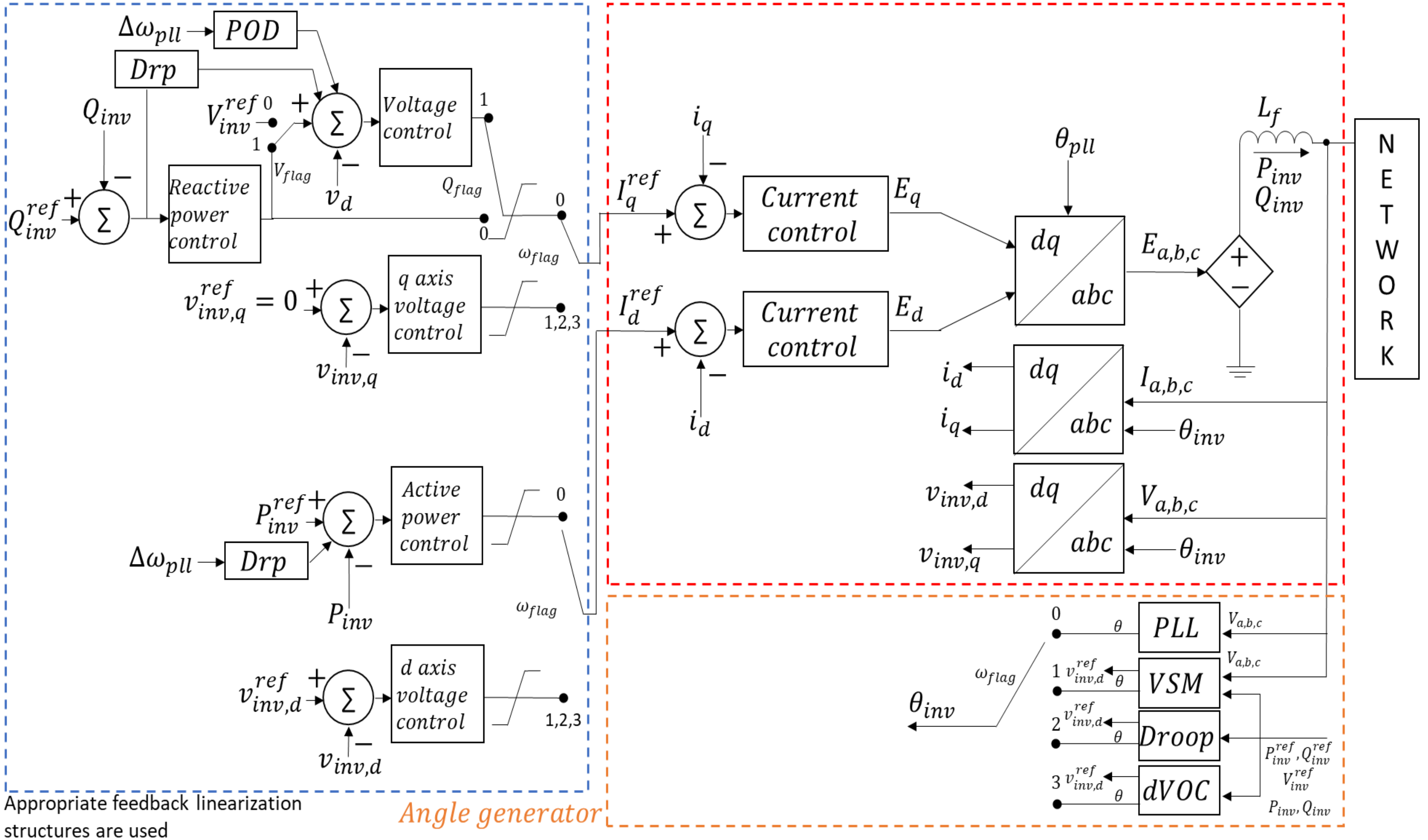


PLL – Voltage controlled oscillator

- 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

‘UNIFI-ed’ Future Inverter Model?



Appropriate feedback linearization structures are used

IBR Behavior	V_{flag}	Q_{flag}	ω_{flag}	Drp
GFL	N/A	0	0	0
	1	1	0	0
I-GFL	N/A	0	0	K
	1	1	0	K
GFM	0	1	0	K
	N/A	N/A	1	N/A
	N/A	N/A	2	N/A
	N/A	N/A	3	N/A

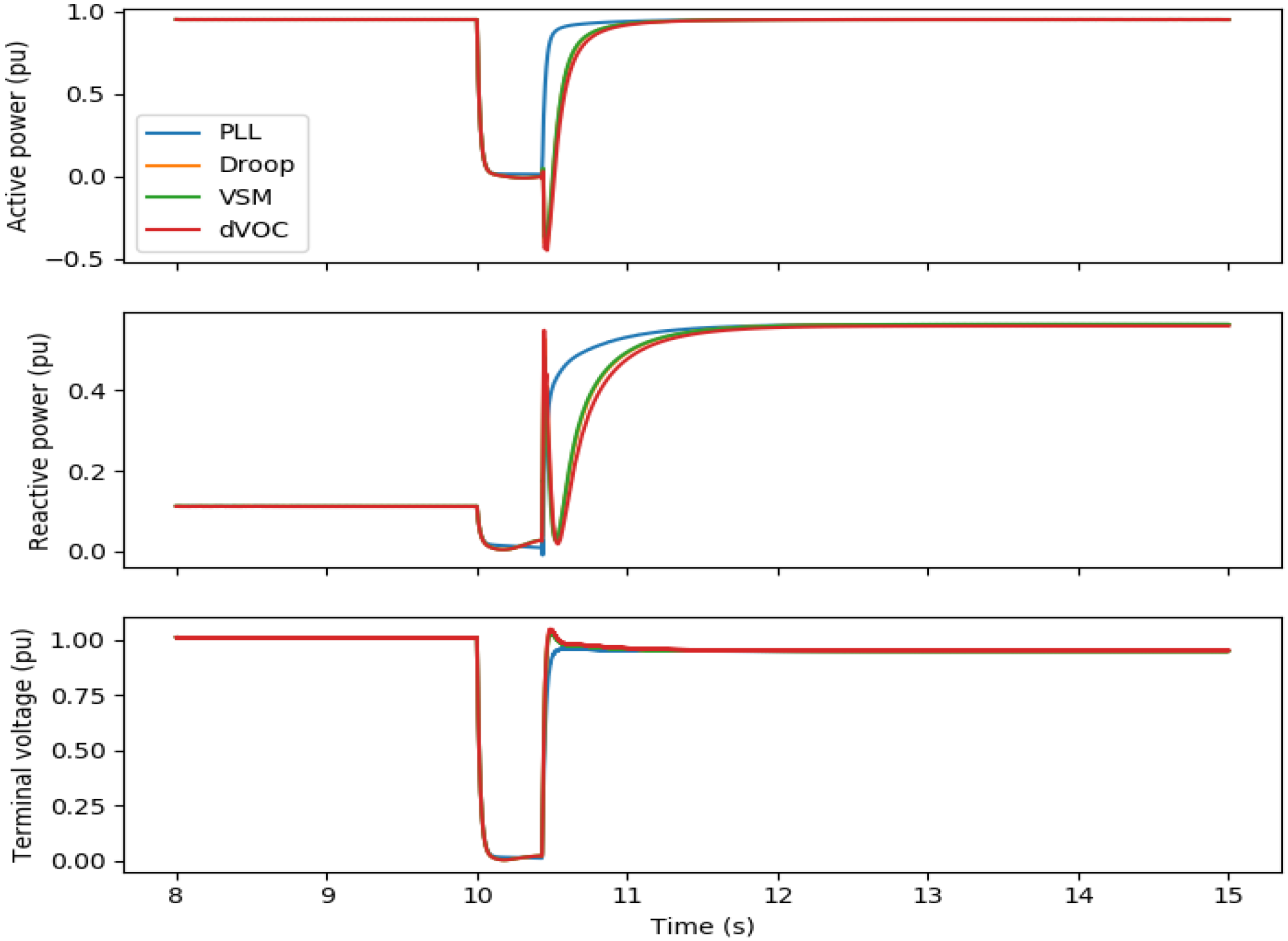
K is an appropriate value of droop gain

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

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*, *[under review]*

Similar response in EMT domain across all 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

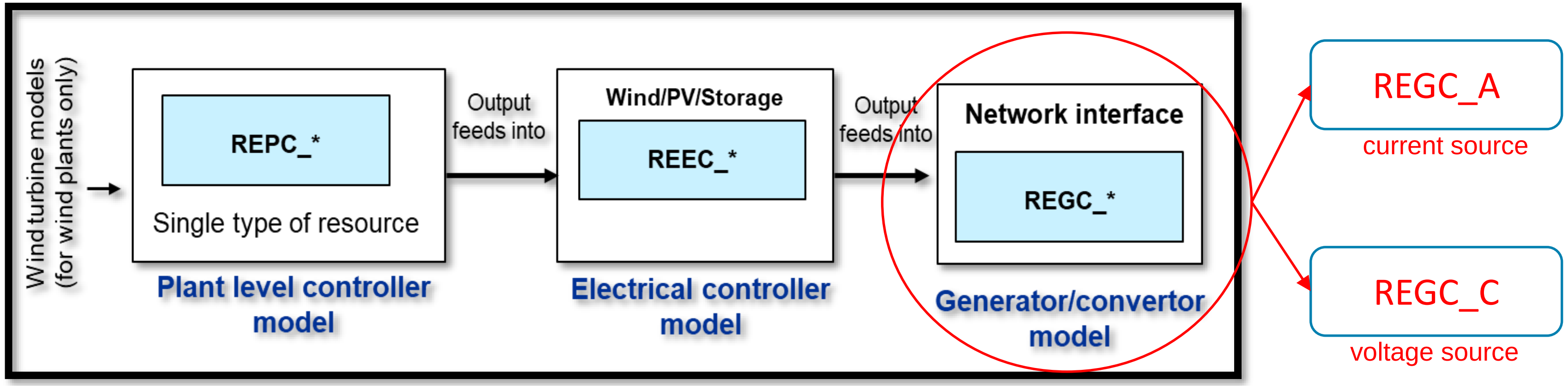


How does this link to positive sequence models?

What is positive sequence simulation domain?

- Transmission power system analysis is carried out almost everywhere using positive sequence simulation software
  - All three phases represented as a single phase
    - Assumption that voltage and current across all three phases is balanced
  - Representation of network impedance using fundamental frequency algebraic representation
    - Assumptions that the inductors and capacitors of the transmission lines have very fast and stable dynamics, so need not be represented
  - Fundamental frequency phasor based approach for transient analysis
    - Assumption of very low harmonic distortion.

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

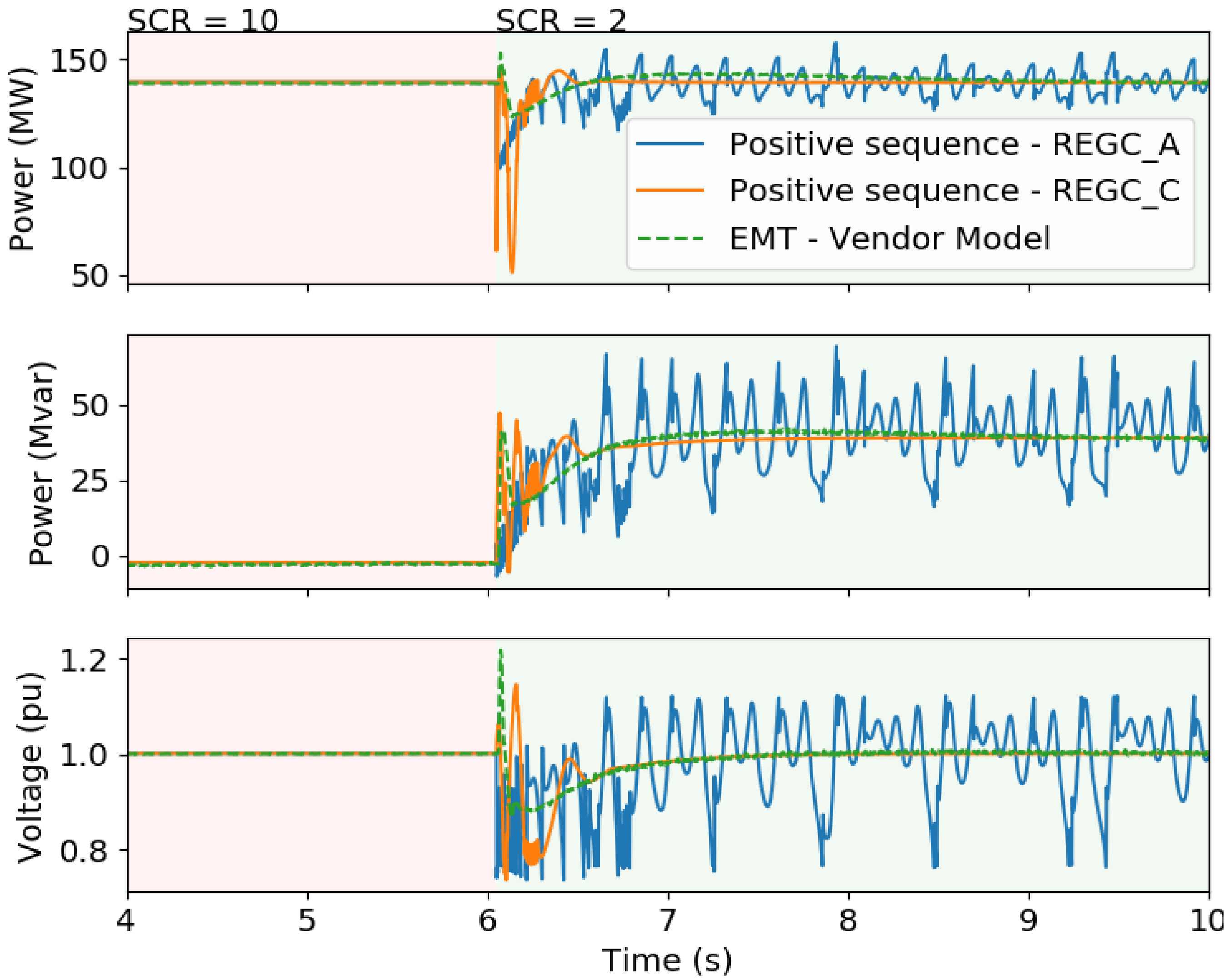


Generic models are vendor-agnostic models that do not necessarily represent the exact control algorithm of any particular IBR vendor. When appropriately parameterized, these models can subsequently provide the trend of dynamic behavior expected from IBR plants.

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

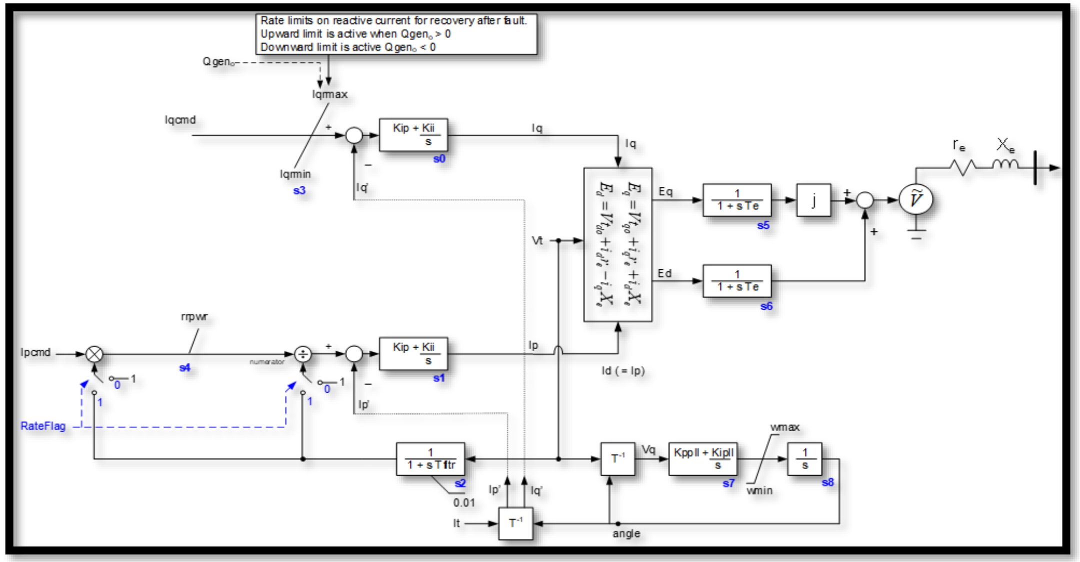
Existing REGC_A generic model

- 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



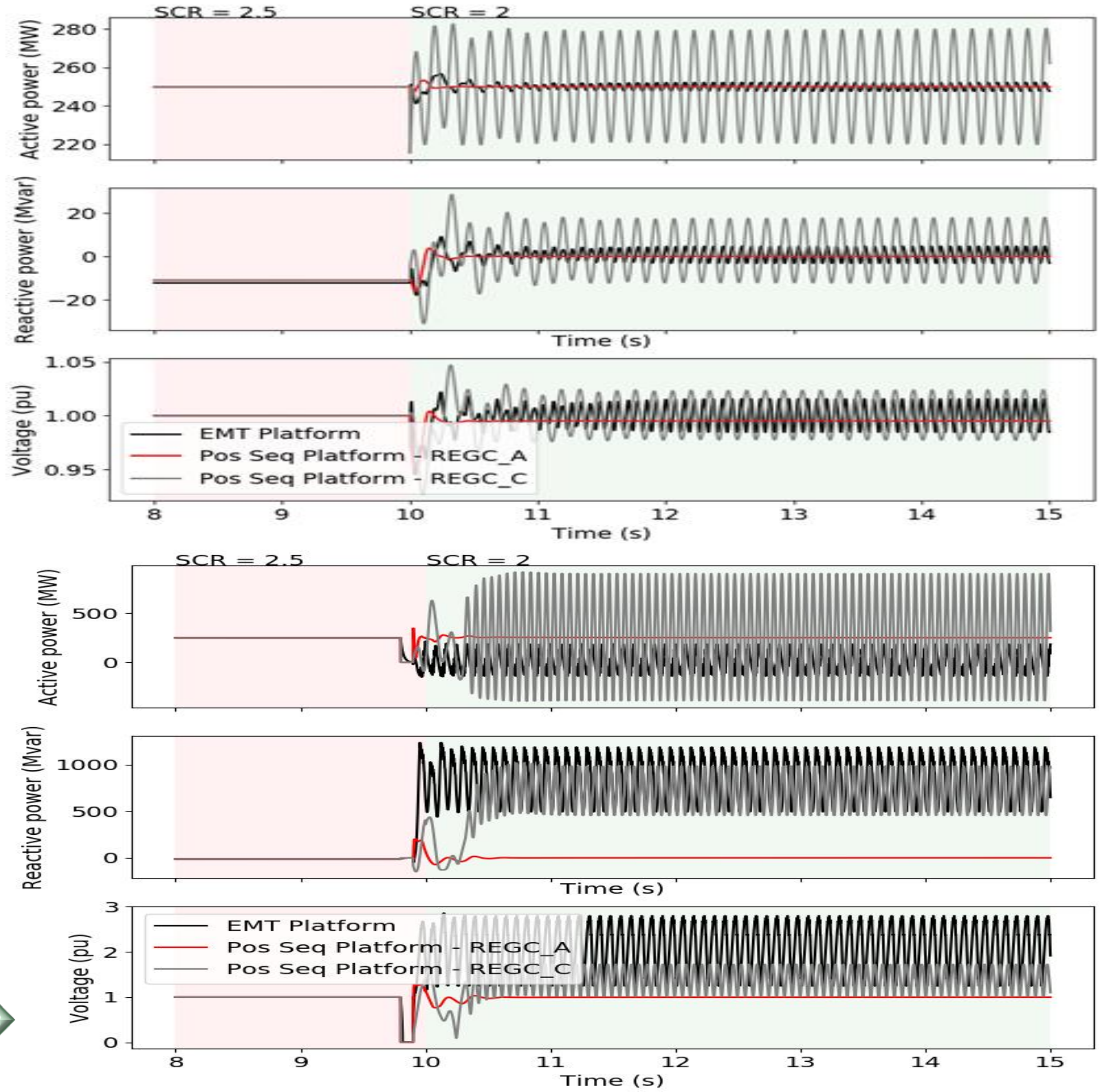
Deepak Ramasubramanian, Wenzong Wang, Pouyan Pourbeik, Evangelos Farantatos, Anish Gaikwad, Sachin Soni, and Vladimir Chadliev, "Positive Sequence Voltage Source Converter Mathematical Model for Use in Low Short Circuit Systems," *IET Generation, Transmission & Distribution*, vol. 14, no. 1, pp. 87-97,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

The REGC_C generic model



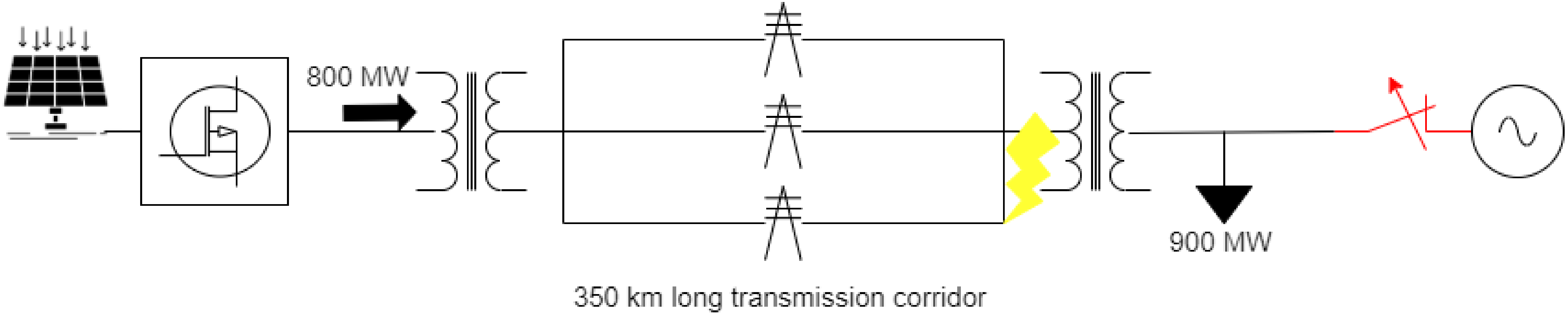
- Approximate representation of dynamic behavior of
  - inverter's inner current control loop.
  - Inverter's phase locked loop
- Current commands are translated into voltage reference commands behind an impedance

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," *Electric Power System Research [under review]*

Use of positive sequence REGC_C model to represent grid forming behavior

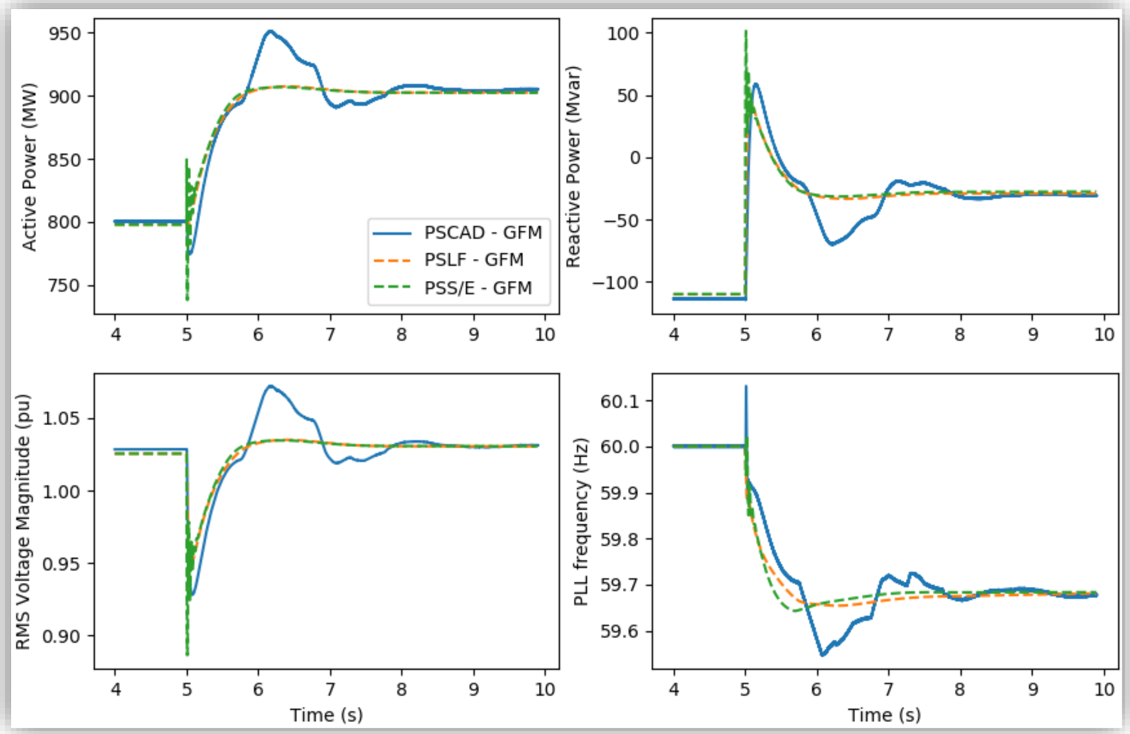


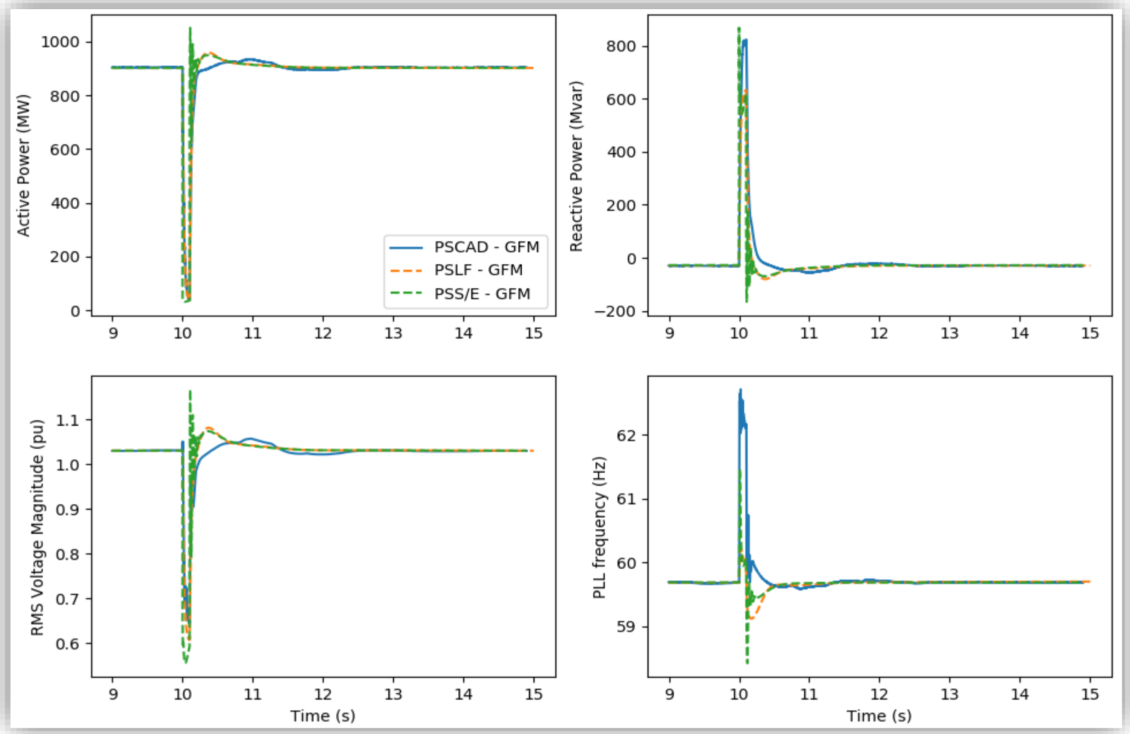
- Voltage at PV plant point of interconnection to be controlled
- Frequency control is implemented at device level
  - 10pu/s ramp rate limit

» 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

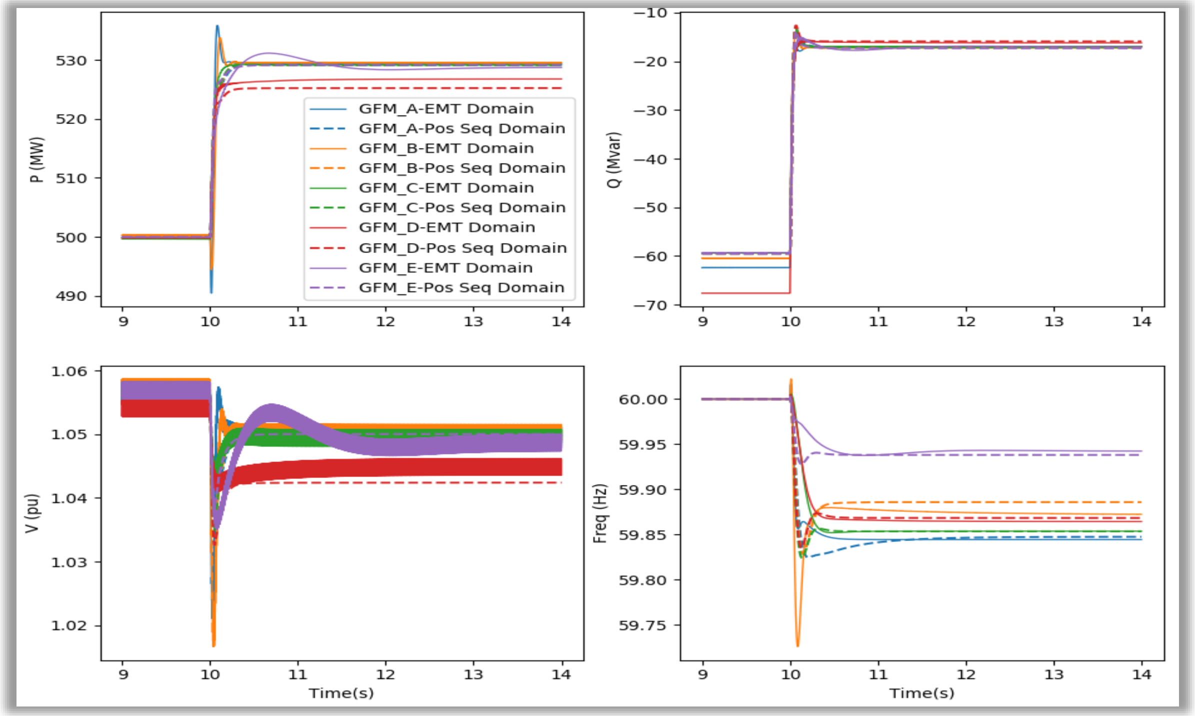


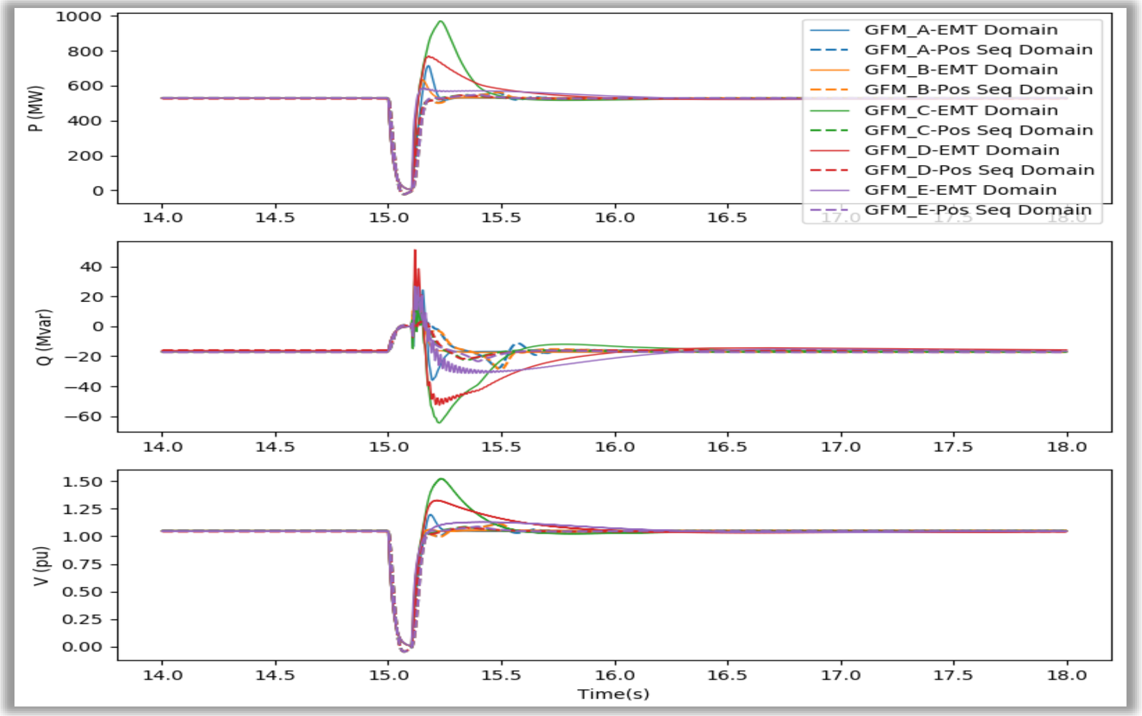


- Positive sequence response obtained using approved WECC generic models
  - REGC_C + REEC_D + REPC_A
- Models should be parameterized with diligence and thoroughness

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

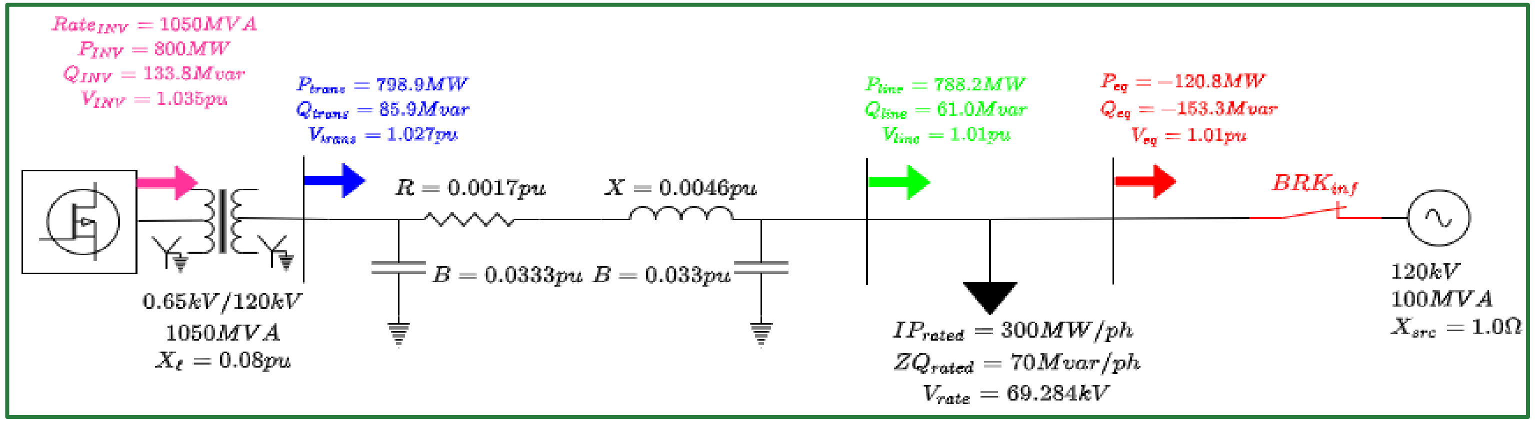


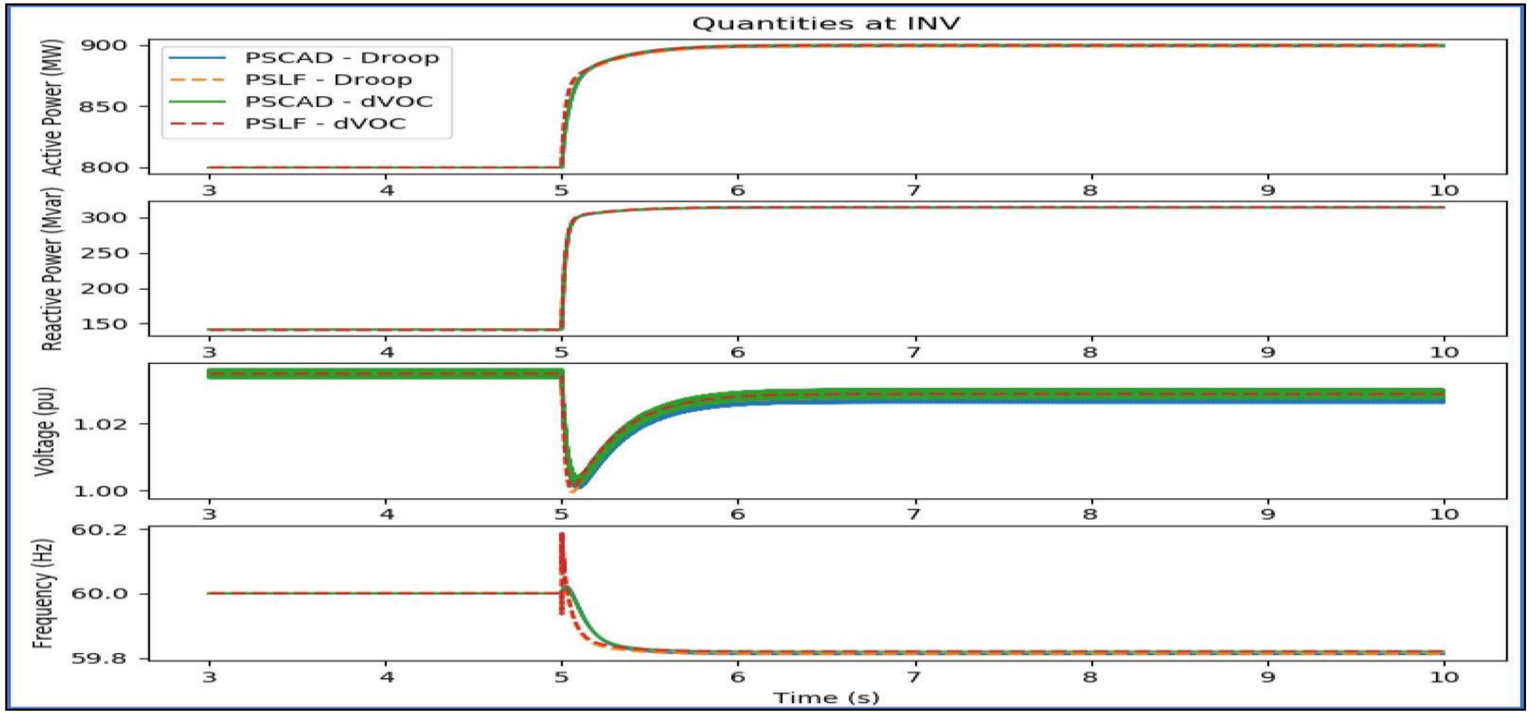


EMT domain GFM implementations include virtual oscillator based, droop based, PLL based, and unknown implementations

- Different GFM implementations, without additional tuning, can have different transient behavior
- Complete tuning of generic positive sequence model is yet to be completed
  - Results are encouraging, but there is always room for improvement

‘UNIFI-ed’ grid forming positive sequence model?



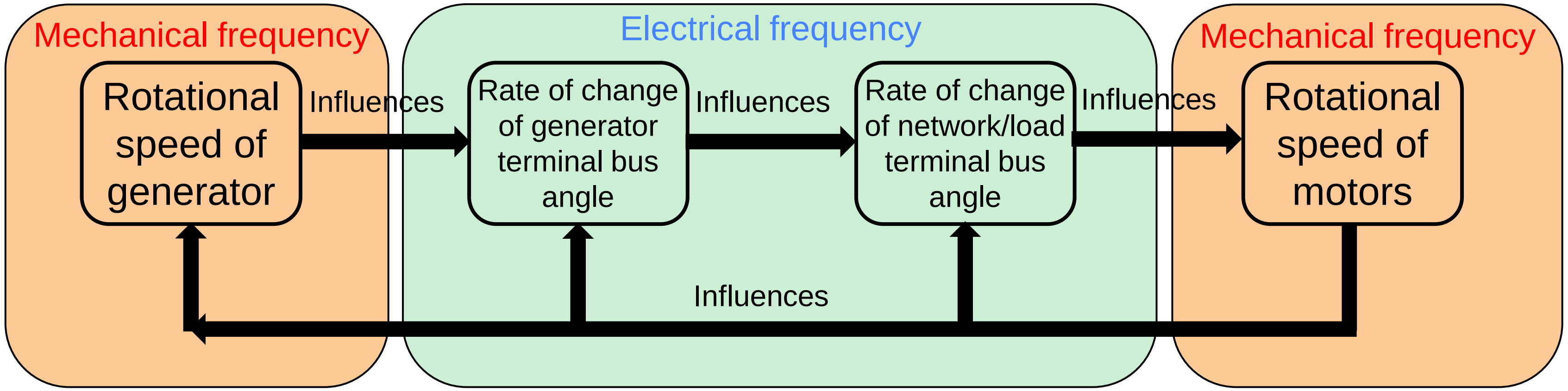


- In this setup, both EMT domain and positive sequence domain models have same control structure and hence values of control gains.
- This need not be the case when comparing generic model behavior against a black box model.

Potential new operation paradigm

Frequency in a conventional system…

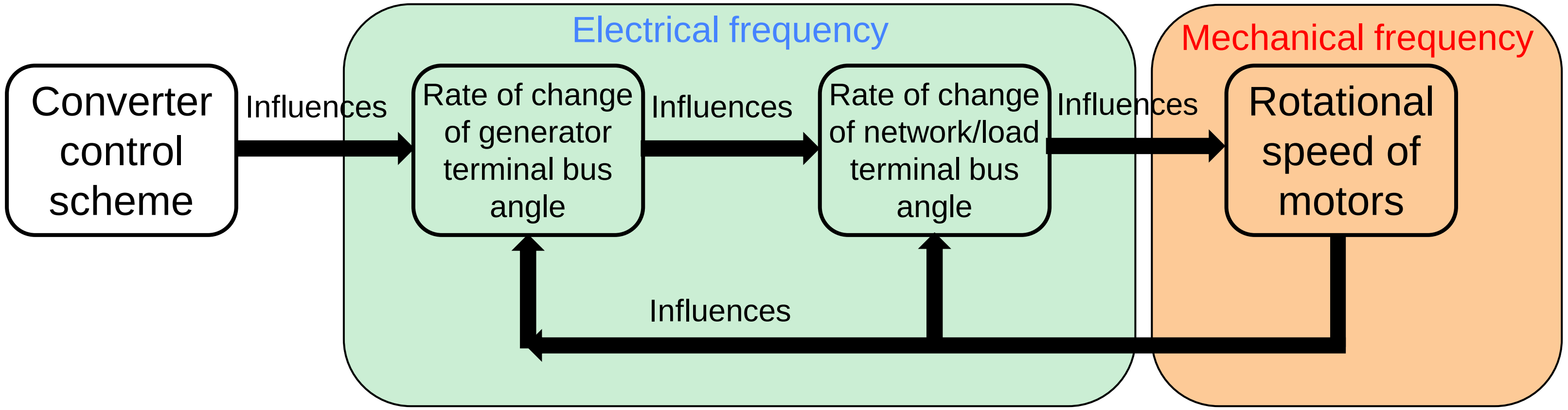
- Conventional system:
  - Electromagnetic properties of the network and machines lock their behavior to be in sync
  - A change in load is automatically/naturally reflected in speed of rotation of the machine
  - System frequency is governed by speed of rotating machines



What changes with 100% inverters?

- 100% IBR system:
  - Break in the electromagnetic link between source and network
    - Lock presently has to be obtained through a controller
  - No physical link between generation/load balance and frequency
  - Converters can operate at any frequency

Can this be leveraged to bring about superior frequency control?



Can ideal L shaped frequency response, or better, be achieved?

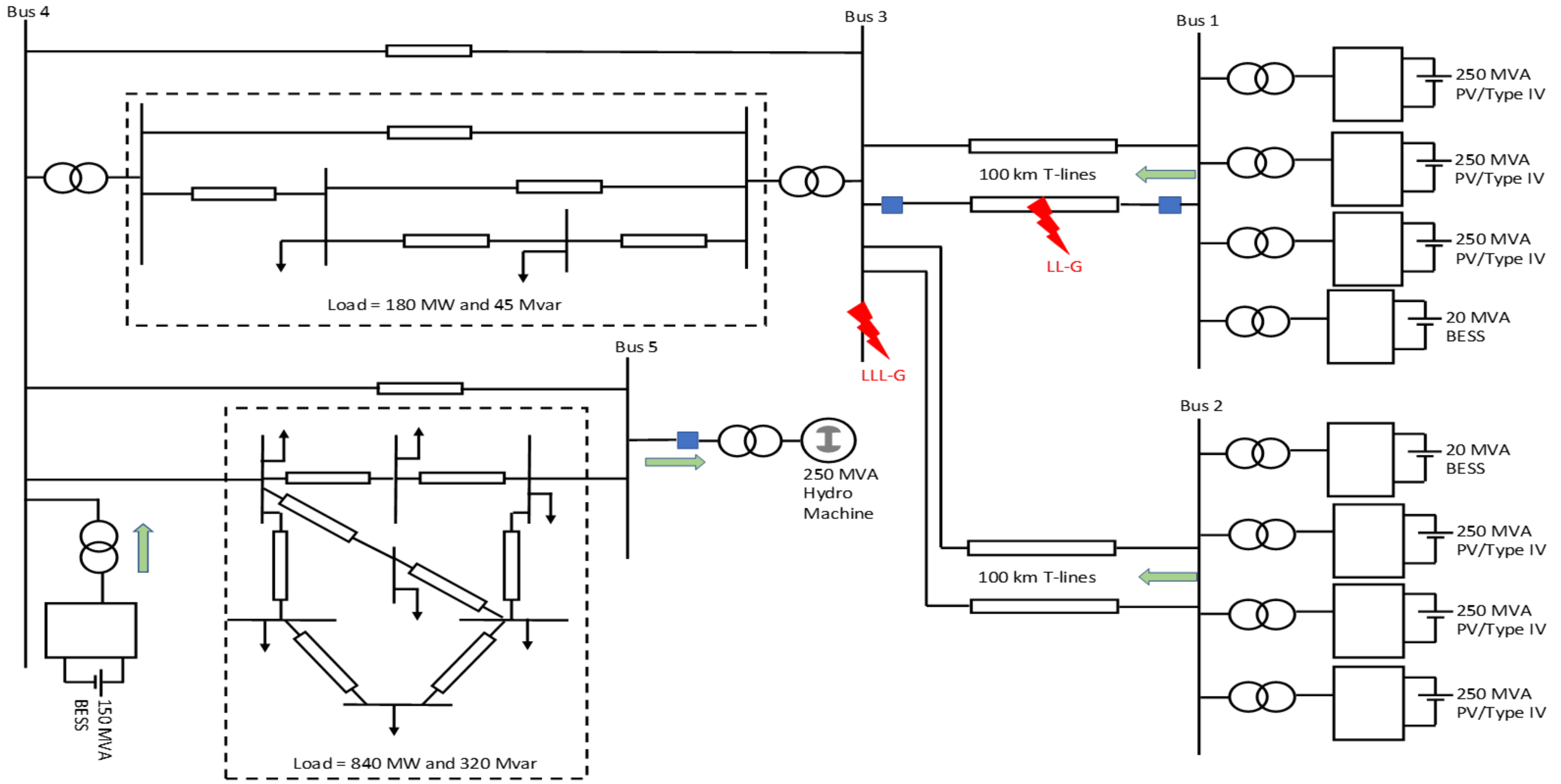
Could we employ a form of distributed slack bus control?

- In steady state power flow solutions, single slack bus is a concept of convenience
  - In reality, a large power system has a distributed slack bus
  - Frequency is ‘constant’ in a power flow solution
- With inverters, potential is there to achieve a similar response
  - Frequency can be strictly controlled by inverters after a transient
  - Distributed slack bus representation can bring about power sharing

$$P = P_{ref} + \underbrace{K_{\delta err}\left(\delta_{ref} - \int K_{ferr}\left(1.0 - \dot{\hat{\theta}}\right)dt\right)}_{\text{Distributed slack bus-based angle droop}} + \underbrace{Drp\left(1.0 - \dot{\hat{\theta}}\right)}_{\text{Frequency droop}}$$

Deepak Ramasubramanian, “Would Traditional Primary Frequency Response and Automatic Voltage Control Naturally help Usher in Grid Forming Control?,” *CIGRÉ Science & Engineering*, vol. 20, pp. 52-60, February 2021.

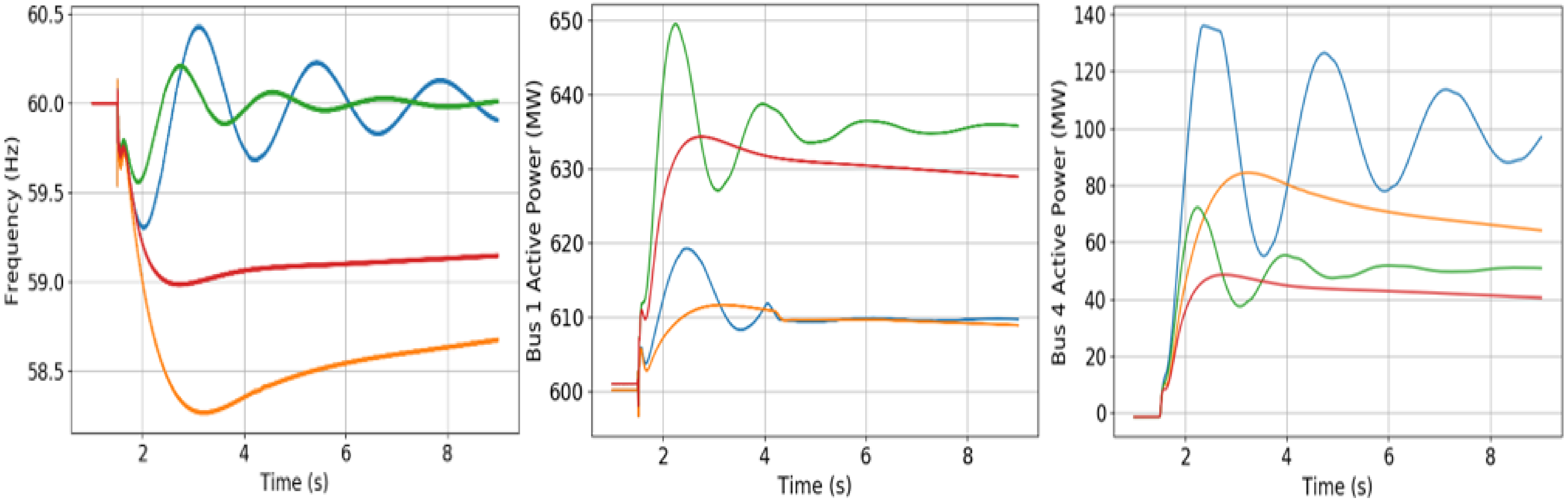
Working of this concept in a system with 90% inverters



All inverters have capability for fast voltage control

Only BESS have frequency control capability

Response for 10% load increase

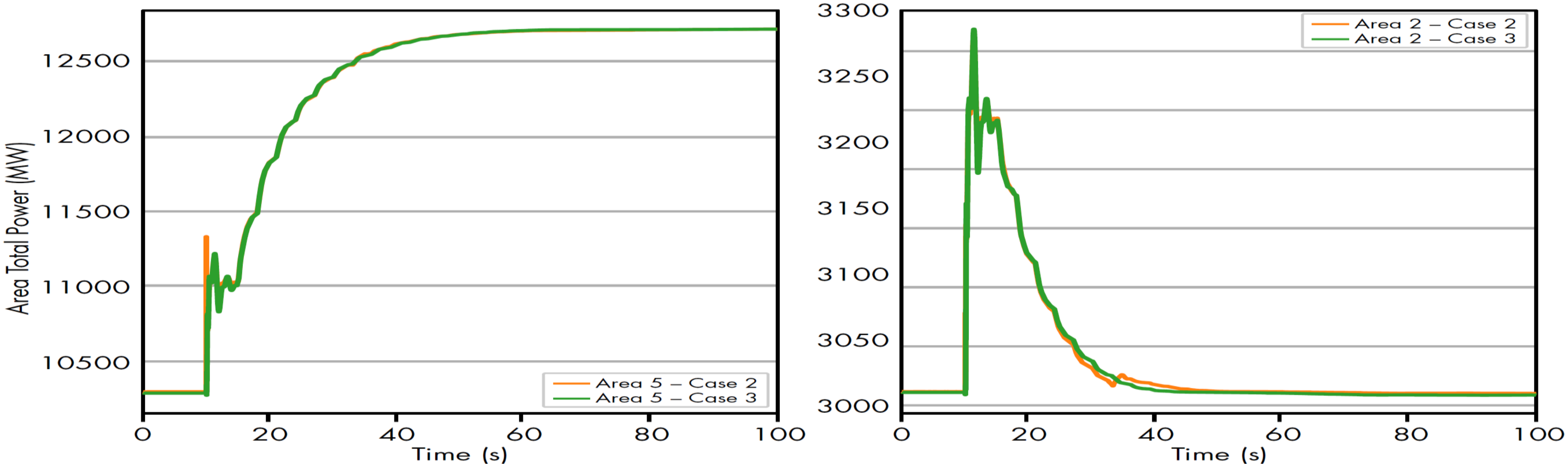


- 20 MVA storage, distributed slack power sharing
- 20 MVA storage, conventional frequency droop
- 100 MVA storage, distributed slack power sharing
- 100 MVA storage, conventional frequency droop

Only 10kWh of additional energy required from storage to bring about constant frequency operation

Extension of the concept to balancing areas

- Re-imagine a way to carry out tie line control across multiple areas



- Visibility of generation/load event only based on tie line flow
  - Impact of SCADA/EMS refresh rate
- BA’s evaluation of NERC’s Control Performance Standards (CPS)?

Deepak Ramasubramanian and Evangelos Farantatos, “Constant Frequency Operation of a Bulk Power System with Very High Levels of Inverter Based Resources,” *CIGRÉ Science & Engineering*, vol. 17, pp. 109-126, February 2020.

Black start of a system with GFM IBRs

Blackstart of a system with IBRs – A grid forming service

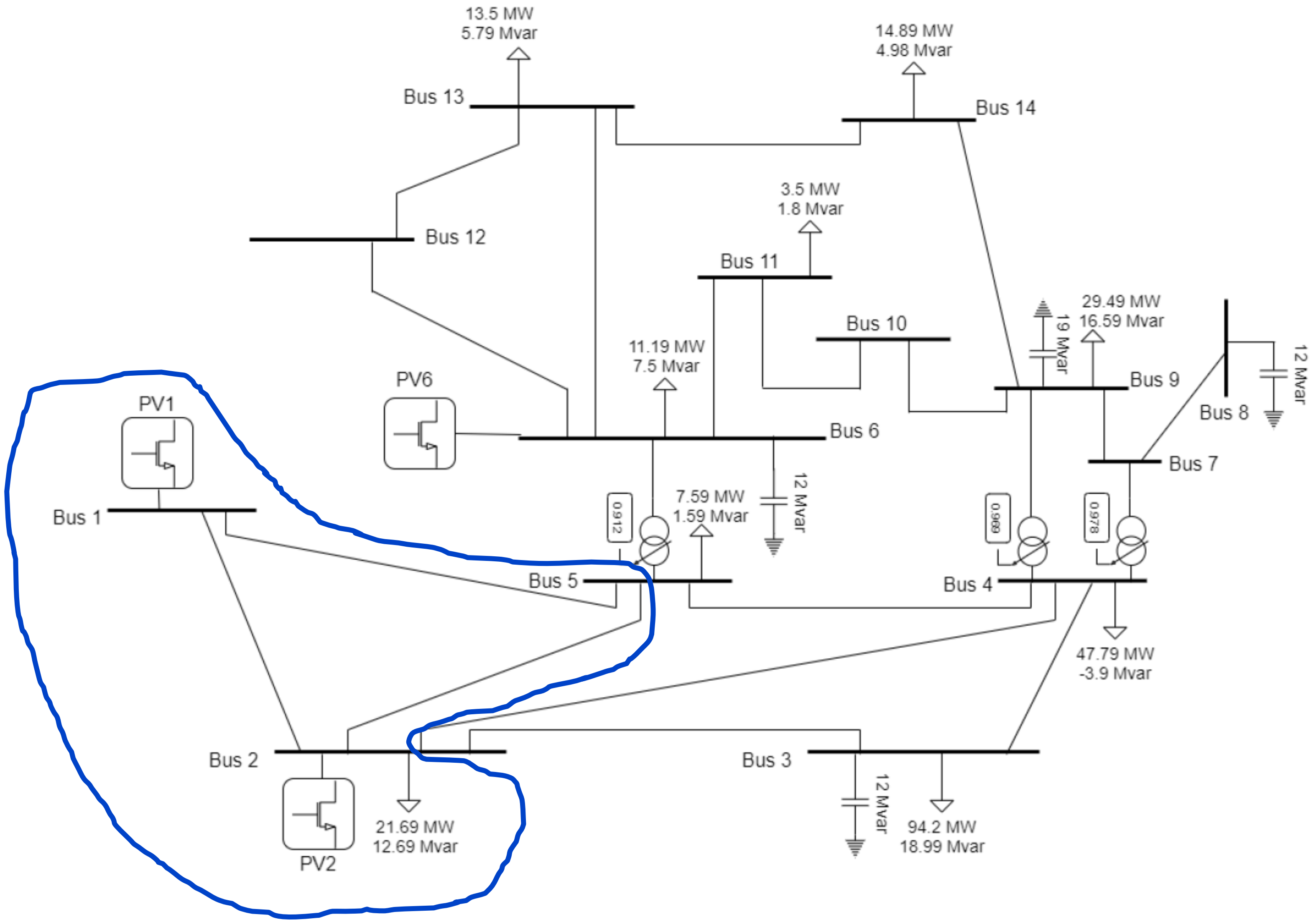
- A cranking path should be identified for system restoration

- 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

- A GFM IBR can be this first black start resource
  - Not all GFM IBRs need to be capable of providing such services

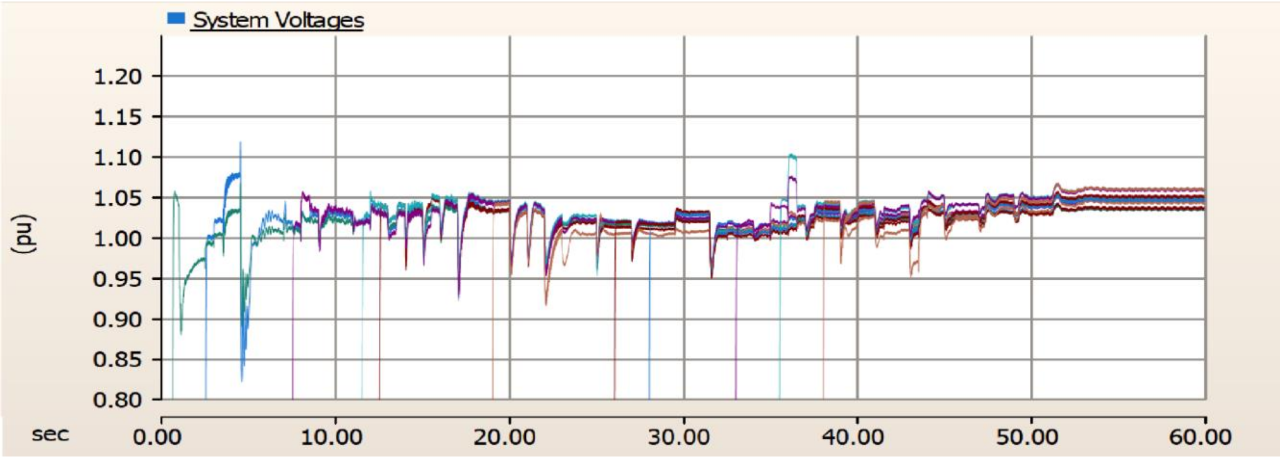
Vikas Singhvi, Deepak Ramasubramanian, Sunitha Uppalapati, Wes Baker, and Evangelos Farantatos, "An Analytical Procedure to Evaluate Optimal Restoration Path with Multiple Blackstart Units Including Inverter Based Resources," *2021 IEEE Power & Energy Society General Meeting (PES)*, Washington D.C., USA, 2021

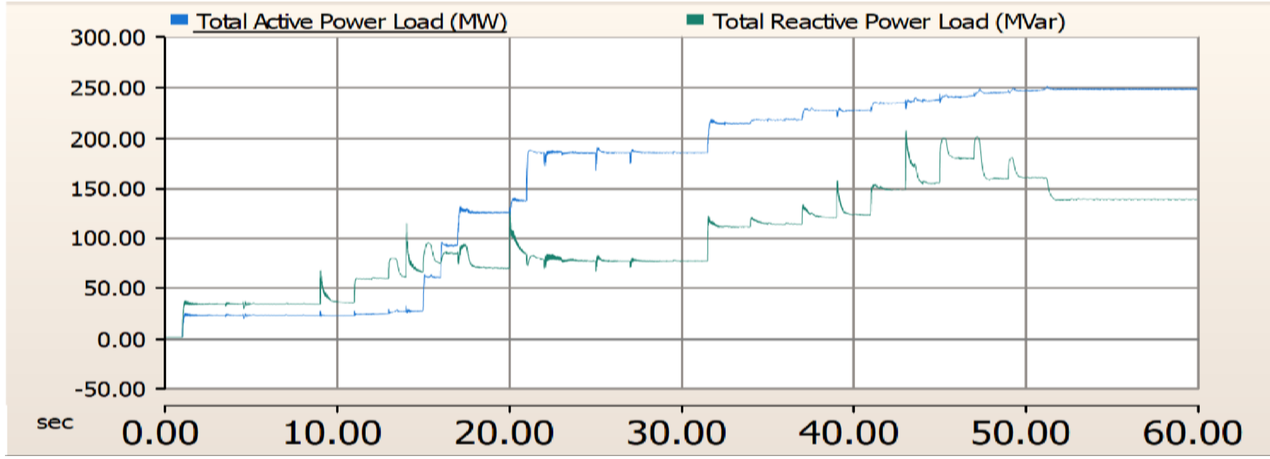
Black start of IEEE 14 bus test system

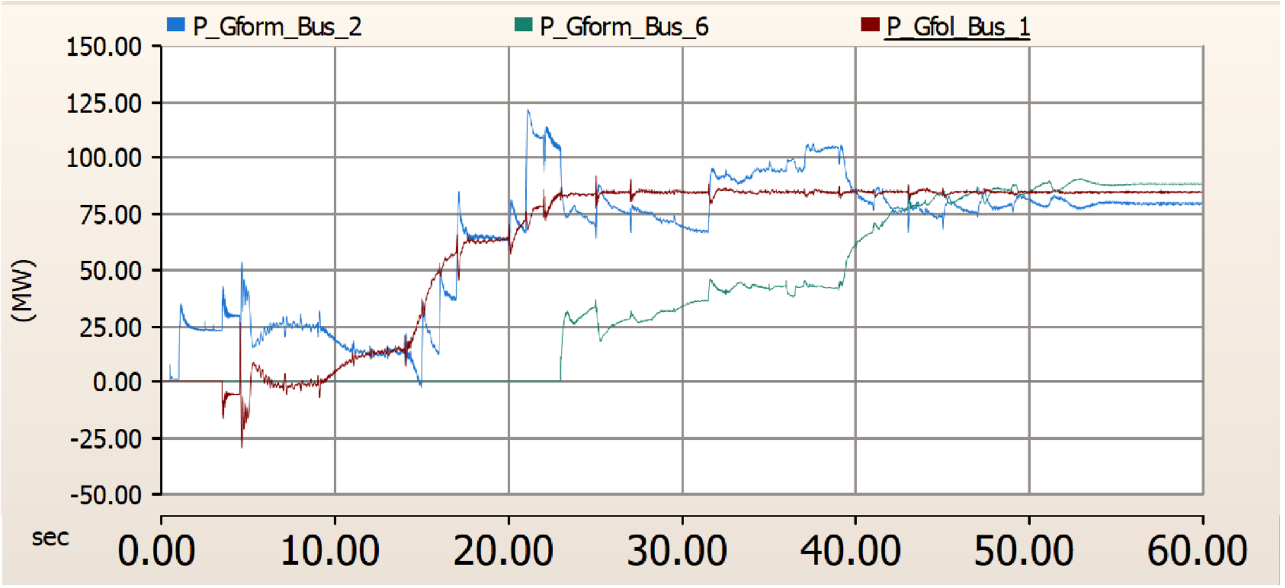


- PV at bus 2 and 6 are grid forming
- PV at bus 1 is grid following
- First black start bottom portion of the network
- Then bring PV6 online
- Then restore rest of the network

If controllers are tuned well, it is possible to energize the entire network

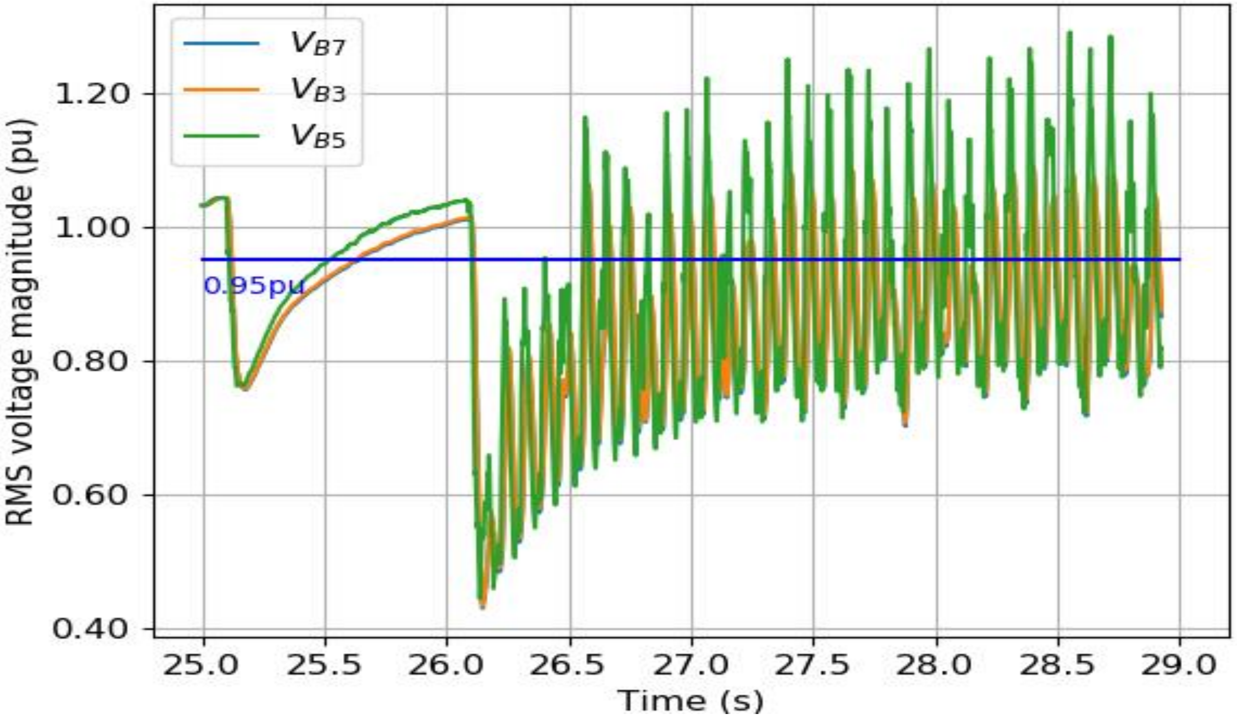


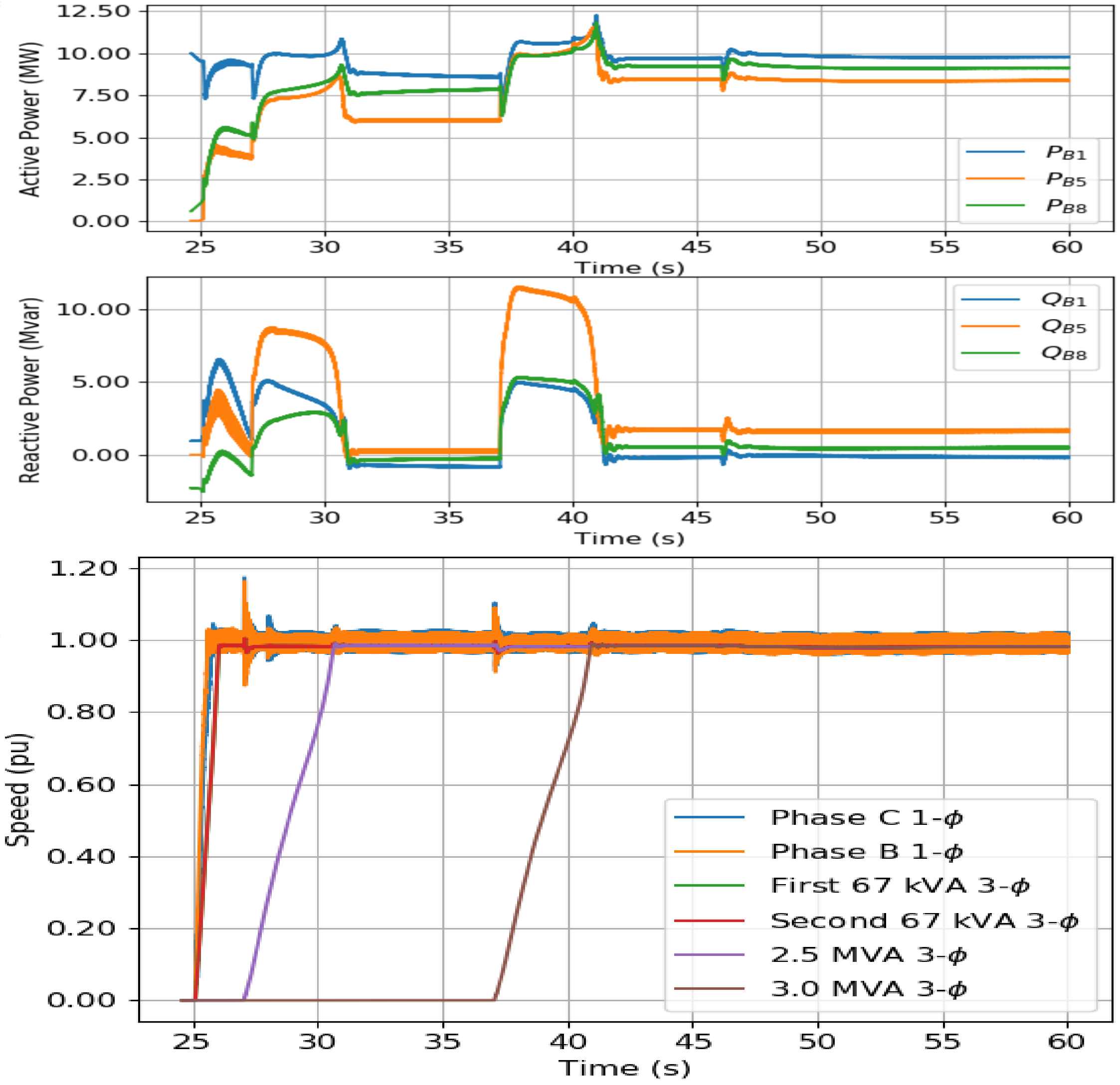




- Second GFM synchronizes at 22s
- Large variety of induction motor load present
- Start up of induction motors have to be coordinated

Possibility of control interactions between large motor soft-start scheme and single-phase induction motors





- Control interactions when three phase motor tries soft start
  - Solved by carrying out staggered start of three phase induction motors

Deepak Ramasubramanian, Wes Baker, Vikas Singhvi, Sunitha Uppalapati, Evangelos Farantatos, "System Blackstart and Restoration using Inverter Based Resources," *IEEE Transactions on Power Systems*, *[under review]*

Summary and future research

- Future power system planning needs good validated models
  - Important to identify when a particular simulation environment can be used.
- From system planning perspective, services needed are crucial to be identified
  - Individual equipment vendors then have ‘control’ on the design.
- Generic models can provide good benefit when used in planning studies
  - Important to validate and verify behavior as equipment is commissioned in the field
- IBRs can be used to carry out blackstart and restoration of the network
  - Important to control transformer energization and in-rush currents.

All mathematical models have limitations, some are useful if used appropriately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