ESIG Tutorial, Inertia
Part 1: What's What and Terms

GE Energy Consulting

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Agenda – Inertia & Frequency Response

1. What are we talking about? How do we call it?
2. What participates?
3. Physics
4. Why do we care?

Industry Terminology

An Example Event

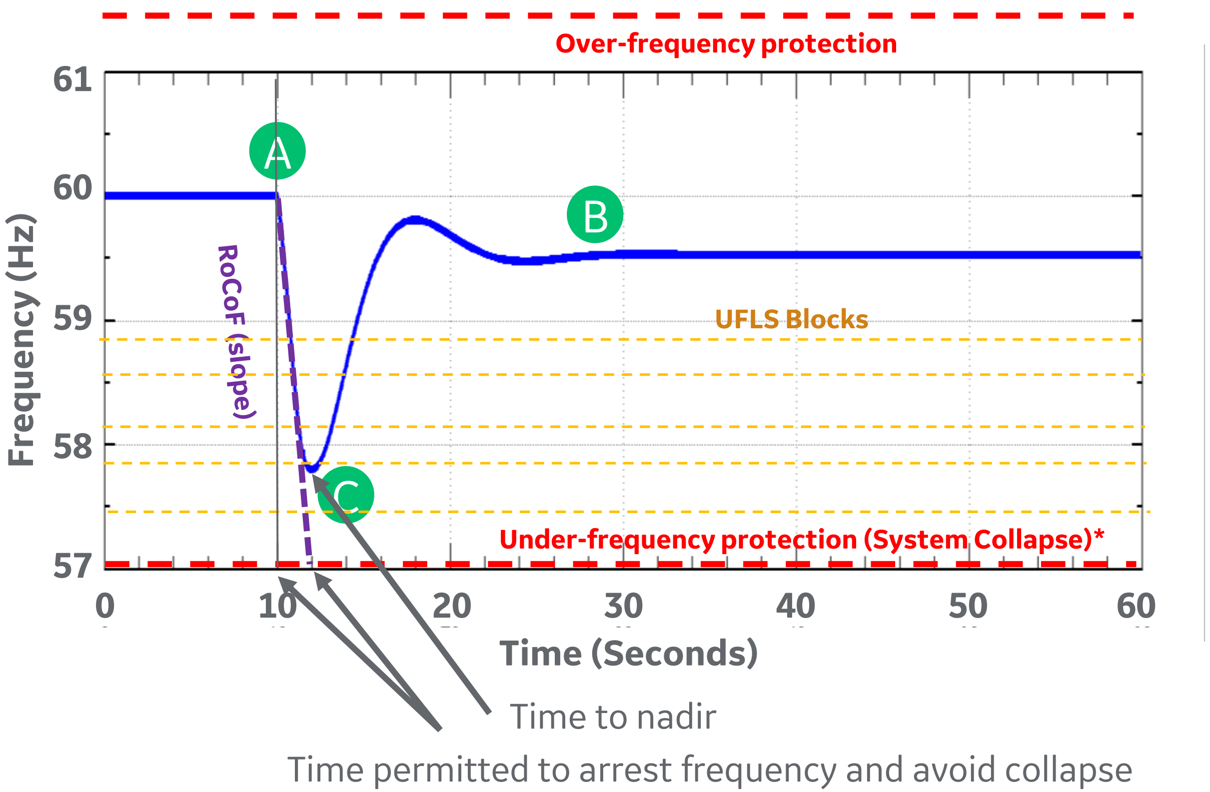
- Initial frequency (A)
- Frequency nadir (C)
- Rebound frequency (B)

Remember:

UFLS blocks are often discrete and static (but they don't have to be)

Over-frequency events (loss of load, over-shedding) can lead to system collapse, too!

The system can separate within this frequency range, and then collapse



Source: adapted from NERC Essential Reliability Services Working Group

Industry Terminology - Categories

Frequency Response: Modifying active power in response to a change in system frequency (generation OR load side)

Primary Frequency Response (PFR) – automatic, local, autonomous

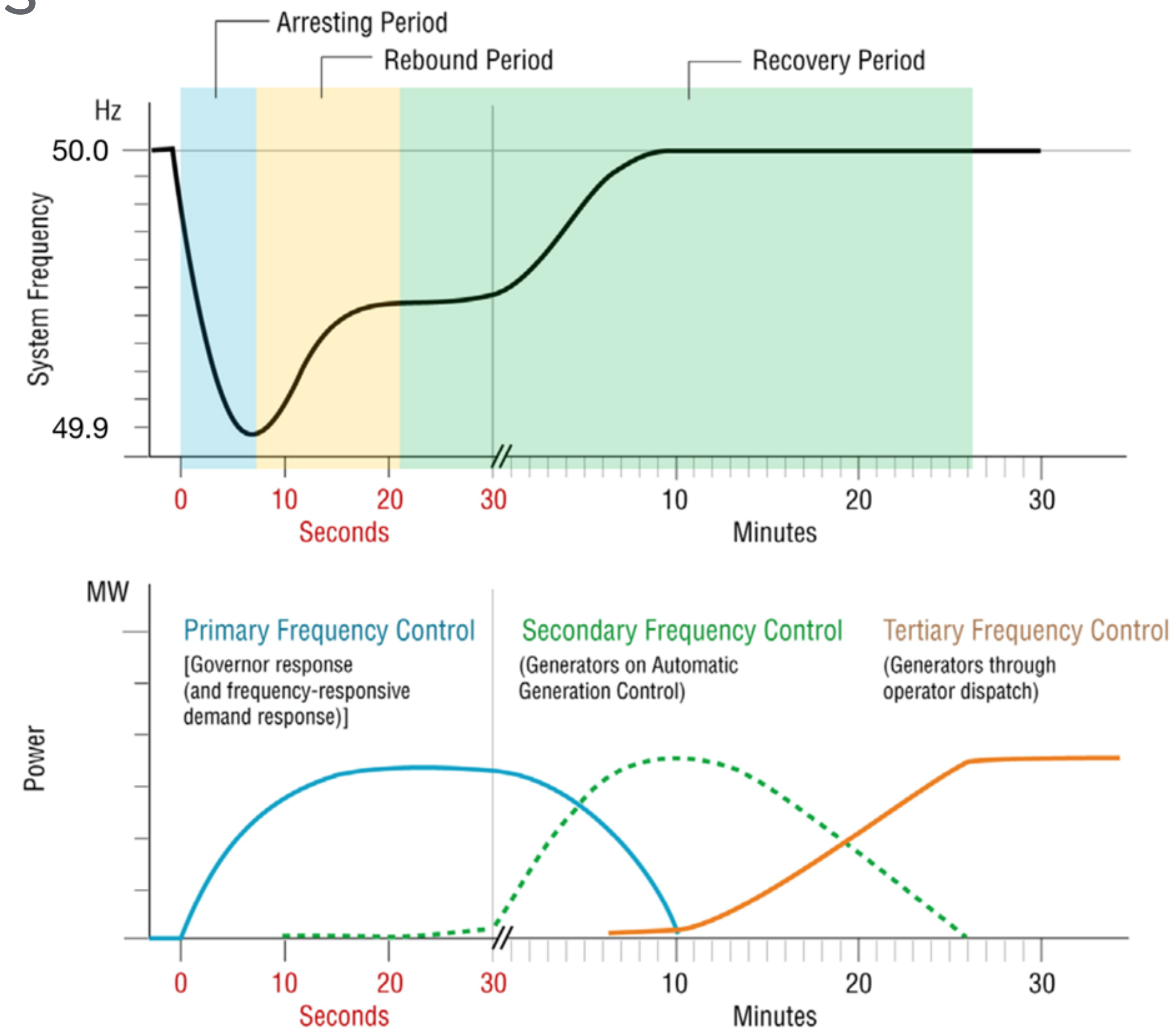
Purpose: Save and stabilize system

Secondary Frequency Response – automatic, centralized command like Automatic Generation Control (AGC)

Purpose: Return frequency to nominal

Tertiary Frequency Response – typically manual, central command

Purpose: Re-dispatch or recommit units to optimal operations



So what about Inertia, FFR, SIR, etc?

Industry Terminology – Subcategories

Synchronous Inertia – Inherent response from synchronous rotating electric machines

(ie. synchronous generators/motors, synchronous condensers)

Fast Frequency Response (FFR) – fast-acting, controlled response from generation or loads

(Detailed examples in slides to come)

Under-frequency load-shedding (UFLS) – involuntary protection system, typically operating in discrete “blocks”

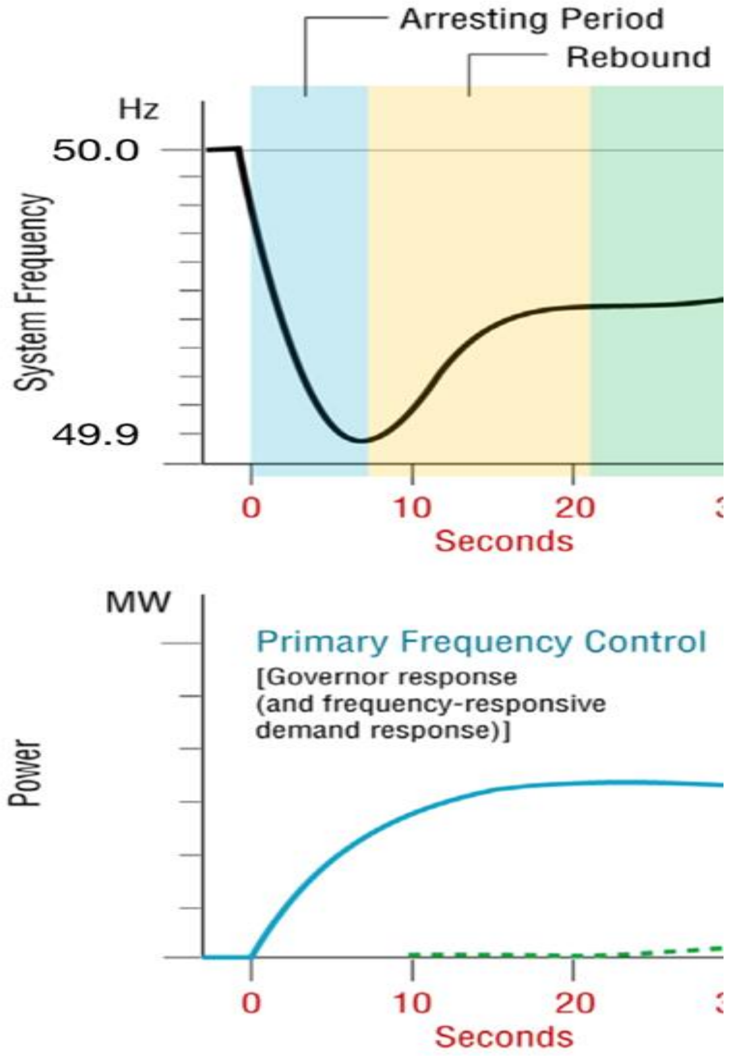
(ie. distribution feeder relays)

Frequency-dependent loads – loads where power consumption is a function of frequency

(ie. induction motor load)

What’s missing: synthetic inertia – typically a fast-acting controls-based response, therefore it’s considered FFR

(ie. Wind inertia)



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Illustrative Simulation

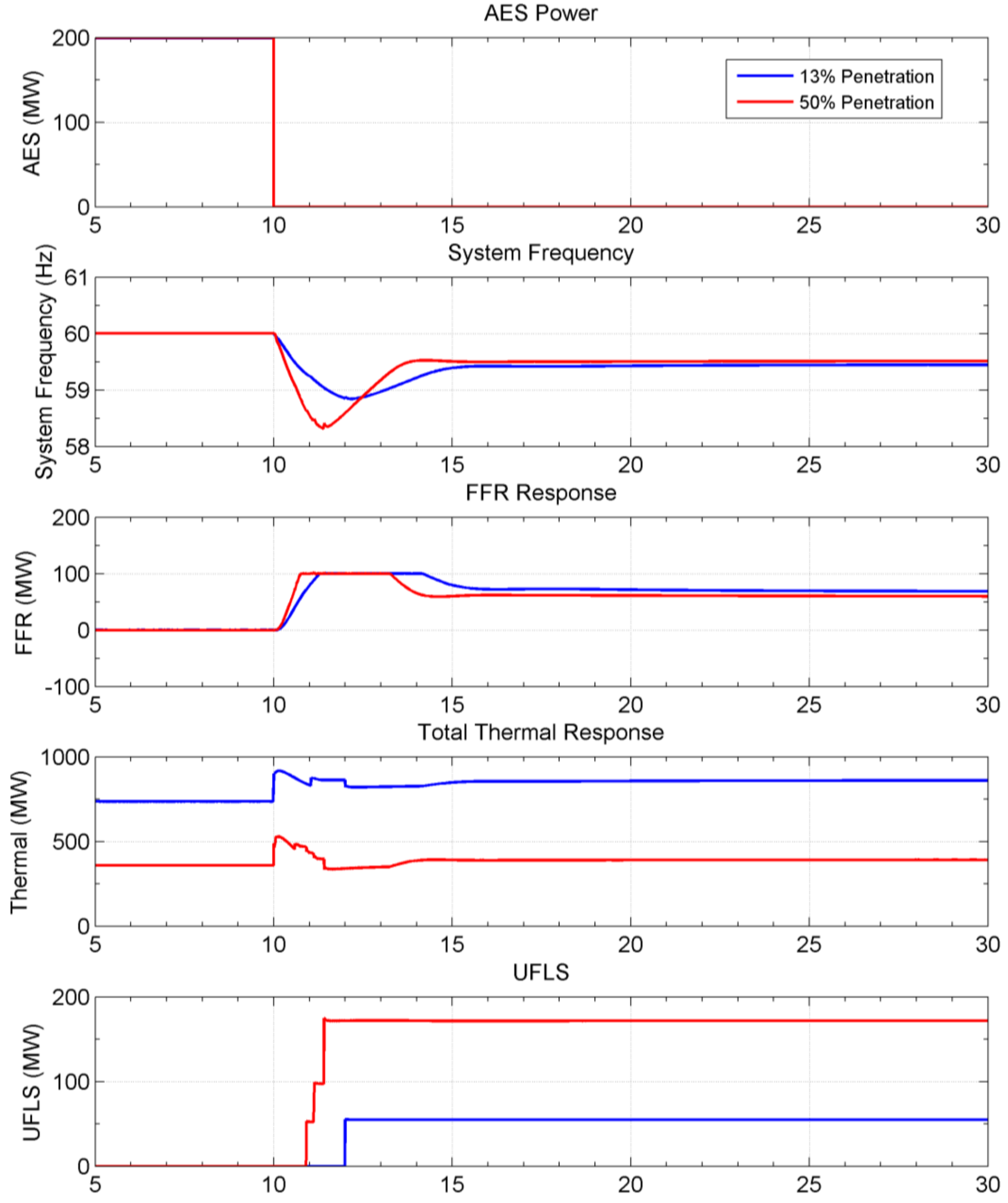
AES Unit (200MW Trips) at 10 seconds →

System frequency declines →

100MW FFR Injection (trip response) →

Total thermal units response →

UFLS is triggered →



What Can Provide FFR?

Energy Storage (Battery, Flywheel, etc)

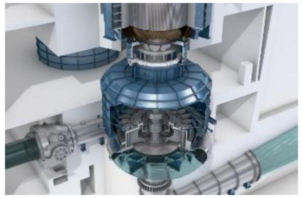
Fast to respond, easy to deploy, but relatively expensive and requires SoC management (power & energy headroom)

Wind Turbines

Wind Inertia can provide a short duration (~6sec) response that can be an effective way to arrest system frequency decline. Curtailed wind energy allows longer response for under frequency events, but opportunity cost associated. Very effective for over-frequency response.

Solar PV

Curtailed solar can respond quickly to under frequency events, but opportunity cost associated. Very effective for over frequency.



Variable-Speed Pumped-Storage Hydro (VSPSH)

Fast, controlled response available (similar to wind) and with the duration of energy storage systems.

Frequency Responsive Loads

Demand response can be very effective because it is only required for rare, short duration events. But must be able to detect and respond to frequency deviations locally (no time for communication signals).

Physics

Dissection of a Generation Trip Event

1. Steady-state – Electrical power and mechanical power in balance

2. Upon a trip, electrical power essentially unchanged (neglecting voltage and frequency dependence of loads)

But there's a system-wide mechanical power deficit

The electrical power of the lost unit is immediately extracted from the mechanical system of all synchronous units; speed decreases

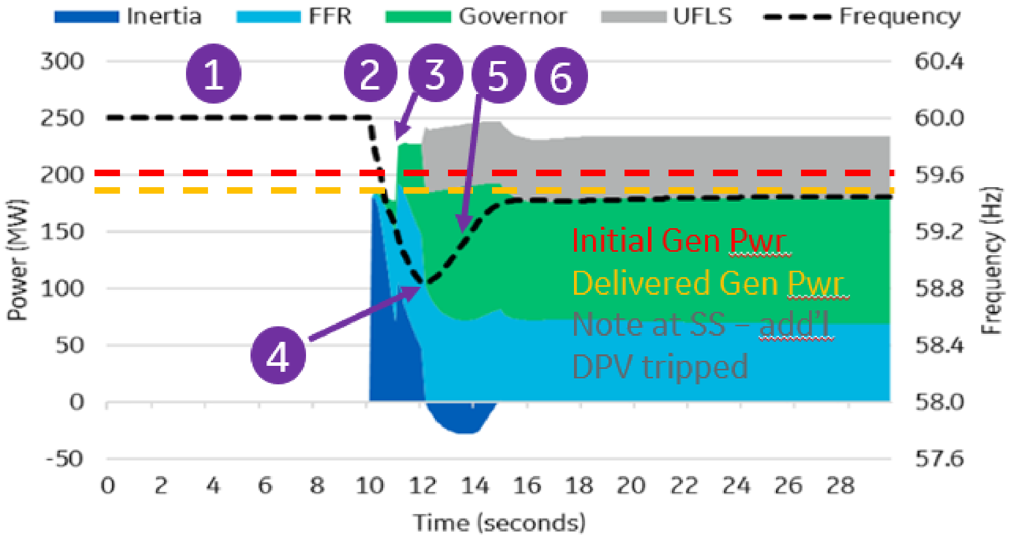
3. As assets (governors, FFR, UFLS) respond, mechanical and electrical power are restored to balance.

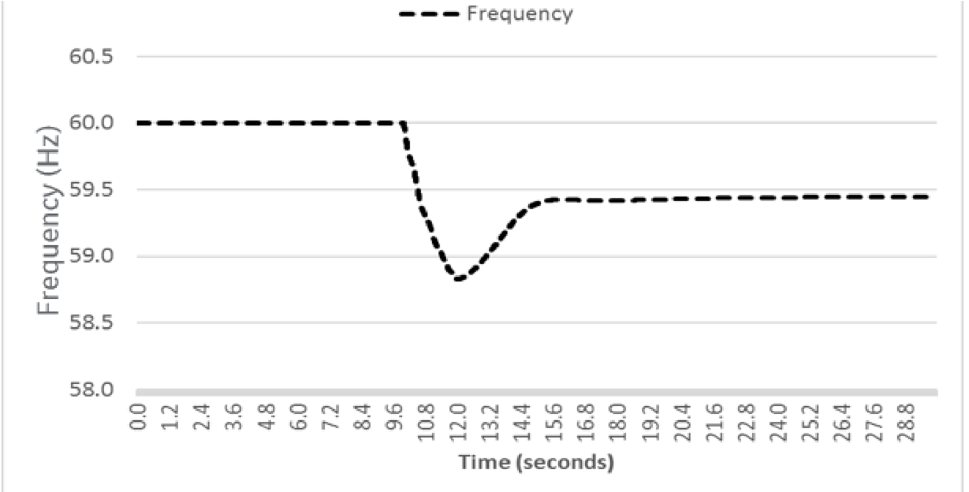
4. The moment this happens, df/dt = 0 → frequency nadir

5. Mechanical power increases above electrical power to increase system frequency (energy flows into rotating masses).

6. This happens until a new equilibrium is achieved with frequency droop settings. Droop is prop-only control… therefore SSE is expected.

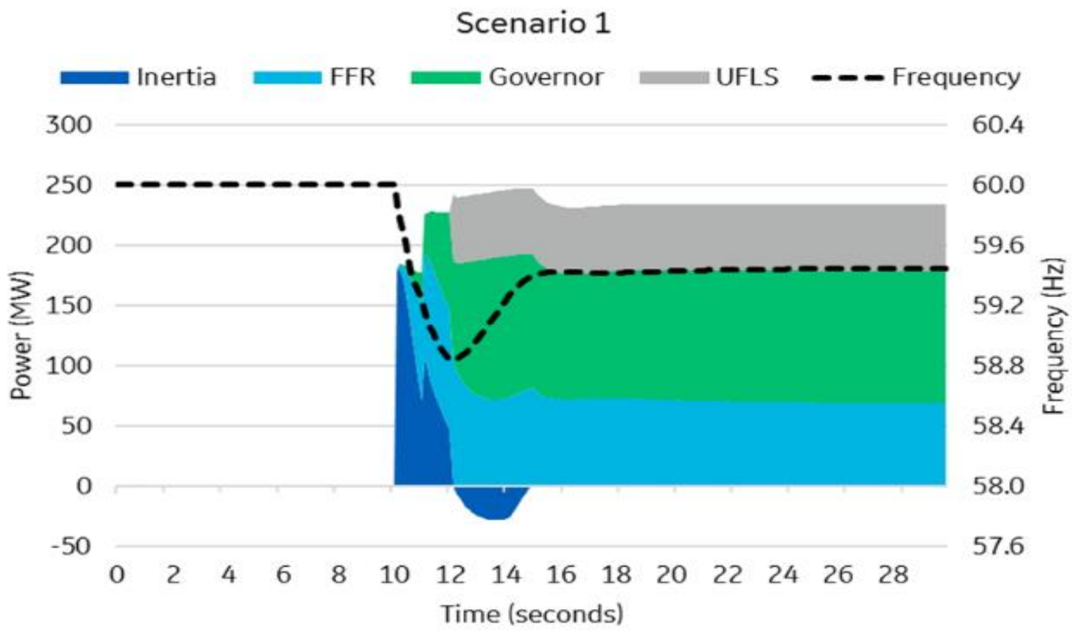
7. Secondary frequency response (like AGC) returns system frequency to nominal

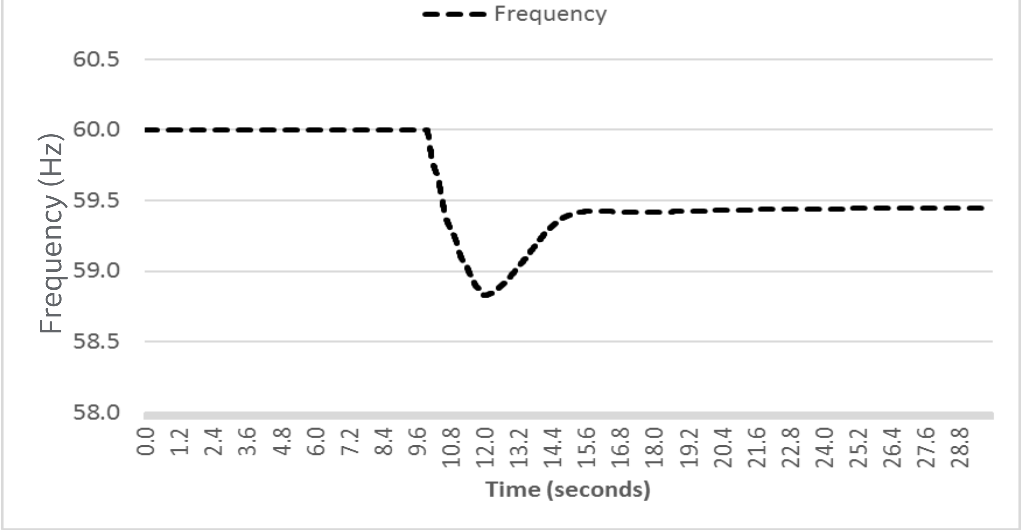




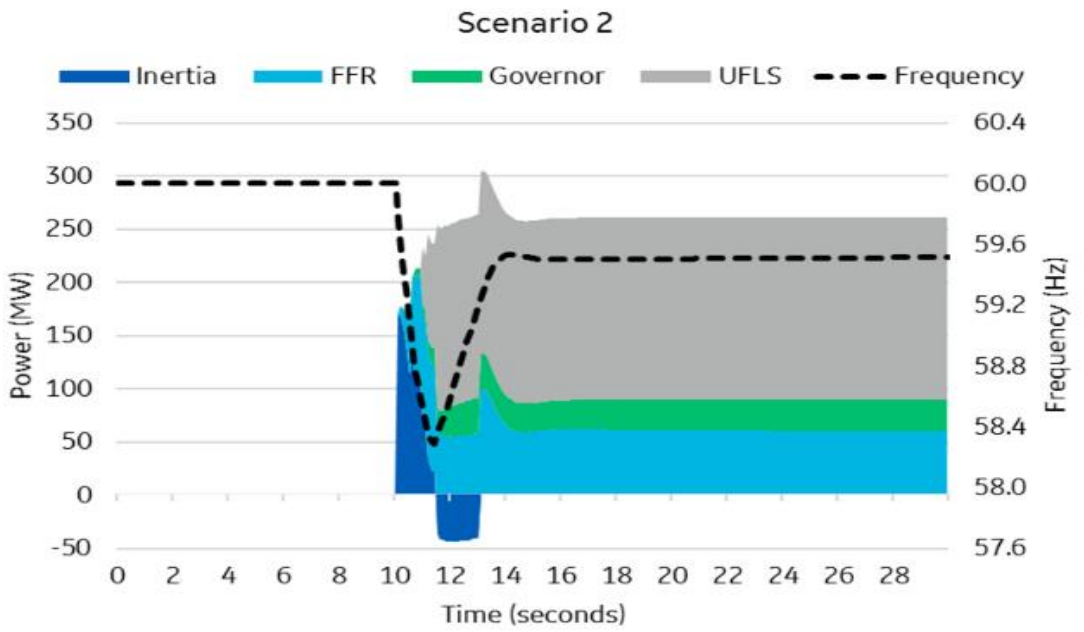
Deconstructing Frequency Response

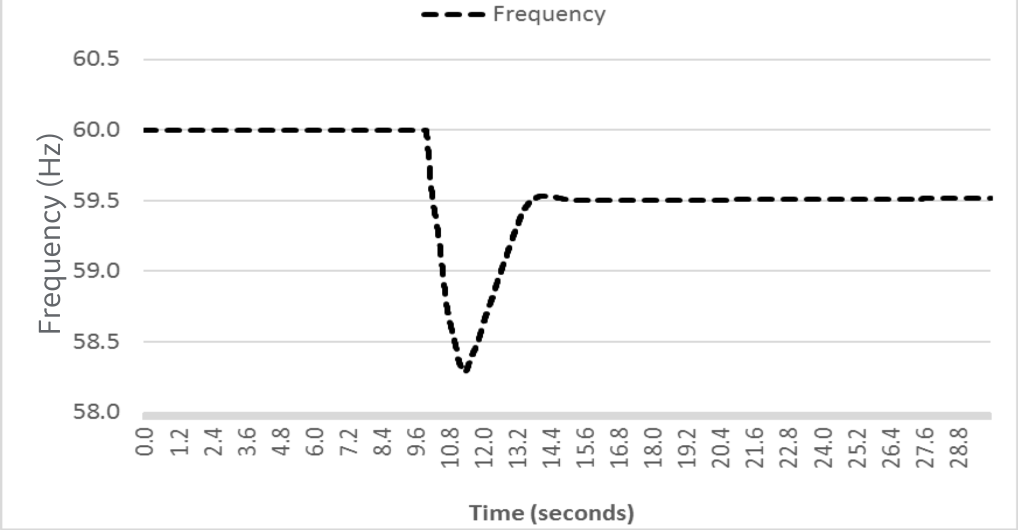
Scenario 1: 17% Inst. Penetration





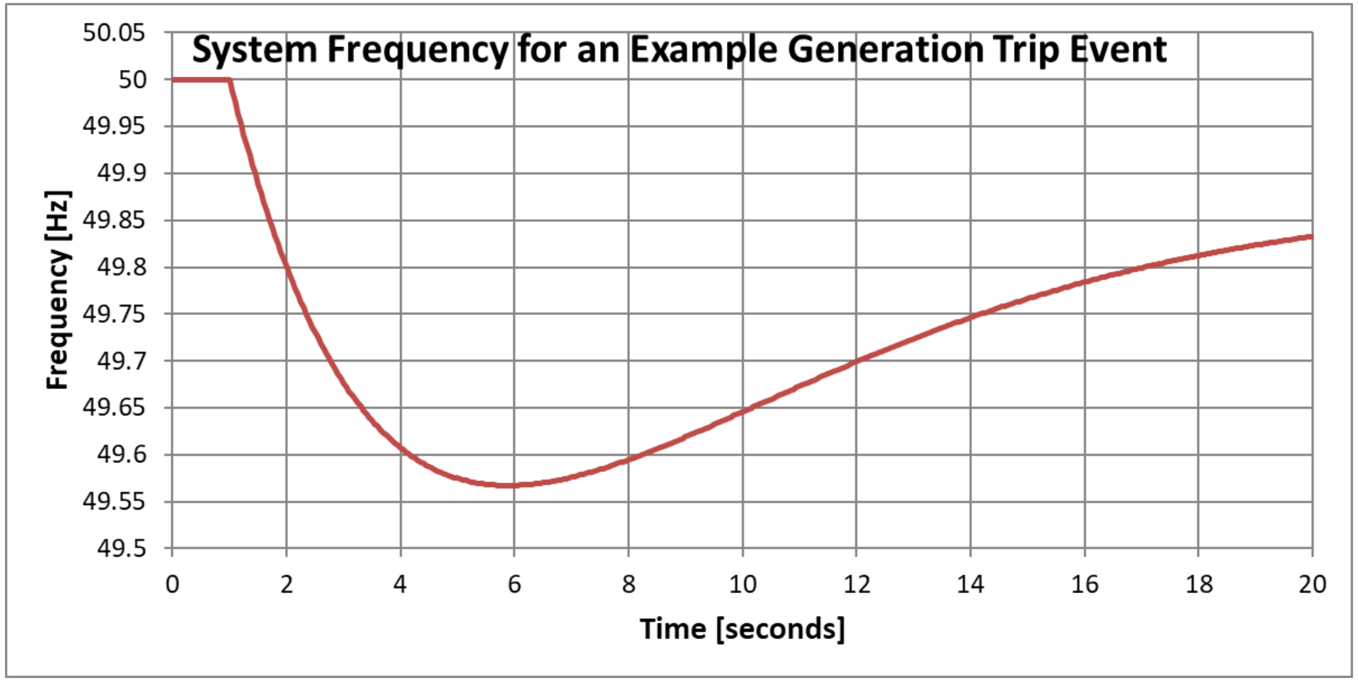
Scenario 2: 50% Inst. Penetration

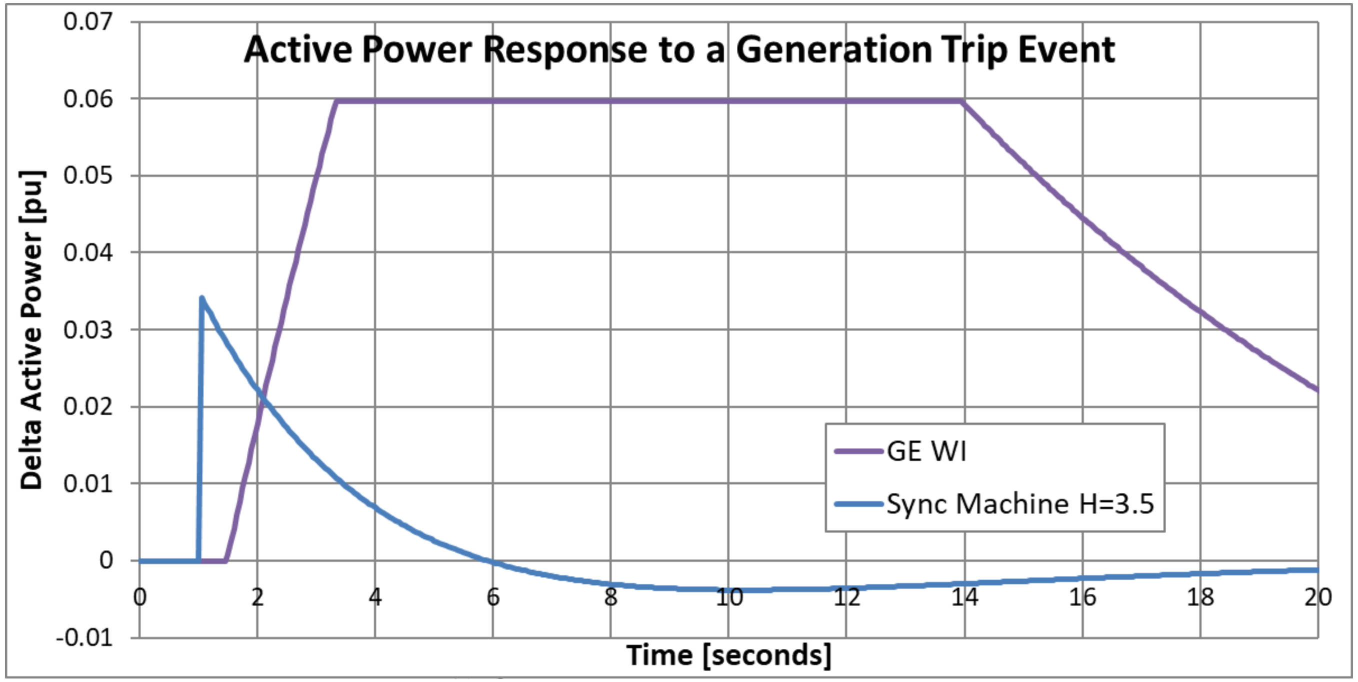




Comparison to Synchronous Machines

- Consider an example under-frequency event, ~49.6Hz nadir, ~200mHz/sec RoCoF
- Synchronous machines can only access a small fraction of this energy because speed only deviates a few percent throughout an event.
- Controlled-response (decoupled drivetrain) equipment is not subject to the limits of system speed.
- For instance, WTGs can access more of its drivetrain energy since it can slow the drivetrain by >30% for a 1% change in system frequency.





Why Do We Care?

Why Should We Care?

System Risks

Frequency stability – common-mode system collapse

Angular stability – system separation, often leads to system collapse

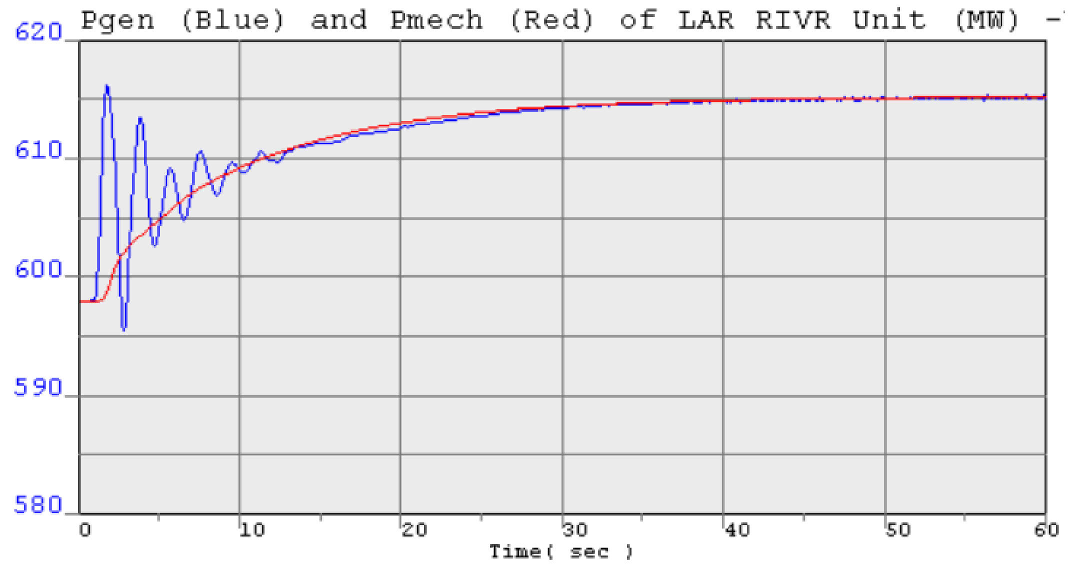
Equipment Risks

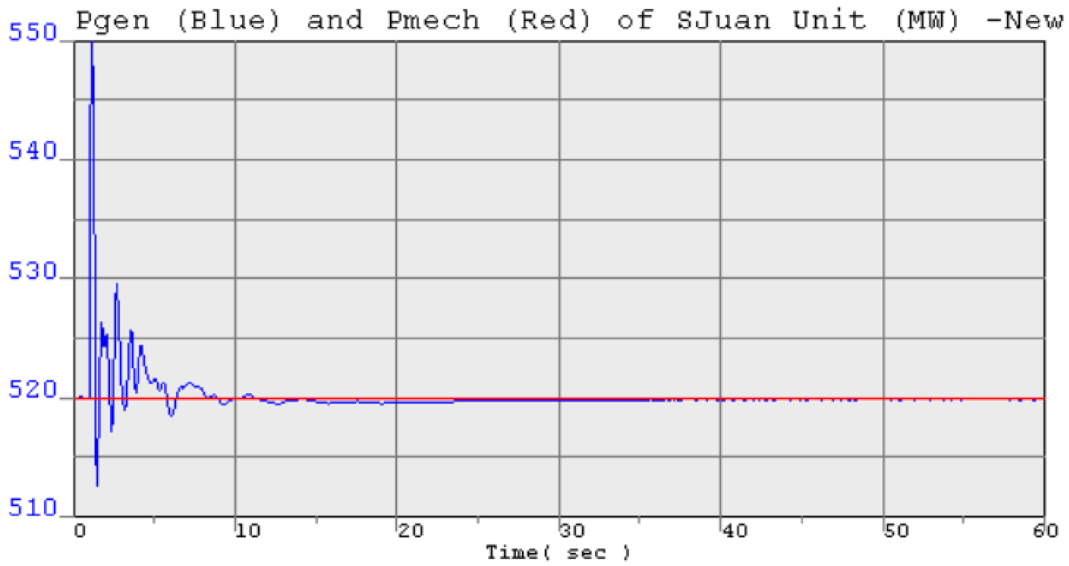
Low frequency – margin from the protection thresholds, STG last-stage bucket resonances

High RoCoFs – UFLS time to act, power electronic tracking, CTG performance (lean blow-out)

Angular Stability & Power System Swings

- For larger systems, frequency isn't uniform
- Synchronous units interact, creating power system swings, as evidenced by oscillating electrical power
- The power swings can create high power transfers and power angles across lines in the system
- In extreme cases, lines can trip, causing the system to separate
- Fast-frequency responsive assets with bandwidth in this frequency range should not exacerbate oscillations or increase the risk of separation





Equipment Risks

Low-Frequency operation

- Reduced margin from protection thresholds
- Steam turbine last-stage bucket resonances

High RoCoFs

- Less time to detect an event and act (UFLS, FFR, etc)
- Combustion turbines have lean blow-out risk (particularly for power-reduction events like a frequency back-swing or loss of load)

Summary

- Language can be tricky – it's important to confirm a common understanding
- There are several different time-frames of interest & importance for frequency response
- Lots of equipment (generation AND load side) can participate, each with advantages and disadvantages → using everything available reduces system risk
- We have a solid understanding of the system and equipment… and we also know that many exciting challenges lie ahead