Grid Forming Converter System Control Strategies

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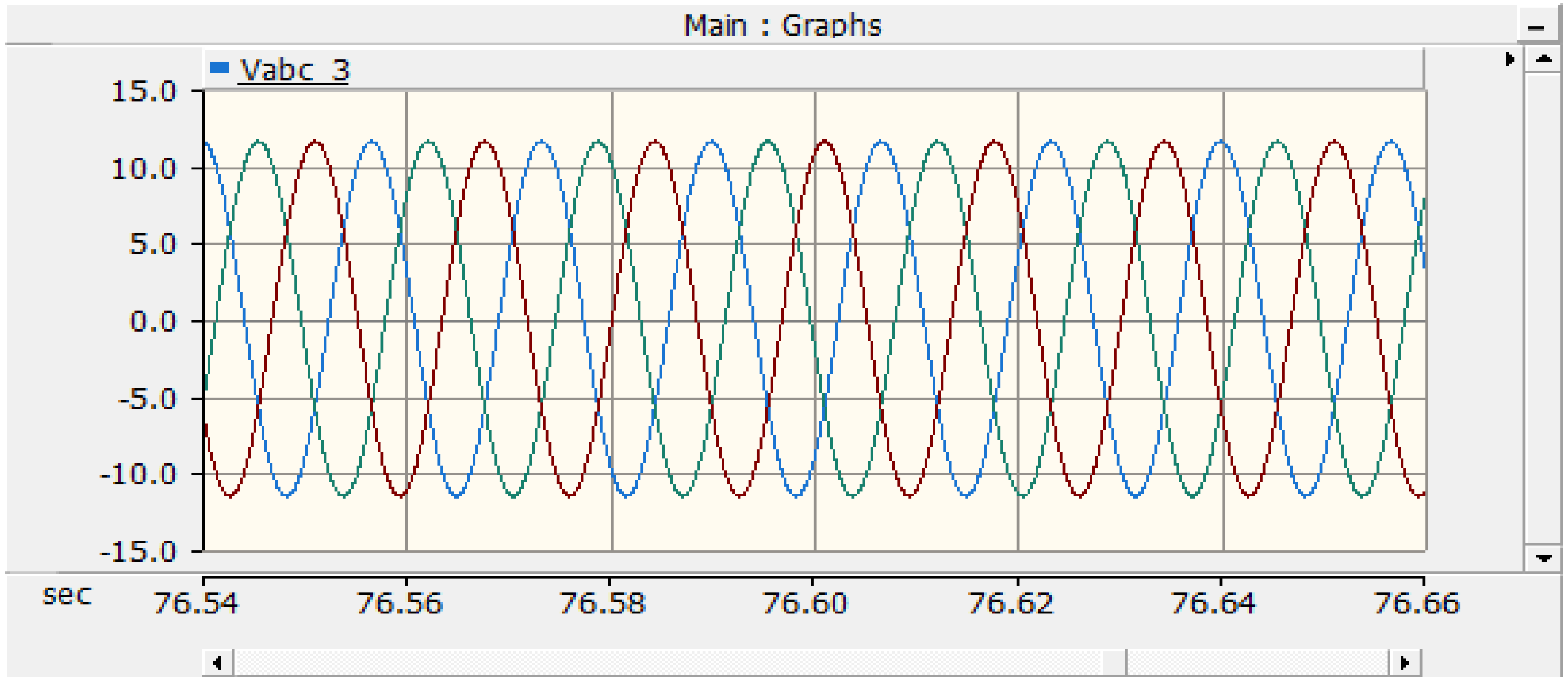
Basic quantities of power system…

- Sinusoidal voltage/current wave has three quantities:
  - Magnitude (V/I)
  - Phase angle displacement (δ/θ)
  - Frequency (ω)



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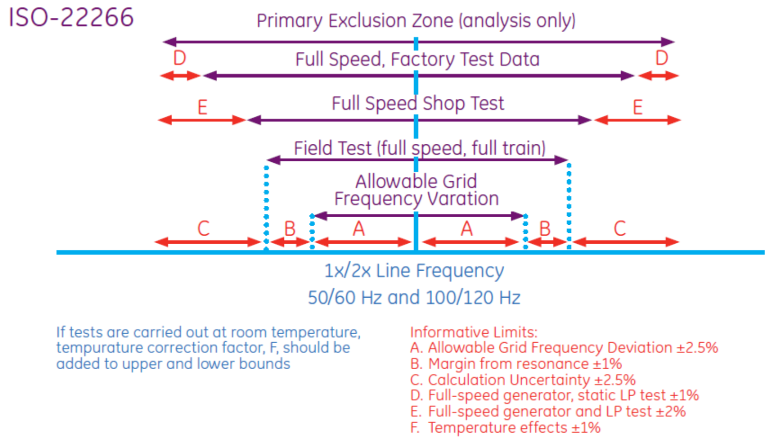
Creation of a sinusoidal wave…

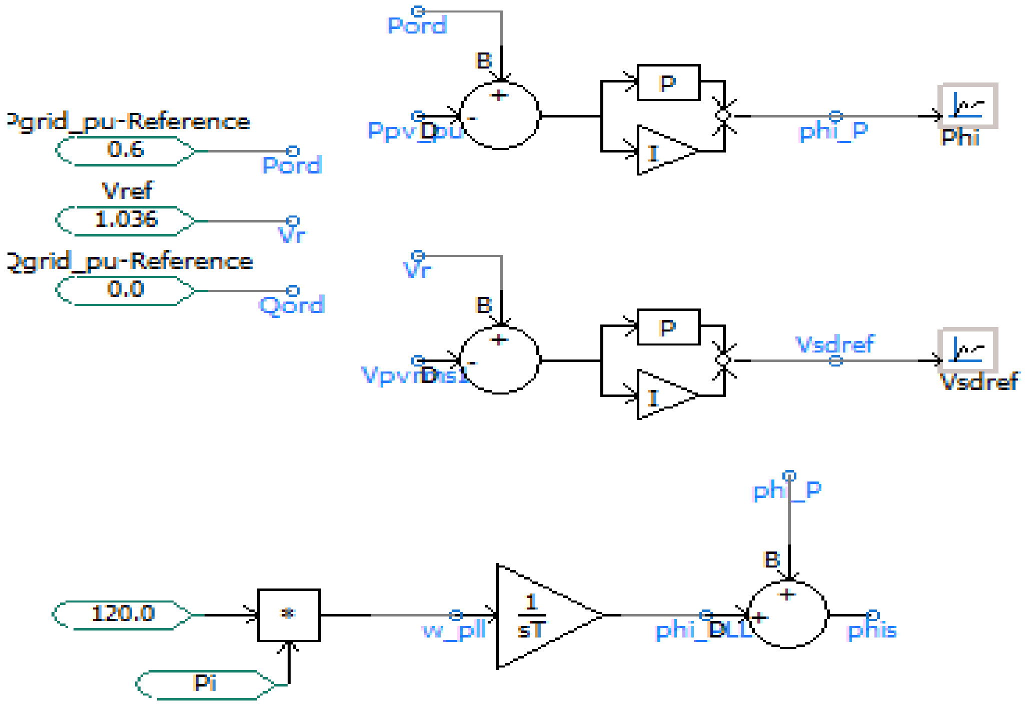
- In a synchronous machine…
  - Voltage magnitude is mainly controlled by level of excitation
  - Phase angle is mainly controlled by governor position
    - Which controls the angular displacement of the rotor shaft
  - Frequency is mainly controlled by speed of rotation of rotor
    - Actual value of speed of rotation is very important for the machine



- In a converter…
  - Voltage magnitude is controlled by reactive power – voltage control loop
  - Phase angle is controlled by deriving from input voltage wave
    - The all important phase locked loop – requires a strong and smooth voltage wave.
    - Angle of converter sinusoidal wave follows angle of grid sinusoidal wave
  - Frequency..?
    - Actual value is not really important for the converter
    - Maintaining a nominal value is important for the grid.

An individual grid forming converter…

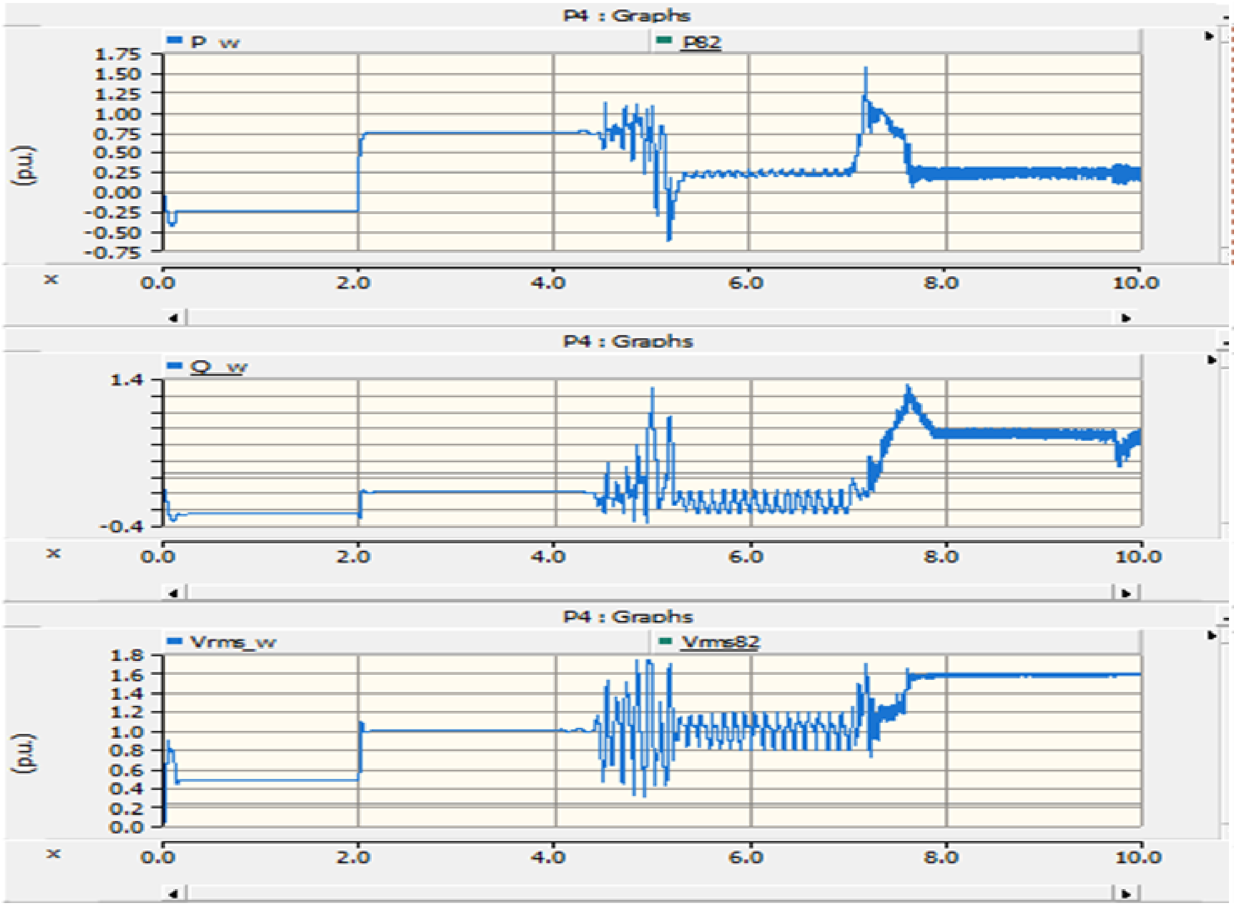
- The converter controls do not rely on a phase locked loop to provide an angle based on voltage measurements
  - Some form of grid tracking has to be present in order to be a ‘good citizen’ of the power system
- Converter controls make the converter a current independent (to a large extent) voltage source.
- One way of accomplishing this:
  - The angle is derived by an active power controller
  - The voltage magnitude is derived by a voltage controller
  - The derived angle is added to nominal frequency



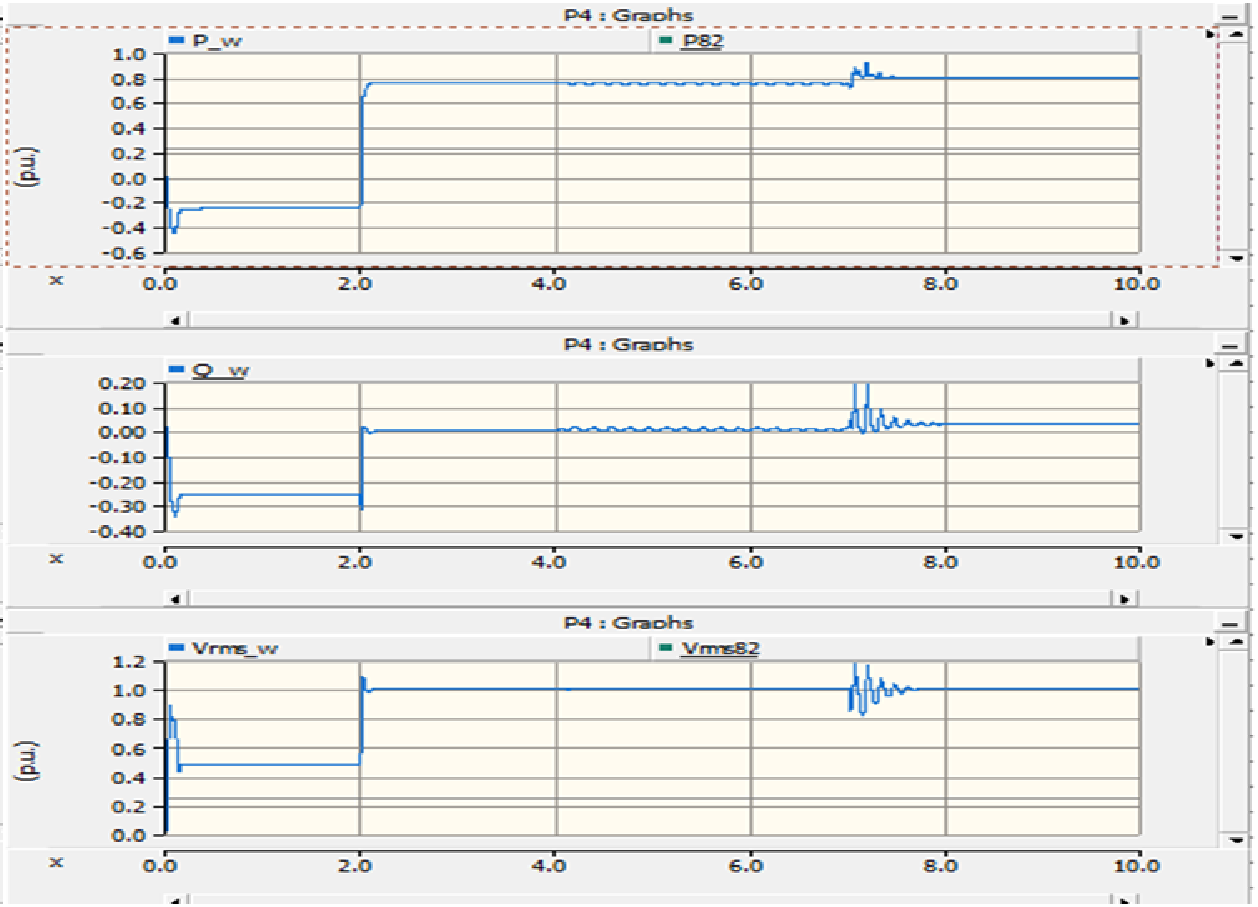
This is just one of the ways in which a grid forming converter can be constructed

Example application – 1

- Nine converters in the system, one equivalent voltage source
- At t = 2s, all converters are synchronized
- At t = 4s, the grid (equivalent voltage source) is disconnected
- At t = 7s, a converter is tripped



Without grid forming



With grid forming

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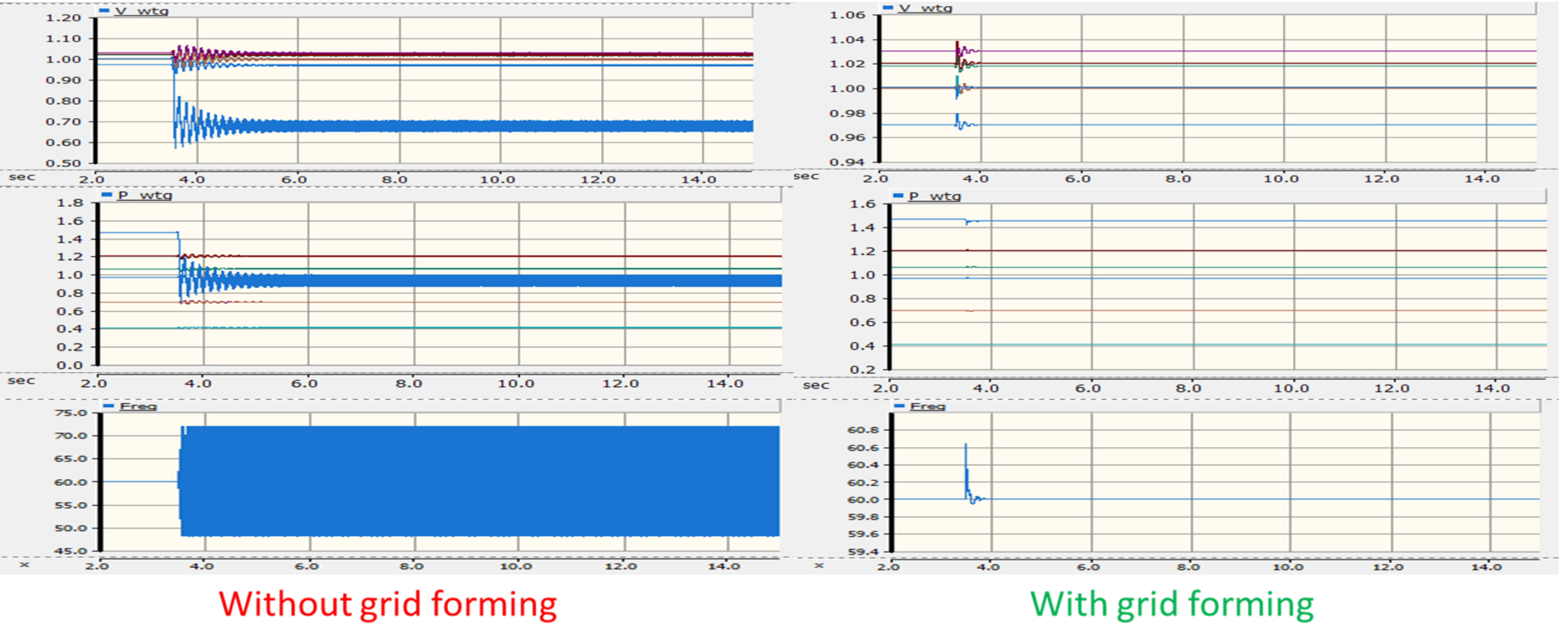
Example application – 2

- Seven converters in the system, two equivalent voltage sources
- At t = 3.5s, a line is opened without a fault.



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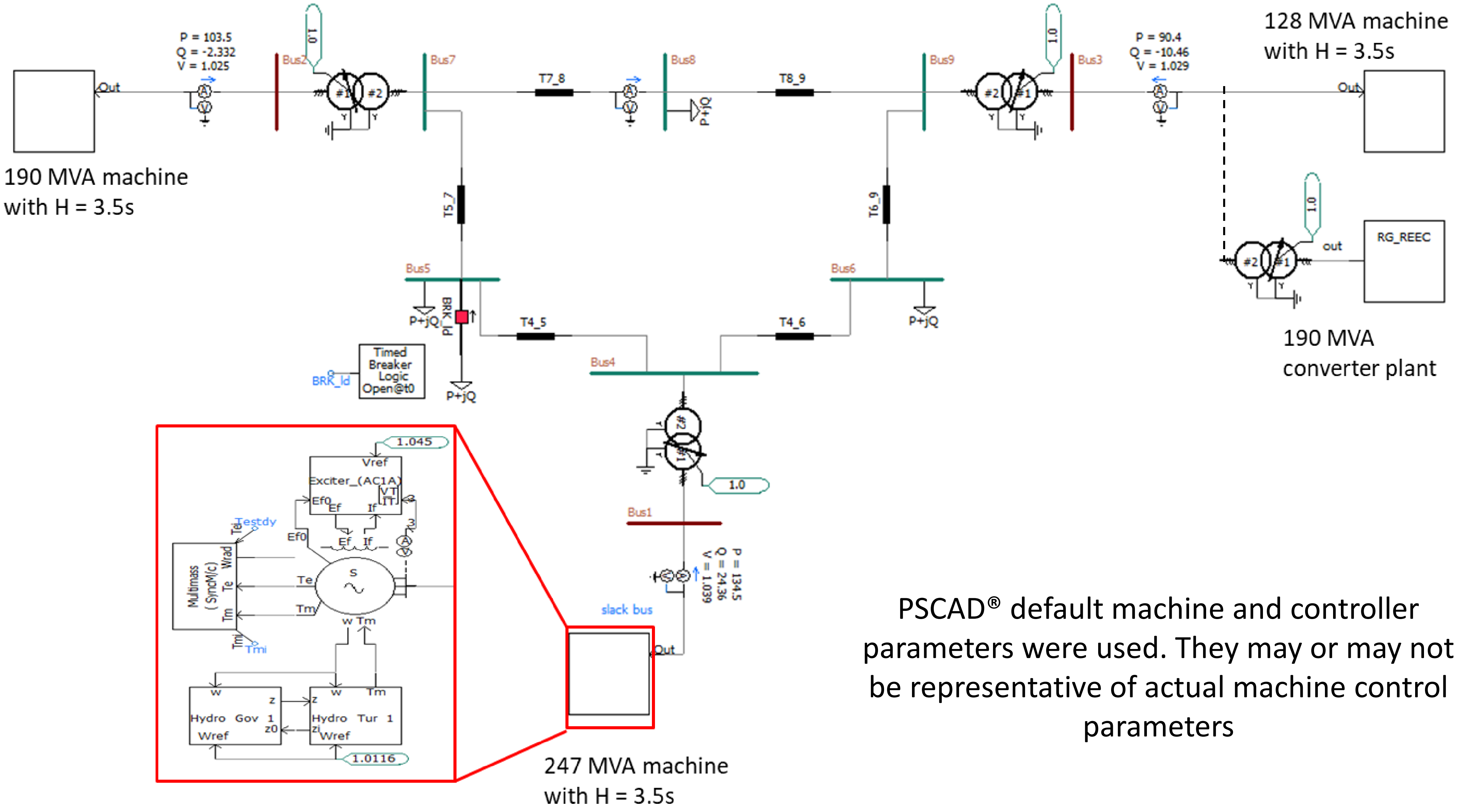
What about sharing of power…?

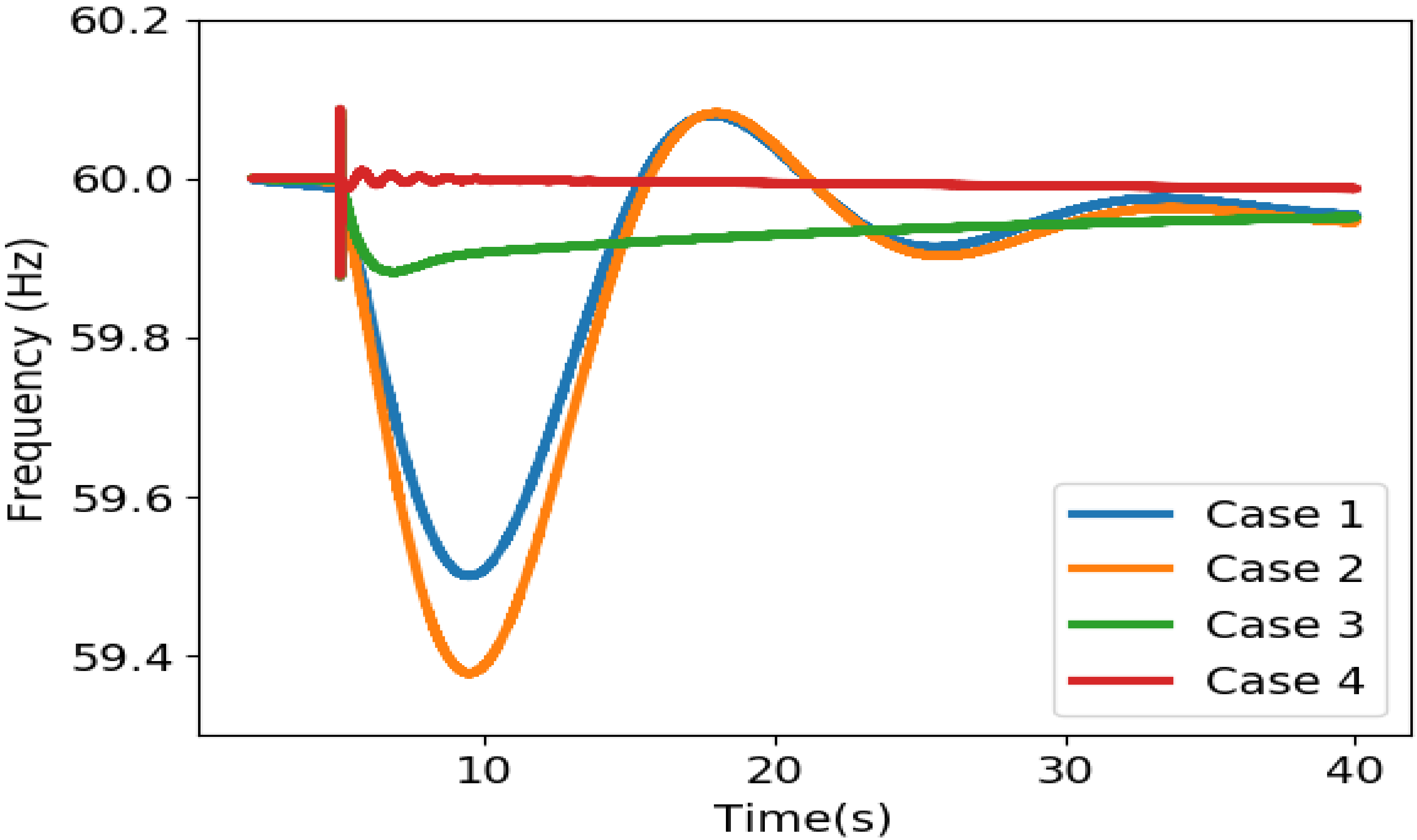
- Having a grid forming converter is good as converters can operate in a stable manner and inject current.
- However, it is now another converter on the system in addition to the many already present.
- So, how should the frequency of its sinusoidal way change with respect to a load/generation disturbance?
  - In a synchronous machine, this change occurs naturally due to deceleration or acceleration of the rotor.

Another example…



PSCAD® default machine and controller parameters were used. They may or may not be representative of actual machine control parameters

Movement of electrical frequency for load increase…

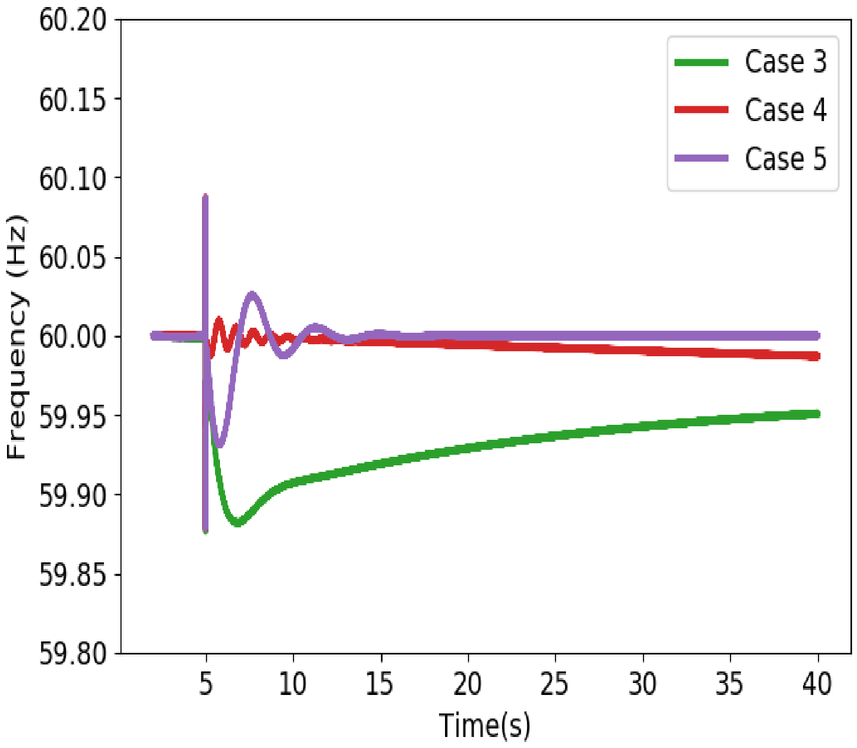


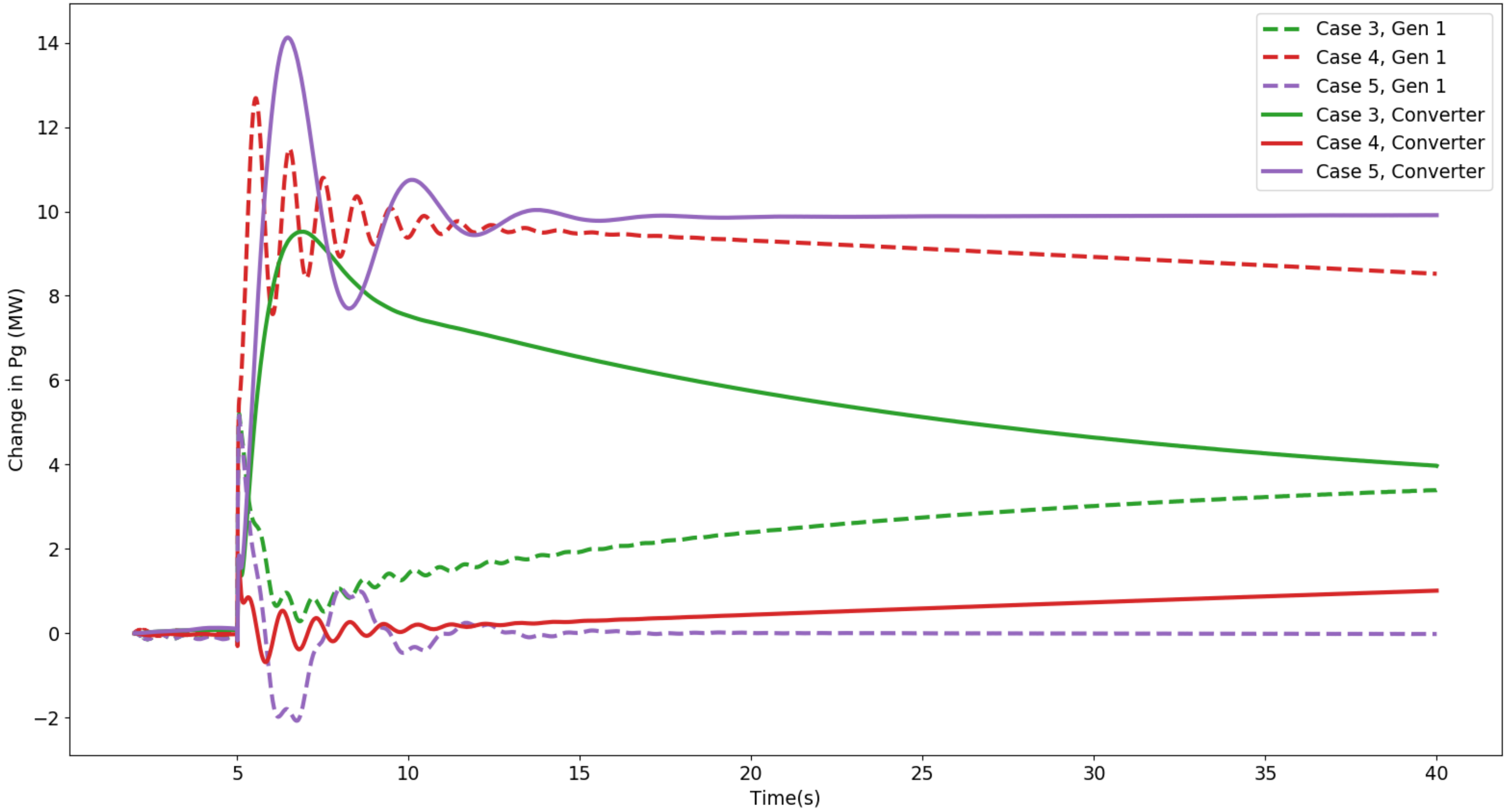
- Case 1 – all three machines in service, converter out of service
- Case 2 – converter replaces machine at bus 3
- Case 3 – converter abides by FERC Order 842
  - With headroom available
- Case 4 – large machine connected at bus 1.

From the perspective of only system frequency response is Case 4 an acceptable operational scenario?

Can the same response as Case 4 be obtained without a large machine…?

- Case 5 – Near ideal grid forming converter behaves almost as a pure voltage source
  - Steady voltage output and steady frequency output
    - Essentially constant frequency



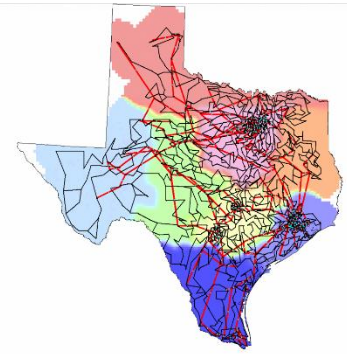


[1] D. Ramasubramanian, E. Farantatos, S. Ziaeinejad and A. Mehrizi-Sani, “Operation Paradigm of an All Converter Interfaced Generation Bulk Power System,” IET Generation, Transmission & Distribution, vol. 12, no. 19, pp. 4240-4248, Oct 2018.

[2] Mohammad Mousavi, Ali Mehrizi-Sani, Deepak Ramasubramanian and Evangelos Farantatos, “Performance Evaluation of an Angle Droop–Based Power Sharing Algorithm for Inverter-Based Power Systems,” 2019 IEEE Power & Energy Society General Meeting (PES), Atlanta, GA, 2019 [accepted for publication]

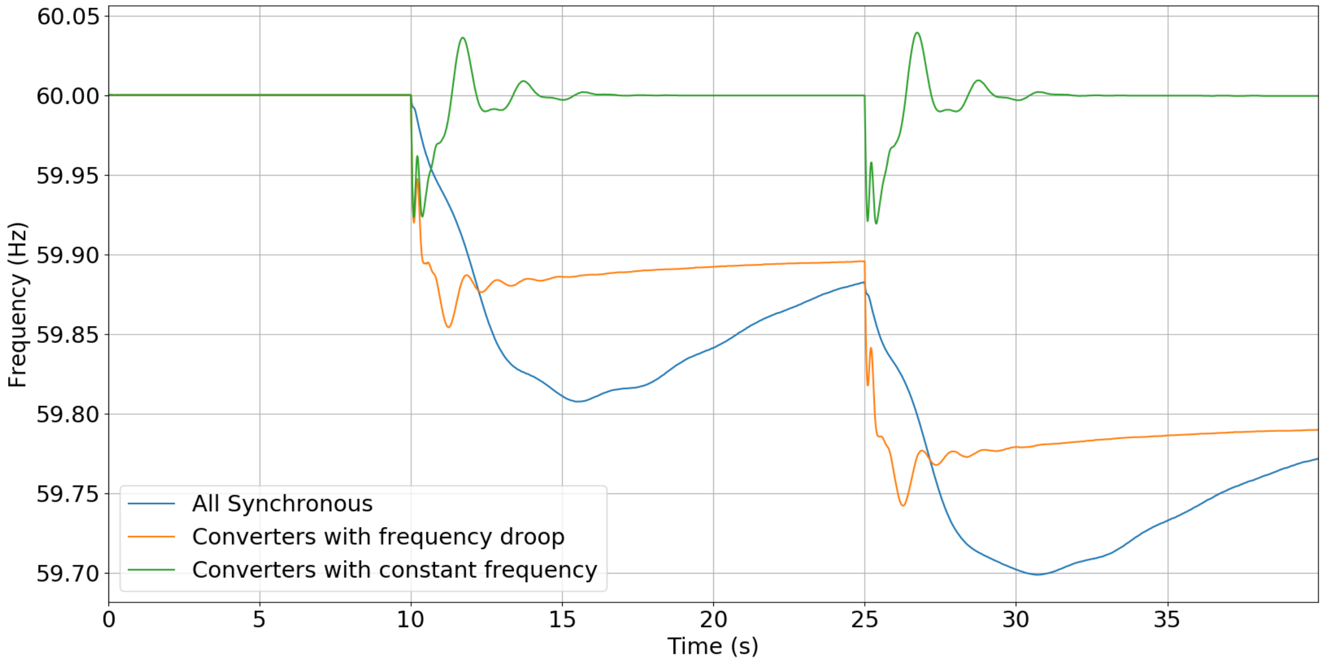
How would it translate to a large system…?

- Test System:
  - 2000 bus synthetic Texas system
- 3 Scenarios
  - All sources synchronous generators with governors
  - All converter sources with frequency droop control
  - All converter sources with constant frequency operation control

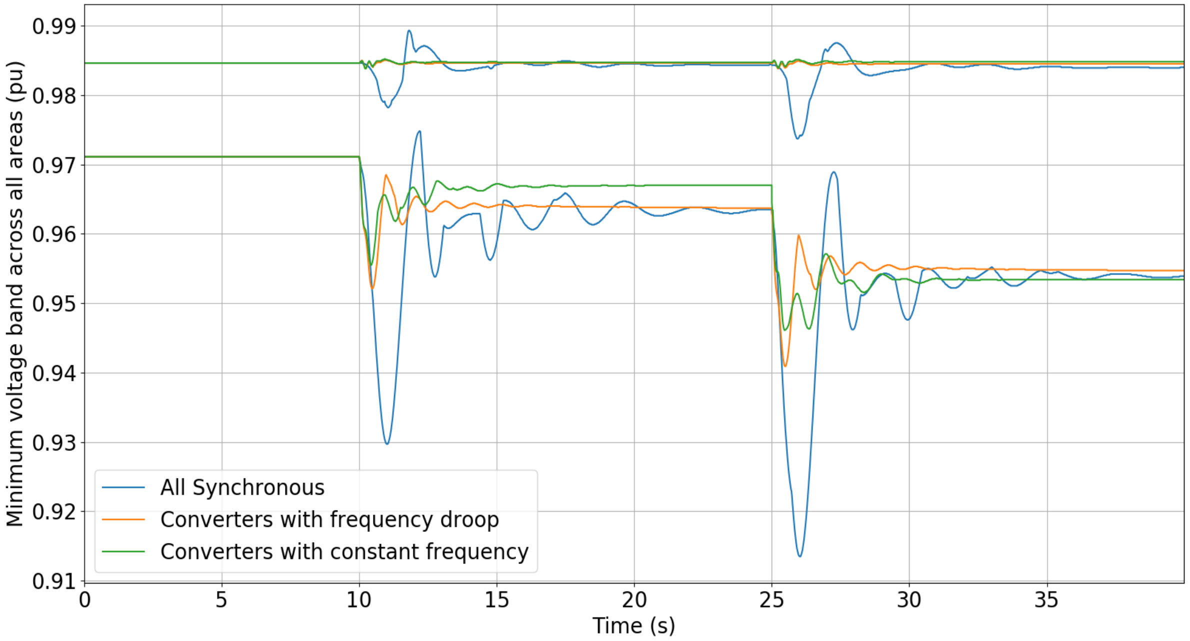


Source: http://icseg.iti.illinois.edu/synthetic-power-cases/texas2000-june2016/

Generation Trip – Frequency Response



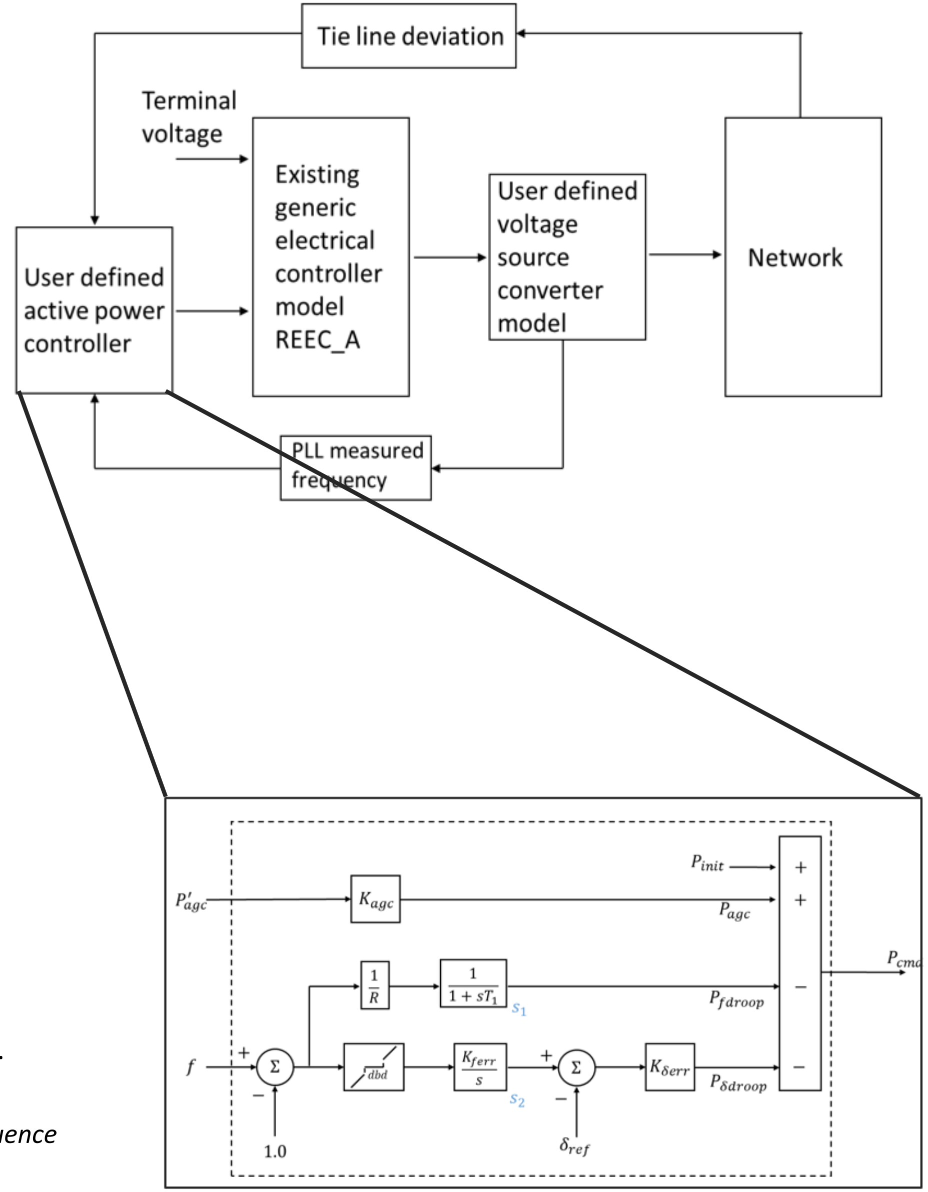
Generation Trip – Voltage Response



Would it work in a large system with synchronous machines present…?

	Source Type	Control Type
Case 1	All 433 synchronous machines	Simple governor and static excitation system
Case 2	417 grid forming converters	Constant frequency and voltage control
	16 synchronous machines	Simple governor and excitation system
Case 3	417 grid following converters	Constant frequency and voltage control
	16 synchronous machines	Simple governor and excitation system
Case 4	417 grid forming converters	Frequency droop and voltage control
	16 synchronous machines	Simple governor and excitation system
Case 5	417 grid following converters	Frequency droop and voltage control
	16 synchronous machines	Simple governor and excitation system

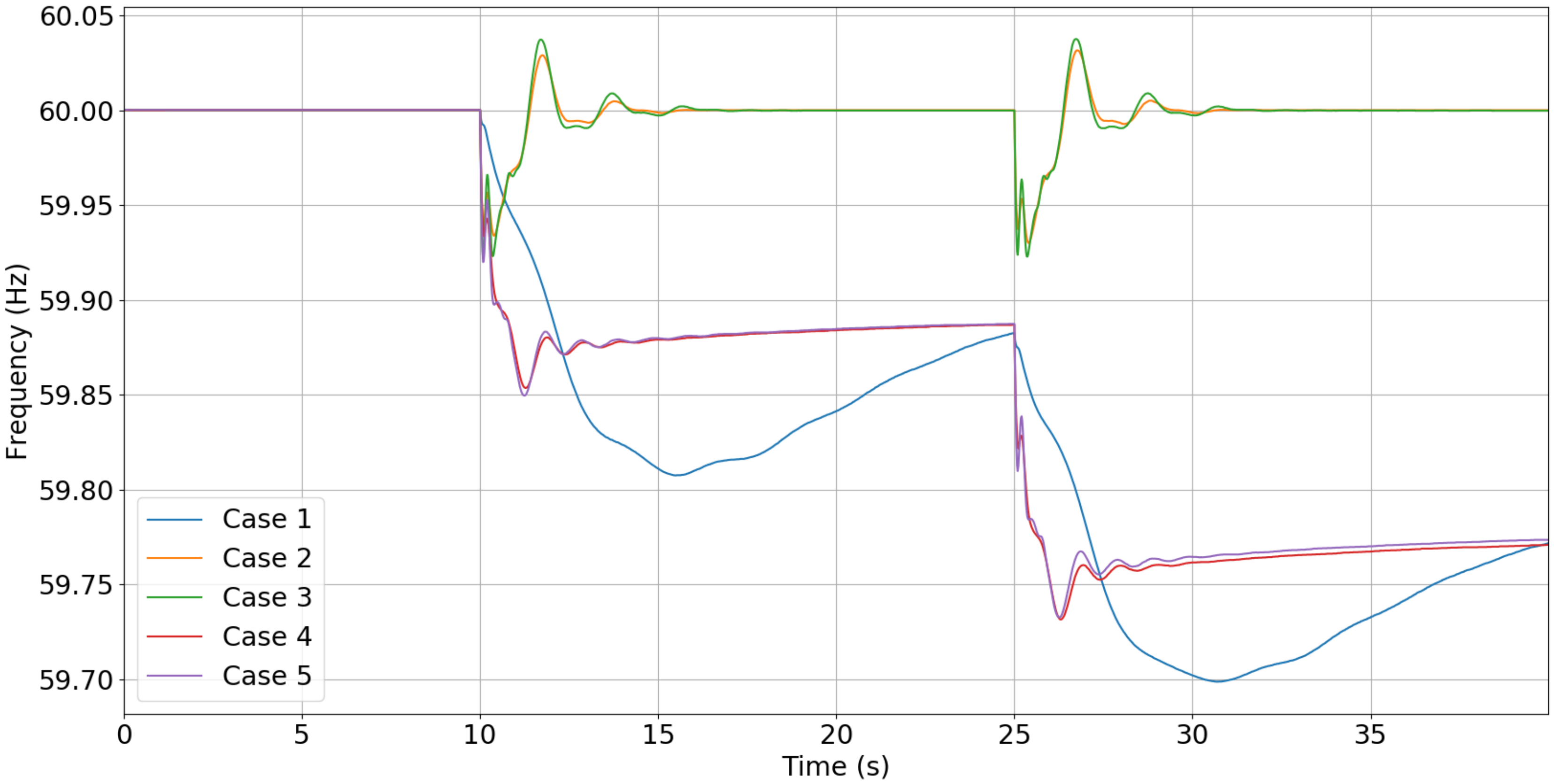
- In cases 2 – 5, sixteen synchronous machines are present in addition to IBR, accounting for around 16% of capacity (and 11% of MW) of all generation
- Inter area 'AGC' control has also been implemented



[3] *Grid Operation with 100% Inverter-Interfaced Supply Resources: Final Report*, EPRI, Palo Alto, CA: 2018, 3002014775. (https://www.epri.com/#/pages/product/000000003002014775/?lang=en-US)

[4] *Guidelines for Studies on Weak Grids with Inverter Based Resources: A Path from Screening Metrics and Positive Sequence Simulations to Point on Wave Simulations*, EPRI, Palo Alto, CA: 2018, 3002013639. (https://www.epri.com/#/pages/product/000000003002013639/?lang=en-US)

Generation Trip Response

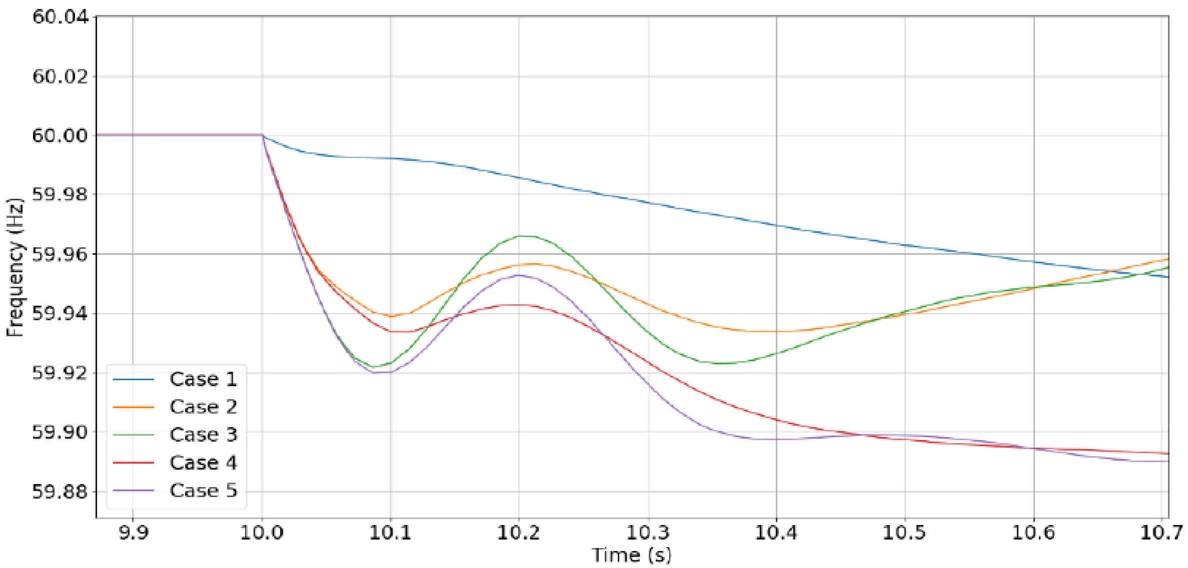


- Trip of two largest generators (approximately 1.2 GW each) sequentially at t = 10s and 25s

Robust power sharing and frequency control

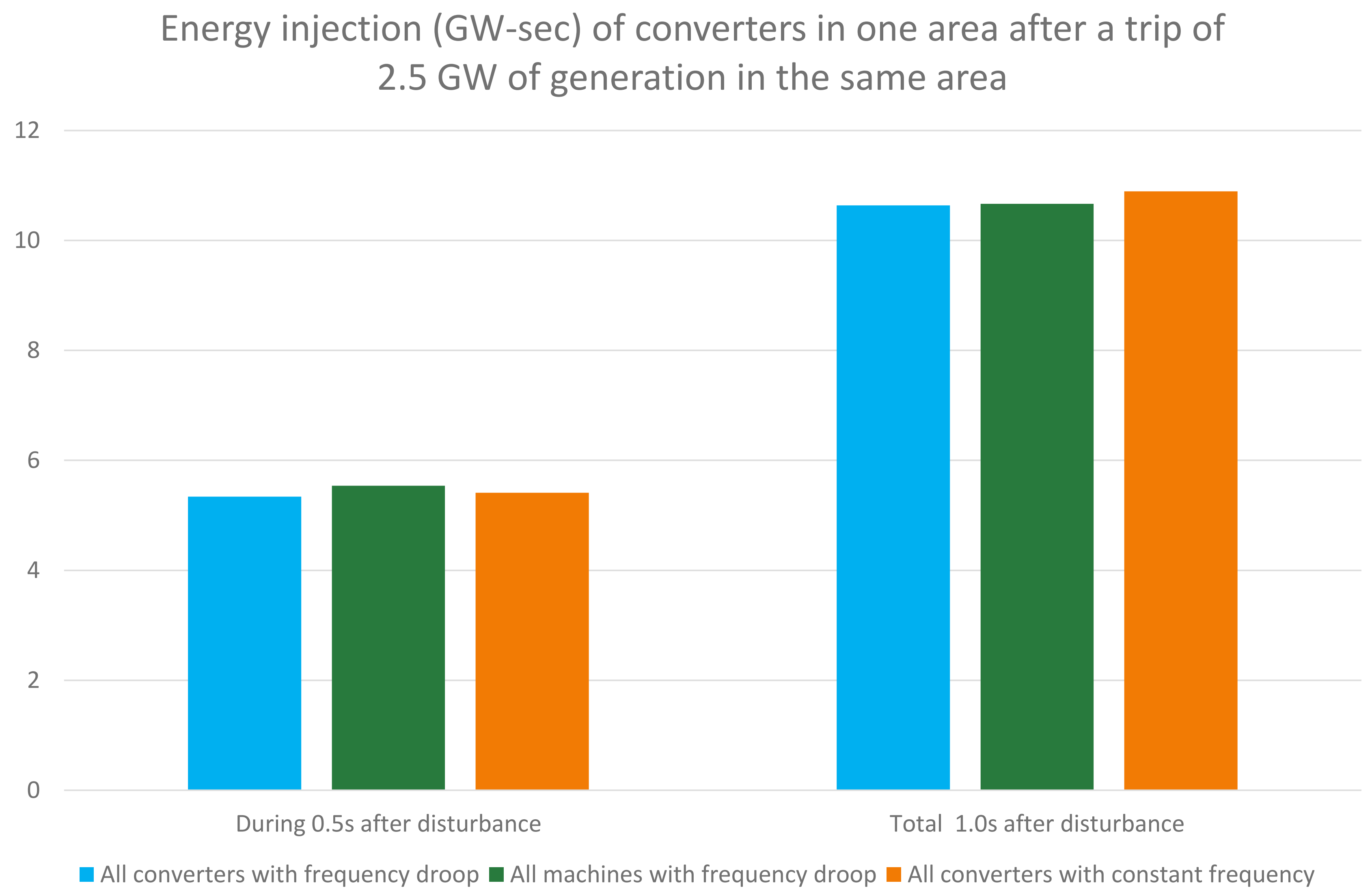
Rate of Change of Frequency (ROCOF)

Case	Frequency (Hz) at 10s	Frequency (Hz) at 10.5s	Rate of change (Hz/s)
1	60.0	59.962	$\frac{59.962 - 60.0}{0.5} = -0.076$
2	60.0	59.94	$\frac{59.94 - 60.0}{0.5} = -0.12$
3	60.0	59.94	$\frac{59.94 - 60.0}{0.5} = -0.12$
4	60.0	59.898	$\frac{59.898 - 60.0}{0.5} = -0.204$
5	60.0	59.898	$\frac{59.898 - 60.0}{0.5} = -0.204$

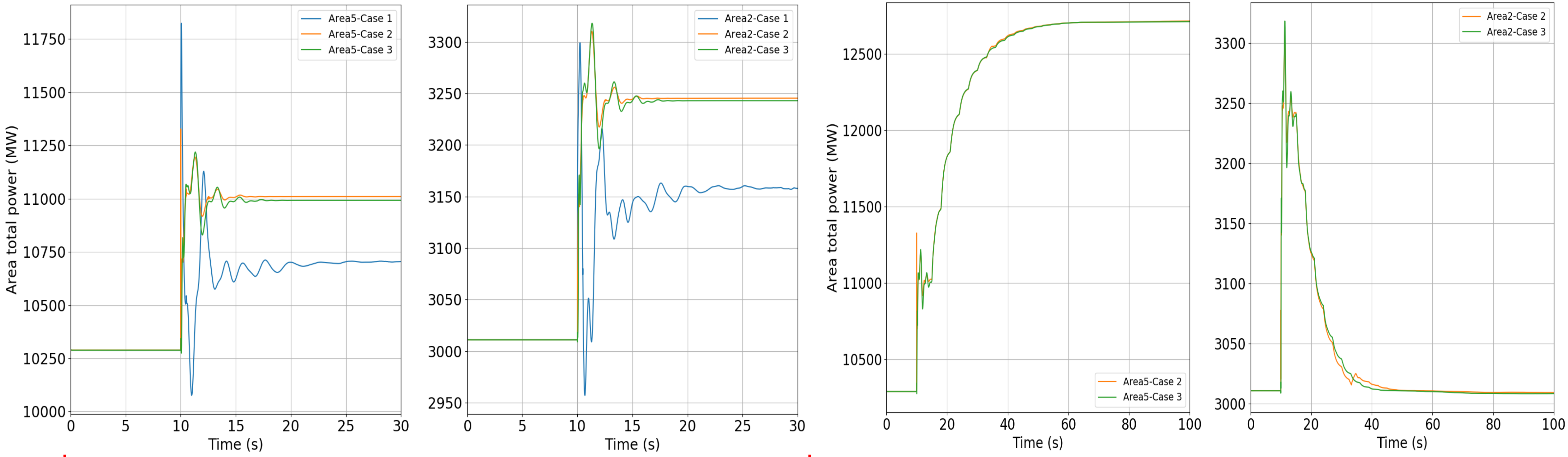


- ROCOF calculated at 10.5 secs
- System wide ROCOF increases in the presence of IBR
  - But at individual generator locations, well within the tolerance

Energy requirements based on converter control strategy…



Active Power Sharing Across Areas



Short term sharing

Long term sharing

- Event in Area 5
- Angle droop control allows for IBR in all areas to share the burden of generation – load imbalance
  - Sharing of power is inversely proportional to the electrical distance of a converter to the location of disturbance
- Power sharing amongst areas is achieved by monitoring flow of power across tie lines, and subsequently providing commands to IBR

Summary

Frequency Definition	• Maintaining nominal electrical frequency is important for the grid. • Deviation, or rate of deviation, of frequency from nominal is not important for converters as compared to synchronous machines
Grid Forming Converter/Constant Frequency System Operation	• Grid forming converter → constant frequency system operation • Development of converter models and associated controls in positive sequence and three-phase point-on-wave simulation platforms
Reliability Implications	• Can share power across sources and areas • Can maintain adequate and stable voltage profiles • Would need additional energy resources on the dc side of the converter

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