THE NEGATIVE IMPACT OF VARIABLE RENEWABLE ENERGY (VRE) ON THE POWER SYSTEM STABILITY

THE RENAISSANCE OF SYNCHRONOUS CONDENSERS

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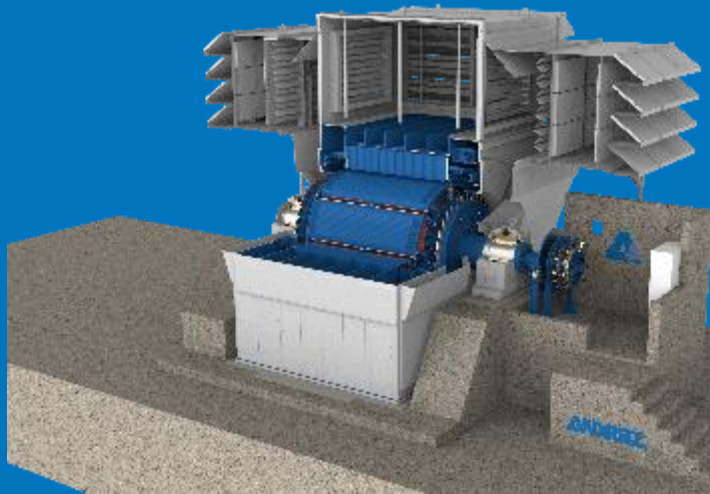
EnInnov2024
18. Symposium Energieinnovation | 14.02.-16.02.2024

ANDRITZ
ENGINEERED SUCCESS



AGENDA

01 SYNCHRONOUS GENERATION AND VARIABLE RENEWABLE ENERGY

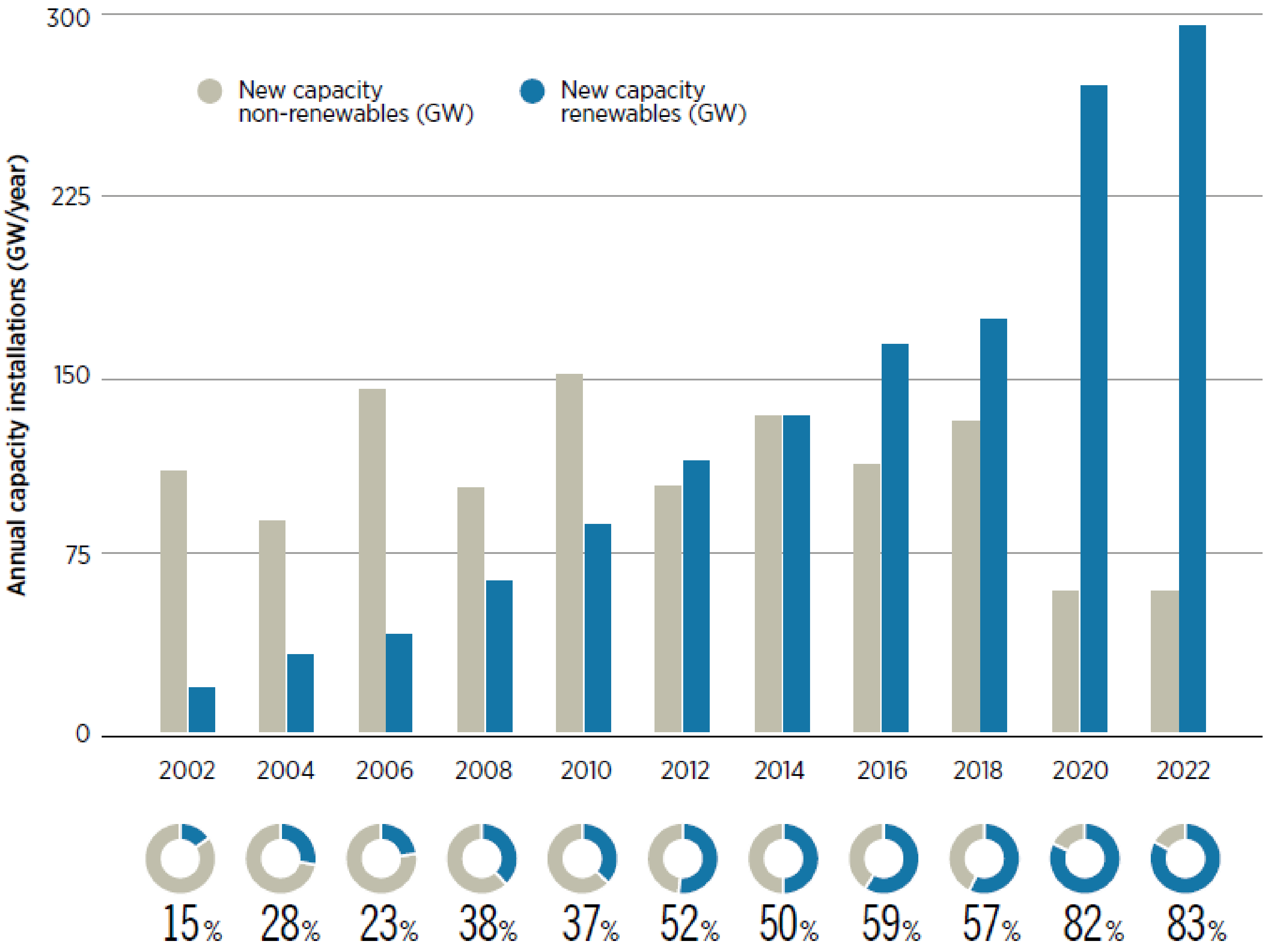
02 POWER SYSTEM STABILITY

03 CONTRIBUTIONS OF SYNCHRONOUS GENERATION AND SYNCHRONOUS COMPENSATION

04 SHOWCASES OF SYNCON SYSTEMS

ANNUAL POWER CAPACITY EXTENSION, 2002–2022

Source: IRENA, WORLD ENERGY TRANSITIONS OUTLOOK 2023



– Added capacity is **predominantly renewable**

– Mostly **Wind & PV**

– Therefore **synchronous generation diminishes** with each active Wind & PV power plant

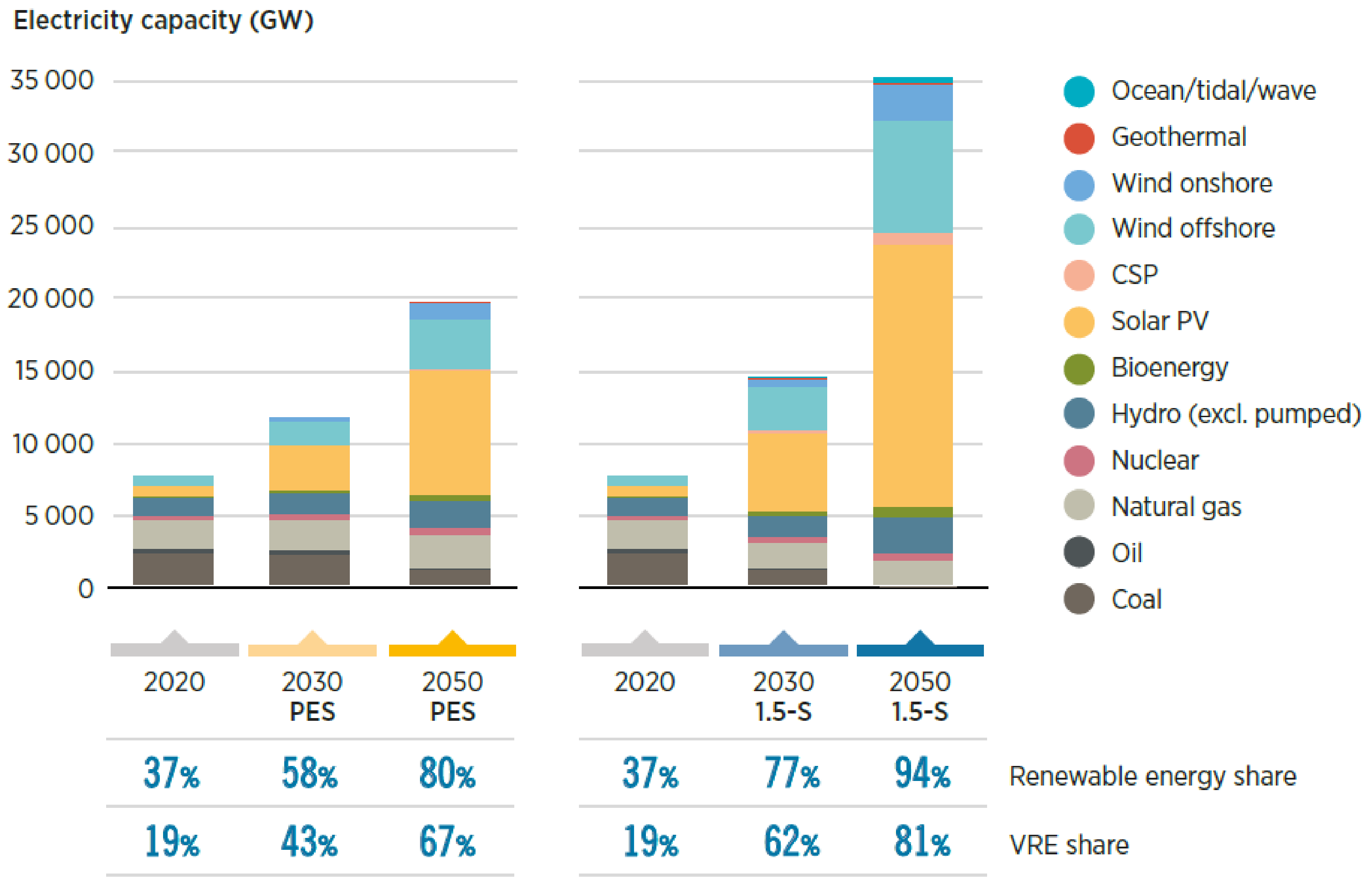
➔ **reduces INERTIA**

➔ **reduces SYSTEM STRENGTH**

(reduced Short Circuit Power)

GLOBAL INSTALLED CAPACITY OUTLOOK

Source: IRENA, WORLD ENERGY TRANSITIONS OUTLOOK 2023



Notes: 1.5-S = 1.5°C Scenario; CSP = concentrated solar power; GW = gigawatt; PES = Planned Energy Scenario; PV = photovoltaic; VRE = variable renewable energy; TWh = terawatt hour. Bioenergy includes biogas, biomass waste, biomass solid, and biomass solid CCS; CCS = carbon capture and storage.

– 1.5°C Scenario in 2020, 2030 and 2050

– Share of Variable Renewable Energy (VRE, SYNCHRONOUS generation with NO inertia) will increase significantly

2020: 19% VRE

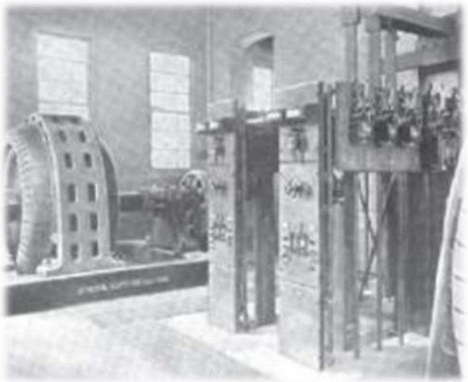
2030: 62% VRE

2050: 81% VRE

➔ **VALUE of low carbon synchronous machines will increase**

CHANGE IN SYNCHRONOUS GENERATION

Impact on they type of compensation needed



Synchronous Condenser 1911 – GE [now Andritz]

PAST
(>85% SYNCHRONOUS GENERATION)

DRIVER in grid stability service:

1. VAR compensation
2. VAR compensation
3. VAR compensation

SOLUTION:

1. (plenty of synchronous generation)
2. Synchronous condensers

Static VAR Compensator (SVC)

PRESENT
(>70% SYNCHRONOUS GENERATION)

DRIVER in grid stability service:

1. VAR compensation
2. Inertia
3. SCC (short circuit contribution)

SOLUTION:

1. STATCOM
2. Static VAR Compensator (SVC)
3. Synchronous condensers

FUTURE
(<35% SYNCHRONOUS GENERATION)

DRIVER in grid stability service:

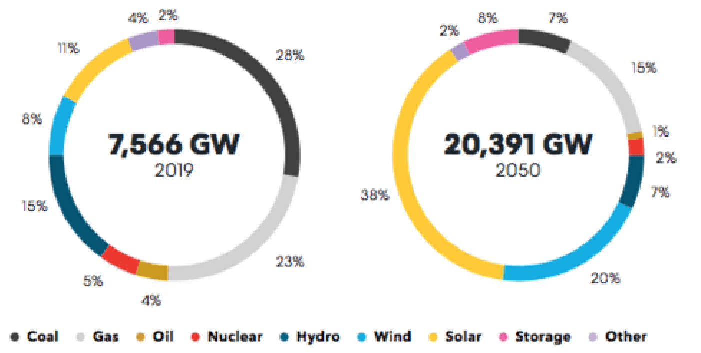
1. Inertia
2. SCC
3. VAR compensation

SOLUTION:

- Synchronous Condensers,
- Virtual inertia (e.g. grid forming inverters) with BEES
- Demand-side contributions (e.g. electric vehicles, smart load sheading – smart grid)
- …

BloombergNEF Outlook:

Figure 4: Global installed capacity mix, 2019 and 2050



Source: BloombergNEF

Huge reduction and high intraday fluctuation of synchronous generation with high penetration of wind and solar results in an unstable electricity grid:

➔ **less Inertia =** unstable system frequency

➔ **less SCC =** unstable system protection

➔ **risk of blackout**

Industry Trend:
Inertia (Low Carbon Inertia) and/or Short Circuit Contribution to become a traded auxiliary service in electricity grids (already the case in Ireland and Australia)

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POWER SYSTEM STABILITY

is determined by…

PHYSICAL CONFIGURATION

- Network topology
- Generation technology mix
- Generation dispatch
- Load side technology mix and DER
- Load size and location
- Device controls and settings
- Protection coordination
- Control system

POWER SYSTEM PROPERTIES

- Active and reactive power flows
- Active power reserves
- **Reactive power reserves**
- Load dynamics
- **Inertia**
- **Synchronizing torque**
- **Damping torque**
- Protection coordination
- **System strength**

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DEFINITION OF POWER SYSTEM STABILITY

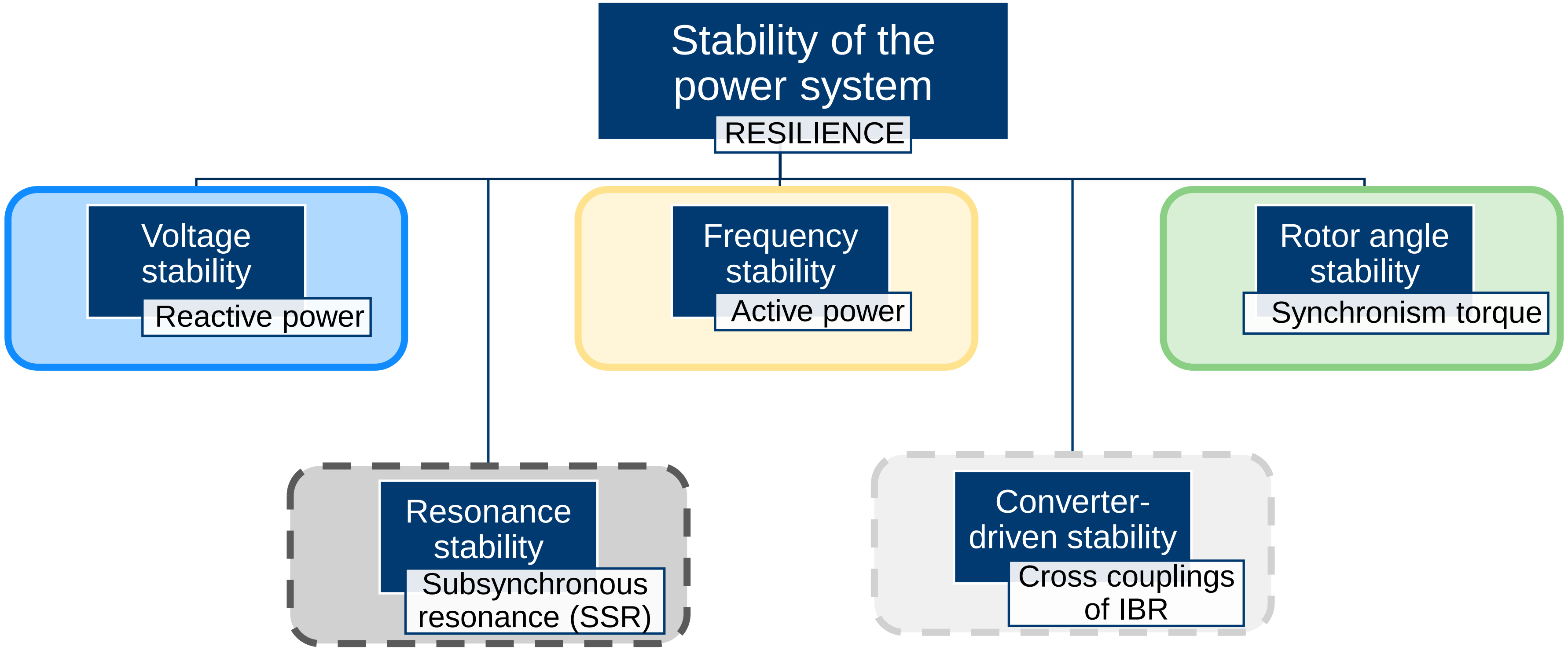
Power system stability is the ability of an electric power system, for a given initial operating condition, to **regain a state of operating equilibrium after being subjected to a physical disturbance**, with most system variable bounded so that practically the entire system remains intact.

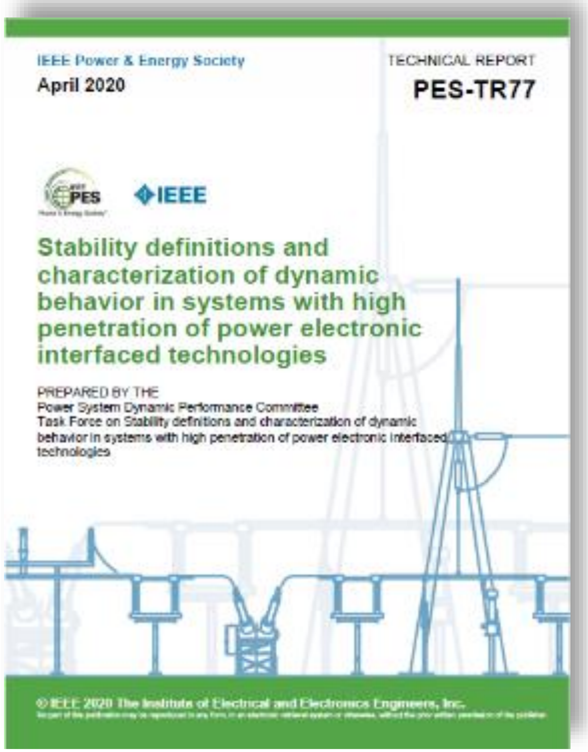
Source: IEEE PES-TR77

STABILITY OF THE POWER SYSTEM

Resiliency: The ability to maintain stability after faults and intended changes in the operation

IEEE added 2 new categories (dotted line) due to increased penetration of inverter based resources (IBR), i.e. power electronic converters





VOLTAGE STABILITY

= good system strength

Voltage stability
Reactive power

DEFINITION OF SYSTEM STRENGTH

System strength can broadly be described as the ability of the power system to **maintain and control the voltage waveform** at any given location in the power system, both during steady state operation and following a disturbance.
Three phase fault levels are used to define minimum system strength requirements, **measured in MVA**, which is proportional to the fault current (in Amps) and the voltage (in Volts).

Source: https://aemo.com.au/-/media/files/electricity/nem/system-strength-explained.pdf

CHARACTERISTICS OF LOW SYSTEM STRENGTH

– Mal-operation or failure of protection equipment to operate
– Prolonged voltage recovery after a disturbance
– Deeper voltage dips and higher over-voltages (e.g. transients)
– Larger voltage step changes after switching capacitor or reactor banks
– Wider area undamped voltage and power oscillations
– Generator fault ride-through degradation
– Instability of generator / dynamic plant voltage control systems
– Increased harmonic distortion (a by-product of low system strength and higher system impedances)

Source: https://aemo.com.au/-/media/files/electricity/nem/system-strength-explained.pdf

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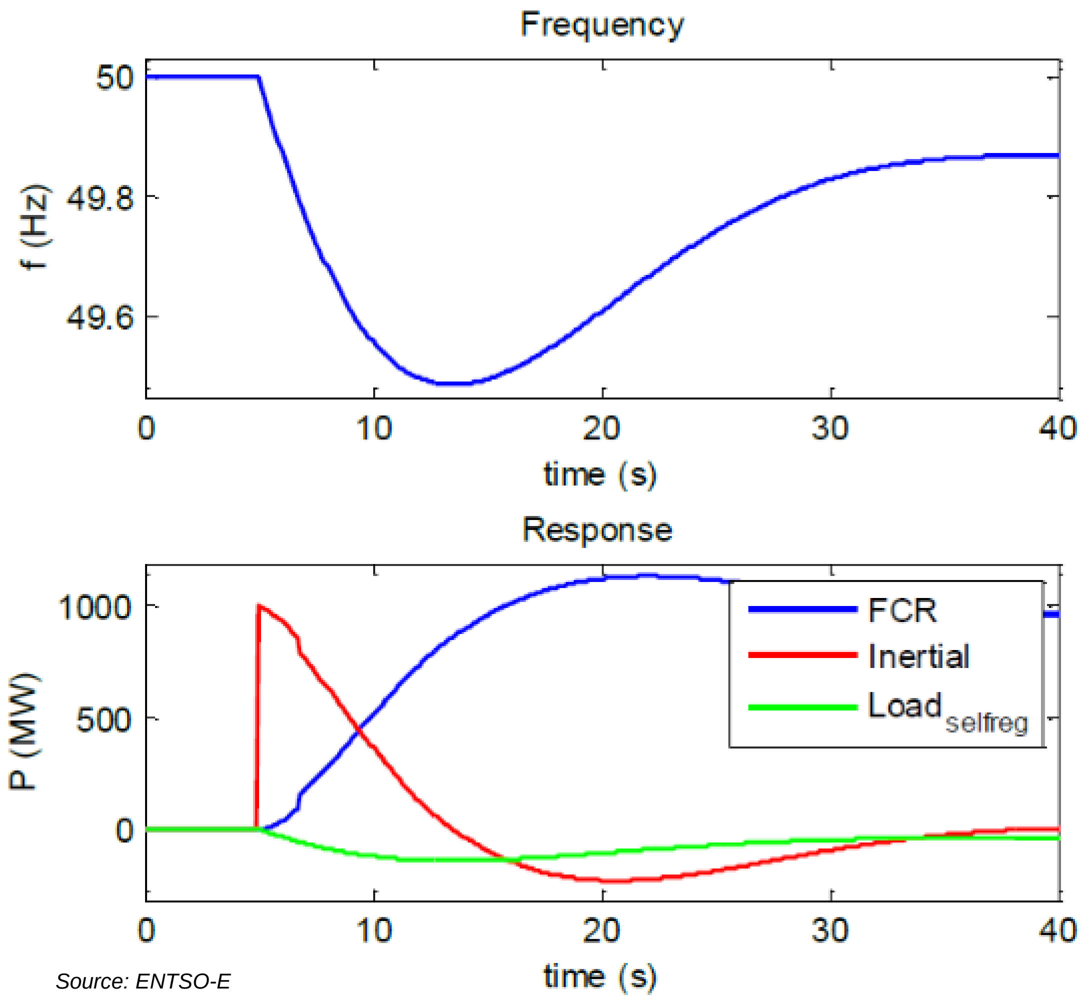
FREQUENCY STABILITY

Frequency stability
Active power

Why is inertia needed?
Inertia acts instantaneously before operating reserve can react



Source: ENTSO-E

DEFINITION OF INERTIA: a property of large **synchronous generators**, which contain **large rotating masses**, and which acts to **overcome the immediate imbalance** between power supply and demand for electric power systems, typically the electrical grid. (Source: Wikipedia)

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LACK OF INERTIA

– High RoCoF

– High frequency nadir

– Deterioration of fault detection

– Severe power system transients

– Inability to further integrate VRE (variable renewable energy)

INERTIA

Calculation of inertia

Inertia [Ws]

aka „kinetic energy“ aka „rotational energy“ aka „angular energy“

Symbol of inertia → KE or Ek or K or T

Unit of inertia → Ws or J (joules) or $\frac{kg.m^2}{s^2}$

Inertia formula

$$KE = \frac{J.\omega^2}{2}$$

Moment of inertia [kg.m²]

aka “mass moment of inertia” aka “angular mass”
aka “second moment of mass” aka “rotational inertia”

Symbol of moment of inertia → J or MR^2 or I or WR^2

Unit of moment of inertia → $kg.m^2$

Examples of Inertia for SynCon (ANDRITZ: 250 MVA)

Nameplate rating:	250 MVA
Q+:	250 MVAr
WR²:	350 000 kg.m²
rpm:	750 (8-poles)

$$KE = \frac{J.\omega^2}{2}$$

$$\omega = \frac{2.\pi.rpm}{60}$$

$$KE\ [Ws] = \frac{350\ 000\ [kg.m^2].(\frac{2.\pi.750}{60})^2}{2}$$

$$KE\ [Ws] = \frac{350\ 000 . 6\ 168.50}{2}$$

$$KE\ [Ws] = 1\ 079\ 487\ 500$$

$$\boldsymbol{INERTIA} = \textbf{1 079 MWs}$$

RATE OF CHANGE OF FREQUENCY (RoCoF)

Frequency stability
Active power

Swing equation

aka „frequency gradient”

Symbol ➔ RoCoF

Unit ➔ Hz/s or $\frac{\Delta f}{\Delta t}$

Swing equation

$$RoCoF = \frac{f_n . \Delta P}{2. KE_{sys}}$$

$f_n = \text{ system frequency}$

$\Delta P = \text{ size of contingency}$

$KE_{sys} = \text{ Kinetic engery of the total system}$

Example RoCoF: **small** generation plant trip

Contingency (ΔP): 50 MW
KE_{sys}: 50 GWs
System frequency: 50 Hz

$$RoCoF = \frac{f_n . \Delta P}{2. KE_{sys}}$$

$$RoCoF = \frac{50\ [Hz]. 50\ 000\ 000\ [W]}{2. 50\ 000\ 000\ 000\ [Ws]}$$

$$\mathbf{RoCoF = 0.025\ Hz/s}$$

Example RoCoF: **big** generation plant trip

Contingency (ΔP): 1 GW
KE_{sys}: 50 GWs
System frequency: 50 Hz

$$RoCoF = \frac{f_n . \Delta P}{2. KE_{sys}}$$

$$RoCoF = \frac{50\ [Hz]. 1\ 000\ 000\ 000\ [W]}{2. 50\ 000\ 000\ 000\ [Ws]}$$

$$\mathbf{RoCoF = 0.5\ Hz/s}$$

SYNCHRONOUS INERTIA RESPONSE (SIR)

Frequency stability
Active power

Calculation of SIR

Symbol ➔ SIR

Unit ➔ W

Swing equation variant

$$SIR = \frac{RoCoF.2.KE}{f_n}$$

$f_n = system\ frequency$

$RoCoF = Rate\ of\ Change\ of\ Frequency$

$KE = Kinetic\ engery\ (inertia)\ of\ SynCon$

Example SIR: **small** RoCoF

RoCoF:	0.1 Hz/s
KE:	1 079 MWs
System frequency:	50 Hz

$$SIR = \frac{RoCoF\ x\ 2\ x\ KE}{f_n}$$

$$SIR = \frac{0.1\ \left[\frac{Hz}{s}\right] x\ 2\ x\ 1079\ 000\ 000\ [Ws]}{50\ [Hz]}$$

$$SIR = 4\ 316\ 000\ W$$

$$SIR = \sim 4.3\ MW$$

Example SIR: **big** RoCoF

RoCoF:	0.5 Hz/s
KE:	1 079 MWs
System frequency:	50 Hz

$$SIR = \frac{RoCoF\ x\ 2\ x\ KE}{f_n}$$

$$SIR = \frac{0.5\ \left[\frac{Hz}{s}\right] x\ 2\ x\ 1079\ 000\ 000\ [Ws]}{50\ [Hz]}$$

$$SIR = 21\ 580\ 000\ W$$

$$SIR = \sim 21.6\ MW$$

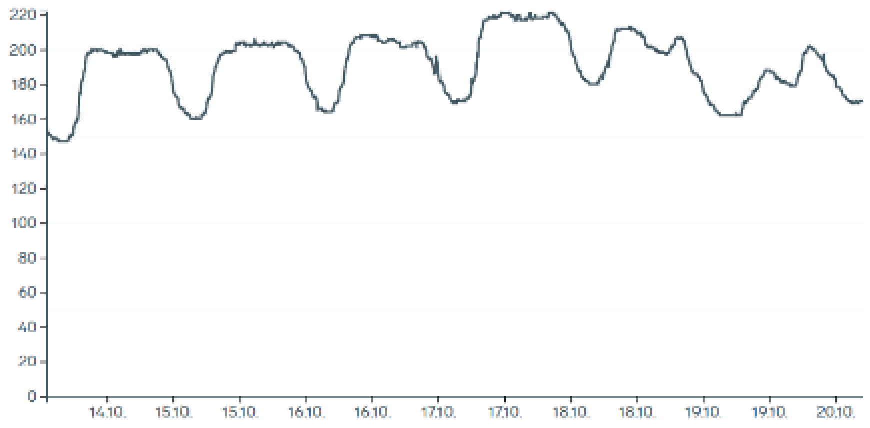
INERTIA IS NOT CONSTANT!

Frequency stability
Active power

The system inertia depends on the generation mix in the system!

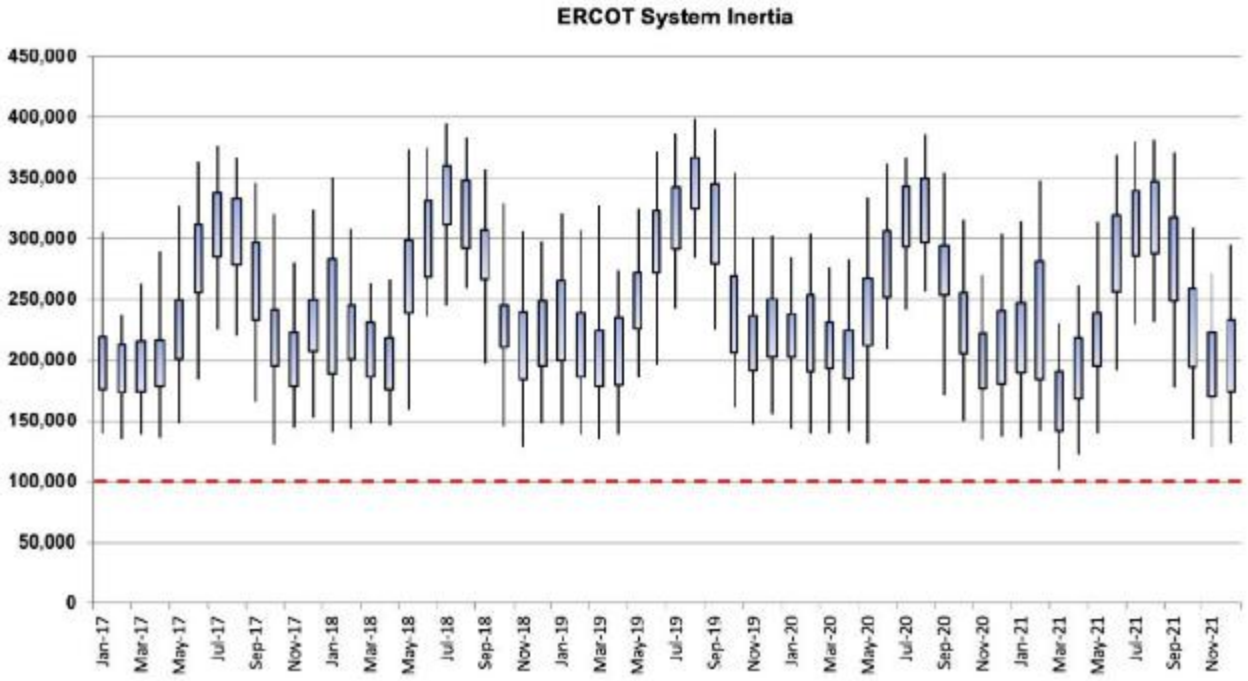
Example from **Nordic Power System (Europe)**

- **6 days** (14.10.2019 - 20.10.2019)
- Minimal Inertia: 147 GWs
- Maximum Inertia: 222 GWs
- Average Inertia: 191 GWs



Source: https://www.fingrid.fi/en/electricity-market/load-and-generation/InertiaofNordicpowersystem/

Example from **ERCOT (USA), 2017 – 2021**



Source: TEXASRE, 2021 Assessment of reliability performance

- **Increasing PV / Wind generation is causing increased volatility of system inertia**

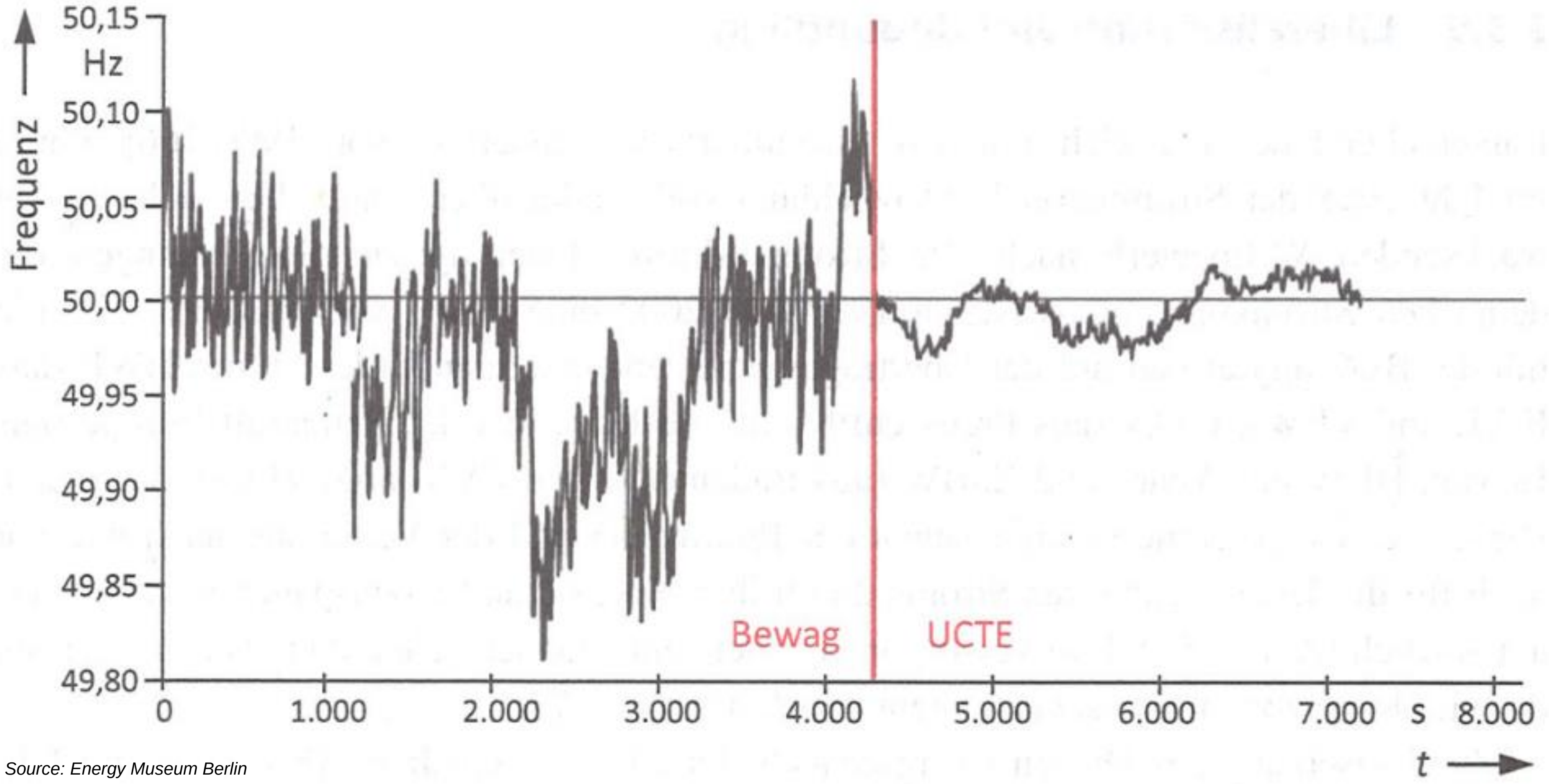
  ➔ **Requirement for fast control reactions is increasing**

- **<u>Synchronous condensers can reduce the inertia volatility</u> thereby reducing control reactions**

INERTIA EXAMPLE

December 1994: Interconnection of West-Berlin grid to the western European UCTE grid

Frequency stability
Active power



Source: Energy Museum Berlin

ROTOR ANGLE STABILITY

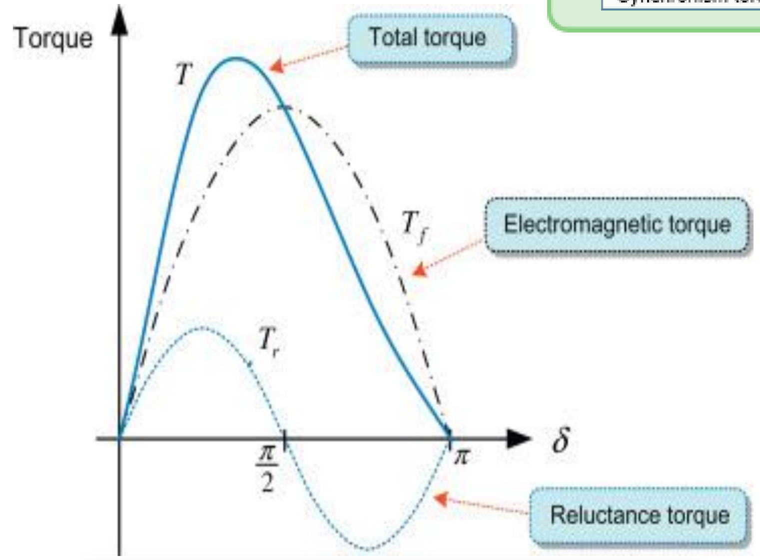
Rotor angle stability
Synchronism torque

This type of stability depends on the ability of the synchronous machines to maintain or restore the equilibrium

Stable and well-damped response of the system can be ensured through the existence of sufficient positive **synchronizing torque** and **damping torque**:

– Salient pole synchronous machines (Hydro) have **higher synchronizing torque** than cylindrical rotor machines (Thermal).
A cylindrical rotor machine does basically not have reluctance torque because of round magnetic field. Therefore, the total torque at same load angle is higher for salient pole machines.

– Salient pole synchronous machines (Hydro) have **higher damping torque** than cylindrical rotor machines (Thermal).
The damping torque is mainly provided by the damper windings. Due to the pole design of salient poles the damper winding can be built bigger and more robust, therefore the salient pole design has a better damping function.



ANDRITZ damper winding design: very robust, integrated, interconnected

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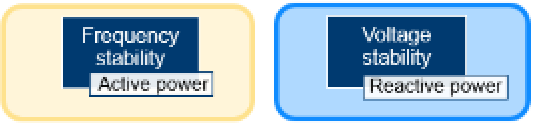
CONTRIBUTIONS OF SYNCHRONOUS GENERATION AND SYNCHRONOUS COMPENSATION



1. Frequency stability ≙ ***INERTIA [MWs]***

– instantaneous **active power** supply at **grid disturbance** (load or generation trip)

2. Transient Voltage stability

– instantaneous **reactive power** supply at **grid disturbance** (during short circuit)

- ➢ ≙ ***Short Circuit Contribution – SCC [MVA]***
- ➢ X''d (sub-transient reactance)

– fast **reactive power** supply at **grid disturbance** (after short circuit, once fault is cleared)

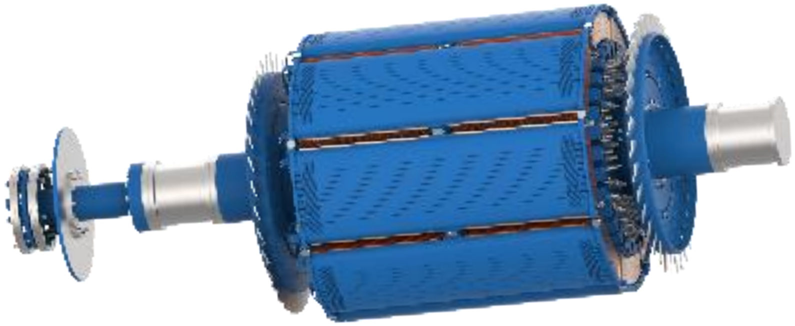
- ➢ Dynamic voltage recovery [MVA]
- ➢ X'd (transient reactance) and fast excitation control

3. Steady-state Voltage stability

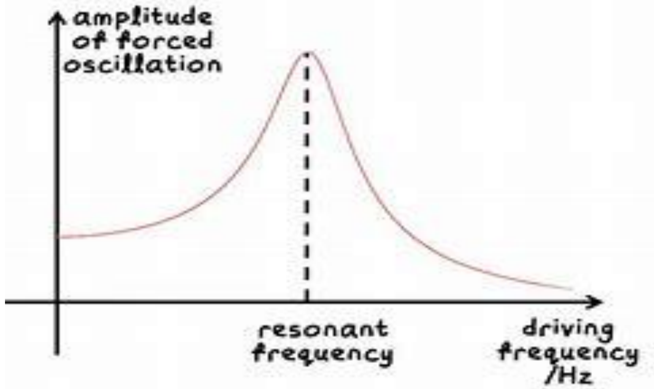
– controlled **reactive power** supply at **normal grid operation**
(diurnal load changes / VRE generation profile changes)

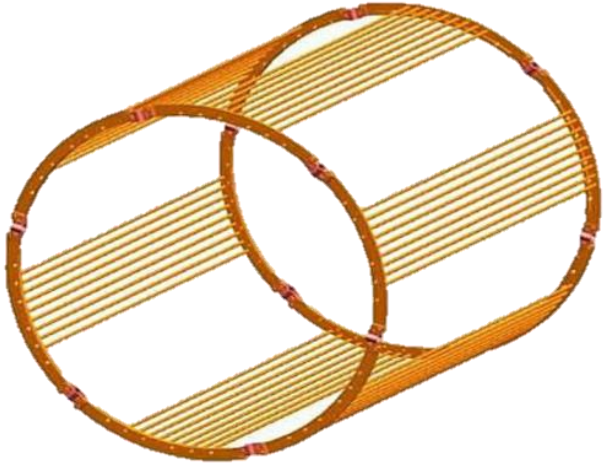
- ➢ ≙ ***reactive power [MVAr]*** injection Q+ (raises voltage) or absorption Q- (lowers voltage)

MAIN ADVANTAGES OF SALIENT POLE DESIGN
(COMPARED TO CYLINDRICAL ROTOR DESIGN)



1. **Higher natural inertia**
   – 2 to 3 times higher
2. **Better dynamic behaviour during system faults**
   – Higher total synchronization torque (because of additional reluctance torque)
   – Higher moment of inertia
   – Bigger and more robust damper winding design ➔ higher damping torque
3. **Enhanced under-excited range**
4. **Design speed is below critical bending speed**





ANDRITZ damper winding design: very robust, integrated, interconnected

INERTIA

Salient pole design vs. cylindrical rotor design – **EXAMPLE 165 MVAr SynCon**

Frequency stability
Active power

ANDRITZ salient pole: 165 MVAr

Nameplate rating:	165 MVA
Q+:	165 MVAr
Q-:	120 MVAr
WR^2:	250 000 kg.m^2
rpm:	750 (8-poles)

$$KE = \frac{J.\omega^2}{2}$$

$$\omega = \frac{2.\pi.rpm}{60}$$

$$KE\ [Ws] = \frac{250\,000\ [kg.m^2].(\frac{2.\pi.750}{60})^2}{2}$$

$$KE\ [Ws] = \frac{250\,000\ .\ 6\,168.50}{2}$$

$$KE\ [Ws] = 771\,062\,500$$

$$\boldsymbol{INERTIA} = \textbf{771 MWs}$$

Typical cylindrical rotor competition: 165 MVAr

Nameplate rating:	200 MVA
Q+:	165 MVAr
Q-:	93 MVAr
WR^2:	7 325 kg.m^2
rpm:	3000 (2-poles)

$$KE = \frac{J.\omega^2}{2}$$

$$\omega = \frac{2.\pi.rpm}{60}$$

$$KE\ [Ws] = \frac{7\,325\ [kg.m^2].(\frac{2.\pi.3\,000}{60})^2}{2}$$

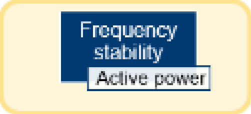
$$KE\ [Ws] = \frac{7\,325\ .\ 98\,696.04}{2}$$

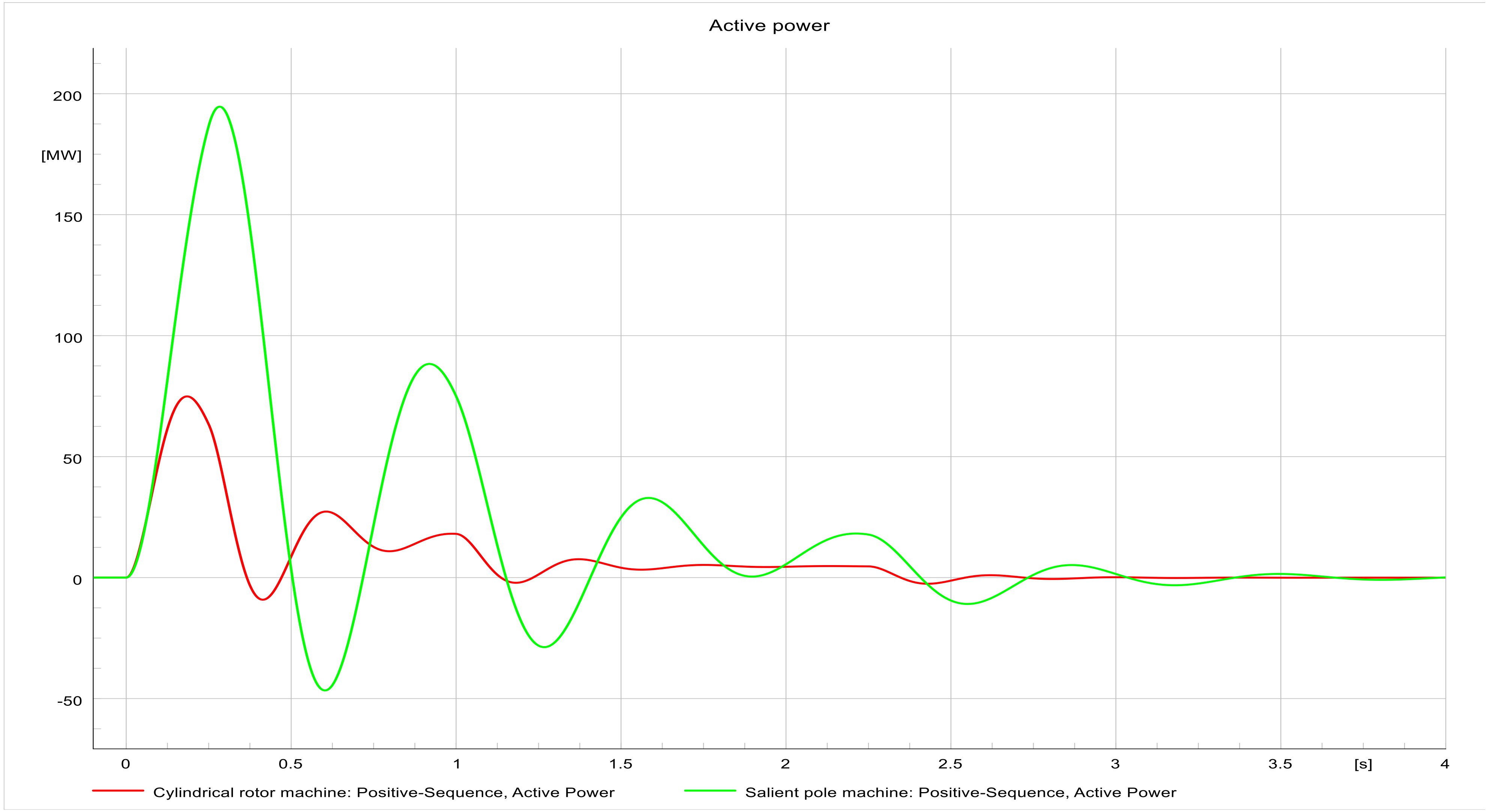
$$KE\ [Ws] = 361\,474\,261$$

$$\boldsymbol{INERTIA} = \textbf{361 MWs}$$

INERTIA

Salient pole design vs. cylindrical rotor design – **EXAMPLE 165 MVAr SynCon**





SYNCON VS. OTHER COMPENSATION EQUIPMENT

		Salient Pole Synchronous Condenser Systems	STATCOM Static synchronous compensator	SVC Static VAR compensator	GRIDFORMING SOLUTION (STATCOM incl. BEES / supercapacitor, or VRE power plants with active power headroom)
Technical Performance	*Inertia*	✓✓ (high natural inertia with salient pole design)	✗✗ (no inertia provided)	✗✗ (no inertia provided)	✓✓ (inertia can be controllable)
	Short circuit contribution	✓✓ 3 - 5 p.u.	✗✗ (1.2 p.u.)	✗✗	✗✗ (1.2 p.u.)
	Dynamic reactive response	✗	✓✓	✓	✓✓
	Static VAR compensation	✗	✓✓	✓	✓✓
	VAR supply at low voltage	✓✓ can increase reactive current when voltage decreases	✗ linear dependency: VAR output - system voltage	✗✗ quadratic dependency: VAR output - system voltage	✗
	Low Voltage Fault Ride Through (LVFRT)	✓	✗	✗	✗
	Harmonics mitigation	✓✓	✓	✗	✓
	Transient distortion (switching transients)	✓ No switching transients	✗ Switching transients due to power electronic circuit	✗ Switching transients due to power electronic circuit	✗ Switching transients due to power electronic circuit
Others	*Useful economic life*	✓ > 40 years	✗	✗	✗
	Losses	✗	✓	✓	✓
	Footprint	✓	✓	✗	✓
	Noise	✗	✓	✓	✓
	Maintenance effort	✗	✓	✓	✓
	CAPEX	✗	✗	✓	✗✗

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SYNCHRONOUS CONDENSER REFERENCES
(SELECTION)

Greenfield: EnergyConnect project / Australia / order: 08/2021

Customer:	**Secure Energy JV**
Quantity:	4 units @ Buronga & Dinawan substations 330 kV
Commissioning:	2023 / 2024
Output:	120 MVA, +100 / -50 MVAr @ 12.0 kV
Overload:	**200% of rated MVAr for 10s**
Speed:	750 rpm (8-pole salient)
Inertia time const.:	**7s (natural)**

Scope of Supply

- Synchronous Condenser, TEWAC
- MV & LV auxiliary equipment
- Power transformers, SFC, IPB, GCB
- HV connection to PCC
- Excitation, protection, measuring, synchronization and automation
- Transport, erection, commissioning
- Long Term Maintenance Agreement (LTMA) in a separate contract

Major features

Enhance system strength in the Transgrid synchronous area

Project EnergyConnect

ElectraNet TransGrid

SYNCHRONOUS CONDENSER REFERENCES (SELECTION)

Greenfield: ARARAT/ Australia / order: 08/2023

Customer:	**Australian Energy Operations / BEON**
Quantity:	1 unit @ Ararat substation 230 kV
Commissioning:	2025
Output:	250 MVA, +225 / -190 MVAr @ PCC, Un: 15.5 kV
Short circuit contr.:	1050 MVA
Speed:	750 rpm (8-pole salient)
Inertia time const.:	4.7 s (natural)

Scope of Supply

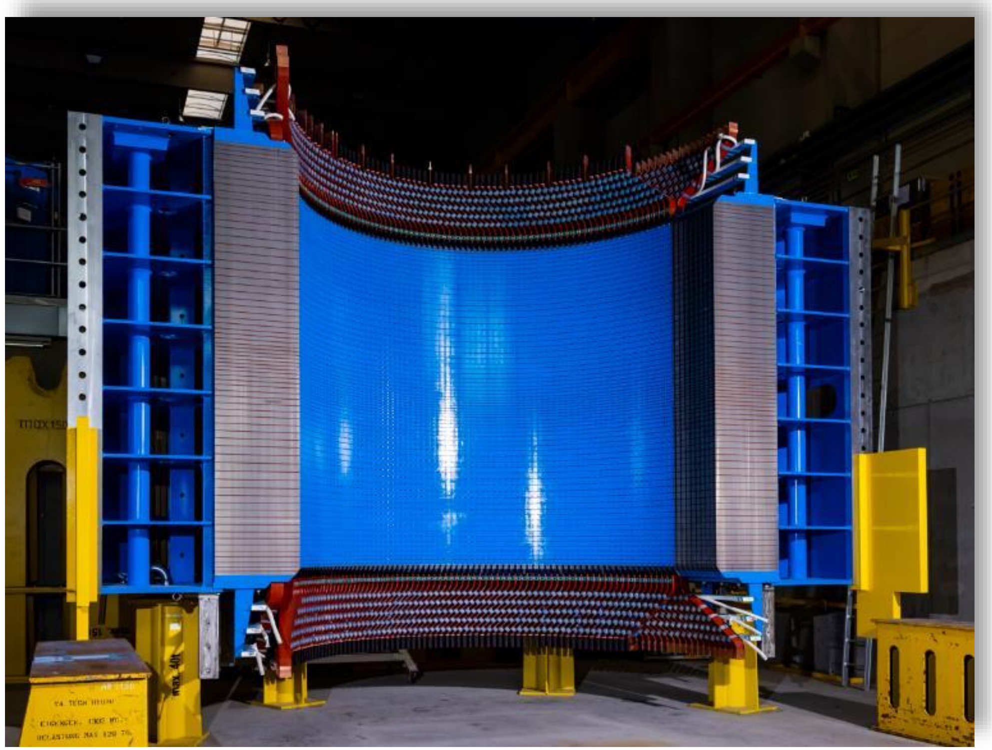
- Synchronous Condenser, TEWAC
- MV & LV auxiliary equipment
- Power transformers, SFC, IPB, GCB, HV connection to PCC
- Excitation, protection, measuring, synchronization and automation
- Transport, commissioning
- Long Term Maintenance Agreement (LTMA) in a separate contract

Major features

- **World's largest [MVAr] air-cooled salient pole synchronous condenser**
- Enhance System Strength in the Western Victorian Transmission Network

beon Energy Solutions

Australian Energy Operations



generic image – one half of a split stator after assembling in Austrian shopfloor

THANKS

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