Modeling System Stability Behavior for System with 100% Converter Fed Generation

Deepak Ramasubramanian
Sr. Engineer Scientist
Grid Operations & Planning
dramasubramanian@epri.com

UVIG 2018 Spring Technical Workshop
14 March 2018

Tucson, AZ

Few immediate questions that come to mind..

Not discussed in this presentation

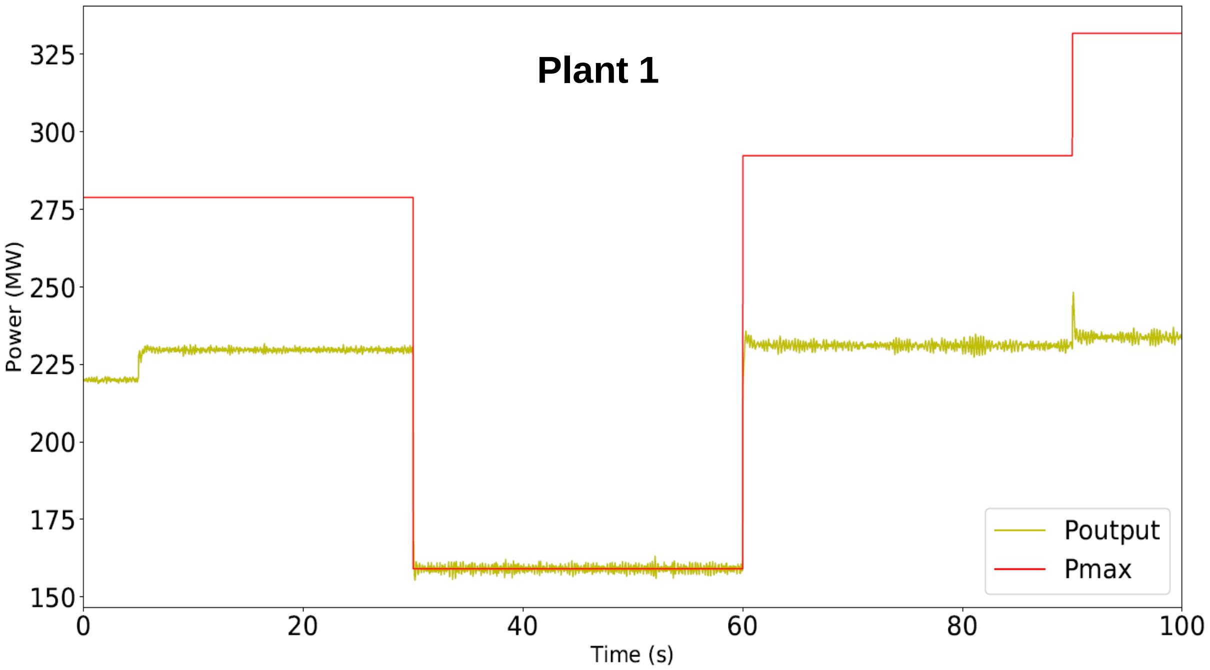
- How to handle the transition from a present system to future system?

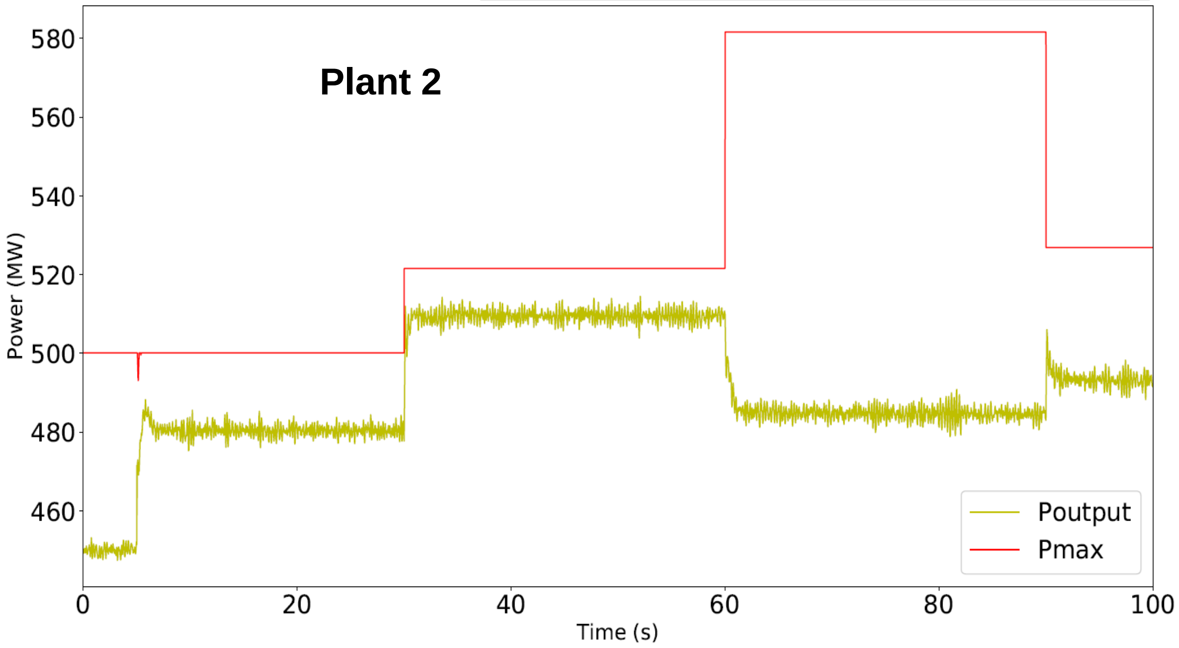
Discussed in this presentation

- Can we operate a system with all non synchronous sources?
- What kind of control mechanism will be required?
  - Do the converters have to be structured in a particular way?
- What will be the reliability of the system for extreme events?
- How to plan the system considering the uncertainty of resources?
- How would motor loads behave?

Stochastic Transient Simulation – Single Simulation Run

Simulation details in the appendix

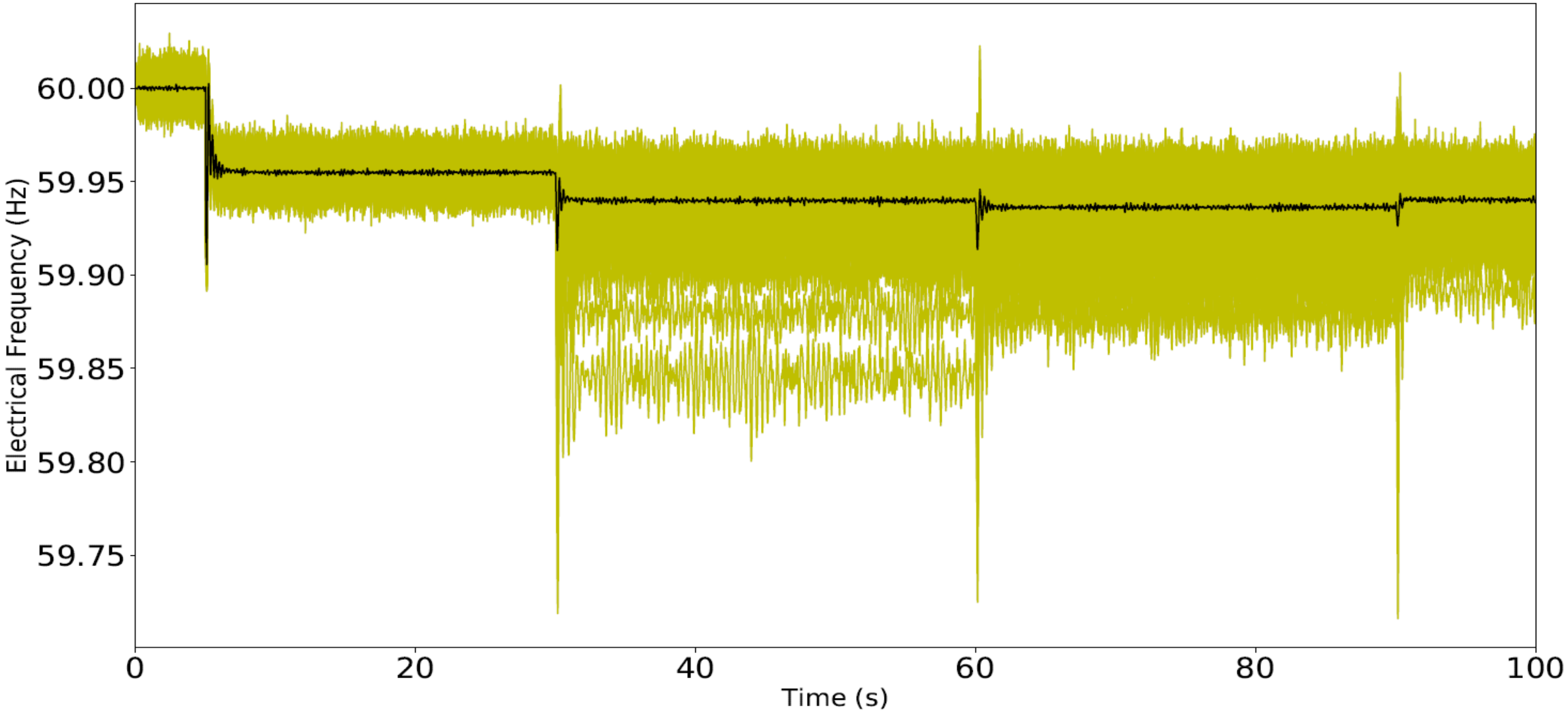




Observations

- Continuous “noise” due to induction motor load variation
- Wind speed variations reduce/increase available headroom
- Decrease in headroom from one plant results in other plants taking up the surplus
- Droop control based on evaluated electrical frequency at the terminal bus of the converter source
- Possibility for scenarios with no available headroom

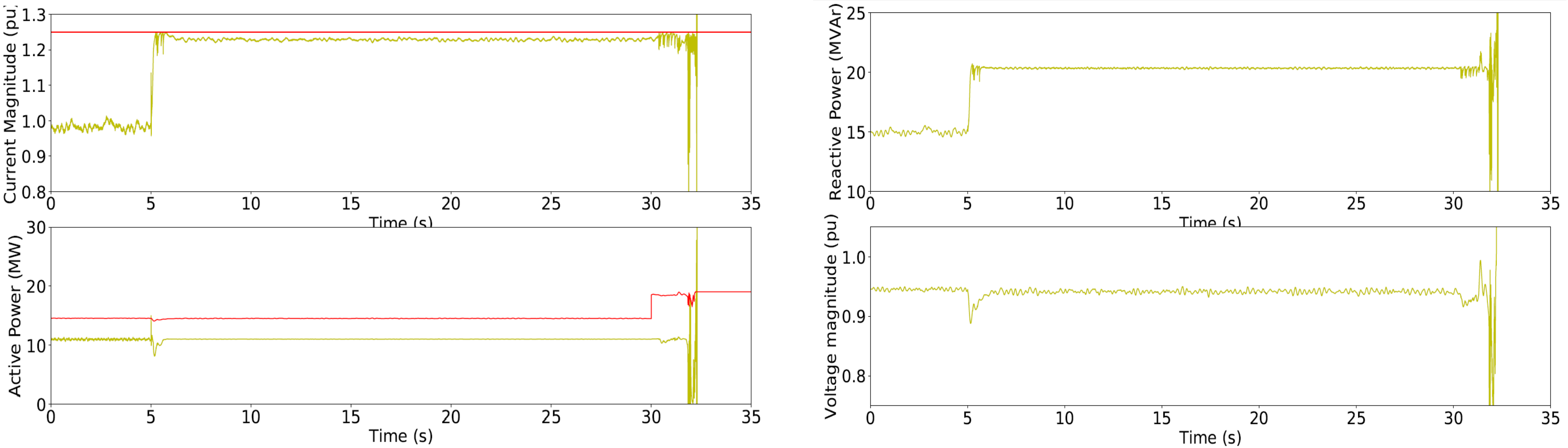
Monte Carlo Simulations



- 100 Monte Carlo simulation runs
- Monte Carlo simulations can capture extreme circumstances of reserve availability due to wind speed variability
- Large deviations in system mean frequency (olive colored curves) observed
- 7 simulation runs numerically diverged

Diverging Cases

In a 100% converter system, instability can simply relate to current injection deficit.

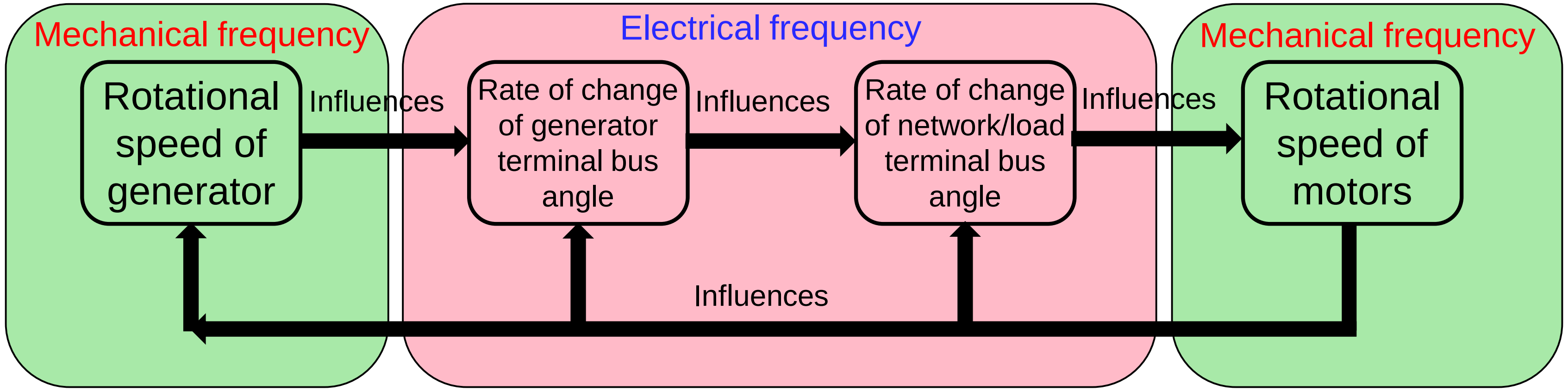


- The converter is already near its current limit following the load change due to increase in reactive power supply.
- Although active power headroom is available when the wind changes, current limit violation does not allow it and simulation diverges.

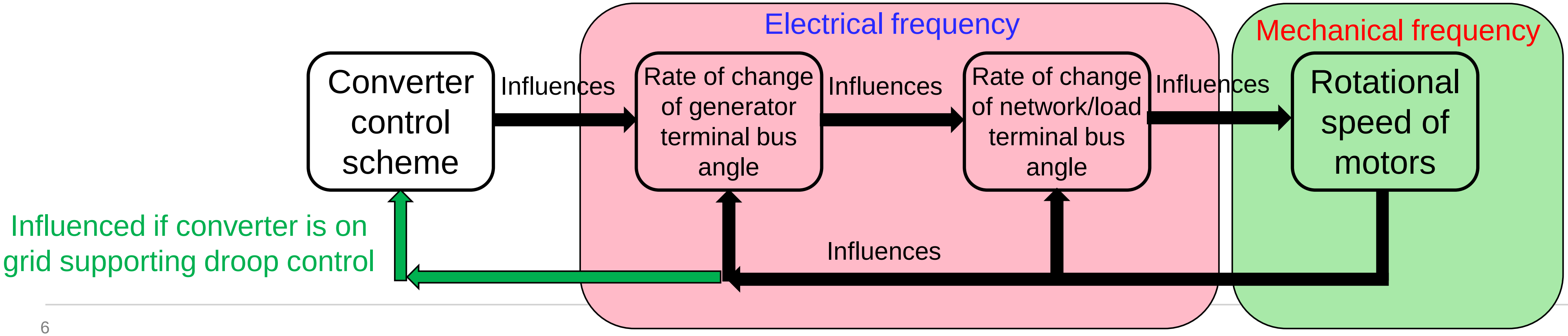
Conventional System Frequency vs. All-Converter System Frequency

Research Question: Frequency definition and its importance in an all converter system?

- Conventional system:
  - System frequency governed by speed of rotating machines.

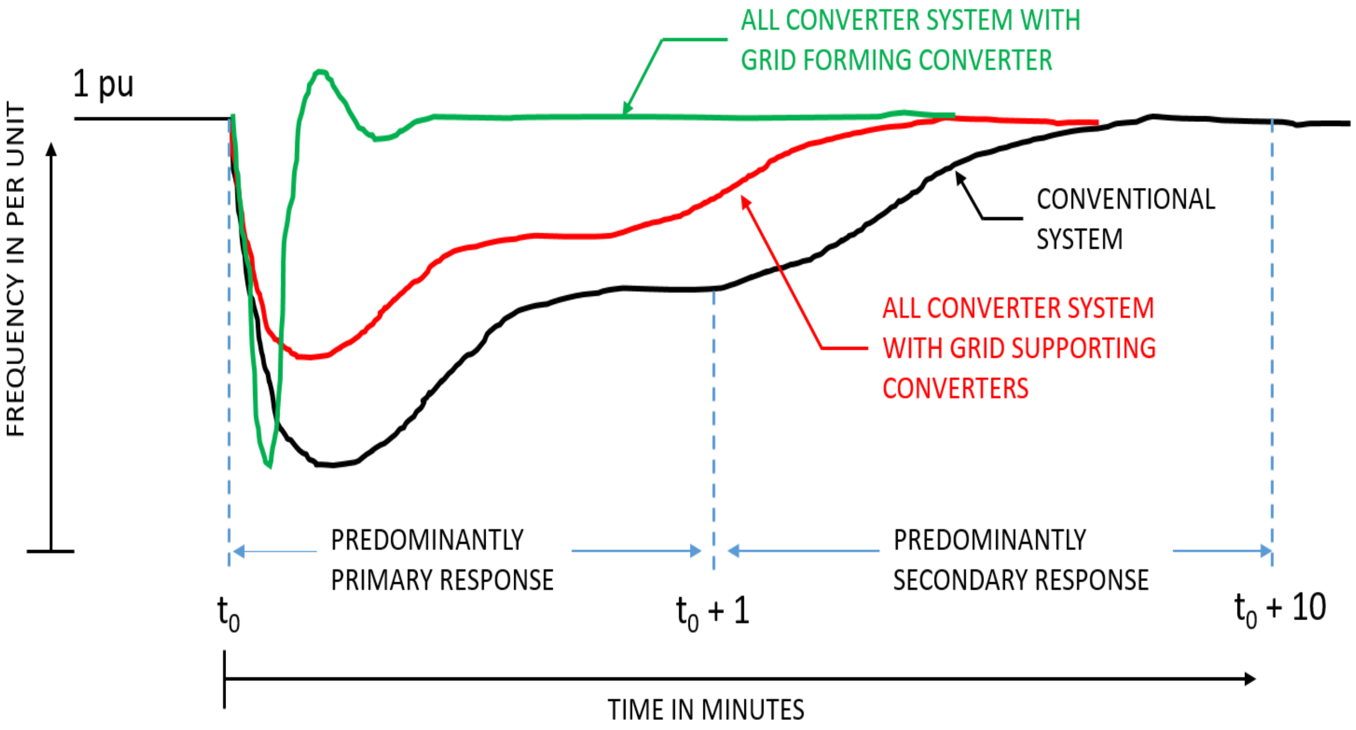


- All converter system:
  - No physical link between generation/load balance and frequency
  - Converters can operate at any frequency. Predominantly only electrical frequency



What is Constant Frequency System Operation & Why?

- Grid side converters have the capability to operate in a quick manner, with reduced mechanical constraints.
- Controlling the converter to mimic a synchronous machine operation could be restrictive with regards to the capability of a converter



Conventional system response to disturbance:

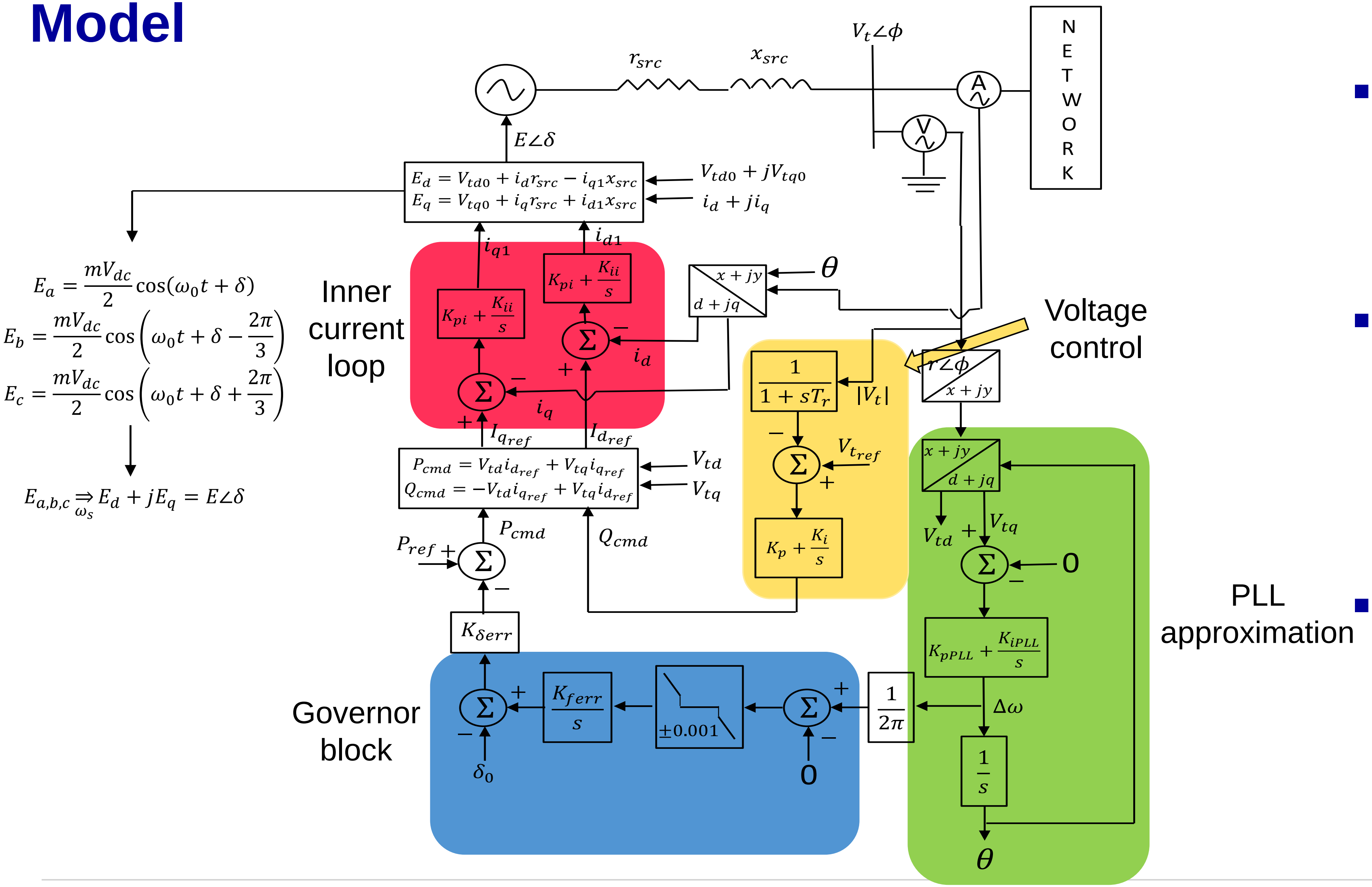
- Inertial response
- Primary frequency response to stabilize frequency: Timeframe ~ 1 minute
- Secondary frequency response to restore nominal frequency. Only the area affected takes up the burden. Timeframe ~ 10 minutes

All converter system with grid forming converter response to disturbance:

- Frequency restores to nominal value within seconds.

Open question: How will a BA’s ACE and CPS scores be calculated with such a constant frequency operation?

Constant Frequency Controlled Grid Forming Positive Sequence Model



$$E_a = \frac{mV_{dc}}{2}\cos(\omega_0 t + \delta)$$

$$E_b = \frac{mV_{dc}}{2}\cos\left(\omega_0 t + \delta - \frac{2\pi}{3}\right)$$

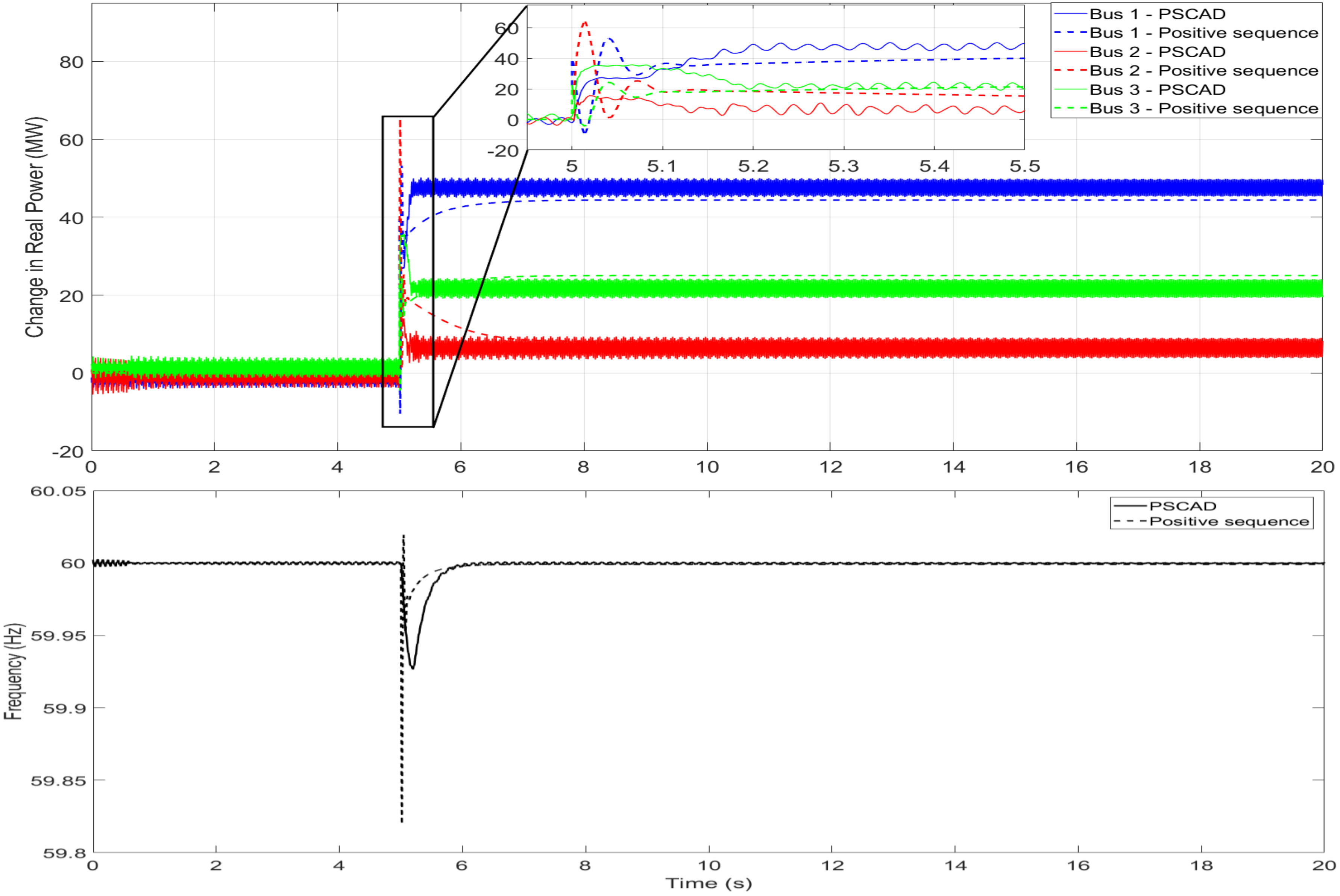
$$E_c = \frac{mV_{dc}}{2}\cos\left(\omega_0 t + \delta + \frac{2\pi}{3}\right)$$

$$E_{a,b,c} \underset{\omega_s}{\Rightarrow} E_d + jE_q = E\angle\delta$$

- Maintains the terminal voltage while limiting the amount of current output.
- Allows for having power sharing schemes with other energy sources in the network.
- A ‘means to an end’ model

Validation with Three-Phase point on wave Converter Models

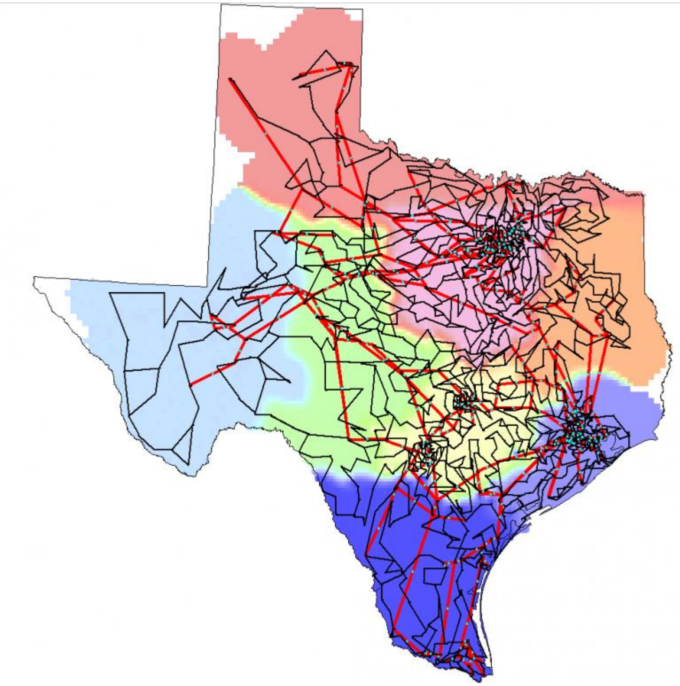
- Developed three-phase point on wave models of grid supporting and grid forming converters in PSCAD.
- Ascertain sufficiency of positive sequence models for large system studies.
- Load increase of 80MW with one grid forming and two grid supporting converters



In collaboration with Washington State University

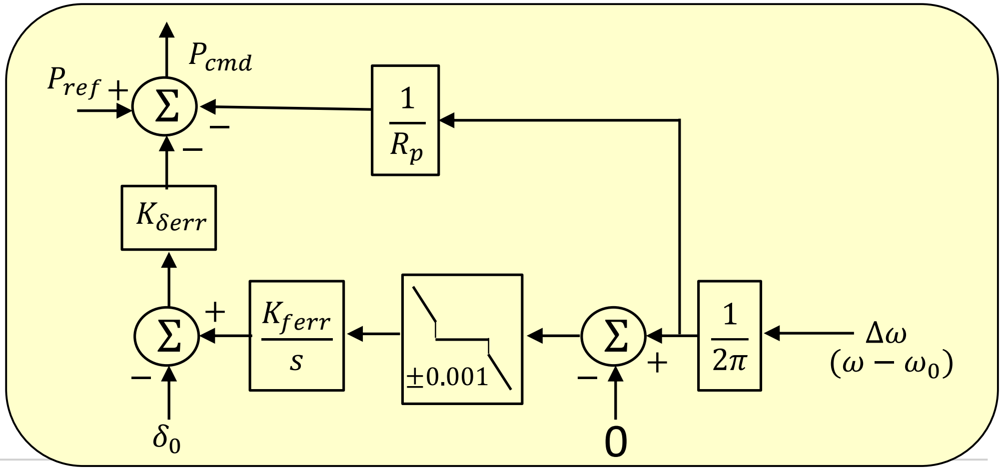
2000 Bus Synthetic Texas System

- Overview of the system:
  - 2000 bus system
  - 433 in-service sources
  - Total generation – 69 GW
  - Total load – 67 GW and 19 GVAr
  - Constant impedance representation of load
  - Two scenarios:
    - Scenario 1: All 433 sources represented by grid supporting converter with frequency droop.
    - Scenario 2: 432 sources represented by grid supporting converter with frequency and angle droop and one constant frequency controlled grid forming converter of 1600 MVA.

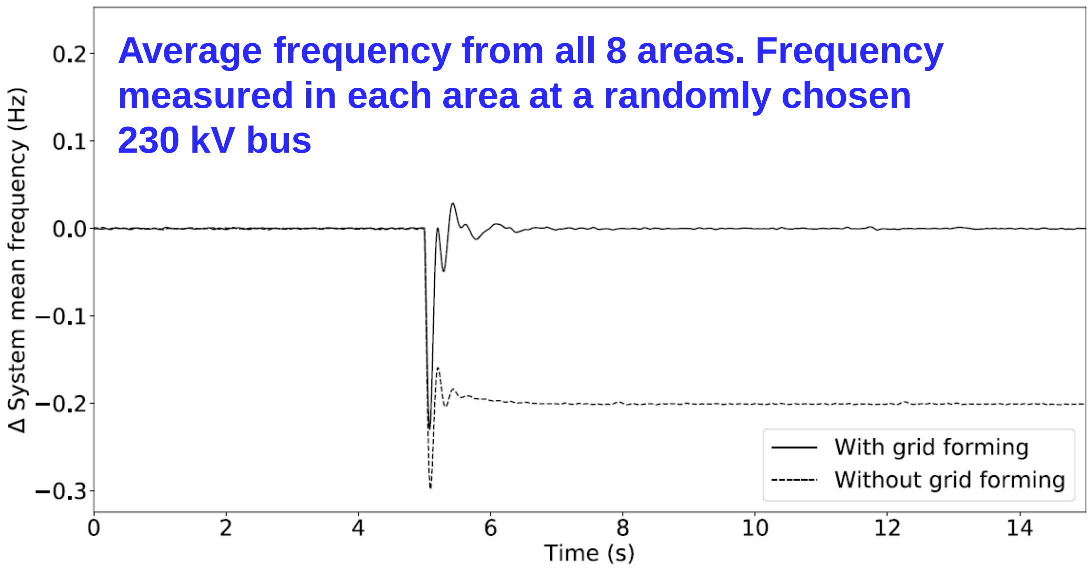


Source: http://icseg.iti.illinois.edu/synthetic-power-cases/texas2000-june2016/

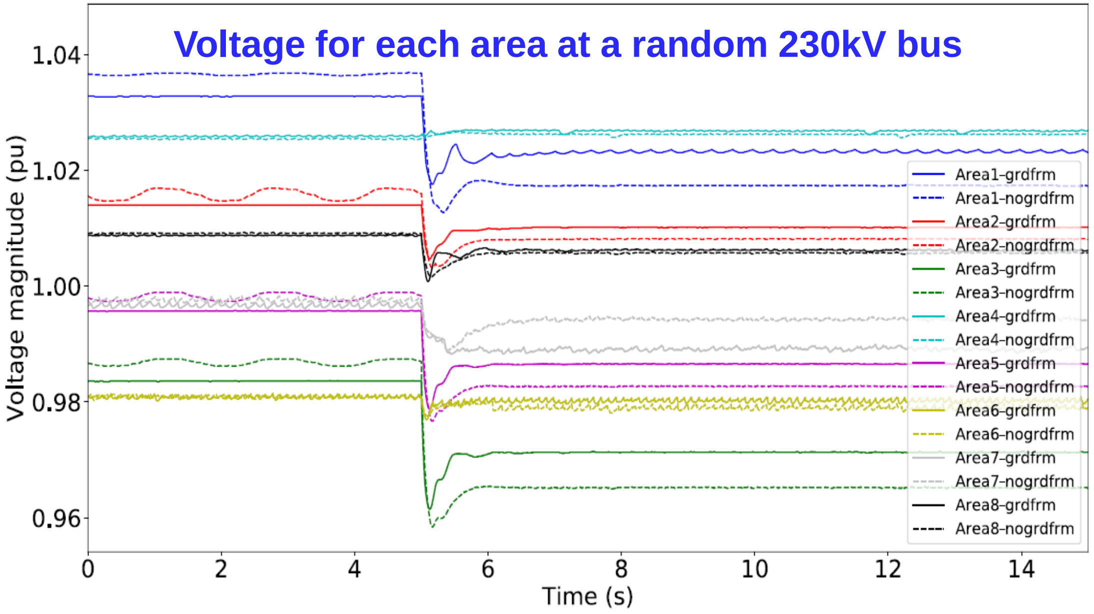
Frequency & Angle Droop



Simulation of generation outage

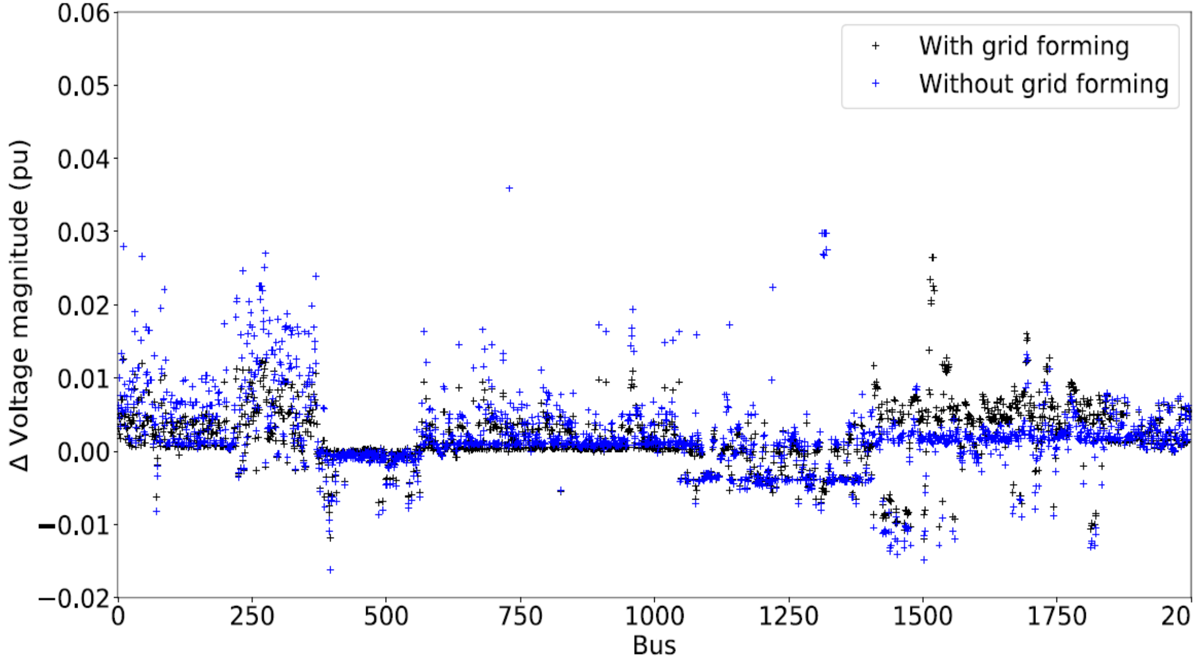


Average frequency from all 8 areas. Frequency measured in each area at a randomly chosen 230 kV bus



Voltage for each area at a random 230kV bus

Difference between voltage magnitude at t = 4.99s & t = 15s



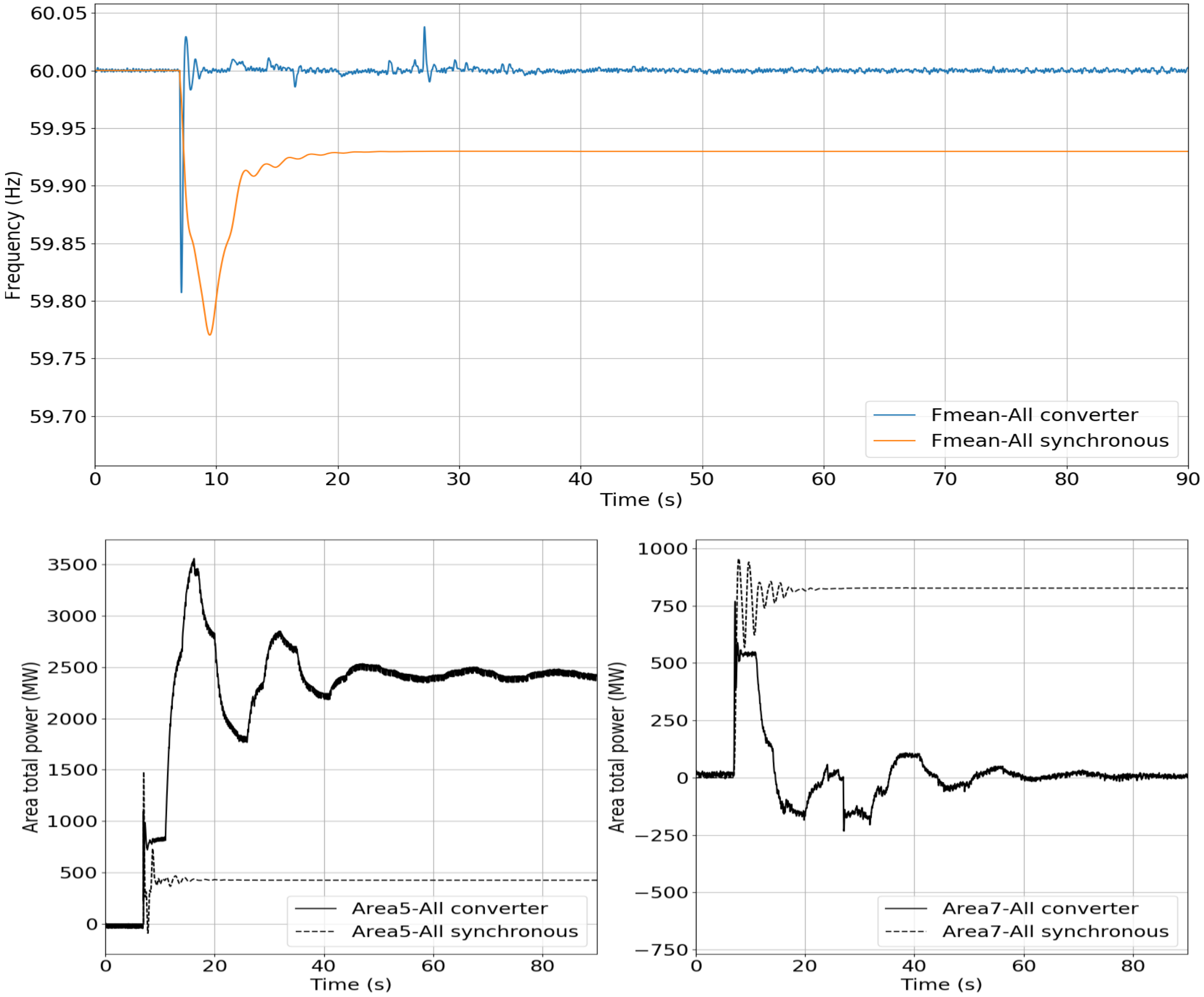
- Generation outage of 2569 MW
- Reliable operation of the system at constant frequency.
- Mode of operation: combination of conventional primary and secondary frequency response?

Implementation of Area Control

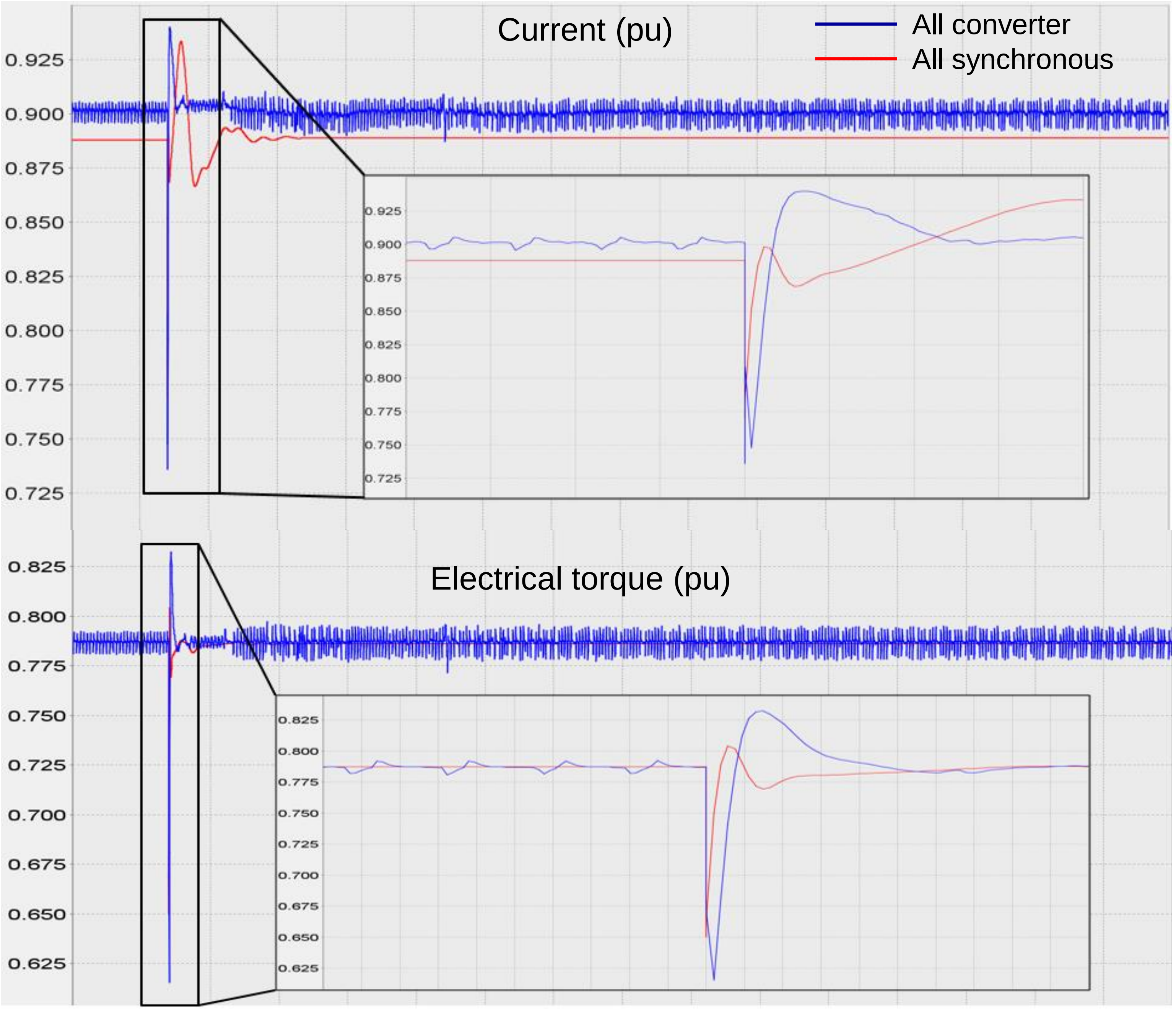
- A rudimentary ACE evaluation system was implemented:
  - Tie flows measured once in 2 seconds.
  - Output of ACE integral controller sent to individual energy source once in 3 seconds with a further low pass filter time constant of 1.0 second.
  - Assumed that all units in an individual area participate equally in secondary control.
- Load models:
  - $0.0 \text{ MW} < P_{load} \leq 20.0 \text{ MW}$ – Constant Impedance
  - $20.0 \text{ MW} < P_{load} < 60.0 \text{ MW}$ – Three phase induction motor ($H = 0.5s$, quadratic P vs ω)
  - $P_{load} \geq 60.0 \text{ MW}$ – Composite load model with NERC default data

Simulation of 2 GW Generation Outage in Area 5

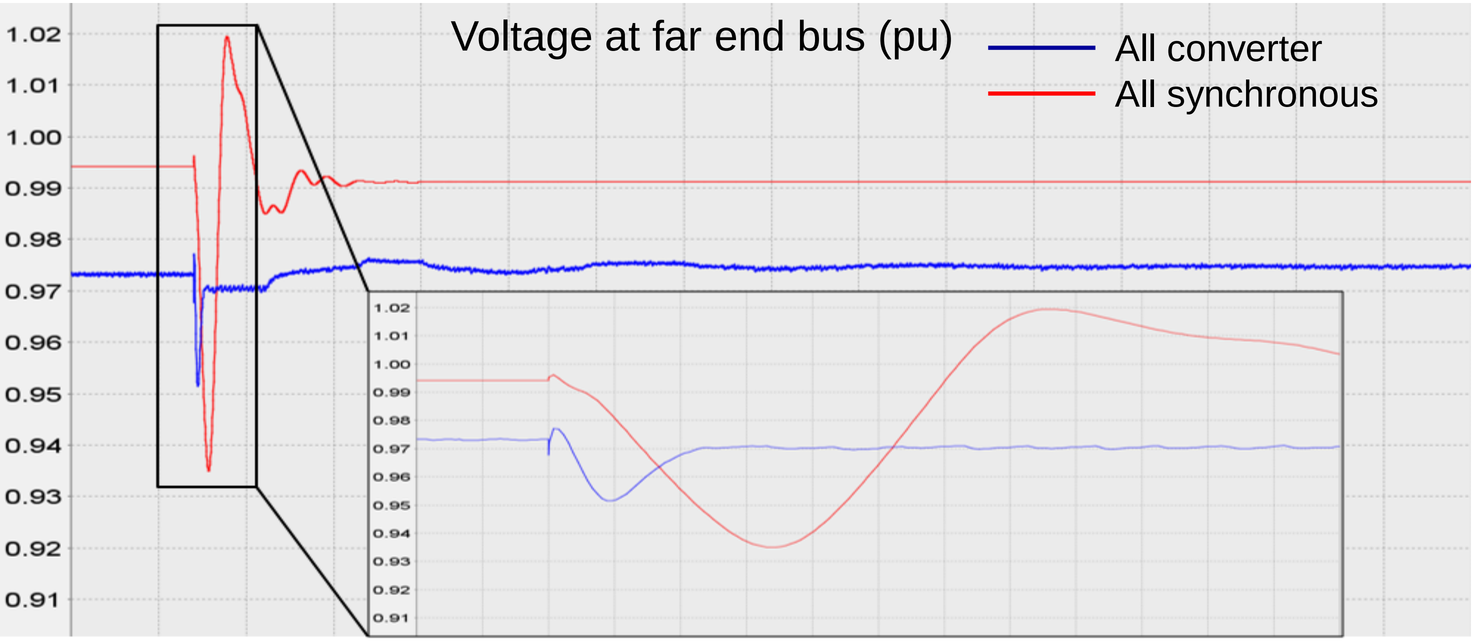
- Comparison with system response with all synchronous machines:
  - Round rotor generator
  - Basic thermal governor and static exciter
  - No area control
- Not a complete “pure” comparison – but the trend is representative of the present system operation paradigm.

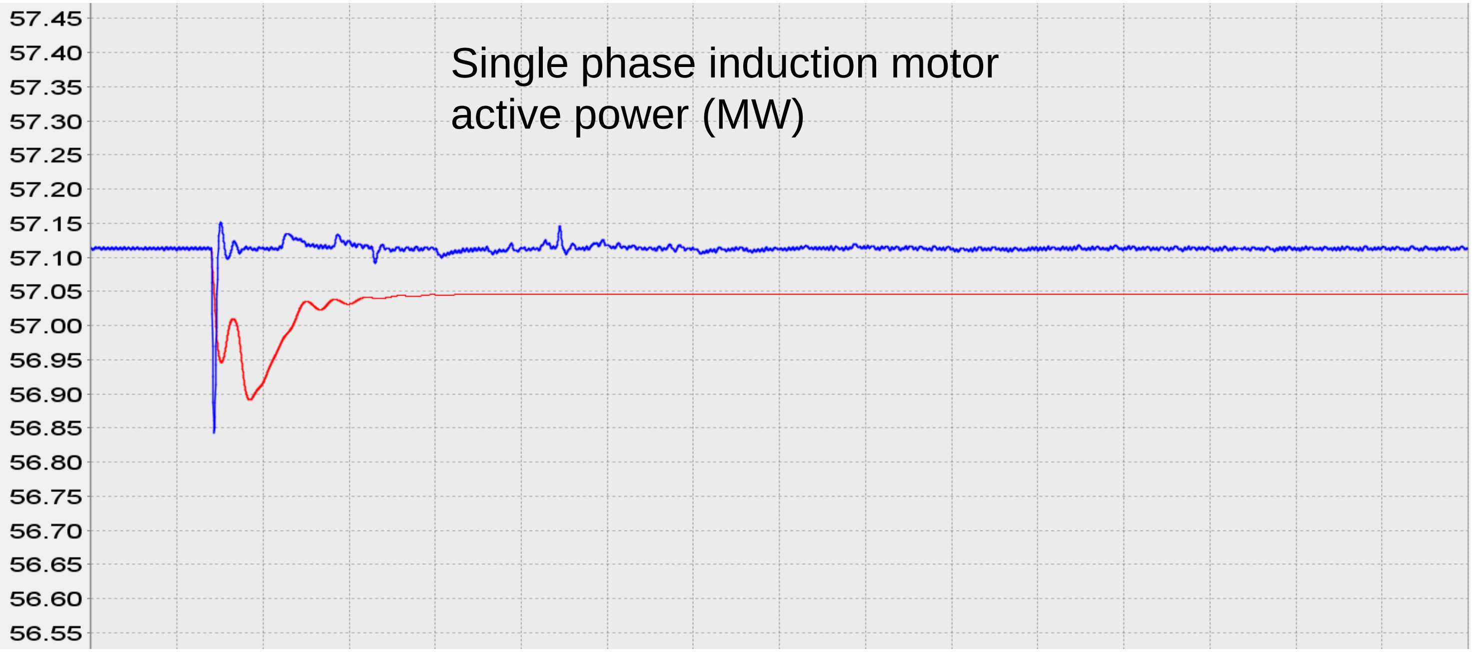


- Response of 63 MVA three phase induction motor in Area 5 with P_{load} = 55 MW
  - Large signal transient response is similar between an all synchronous case and all converter case.
  - Significant difference in small signal transient response primarily due to step deadband in angle droop loop



- Composite load model in Area 5 with total P_{load} = 240 MW
  - All synchronous operation results in some amount of single phase induction motor load tripping.
  - Voltage recovery at the far end bus superior during all converter operation.
- However, this is not a completely conclusive study and more analysis is required.





Conclusions, Open Questions & Next Steps

Frequency Definition

- In a power system with only converter-interfaced generating resources, the physical link between generation/load and frequency is lost due to the power electronics interface between the network and the energy source (frequency is no more related to the speed of rotating energy sources)

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

- Power sharing
- Voltage & reactive power control
- How would load dynamics affect the system behavior?
- Are the dynamics of source behind converter important for consideration?

Conclusions, Open Questions & Next Steps

Resource Uncertainty

- In an all converter system resource uncertainty will drastically affect reserve requirements and scheduling

Stochastic Transient Simulation Framework

- Need for longer time frame simulations to assess the effect of uncertainty between two dispatch intervals.
- Without slow evolving dynamics, long term simulations for planning studies including source uncertainties are feasible to implement using stochastic approaches
- Suitability of standard commercial simulation software for such simulations is to be investigated

Probabilistic Assessment of System Response

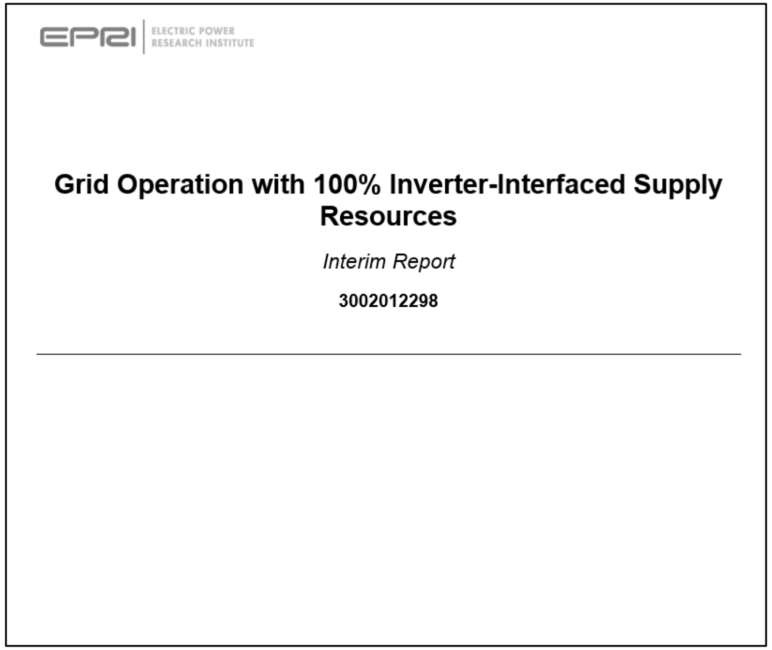
- Monte Carlo Simulations – Computationally challenging due to large number of random variables (resources uncertainty)
- Stochastic Response Surface Method – Computationally efficient. Provides a good conservative estimate of statistical characteristics of output parameters
- Probabilistic indexes in a risk-based analysis is to be explored

EPRI Reports on this project

1. Report: **PID# 3002012298**

2. Webcast Recording & Slides: **Link Below**

https://membercenter.epri.com/Sectors/0TIZ12/pages/eventdetails.aspx?eventID=72815946-1141-4EB3-8AC3-8169D6F77240&eventScope=Cockpit&referer=EVENT_LIST



Grid Operation with 100% Inverter-Interfaced Supply Resources

Interim Report

3002012298

Grid Operation with 100% Inverter-Interfaced Supply Resources

Deepak Ramasubramanian
Sr. Project Engineer, Grid Operations & Planning

Evangelos Farantatos
Technical Leader, Grid Operations & Planning

EPRI Webcast
December 15 2017

Questions & Feedback?

Together…Shaping the Future of Electricity

Appendix

Reliability Impacts of Wind/Solar Uncertainty in a 100% Converter-Based System

Research Question: With resource uncertainty, how to identify and plan for limited reserve scenarios?

- Sudden uncertain change in wind speed/solar irradiation reduces/increases **power headroom** & thus **reserve**.
- **Loss of headroom** in one renewable plant has to be compensated with available headroom in another plant.
- What is the grid response if **no available headroom** is left or converter **current limit** has been hit?
- Requirement for **longer time** frame simulations of large systems.
- All converter based generation system: Uncertainty in all generation sources → **Extremely large number** of Monte Carlo simulations to capture the entire search space of the random variables.
- Need for **probabilistic scenarios assessment** including information on scenarios of system instability due to inadequate power reserves

In this work: Developed a stochastic transient simulation framework to simulate system behavior between dispatch signals

Wind Plant Stochastic Modeling & Process in Stochastic Transient Simulation Framework

Wind Plant Stochastic Model

Wind speed – Weibull distribution

$$Wind_{PDF}(v) = \begin{cases} \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} e^{-(v/\lambda)^k} & v \geq 0, \\ 0 & v < 0 \end{cases}$$

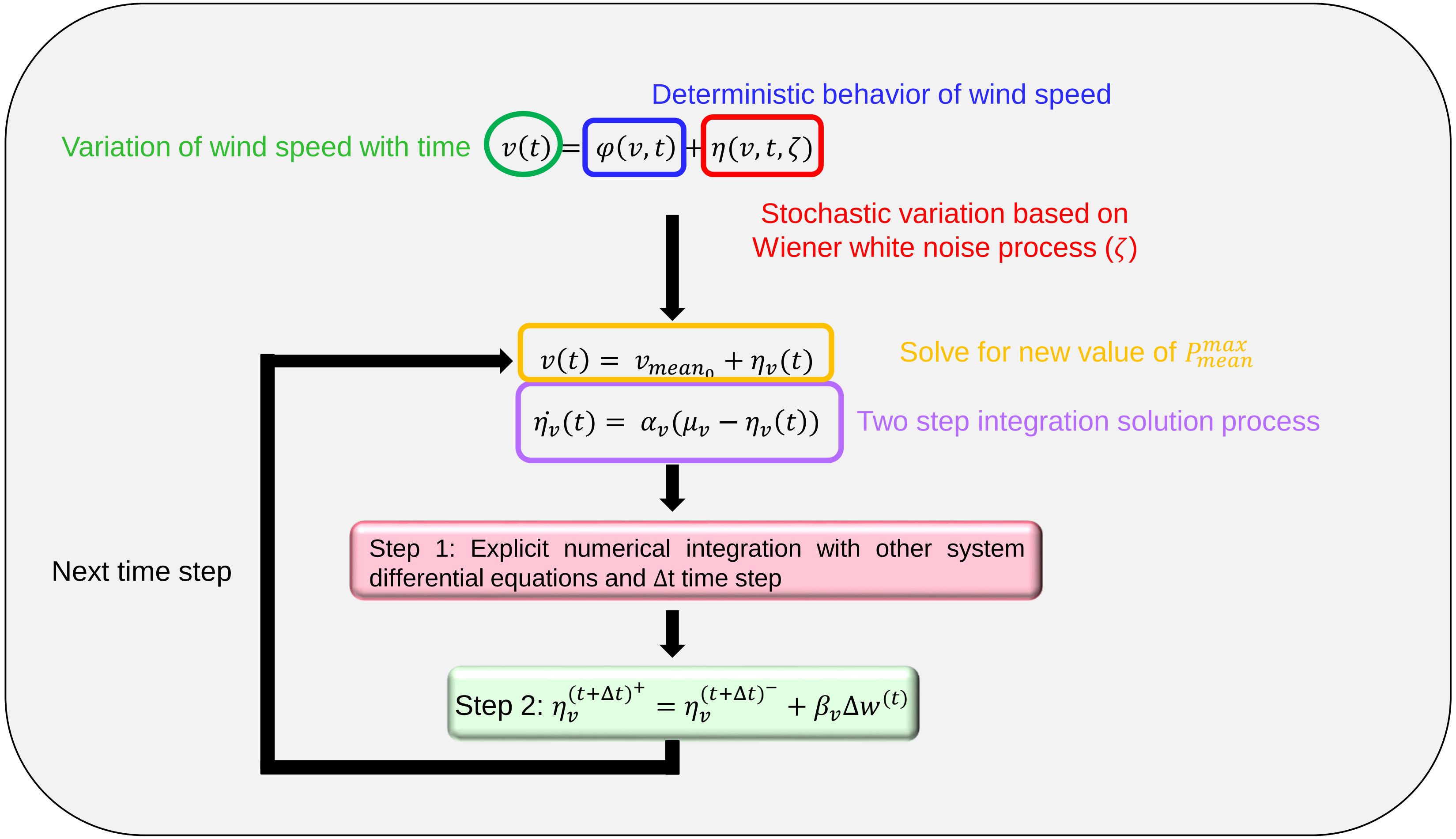
Power output of turbine –
Quadratic polynomial function

$$P_{wind}(v) = \begin{cases} 0 & v \leq v_{CI} \text{ or } v > v_{CO} \\ P_{rated}\frac{v^2 - v_{CI}^2}{v_{rated}^2 - v_{CI}^2} & v_{CI} < v \leq v_{rated}, \\ P_{rated} & v_{rated} < v \leq v_{CO} \end{cases}$$

Power output of plant –
Cumulative distribution over
mean wind speed range.

$$P_{mean}(v_{mean}) = \Delta v \left[\sum_{v=0}^{20} Wind_{PDF}(v)\, P_{wind}(v)\right]$$

Stochastic Transient Simulation Methodology



Deterministic behavior of wind speed

Variation of wind speed with time $v(t) = \varphi(v,t) + \eta(v,t,\zeta)$

Stochastic variation based on
Wiener white noise process (ζ)

$v(t) = v_{mean_0} + \eta_v(t)$

Solve for new value of P_{mean}^{max}

$\dot{\eta_v}(t) = \alpha_v(\mu_v - \eta_v(t))$

Two step integration solution process

Step 1: Explicit numerical integration with other system differential equations and Δt time step

Step 2: $\eta_v^{(t+\Delta t)^+} = \eta_v^{(t+\Delta t)^-} + \beta_v \Delta w^{(t)}$

Next time step

Test System - Simulation & Modeling Assumptions

- IEEE 118 bus system
  - Loading level increased to stress the system
- All 54 generation units represented by a controlled voltage source converter.
  - Converters in Q priority mode with $I_{max} = 1.25pu$ and $I_{qmax} = 1.05pu$
- Single cage induction motor load placed on random 23 buses
- Remaining loads modeled as constant impedance
- Monte Carlo Simulations
  - Long time-frame simulation to assess effect of uncertainty between consecutive dispatch intervals.
  - Mean wind speed varied in 30 second intervals (Weiner process with zero mean and standard deviation of 0.1)
  - Large increase of various loads totaling 127 MW at t=5 secs
  - Continuous load torque variation with zero mean distribution

Stochastic Response Surface Method (SRSM)

- In an all converter system the uncertainty of all resources would require an **extremely large number** of Monte Carlo simulations to capture all possible scenarios
- Stochastic Response Surface Method: Method to significantly reduce the number of Monte Carlo simulation runs while providing comparative results

Output parameter: $y = \sum_{i=0}^{N} a_i H_i(\Gamma)$ where,

$\Gamma = [\gamma_1, \gamma_2, \dots, \gamma_n]$ *zero mean normally distributed random variables*

$H_i(\Gamma)$ *Hermite polynomial of degree i*

a_i, q *coefficient and order of polynomial*

$N = \frac{(n+q)!}{n!\,q!}$ *maximum number of terms*

↓ for $q = 2$

$$y(t) = y_0(t) + \sum_{i=1}^{n} y_i(t)\gamma_i + \sum_{i=1}^{n} y_{ii}(t)\left(\gamma_i^2 - 1\right) + \sum_{i=1}^{n-1}\sum_{j>i}^{n} y_{ij}(t)\gamma_i\gamma_j$$

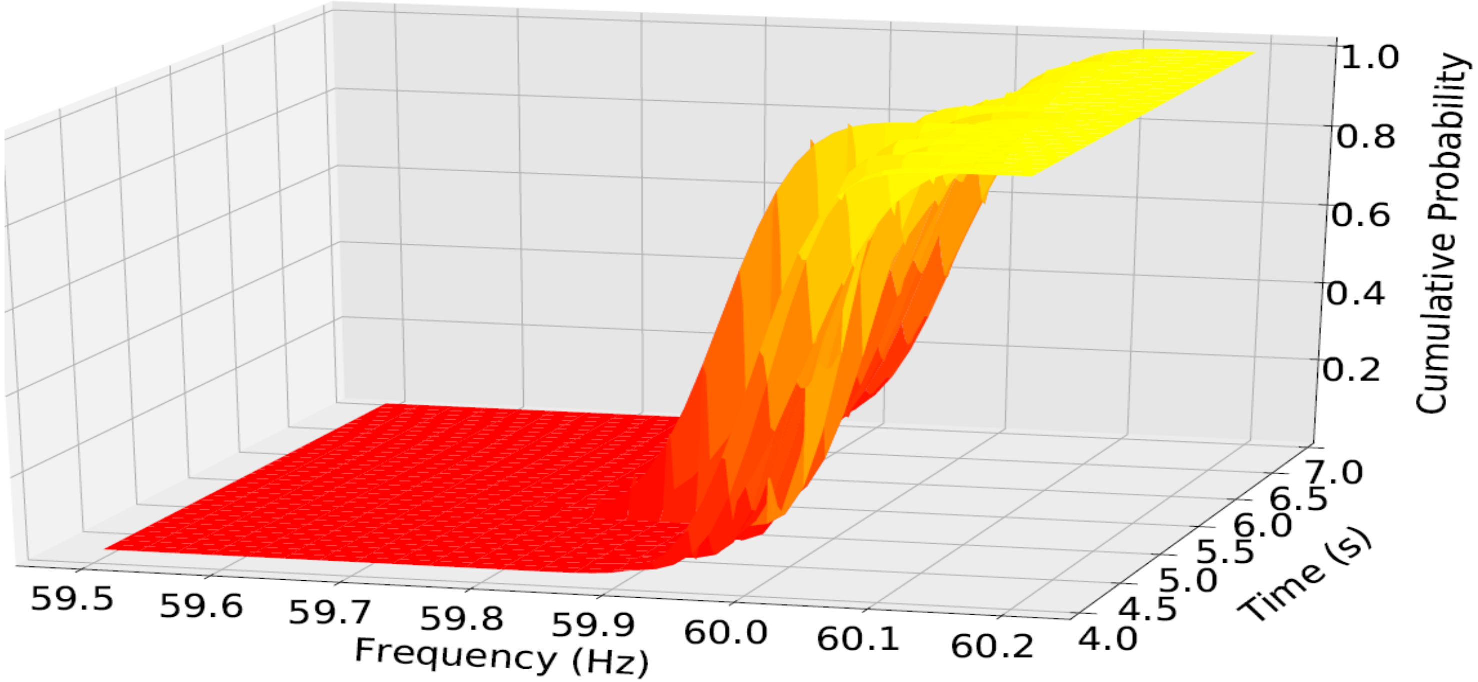
↓ and for also $n = 2$, $N = 6$

$$\begin{bmatrix} y_0(t) \\ y_1(t) \\ y_2(t) \\ y_3(t) \\ y_4(t) \\ y_5(t) \end{bmatrix} = \begin{bmatrix} 1 & \gamma_{1_1} & \gamma_{2_1} & \gamma_{1_1}^2 - 1 & \gamma_{2_1}^2 - 1 & \gamma_{1_1}\gamma_{2_1} \\ 1 & \gamma_{1_2} & \gamma_{2_2} & \gamma_{1_2}^2 - 1 & \gamma_{2_2}^2 - 1 & \gamma_{1_2}\gamma_{2_2} \\ 1 & \gamma_{1_3} & \gamma_{2_3} & \gamma_{1_3}^2 - 1 & \gamma_{2_3}^2 - 1 & \gamma_{1_3}\gamma_{2_3} \\ 1 & \gamma_{1_4} & \gamma_{2_4} & \gamma_{1_4}^2 - 1 & \gamma_{2_4}^2 - 1 & \gamma_{1_4}\gamma_{2_4} \\ 1 & \gamma_{1_5} & \gamma_{2_5} & \gamma_{1_5}^2 - 1 & \gamma_{2_5}^2 - 1 & \gamma_{1_5}\gamma_{2_5} \\ 1 & \gamma_{1_6} & \gamma_{2_6} & \gamma_{1_6}^2 - 1 & \gamma_{2_6}^2 - 1 & \gamma_{1_6}\gamma_{2_6} \end{bmatrix}^{-1} \begin{bmatrix} y\,(t, \Gamma_1) \\ y\,(t, \Gamma_2) \\ y\,(t, \Gamma_3) \\ y\,(t, \Gamma_4) \\ y\,(t, \Gamma_5) \\ y\,(t, \Gamma_6) \end{bmatrix}$$

→ $\mu(t) = y_0(t);\ \sigma^2(t) = \sum_{i=1}^{N-1} y_i^2(t)$

Stochastic Response Surface Method – Demonstrating Results

- 54 generation sources with uncertainty - 100 simulation runs would cover only a small portion of the random number search space.
- 1540 simulation runs were performed (instead of full Monte Carlo analysis)
- SRSM provides the cumulative probability of output parameter (e.g. frequency or voltage) at every time instant
- Provides the planning engineer with a probabilistic assessment of the system response upon an event



Ref: Deepak Ramasubramanian, Evangelos Farantatos, Aidan Tuohy and Vijay Vittal, "Investigation of the frequency response of an all converter-based generation power grid using a stochastic simulation framework," *16th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, Berlin, Germany, 2017