NTNU | Norwegian University of Science and Technology

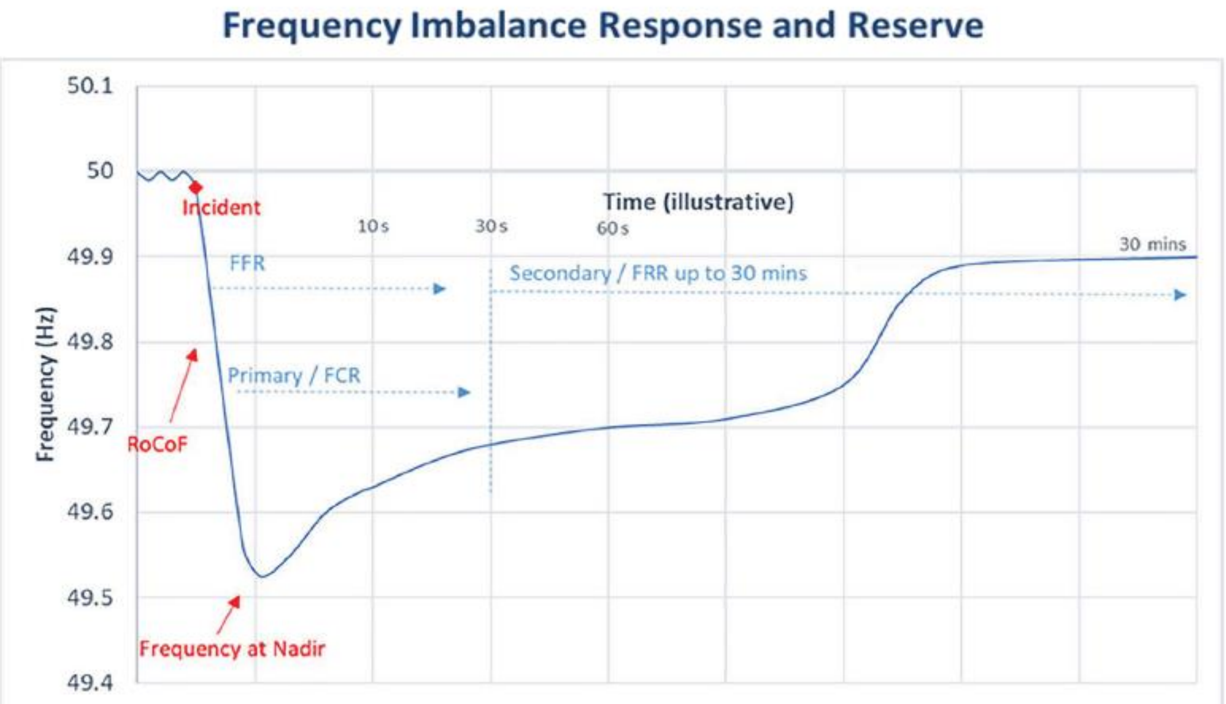
Stability analysis for modern power systems with low inertia and high penetration of power electronic converters

Olav Bjarte Fosso
Electric Power Engineering
28. April 2022

Introduction

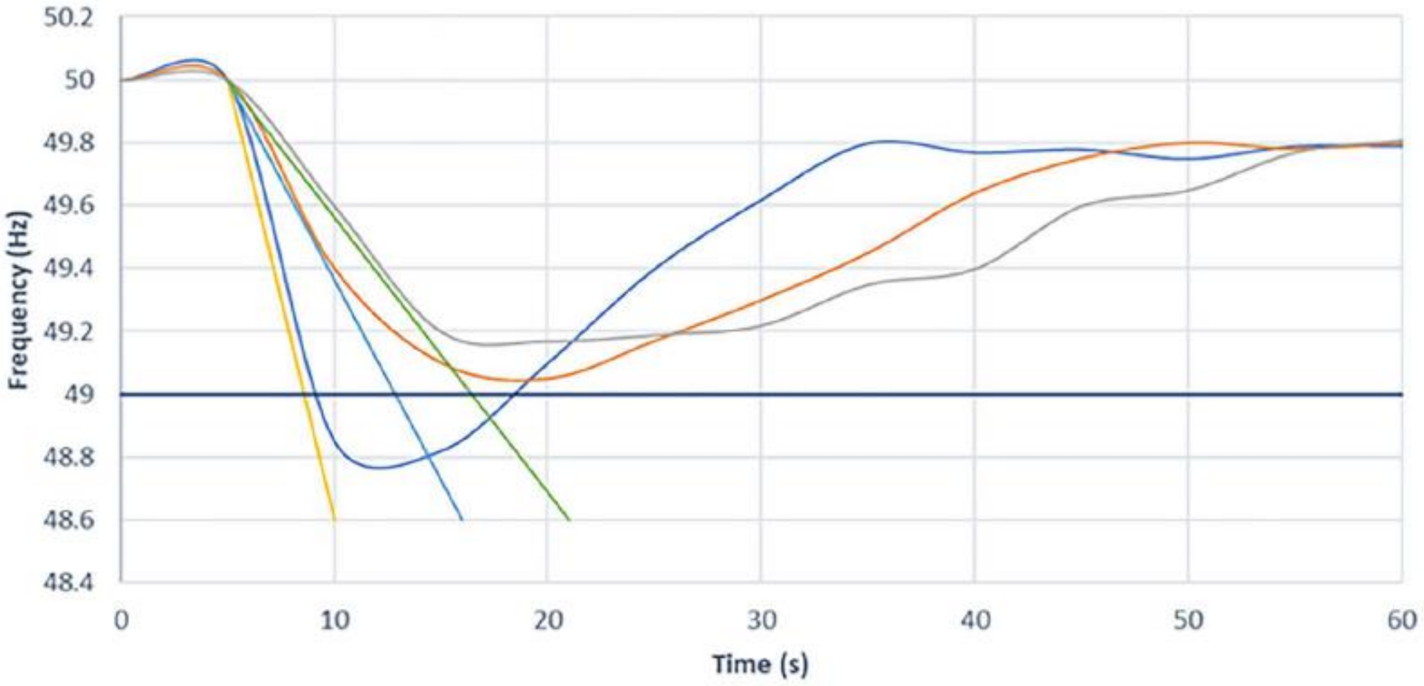
- As power systems worldwide shift their generation resource mix from conventional power plants to a high proportion of renewable resources, new issues arise for ensuring stable system operation.
  - Traditionally, spinning conventional generators have provided system synchronous inertia.
  - With increasing penetration of asynchronous resources, inertia declines.
- Low inertia grid could be potentially at a risk of experiencing excessive rate of change of frequency (ROCOF) after a contingency.
  - A high ROCOF may initiate tripping of other generators
- Network frequency response may become more vulnerable, and system may be subjected to significant under frequency load shedding or at a risk of blackout.

Illustration of system frequency response



Ref 1: EPRI, 2019

Illustration of System Inertia and RoCoF



Ref 2: EPRI, 2019

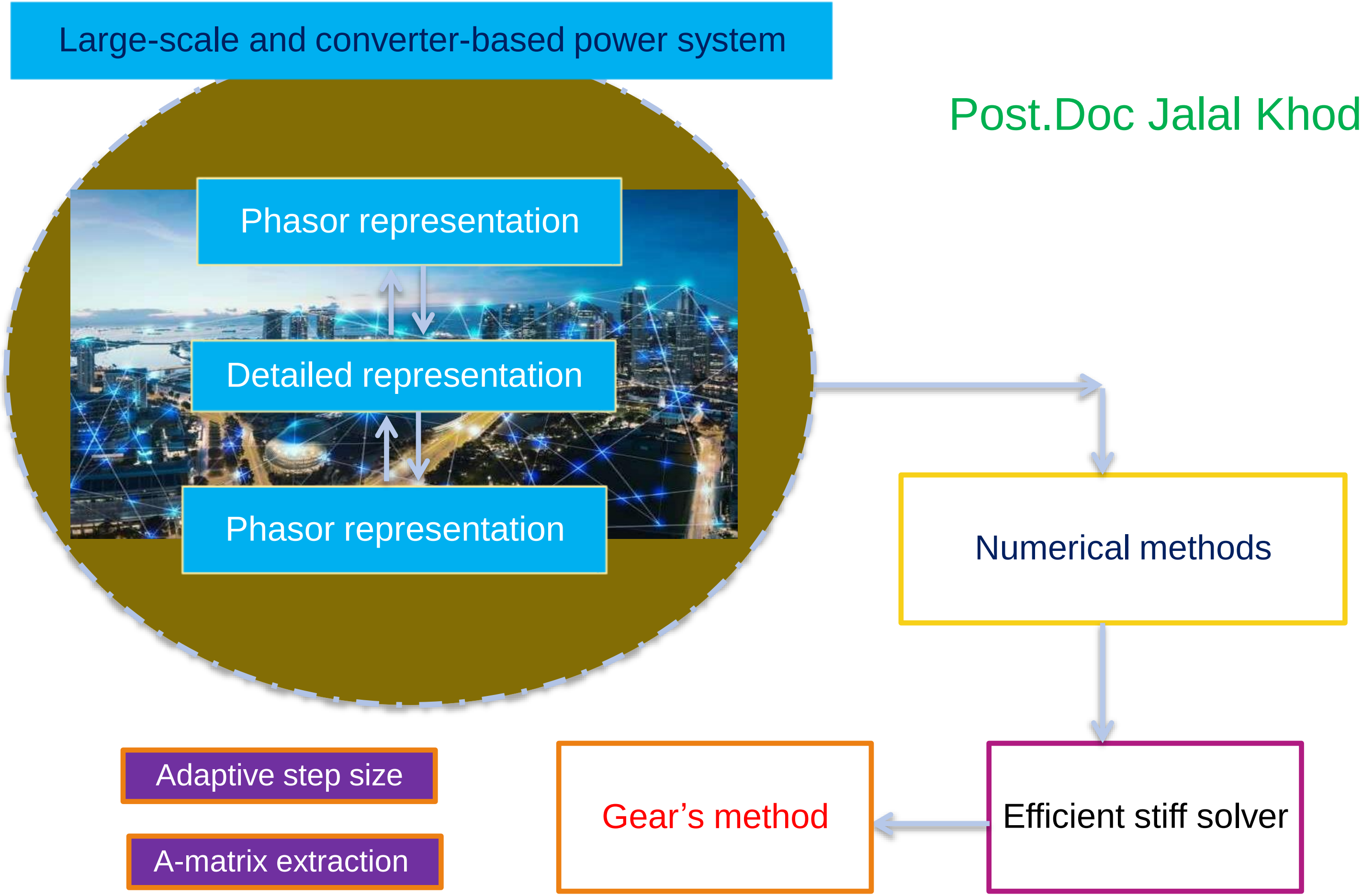
Power System Stability with Low Intertia

- System operators use layers of frequency control measures to ensure stability of the system.
- In ordinary operation, operators accomplish small-scale steady-state regulation in response to small load changes using automatic and manual frequency restoration reserves (FRR).
- In contingencies, the system operator deploys frequency containment reserves (FCR). In larger systems, these are usually distinct from steady-state frequency control services.
- By managing the rate of change of frequency, the system operator seeks to:
  - Limit load shedding due to large frequency deviations
  - Avoid cascading outages that can lead to a blackout, if at all possible
- At each level, system inertia plays a role in managing stability.

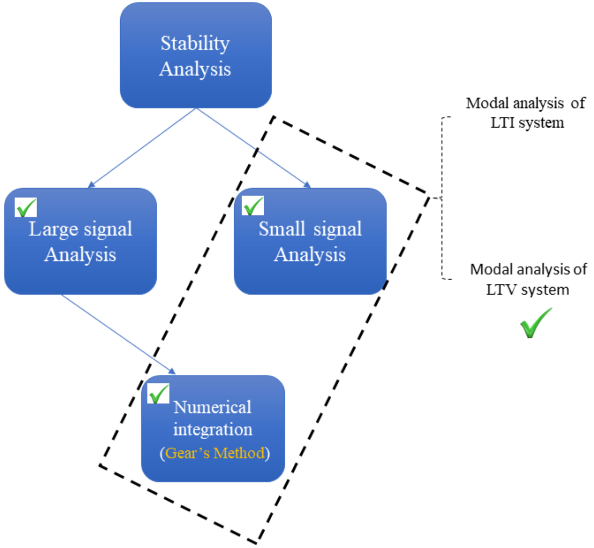
Dynamic analysis

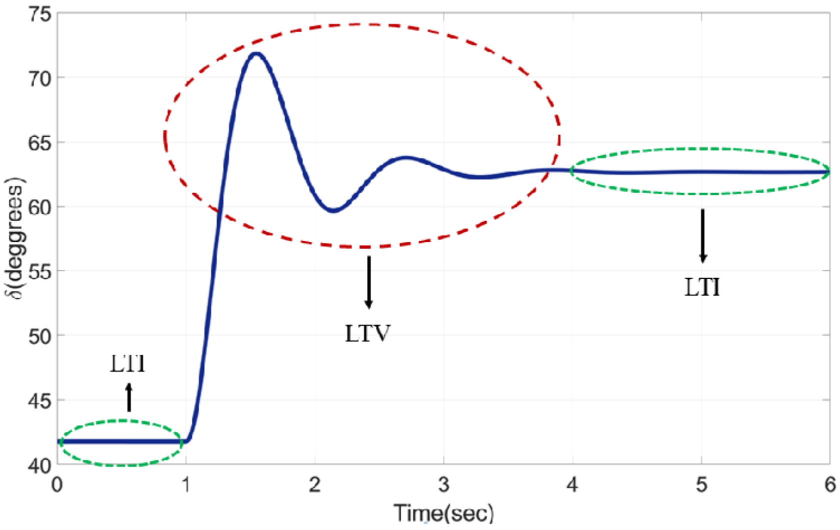
- With lower inertia, the frequency excursions will be increased, and adequate component models must be available
- With the increasing penetration of converter-based interfaces of loads and sources there will be:
  - Large span in time-constants for the simulation processes
  - Need more detailed component models
  - More of the system and component protection may be activated
- The analysis becomes challenging, and the conclusions will depend on the accuracy of the models
- A proper tuning of the different controllers and dynamic performance will be challenging
- It is experienced that different tools may give differences in response for larger disturbances
- Tools are needed to assess the system performance and to support the tuning of controllers of components

Post.Doc Jalal Khodaparast



Unified stability analysis





Gear's method:

Nonlinear Algebraic-Differential Equation (ADE):

$$\begin{cases} y' = f(y,x,t) \\ 0 = g(y,x,t) \end{cases}$$

Solution and its first and second derivatives are predicted:

$$\begin{cases} y_{n+1}^{p} = y_n + H_n y'_n + \dfrac{H_n^2 y''_n}{2} \\ y'^{p}_{n+1} = y'_n + H_n y''_n \\ y''^{p}_{n+1} = y''_n \end{cases}$$

Prediction step

The predicted values are corrected :

$$\begin{cases} y_{n+1} = y_{n+1}^{p} + \Delta y \\ y'_{n+1} = y'^{p}_{n+1} + \dfrac{\Delta y I_1}{H_n} \\ y''_{n+1} = y''^{p}_{n+1} + \dfrac{2\Delta y I_2}{H_n^2} \end{cases}$$

Correction step

$$U_{n+1} = y'_{n+1} - f(y_{n+1}, x_{n+1}, t_{n+1}) = 0$$

$$\begin{pmatrix} U_{n+1} \\ g_{n+1} \end{pmatrix} = \begin{pmatrix} I - H\dfrac{\partial f}{\partial y} & -H\dfrac{\partial f}{\partial x} \\ \dfrac{\partial g}{\partial y} & \dfrac{\partial g}{\partial x} \end{pmatrix} \begin{pmatrix} \Delta y \\ \Delta x \end{pmatrix}$$

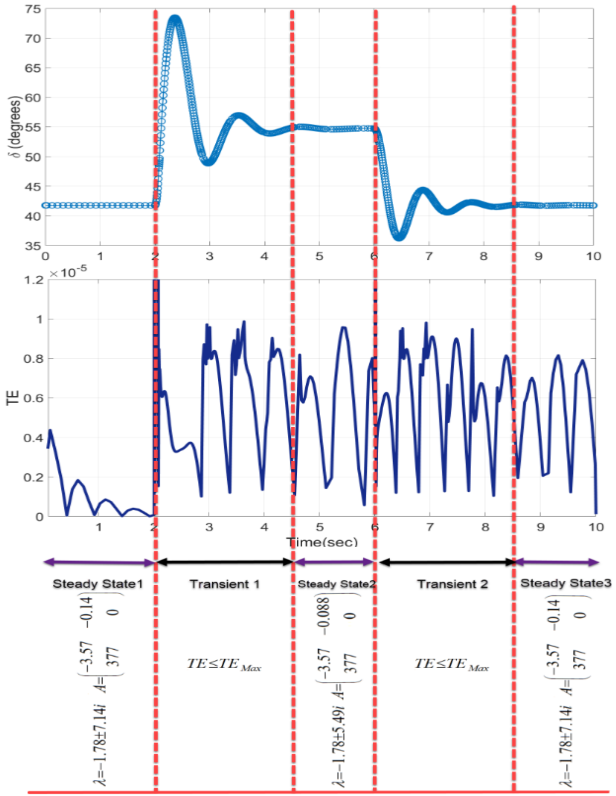
Truncation Error:

$$TE = 2K_2 I_2 \left\| [y, x] \right\|$$

Integration step size of the algorithm is adapted:

$$H_{new} = K_{sc} \sqrt{\frac{TE_{ds}}{2K_2 I_2 \left\| [y, x] \right\|}}\, H_{old}$$

Gear's method:



UNIFIED STABILITY ANALYSIS

1) Detection of transient instability

if $TE < TE_{\max}$ → System is stable

if $TE > TE_{\max}$ → System is unstable

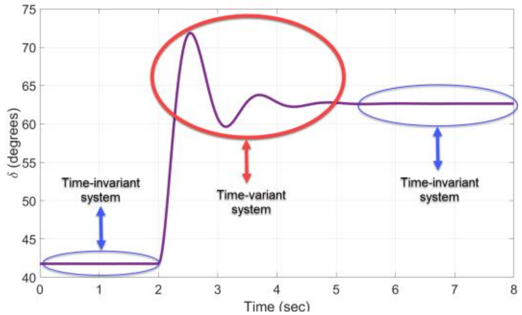
2) Extraction of small-signal indices

$$\begin{pmatrix}\Delta f\\ \Delta g\end{pmatrix} = \begin{pmatrix}\frac{\partial f}{\partial y} & \frac{\partial f}{\partial x}\\ \frac{\partial g}{\partial y} & \frac{\partial g}{\partial x}\end{pmatrix}\begin{pmatrix}\Delta y\\ \Delta x\end{pmatrix}$$

$$A = \frac{\partial f}{\partial y} - \left(\frac{\partial f}{\partial x}\left(\frac{\partial g}{\partial x}\right)^{-1}\frac{\partial g}{\partial y}\right)$$

NTNU | Norwegian University of Science and Technology

1-Modal analysis



A-matrix extraction

Solve Riccati equation

✓ Mode-vector calculation

Stability Analysis

Solution of system

Mode-vector ← $m_i(t) = e^{\int_{t_0}^{t} \lambda_i(\tau)d\tau} e_i(t)$

$x(t) = \sum_{i=1}^{i=N} c_i . m_i(t)$

LTV System is stable, if norm of mode-vector is bounded

LTI system:

$m_i(t) = e^{\lambda_i(t-t_0)} e_i$

$\mathrm{Re}\{\lambda_i\} < 0$ → $\|m_i(t)\| \to 0$ → Stable

LTV system:

$m_i(t) = e^{\int_{t_0}^{t} \lambda_i(\tau)d\tau} e_i(t)$

$\|m_i(t)\| \to 0$ → Stable

1-Modal analysis

LTV system

A-matrix extraction

Solve Riccati equation

Mode-vector calculation

✓ Lyapunov exponent calculation

Mode-vector ← $m_i(t) = e^{\int_{t_0}^{t} \lambda_i(\tau)d\tau} e_i(t)$

LTV System is stable, if the norm of every mode-vector is bounded

Lyapunov exponent → $LE_i = \lim_{t\to\infty} \operatorname{Re}\left\{\frac{1}{t}\ln\|e_i(t)\| + \frac{1}{t}\int_{t_0}^{t} \lambda_i(\tau)d\tau\right\}$

$$LE_i(k\Delta t) = \frac{1}{Nk\Delta t}\sum_{m=1}^{N}\log\frac{\|m_i((k+m)\Delta t) - m_i((k+m-1)\Delta t)\|}{\|m_i(m\Delta t) - m_i((m-1)\Delta t)\|}$$

Time window Lyapunov exponent

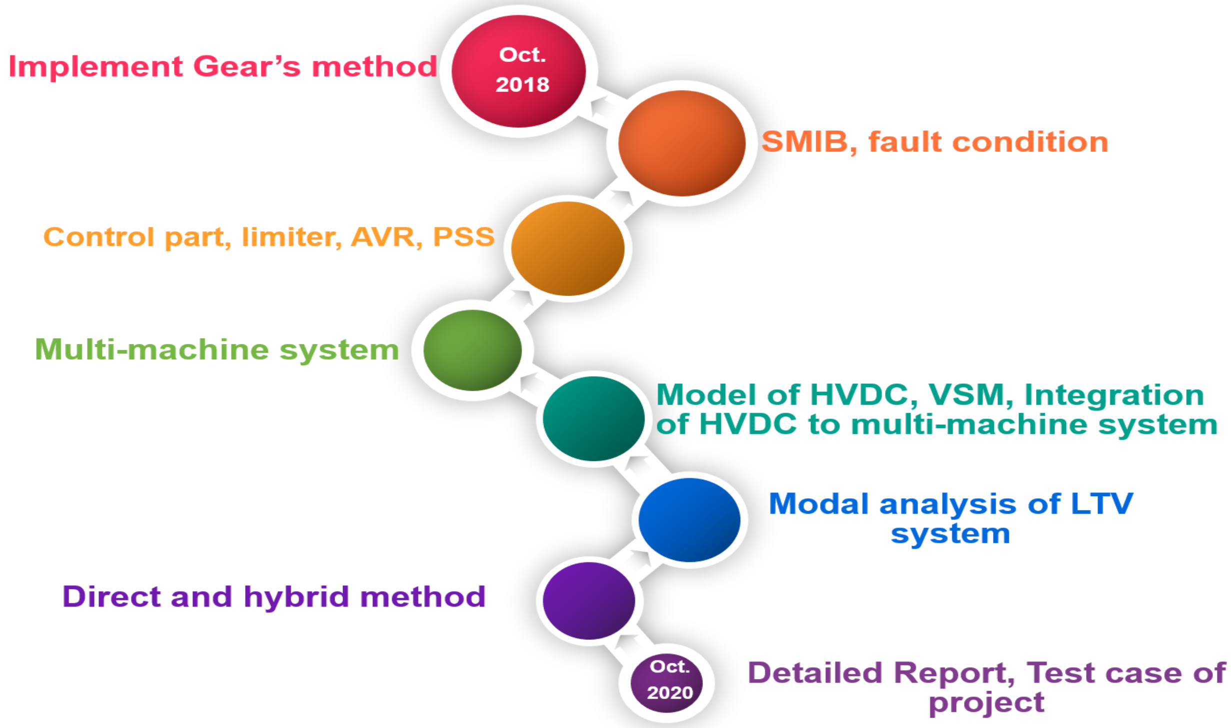
LE>0 → Unstable system

LE<0 → Stable system

LTI system:

$$LE_i = \operatorname{Re}\{\lambda_i\}$$

Development stages



Factors Relating Inertia, RoCoF, and Frequency Nadir (1)

- Largest contingency
- RoCoF Protection Relay Setting (0.1 Hz – 1 Hz)
  - Installed on DER, trips when rate of change exceed setting
- Under-Frequency Events and Conventional Generators
  - Lack of RoCoF-relay may in low inertia systems bring generators into untested modes of operation
- Under-Frequency Load Shedding Setpoints
  - Last sort of action but too low they will define the minimum frequency
  - Too high will cause wide-spread load shedding

Factors Relating Inertia, RoCoF, and Frequency Nadir (2)

- Fast Frequency Response from Inverter-Based Resources
  - inverter-based resources can be programmed to quickly inject power, which serves a similar but not identical function to inertia.
  - The power injection can help slow the RoCoF, help stabilize the system, and avoid dropping loads
- Frequency Containment Reserve (FCR)
  - More units online may reduce the efficiency
- The Contribution of Load and Energy Storage
  - Load adjustment can provide quick frequency response without requiring additional inertia on the system.
- System Protection Device Sensitivity

System characteristics

Name	Nordic System	Great Brittain
Under Frequency Load Shedding (UFLS)	48.85 Hz	48.8 Hz
Rate of Change of Frequency (RoCoF)	0.5 Hz/s	0.5 Hz/s
Largest Contingency	1.4 GW	1.25 GW
Peak Demand	72 GW	60 GW
Inertia Floor	125 GWs	135 GWs

Low Intertia Operation

- Assessing the need for Intertia
  - Accurate models of the system
  - Careful dynamic studies of current and future scenarios

- Main groups of Inertia and FFR providers:
  - Synchronous Solutions
  - Asynchronous Solutions: Synthetic Inertia and FFR

Synchronous Solutions

- Synchronously connected generators
  - Most direct solution to impose a minimum system inertia level
- Pumped hydro-electric storage
- Compressed air energy storage
- Synchronous flywheel storage
- Synchronous condensers
  - Much replaced by STATCOM and SVC
  - Increasing interest again

Asynchronous Solutions

- Exploit the inverter controls of power electronics to use asynchronous or DC resources to provide rapid power injections in response to events.

- Fast frequency response can come from:
  - wind
  - PV plants,
  - Battery energy storage, systems,
  - HVDC interconnectors
  - Inverter-based resources

Asynchronous Solutions - Issues

- Detection of RoCoF
  - RoCoF needed to asynchronously-connected synthetic inertia solutions
  - Estimation of RoCoF has an inherent time delay (time window)
  - Concerns about potential delay before response activation
- Inertia Emulation: A Different Response than Synchronous Machines
  - Operating condition of for example wind-turbine will influence the response
  - Acceleration after deceleration
- “De-Loading” Renewable Resources
  - A possibility to operate them de-loaded to have some margin
  - Not the best approach

Frequency service capabilities

Services	Technology										
	Synchronous					Nonsynchronous					
	Fossil	Nuclear	Synchronous Condenser	Pumped Hydro	CAES	Asynchronous Flywheel	HVDC	Type 3/4 Wind	Battery	PV	Demand
Inertia (Instantaneous)	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	25%
FFR (Cycles)	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	75%
FCR (Seconds)	100%	25%	0%	100%	100%	50%	100%	100%	100%	100%	25%
FRR (Minutes)	100%	0%	0%	100%	100%	0%	100%	50%	25%	50%	0%
Maturity	100%	100%	100%	100%	75%	50%	75%	75%	75%	75%	25%

Key: 100% 75% 50% 25% 0%

Ref 1: EPRI, 2019

Conclusions

- As system inertia decreases and the system is becoming more complex, transmission system operators face new challenges in planning, operating, and protecting transmission systems.
- The industry needs new analytical tools for simulation, coordination, tuning of controllers and decision support, as well as high-quality real-world data on the effects of reduced system inertia during disturbances.
- In the meantime, new techniques for supporting system inertia require study to establish their value and effectiveness in supplementing or replacing synchronous inertia – still there is a long way to go

References

1. “Implications of Reduced Inertia Levels on the Electricity System, Technical Report on the Challenges and Solutions for System Operations with Very High Penetrations of Non-Synchronous Resources” 3002014970, EPRI, June 2019
2. “MEETING THE CHALLENGES OF DECLINING SYSTEM INERTIA”, EPRI, April 2019
3. “Impact of High Penetration of Inverter-based Generation on System Inertia of networks”, CIGRE JWG C2/C4.41, Technical Brochure, Reference: 851, October 2021
4. «Stability Analysis of a Virtual Synchronous Machine-based HVDC Link by Gear’s Method», Jalal Khodaparast ;Olav Bjarte Fosso; Marta Molinas; Jon Are Suul, 2020 6th IEEE International Energy Conference (ENERGYCon), IEEE
5. “Static and Dynamic Eigenvalues in Unified Stability Studies”, J. Khodaparast, O. B. Fosso, M. Molinas, J. A. Suul (In review)
6. “Prediction of Instability by Gear's Method and Differential Riccati Equation”,Jalal Khodaparast, Olav Bjarte Fosso, Marta Molinas, Jon Are Suul (To be submitted)

Thank you very much for the attention!