Panel Session: Finding the Sources of Sustained Oscillations – From Theory to Industry Practice

Theoretical Perspective of Forced Oscillations and Their Signatures

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Overview

- Small Signal Model
- Natural Responses
- Forced Responses
- Combined Responses
- Power System Simulation Examples
  - Two-Area System
  - IEEE 39 Bus System
  - miniWECC System
- ISO New England Event

Small Signal Model

- We assume a linear system with
  - Random inputs: often conceptualized as Gaussian White Noise due to small, random load changes
  - Deterministic inputs: considered here to be a periodic forcing function

$$f(t) = \sum_{m=1}^{\infty} 2|A_m| \cos(m\omega_o t + \angle A_m) = \sum_{m=-\infty}^{\infty} A_m e^{jm\omega_o t}$$

System Response

$$x_r(t) = \sum_{i=1}^{n} u_{i,r} \underline{v}_i \underline{x}(0) e^{\lambda_i t}$$ → Transient

$$+ \sum_{k=1}^{p_e} \left(\sum_{i=1}^{n} u_{i,r} \underline{v}_i \underline{b}_{e,k} e^{\lambda_i t} \right) * e_k(t)$$ → Ambient

$$+ \sum_{m=-\infty}^{\infty} \left(\sum_{i=1}^{n} u_{i,r} \underline{v}_i \underline{b}_f e^{\lambda_i t} \right) * \left(A_m e^{j m \omega_o t} \right)$$ → Forced

Function of the components of the state space model of the linearized power system and the system inputs (see task force report for details)

Transient Response

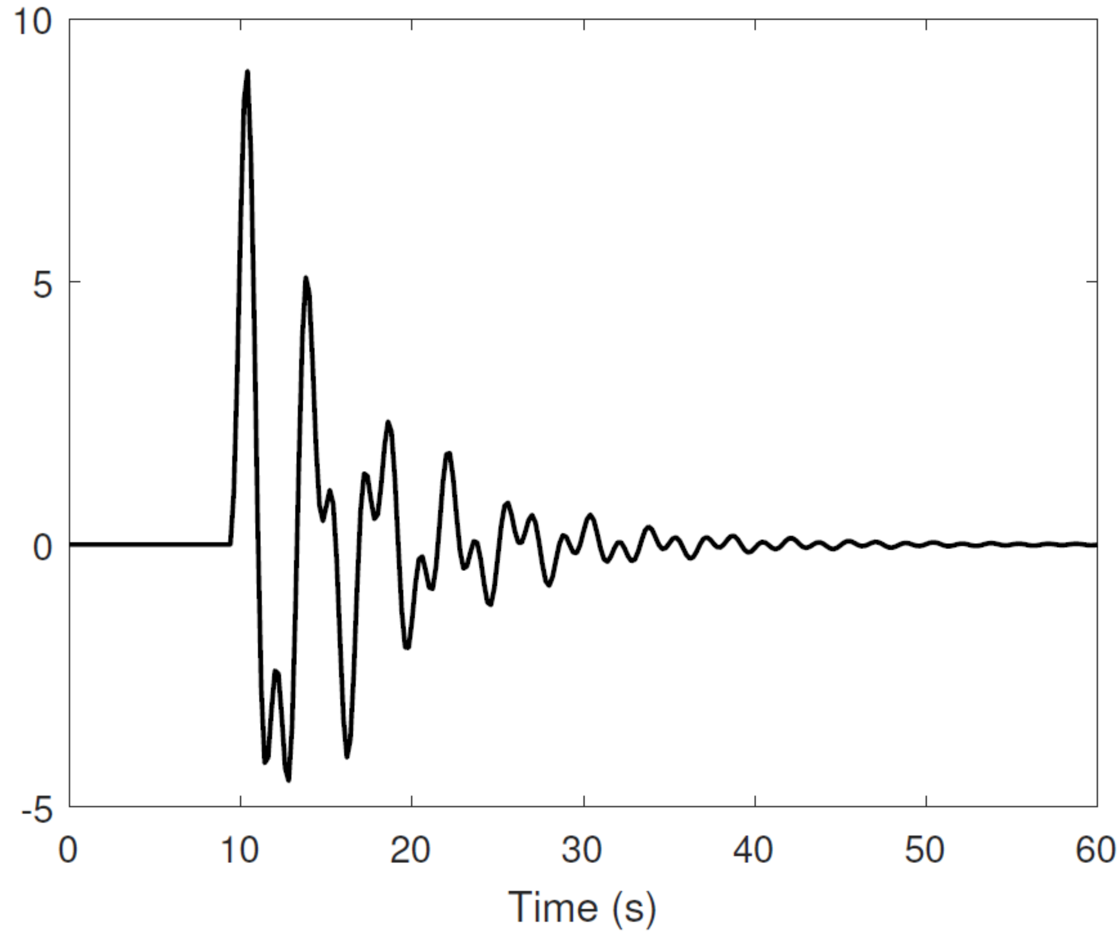
- Natural Response
- Deterministic signal comprised of a sum of damped sinusoids, one for each system mode
- For a particular mode,

$$x_{r,trans,i}(t) = u_{i,r}\underline{v_i}\underline{x}(0)e^{\sigma_i t}e^{j\omega_i t} = \beta_{i,r}e^{\sigma_i t}e^{j\omega_i t}$$

- Depends on
  - System properties
  - System initial conditions
  - Neither system input is present here

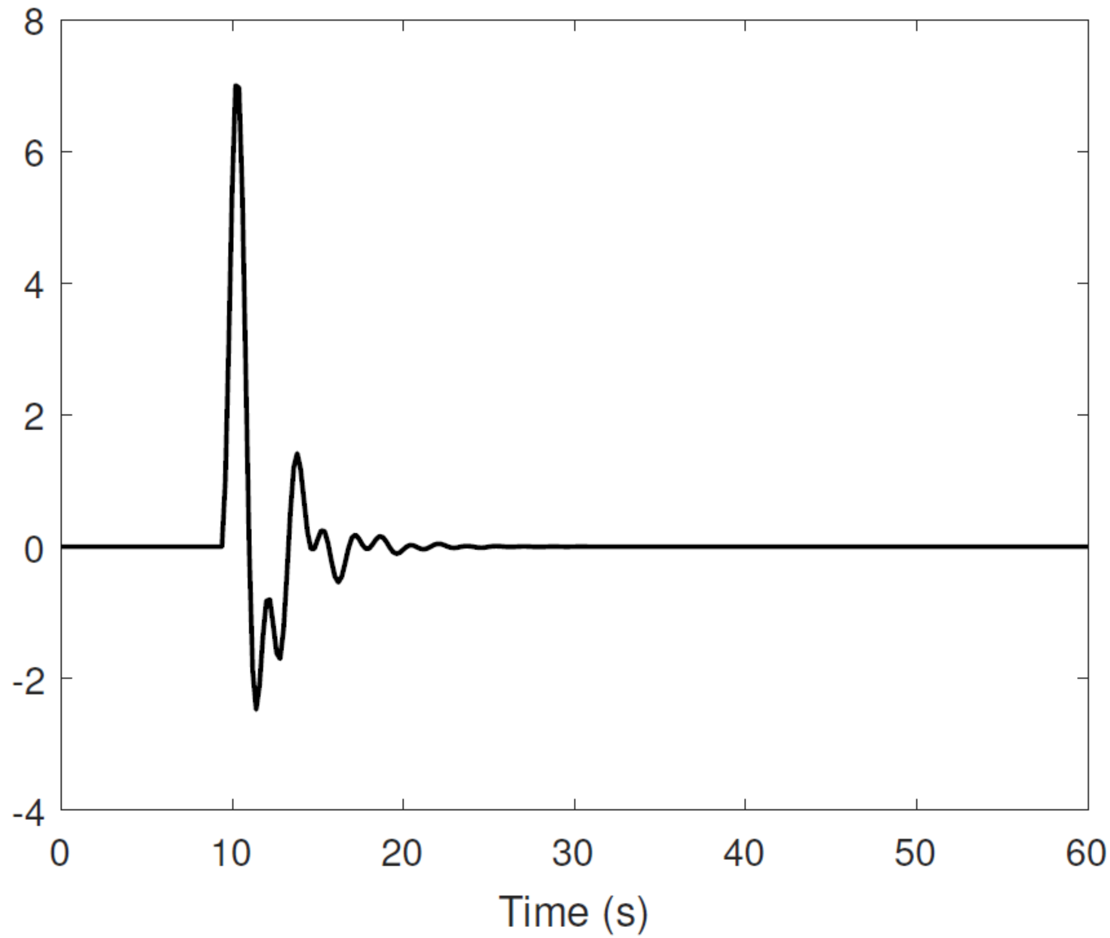
Transient Response

- Stable system
  - 0.25 Hz with 10% damping
  - 0.6 Hz with 3% damping



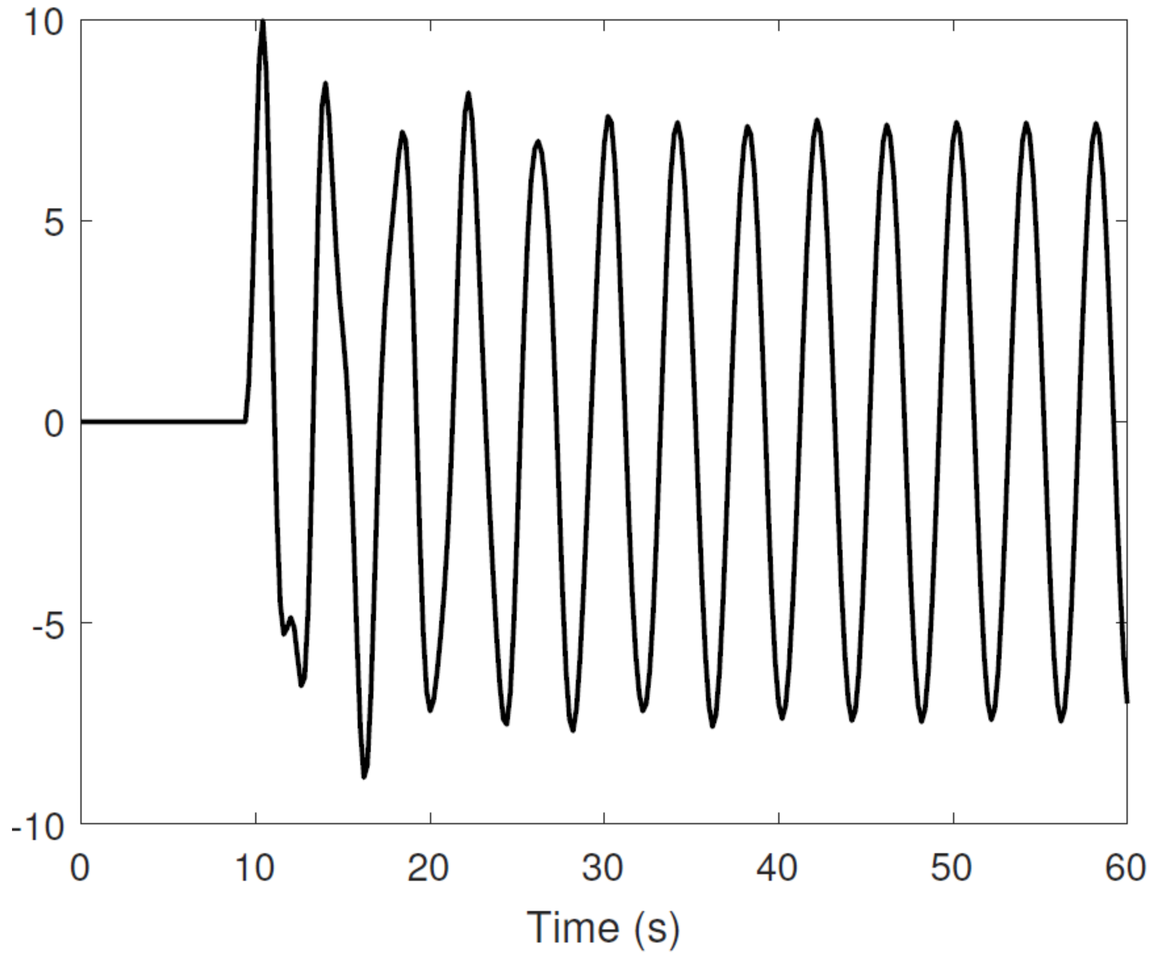
Transient Response

- Stable system
  - 0.25 Hz with 30% damping
  - 0.6 Hz with 10% damping
- The increased damping means the oscillations decay faster



Transient Response

- Marginally stable system
  - 0.25 Hz with 0% damping
  - 0.6 Hz with 3% damping
- We have one oscillation that decays, and one that is sustained



Ambient Response

- Natural Response
- Random signal that is the sum of system input noise terms filtered by the system dynamics

$$x_{r,ambient}(t) = \sum_{k=1}^{p_e} \left(\sum_{i=1}^{n} u_{i,r} \underline{v}_i \underline{b}_{e,k} e^{\lambda_i t} \right) * e_k(t)$$

- Depends on
  - System properties
  - Random system input variance (scales the response)

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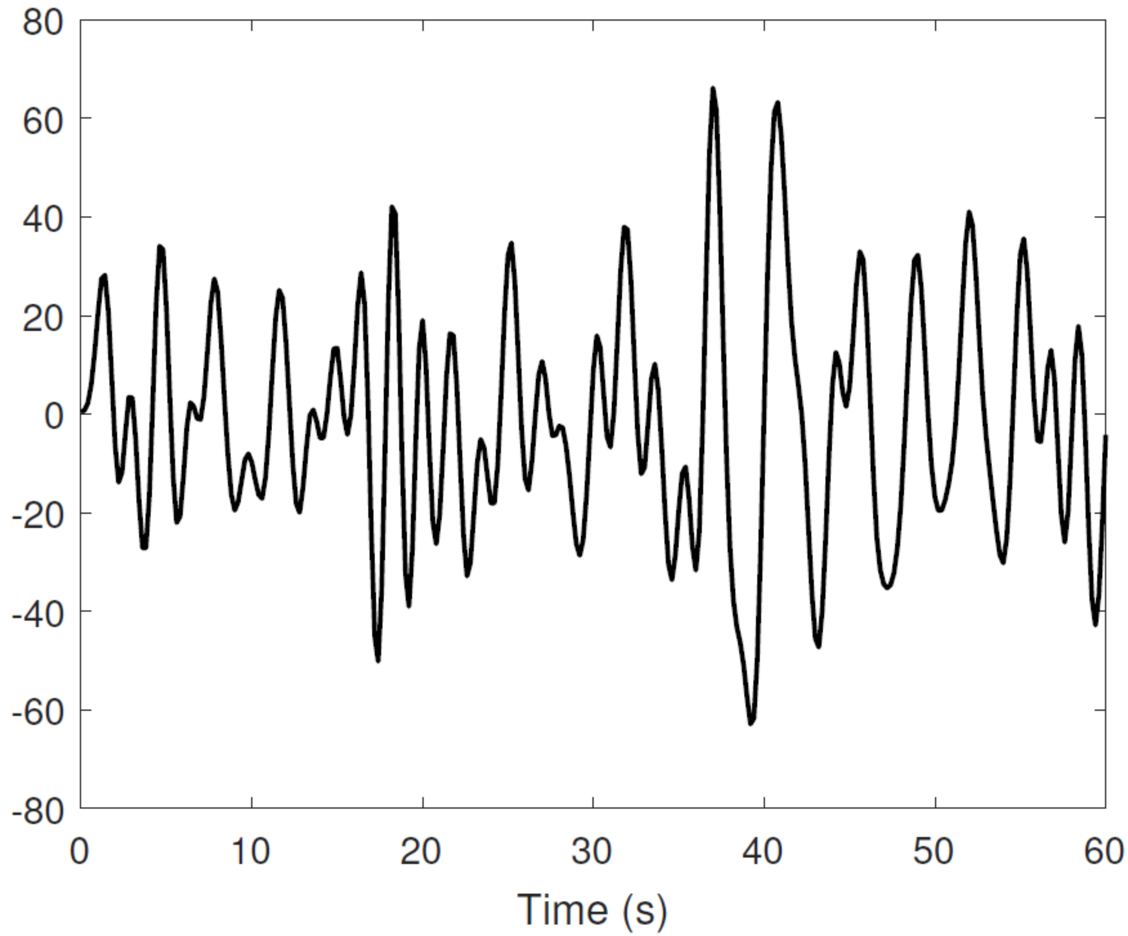
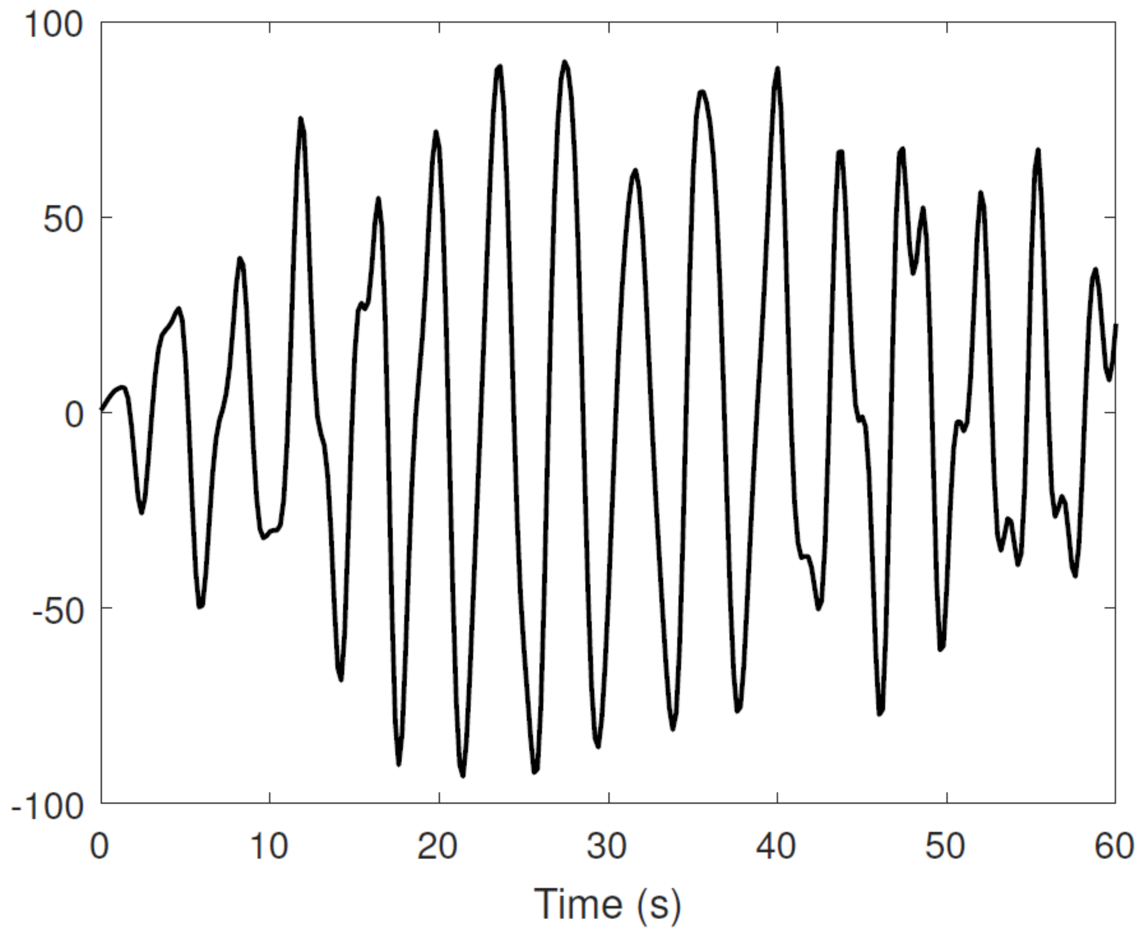
Ambient Response

- Stable system
  - 0.25 Hz with 10% damping
  - 0.6 Hz with 3% damping



Ambient Response

- Marginally stable system
  - 0.25 Hz with 0% damping
  - 0.6 Hz with 3% damping
- Despite appearances, this is still a random signal, NOT a sustained oscillation



Forced Response

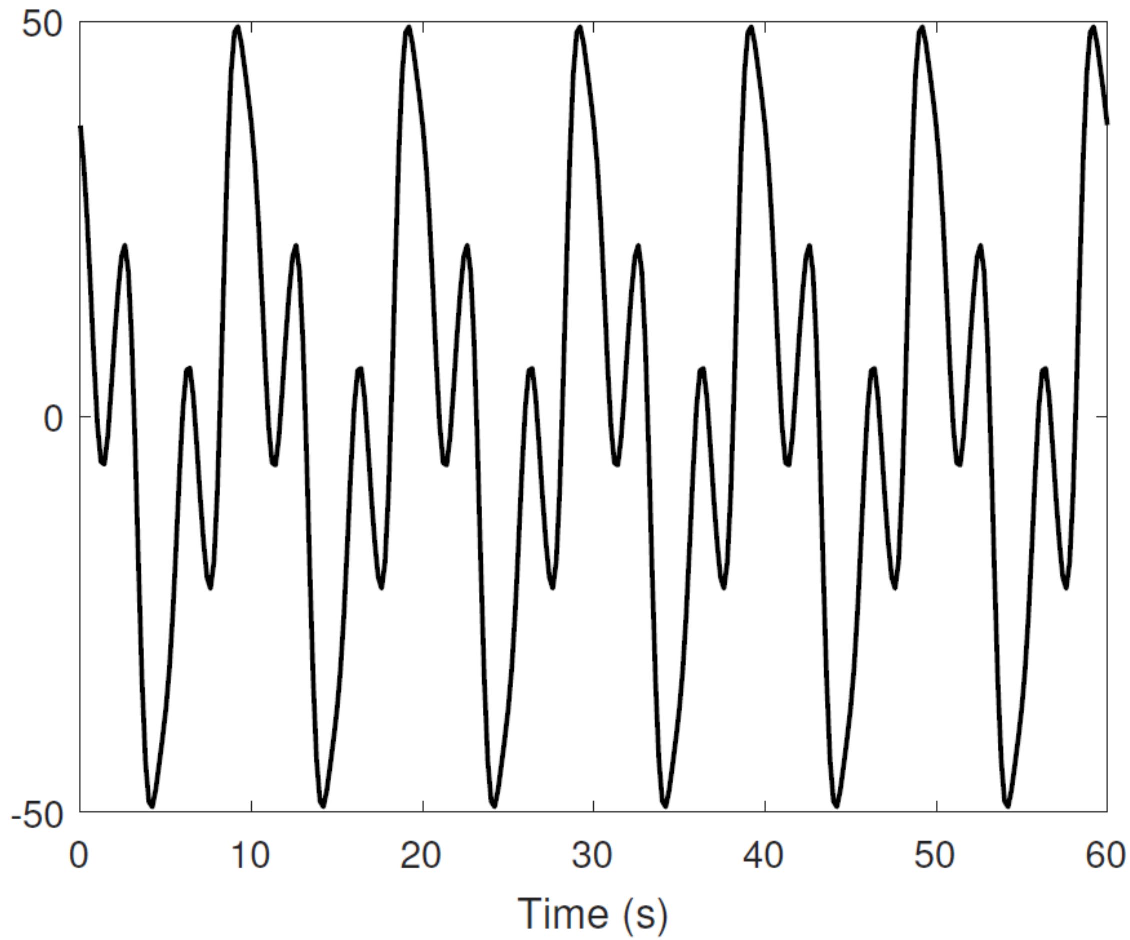
- NOT a Natural Response
- Deterministic signal that is the sum of the input sinusoids filtered by the system dynamics

$$x_{r,forced}(t) = \sum_{m=-\infty}^{\infty} \left(\sum_{i=1}^{n} u_{i,r} \underline{v}_i \underline{b}_f e^{\lambda_i t} \right) * \left(A_m e^{jm\omega_o t} \right)$$

- Depends on
  - System properties
  - Sinusoidal input properties (amplitude, phase, frequency)

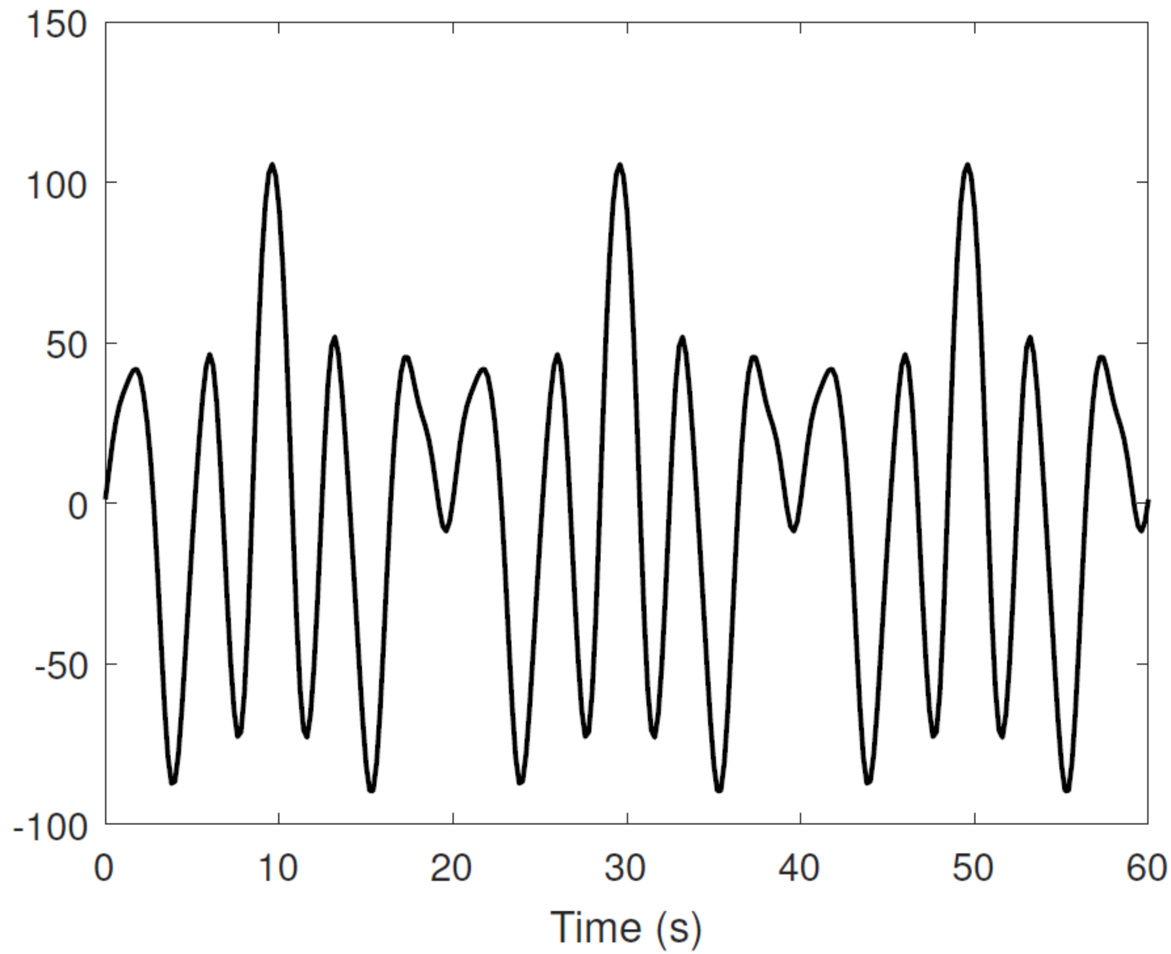
Forced Response

- Stable system
  - 0.25 Hz with 10% damping
  - 0.6 Hz with 3% damping
- 0.1 Hz square wave input
- Output is not a square wave, but has sinusoids at 0.1, 0.3, 0.5 Hz, etc.



Forced Response

- Marginally stable system
  - 0.25 Hz with 0% damping
  - 0.6 Hz with 3% damping
- 0.1 Hz square wave input
- Output includes sinusoids at 0.1, 0.3, 0.5 Hz, etc, AND 0.25 Hz

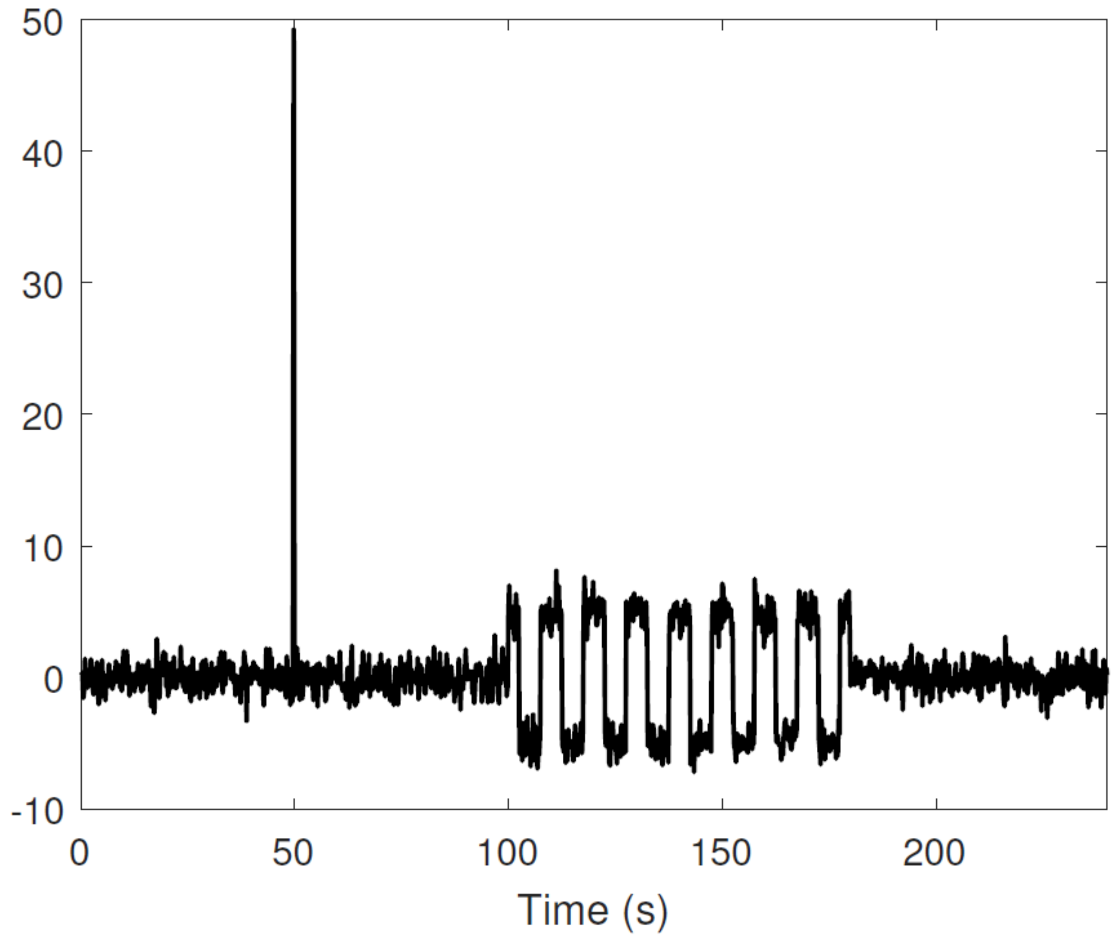


Combined Responses

- In general, the system experiences all three responses at once
  - Ambient response from constant perturbations by random inputs
  - Transient response from occasional disturbances
  - Forced response from occasional presence of oscillatory inputs
  - Transient response from forced input turning on and off

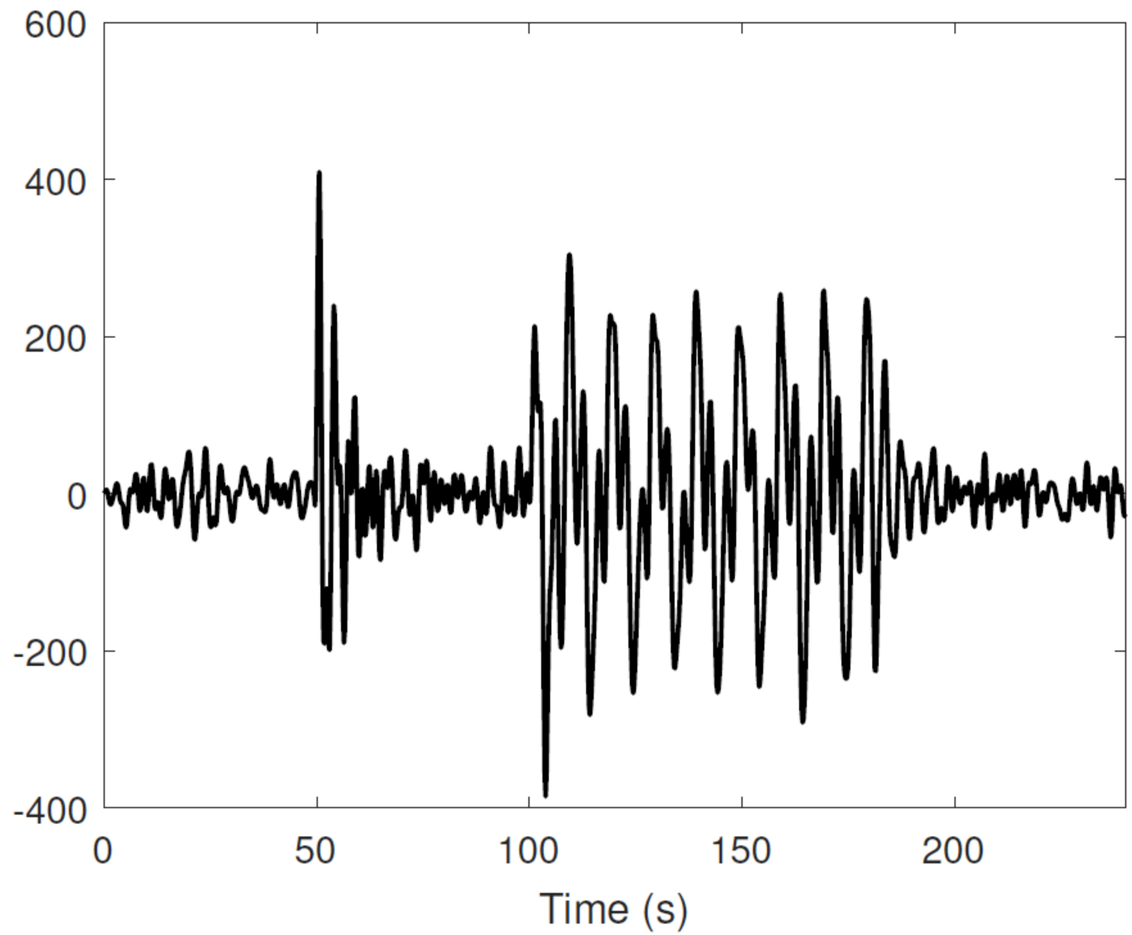
Combined Response – Input Signal

- Stable system
  - 0.25 Hz with 10% damping
  - 0.6 Hz with 3% damping
- Input with
  - Noise throughout
  - Disturbance at 50 s
  - 0.1 Hz square wave from 100 s to 180 s

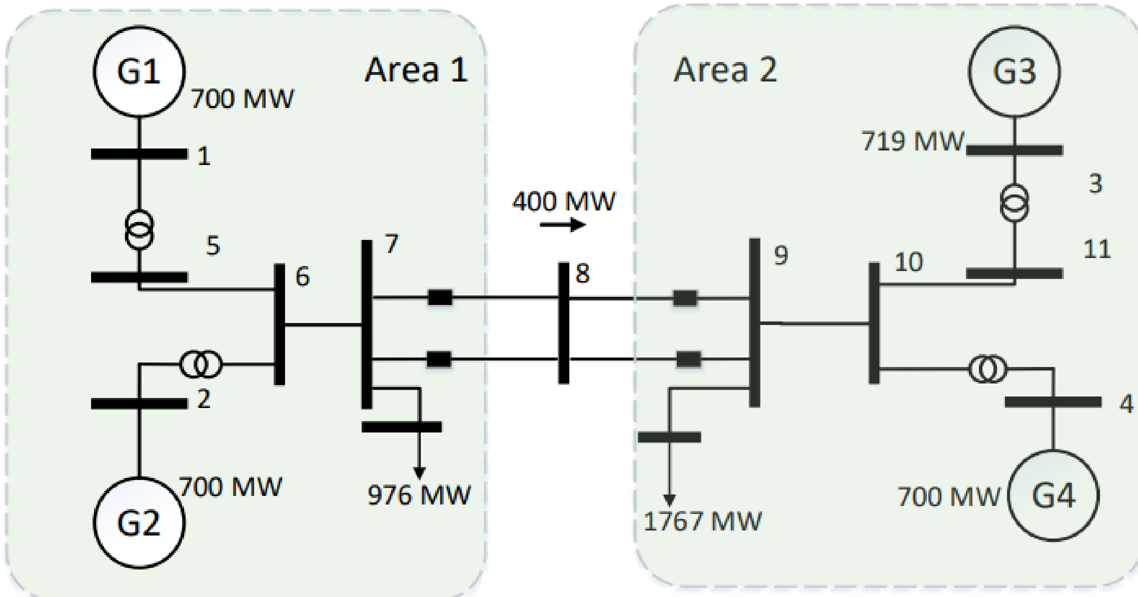


Combined Response – Output Signal

- Stable system
  - 0.25 Hz with 10% damping
  - 0.6 Hz with 3% damping
- Input with
  - Noise throughout
  - Disturbance at 50 s
  - 0.1 Hz square wave from 100 s to 180 s



Two Area system



- For modeling, IEEE Type EXAC4 is used for voltage regulation and IEEEG1 is used to model governor and STAB1 is uses a power system stabilizer.
- Table shows the electromechanical modes based on small signal stability analysis.
- Mode 3 is excited in this study. Mode 3 without PSS has 0% damping

Modes	Frequency (Hz)	Damping (%)	Dominant State
Mode 1	1.3079	24.79	Gen 2 speed
Mode 2	1.3507	24.38	Gen 4 speed
Mode 3	**0.6200**	**10.08**	**Gen 1 speed**

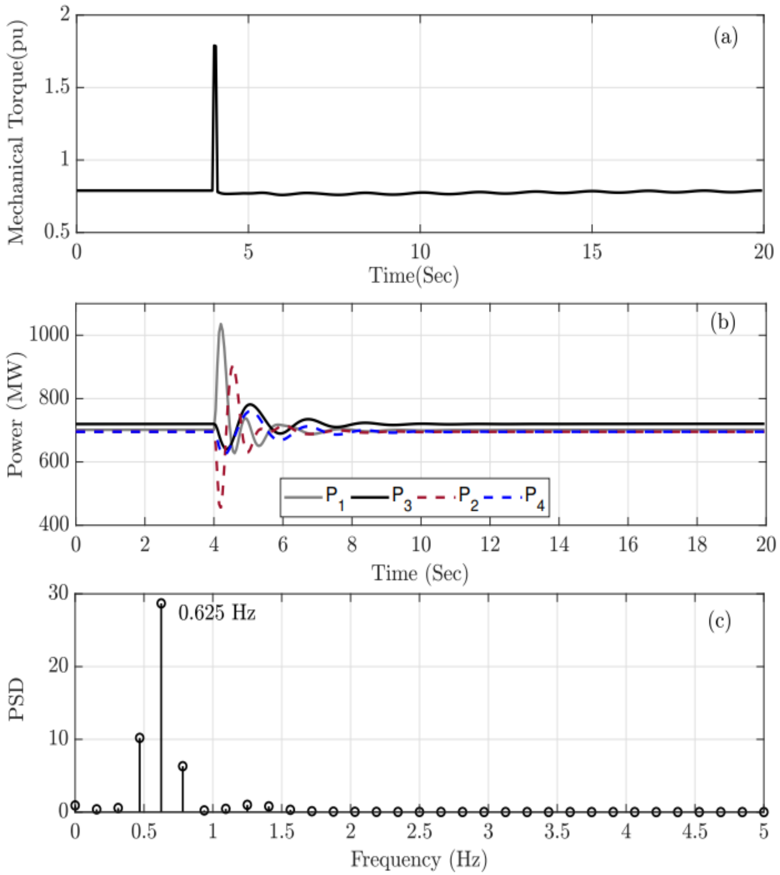
Case studies on Two Area system

Test System	Case	Description
Two Area	Transient Response	Natural response of the system where the inter area oscillation mode of 0.625 Hz is excited
	Ambient Response	Ambient signal generated by random load changes
	Forced Response	Different cases of external disturbances are analyzed
	Case 1	Square wave of 0.4 HZ is injected at the governor reference set point of generator 1
	Case 2	Square wave of 0.35 HZ is injected at the governor reference set point of generator 1 and a square wave of 1 Hz at the governor reference set point of generator 2
	Case 3	A square wave of 0.62 HZ is injected at the governor reference set points of generator 1 which coincides with the inter area oscillation mode of 0.6026 Hz
	Combined Response	All three types of disturbances are applied together

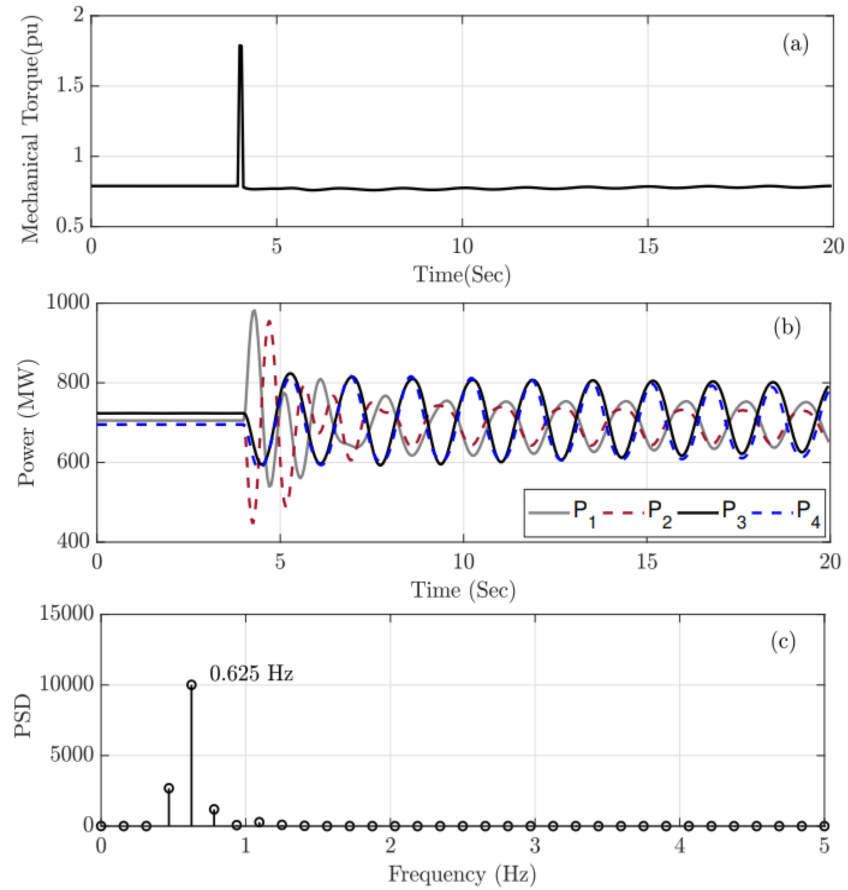
- Transient Response:
  - Impulse disturbance at the governor mechanical torque output of generator 1.
- Ambient Response:
  - Random load changes are made to the load connected to the area 1

Two Area System: Transient Response

- Time domain response, and PSD from Welch periodogram is shown below. 0.625 HZ is the interarea oscillation mode, so the generators in area 1 is oscillating against generators in area 2.
- Figure (left) PSS's is enabled (10% damping) and figure (right) PSS's are disabled (0% damping).



PSS's is enabled

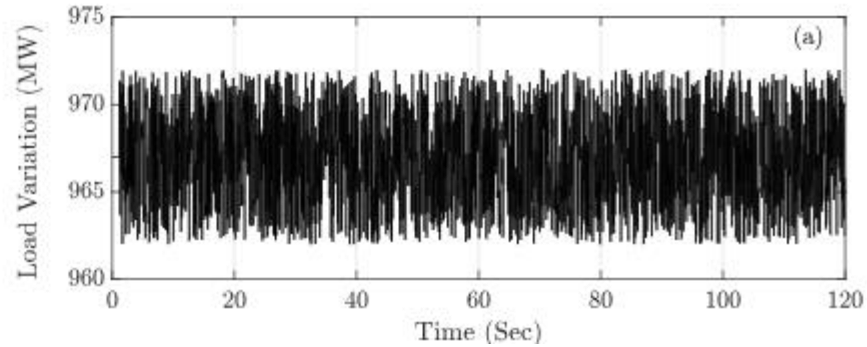


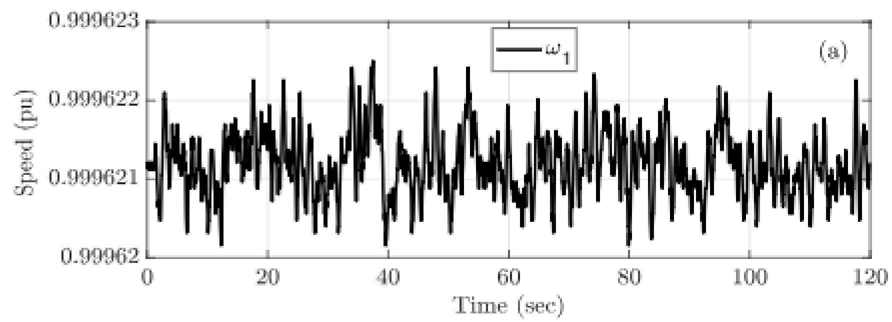
PSS's disabled

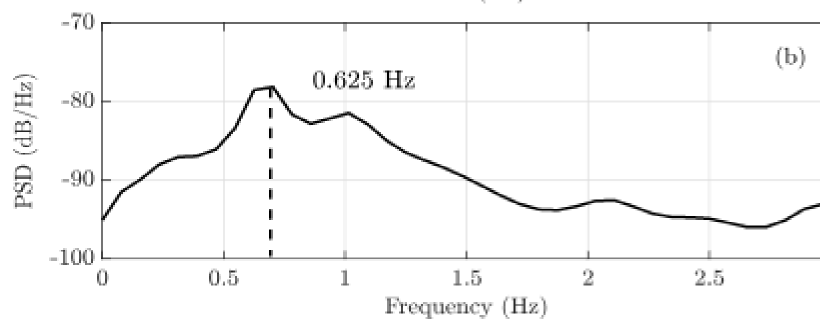
Two Area System: Ambient Response

- Random load changes are made to the load connected to the area 1 (see figure).
- Inter-area mode of 0.625Hz is initiated (the highest energy).
- Same frequency component is prominent on all generators.

Modes	Frequency (Hz)	Damping (%)	Dominant State
Mode 1	1.3079	24.79	Gen 2 speed
Mode 2	1.3507	24.38	Gen 4 speed
Mode 3	**0.6200**	**10.08**	**Gen 1 speed**





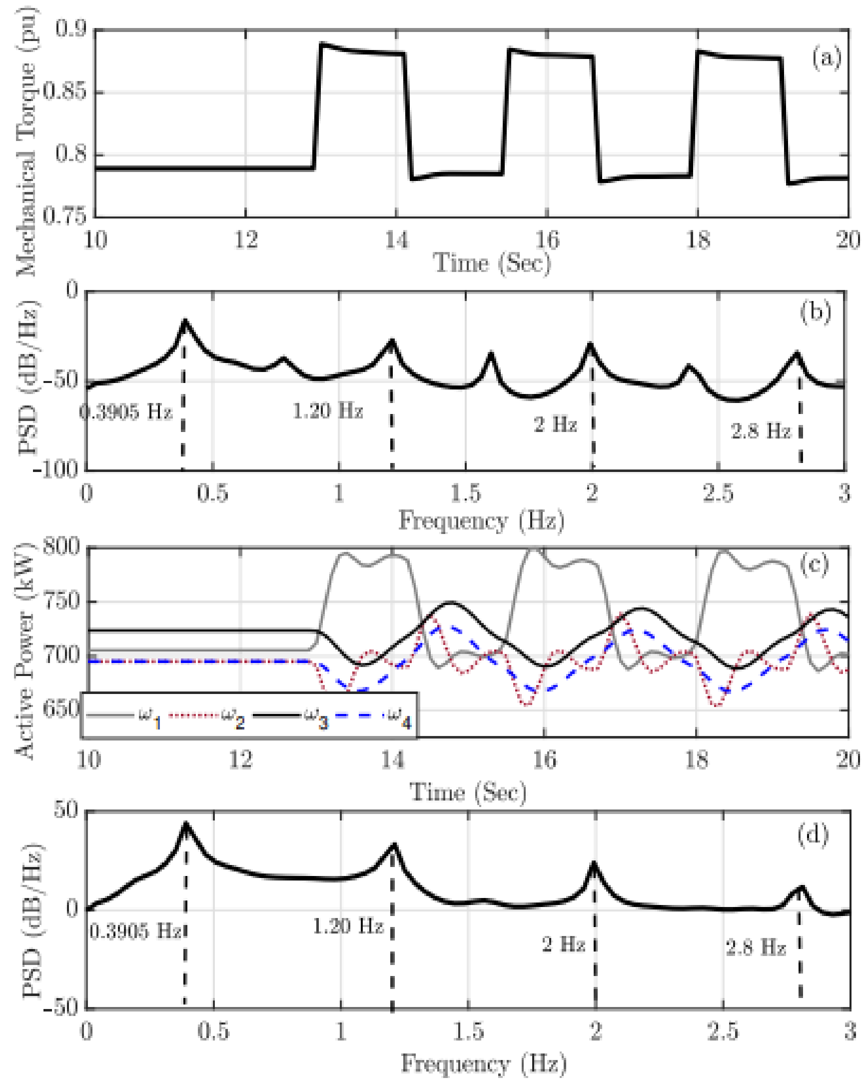


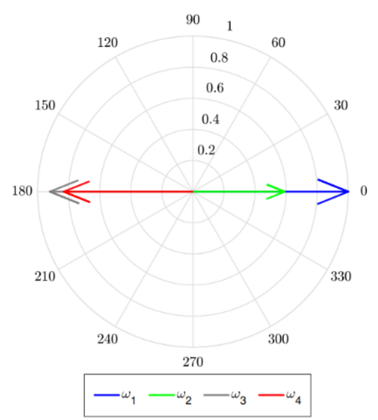
Remarks:

1) Shows system modes
2) System conditions describes how the oscillation decays

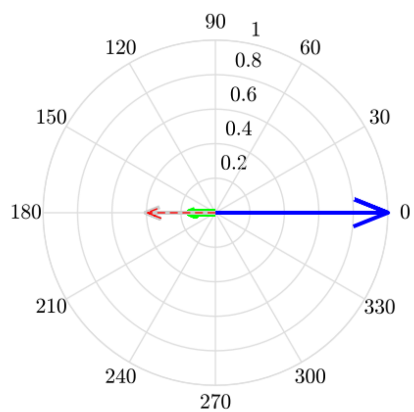
Two Area System: Forced Response

- **<u>Case 1:</u>** A square wave of 0.4Hz is injected to the governor mechanical torque of generator 1.
- Only a single periodic disturbance is introduced (See figure (a)).
- Dynamics is shown in the figure (b). Odd harmonics of 0.4 Hz is visible.
- Power dynamics is shown in figure (c) and PSD in figure (d).





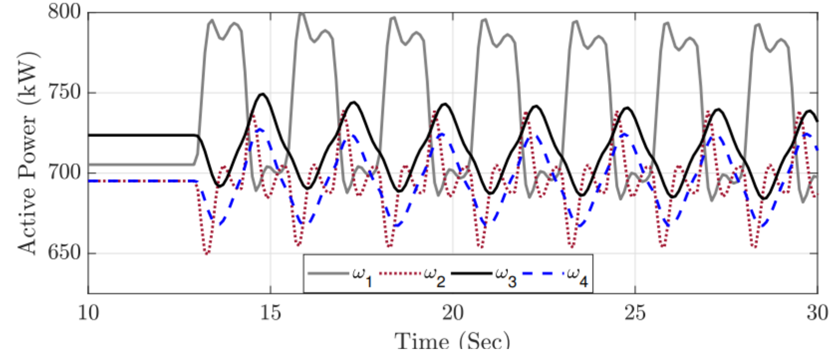
0.625Hz shape (Natural)

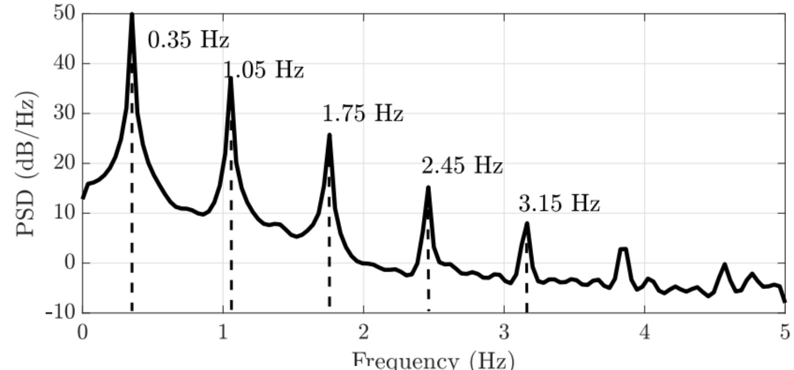


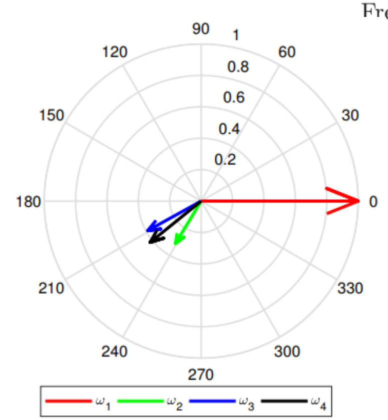
0.4Hz shape (Forced)

Two Area System: Forced Response

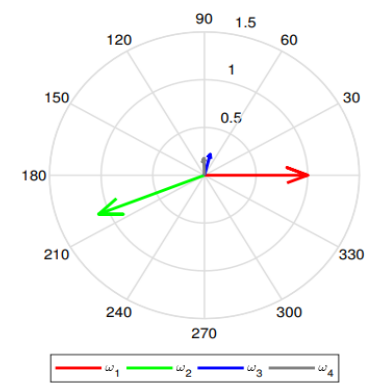
- **<u>Case 2:</u>** 0.35Hz and 1Hz is injected to the governor mechanical torque of generator 1 and generator 2.
- The goal is to study the response with multiple periodic disturbances.
- Peaks are seen at the odd harmonics of of 0.35 Hz. The narrow peak indicates very less damping.
- Oscillation shape shows 0.35 Hz and 1 Hz mode respectively.
- For 0.35 Hz mode, generator 1 is oscillating against the rest of the generators.
- For 1 Hz mode, generator 1 and 2 are oscillating against each other (close to local mode)







0.35Hz machine 1 (Forced)



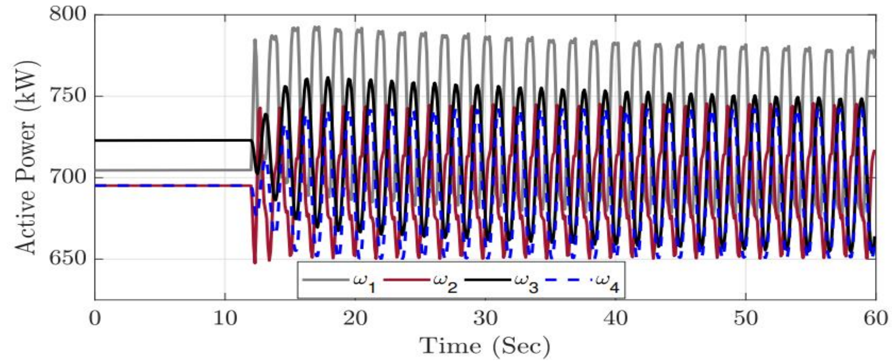
1 Hz machine 2 (Forced)

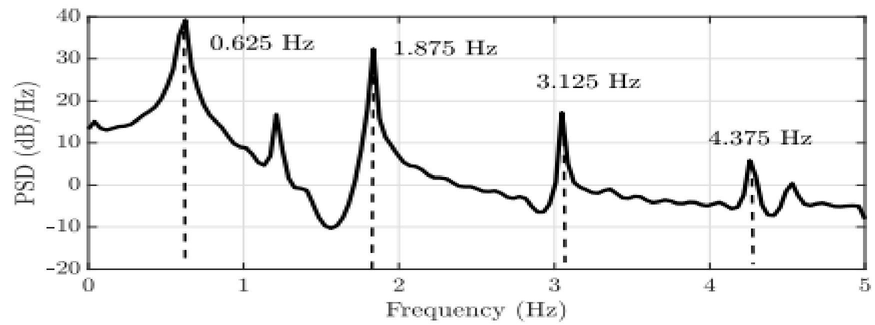
Two Area System: Forced Response

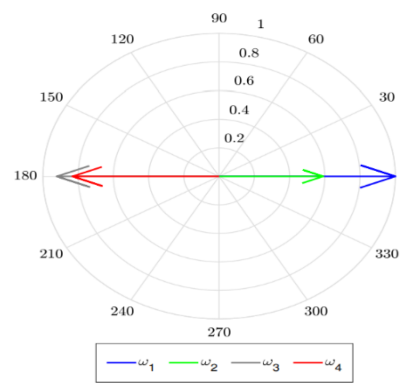
- **Case 3:** A periodic disturbance is applied to generator 1 with frequency of 0.625Hz (resonate with inter-area mode).
- 0.625 Hz mode less damping (narrow peaks) and harmonic peaks are visible. Narrow peaks is because of the presence of forced oscillations.
- Presence of forced oscillation with natural oscillation frequencies can give a wrong estimate of natural oscillation modes.
- Comparisons of oscillation shape show the affect of resonance.

Remarks:

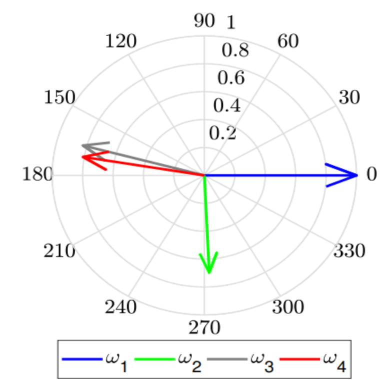
1) Non-zero damping (not a system property)
2) Phase and magnitude of forced oscillations seen in model shapes





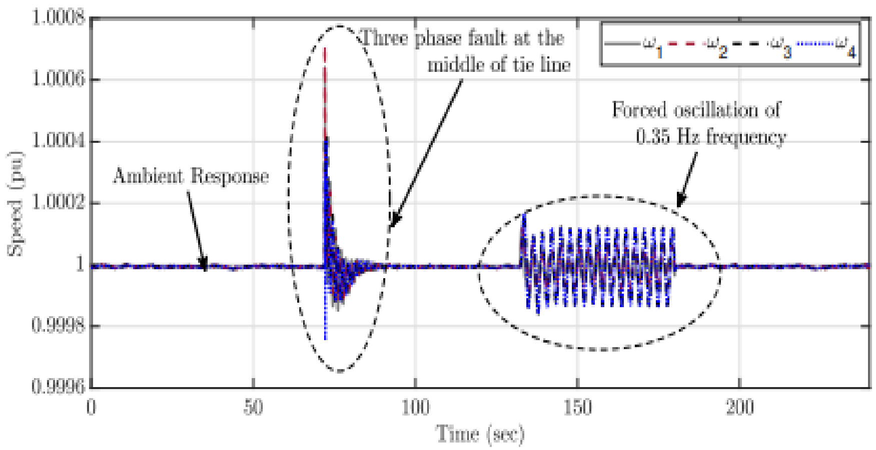


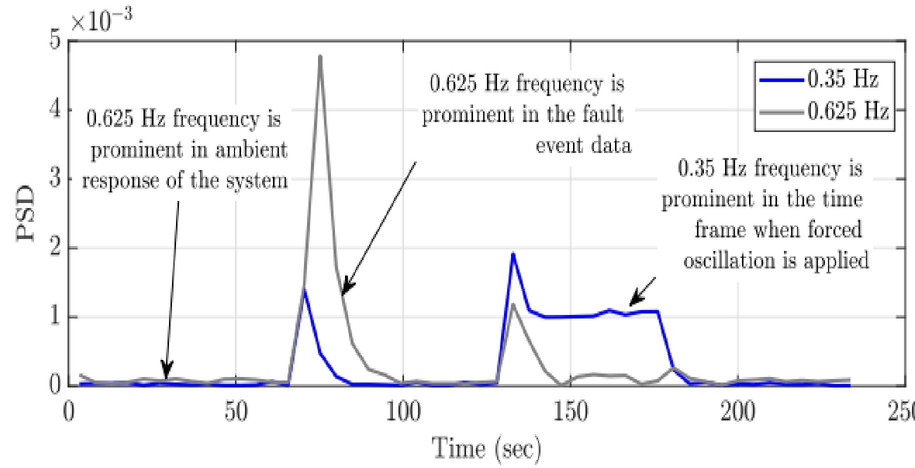
0.625Hz shape (Natural)



0.625Hz shape (Forced)

Two Area System: Combined Response



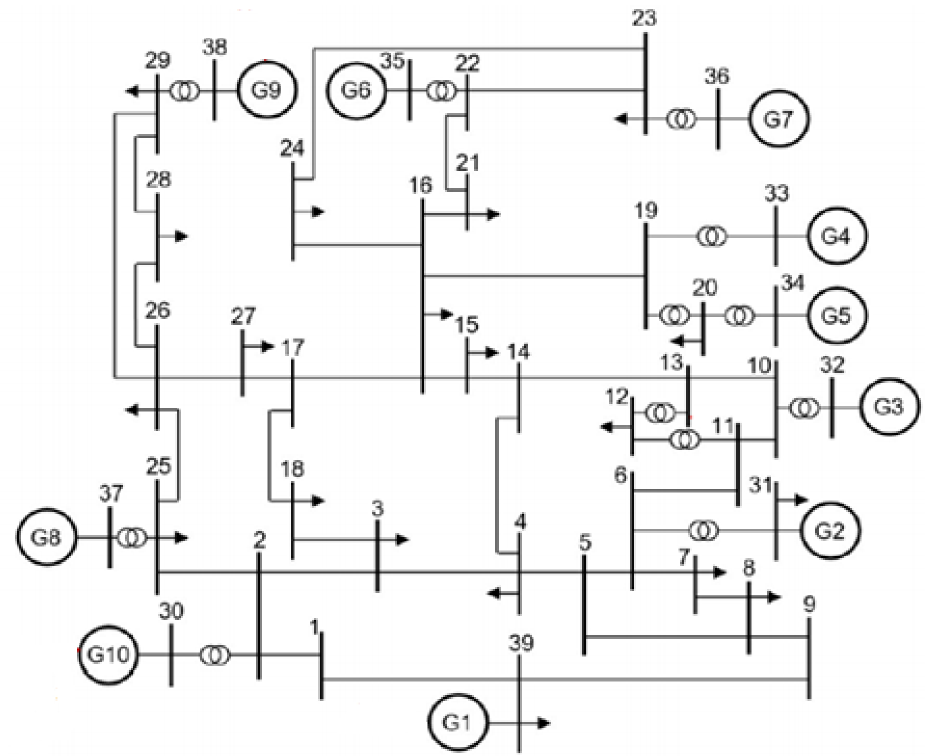


- Three responses (Transient, Ambient and Forced) are initiated. a) A random white noise with a magnitude of 5% of the connected load is added to the loads connected in area 1 and area 2. b) Around 80 second a three phase fault occurs at the middle of tie line connected between bus 7 and bus 9 (cleared after 5 cycles). c) Around 140 sec an external disturbance of 0.35 Hz is applied to the governor of the generator 1.
- 0.625 Hz is visible in ambient response, become more visible during transient response.
- The external oscillation frequency of 0.35 Hz become prominent when the external disturbance is applied.

IEEE 39 Bus System

Natural electromechanical modes of the System

Modes	Frequency (Hz)	Damping (%)	Dominant State
Mode 1	**1.5178**	**9.19**	**Gen 8 speed**
Mode 2	1.4597	10.61	Gen 7 speed
Mode 3	**1.2778**	**6.98**	**Gen 10 speed**
Mode 4	1.1280	8.06	Gen 6 speed
Mode 5	0.6618	6.94	Gen 1 speed
Mode 6	1.3880	8.40	Gen 4 angle
Mode 7	1.2160	8.34	Gen 3 angle
Mode 9	0.9707	8.67	Gen 9 angle
Mode 10	1.0293	8.18	Gen 2 angle



IEEE 39-Bus system is a reduced equivalent of the New England test system (NETS)

- This system has 10 generators and 39 buses. Generator 1 located at bus 39 is an aggregated generator and hence has high inertia and output power.
- Exciter model used for voltage regulation is of ’IEEE type 1’ and governor model is of type ’TGOV’. The generator and governor data is modified slightly for EMT simulation studies compared to [2].

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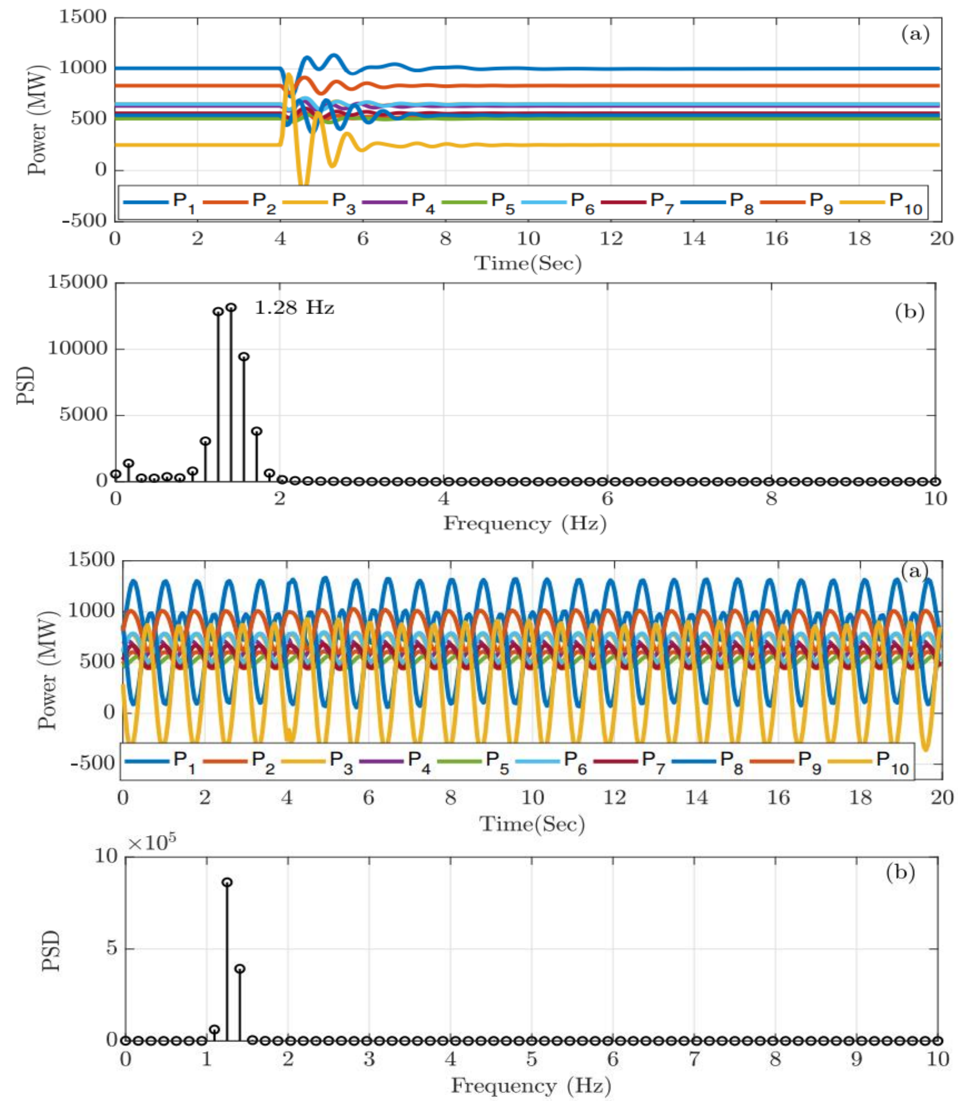
Case studies for IEEE 39 Bus system

Test System	Case	Description
IEEE 39 Bus	Transient Response	Natural response of the system where the inter area oscillation mode of 0.3038 Hz and local mode of 1.2711 Hz are excited
	Ambient Response	Ambient response of the system generated by random load change
	Forced Response	Different cases of external disturbances are analyzed
	Case 1	A square wave of 0.5 HZ is injected at the governor reference set points of generator 10
	Case 2	A square wave of 0.30 HZ is injected at the governor reference set points of generator 1 and generator 9
	Case 3	A square wave of 1.28 HZ is injected at the governor reference set points of generator 10 which coincides with 1.2711 Hz
	Combined Response	All three types of disturbances are applied together

- Transient Response: Exciting interarea and local modes.
- Ambient response: Random load changes
- Forced response: External inputs at the governor reference

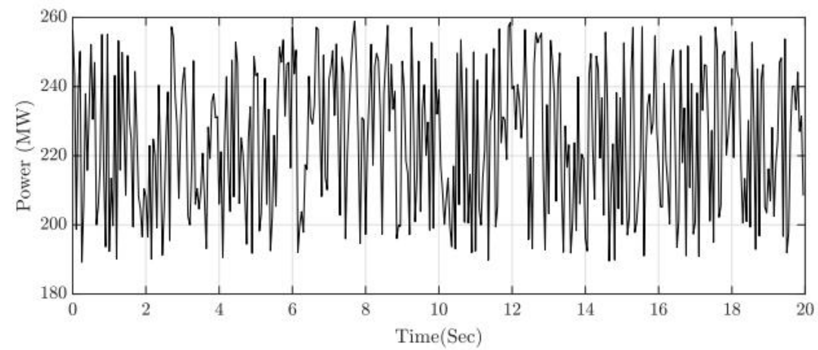
IEEE 39 Bus System: Transient Response

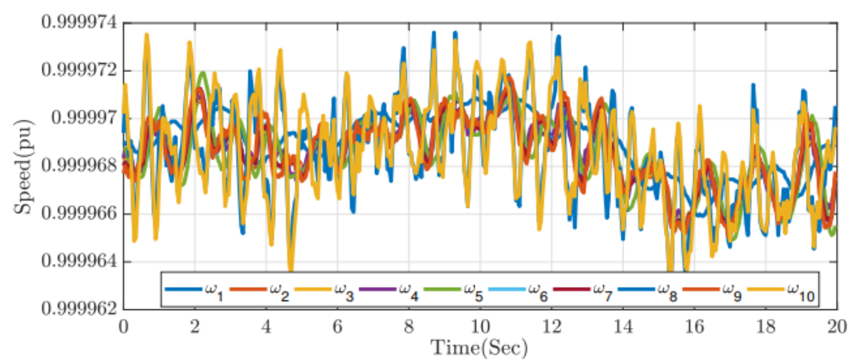
- Three phase fault initiated at bus 30
- Generator 10 and generator 8 speed and angle has largest deviations due to proximity to fault (generator 10 power output with and without damping shown)
- Generator 1 is an aggregated representation with larger inertia so higher damping is visible.
- Two frequencies are excited a) 0.3038Hz (inter area) b) 1.2711 Hz (local mode)
- Characteristics shows that of a transient response
  - Deterministic with no random components
  - Stable as the mode shapes and dynamics of the system is stable with specific modal frequency and damping.

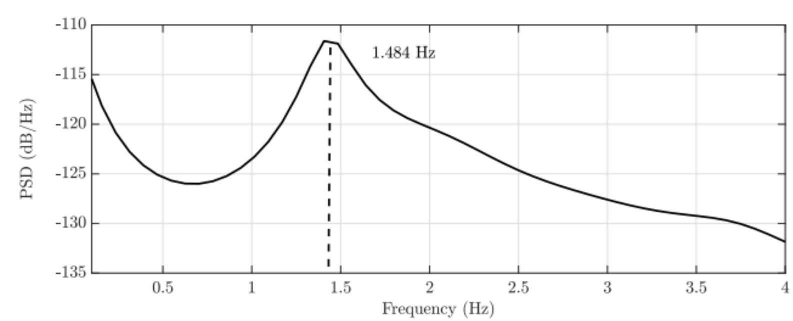


IEEE 39 Bus System: Ambient Response

- Gaussian white noise (5%) applied to all loads in the system. Example on bus 25 is shown
- Disturbance observed on all machine.
- Power spectral density analysis shows peak near 1.484Hz.
- Small signal stability analysis shows that natural oscillation modes are 1.51 Hz with generator 8 speed as domain state.
- Characteristics shows the impact of ambient response on natural system oscillations containing system modal information.

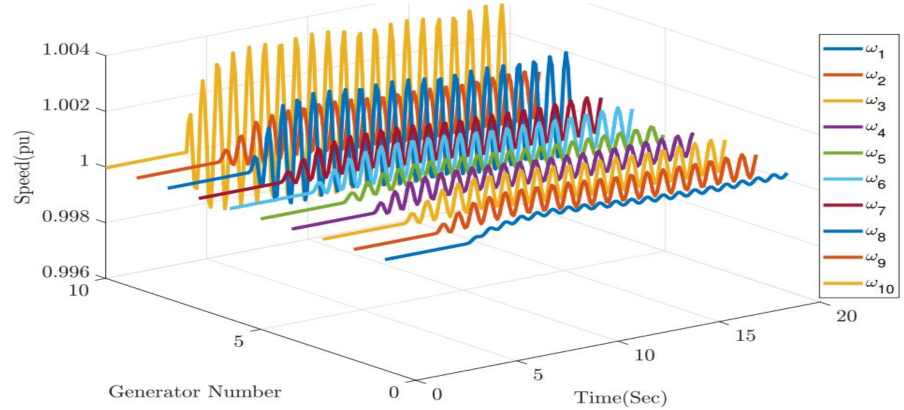


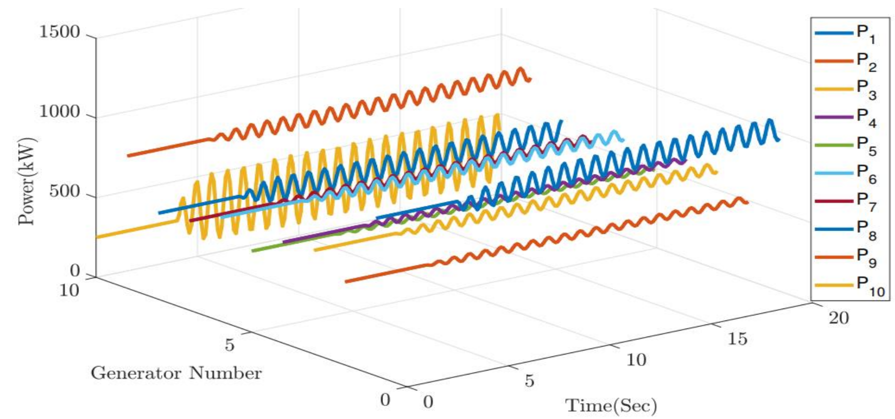


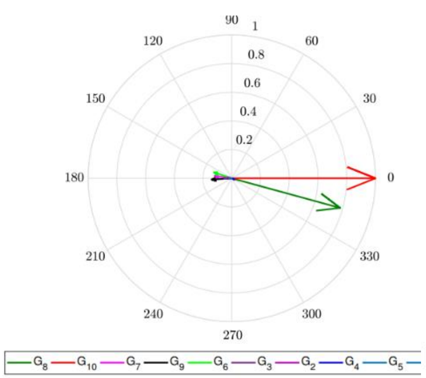


IEEE 39 Bus System: Forced Response

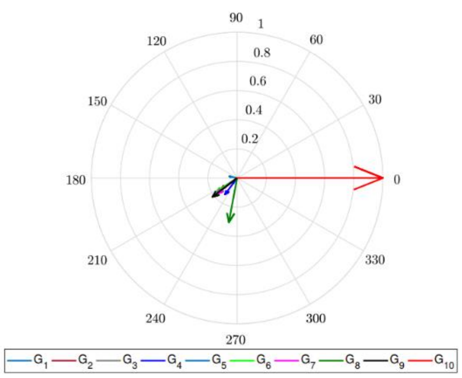
- External disturbance is applied to the governor of generator 10 with a frequency of 1.28 Hz which coincides with the electromechanical mode of 1.2788 Hz.
- Oscillation shape of the forced oscillation indicate that generator 10 speed has the highest contribution.







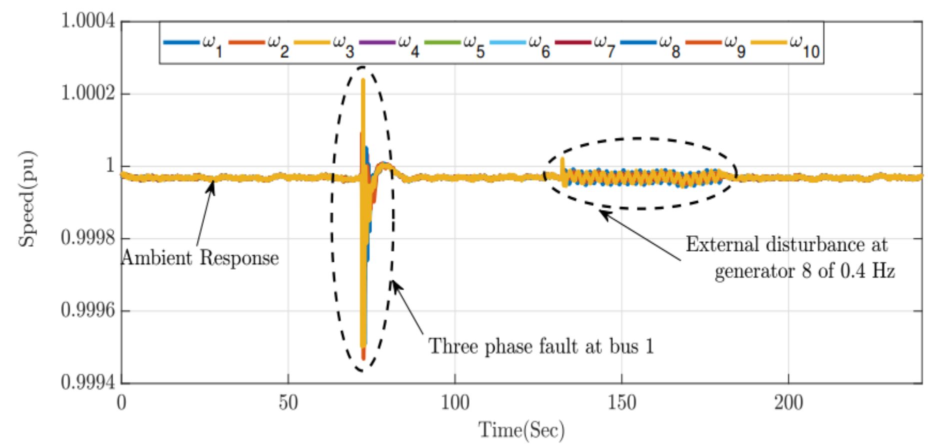
1.28 Hz shape (natural)

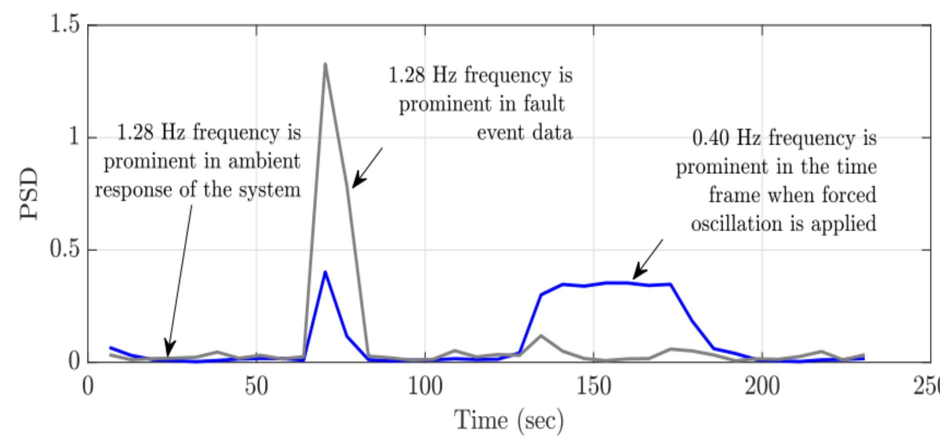


1.28 Hz shape (Forced)

IEEE 39 Bus System: Combined Response

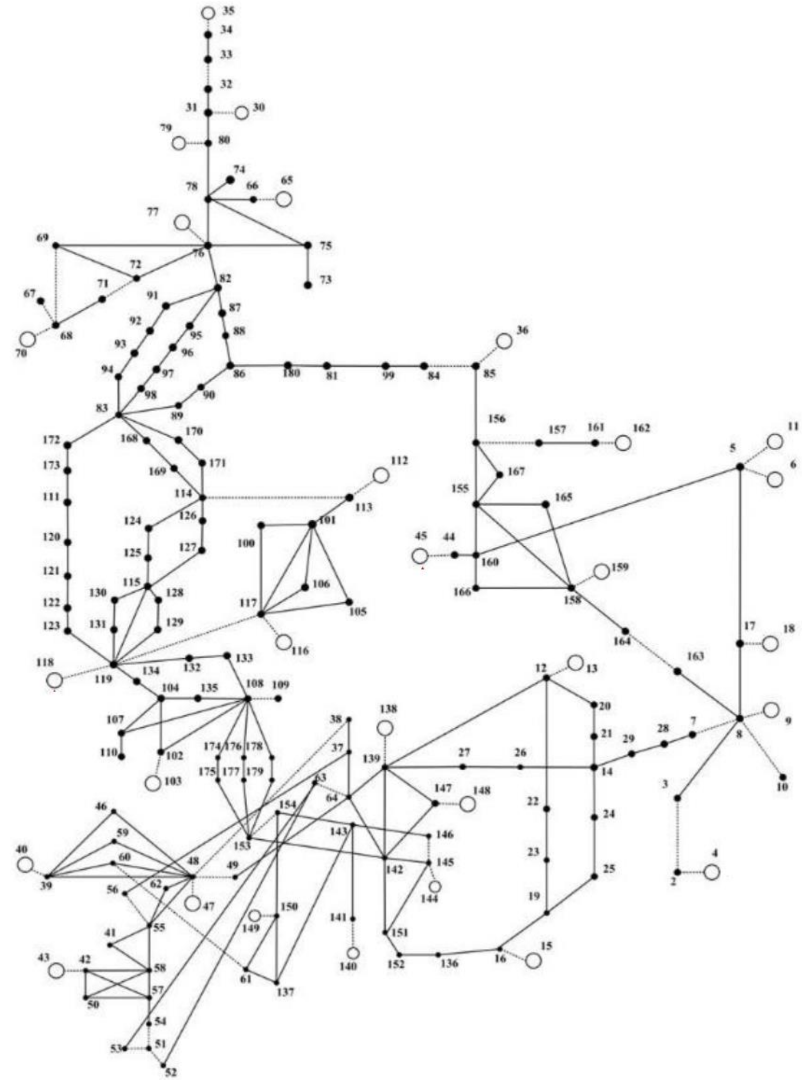
- Random load changes are simulated by adding Gaussian white noise with a magnitude of 5% of the connected loads. A three phase fault is applied at bus 1 to simulate transient response. And an external disturbance of 0.4 Hz is applied to the generator 8 governor response to simulate forced response.
- The ambient response shows that a electromechanical frequency of 1.28 HZ is excited and this conforms with the small signal stability analysis of the system.
- The frequency of 1.28 Hz is more visible at 70 second to 100 second when the transient response of the system is excited.





miniWECC System

Modes	Frequency (Hz)	Damping (%)	Dominant State
Mode 1	1.6387	3.79	Gen at Bus 6 speed
Mode 2	1.5944	2.62	Gen at Bus 47 speed
Mode 3	0.4763	9.89	Gen at Bus 65 speed
Mode 4	1.4853	2.61	Gen at Bus 116 speed
Mode 5	1.3744	2.29	Gen at Bus 40 speed
Mode 6	**0.8665**	**5.63**	**Gen at Bus 15 speed**
Mode 7	0.8446	4.99	Gen at Bus 30 speed
Mode 8	0.9795	4.93	Gen at Bus 77 speed
Mode 9	1.0896	3.54	Gen at Bus 112 speed
Mode 10	1.0625	5.02	Gen at Bus 162 speed
Mode 11	1.8834	3.07	Gen at Bus 18 angle
Mode 12	1.7232	3.24	Gen at Bus 144 angle
Mode 13	1.6177	3.20	Gen at Bus 70 angle
Mode 14	0.2626	18.21	Gen at Bus 35 angle
Mode 15	0.3721	13.46	Gen at Bus 35 angle
Mode 16	0.4447	12.43	Gen at Bus 11 angle
Mode 17	1.4982	3.04	Gen at Bus 103 angle
Mode 18	1.4478	2.61	Gen at Bus 49 angle
Mode 19	0.6675	7.59	Gen at Bus 49 angle
Mode 20	**1.4088**	**3.98**	**Gen at Bus 159 angle**
Mode 15	0.7175	7.28	Gen at Bus 11 angle
Mode 16	1.3506	3.26	Gen at Bus 13 angle
Mode 17	0.7667	6.55	Gen at Bus 140 angle
Mode 18	1.3050	4.35	Gen at Bus 4 angle
Mode 19	1.2314	3.16	Gen at Bus 148 angle
Mode 20	1.1291	3.85	Gen at Bus 149 angle
Mode 21	1.2654	5.25	Gen at Bus 36 angle
Mode 22	1.0220	3.97	Gen at Bus 15 angle

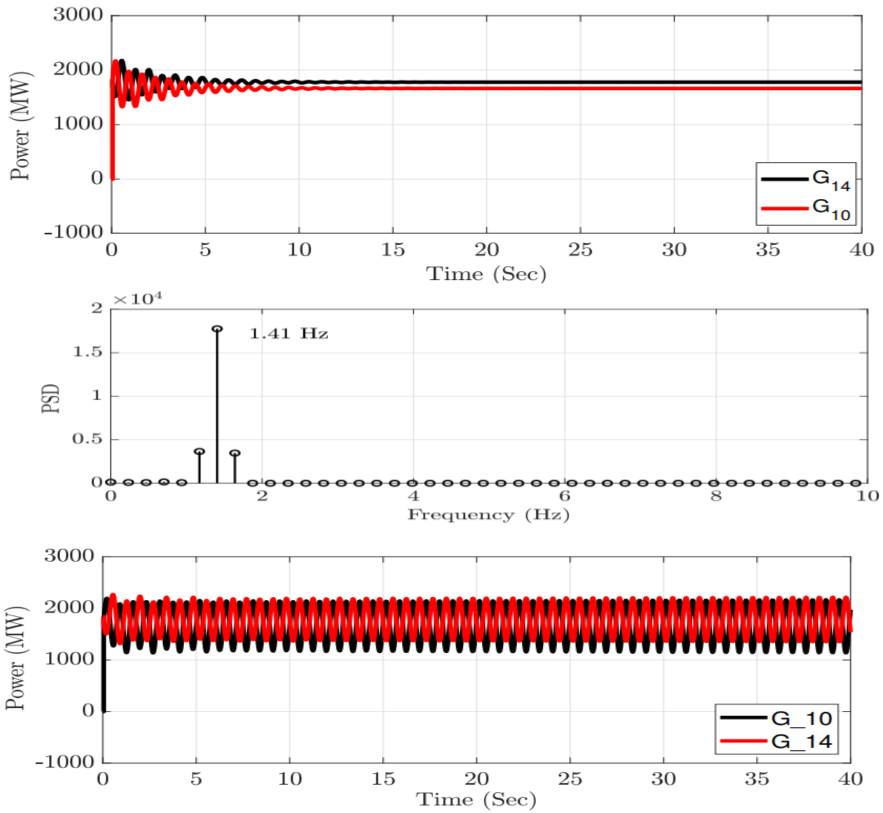


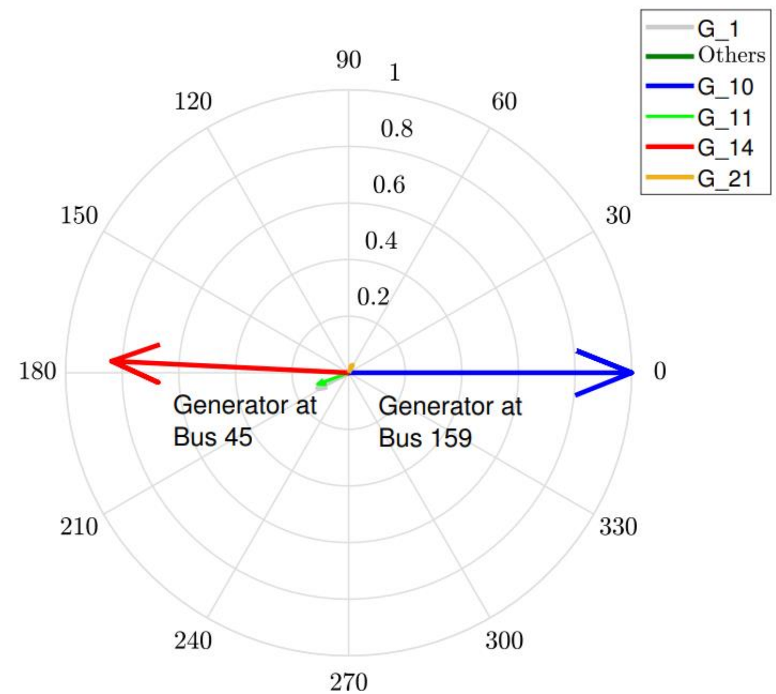
Case studies for miniWECC System

Test System	Case	Description
miniWECC	Transient Response	Natural response of the system where the local oscillation mode of 1.41 Hz is excited
	Forced Response	A sine wave of 0.86 Hz is injected at the governor reference set points of generator located at bus 4 which coincides with the natural mode of 0.86 Hz

- Transient Response: Local modes are excited.
  - A three phase short circuit fault is added at the bus 159 and the fault is cleared after 0.05 second. This fault excites the 1.41 Hz natural mode which has a damping of 3.98 %
  - A sustained natural oscillation is created by altering the damping of two generators. The damping coefficient of generator located at bus 45 is changed from 4 to -2 and the damping coefficient of generator located at bus 159 is changed from 4 to 1. The rest of the generators have a damping coefficient of 4.
- Forced response: External inputs at the governor reference
  - An external sinusoid disturbance is applied to the exciter reference of generator 4 (connected at bus 35) to introduce a forced response.
  - The frequency of external disturbance is 0.86 Hz which coincides with the system natural oscillation mode of 0.86 Hz. The gain of the external sinusoidal disturbance is adjusted to keep the power swings within 157 MW.

Transient Response: miniWECC System



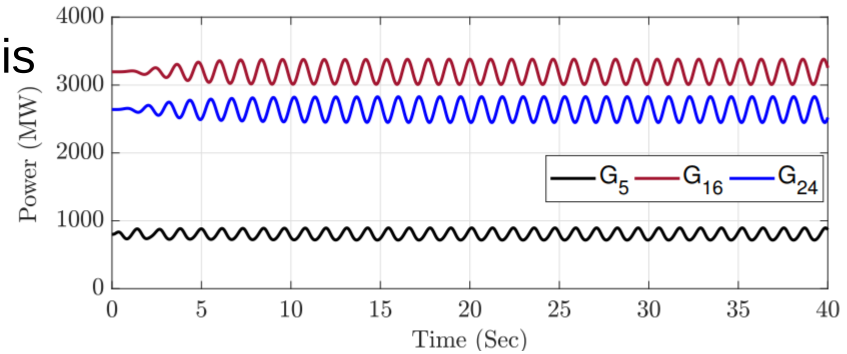


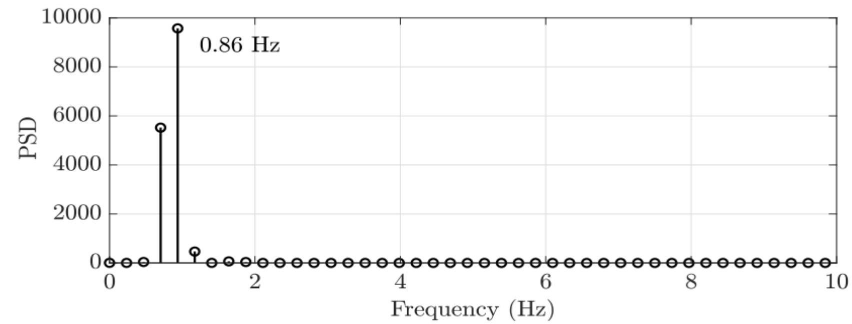
1.4 Hz shape (natural)

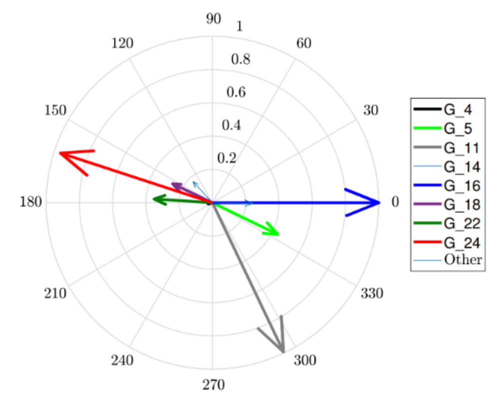
- A three phase short circuit fault is added at the bus 159 and the fault is cleared after 0.05 second. Active power measured at the terminal of the generators located at bus 45 and at bus 159 is shown.
- A sustained natural oscillation is created by altering the damping of two generators.

Forced Response: miniWECC System

- The frequency of external disturbance is 0.86 Hz. It coincides with the system natural oscillation mode of 0.86 Hz.
- This superposition of external disturbance with the system's natural response causes resonance.
- Active power output of the generators are shown. Oscillation magnitude is highest at the output power of the generator where the external disturbance is applied.
- External disturbance is applied to the generator located at bus 4 (generator 5). The forced oscillations resulted from the external disturbances inflicts sustained oscillations and poor damping.



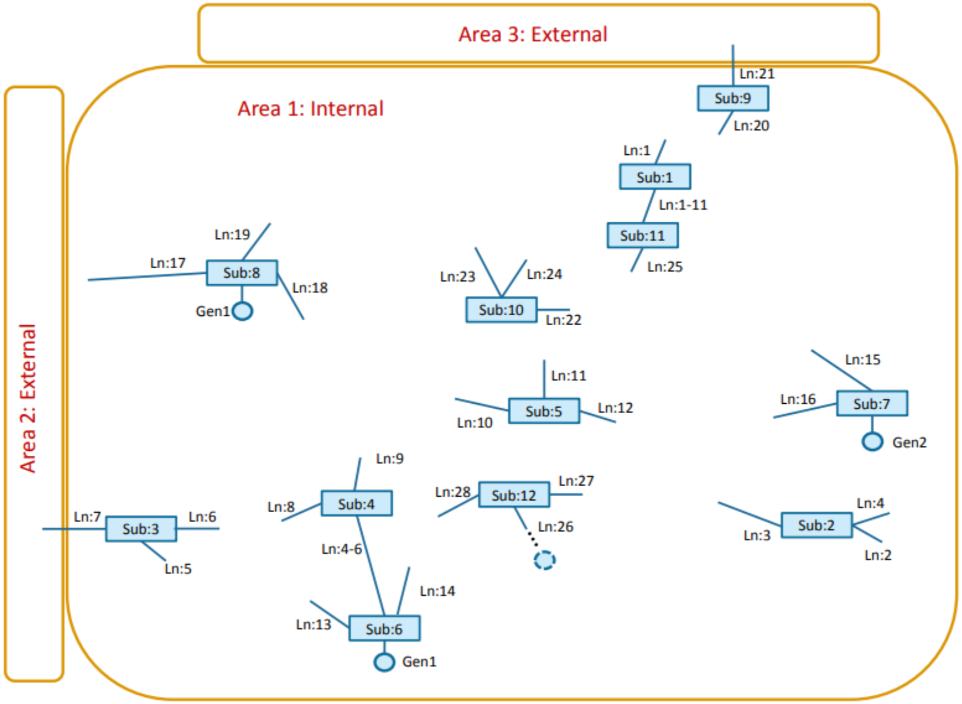




0.86 Hz shape (forced)

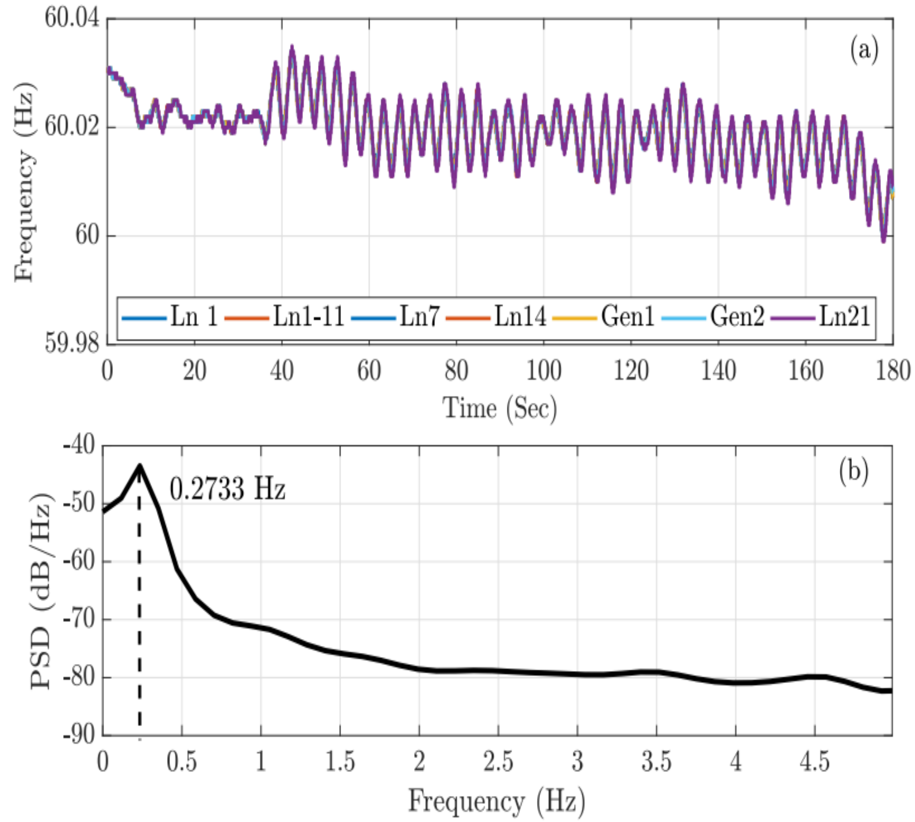
ISO New England Event

- ISO New England is located at the North-East part of the Eastern Interconnection in the USA where the peak load is about 26,000 MW.
- ISO New England has reported several incidence of forced oscillations observed in their system and listed the relevant data associated with these cases in [4].
- One of these oscillatory event has been analyzed here as an example to demonstrate the phenomenon of forced oscillation in real system data.
- ISO New England provided three minute data of frequency, voltage magnitude, voltage angle, current magnitude and current angle measured at different locations in their system



ISO New England Event

- Figure represents the frequency as seen at different line and generator location inside ISO NEW England area 1.
- Oscillations are seen at all locations but the figure shows only selected frequency measurements.
- Frequency domain analysis of one of the line frequency and the peak near 0.2733 Hz indicates the presence of an oscillation.
- Further analysis revealed that the source of oscillation is a large generator located at an external area 2.



Remarks – Damping

- Natural Oscillations:
  - Function of system eigenvalues
  - Describes how a natural oscillation decays
  - Indicator of overall system stability
- Forced Oscillations:
  - If it is a sustained oscillation, it has 0% damping
  - If the forcing function has nonzero damping, so will the forced response
  - This nonzero damping is NOT a system property!
  - The damping of a forced oscillation is NOT an indicator of system stability!

Remarks - Oscillation Shape

- Natural Oscillations – "mode shape"
  - Describes the phasing and amplitude of natural oscillations throughout the system
  - System eigenvectors
- Forced Oscillations – "oscillation shape"
  - Describes the phasing and amplitude of forced oscillations throughout the system
  - Function of system frequency response at FO frequency, which does include eigenvectors
  - However, this is NOT a system mode shape

Summary
List of Oscillation Properties

Oscillation Type	Characteristics/Properties	Source
Natural response	- Oscillation characterized by the frequency, damping and modes of the system	Small load changes or big events like line tripping, generator tripping etc.
a) Transient response	- Deterministic with no random components - Fundamentally oscillatory for complex eigenvalues - Stability is determined by modal dynamics	Sudden disturbances eg., fault, generator tripping, line tripping, etc.
b) Ambient response	- Random process and may appear oscillatory - Contain system modal information	Random load changes
Forced response	- Deterministic with different amplitude and phases - Only contains energy at the frequency of the input - Contain harmonic frequency component	Cycling loads, equipment malfunctions, mistuned controllers etc.

Summary – Distinguishing Oscillation Features

- We observe a sustained oscillation. Is it a
  - Natural response to an undamped system? (BAD)
  - Forced response to a sustained oscillation input (OK?)
- We can leverage the physical properties of the oscillation types to help classify them
  - Harmonics imply forced response since it's highly unlikely the system modes happen to be harmonically related
  - Undamped natural responses are stochastic, while forced responses are deterministic

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Questions