Power System Stability Challenges in the Renewable Integration Process

Role of Inertia, International Tendencies and Potential Regulatory Considerations

2022.02.09.

István Táczi
PhD Candidate, Budapest University of Technology and Economics

Content

- Effects of the generation portfolio changes
  - Global key facts
  - Inertia reduction
- Power system stability in a nutshell
- International practice
  - European Network of Transmission System Operators – Electricity (ENTSO-E) key learnings
  - MIGRATE H2020 project
  - Classification of systems by size
- Mitigation possibilities – technology
- Mitigation possibilities - markets
- Regulatory considerations

Global trends & physical effects

- IEA – In 2021, 290 GW new renewable capacity → 50% is PV
- Between 2020-2026, the newly installed renewable capacity will equal the current fossil&nuclear capacity (4800 GW)
- Synchronous generator – directly coupled electromechanical system
  - The **electrical frequency** is determined by the mechanical speed of the rotating machine
  - The kinetic energy of the rotating mass -> synchronism, angle stability, swing equation
- Power electronic converter interfaced generation (PV, wind)
  - Decoupled from the system → no inherent frequency response
  - The electrical parameters are determined by controlling

Reduction of inertia - physics

- Static equilibrium:

$$P_G = P_M = P_F(+P_V)$$

- Dynamic equilibrium:

$$P_G = P_M - P_F = \frac{d(E_{K.E.})}{dt} = \frac{d(\frac{1}{2}J\omega_R^2)}{dt}$$

- Kinetic energy of the rotating mass:

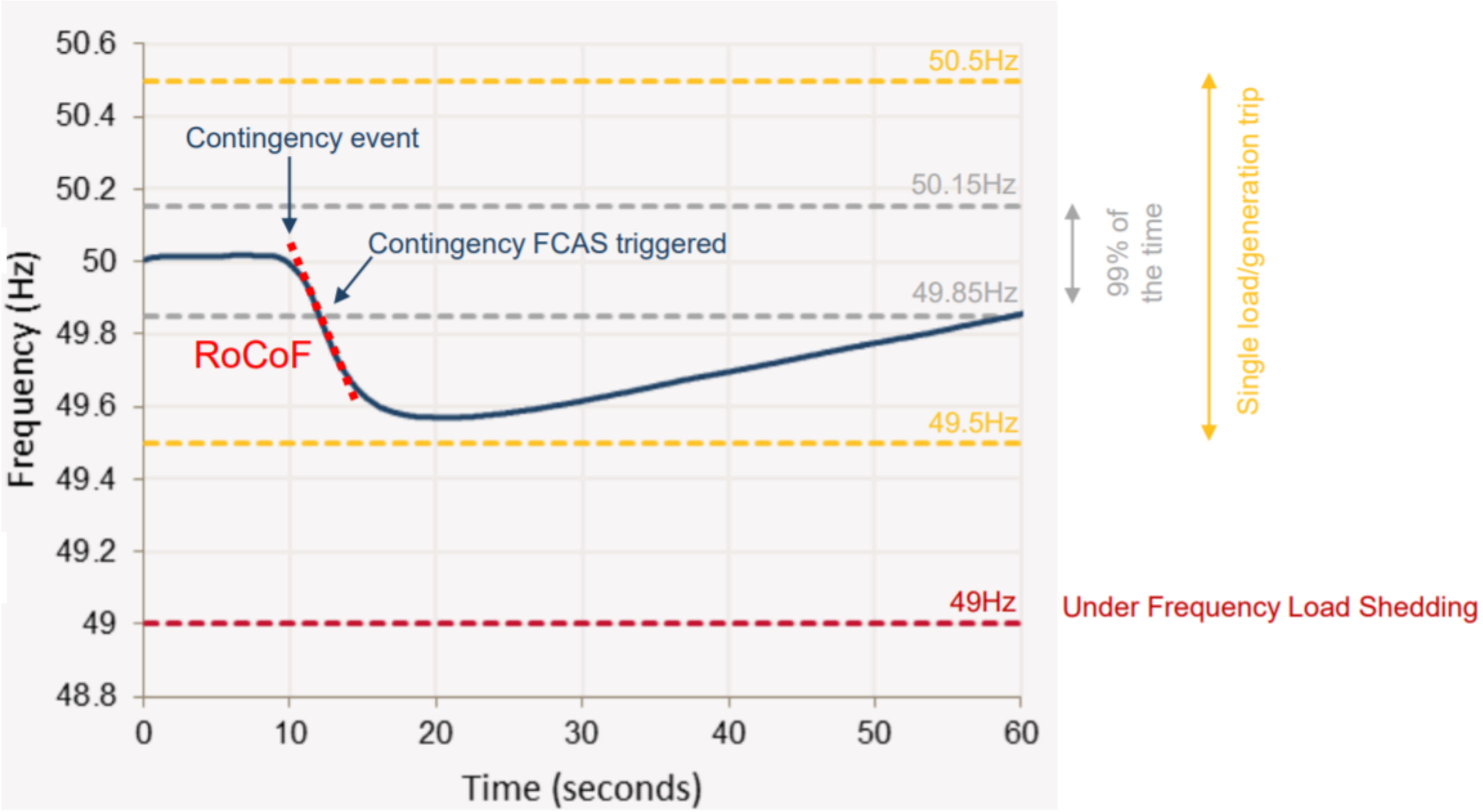
$$\frac{1}{2}J * \omega_n^2 = H_i * S_i$$

- **Inertia constant and rate of change of frequency:**

$$\frac{2H}{\omega_n}\frac{\omega_R}{\omega_n}\frac{d\omega_R}{dt} = \frac{2H}{f_n}\frac{f_R}{f_n}\frac{df_R}{dt} = ROCOF$$

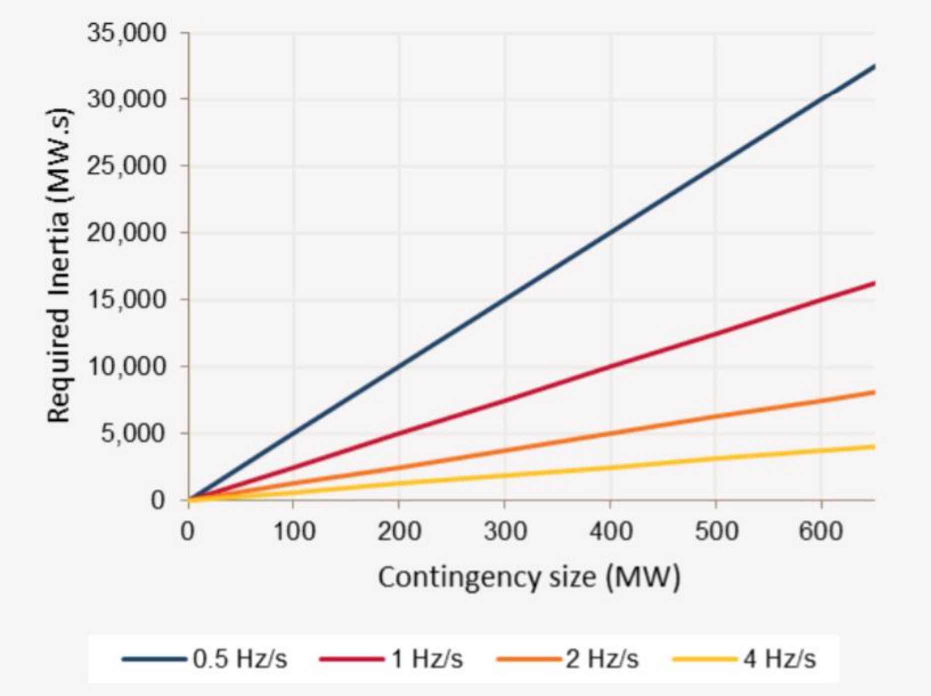
Rate of Change of Frequency

- Possible contingencies – generation/load outage, loss of import/export, network faults (short-circuits)



Inertia & ROCOF

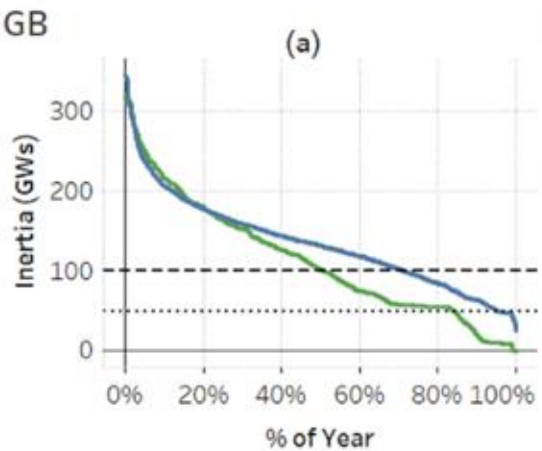
- Y axis: Minimum Inertia (MWs) → acceptable ROCOF
  - Inertia limits ROCOF
- Contingency size → increases ROCOF
- Linear dependency → H inertia constant (slide 4)

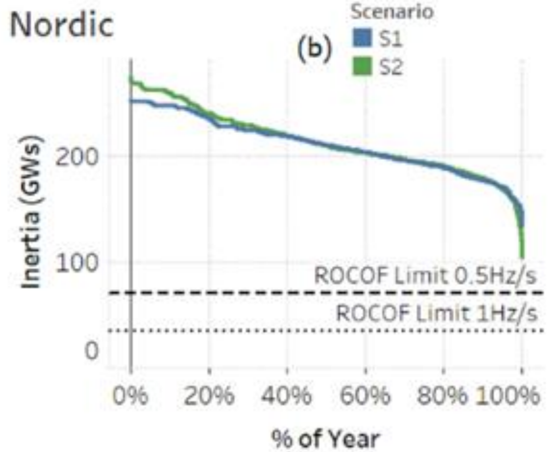


Initial RoCoF depends upon:

$$\text{RoCoF} = \frac{50\text{Hz}}{2} \times \left(\frac{\text{Contingency size (MW)}}{\text{System inertia (MW.s)}}\right)$$

Reduction of inertia

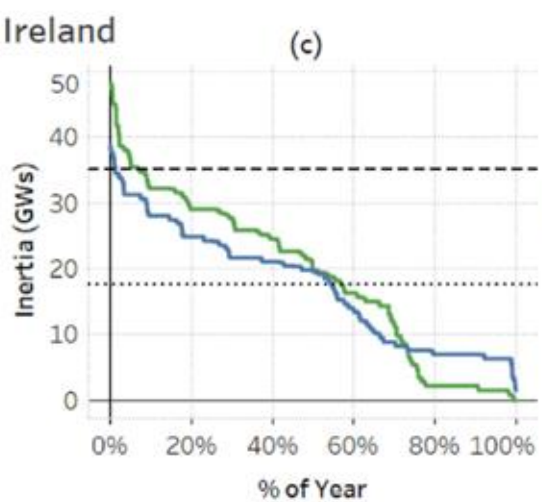


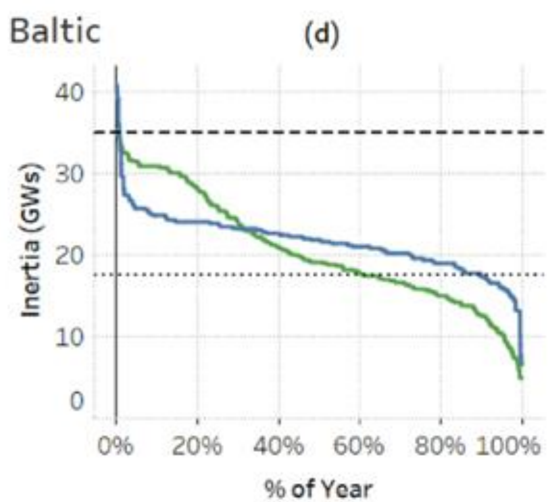


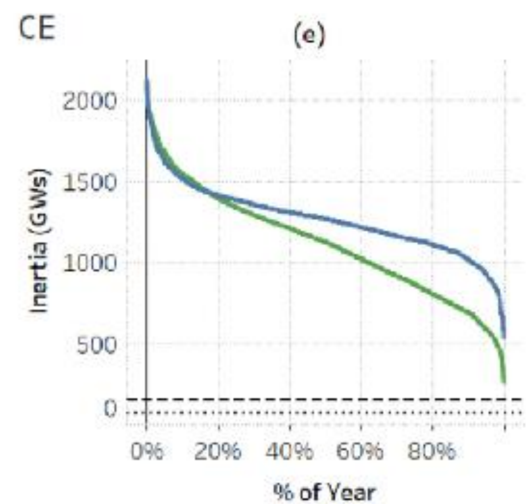
2 scenarios – difference in inertia

Scenario	1	2
Basis	ENTSOE Vision 1	ENTSOE Vision 4
Electricity Demand (TWh)	3434	3616
Variable Renewable Capacity (GW)	388	614
Fuel Prices (€/GJ):	9.5	7.2
Natural Gas	17.3	13.3
Oil	3.0	2.2
Coal		
CO_2 Prices (€/Tonne)	17	76
Merit Order	Coal before gas	Gas before coal

Y axis steps → system size
Limits for ROCOF depends on system size
CE&Nordic → ROCOF under 0.5 Hz/s
Other systems → restrictions apply

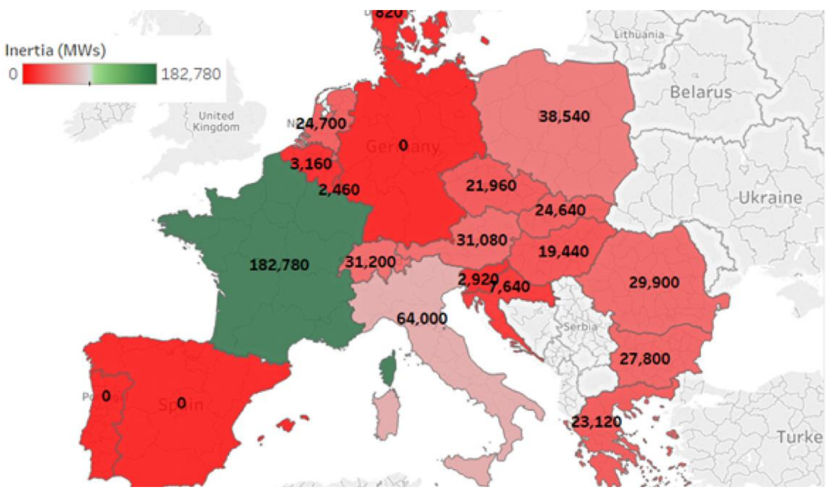


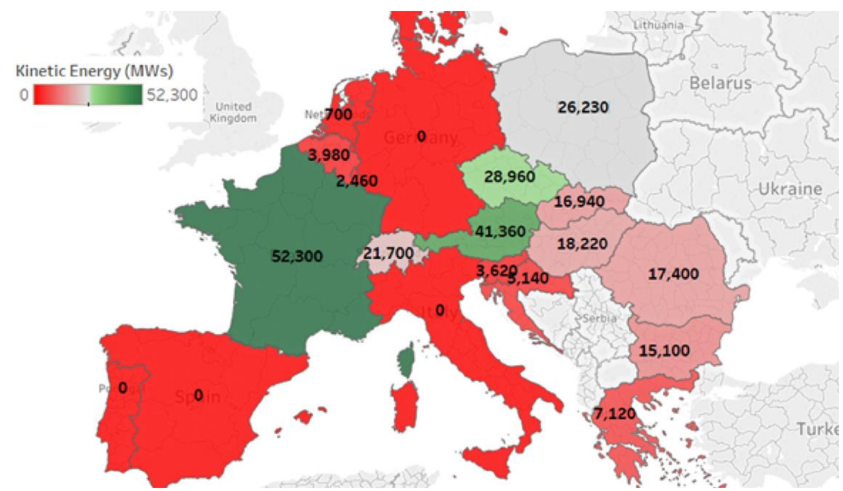




Reduction of inertia – CE trends

- Inertia by country in the CE
- Note that on the right the scale is ~1/3
- Zero values → worst case hour, then these coutries run 100% on wind+solar



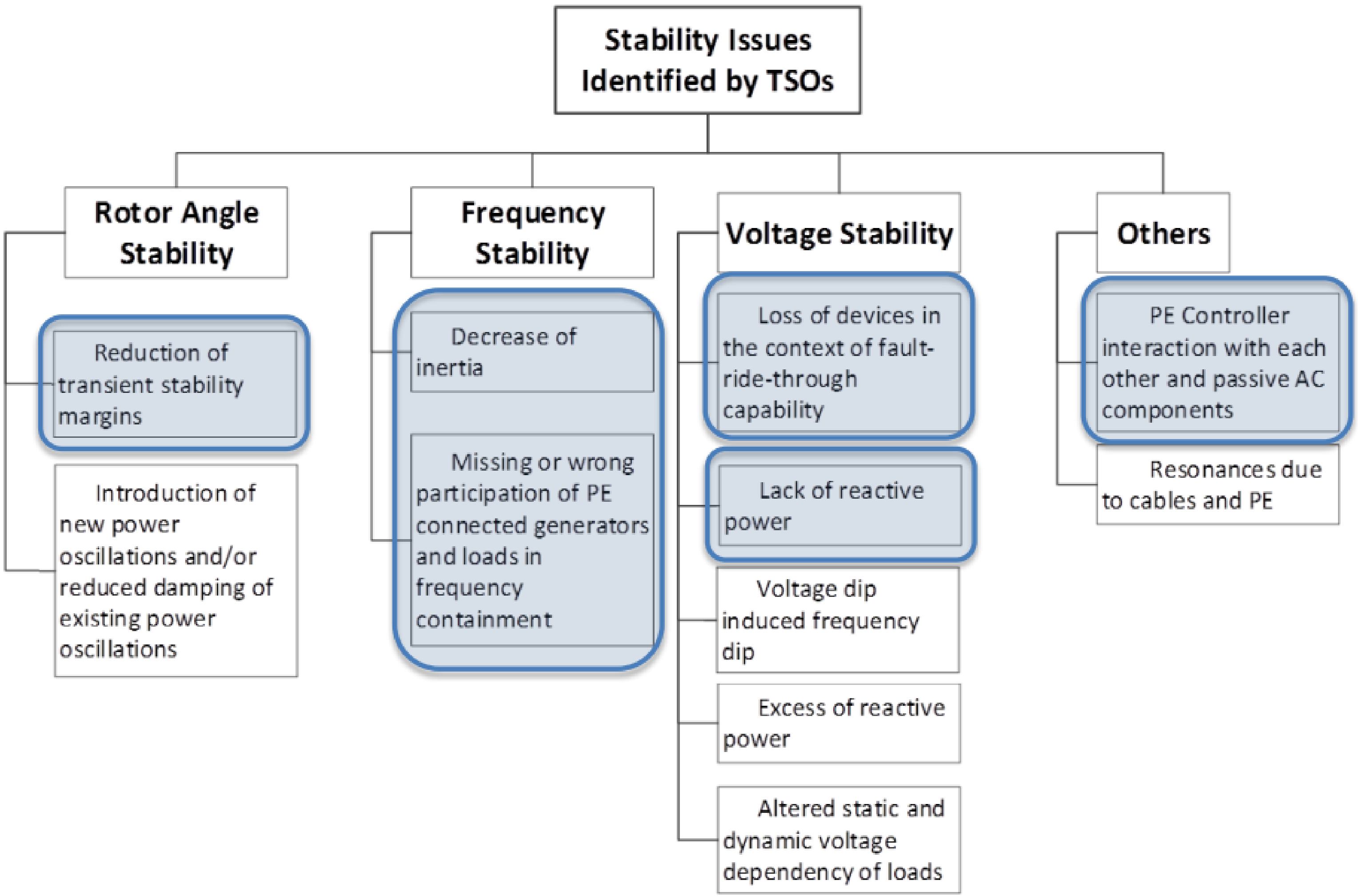


	Largest Infeed (MW)	Assigned minimum inertia for ROCOF limit of 1 Hz/s (MWs)	Assigned minimum inertia for ROCOF limit of 0.5 Hz/s (MWs)
CE	3000	75,000	150,000

ENTSO-E studies

- 2015-2017 → inertia reduction included in 3 key areas
  - Continetal Europe interconnected system analysis
  - Even with a normative incident of 3 GW generation loss, the system state not considered critical
  - In case of system split → frequency stability is critical
  - In case of 20% imbalance – 500 mHz/s – 1 Hz/s transients observed
  - Future system – 40% imbalance, 2 Hz/s gradient
- Analysis of 6 incidents (2003 ITA, 2006 GER, 2007 GRE, 2012 & 2015 TUR, 2016 AUS) → ROCOF over 1 Hz/s
  - East-West system split
  - Iberian Peninsula system split

MIGRATE H2020 Project



International practice

- Limits in the grid codes for ROCOF
  - Measured on 500 ms timeframe
  - 0,5-2 Hz/s
- Mitigation methods – technical/market
  - IRL/GB/AUS/NZL/Nordic/CE

- Great Britain – National Grid
  - 2015: 0.5 Hz/s technical condition assessment
  - Reserve needs could be 3-4 times as now
  - New products – e.g. Enhanced Frequency Response
- Ireland – EIRGRID&SONI
  - Different RoCoF constraints from 2010
  - 2016: system minimum kinetic energy definition

International practice

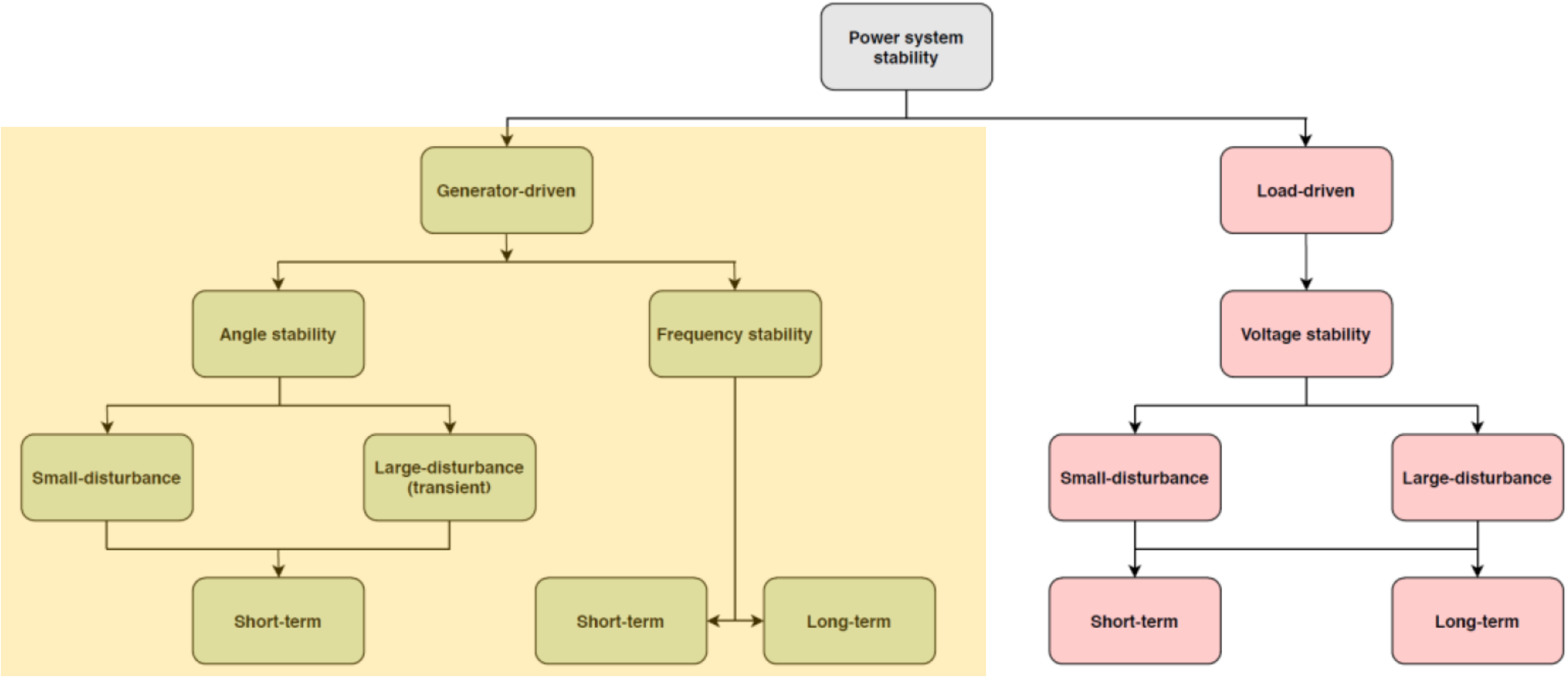
- Australia – AEMO
  - Major blackout in 2016: RoCoF limit proposition
  - New products – e.g. synthetic inertia, fast response regulation
- New Zealand
  - 2014: Revised load shedding scheme
  - Effect of wind turbines RoCoF extremis could double
- Nordic countries
  - 2013: online inertia estimation for all countries
  - 2016: modelling harmonization – no direct threat

Power system stability

- According to general definitions, an electric power system is stable if it has the "ability [...], for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact"

- Important aspects:
  - Parameter – frequency, voltage, angle etc.
  - Size of the disturbance
  - Calculation method

Stability categories



Classification by system size

System Size	Examples	Connections	Observation	Focus Area
Large scale, interconnected	Continental Europe, Nordic countries	Multiple AC connections within a synchronous area	Calculations do not show significant operational challenges, further studies on increasing non-synchronous share is in progress	System splits
Large scale, island	Ireland, Great Britain, Australia	No synchronous connection (only through HVDC or other converter solution) or very limited, weak connections	Calculations show operational challenges, TSOs already address solutions	Outages (HVDC, generator)
Small scale, island	Hawaii, Microgrids	No synchronous connection (only through HVDC or other converter solution), or very limited, weak connections	Wider limits, severe disturbances already observed, different measures for operation	Outages, faults

Mitigation possibilities - technical

- Synchronous condensers/compensators
- New controlling mechanisms
  - Fast Frequency Response
  - Synhtetic/artificial/augmented/virtual inertia
  - Exploitation of fast-acting technologies, such as storage
  - **Market based / connection or operation requirement?**
- Operation constraints
  - Minimum inertia requirements in system operation
- New protection schemes/integration of demand side response

Mitigation possibilities - market

- Ireland example

Short	Name	Response
New products		
SIR	Synchronous Inertial Response	Instant
FFR	Fast Frequency Response	2 s, 8 s duration
RM1	Ramping Margin 1 Hour	1 h, 2 h duration
RM3	Ramping Margin 3 Hour	3 h, 5 h duration
RM8	Ramping Margin 8 Hour	8 h
FPFAPR	Fast Post-Fault Active Power Recovery	250 ms after fault, 90% of rated power
Available products		
POR	Primary Operating Reserve	5-15 s (at frequency nadir)
SOR	Secondary Operating Reserve	15 s, 90 s duration
TOR1	Tertiary Operating Reserve 1	90 s, 5 min duration
TOR2	Tertiary Operating Reserve 2	5 min, 20 min duration
RRD	Replacement Reserve (De-synchronised)	20 min, 1 h duration
RRS	Replacement Reserve (Synchronised)	20 min, 1 h duration

Mitigation possibilities - market

- Texas example

Short	Name	Response time
SIR	Synchronous Inertial Response	instant
FFR1	Fast Frequency Response	0,5 s, 10 min duration
FFR2	Fast Frequency Response	0,5 s, unlimited
PFR	Primary Frequency Response	1,5 s, 16 s full activation, 1 h duration
Reg	Regulating Reserve	4-6 s, 5 min-ig full activation, 20 min duration
CRS	Contingency Reserve Service	5 min, 10 min full power, 1 h duration

Regulatory considerations

- Regulators should define and support the development of calculations and actions which allow significant renewable generation connection
- **Challenges depend on system size**
  - Large-interconnected – concentrate on system splits
  - Low level of interconnections – operation constraints even now
  - Microgrids – completely new area
- TSOs must assess the effects of the generation portfolio changes on **frequency stability** → ENTSO-E: 2 years
  - Long-term system adequacy plans
- **Toolsets** for TSOs
  - Piloting through sandboxes → technical viability
  - Market development → new products
  - Grid codes → system security ensured
- Development of technical calculation methods → research entities
- Technology providers → piloting in practice

References & readings

- Effects of decreasing synchronous inertia on power system dynamics—Overview of recent experiences and marketisation of services https://onlinelibrary.wiley.com/doi/full/10.1002/2050-7038.12128
- European Network of Transmission System Operators for Electricity (ENTSO-E): Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe – Requirements and impacting factors, 2016. https://www.entsoe.eu/Documents/SOC%20documents/RGCE_SPD_frequency_stability_criteria_v10.pdf
- European Network of Transmission System Operators – Electricity: Inertia and Rate of Change of Frequency (RoCoF), System Protection and Dynamics Inertia Task Force, 17. verzió, 2020. https://eepublicdownloads.azureedge.net/clean-documents/SOC%20documents/Inertia%20and%20RoCoF_v17_clean.pdf
- European Network of Transmission System Operators – Electricity: Frequency Stability in Long-term Scenarios and Relevant Requirements, Project Inertia Team, 2021. https://eepublicdownloads.azureedge.net/clean-documents/Publications/ENTSO-E%20general%20publications/211203_Long_term_frequency_stability_scenarios_for_publication.pdf
- https://www.h2020-migrate.eu/downloads.html
- https://www.sciencedirect.com/science/article/pii/S0360544220308835

Thank you for your kind attention!

István Táczi

Budapest University of Technology and Economics, Hungary

taczi.istvan@edu.bme.hu