CIGRE Academy Webinar: Impacts of High Share of Inverter-Based Resources on System Inertia and Frequency Control

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Agenda

1. Fundamentals of Frequency Control and Impacts from High Share of Inverter-Based Resources
2. Inertia Monitoring and Estimation, Review of International Practices
3. Procurement of Inertial Products, Example of Great Britain and Ireland
4. Fast Frequency Response around the World, Review of International Practices
5. Inertia and Frequency Control by Generation Technologies
6. Inertia and Frequency Control by Load Resources
7. Methodology to Determine Amounts of Frequency Containment Reserve, Example of ERCOT
8. Closing Remarks
9. Q&A

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Julia Matevosyan is Lead Planning Engineer at the Electric Reliability Council of Texas (ERCOT), Resource Adequacy Group, primarily working on adequacy of system inertial response, system flexibility, frequency control and performance issues related to high penetration levels of inverter-based generation. She received her BSc from Riga Technical University (RTU) in Latvia, and her MSc and PhD from the Royal Institute of Technology (KTH) in Sweden.

Papiya Dattaray has been with EPRI for 2.5years, working as a senior research scientist investigating transmission reliability concerns with high penetration of renewables with focus on system stability and advanced inverter functionalities . She received her PhD from The University of Manchester on Subsynchronous oscillations in 2018 and a master’s from IIT Delhi.

Diptargha Chakravorty is a Senior Consultant with TNEI Services. He is an electrical engineer with over 8 years of experience in the power industry, including a 4-year PhD on the impact of demand response on system stability from Imperial College London. He specialises in modelling and analysis of transmission and distribution networks and automation of system studies. His core expertise includes stability analysis, grid integration of renewable energy and power electronics converter control. He is currently the vice-chair of the Cigre UK NGN steering committee.

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Fundamentals of Frequency Control and Impacts from High Share of Inverter-Based Resources

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14th Oct 2020

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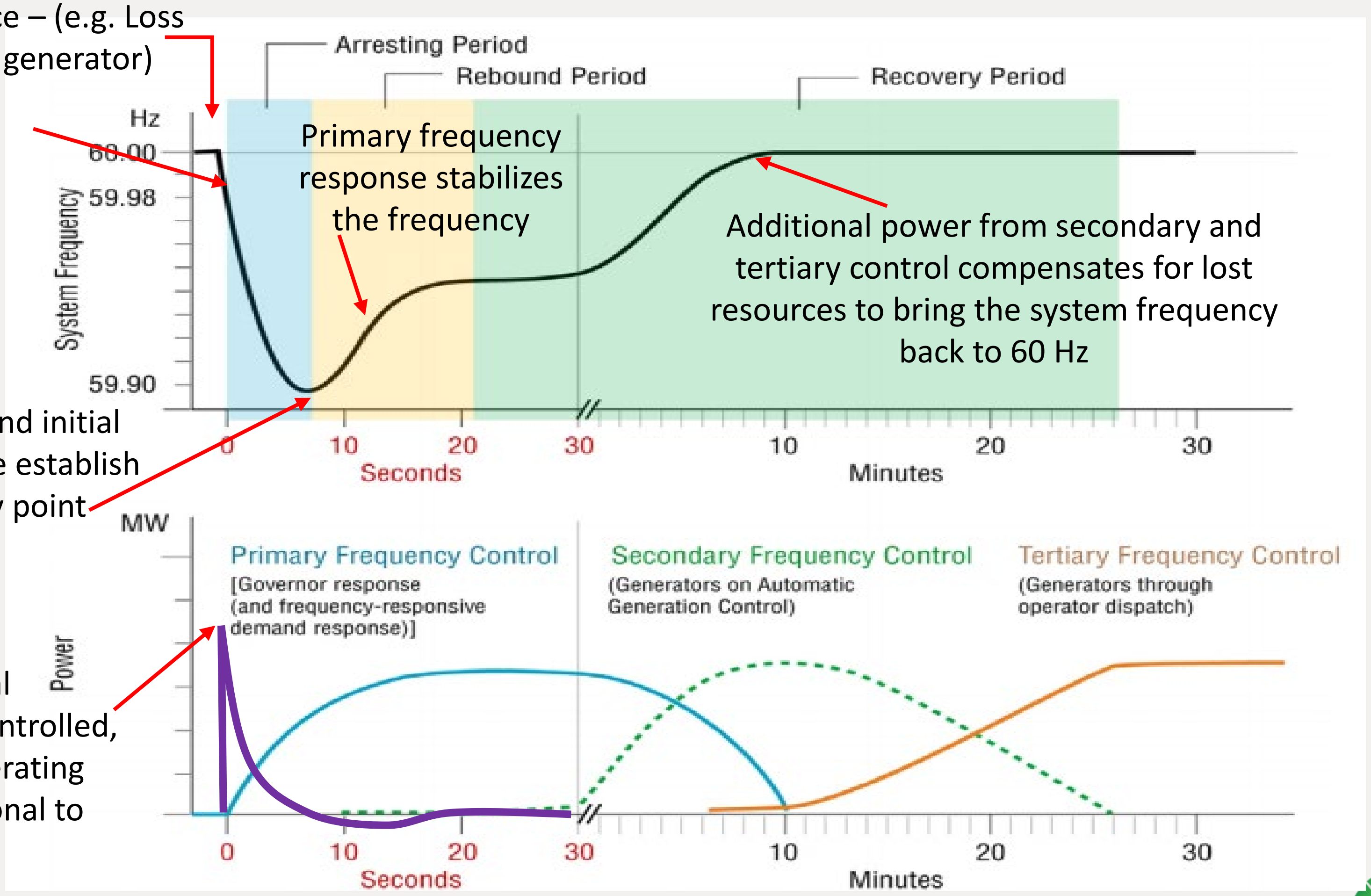
Fundamentals of Frequency Control

Disturbance – (e.g. Loss of large generator)

Synchronous Inertial Response sets initial slope



Fast frequency response and initial primary frequency response establish the minimum frequency point (“nadir”)

Synchronous Inertial Response is “instant”, uncontrolled, and dominated by accelerating power which is proportional to dω/dt

Source: Eto, et al. (2010): Use of a Frequency Response Metric to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation, modified by Nick Miller

Useful Definitions and Acronyms

- **Inverter-Based Resources (IBR):** Generation, Load or Storage Resources that are connected to the grid through power electronic inverters
- **Frequency Containment Response (FCR), also called Primary Frequency Response (PFR):** Local and autonomous increase/reduction in active power from a resource to contain system frequency after a sudden generation or load loss. The response is proportional to frequency deviation (i.e. droop response) once the frequency falls outside of a certain frequency range (deadband). The response is provided by synchronous generators through governor action or by controllable loads and inverter-based generators through control algorithms. This response is in the direction that stabilizes frequency with full response typically 10-15 seconds, depending on resource type.
- **Fast Frequency Response (FFR):** Local and autonomous increase in active power from a resource to reduce initial rate of change of frequency (RoCoF) after a sudden generation loss and allow sufficient time for FCR to be deployed. Typically this is a step or proportional response to a preset frequency trigger or a RoCoF trigger with full response expected between 0.25s-2s once the trigger is reached.

What is Inertia?

- Rotating generators and motors synchronously connected to a power system have stored kinetic energy.
- Immediately after a contingency event (e.g. generation trip), this stored kinetic energy is drawn from the remaining synchronous generators to maintain balance between production and consumption - inertial response.
- Mechanical power input into the generators however is still unchanged.
- Generators will start to slow down and system frequency declines as a result
- The rate of frequency decline depends on the amount of inertial response available at the time of an event.
- **Inertial response currently provides an important contribution to reliability in the initial moments following a generation or load trip event determining the rate of change of frequency (RoCoF).**

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What is Inertia?

Synchronous inertia of a machine is based on the commissioned design capability of the plant. It can be determined through appropriate validation procedures based on the following relationship:

$$\mathit{Stored\ kinetic\ energy} = \frac{J\omega_o^2}{2} = H \cdot S_n \text{ , where}$$

- *Stored kinetic energy* is in MVA-seconds;
- J is the combined moment of inertia of a synchronous machine and turbine prime mover in kg·m^2, based on its size and weight;
- ω_o is the nominal rotor speed in rad/s, and
- S_n is the machine's rated capacity in MVA.
- H is the figure of merit used to analyze the synchronous machine's inertial response inertia constant in seconds. $H = \frac{J\omega_o^2}{2} \cdot S_n$
- The inertia response that a synchronous machine can provide is independent of the machine's power output
- Total system response to an initiating event is determined by the summation of the contributions from each of the online synchronous machines

$$M_{sys} = \sum_{i \in I} H_i \cdot S_{n,i}$$

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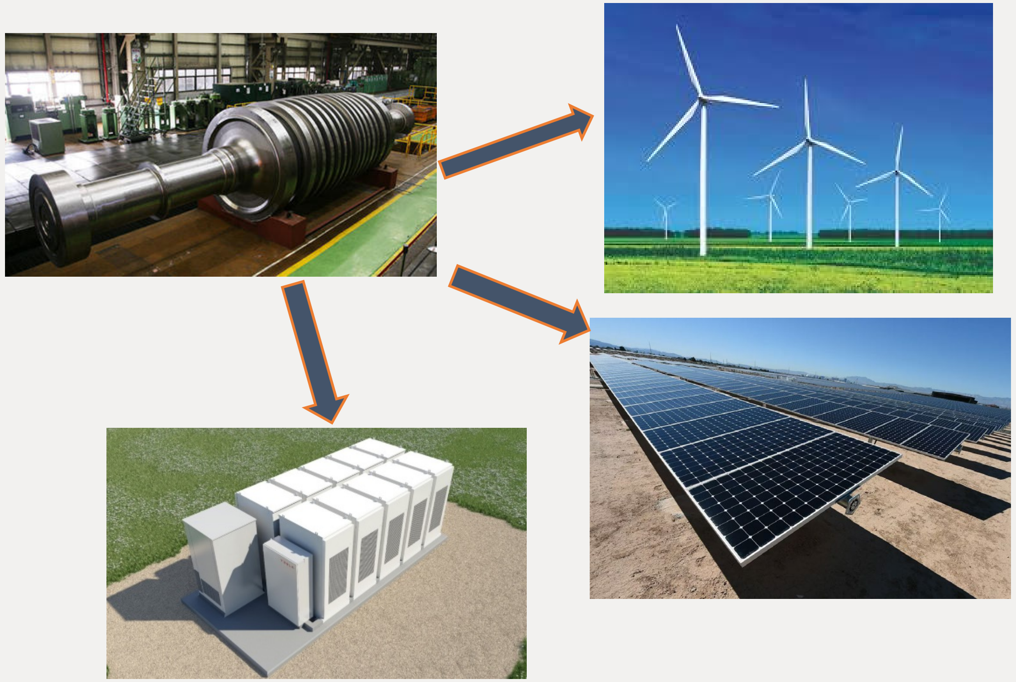
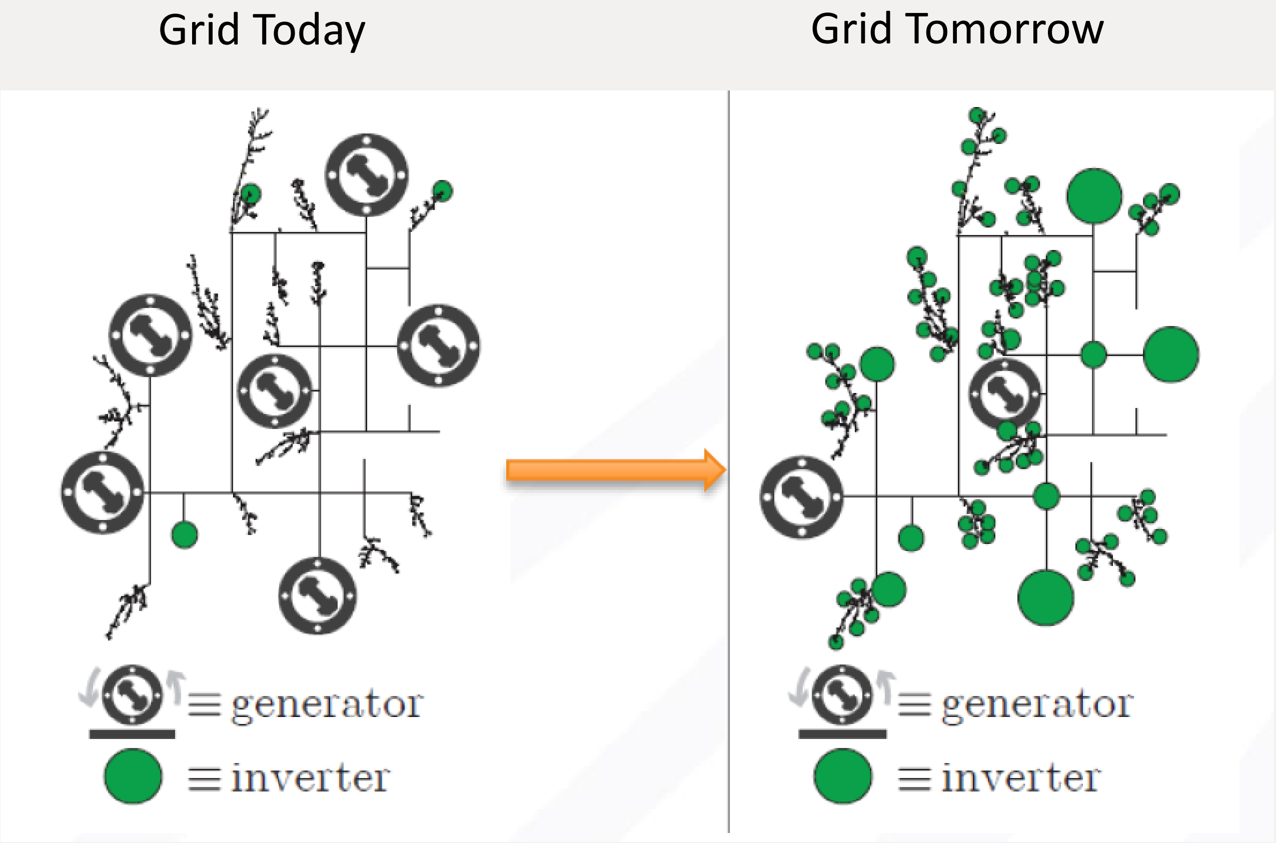
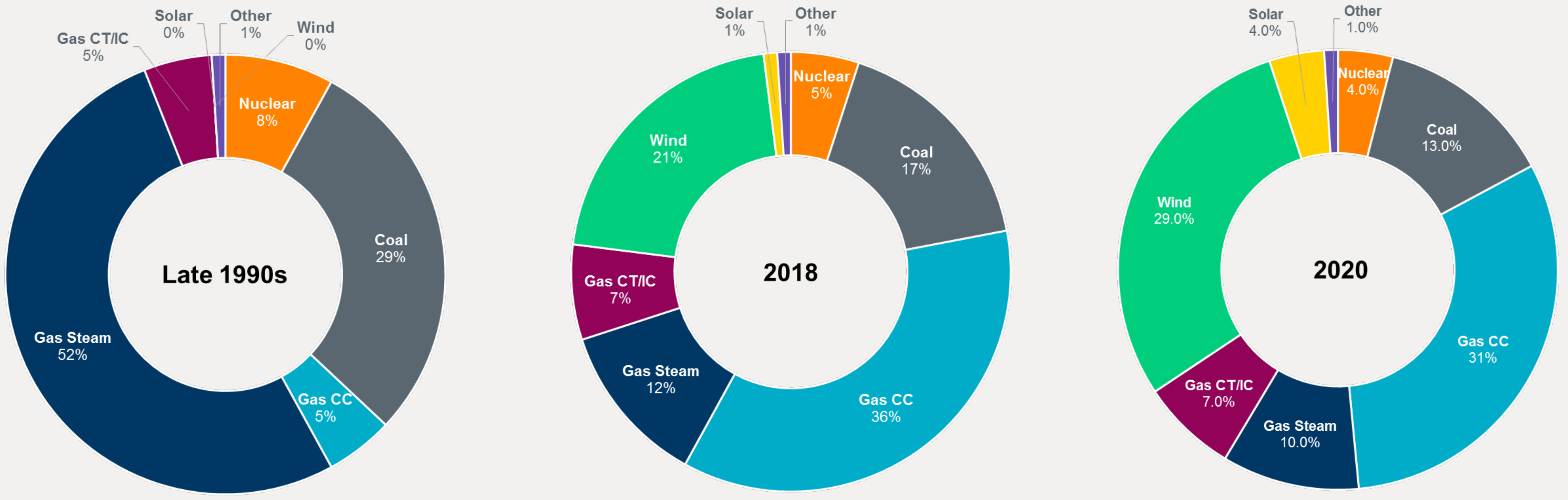
Inverter-Based Resources are Displacing Synchronous Machines





Source: DOE Solar Energy and Technology Office

Changing Resource Mix, Example of ERCOT



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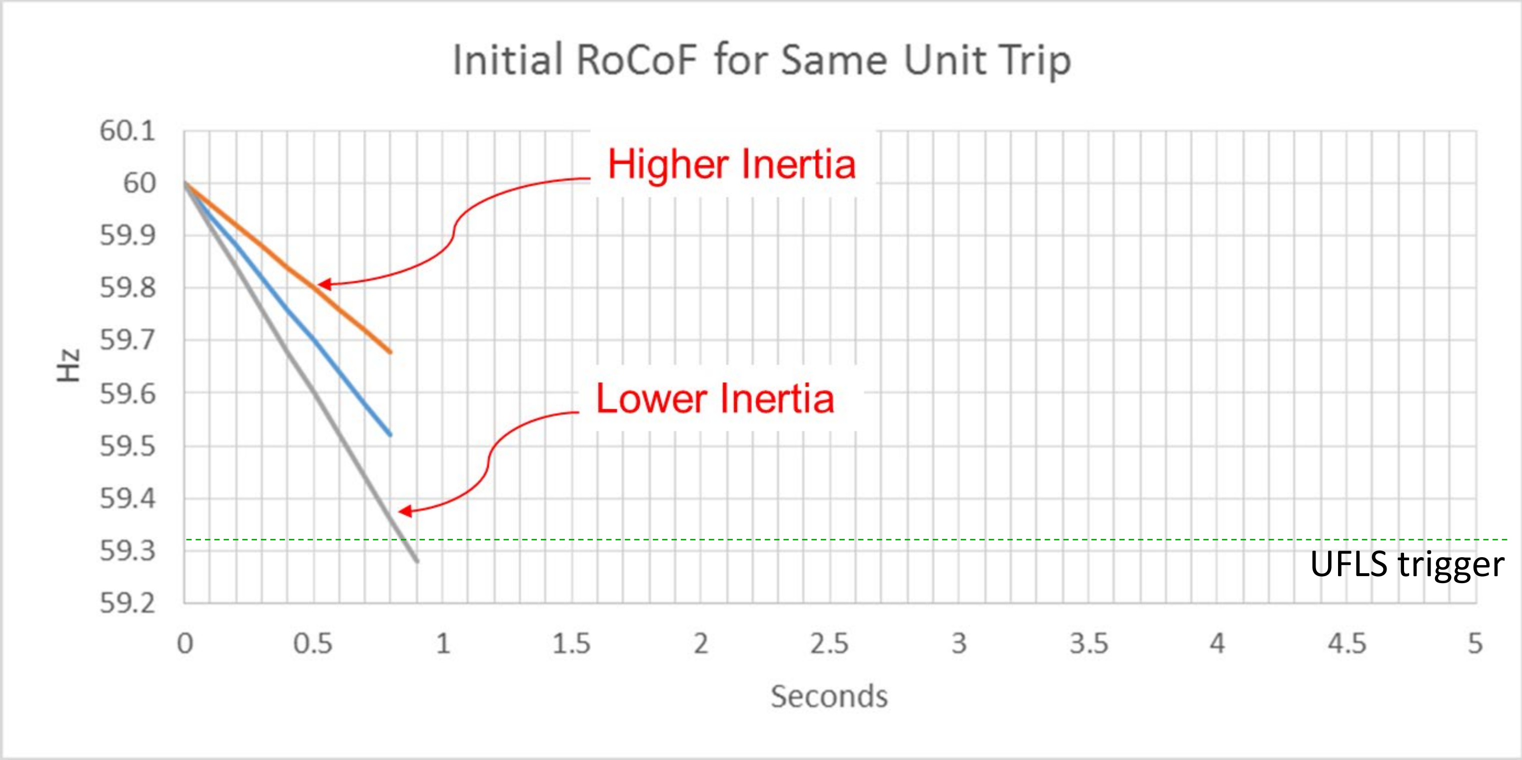
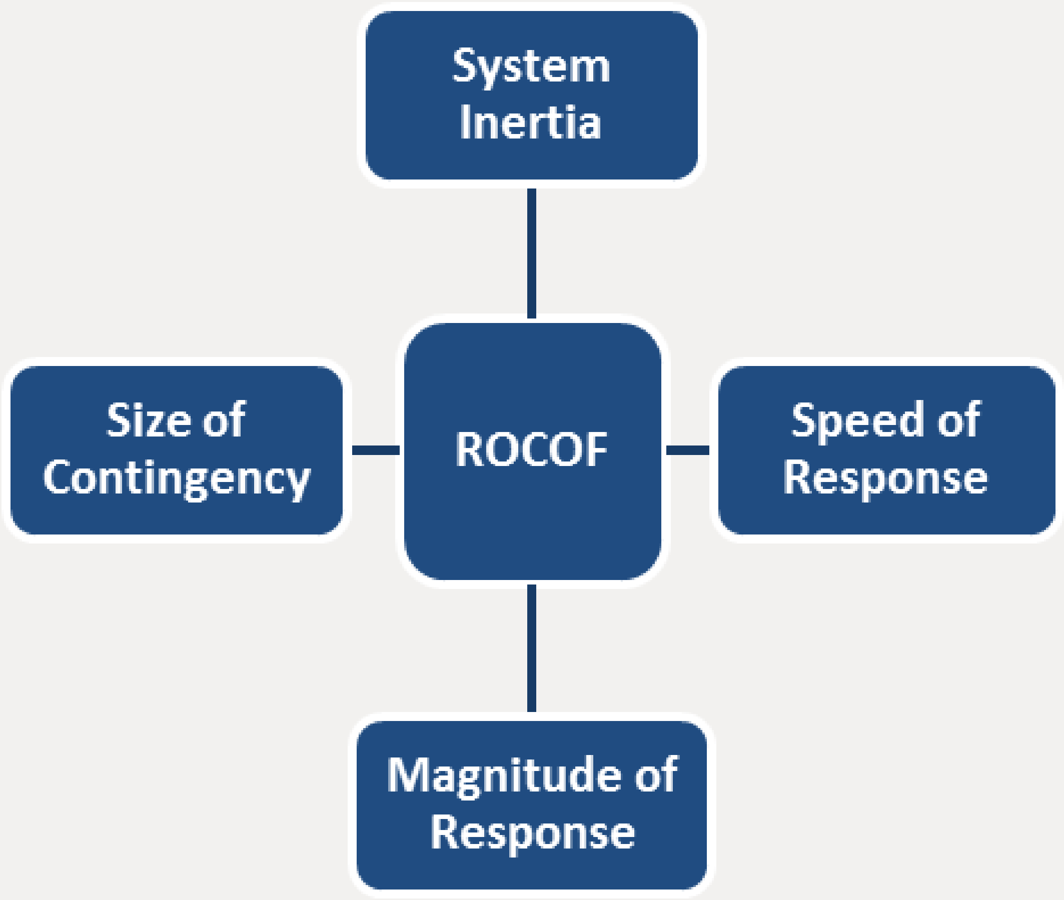
Effect of Synchronous Inertia on System Frequency

- With increasing integration of Inverter- Based Resources (such as wind, solar, battery storage), there could be periods when total inertia of the system could be low, as less synchronous machines will be dispatched.
  - During such situations, it is essential to have adequate frequency response capabilities.



RoCoF – Rate of Change of Frequency

How to Improve Declining RoCoF?



Source: NERC IRPTF White Paper: Fast Frequency Response Concepts and Bulk Power System Reliability Needs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Inertia Monitoring and Estimation

Review of International Practices

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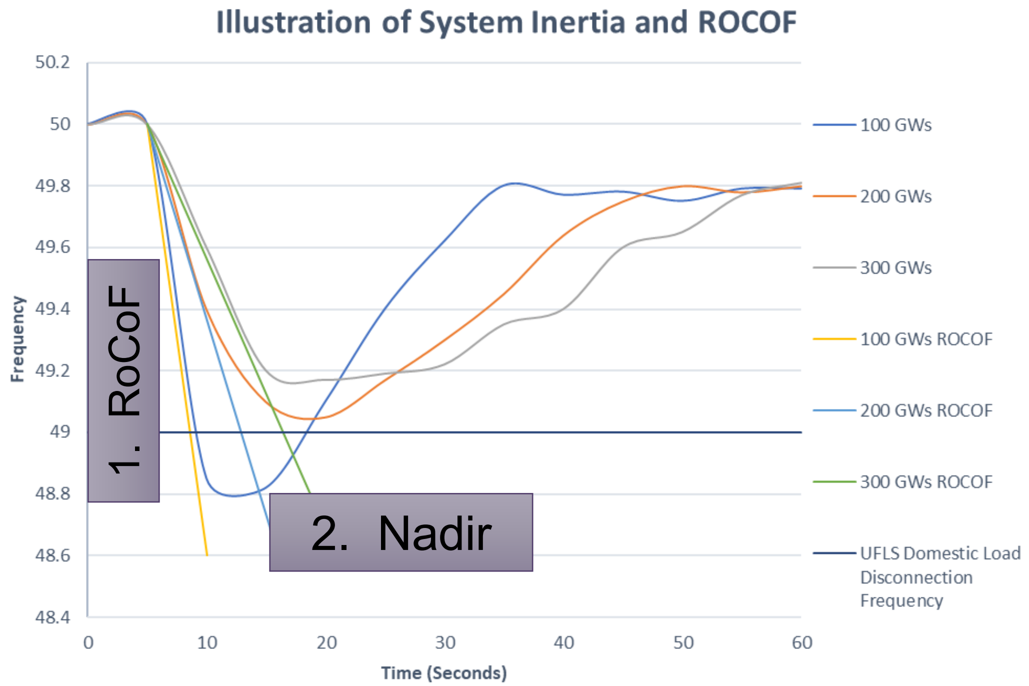
Motivation - Reduced Inertia and Frequency Security



Nadir is a concern :

Operational Security Standards

Customer Load Shedding

Frequency Containment

FFR < 2s

FCR < 10s

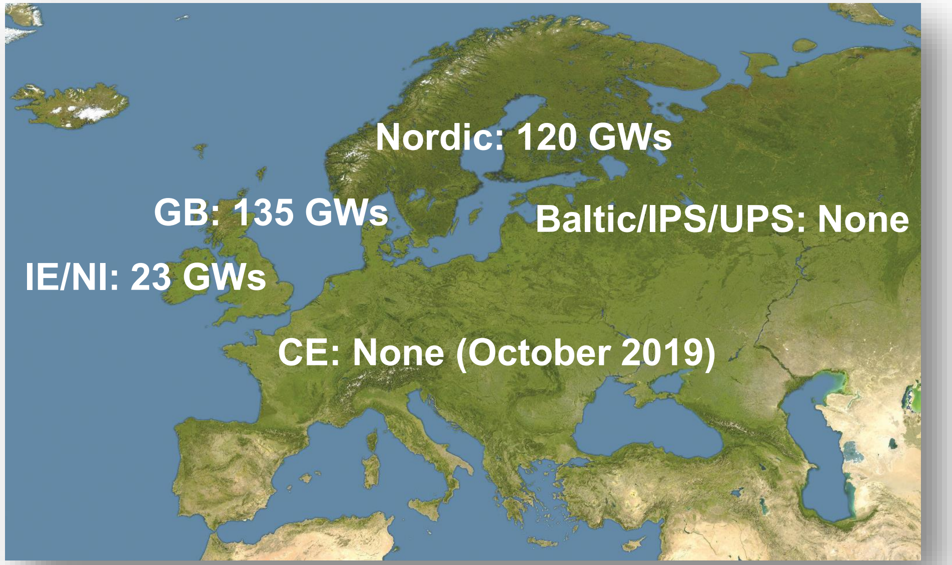
RoCoF is a concern :

- Loss of Mains operation
- Generation withstand

Critical inertia floors

RoCoF Constraint

Loss of Main Relay setting changes



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Inertia Monitoring Methods

Unit commitment - Monitoring

- Sum of online generation inertia (GVAs)

Continuous signal - Estimation

- Real time analysis of known stimulation
- Real time analysis of natural small perturbations

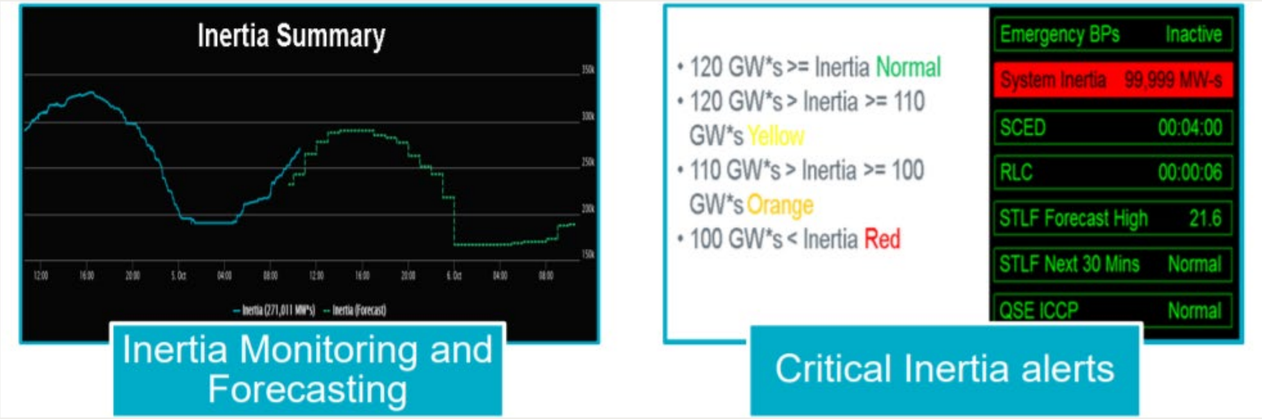
Event driven - Estimation

- Post-mortem analysis of large events
- Real time analysis of large events

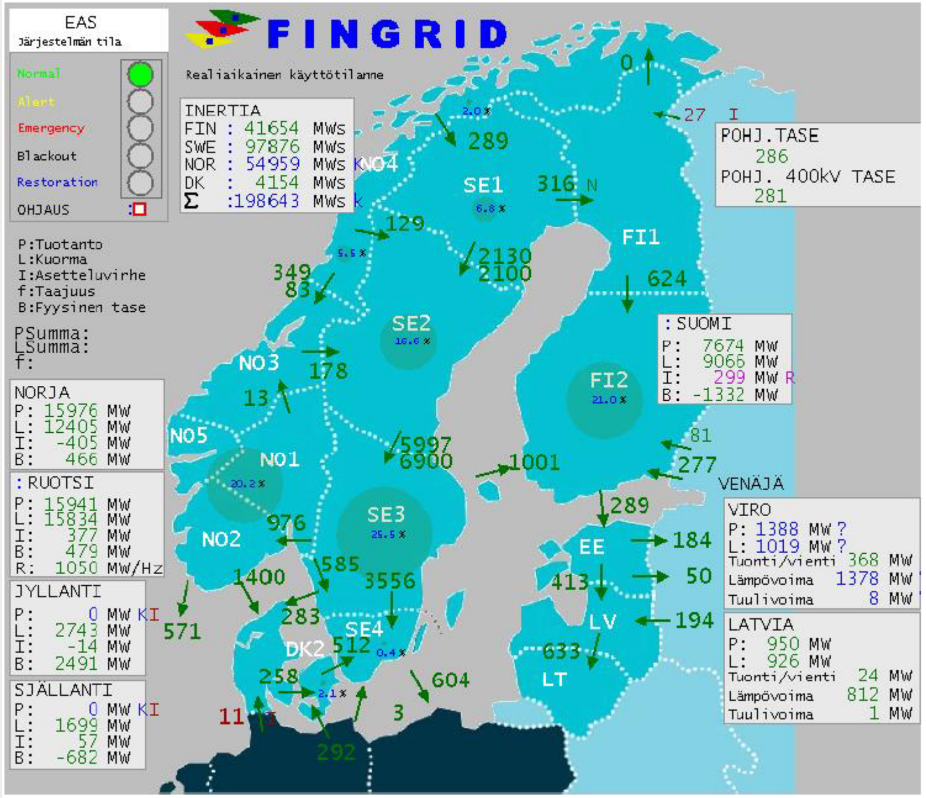
Source: EPRI White Paper
'Online Inertia Estimation & Monitoring: Industry Practices & Research Activities', 000000003002016195

Unit Commitment Based Inertia Monitoring

- Sum the nameplate inertia of all online units
  - Simple and widely adopted
  - Good estimate of system inertia for most systems
  - Does not consider demand inertia without additional work/complexity (NG ESO in Britain use an uplift factor to include load inertia)
- Convenient for real time, forecast and contingency estimates
  - Can be basis for alerts and FFR requirements



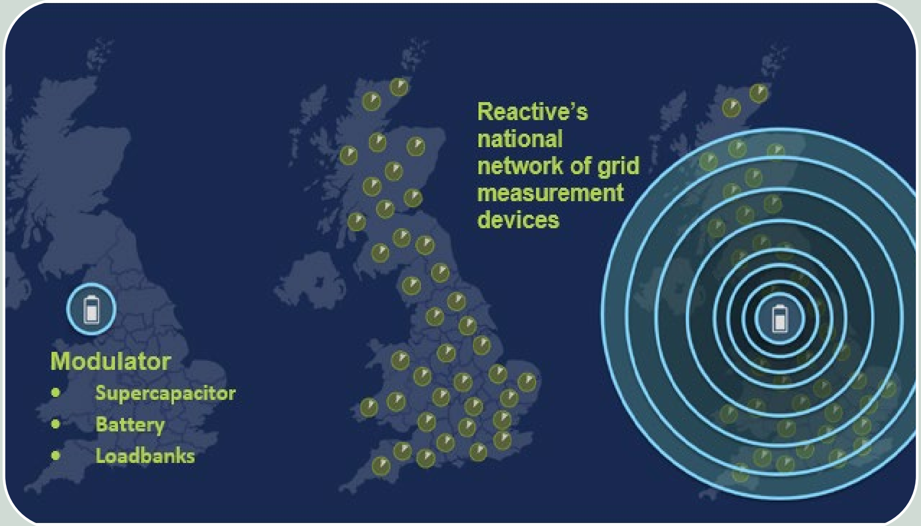
https://www.dena.de/fileadmin/dena/Dokumente/Veranstaltungen/A_Global_Perspective_on_Electricity_Ancillary_Services/4_Julia_Matevosyan.pdf



Source: Nordic report Future system inertia, 2018
https://docs.entsoe.eu/dataset/nordic-report-future-system-inertia

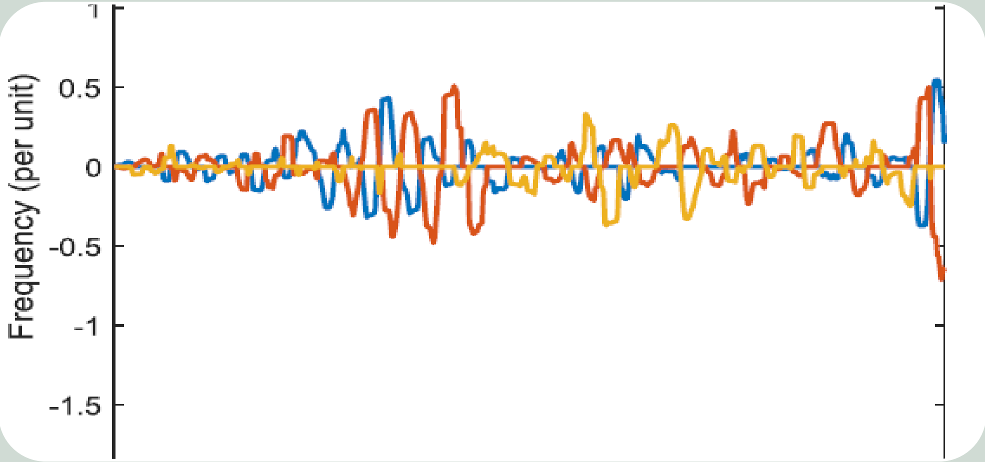
Continuous Signal Based Inertia Estimation Methods

Reactive Technologies - GridMetrix



- Intrusive - Continuous small power stimulus introduced by "Modulator"
- RoCoF measurements by Extensible Measurement Units – Wide area monitoring using XMUs
- Swing Equation based estimation – Signal processing techniques used
- Estimates system inertia

Machine Learning Ambient Data



- Non-intrusive – Use of ambient frequency variations measured by PMUs
  - Require training – data intensive
  - Ambient load variations may not excite dynamic system significantly
  - Susceptible to errors in power measurements
- Estimates system inertia

Event Driven Based Inertia Estimation Methods

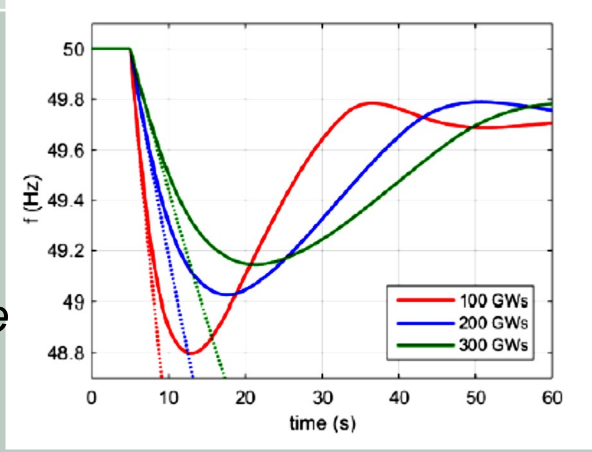
Post-Mortem Large Disturbance

$$H = \frac{1}{2}\Delta\frac{df}{dt}\Delta P$$

Known Disturbance

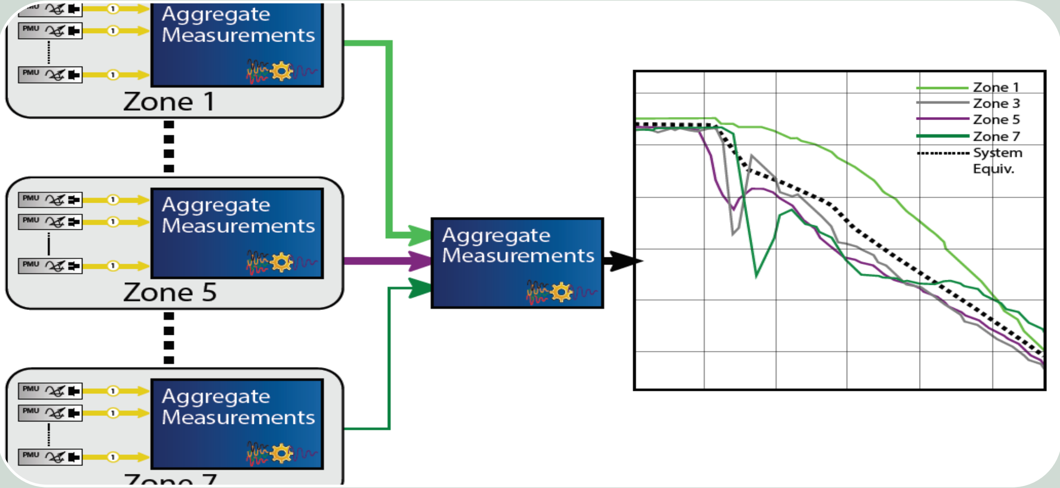
Pm constant

ΔPe only disturbance



- Treat system as a single equivalent machine
- Use frequency measurements to estimate the initial RoCoF, either through simple calculation or polynomial fit
- Assumes constant mechanical power and only the disturbance changes electrical power, this is only strictly true for instant of disturbance so error prone
- RoCoF is intrinsically difficult to estimate especially during a disturbance

GE & MIGRATE – Effective Area Inertia



- Effective inertia measures the combined effects of rotating machines, passive load responses, and active generator controls
- Frequency measured close to generators
- PMUs located on area boundary, non-intrusive
- Swing Equation based
- Effective inertia forecasting with Machine Learning methods
- Estimates both regional and global inertia

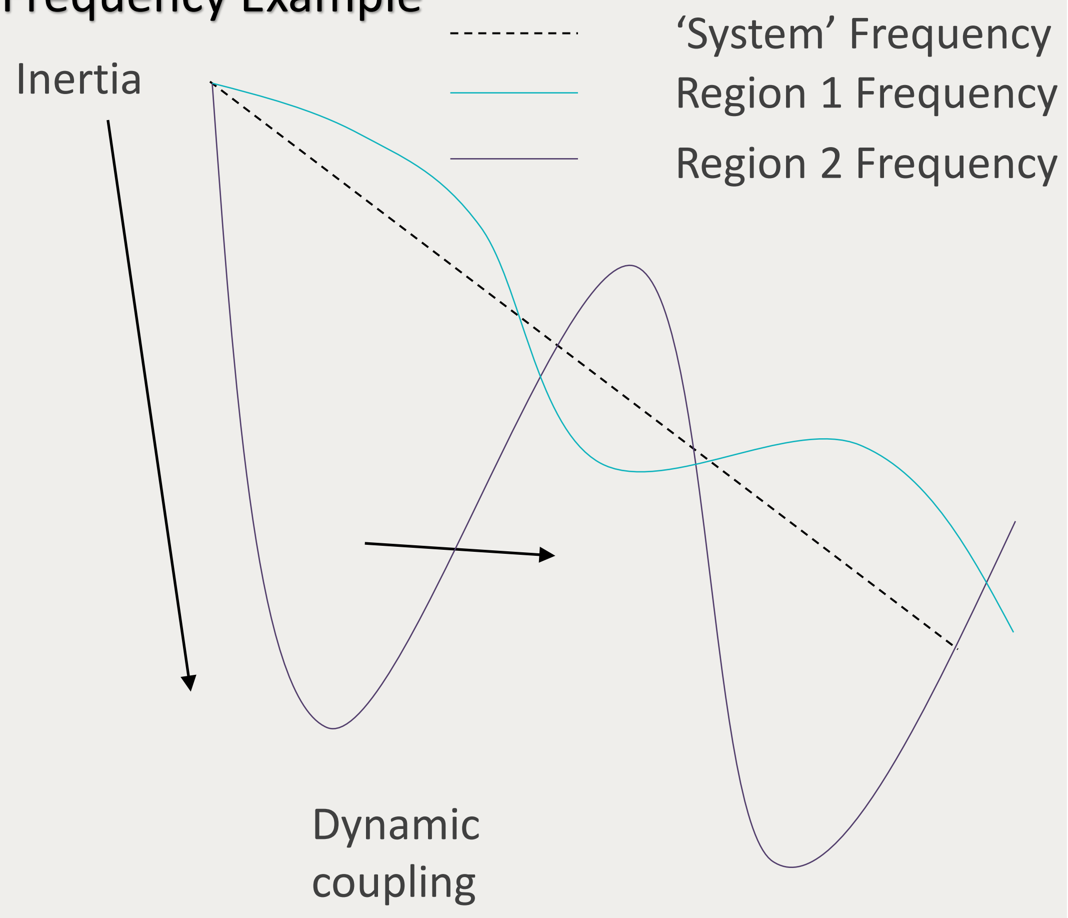
System Frequency vs Regional Frequency

Reduction in inertia is not spatially uniform, which can result in regions of disproportionately low inertia

If low inertia regions are poorly coupled to the system they will swing around the center of inertia frequency

These swings result in different frequency and RoCoF in regions and this may cause system frequency-based methods to be inadequate

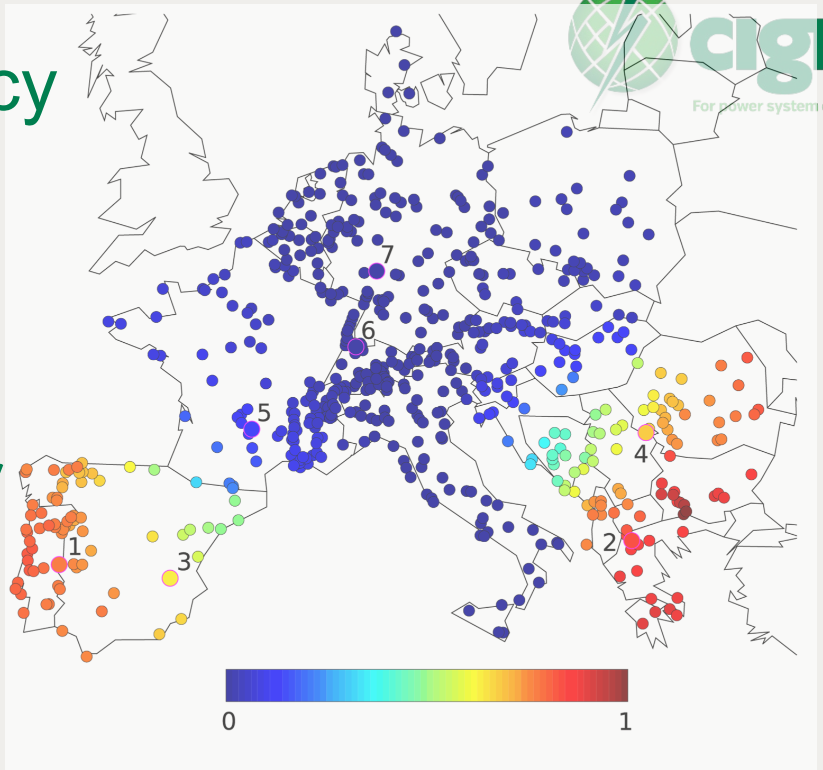
Frequency Example



System Frequency vs. Regional Frequency

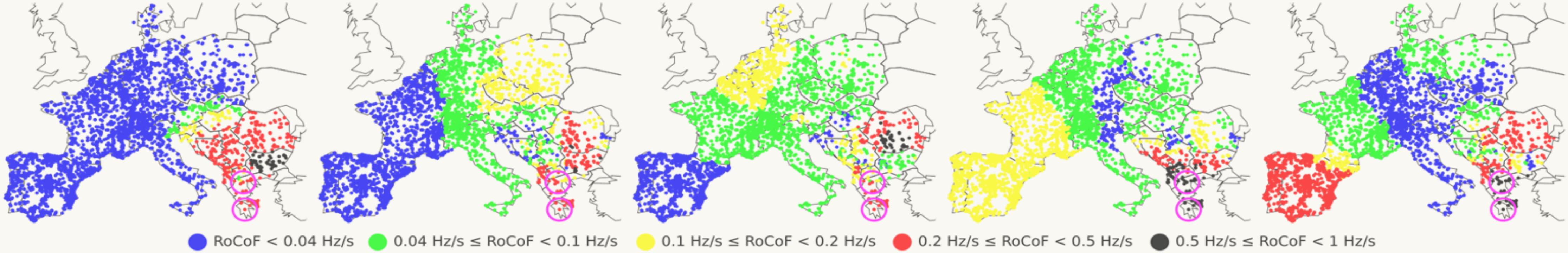
- Certain 'ΔP' (e.g. loss of generation, in-feed) in areas that have high participation in inter-area modes may cause regional issues
- Both are linked to inertia centers coupled poorly with the rest of the system

Participation in fiedler mode



Two large losses in Greece (purple circles, simulated example)

0-0.5[s] 0.5-1[s] 1-1.5[s] 1.5-2[s] 2.5[s]



Source: Pagnier L, Jacquod P (2019) Inertia location and slow network modes determine disturbance propagation in large-scale power grids. PLoS ONE 14(3): e0213550. https://doi.org/10.1371/journal.pone.0213550

Conclusion – State of the Art

	Input Data										
	EMS^	**Frequency**	**Active Power**	**Known Event(s)**	**When**	**Estimates Rotating Inertia?**	**In Use?**	**New Monitoring equipment***	**Modulator**	**Basis for Forecasts^**	**Includes Load Inertia**
Unit Commitment	✓	✗	✗	✗	Real Time	✓	✓	✗	✗	✓	~
Event Driven System	✗	✓	✗	✓	Post Mortem	✓	✓	✗	✗	~	✓
Event Driven Regional	✗	✓	✓	✗	Post Mortem	✗	✓	✓	✗	~	✓
Continuous Signal - Ambient	✗	✓	✓	✗	Real Time	✓	✗	✓	✗	✓	✓
Continuous Signal – Stimulated	✗	✓	✗	✓	Real Time	✓	✓	✓	✓	✓	✓

^EMS data required for forecasting or contingency estimates
*Assuming some PMUs in place

Source: EPRI White Paper
'Online Inertia Estimation & Monitoring: Industry Practices & Research Activities',
000000003002016195


Thank you
For further discussion, reach out to pdattaray@epri.com
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Procurement of Inertial Products

Example of Great Britain and Ireland

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14th Oct 2020

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DS3 System Services – Ireland

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Delivering a Secure, Sustainable Electricity System (DS3)

- Ireland's target under the EU Renewable Energy Directive – 16% of total energy consumptions (transport, heat, electricity) from renewables by 2020 ≈ 40% electricity from renewables
- Growth of non-synchronous generations present a range of operational challenges to the island nation
- DS3 programme has been created to ensure that the system can be operated securely with higher System Non-Synchronous Penetration (SNSP)

Adapt and refine system operational policies

Develop and implement enhanced system tools

Develop policy for large-scale DSM

Implement enhanced performance monitoring system

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DS3 System Services – 14 products

Category	Product	Short Definition
Voltage Control	Steady State Reactive Power (SSRP)	Steady state voltage control within MVAr capability
	Dynamic Reactive Response (DRR)	MVAr capability during large (>30%) voltage dips
Inertial Response	Synchronous Inertial Response (SIR)	(Stored kinetic energy)* (SIR Factor – 15)
Fast Acting	Fast Frequency Response (FRR)	MW delivered between 2 and 10 seconds
	Fast Post-Fault Active Power Recovery (FPFAPR)	Active power >90% within 250ms of voltage >90%
Reserve	Primary Operating Reserve (POR)	MW delivered between 5 and 15 seconds
	Secondary Operating Reserve (SOR)	MW delivered between 15 to 90 seconds
	Tertiary Operating Reserve – 1 (TOR1)	MW delivered between 90 seconds to 5 minutes
	Tertiary Operating Reserve – 2 (TOR2)	MW delivered between 5 minutes to 20 minutes
	Replacement Reserve – synched (RRS)	MW delivered between 20 minutes to 1 hour
	Replacement Reserve – desynched (RRD)	MW delivered between 20 minutes to 1 hour
Ramping	1 hour Ramping Margin (RM1)	Increased MW output that can be delivered with a good degree of certainty for the given time horizon
	3 hour Ramping Margin (RM3)	
	8 hour Ramping Margin (RM8)	

Overview of Scalars

- Scalars proposed by the Single Electricity Market (SEM) Committee
- Objective behind applying scalars to unit prices is that it will *"reduce the level of payment to service providers where value is not being delivered to the consumer and may increase the level of payment to those service providers delivering additional value to the consumer."*

Scalar	Purpose of the Scalar
Performance	Reward and incentivise high levels of performance
Scarcity (Locational and Temporal)	Marginal incentives for providers to make themselves available during periods or in locations of scarcity
Volume (expenditure management and auction procurement)	Ensure consumers are protected from unnecessarily high prices
Product	Incentivising both effective delivery of a service and faster response time (for certain services)

Scalar calculation methodologies detailed in DS3 System Services Protocol document

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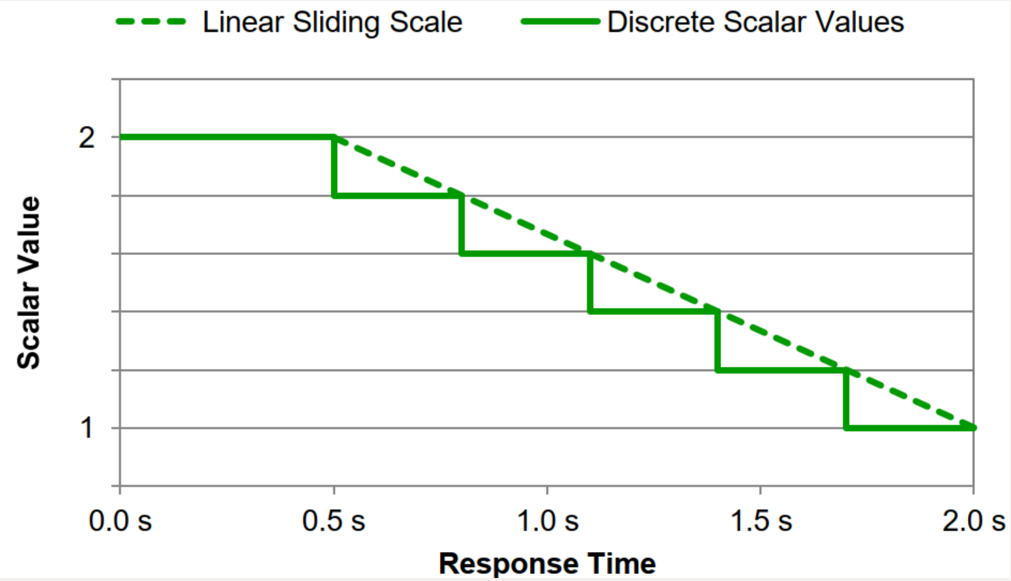
High Level Design of Scalars

Design of Scalars	Options		
Magnitude	**Greater than or equal to one** *Most scalars*	**Values above and below one** *Some temporal and scarcity scalars*	**Less than or equal to one** *Volume scalar, some scarcity scalars and product scalars*
Scale	**Binary Scalar** *Enhanced delivery product scalar*	**Sliding-scale** *All other product and scarcity scalars*	**Calculation** *Volume scalar, will neither be binary or sliding-scale*
Granularity	**With Tariffs** *Product scalars – set once only, but could be reviewed when tariffs are recalculated*	**Annual** *Locational scarcity scalar – takes on value for each year*	**Trading Period** *Temporal scarcity scalar – takes a different value in every trading period*

Scalar Example – Sliding Scale

- For a faster response of FFR, the product scalar could take a value of 1 for a basic response of 2s and a value of 2 for a response time of 500ms. The scale could then be set as
  - 1.2 for a response time of 1.7s
  - 1.4 for a response time of 1.4s
  - 1.6 for a response time of 1.1s
  - 1.8 for a response time of 800ms



These are just indicative values!

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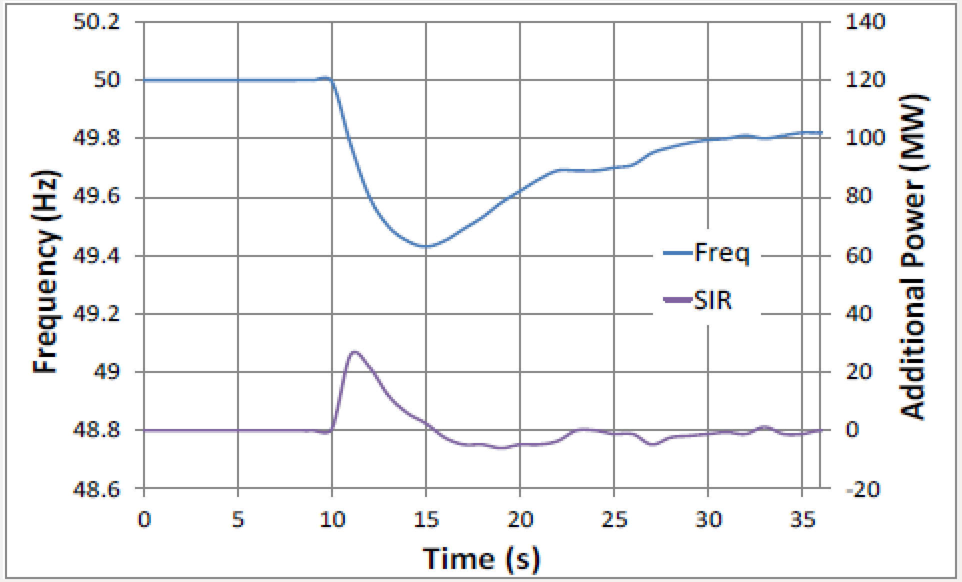
Synchronous Inertial Response (SIR) Product

SIR = stored kinetic energy (at 50Hz) of a dispatchable synchronous providing unit × SIR Factor (SIRF)



- stored kinetic energy = $H \times S_n$ [MWs]
- H = inertia constant [MWs/MVA]
- S_n= rated apparent power [MVA]
- Synchronous providing unit = synchronous generator, synchronous condenser or synchronous motor

Sources:
http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-SS-Protocol-v3.0.pdf
http://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-DS3-System-Services-_Regulated-Arrangements_draft.pdf

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SIR Factor (SIRF)

SIRF = ratio of the stored kinetic energy (at 50Hz) to the lowest MW output at which the unit can operate stably while providing reactive power control (based on design capability)

$$SIRF = \frac{stored\ kinetic\ energy}{Minimum\ stable\ generation}\ [s]$$

- SIRF>15s for a provider to be eligible for payment
- SIRF is capped at 45s for all providers
- SIRF for synchronous condensers and synchronous motors is fixed at 45s

Sources:
http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-SS-Protocol-v3.0.pdf
http://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-DS3-System-Services-_Regulated-Arrangements_draft.pdf

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SIR Payment

SIR Payment = Service provider will receive a payment for each MWs^2 of SIR Available Volume from the providing unit in each Trading Period where synchronised

$$SIR\ Payment = Available\ Volume \times Payment\ Rate \times Scaling\ Factor \times Trading\ Period\ Duration$$

- Available Volume [MWs^2] = SIR×(SIRF-15) × (% of trading period the proving unit is synchronised to the system)
- Payment Rate [$\frac{€}{MWs^2}$] = payment rate for SIR product
- Scaling Factor = Locational Scalar × Temporal Scarcity Scalar
- Trading period duration in hours

Sources:
http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-SS-Protocol-v3.0.pdf
http://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-DS3-System-Services-_Regulated-Arrangements_draft.pdf

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Stability Pathfinder Phase 1– Great Britain

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Stability Pathfinder Phase 1 Tender

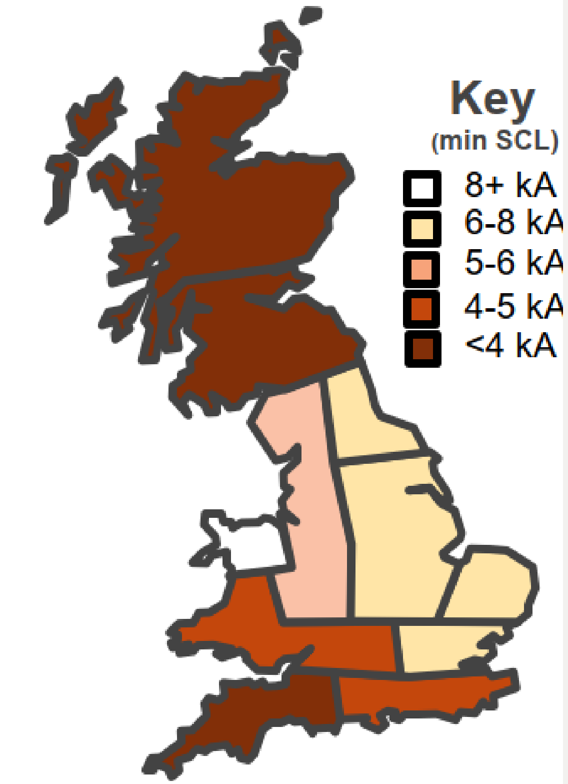
- Zero MW firm availability (24/7) stability service
- Tenders for contracts ending 31st March 2023 or 31st March 2026
- Stability product comprises of three services
  - Inertia
  - Fast acting dynamic voltage control
  - Short circuit level
- The contract payment structure has three parts
  - **Availability** – payment at tendered price (£/settlement period), only paid when the plant is available to provide service (or planned outages) but not for any period when the plant is generating active power
  - **Reactive Power** – paid at default reactive power payment rate (£/MVArh)
  - **Active Power Consumed** – reimbursed at system buy price (£/MWh), capped at steady state power requirements

Sources:
Stability Pathfinder Phase One Tender Information Pack - https://www.nationalgrideso.com/document/157176/download

Phase 1 Minimum Technical Criteria

Around 16 different technical performance criteria, only 4 discussed here

	Technical Criteria	Comment
1	Short circuit level	• Short circuit current contribution of >=1.5p.u. of plant's MVA rating • Operation across a range of minimum short circuit levels (expected to be within a range of 3-13kA)
2	Inertia	• Inertia (MVA.s) contribution of >=1.5p.u of plant's MVA rating • The contribution should not degrade faster than the degradation of a 12s inertia constant
3	Transient voltage magnitude support	• Solution should provide continuous voltage support by reactive current injection within the voltage against time curve defined in the Grid Code • Delivery of reactive current should be prioritised over active current to stabilise the voltage • Dependent on the location, the device is expected to introduce a fast acting power oscillation damping control of nominated speed and frequencies of damping
4	Location	• GB wide onshore at voltage levels 400kV, 275kV and 132kV



Sources:
Stability Pathfinder Phase One Technical Performance and Assessment Criteria - https://www.nationalgrideso.com/document/157176/download

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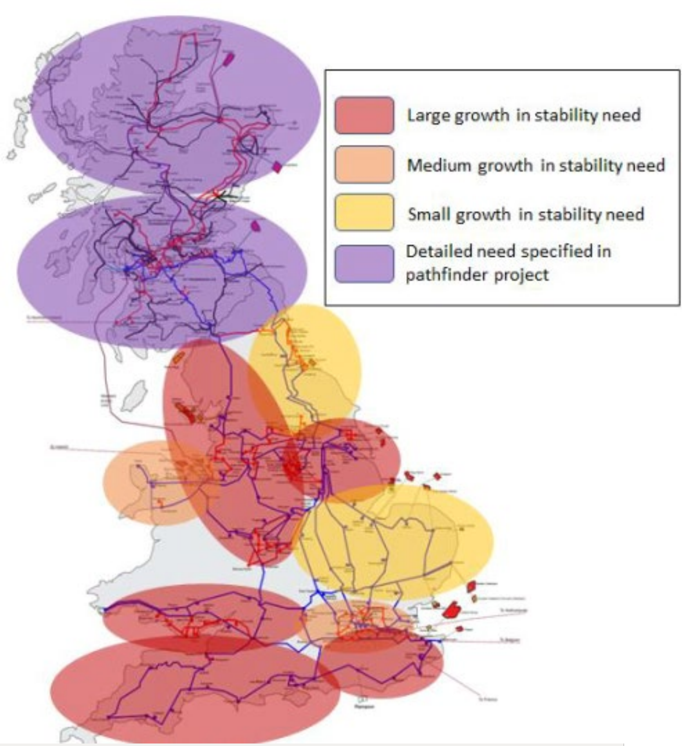
Phase 1 Assessment Principles

Around 8 different assessment principles, 5 included here

	Principle	Comment
1	Inertia contribution	• Providers that have a higher inertia will be valued higher than providers with lower inertia.
2	Reactive range	• Solutions that can provide larger injection and absorption capability will be valued higher than those providing a smaller capability.
3	Stability support – national	• Providers connected at 400kV will be more effective in assisting with the national stability requirement; will be valued higher than those connected at lower voltages (i.e. 275kV or 132kV).
4	Stability support – local	• Providers connected at substations where zonal benefit is higher will be valued more than those where the zonal benefit is low. • NGESO assigned a benefit to each zone and provided a mapping of the substations to the zones
5	Power consumption	• Providers having a smaller demand for power for their inertia contribution will be valued higher than those with a larger demand for power.



Sources:
Stability Pathfinder Phase One Assessment Principles - https://www.nationalgrideso.com/document/157176/download

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Phase 1 Tender Outcome – Jan 2020

- Out of a maximum procurement of 25GVAs, NGESO was offered the potential to award tenders totalling 22.5GVAs
- 12 tenders were awarded to 5 providers across 7 sites totalling 12.5GVAs of inertia until 31st March 2026
- Phase 2 expression of interest is launched and RFI pack released
- While in phase 1 only synchronous condensers and synchronous generators where considered, phase 2 will include a wider range of technologies

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Fast Frequency Response Around the World

Review of International Utility Practices

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Define FFR

Fast Frequency Response: power injected to (or absorbed from) the grid in response to changes in measured or observed frequency[1] during the arresting phase of a frequency excursion event to improve the frequency nadir or initial rate-of-change of frequency

Source: Fast_Frequency_Response_Concepts_and_BPS_Reliability_Needs_White_Paper_NERC

1: In many cases, this is a response to locally measured frequency (or other local signal). In some cases, where speed of response is critical, other types of signals may be used to initiate FFR. For example, RAS actions triggered by specific contingencies may activate FFR.

Means of obtaining FFR

FFR can be obtained through numerous **control philosophies** (i.e., based on magnitude of frequency deviation, ROCOF, or other factors) that each can help during the arresting phase of a frequency excursion.

➢ These various types of controls should not necessarily be dictated unless there is a reliability need.

FFR can be provided by many different **technologies**:

- Synchronous machine inertial response,
- a portion of traditional turbine-governor response,
- wind turbine generator (WTG) controls to extract additional power from the rotational energy of the turbine,
- and other fast-responding controls from batteries and solar PV

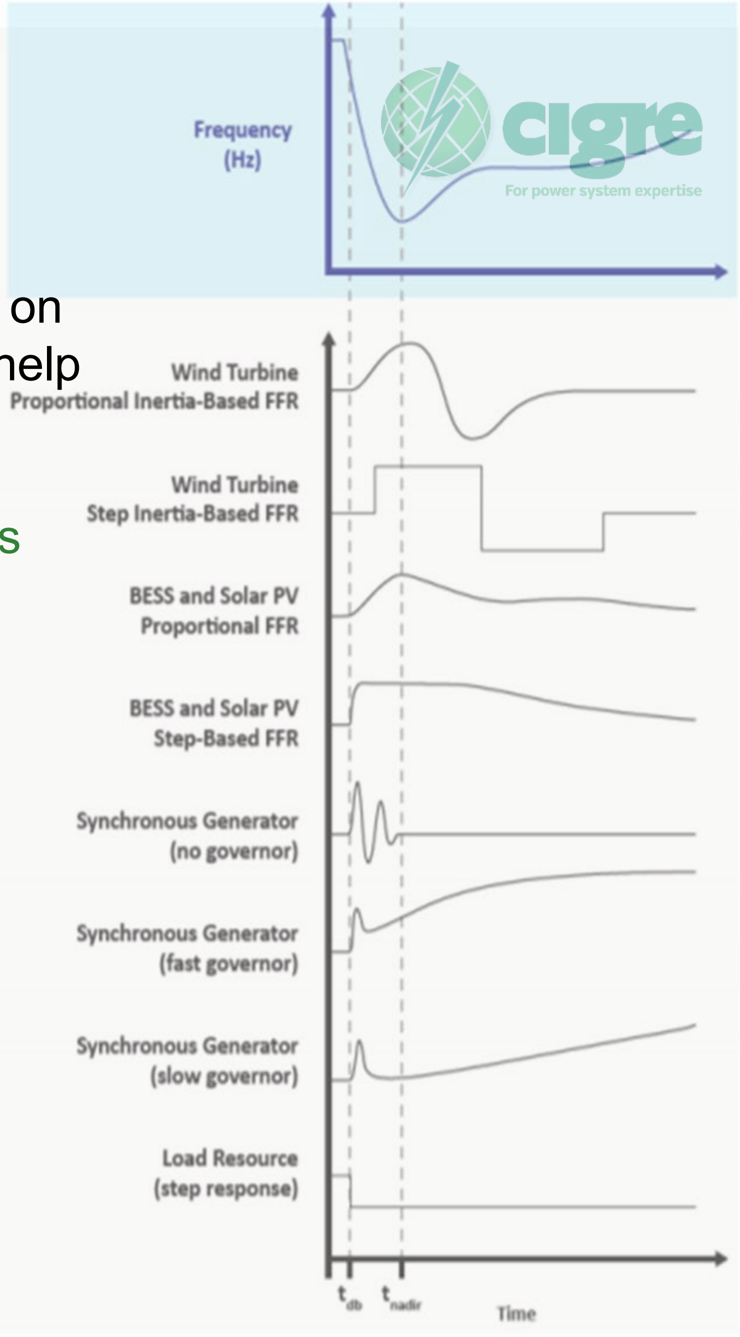


Figure 2.2: Illustration of Frequency Response from Different Resource T

Source: Fast_Frequency_Response_Concepts_and_BPS_Reliability_Needs_White_Paper_NERC

FFR Complements PFR

FFR and PFR controls should be coordinated with other competing inverter controls particularly when the inverter is current-limited

➢ For this reason, faster response may not be desirable for BPS

The term “fast” with respect to FFR is relative to each individual interconnected BPS and should not be generalized

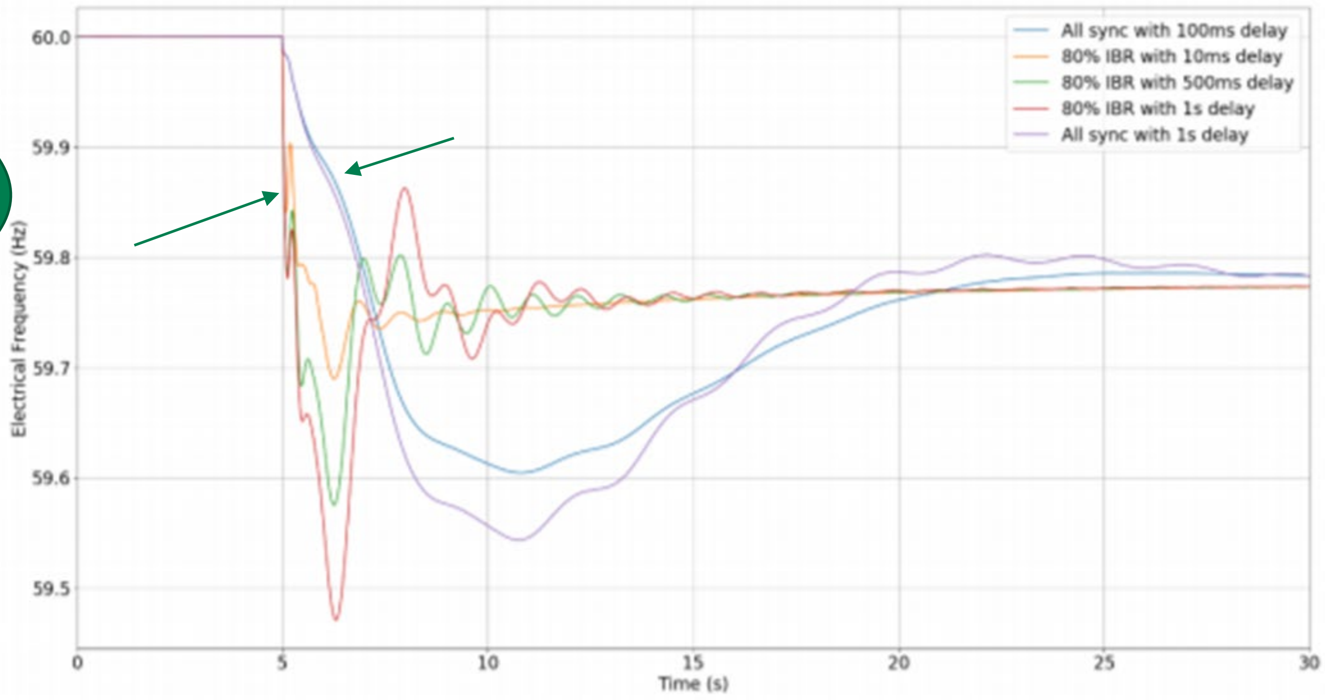
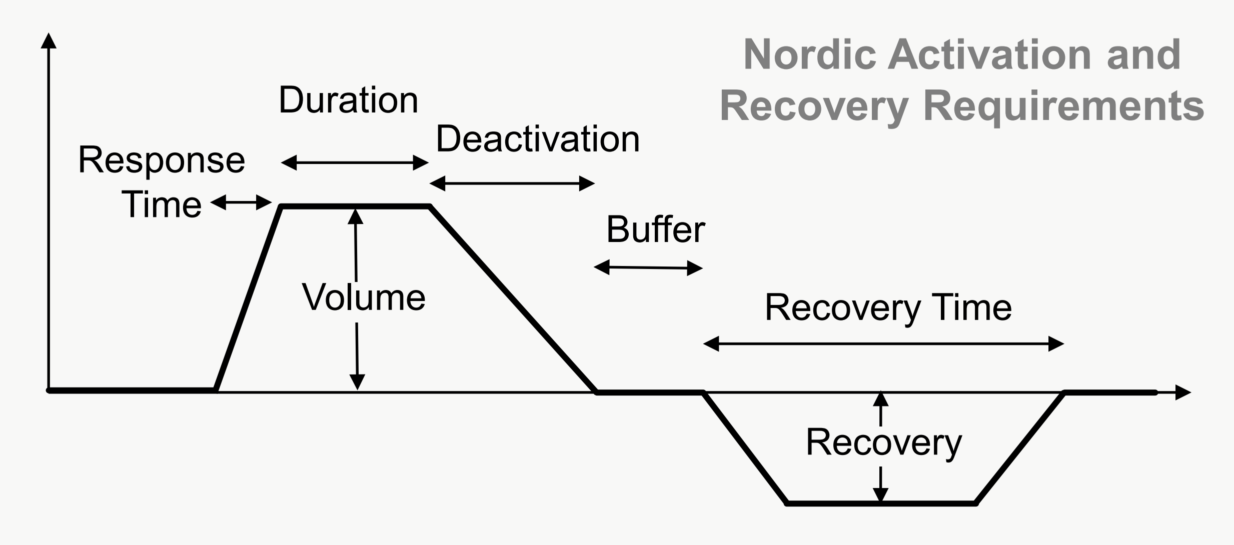


Figure 2.3: Example Simulation of FFR with Varying Controls and IBR Penetrations [Source: EPRI]

- Deepak Ramasubramanian and Evangelos Farantatos, "Constant Frequency Operation of a Bulk Power System with Very High Levels of Inverter Based Resources," CIGRE Science & Engineering, vol. 17, pp. 109-126, February 2020
- Program on Technology Innovation: Grid Operation with 100% Inverter-Interfaced Supply Resources: Final Report, EPRI, Palo Alto, CA: 2018, 3002014775.

Characteristics

- Type of control (Static or Dynamic)
- Trigger
- Speed of Response/Full Activation Time
- Sustaining time
- Magnitude/volume of response
  - Penalty for overprovision
- Recovery time
- Repeatability
- Symmetry
- Procurement

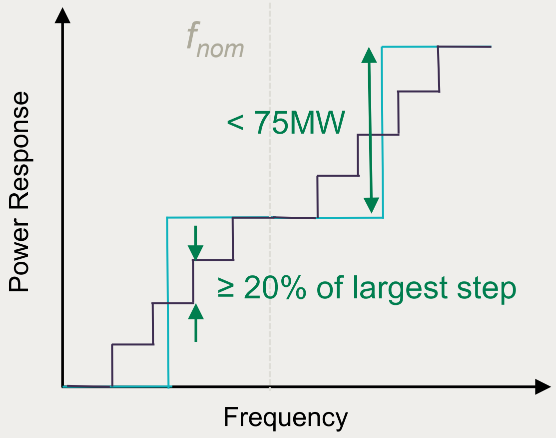


https://www.fingrid.fi/globalassets/dokumentit/en/electricity-market/reserves/fast-frequency-reserve-solution-to-the-nordic-inertia-challenge.pdf

Type of Control

Static

- Step response on trigger, then size of response independent of frequency
- Defined by number of steps and step sizes

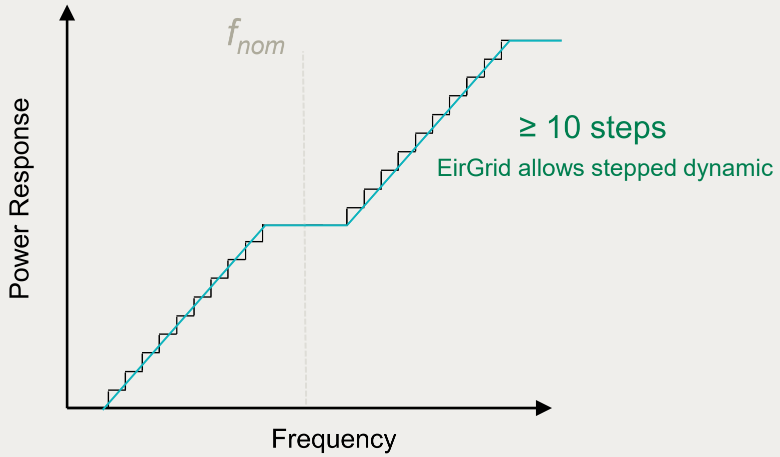


Nordics: Static

ERCOT: Static

Dynamic

- When triggered the response is proportional to frequency deviation
- Defined by droop and maximum response



EirGrid:
Dynamic or Static
Pays more for dynamic and has tight restrictions on step sizes.

National Grid ESO*
Dynamic or Static
Planning separate market cleating for each.

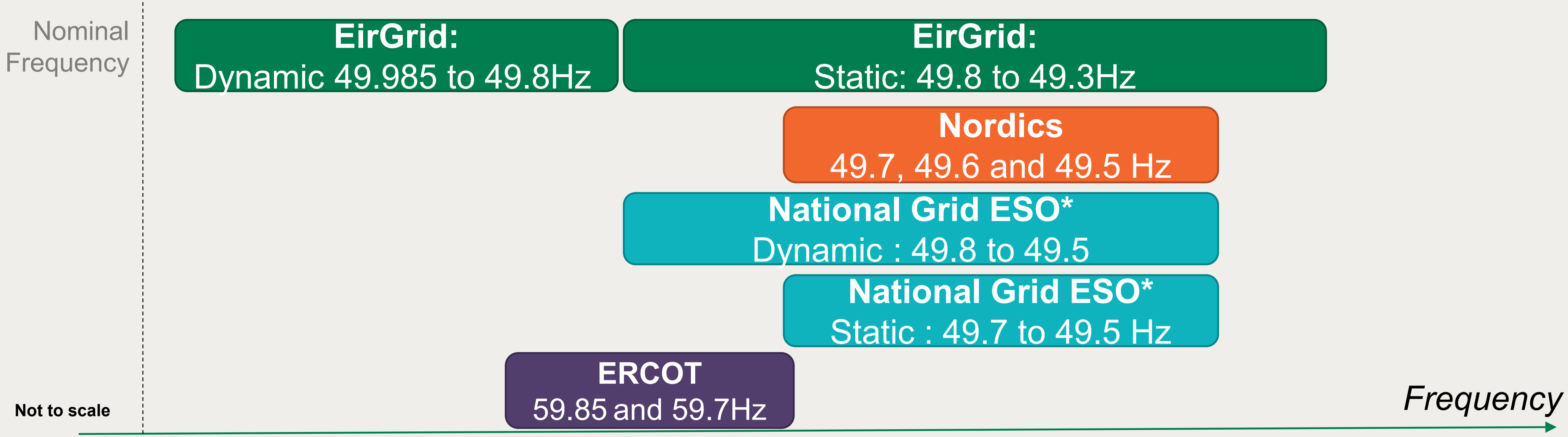
* NG ESO information relates to their future plans under the stability pathfinder

Trigger

- Trigger signal options include:
  - **Frequency (local measurement)**
  - RoCoF (local measurement)
  - Event based SIPS
  - Wide Area Controller

Heavily favored as the trigger signal

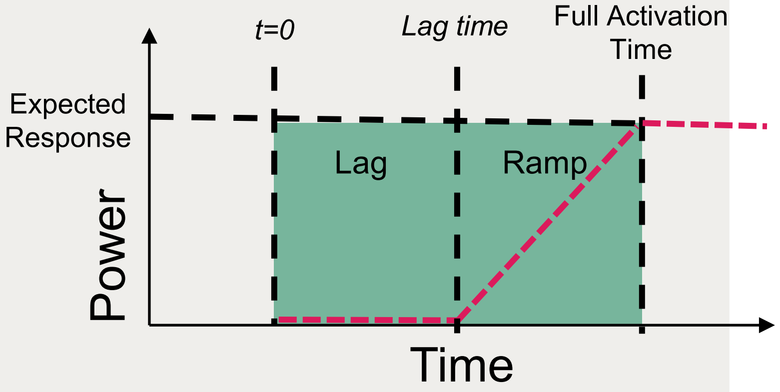
Expressly forbidden by EirGrid

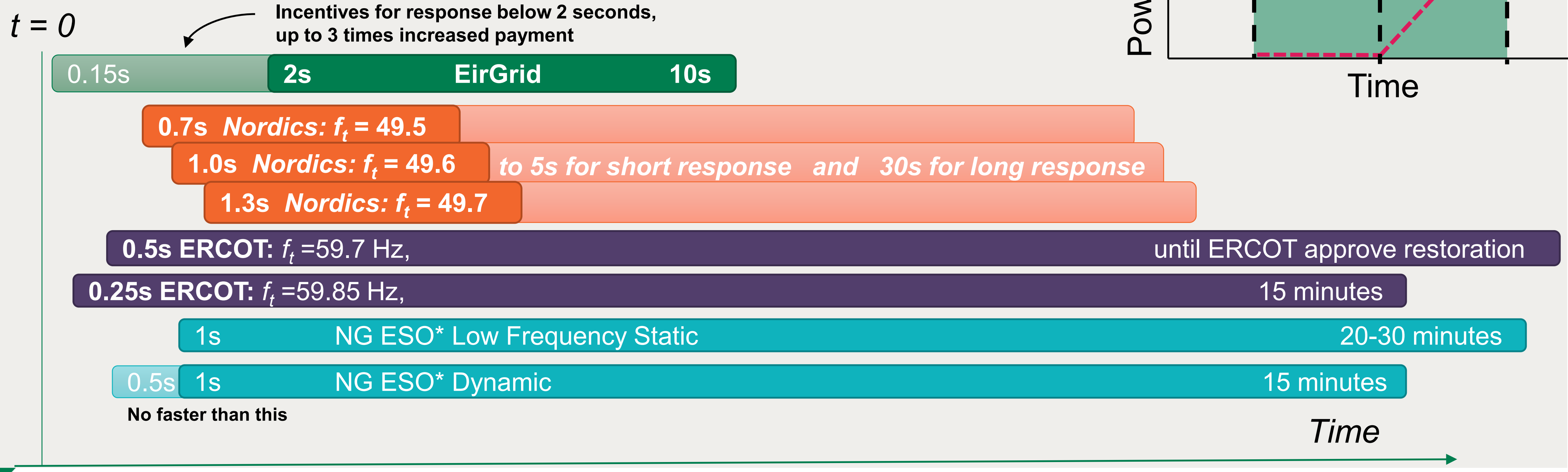


EirGrid: http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-System-Services-Protocol-Regulated-Arrangements-v2.0.pdf

Full Activation Time and Sustaining Time

- t=0 is the moment the resource is triggered (not the disturbance time)
- NG ESO propose lag and ramp time as part of activation time
  - Clearly specify when the resource will start responding





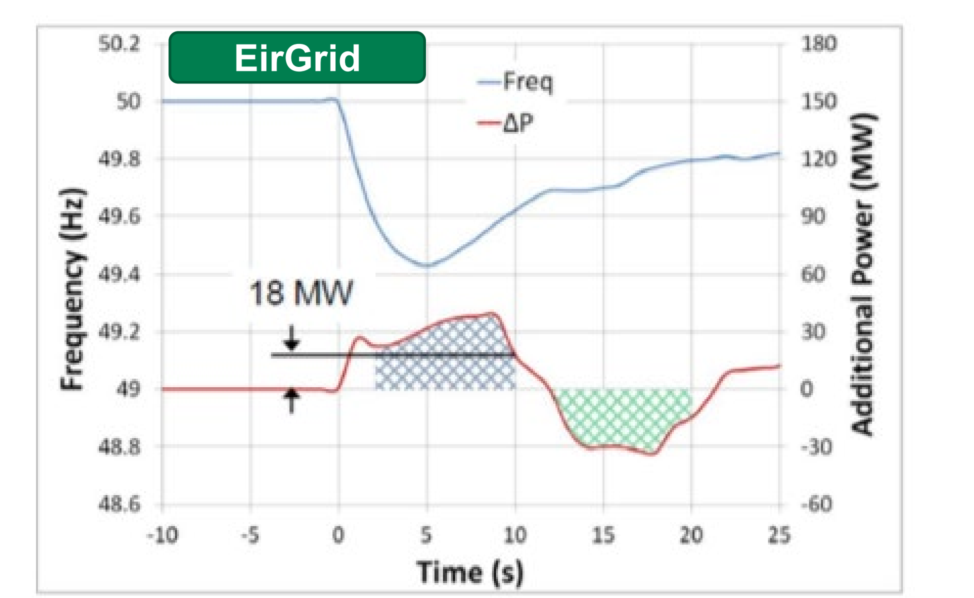
Not to scale

http://www.ercot.com/mktrules/issues/NOGRR187#keydocs

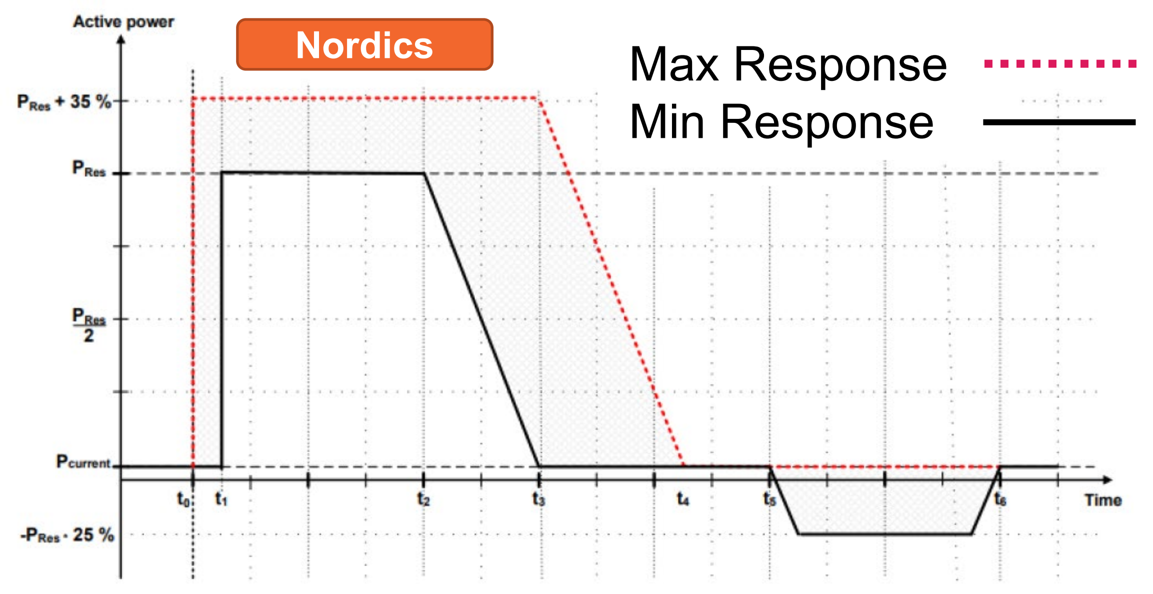
Deactivation

- Abrupt deactivation and short duration may cause second frequency drop, this risk can be avoided by:

Extending duration	• ERCOT, National Grid ESO
Require smooth deactivation	• Nordics
Energy recovery limitations	• Nordics, EirGrid



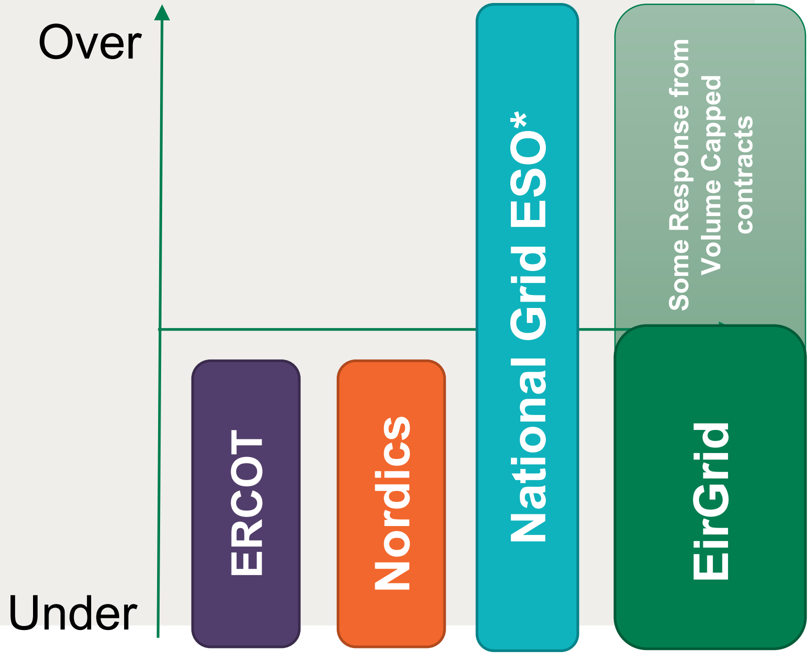
http://www.eirgrid.ie/site-files/library/EirGrid/DS3-System-Services-Portfolio-Capability-Analysis.pdf



https://energinet.dk/-/media/30034F9BE7804480BA721F0620D41FAA.pdf

FFR Symmetry

- FFR symmetry varies between TSOs
- Eirgrid: under DS3, FFR is for under frequency only.
  - Separate 'volume capped' competition contracted limited volume of over frequency FFR from BESS.
- Nordics: FFR is for under frequency after large events
  - studies indicated over frequency well managed without FFR
- National Grid ESO:
  - Static containment can be asymmetrical
  - Dynamic containment is asymmetrical
- ERCOT: Only for underfrequency after large events

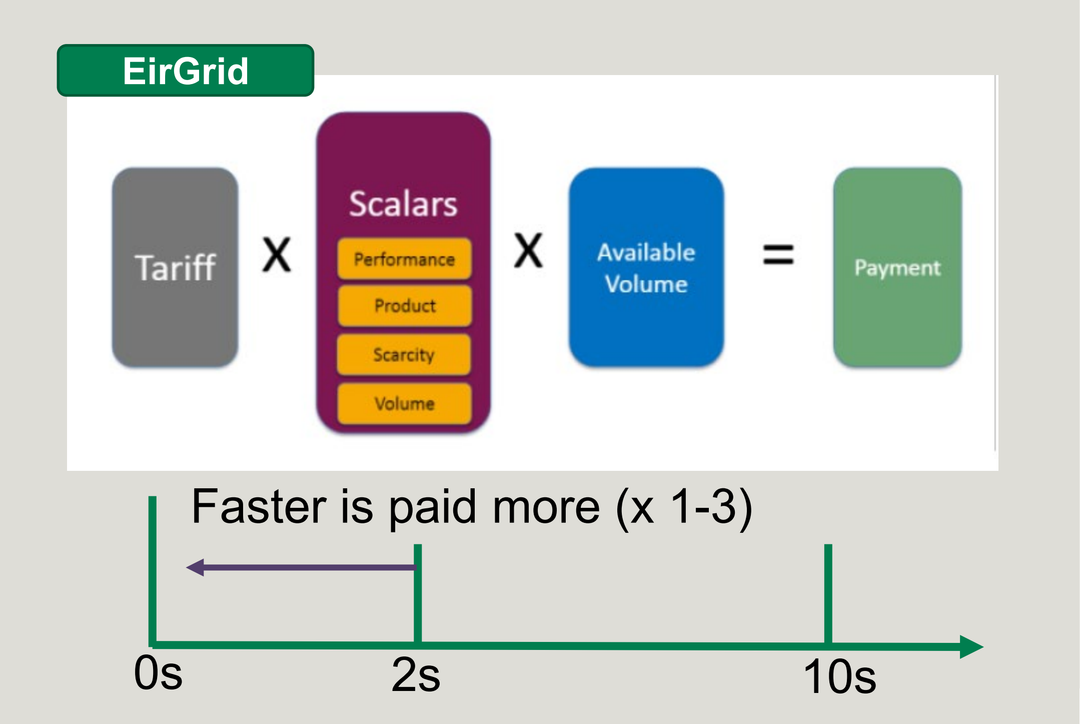


Procurement

Incentive based scheme	Mandated

- Nordics
  - monthly capacity contracts
  - Looking to move to hourly
- ERCOT – Ancillary service
- NG-ESO – Market based service
- EirGrid & SONI
  Flexible service definition on a tariff based regulated arrangement
  - EirGrid: Payments increase as penetration level increases 'Scarcity' or better performance is offered

- Hydro Quebec, Ontario and brazil mandate FFR from wind (0.5 to 1 second)



EU-SysFlex Project: https://eu-sysflex.com/wp-content/uploads/2019/08/D3.1_Final_Submitted.pdf

Key Takeaways

- FFR definition is highly system dependent
- Fast is relative and faster may not always be better (low system strength, current limited inverters)
- Broad split between:
  - Specific definition that is served by:
    - load (Nordics)
    - load and/or BESS (ERCOT)
  - Broad definition that is technology neutral but more complex to study
- Deactivation and recovery are important considerations to avoid secondary frequency drops
- Heavy focus on underfrequency containment

Thank you

For further discussion: pdattaray@epri.com

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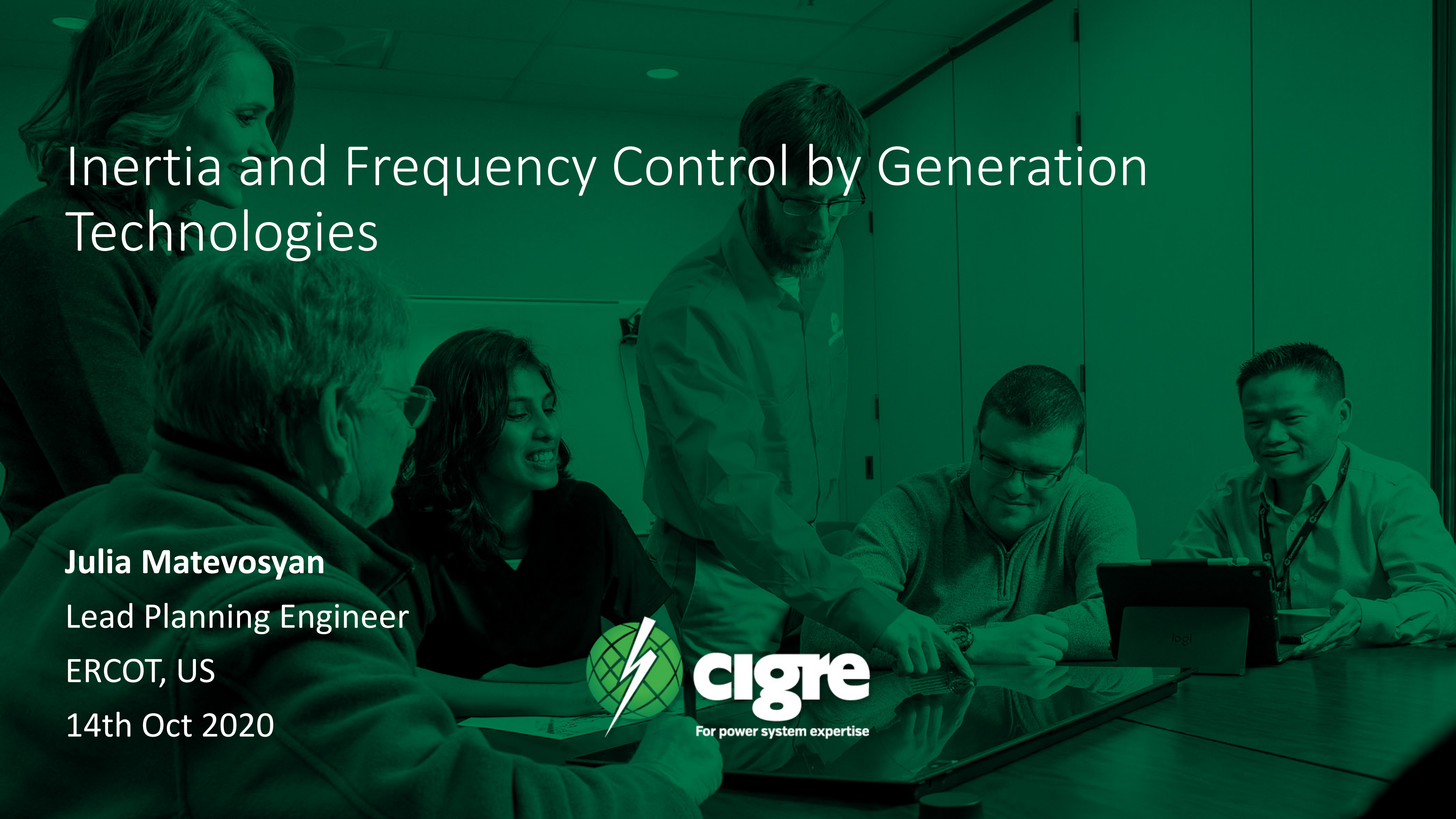

Inertia and Frequency Control by Generation Technologies

Julia Matevosyan

Lead Planning Engineer

ERCOT, US

14th Oct 2020

For power system expertise

Inertia of Synchronous Generators

Synchronous inertia of a machine is based on the commissioned design capability of the plant. It can be determined through appropriate validation procedures based on the following relationship:

$$Stored\ kinetic\ energy\ = \frac{J\omega_o^2}{2} = H \cdot S_n \text{ , where}$$

- *Stored kinetic energy* is in MVA-seconds;
- *J* is the combined moment of inertia of a synchronous machine and turbine prime mover in kg·m^2, based on its size and weight;
- ω_o is the nominal rotor speed in rad/s, and
- S_n is the machine's rated capacity in MVA.
- *H* is the figure of merit used to analyze the synchronous machine's inertial response inertia constant in seconds.

  $H=\frac{J\omega_o^2}{2} \cdot S_n$

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Inertia Contributions of Synchronous Machines, Example of ERCOT

	MVA Range	Avg MVA	Avg H on Avg MVA_base	Avg. Inertia contribution MW*s
Gas-steam	<100	50	3.21	160.5
	100-200	151	3.72	561.72
	200-300	261	3.16	824.76
	300-500	442	2.99	1321.58
	500-800	630	2.5	1575
CT	<100	70	4.37	305.9
	100-200	137	4.7	643.9
	200-300	222	5.27	1169.94
Hydro	<100	20.5	2.43	49.815
Coal	500-800	659	2.65	1746.35
	800-1200	936	2.58	2414.88
CC (train)	<100	60	4.8	288
	100-200	155	5.5	852.5
	200-300	230	5.3	1219
	300-500	411	5.03	2067.33
	500-800	629	4.7	2956.3
	800-1200	934	4.74	4427.16

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Synchronous Condensers

- A Synchronous Condenser or Compensator is an alternating current synchronous machine without any turbine or load connected to its rotor, which is left moving freely, thus, it’s inertia contribution is relatively small.
- Synchronous Condensers were used in transmission grids as a variable reactive power source prior to the introduction of power electronic devices such as SVCs and STATCOM.
- Today, Synchronous Condensers are used to support transmission grids with increasing IBRs and several projects have been built recently around the world (Denmark, Australia, USA).
- Most of the Synchronous Condensers installed till now are aimed at increasing system strength and providing dynamic reactive power support.
- An emerging variation recently is high inertia Synchronous Condensers. Most recently large (200 MVA) Synchronous Condensers with inertia constants of around 8 s have been built to support frequency, voltage and short circuit strength at the inverter end of a new HVDC project in Canada.

Source: Adham Atallah, Siemens

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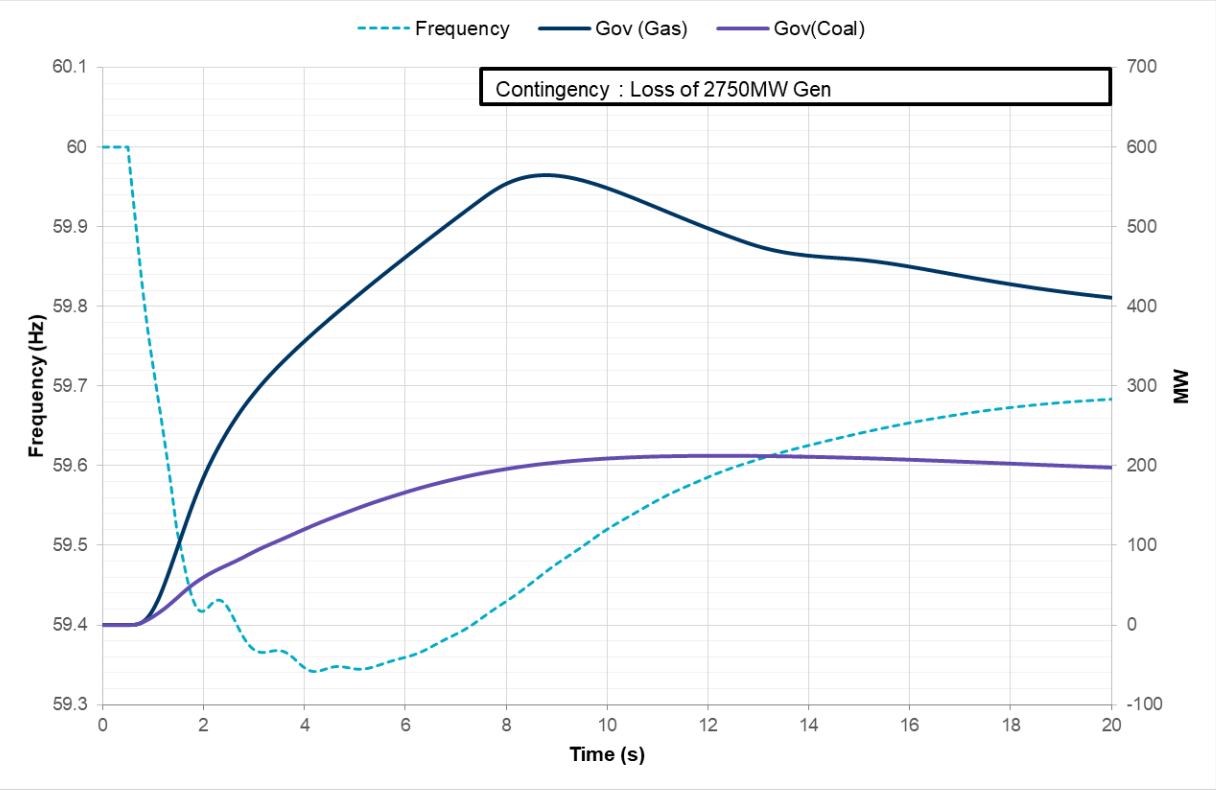
Frequency Response from Synchronous Generators

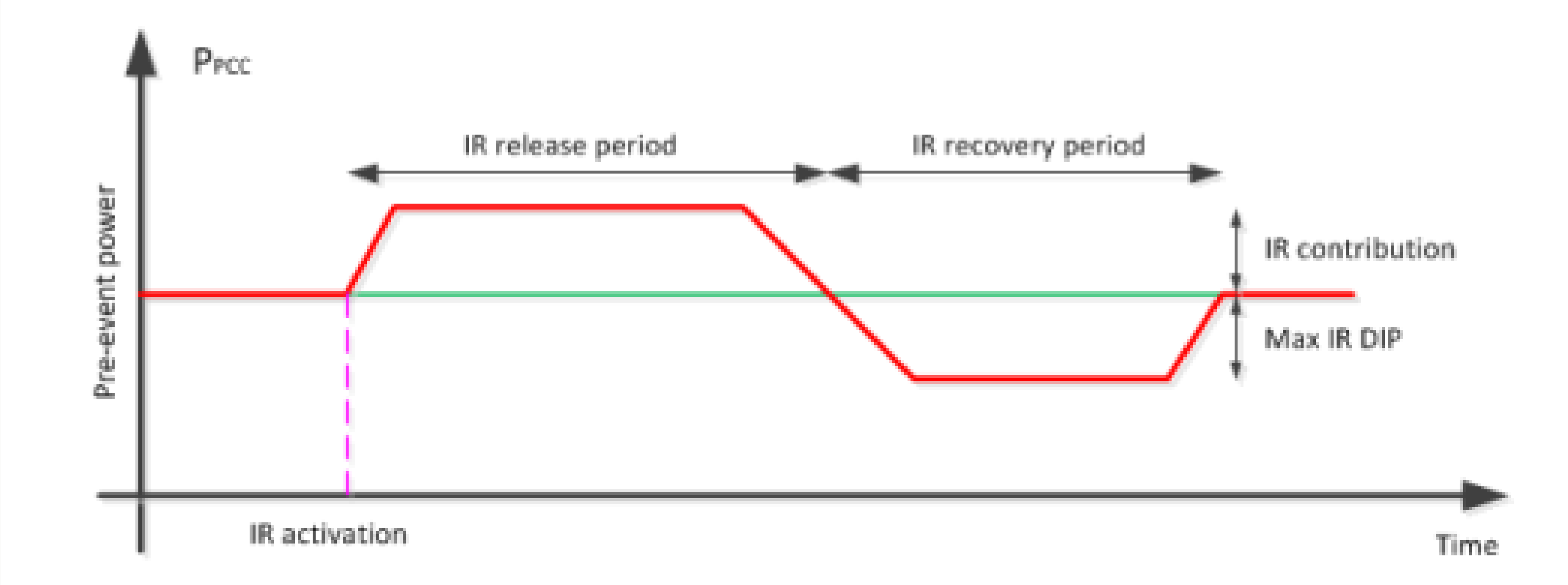
- Synchronous generators are capable of providing frequency containment response using speed governors.
- Speed governors vary prime mover output automatically for changes in system frequency.
- The rate and magnitude of the governor response can be tuned for the characteristics of the generator and the power system to which it is connected.
- To reduce activity of controllers for normal frequency variations a deadband may be introduced
- In the United States typically a deadband of ±36mHz around 60 Hz is used, while ERCOT uses ±17 mHz deadband.
- The rate of response is defined by droop, i.e. % of frequency change that result in output change of 100%.
- Typical droop setting used in the United States is 5%.



Source: https://www.wecc.org/Reliability/Governor%20Tutorial.pdf

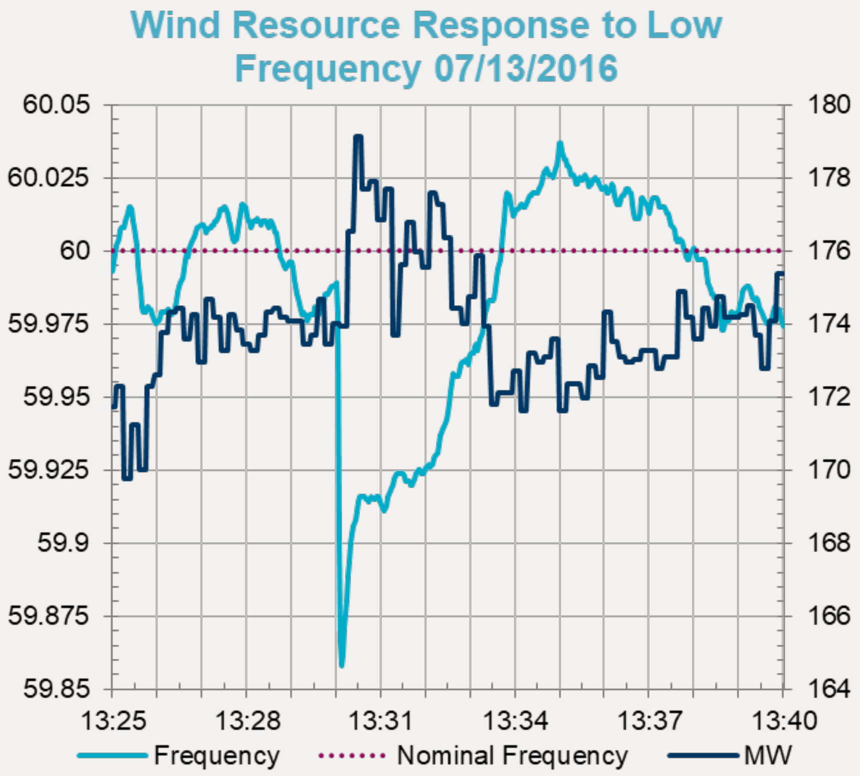
Inertia-Based FFR from Wind Generation

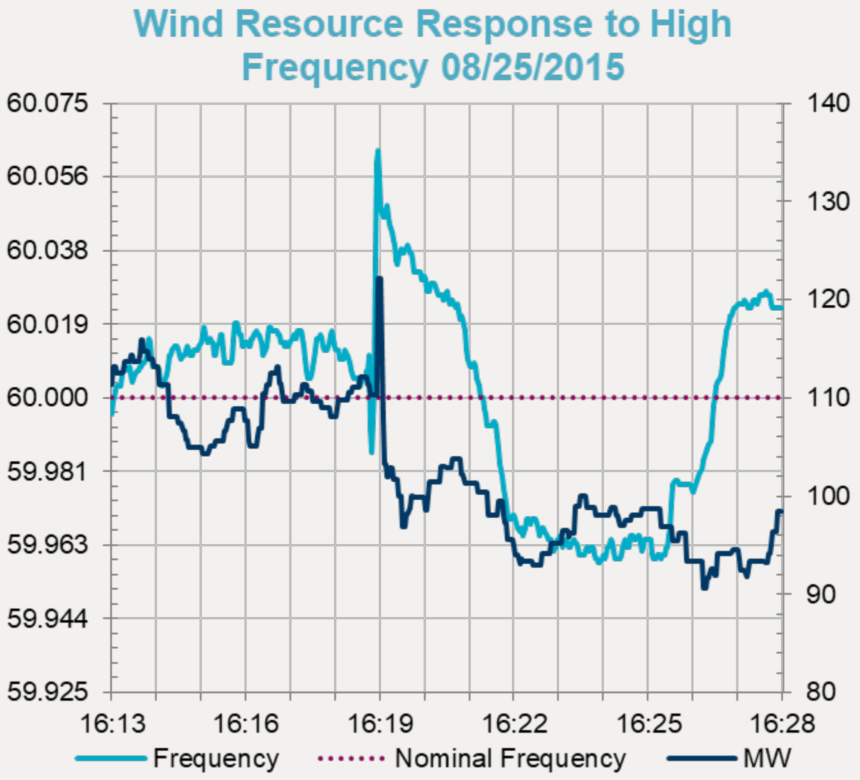
- Control algorithms were developed to extract kinetic energy stored in the rotating mass of a wind turbine and provide temporary active power overproduction to the grid in response to low frequency events.
- Frequency needs to be measured and event identified (>100 ms)
- Then the delivery of active power from the wind turbine to the grid is controlled by power electronics and is almost instantaneous (few cycles).



Source: NERC Industry Webinar, White Paper: Fast Frequency Response Concepts and Bulk Power System Reliability Needs

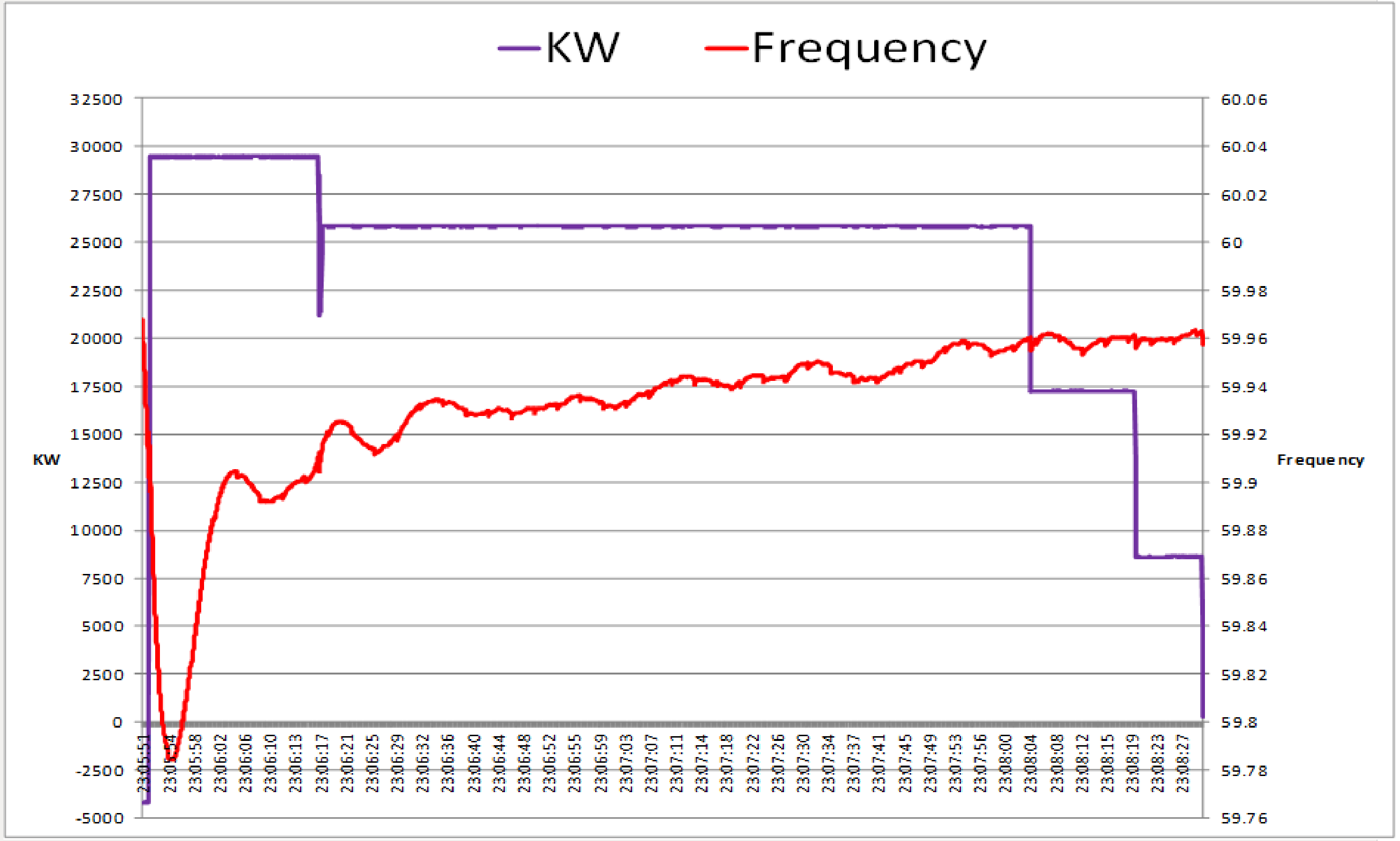
Governor-like Response from Wind Generation





FFR and FCR from Solar PV or Battery

- Solar PV and battery storage can provide FFR (as well as governor-like response)
- Battery storage can provide frequency response both from discharging (generator) and charging (load) operating modes.
- Duration of response is limited by battery state of charge
- Hybrids (i.e. battery storage + another gen type) can be used to combine technology benefits for provision of frequency control



- Frequency response by a battery in ERCOT during a frequency event.
- The battery responded to a frequency trigger at 59.91 Hz
- The requirement was for full response during was 1 second, however it detected the event and fully responded in 92 ms

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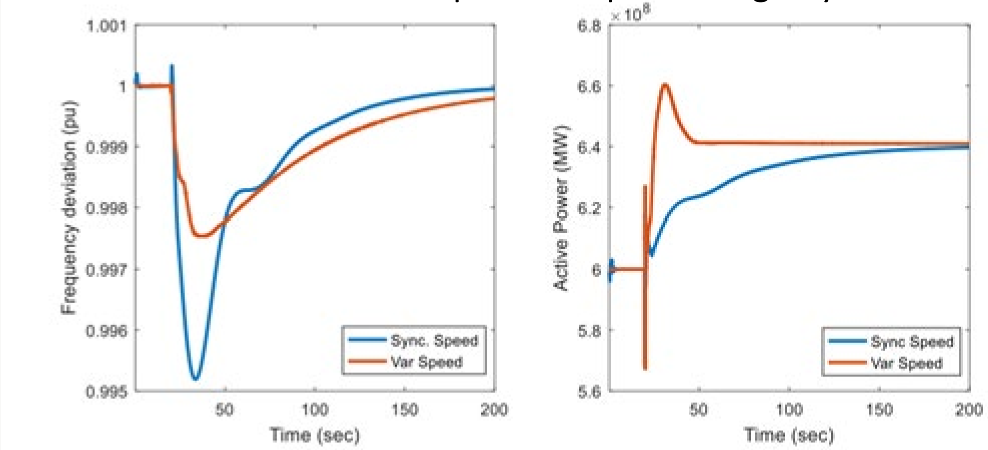
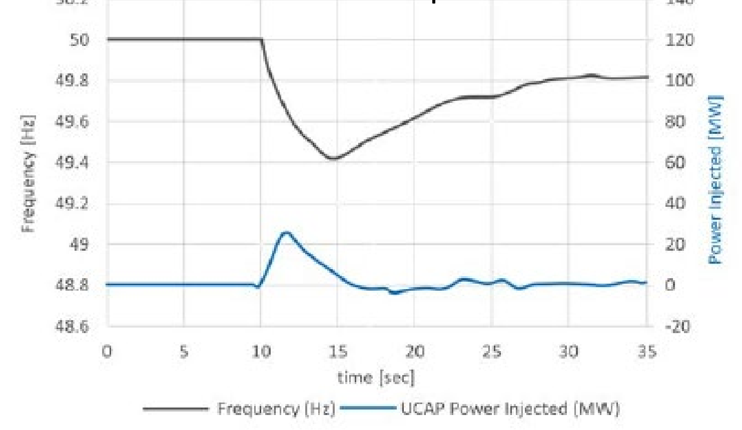
Other Emerging Technologies Providing Frequency Response

- Ultracapacitors (or Supercapacitors): can provide fast frequency response (10-20 ms for 100% response), however response can't be sustained beyond a few tens of seconds, can be combined with other resources for sustained frequency response.
- Flywheel: fast response time (<10 ms for 100% response) and high power to energy ratio. High power flywheels can also recharge in seconds. Typical sustain time is 15 minutes
- Variable Speed Pumped Hydro: can provide frequency response similar to wind turbine and variable speed drive motors
- Compressed Air Storage: frequency response similar to other synchronous generators governor response and Load Resource frequency containment response
- HVDC Links: can provide FFR or Frequency Containment Response similar to Solar PV or Battery Storage.

FFR from Variable Speed Pumped Storage Hydro*



FFR from Ultracapacitor **



* Source: R Bessa, C Moreira, B Silva, J Filipe and N Fulgêncio - IOP Conf. Series: Journal of Physics: Conf. Series 813 (2017) - Role of pump hydro in electric power systems
** Source: Maxwell Technologies

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THANK YOU
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Inertia and Frequency Control by Load Resources

Smart Loads

Dr Diptargha Chakravorty

Senior Consultant

TNEI Services, UK

14th Oct 2020

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Demand Response and Load Resources

- Demand Response (DR) can be useful for a range of system services such as
  - ➢Outage management
  - ➢Ancillary services
  - ➢Capacity release
  - ➢Flexibility services
- Some of the applications have a time scale of a few minutes to hours while others are in the order of a few seconds
- As an example, in ERCOT, Load Resources (LR) provide Responsive Reserve Service which is used to provide Fast Frequency Response
- LR are triggered at 59.7Hz and the full response is delivered within 25 cycles

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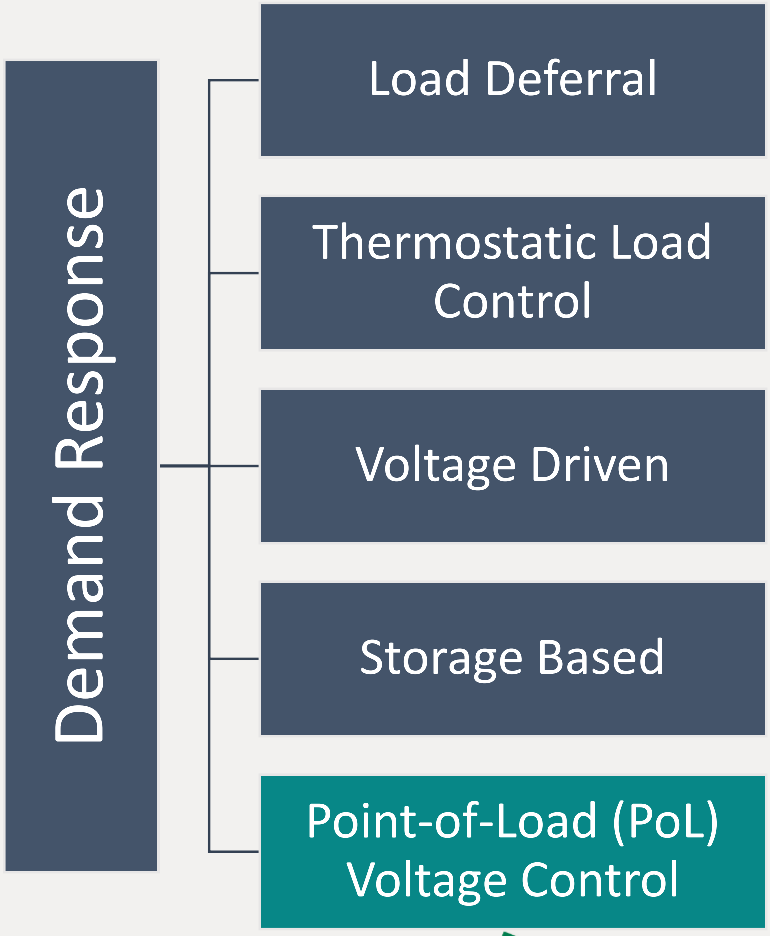
Types of DR

	Principle	Comment
1	Load deferral	• Implemented through load scheduling based on price signals • Suitable for peak shaving • Response time of a few minutes to hours • Schemes like Critical Peak Pricing, Time-of-Use Pricing etc
2	Thermostatic control	• On/off control of thermostatic loads like freezers, HVAC, VSHP • Suitable for shorter time scale, like frequency control • Method restricted to loads having thermal inertia and high load factor
3	Voltage Driven	• Implemented through transformer tap action like CVR • Suitable for peak shaving, energy saving • UK LCNF project CLASS showed that half-hourly DR can be unlocked through OLTC action at 33/11kV transformers – 1.2GW in summer and 3.3GW in winter for the whole of GB • Depth of voltage reduction limited, especially in the future
4	Storage based	• BESS can be used for a wide range of services, at different time scales • Accurate estimation of SoC and uncertainty around degradation on different applications; introduces significant uncertainty in the business model



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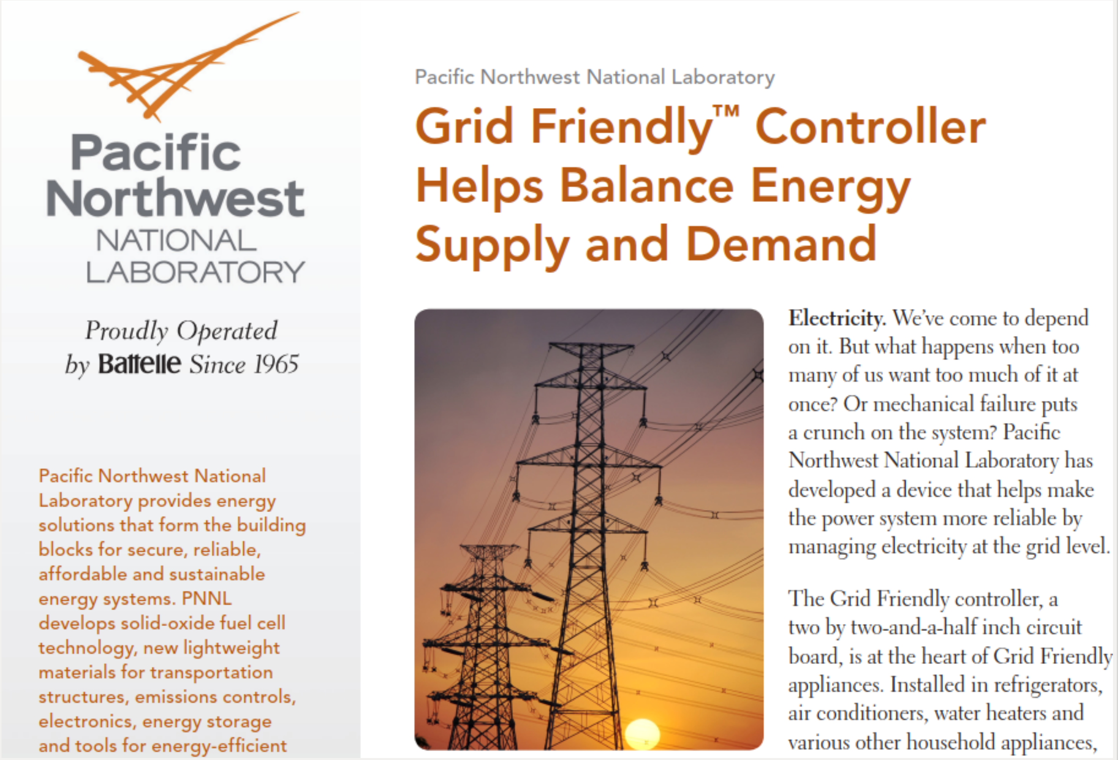
On/Off Control – Grid Friendly Controller

- Grid Friendly controller can be installed in refrigerators, air conditioners, water heaters
- Turns appliances off for a few seconds to a few minutes
- Can provide frequency regulation services
- So far tested in laboratory environment
- Response time ≈ quarter of a second
- Estimated reserve of 10GW controlled load


Pacific Northwest NATIONAL LABORATORY

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Pacific Northwest National Laboratory provides energy solutions that form the building blocks for secure, reliable, affordable and sustainable energy systems. PNNL develops solid-oxide fuel cell technology, new lightweight materials for transportation structures, emissions controls, electronics, energy storage and tools for energy-efficient

Pacific Northwest National Laboratory

Grid Friendly™ Controller Helps Balance Energy Supply and Demand

Electricity. We've come to depend on it. But what happens when too many of us want too much of it at once? Or mechanical failure puts a crunch on the system? Pacific Northwest National Laboratory has developed a device that helps make the power system more reliable by managing electricity at the grid level.

The Grid Friendly controller, a two by two-and-a-half inch circuit board, is at the heart of Grid Friendly appliances. Installed in refrigerators, air conditioners, water heaters and various other household appliances,

Source:

1. https://availabletechnologies.pnnl.gov/technology.asp?id=61
2. D. G. Infield, J. Short, C. Horne and L. L. Freris, "Potential for Domestic Dynamic Demand-Side Management in the UK," 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, 2007

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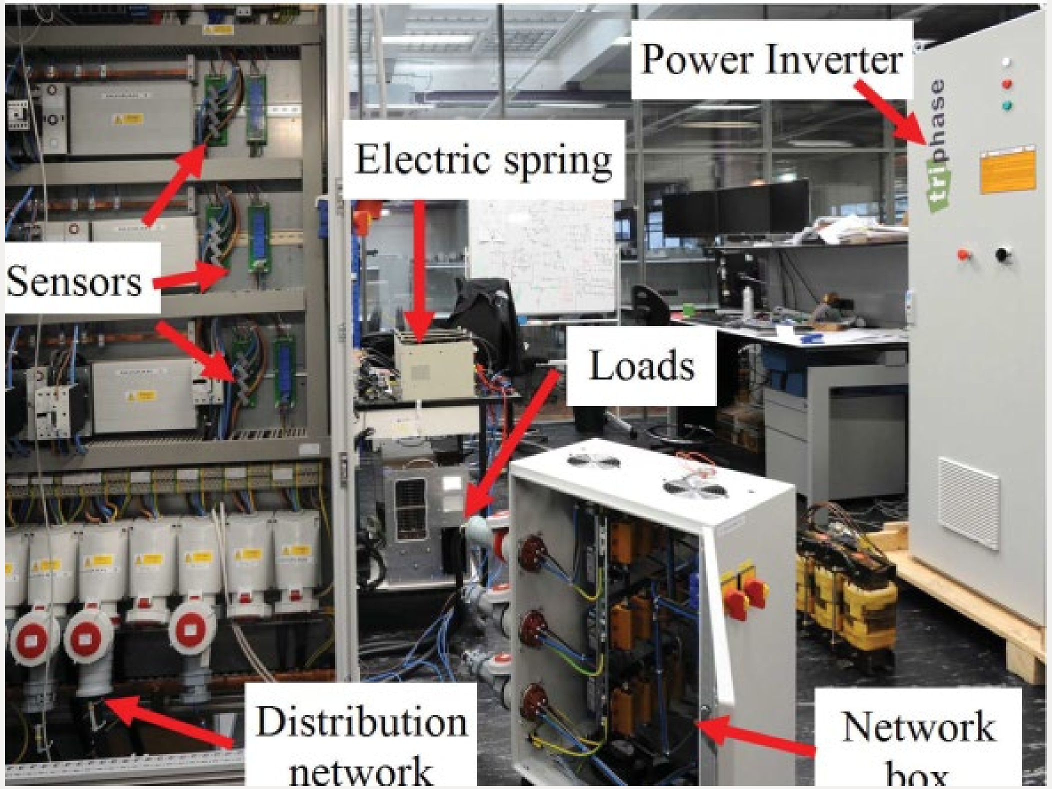
PoL Voltage Control – Electric Spring

- Part rated power electronic compensator in series with a cluster of voltage sensitive loads
- Injected voltage (magnitude and phase) is controlled to regulate mains voltage while allowing load voltage to vary
- Can provide voltage and/or frequency regulation
- Two types of converter configuration
  - ➢ Reactive compensation only (SLQ)
  - ➢ Back-to-back converter arrangement(SLBC)

Smart Energy Laboratory at Imperial College London



Source:

1. C. K. Lee, B. Chaudhuri and S. Y. Hui, "Hardware and Control Implementation of Electric Springs for Stabilizing Future Smart Grid With Intermittent Renewable Energy Sources," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 1, no. 1, pp. 18-27, March 2013, doi: 10.1109/JESTPE.2013.2264091.
2. Chakravorty, Diptargha, "Demand response through point-of-load voltage control", [online] - https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.739640

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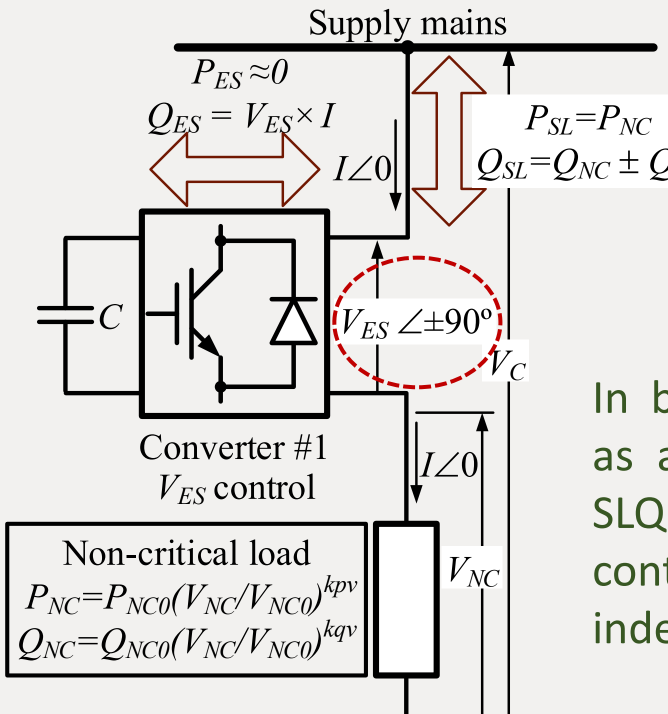
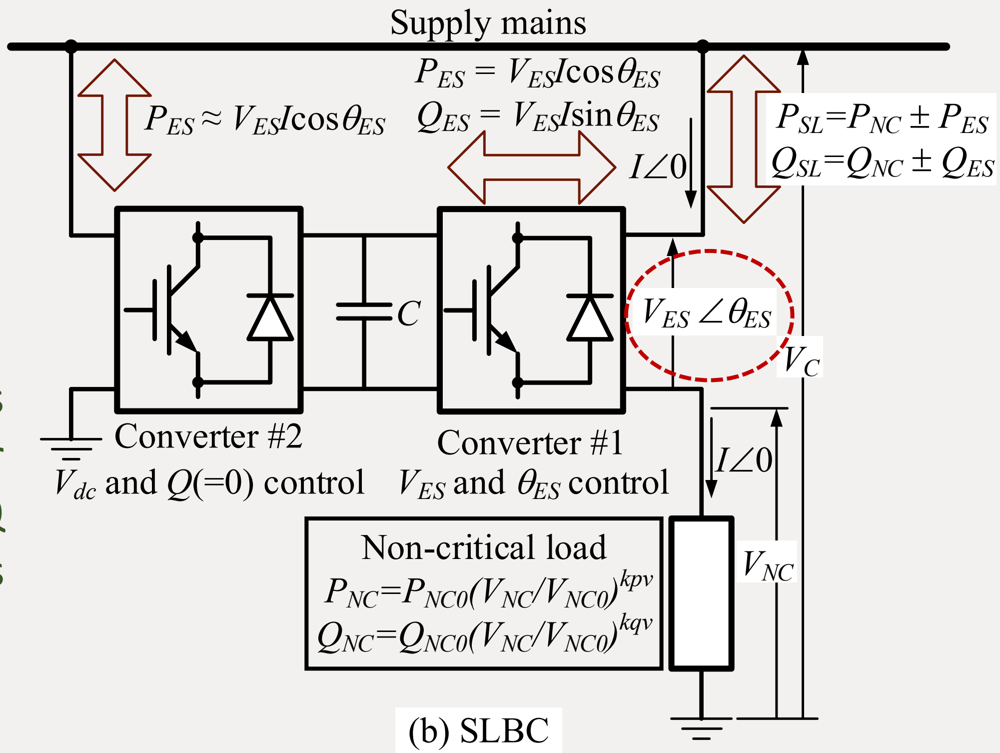
Static Smart Loads



(a) SLQ

In both cases, smart load acts as a controllable P,Q sink. For SLQ it's inter-dependent PQ control while for SLBC it's independent PQ control.



(b) SLBC

- Single converter (cheaper, lower losses)
- **Only Q support** (V_{ES} angle fixed at $\pm 90°$)
- Voltage OR Frequency regulation
- Limited capability

- Two converters (expensive, higher losses)
- **Both P&Q support** (V_{ES} & θ_{ES} control)
- Voltage and/or Frequency regulation
- Wider capability

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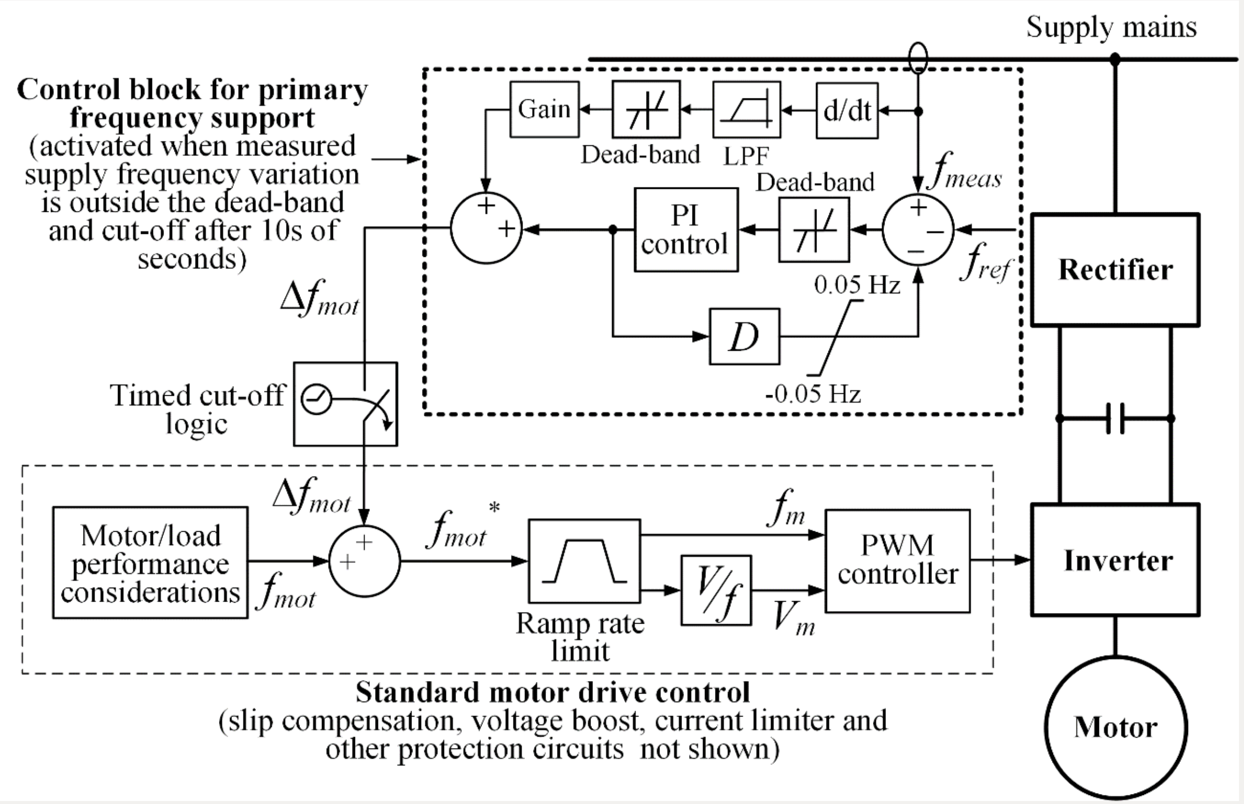
Source:
1. Chakravorty, Diptargha, "Demand response through point-of-load voltage control", [online] - https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.739640
2. D. Chakravorty, B. Chaudhuri and S. Y. R. Hui, "Rapid Frequency Response From Smart Loads in Great Britain Power System," in IEEE Transactions on Smart Grid, vol. 8, no. 5, pp. 2160-2169, Sept. 2017, doi: 10.1109/TSG.2016.2517409.

Motor Type Smart Loads



- Direct on-line (DOL) motors inherently provide inertial response
- Drive connected motors (expected to have significant share in future, only 20% at present in UK) are decoupled from supply
- Subtle modification in drive control circuit will enable contribution to fast frequency response

Source:

1. Chakravorty, Diptargha, "Demand response through point-of-load voltage control", [online] - https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.739640
2. D. Chakravorty, B. Chaudhuri and S. Y. R. Hui, "Rapid Frequency Response From Smart Loads in Great Britain Power System," in IEEE Transactions on Smart Grid, vol. 8, no. 5, pp. 2160-2169, Sept. 2017, doi: 10.1109/TSG.2016.2517409.

Aggregate Reserve from Smart Loads

Reserve from static SLs

- Estimated reserve ≈**1.7 GW**
- Lighting load provides maximum reserve
- Essential public service lighting (e.g. healthcare, transport) not included

Total reserve from static and motor smart loads ≈ 2.6 GW (considering conservative figures for load factor and node voltages)

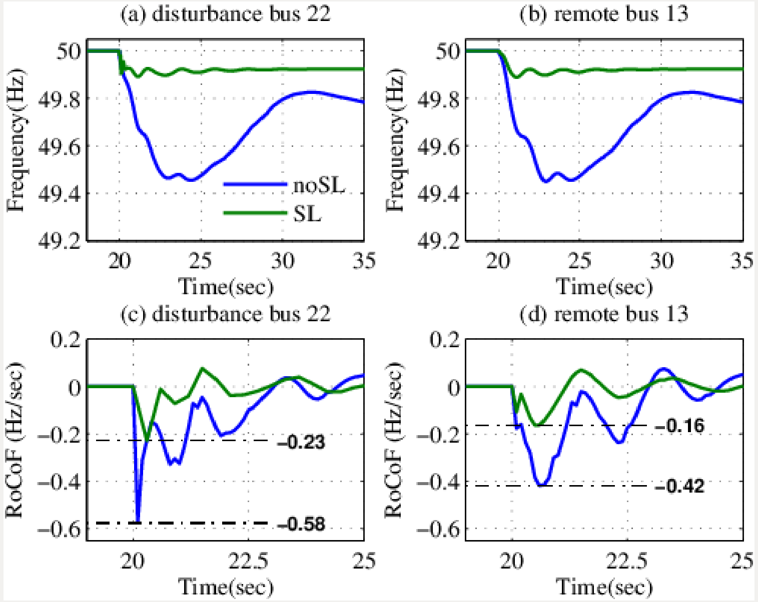
Reserve from motor SLs

- Estimated reserve ≈ **0.8 GW**
- 80% of (industrial + commercial) motor loads are DOL type.
- Out of remaining 20%, 30% of motor drives are for critical application
- DOL motors and critical application motors not considered

Source:
1. Chakravorty, Diptargha, "Demand response through point-of-load voltage control", [online] - https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.739640
2. D. Chakravorty, B. Chaudhuri and S. Y. R. Hui, "Rapid Frequency Response From Smart Loads in Great Britain Power System," in IEEE Transactions on Smart Grid, vol. 8, no. 5, pp. 2160-2169, Sept. 2017, doi: 10.1109/TSG.2016.2517409.

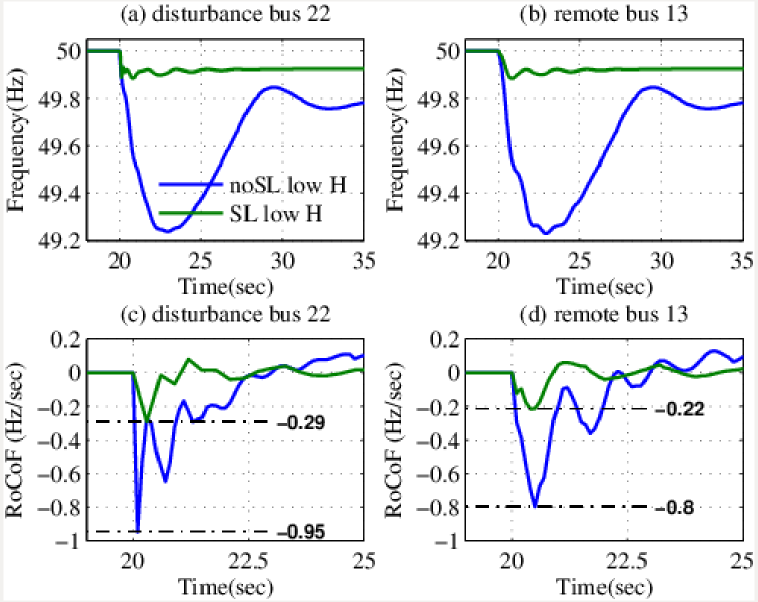
Case Study – Equivalent GB Network

Base case (6.5% NSG)



- SLs effectively arrest frequency nadir and improve RoCoF
- RoCoF values calculated using 100ms sliding window

Low inertia scenario (20% NSG)



- Similar disturbance results in more severe frequency excursion and RoCoF
- Fast reserve required in the future

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Source:

1. Chakravorty, Diptargha, "Demand response through point-of-load voltage control", [online] - https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.739640
2. D. Chakravorty, B. Chaudhuri and S. Y. R. Hui, "Rapid Frequency Response From Smart Loads in Great Britain Power System," in IEEE Transactions on Smart Grid, vol. 8, no. 5, pp. 2160-2169, Sept. 2017, doi: 10.1109/TSG.2016.2517409.

Summary

- Demand Response will certainly play an important role in future system operations
- Smart Load type technologies, which can offer ‘dynamic demand response’, maybe at early stages of development, but they can surely contribute to FFR services along with other products e.g. HVDC, Battery
- Proportion of candidate smart loads are expected to grow in future
  - LED lighting system
  - Drive-controlled motors for non-critical application (for energy efficiency)
  - Space heating, as they are integrated into the electricity sector
- Proven technical capability, commercial model missing

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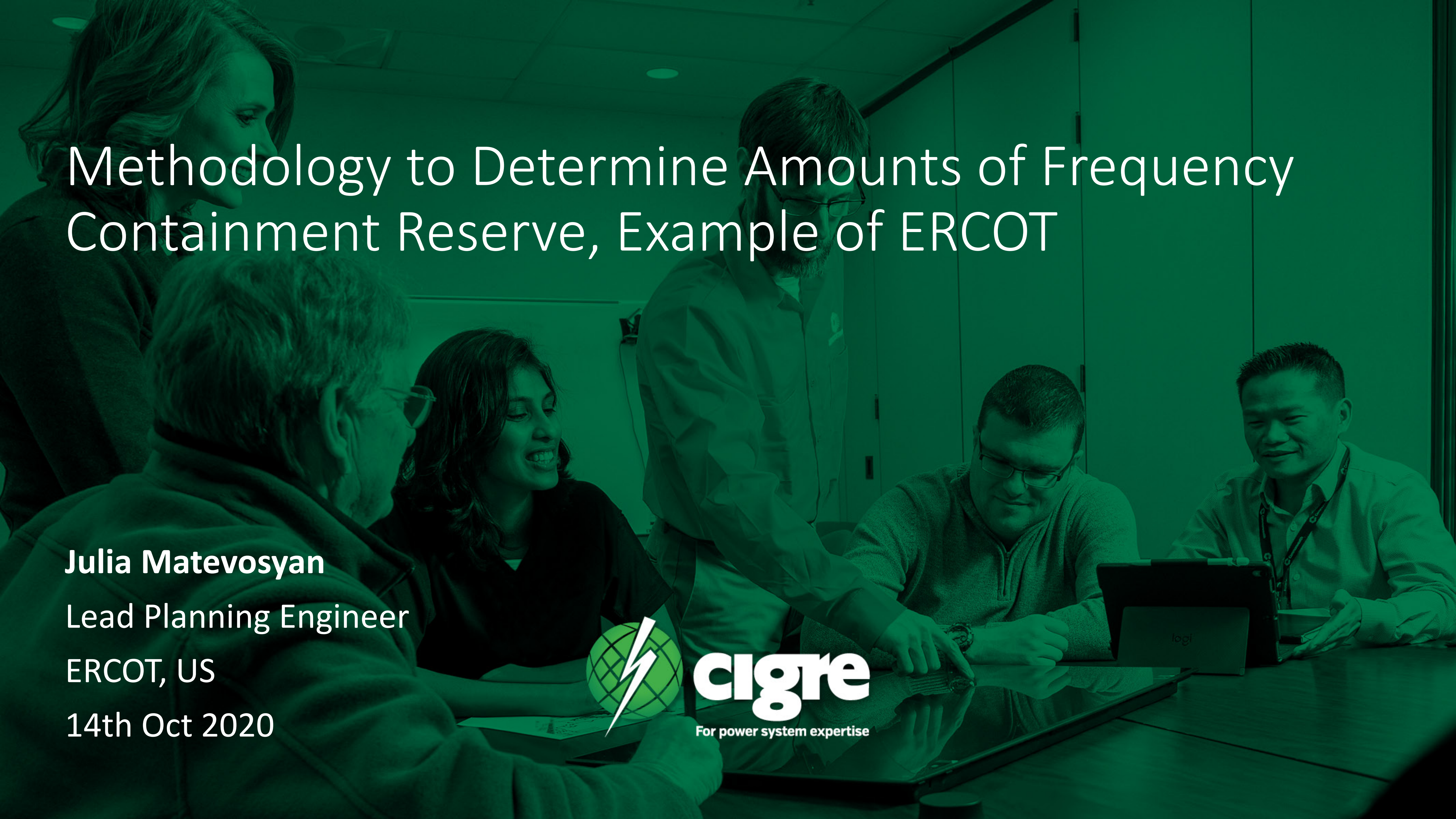

Methodology to Determine Amounts of Frequency Containment Reserve, Example of ERCOT

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14th Oct 2020

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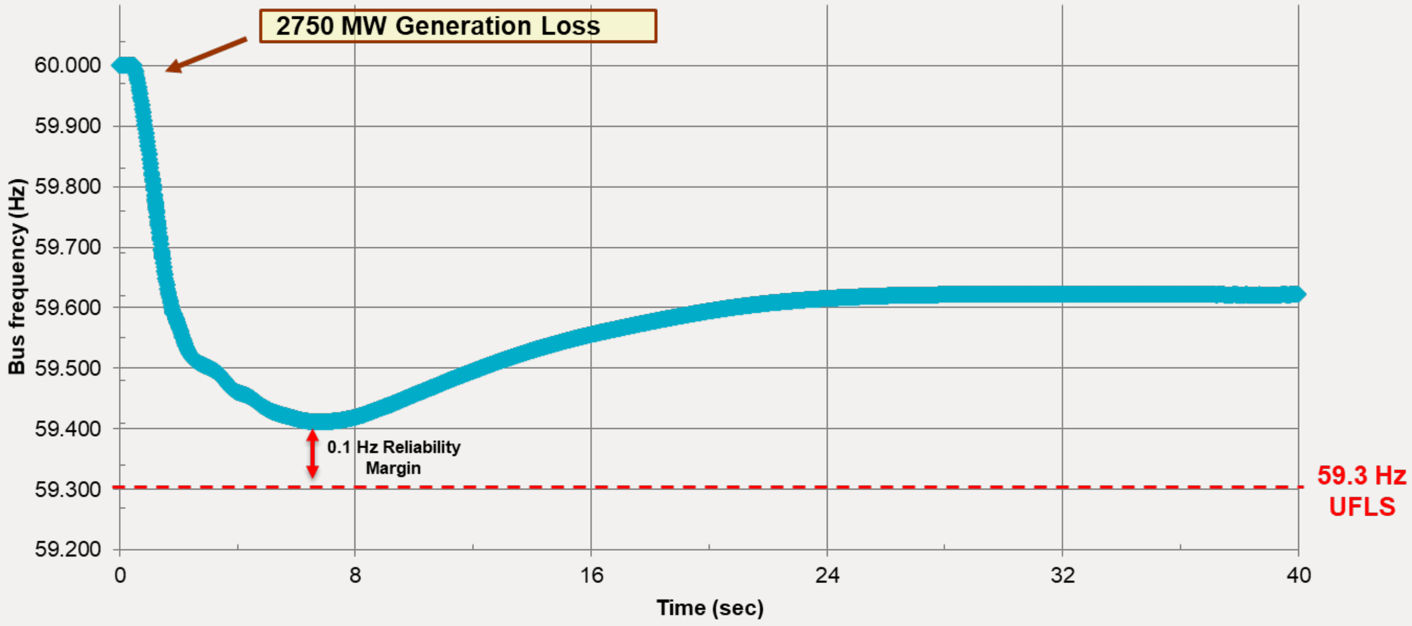
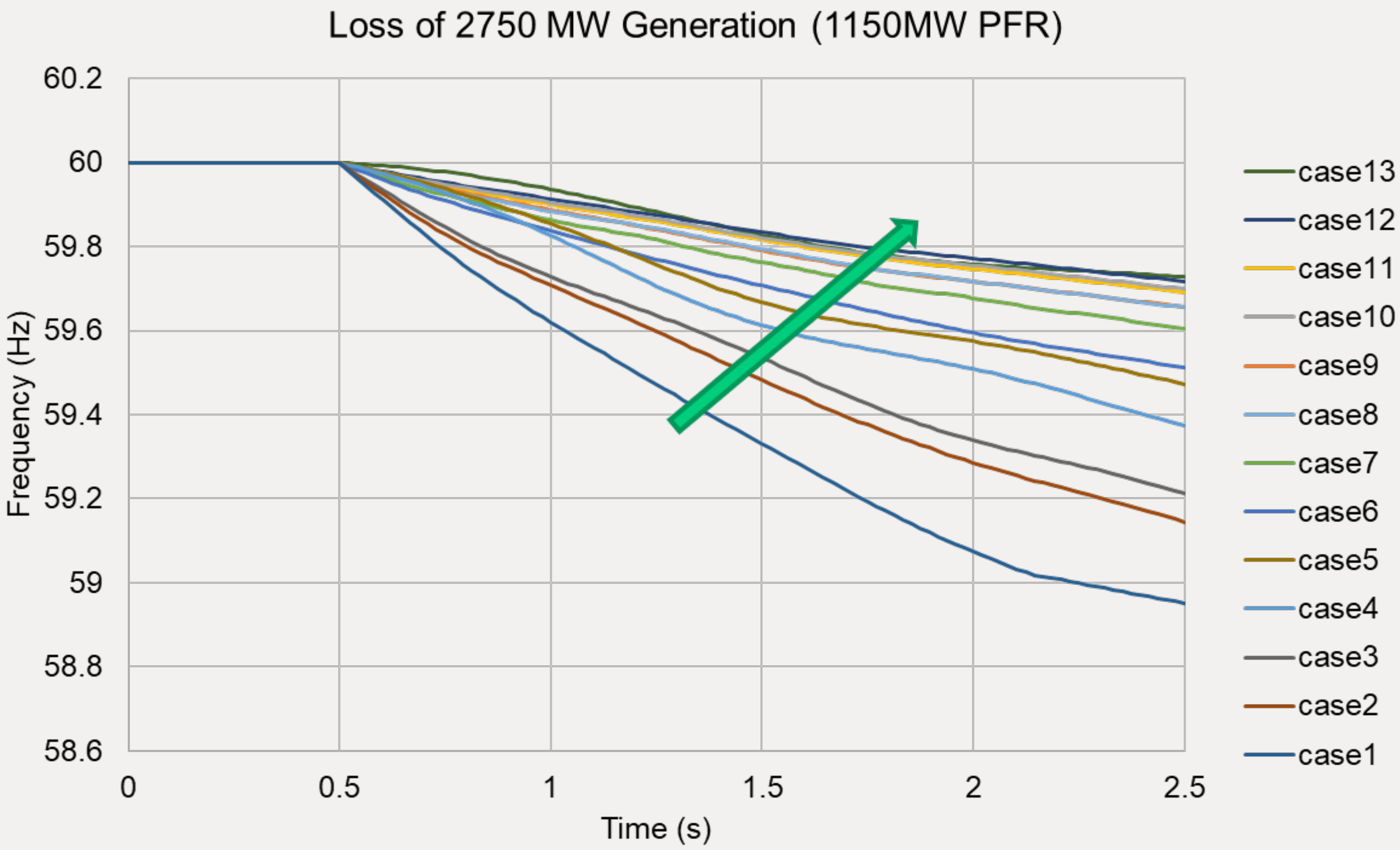
Frequency Containment in ERCOT

- Responsive Reserve Service (RRS) is procured to provide frequency containment during generation trip events
- RRS can be provided by Generators through governor response (droop response or PFR) or
- Load Resources with underfrequency relays, responding within 0.5 second to 59.7 Hz (step response)
- ERCOT used to procure 2800 MW of RRS for all hours
- Studies shown that during lower inertia times due to higher RoCoF after generation trip this amount is not sufficient



Source: Weifeng Li, ERCOT

Impact of Inertia on System Frequency



	Inertia (GW.s)
case13	376
case12	358.5
case11	340
case10	324
case9	307
case8	290
case7	260
case6	224.3
case5	190
case4	184.3
case3	153.6
case2	140
case1	108

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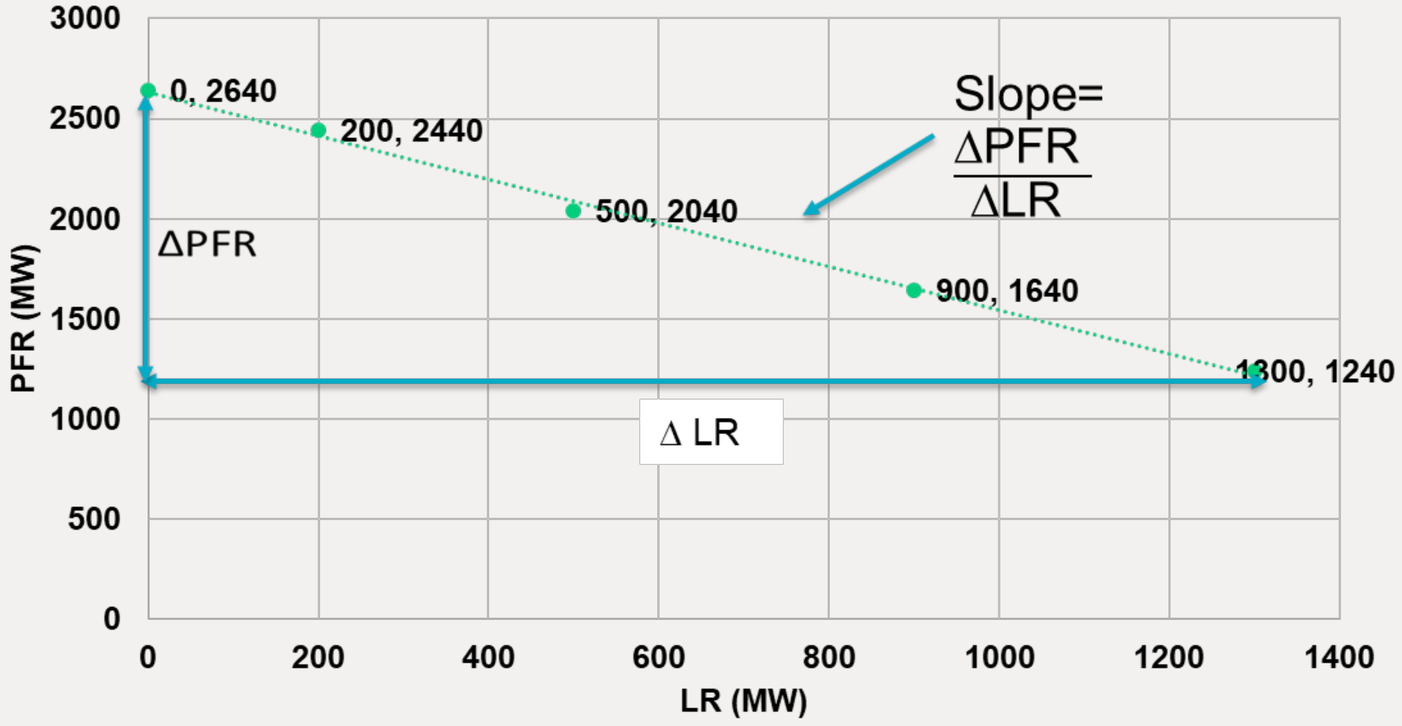
Equivalency Ratio between PFR and Load Resources



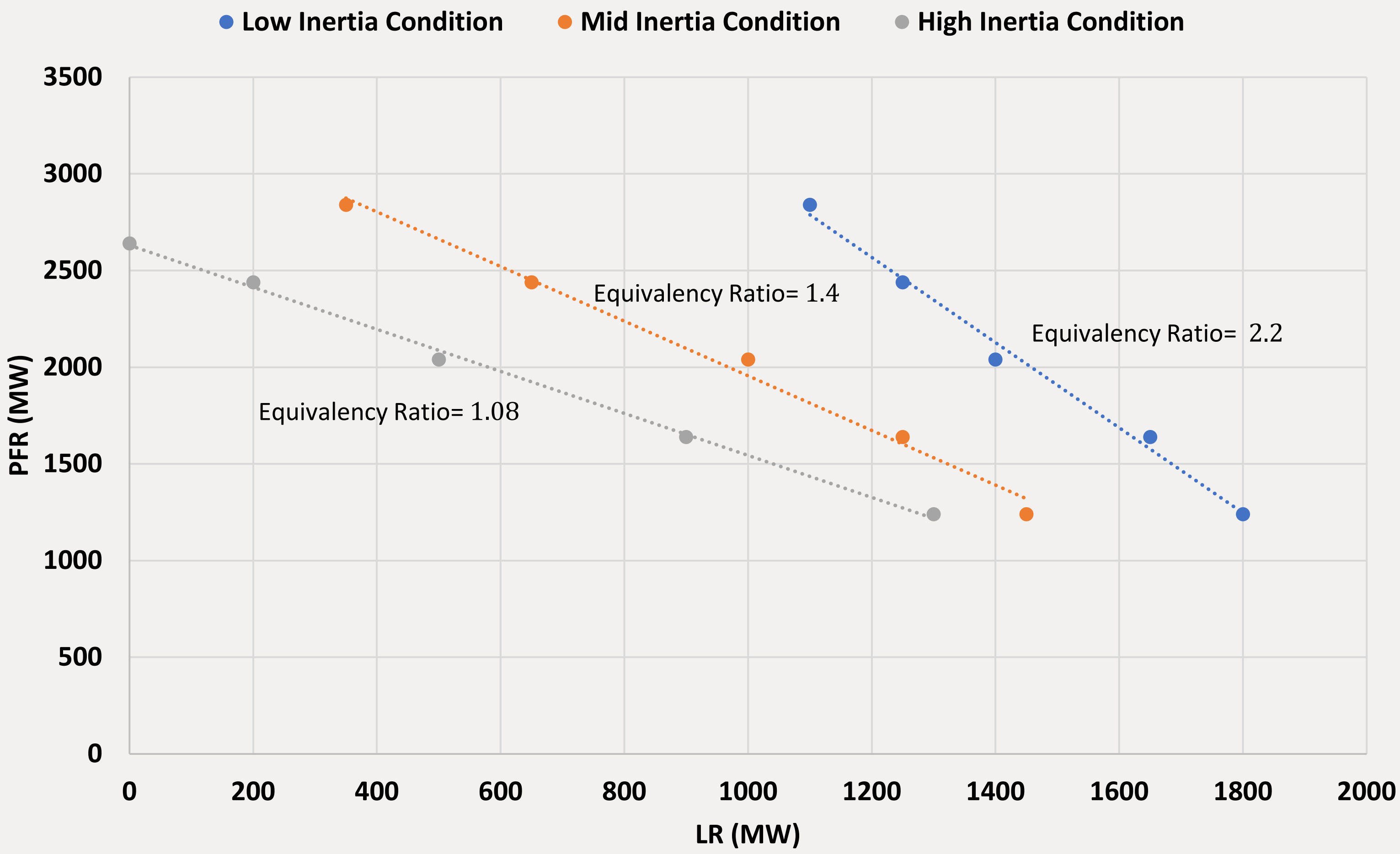
PFR/LR Equivalency Ratio= - Slope= $-\frac{\Delta PFR}{\Delta LR}$

Interpretation: To replace 1MW of LR, $-\frac{\Delta PFR}{\Delta LR}$ MW of PFR is needed

(1MW FFR = $-\frac{\Delta PFR}{\Delta LR}$ MW PFR)

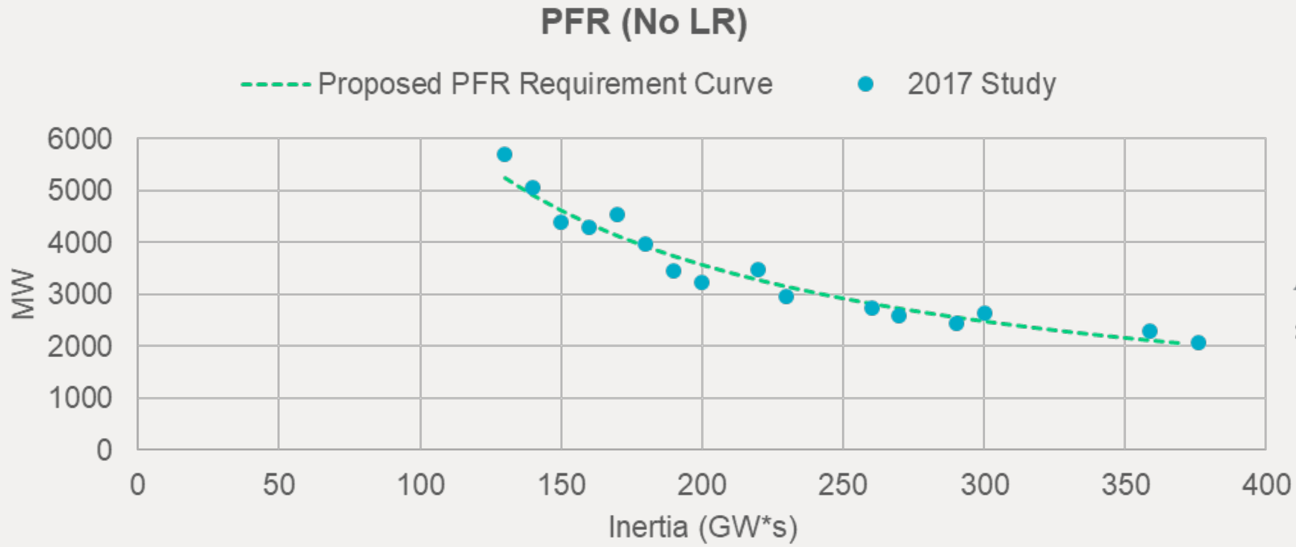
Source: Weifeng Li, ERCOT

Equivalency Ratio at Different Inertia Conditions

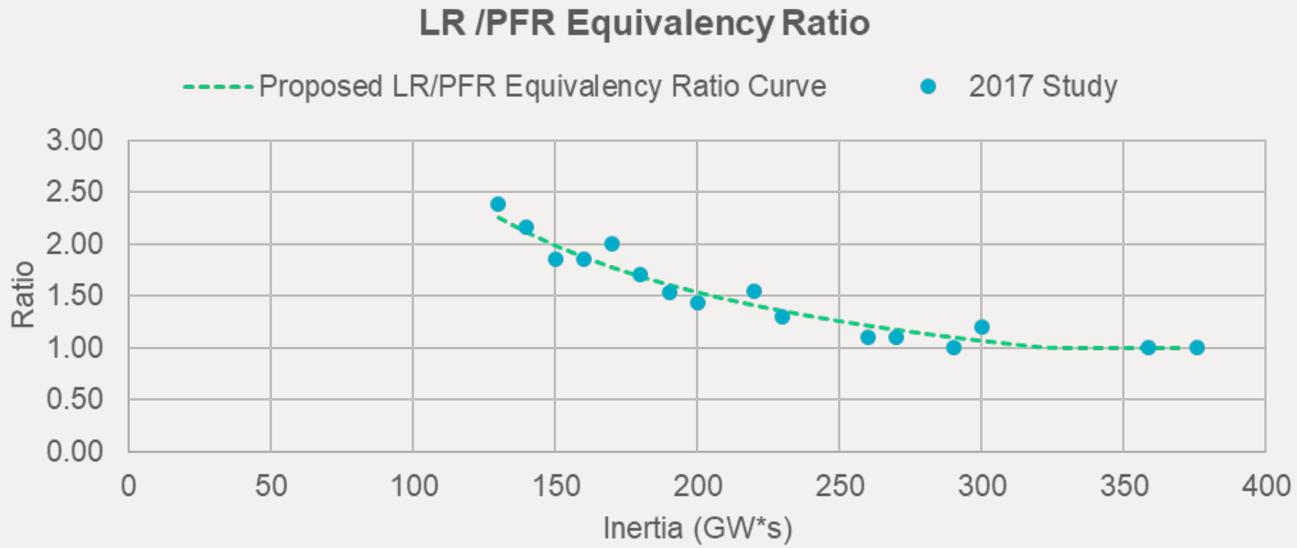


Source: Weifeng Li, ERCOT

RRS Requirements



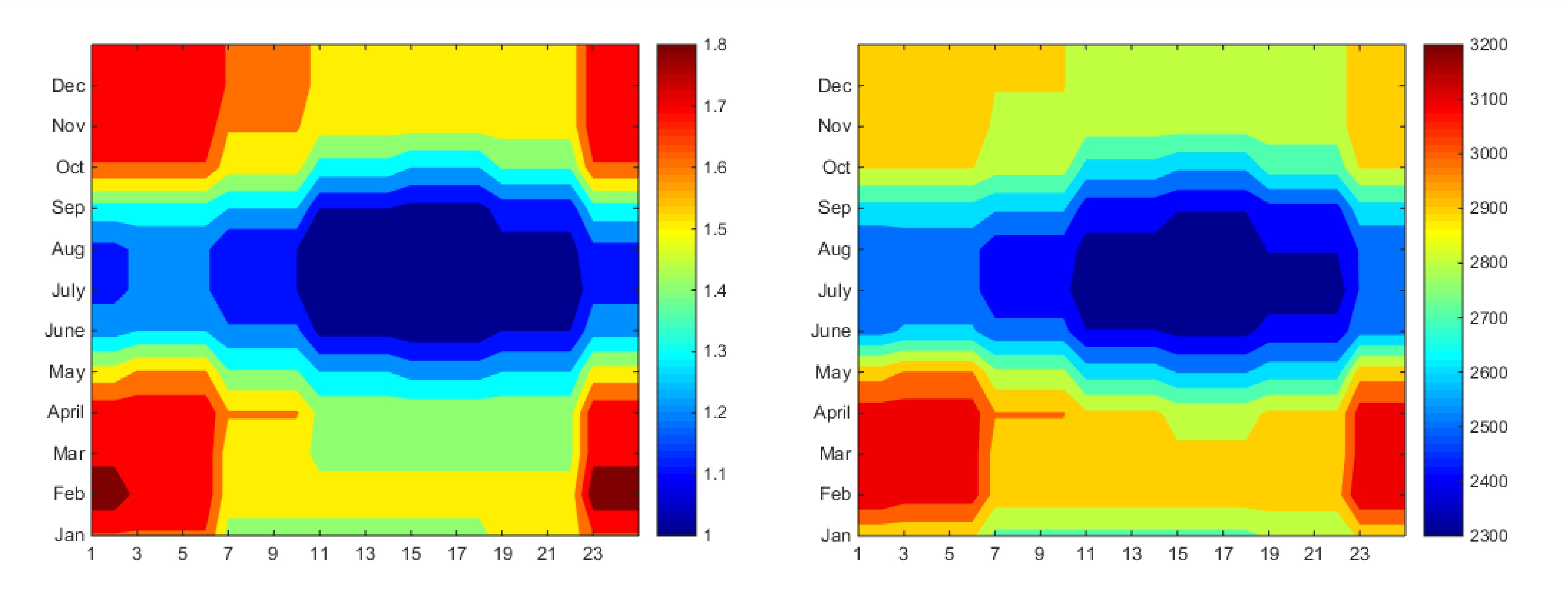
$$PFR(No\ LR) = 399275 \times Inertia^{-0.890}$$



$$LR/PFR = 173.28 \times Inertia^{-0.892}$$

Source:http://www.ercot.com/content/wcm/key_documents_lists/108744/05._RRS_Study_2017_Methodology_11022017.docx

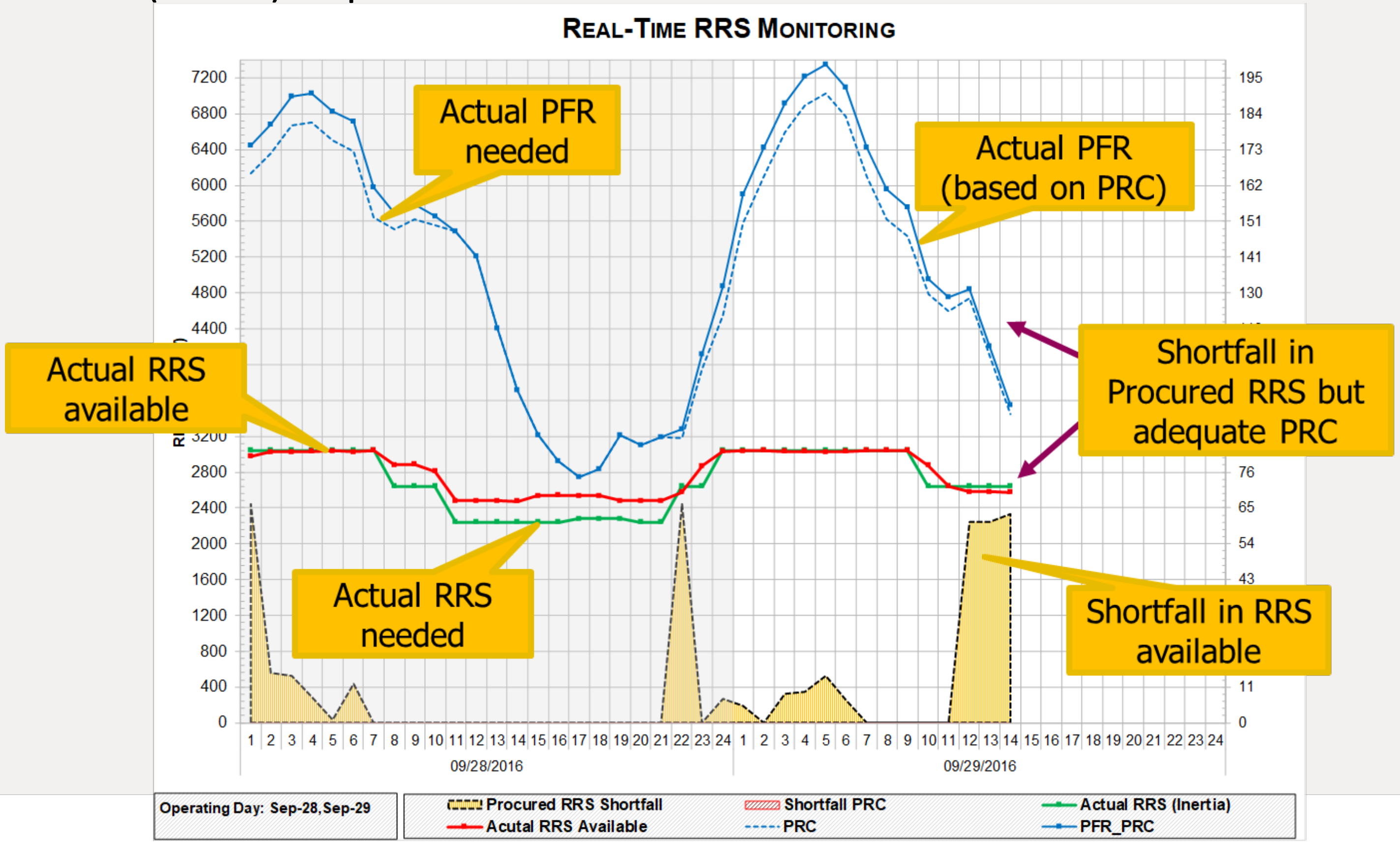
RRS Monthly Procurement, Example 2018



Source: Weifeng Li, ERCOT

RRS Sufficiency Monitoring

- RRS requirements are determined before the operating year, for the whole year.
- ERCOT determines actual RRS needs based on expected inertia conditions in the day ahead and closer to real time, and monitors RRS sufficiency.
- If RRS is insufficient, ERCOT can rely on other available frequency-responsive capacity or open the Supplemental Ancillary Services Market (SASM) to procure additional RRS.

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Closing Remarks

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Key Takeaways

- As generation mix is changing towards higher shares of IBRs, synchronous inertia is declining, leading to higher RoCoF after large disturbances.
- System operators experiencing faster growth of IBRs are adapting by introducing new situational awareness tools, such as inertia monitoring and forecasting.
- New faster frequency response products are being formulated around the world and procured as Ancillary Services.
- Some areas started procuring inertia as Ancillary Service to ensure sufficiently slow RoCoF for available fast frequency response and frequency containment reserves to respond.
- A number of existing and emerging technologies, including inverter-based resources and load are capable of providing FFR and frequency containment response.
- Frequency Reserve requirements are evaluated based on expected system conditions and capabilities of technologies providing frequency response. Reserve sufficiency is monitored in real time.
- Inverter-based resources are playing an increasing role providing essential reliability services.

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Joint Working Group C2/C4.41: Impact of high Penetration of Inverter-Based Generation on System Inertia of Networks

The objective of the WG is to advise and formulate philosophies for system operation to prepare to the energy transition. World-wide experience and studies on the subject of inertia and frequency control of power systems with high inverter based generation have been pulled together in the Technical Brochure addressing the following topics:

- Role of Inertia, Inertia Estimation, Fundamentals of Frequency Response
- Inertia and Frequency Response Survey
- Challenges with High Penetration of Inverter-Based Generation
- Capabilities of Existing and Emerging Technologies to Provide Inertia and Frequency Response
- Quantification of Frequency Containment Requirements
- Inertia as Ancillary Services
- Grid Policies around Frequency Containment Reserve Requirements

Upcoming Milestones:

- CIGRE Academy Webinar, on December 10th, 12-1 pm (Paris Time)
- Technical Brochure, Q1 2021

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Useful References

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- Inertia: Basic Concepts and Impacts on the ERCOT Grid, http://www.ercot.com/news/presentations/2018
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- D. Chakravorty, B. Chaudhuri and S. Y. R. Hui, "Rapid Frequency Response From Smart Loads in Great Britain Power System," in IEEE Transactions on Smart Grid, vol. 8, no. 5, pp. 2160-2169, Sept. 2017, doi: 10.1109/TSG.2016.2517409.

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