Paris Session 2022

Guide on the Assessment, Specification and Design of Synchronous Condenser for Power System with Predominance of Low or Zero Inertia Generators

A1/C4 WG, JWG66

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SPEAKERS

D K Chaturvedi (India)
Fellow Member, CIGRE Paris
Convener of this JWG on Synchronous Condenser specifications
Convener of TB 724 published in 2018
Retired as General Manager (Electrical) from NTPC India, 70GW Power Generation company.

Fabian Spescha (Australia)
Mr. Fabian Spescha is currently Stream Lead Power System Analysis and the leader of the Australian Energy Market Operator (AEMO) task force looking into synchronous condensers operation and future requirements for the Australia power grid. AEMO is responsible for the Australian power grid stretching from Northern Queensland to South Australia as well as Western Australia.

Dr Fabian Koehler (Scotland)
Dr Fabian Koehler got his doctorate from the Heriot-Watt-University, Edinburgh, UK in 2018. He is Lead Subject Matter Expert working in SSEN transmission. He is responsible for transmission network design, FACTS and Synchronous Condensers.

Introduction

- This JWG planned in CIGRE session 2018 and TOR was approved in Jan 2019.
- This guide is prepared by a group of 42 experts from 18 countries. Our team of experts are from academia, generator manufacturers, TSOs and utilities.
- The tutorial will cover
  - Overview of large scale renewable power addition - DKC
  - Synchronous condenser performance - Spescha
  - Synchronous condenser case studies - Spescha
  - Synchronous condenser specifications - DKC
  - Synchronous condenser retrofit solution - DKC
  - Synchronous condensers installations - Dr Koehler

Background: Power Generation Transition

- 1kW-Hr electricity generated from thermal power plant release 855 grams of CO2.
- A 4000MW Coal based power plant burn Coal and releases every hour 3500 Tons CO_2 .
- On annual basis this size power plant produces 28 million tons of CO2,
- In order to lower Green House Gas emissions, worldwide trend is to increase Renewable Power Generation and retire fossil fuel-based power plants.

Transition towards solar and wind power generation

- As part of carbon emission reduction initiatives, Wind and Solar based power generation have proven to be the most economical choices.
- They have been deployed both at transmission (large solar park or wind farm) and distribution voltage levels (rooftop solar).
- Battery systems are also deployed increasingly to provide large-scale energy storage.

Solar and wind power generation - Issues

- Power generation depends on solar radiation level and wind speed, and so variable and intermittent in nature.
- Load and power generation patterns are different, makes energy dispatch difficult.
- The peak electrical demand may not coincide with the peak electrical generation.
- Also, the displacement of synchronous machines with power electronic (PE) interfaced energy sources has impacted power system steady-state and dynamic behaviour.
- This transition has resulted in
  - **Reducing levels of system inertia.**
  - **Reducing levels of system strength.**
  - **Reduced overload capability.**

Power generation technology transition

The high speed turbine driven machines, support the electrical network for inertia and also support short circuit power.

- In case of any system frequency deviation, the machine inertia resist the change and limits the rate of change of frequency (RoCoF). Higher the inertia, lower will be the RoCoF.
- The machine sub transient reactance plays important role to provide instantaneous very high fault current and thus facilitates operation of the protection system.
- In case of any fault, the same can be cleared by protection system, as fault current is much higher than the rated current (say 3-4 times of rated current). However as fault current in solar plant inverter is limited to 1.4 times rated current, it may not be able to cleared the fault with conventional protection system.

General comparison of various reactive power devices

SOLUTION	VAR SUPPORT	Dynamic VAR Support	Overload	Short Circuit Duty	Inertia
Capacitors	Weak	No	No	No	No
SVC	Weak	Yes	No	No	No
STATCOM	Strong	Yes	No	No	No
Synchronous Condensers	Strong	Yes	Yes	Yes	Yes

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SYNCHRONOUS CONDENSER PERFORMANCE

By Fabian Spescha

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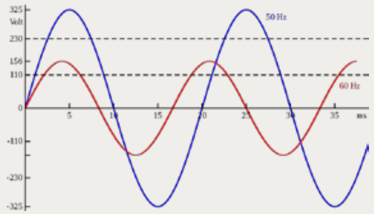
For power system expertise

Performance based on operational and design parameters

- Key performance indicators of any power systems are:
  - Frequency (stability, resilience and quality)
  - Voltage (stability, resilience and quality)



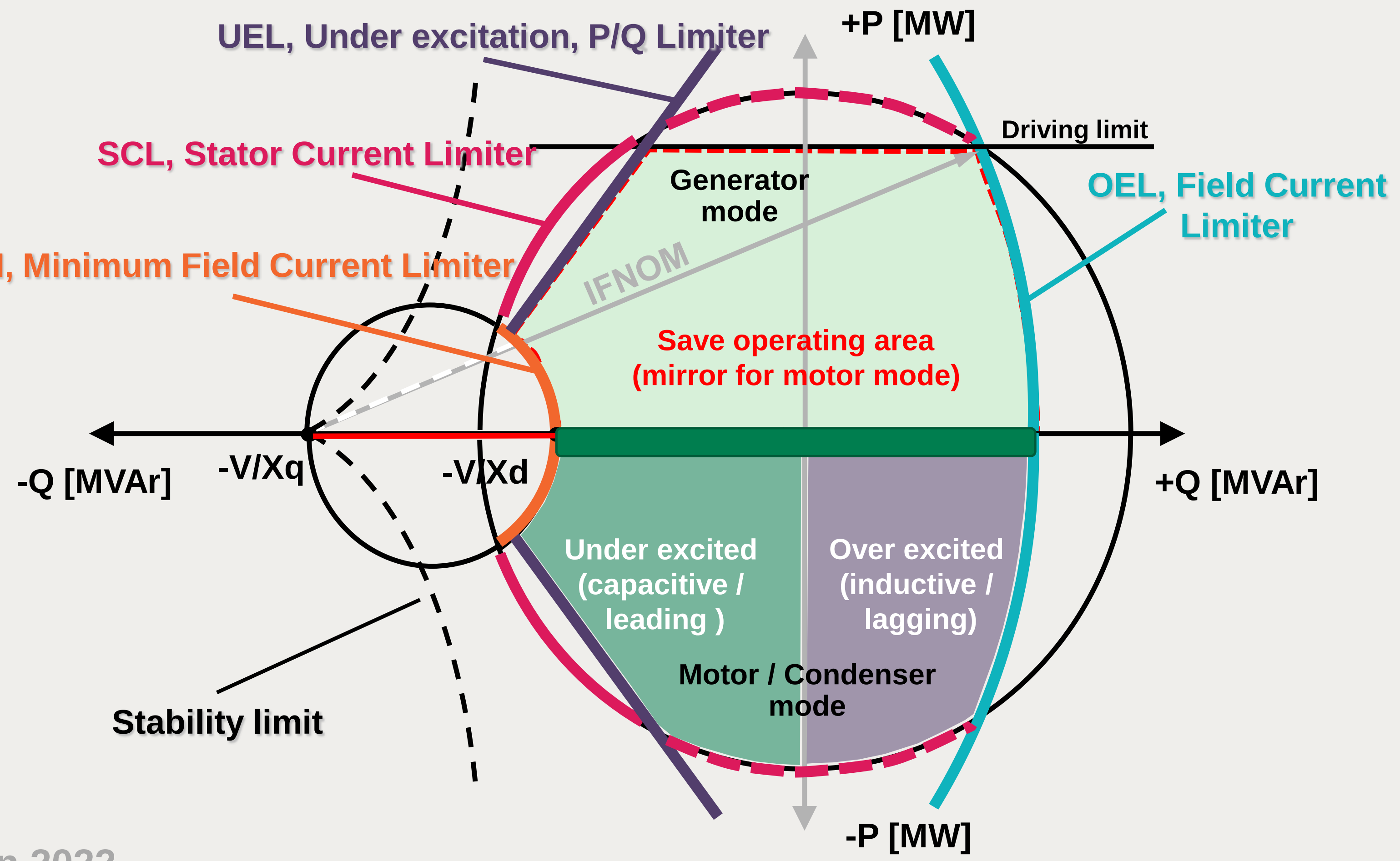
- Synchronous condenser performance is directly linked to operation and design parameters and main criteria's are:
  - Reactive capabilities
  - Reactance / Fault level
  - Transient stability
  - Inertia & Frequency

Attribute	Synchronous generator	Synchronous condenser
System strength	✓	✓
Inertia	✓	✓ (could vary substantially)
Voltage control	✓	✓ (trends in reduced losses and voltage control capability)
Frequency control	✓	✗
Continuous energy	✓	✗

Understanding Reactive Power

- Reactive **power ensures efficient transport of real power to load center**.
- Reactive support required for Inverter Based Resource (IBR) power plants and HVDC terminal.
- **Solar and Wind-based IBR can consume large amount of reactive power required to energise inverters**.
- Rooftop/DER generation also **withdraw large reactive power to charge solar inverters** and may overload distribution network and associated transformers.

Reactive Power capability of rotating machines



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Grid code requirements - Specified in different countries

Code	Reactive requirement specified location	Reactive power range (p.u. of rated output)	Equivalent full load p.f.
Denmark	Point of connection of the grid	-0.33 to 0.43	0.95 to 0.9
Germany	Grid connection point (transmission code)	-0.228 to 0.48 -0.33 to 0.41 -0.41 to 0. 0.33	0.975 to 0.9 0.95 to 0.925 0.925 to 0.95
UK	Grid entry point	-0.33 to 0.33	0.95
Ireland	LV side of grid transformer	-0.33 to 0.33	0.95
Spain		-0.3 to 0.3	
Texas	Point of interconnection		0.95
Alberta	Low voltage side of the transformer		0.95 to 0.9
Québec	HV side of transformer at the point of interconnection		0.95
Ontario	Connection point	-0.33 to 0.33	
Australia	Connection point	-0.395 to 0.395	

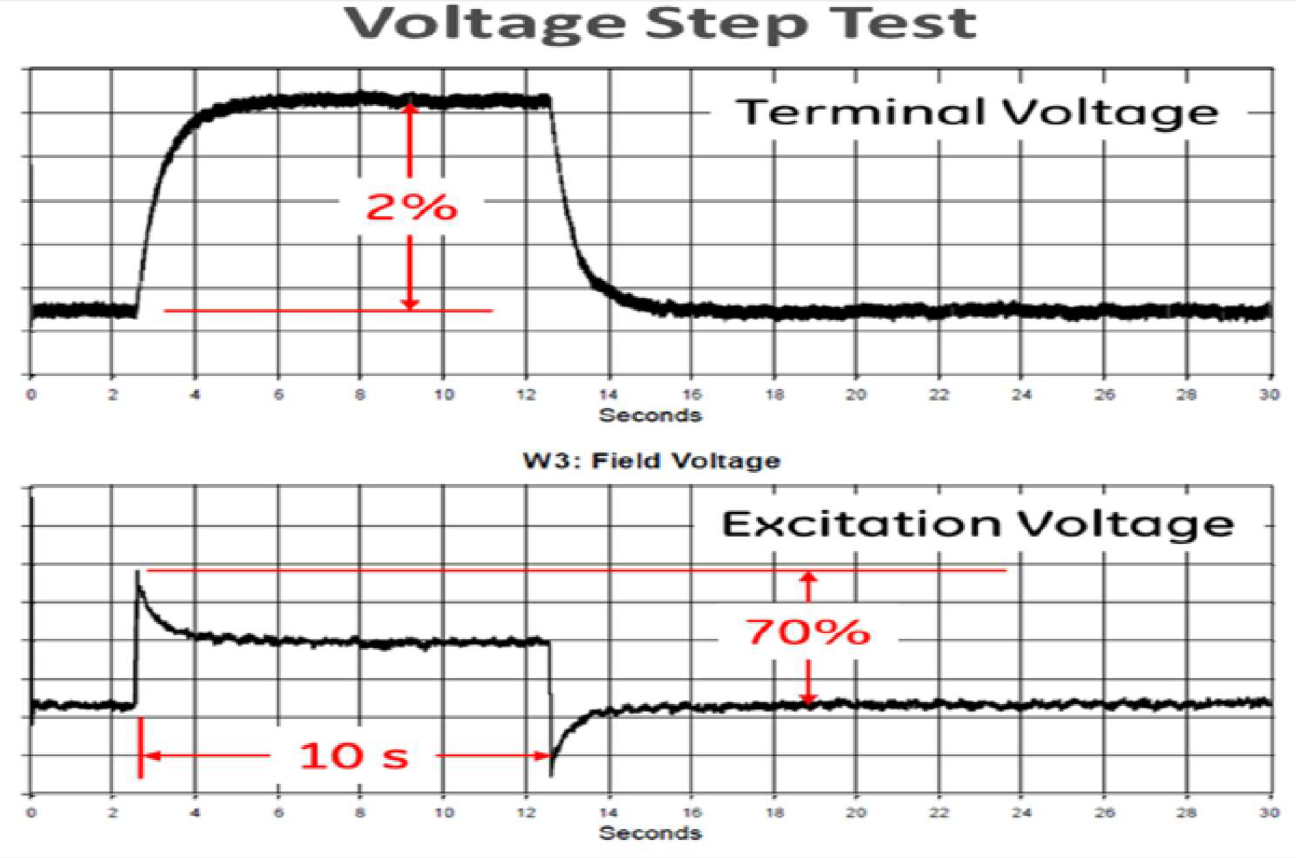
Depending on the network requirements, one of the 3 variants provided by the German grid code is selected by the TSO

Meeting Reactive Power support requirement

- The reactive power support can be done either by a Static Device e.g. **SVC, STATCOM** or rotating machine i.e. **Synchronous Condenser (rotating synchronous machine connected to grid and disconnected with turbine)**.
- In the event of a fault, static device output at low voltage is reduced drastically, **SVC output reduces as V^2** , STATCOM output reduces in proportion to V.
- Contrary, the output of Synchronous condenser is increased at low voltage to support grid with additional reactive power.
- The response of Synchronous Condenser is rather fast (as shown in next slides).
- Thus **Synchronous Condenser are selected to support Dynamic Voltage Stability.**

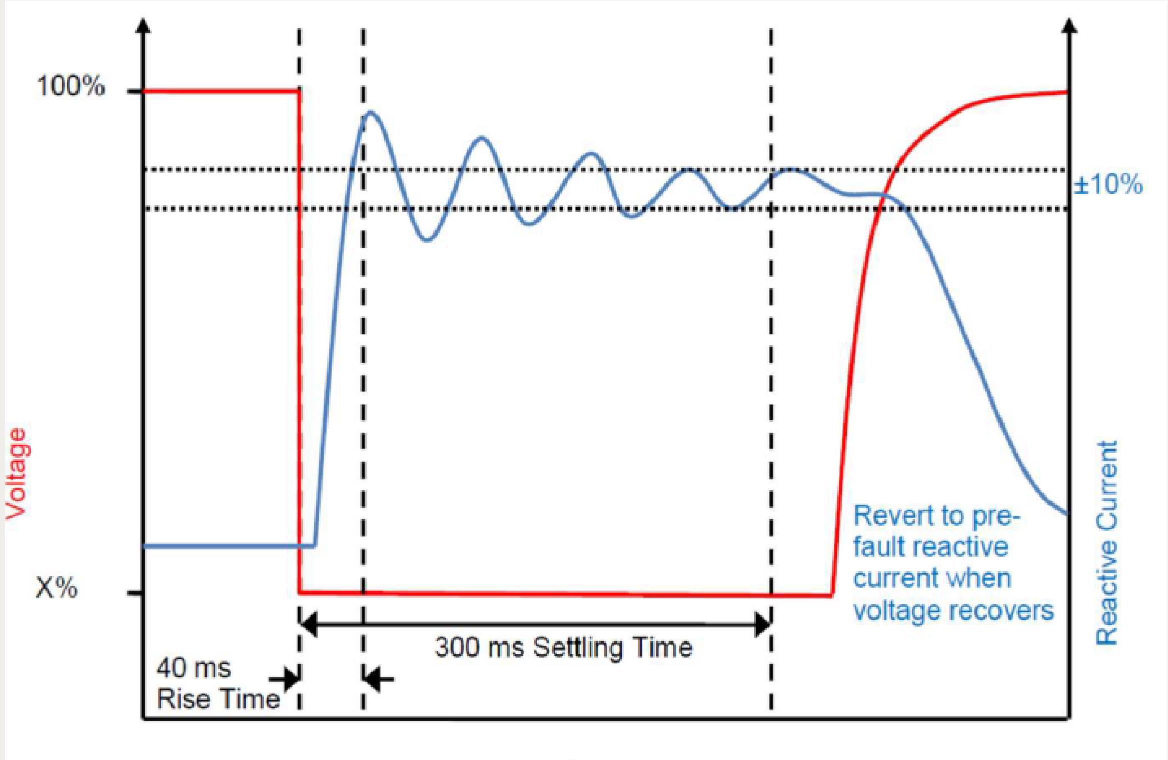
Instantaneous response of Synchronous Condenser

- Since the field winding receive an excitation current from a fast exciter, the flux in the machine can be almost instantaneously adjusted so that the synchronous condenser can support the grid within less than a cycle of a transient event (i.e. **appropriate tuning required**)
- The newer generation of power electronic exciters/AVR can increase field to 1.6 or 2.5 times of its normal operating value (i.e. **vital input during design stage**).
- Due to massive thermal capability, overload is seen as normal event.



Dynamic Reactive Response (DRR) - Example

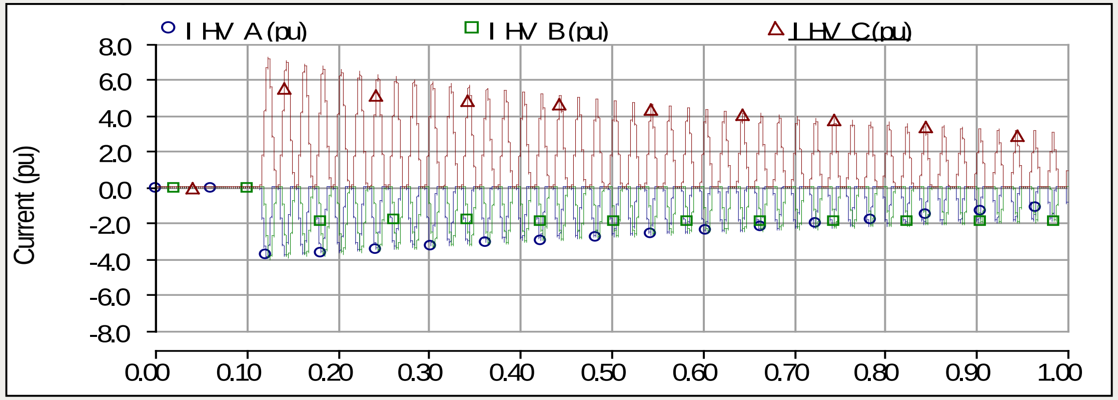
- The DRR is defined by EirGrid as ability to deliver a reactive current response for voltage dip in excess of 30% that would achieve at least a reactive power in MVAR of 31% of rated capacity at normal voltage.
- The reactive current is supplied within rise time of less than 40 msec and settling time less than 300 msec.
- SynCon with a Static Excitation System (SEE) meet this requirement.



Reactance / Fault level / Transient stability

- Sub transient fault current can be 5-8 times higher than the steady state fault current → Provides stabilisation following system events
- Synchronous machines **inherently** provide these features
  - Current fleet of asynchronous generators (wind, solar PV, batteries) not, unless it's specifically designed from factory = **increased costs**
  - OEMs further pushing the boundaries using new approaches to manufacturing
- Energising network components requires **short circuit power → system strength**

Key capability:
Sustain large changes for a prolonged time



Power System Inertia – Supported by rotating machines

- System inertia is inversely proportional to system RoCoF and has strong implications to frequency control

$$\text{RoCoF}\ \left(\frac{df}{dt}\right) = \frac{\Delta P * fNom}{2 * \Sigma HS}$$

- Inertia or the stored inertial energy of synchronous condenser is determined by two factors:
  - Machine speed
  - Design / rotational mass

$$E = \frac{1}{2} J\, \omega^2 = \frac{1}{2} J \left(2\pi \frac{RPM}{60}\right)^2$$

Type of synchronous generator		Speed	Inertia Constant H[s]
Thermal Generator	Condensing	1800 rpm	6 – 9
		3000/3600 rpm	4 – 7
	Non-Condensing	3000/3600 rpm	3 – 4
Hydraulic Generator	Slow speed	< 200 rpm	2 – 3
	High speed	> 200 rpm	2 – 4
Synchronous Condenser	Cylindrical Rotor		1 – 2
	Salient Pole Rotor		3 – 5
	With Flywheel		5 – 9

Note: Grid Forming IBR - Advancements in synthetic inertia and FFR/RoCoF

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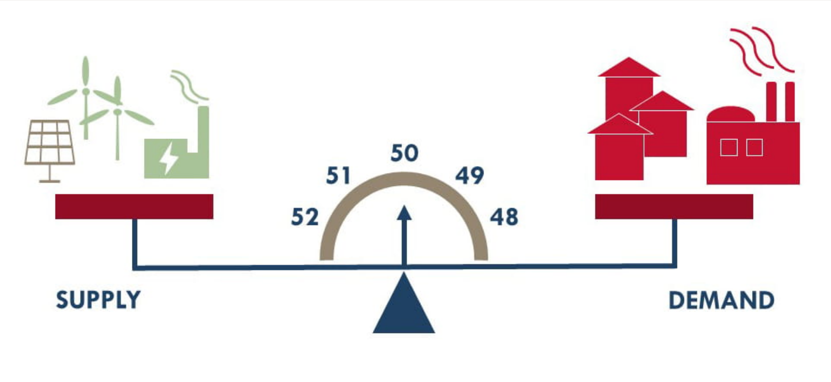
Power System Inertia – Supported by rotating machines

- Inertia refers to the tendency of the power system to resist changes in frequency when an imbalance between supply (generation) and demand (load) occurs.
- The transition from **synchronous machine to solar and wind-based power generation**, has resulted in a drastic reduction of system inertia.
- During a sudden decrease in system frequency, the rotating masses will slow down, releasing kinetic energy in the form of **active power injection to the grid, reducing the frequency decay**, and damping further oscillations.
- The inertia constant of Generator is about 1, Turbine and Generator about 4 and Generator with flywheel about 7-8.
- **Synchronous generators adds inertia** to the power system.

Frequency Stability - Inertial support for renewables

- It is desired to **maximize solar park and wind farm output** for real power at point of connection.
- External inertial support is required to **contain and limit RoCoF**, regularly during switching of IBR plants.
- **Short Circuit Power support** required to ensure timely detection and isolation of fault.
- **Synchronous condensers** are considered a principal solution, common in use for grid support in USA, UK, Germany, Denmark, Norway, Australia, Korea, Peru and Italy.



Power System Inertia – A focus on flywheels

Synchronous Condensers are provided with flywheels to add inertia.

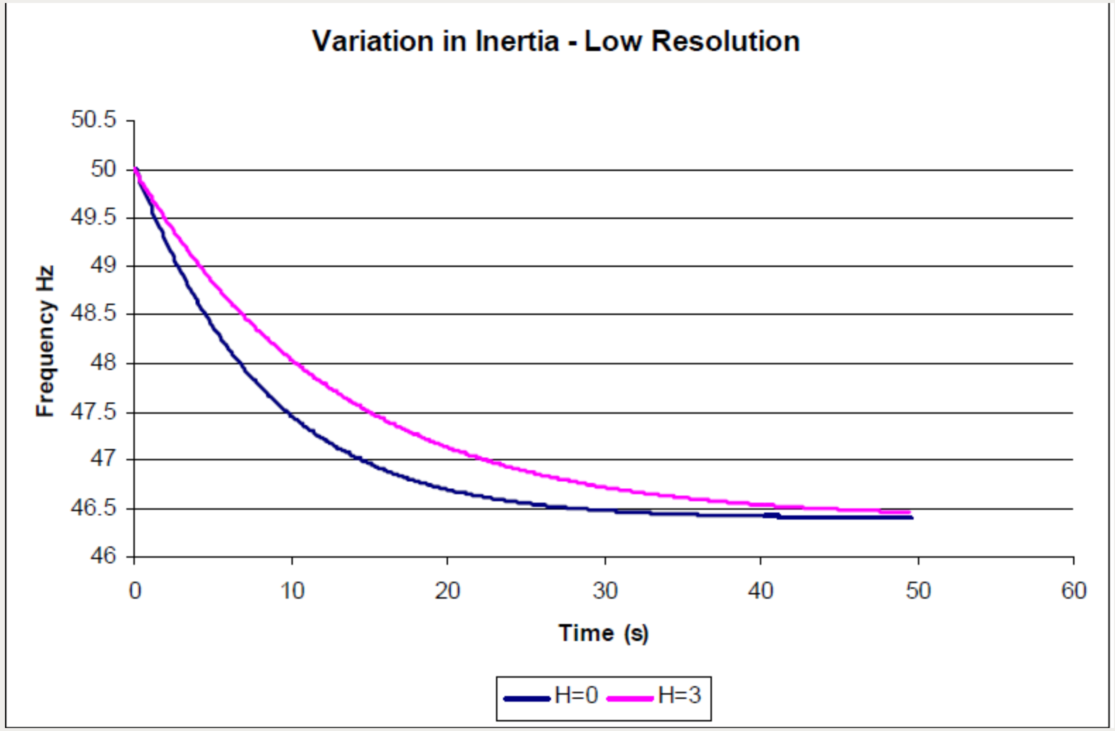
A flywheel can be connected to generator / turbine in thermal power plants.

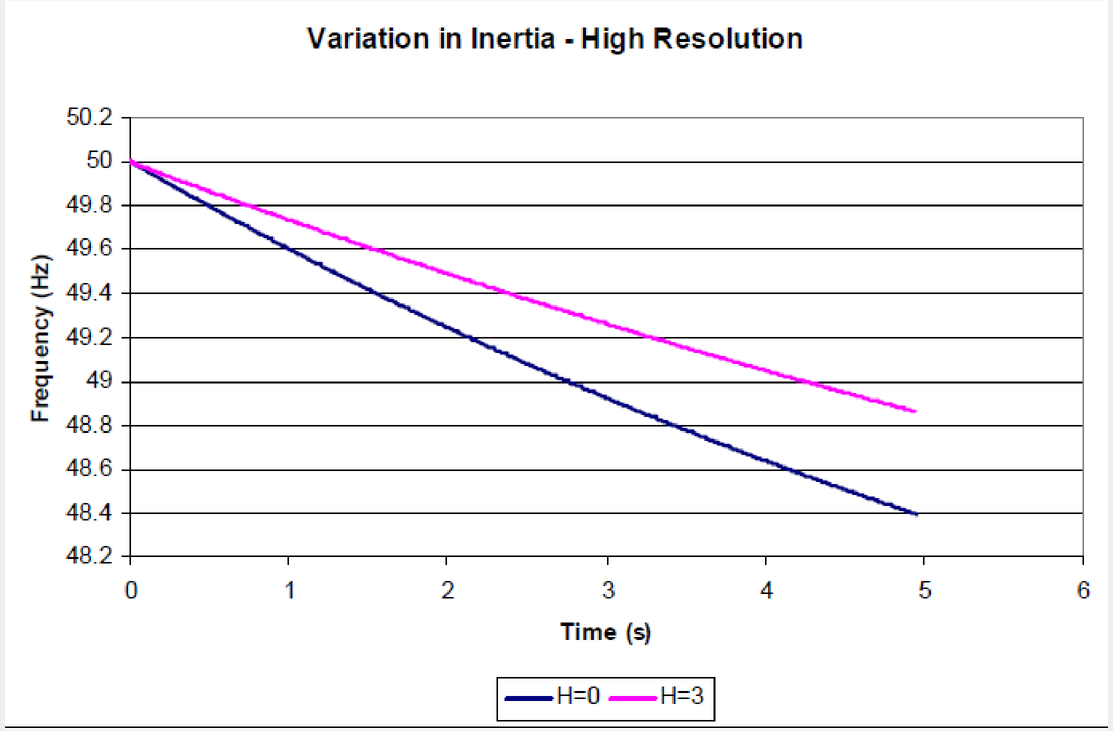
The flywheel can help injecting short duration real power into the system.

Helps in limiting RoCoF in weak grid. The suggested value of ROCOF is 0.5Hz/sec measured over a period of 500 msec.

Effect of Inertia on Frequency drop/increase

- Inertia constant H (MW.s/MVA) = 7-8 for flywheel, about 3 for Hydro Generator - Salient pole low speed machine, and less than 1 for turbo generator high speed machine

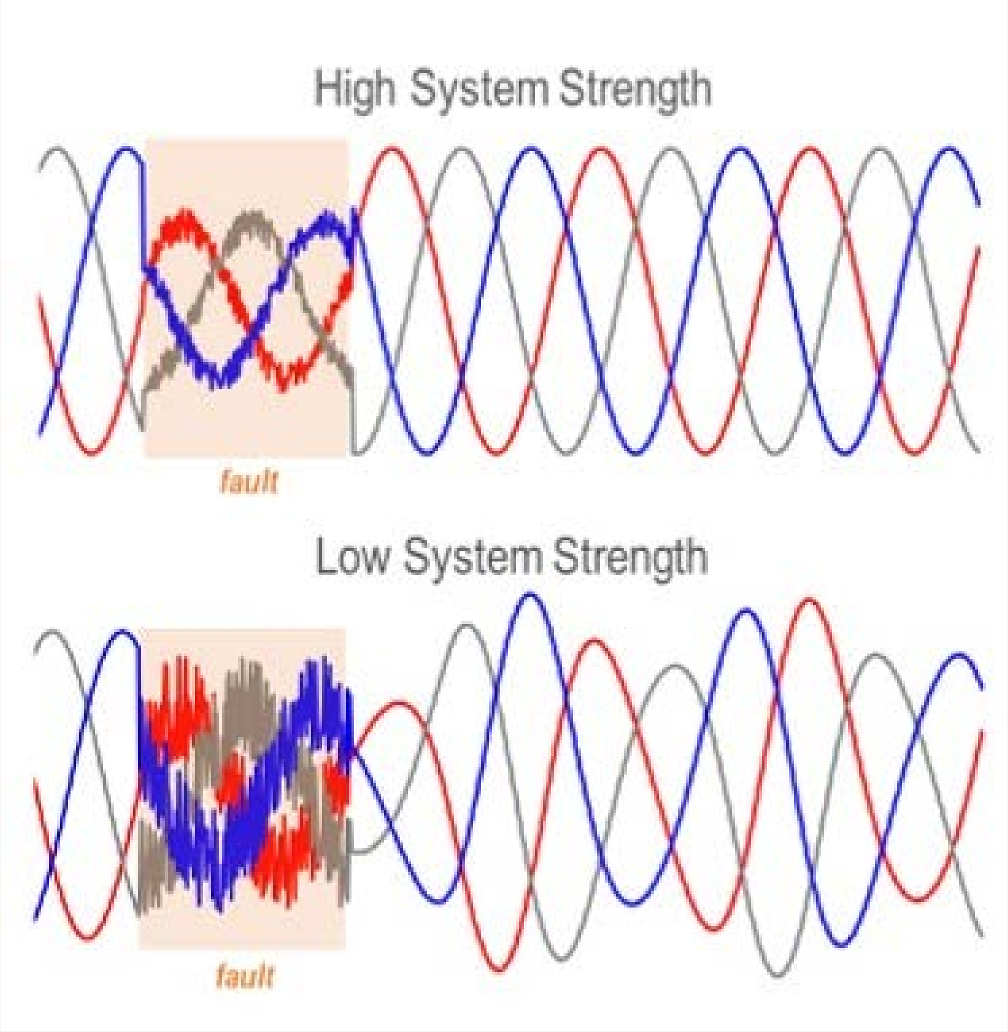




Power System Strength - support of Synchronous condenser

- Support in terms of fault level
  - Fault level is commonly used to quantify the system electromagnetic strength measured in short-circuit current Ik'' [kA] or short circuit power Sk'' [MVA]
  - System electromagnetic strength (or fault level) is **regional**
  - Fault level contribution is an **important and <u>inherent</u> feature** of synchronous condensers

	Synchronous generator	Asynchronous generator
Fault current provision	High	Low
Ability to operate stably under low fault current conditions	High	Low



https://www.aemo.com.au/learn/energy-explained/energy-101/energy-explained-system-strength

Benefits of Synchronous Condenser over other solutions

- Supports development and uptake of small and large scale intermittent renewables as Inverter Based Resources (IBRs)
- Maintaining power system security and essential grid services
- Synchronous condenser is considered as one of the key solutions to tackle this challenge and the transition to a future power system predominately driven by IBR.
- Some of the essential ancillary services of SynCons are:
  - **Fault current support** to improve power system electromagnetic strength.
  - **Physical inertia** to limit the initial RoCoF in the first swing.
  - Reactive power support.
  - Inherent sine wave to **stabilize the voltage distortion** following a transmission fault and facilitate grid following inverter Fault Ride Through.
  - Harmonics free.

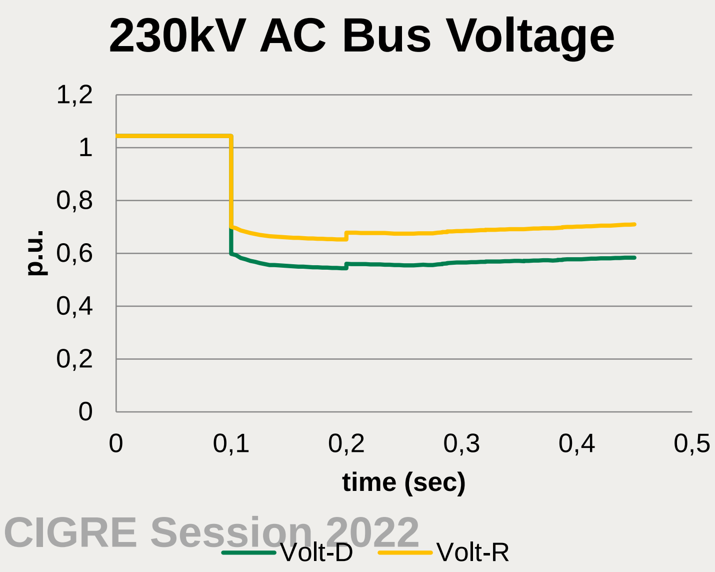
SYNCHRONOUS CONDENSER CASE STUDIES

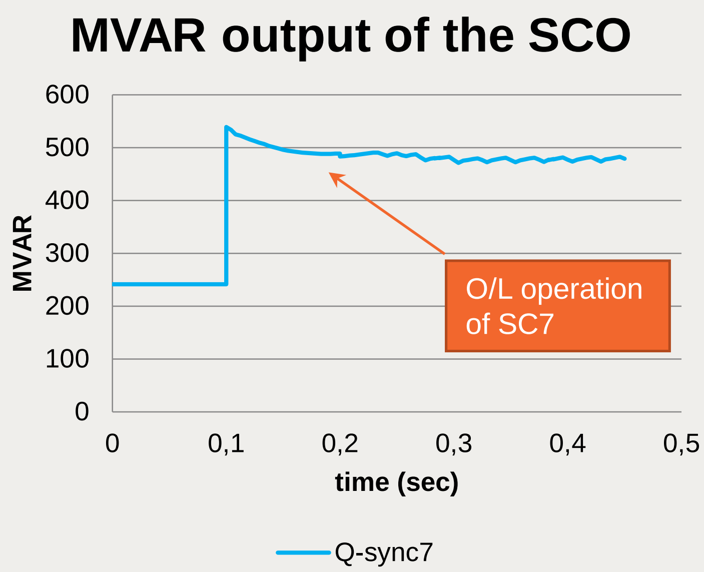
By Fabian Spescha

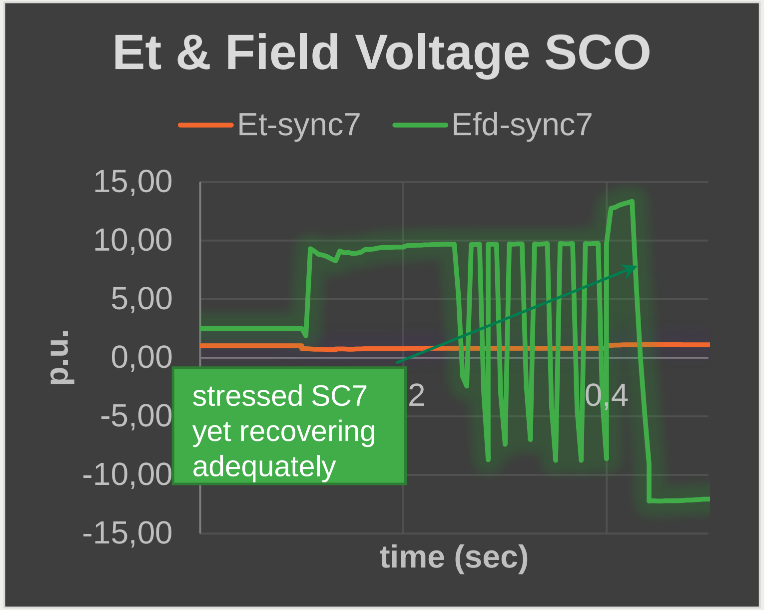
For power system expertise

Dynamic Voltage Response, Compensation and its limits

- Manitoba Hydro Case Study - Reactive power demand following an AC system disturbance
  - Disturbance: stuck CB, single line to GND fault
  - Clearing time: 18 cycles
- Detailed assessment and comprehensive evaluation of the system dynamic

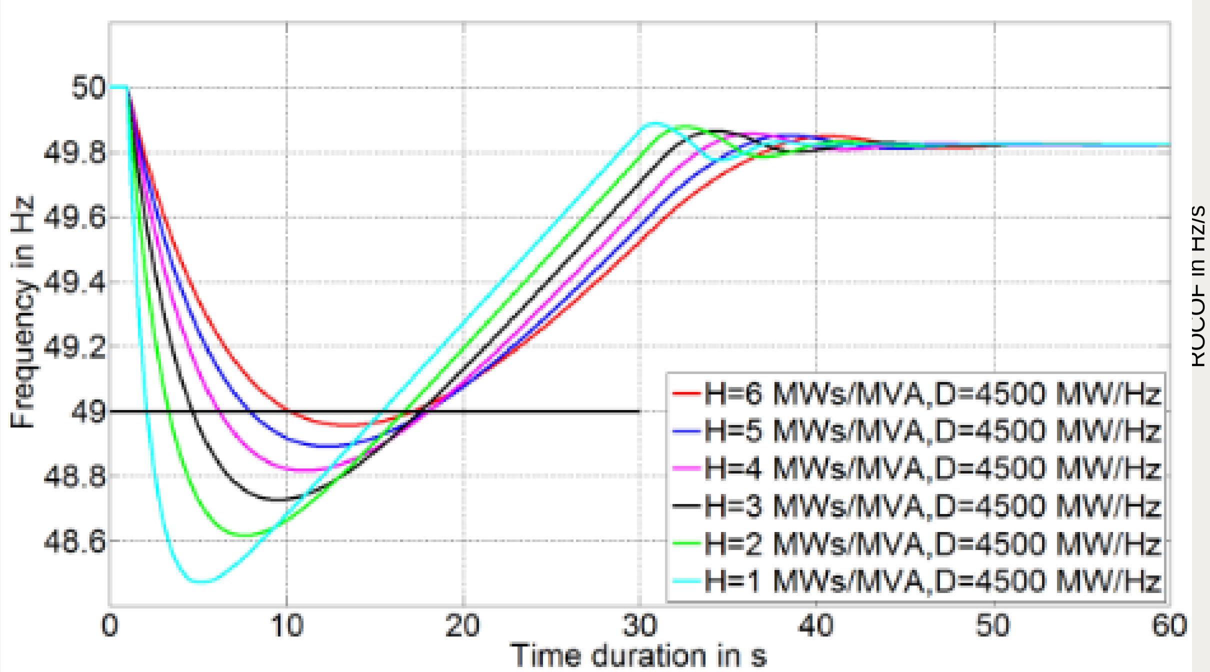


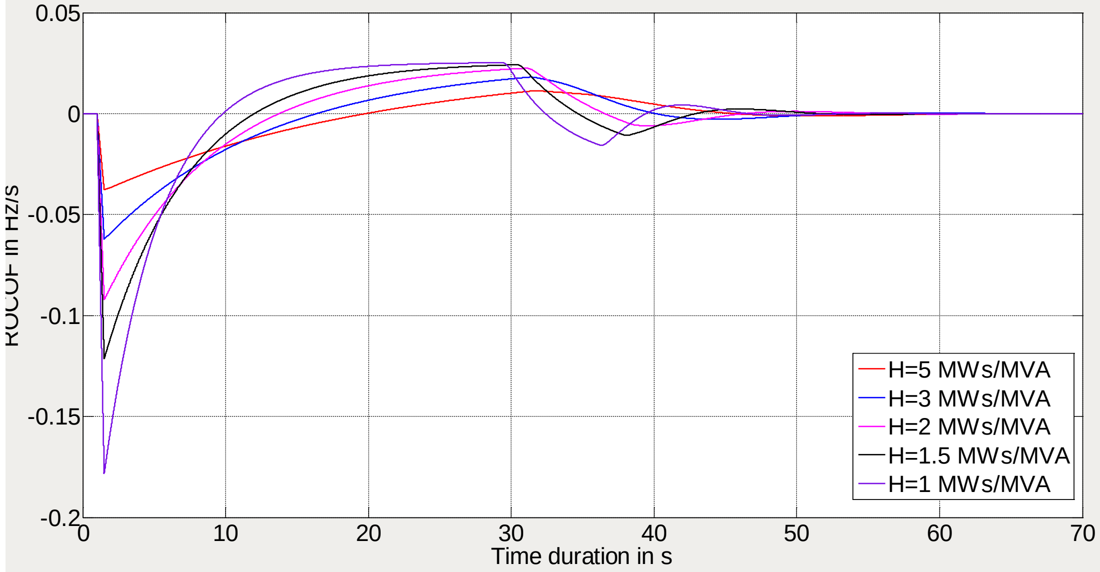




High IBR penetration and consequences (e.g. frequency stability)

- Relation of Inertia constant to the frequency deviation and RoCoF
- German and Indian power system was represented as a single area and a single mass model





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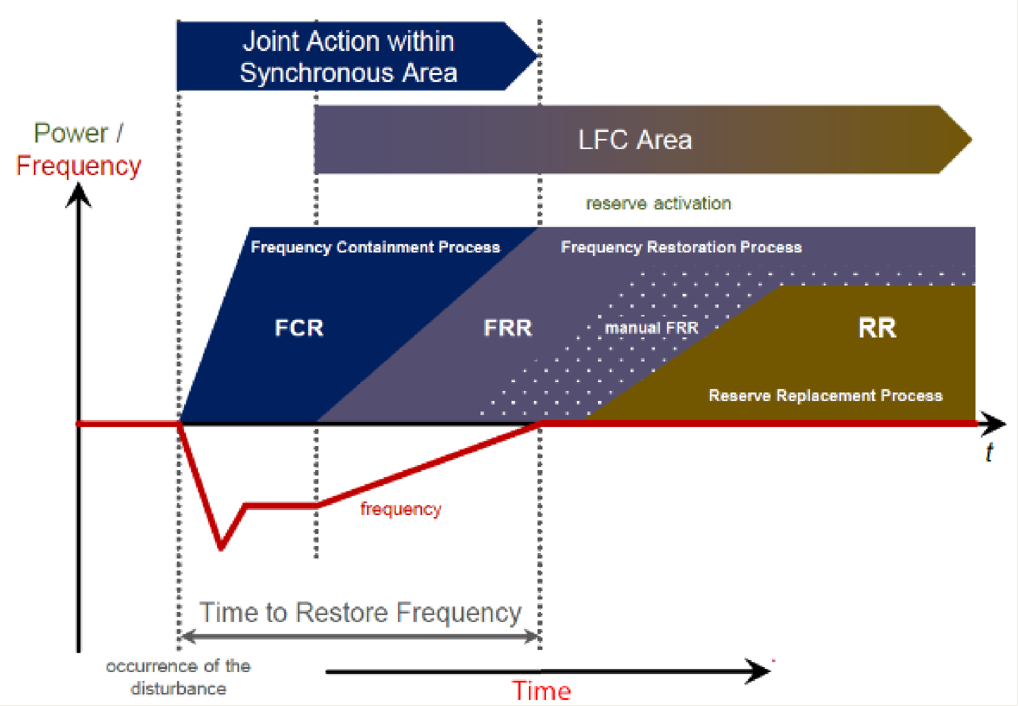
High IBR penetration and consequences (e.g. frequency stability)

- Dynamic frequency response for a step load disturbance using a conventional LFC model
- Reduction in system inertia due to an increase in IBR/renewables
  - Increase in the frequency deviation/RoCoF
  - Time to reach the minimum frequency point is faster
- With the higher number of IBR which are decoupled from the electrical grid, there is a *necessity to provide fast FCR* using renewables **or installing synchronous condenser in order to maintain the system frequency** within the allowable limits



Grid operation with high penetration of voltage source converter (VSC) based sources with synchronous condensers

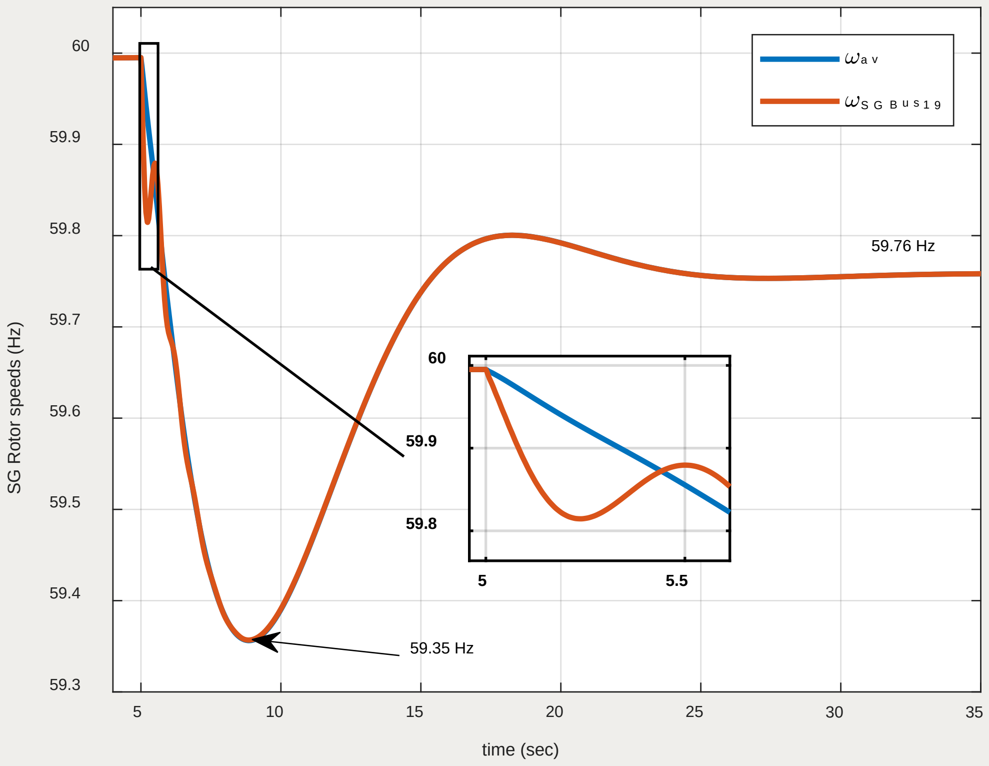
- Feasibility of operating a power system with:
  - very high penetration of Voltage Source Converter (VSC)-based sources
  - **supported** by synchronous condensers (SCs); and
  - battery energy storage systems (BESS).

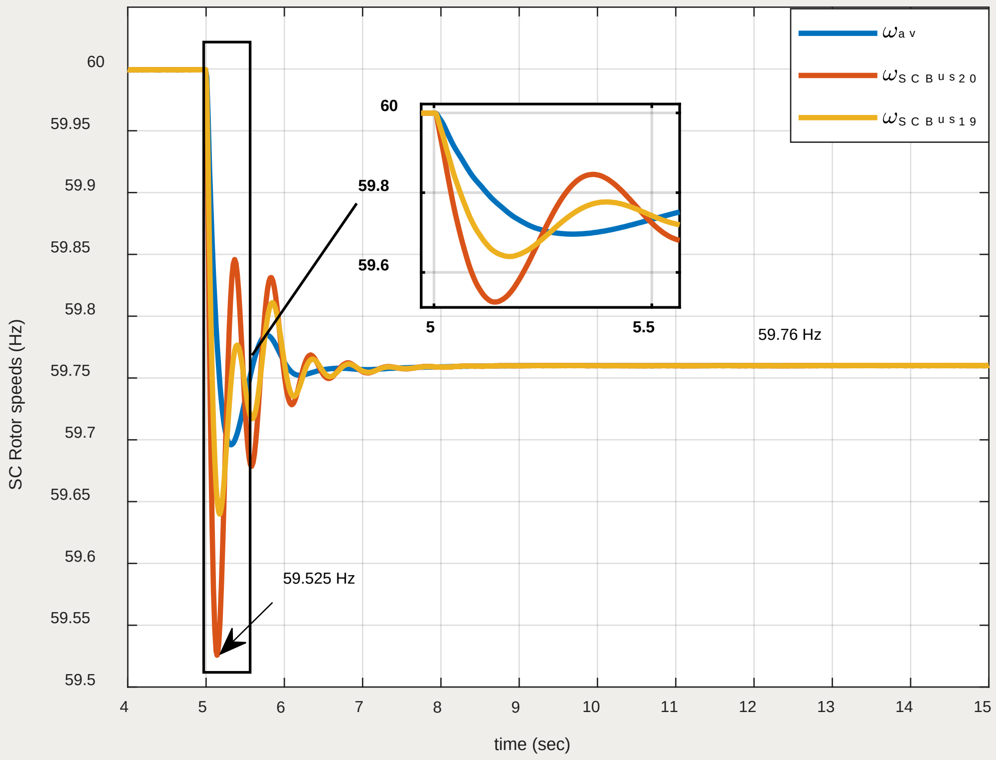
Scenarios	Scenario 1 – 100% SG	Scenario 2 – 100% VSC
Number of SGs	9	0
Number of SCs (270 MVA rated power)	0	9
Number of BESSs (50 MW rated power)	0	10
Kinetic energy (E_{sys})	» 28.2 GW.s	» 8.4 GW.s
Total load	» 5 GW	
K-factor (K_{sys})	» 2 GW/Hz	

Grid operation with high penetration of voltage source converter (VSC) based sources with synchronous condensers

- **Scenario 1:** 100% SG-based system

Scenario 2: 100% VSC-based sources



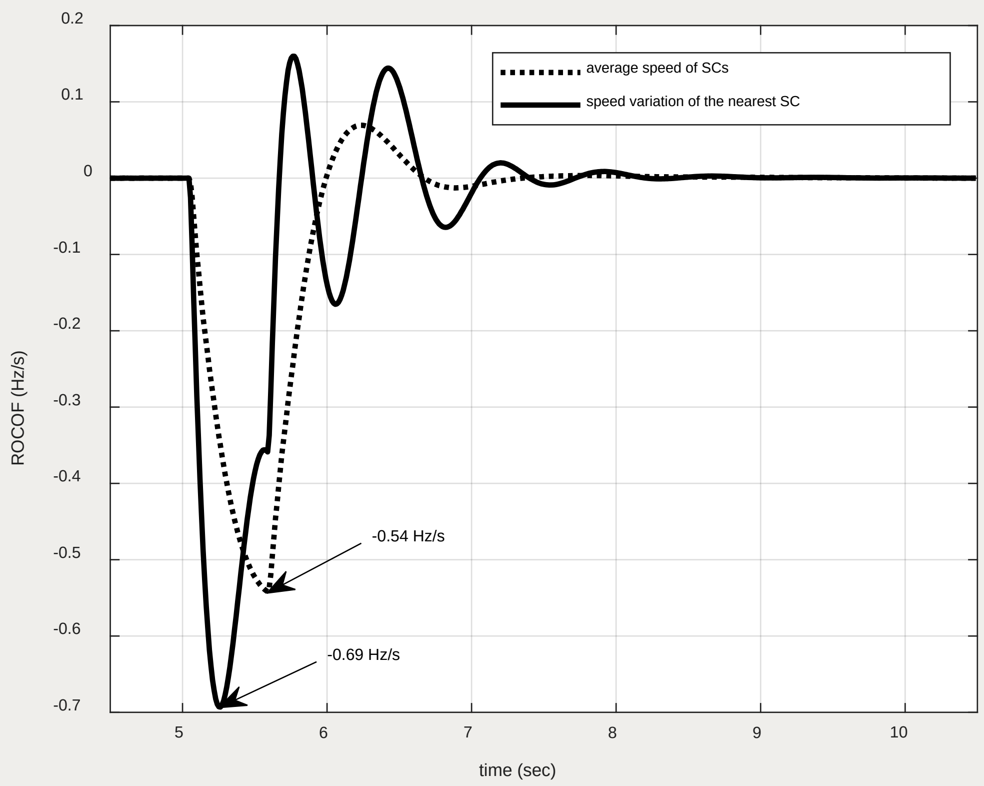


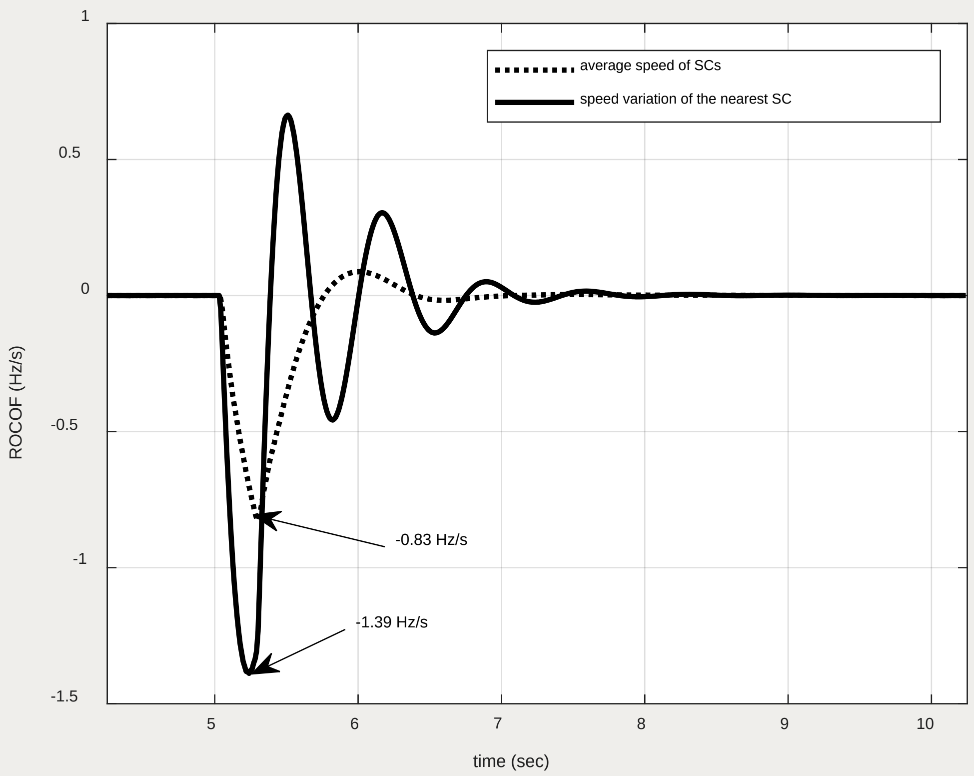
Response in case of loss of the generation at bus 20

Grid operation with high penetration of voltage source converter (VSC) based sources with synchronous condensers

- 500 ms measurement window

250 ms measurement window





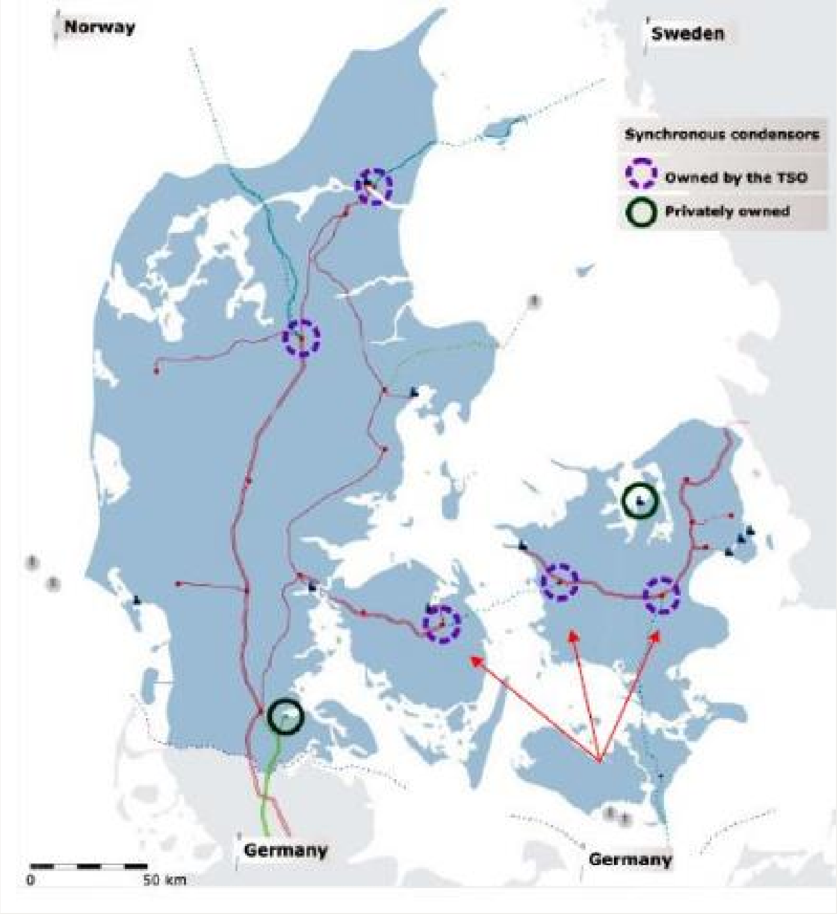
RoCoF using two different size of measurement window

Transmission system strengthening

- Application and use of condensers in the following countries such as Denmark, Germany, Iceland, Ireland, Italy, USA and Australia
- Purpose of the synchronous condensers in these countries are strengthening the network (or support HVDC systems - Canada) either by:
  - synchronous machine **“reuse” as condenser** (e.g. Denmark, Germany and USA)
  - new projects as **“greenfield” condenser installation** (e.g. USA, Italy, Australia etc.)

Transmission system strengthening

- Demand in Denmark is 33 TWh per annum
- Two independent large transmission systems:
  - Western transmission system serves North Jutland, Central Jutland and Southern Denmark
  - Eastern transmission system serves the area of Greater Copenhagen and Zealand
- Two systems are connected via HVDC link
- Since 2009 the share of wind and solar generation increased rapidly from 19.4% to 43.5%.
- **Network strengthening work was carried out**
  - **7 synchronous condensers (status: 2015)**



Case study summary

- No single or standard approach to addressing system strength or inertia challenges
- Synchronous condensers are being used as a **prime solution**
- Generator conversion to synchronous condensers have taken place where system support is needed most urgently
- Condenser solutions is very specific to local challenges and usually owned by local TSOs

SYNCHRONOUS CONDENSER SPECIFICATIONS

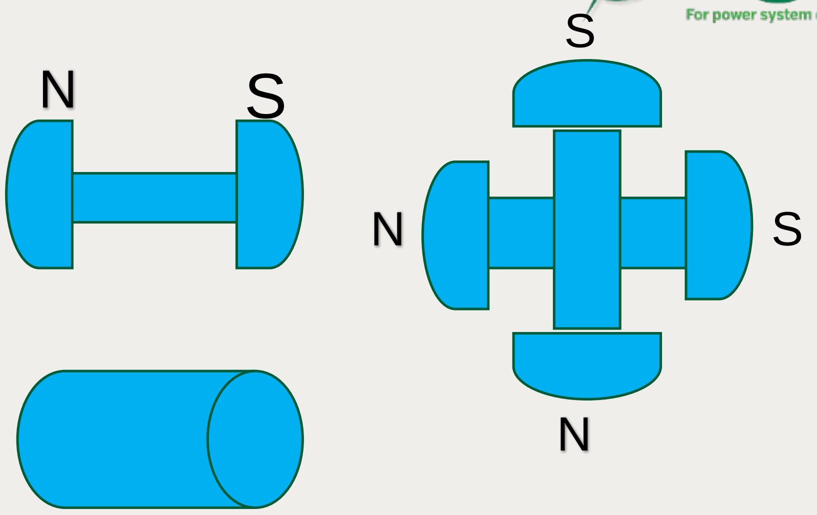
By D K Chaturvedi

For power system expertise

Specifications –Synchronous Condenser

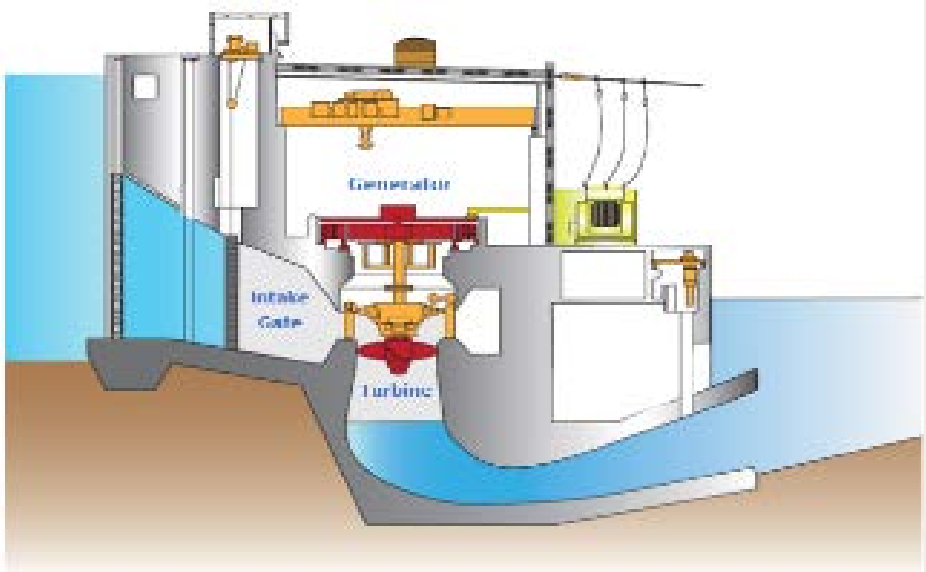
Constructional features of cylindrical rotor machines;

- Number of poles: 2 or 4 pole
- Rotating Speed: 2 pole – 3000rpm for 50Hz or 3600rpm for 60Hz
- 4 pole – 1500rpm for 50Hz or 1800rpm for 60Hz
- Capacity: 5MVA – 2000MVA
- Install position: Horizontal mounted.
- Cooling type:
  - Air cooled machines are in range of 5MVA-300MVA
  - Hydrogen cooled machines are in range of 200MVA-600MVA
  - Water cooled machines are generally above 600MVA.



Salient pole machine

Constructional features of salient pole rotor machines	
Pole number:	4-64 pole
Rotating Speed:	Typically, in range of 100rpm to 1500rpm
Capacity:	0.5MVA – 800MVA
Cooling type:	Air cooling



Technical data requirements in specifications

• **Maximum inductive reactive power at pf=0 in Mvar**
• **Maximum capacitive reactive power at pf=0 in Mvar**
• **Inertia of rotor in kg-m2** (Synchronous Condenser itself)
• **Inertia of shaft line in kg-m2** (Including Synchronous condenser, Flywheel & rotating parts)
• Kinetic energy of rotor at rated speed: unit is MW.s or MJ (Synchronous Condenser itself)
• **Kinetic energy of shaft line at rated speed**: unit is MW.s or MJ (Including Synchronous condenser, Flywheel, and other rotating components)
• **Inertia constant H in MW.s/MVA** (Total value of the system, for reference)
• **Rated synchronous condenser terminal voltage**
• Rotor type: **Cylindrical type** or Salient pole type • **Number of poles.**

Technical data requirements in specifications

- **Rotating Speed** 3000/1500 rpm or 3600/1800rpm
- **Insulation class**: Thermal class F(155) with temperature limits of class B (130)
- **Cooling type** Air or hydrogen cooling
- Cooling System (TEWAC-totally enclosed water air cooled or DAC Direct air-cooled)
- **Impedance**: Machine Xd, Xd', and Xd" should be specified.
- **Operational Requirements:**
  - Permissible Voltage variation
  - Permissible Frequency variation
  - Permissible Combined voltage and frequency variation

The detailed specifications of Cylindrical rotor machines are available in TB appendix F to H

Key ratings of synchronous condenser										
		50Hz							50Hz	
Capacity	MVA	780	670	615	500	386	211	195	39	222
Frequency	Hz	50	50	50	50	50	50	50	50	50
Pole Number	-	2	2	2	2	2	2	2	18	36
Rotating Speed	min-1	3000	3000	3000	3000	3000	3000	3000	333	166.6
Cooling Type	-	H2/Water	H2	H2	H2	H2	Air	Air	Air	Air
Lagging reactive power @ Prated & Vt=1.0 p.u.	MVA	580	505	473	400	310	170	195	21	115
Leading reactive power @ Prated & Vt=1.0 p.u.	MVA	340	400	258	165	170	82	80	25	200
Impedance Xd	%	181	184	200	220	181	200	173	119	90
Sub-transient Reactance Xd" (saturated) with tol.	%	21.3	26.2	15	18	16.4	12	15.3	27	24
Moment of Inertia (approx., SI Unit)	kg-m2	12300	8900	14300	9550	9200	6500	7300	131500	5250000
Kinetic Energy	MJ	607	440	705	471	454	318	361	80	799

Technical parameters of the new designed 300MVar condenser		
Steady state reactance /%	X_d	150.5~15
Transient reactance /%	X_d'	14~16.5
Sub-transient reactance/%	X_d''	11.1~11.3
Force excitation factor	K_M	3.5
Rotor overload capacity	-	2.5 I_{fn} for 15s
Stator overload capacity	-	3.5 I_n for 15 sec
Leading phase operation ability in MVar	-	150-165
Power loss	-	1.07-1.15%

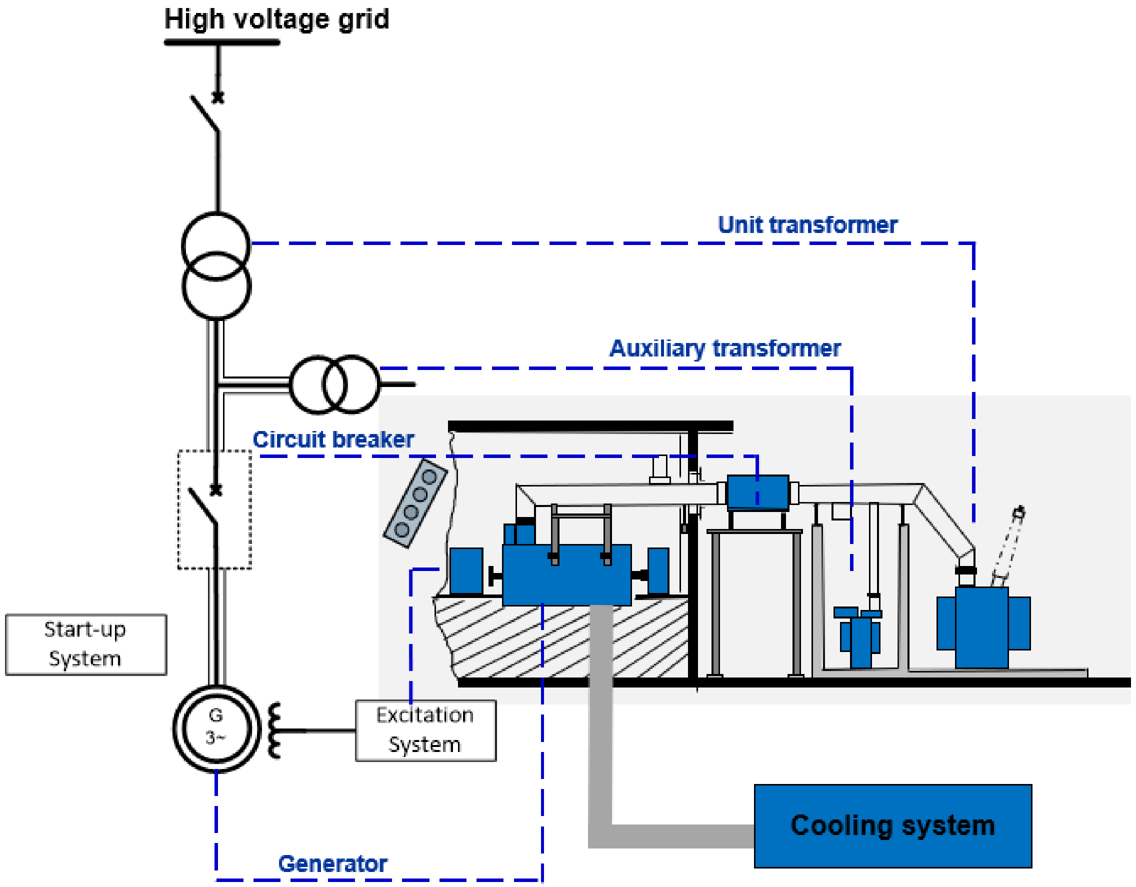
Synchronous Condenser main rating data	Symbol	Typical Values for a 130MVAr generator	Unit
Rated apparent power	Sn	130	MVA
Rated reactive power (over-excited)	Qn	130	MVAR
Reactive power (under-excited)	Qmin	-65	MVAR
Rated power factor	cosjn	0.00	-
Rated terminal voltage (+5.0 % / -5.0 %)	Un	15000	V
Rated phase current	In	5000	A
Rated frequency (+2.0 % / -2.0 %)	fn	50	Hz
Rated speed	nn	3000	rpm
Generator field current at no load and rated terminal voltage	Ifo	800	A
Generator field voltage at no load and rated terminal voltage	Ufo	50	V
Generator field current at rated conditions	Ifn	2000	A
Generator field voltage at rated conditions	Ufn	200	V
Ceiling factor	fpl	1.5	p.u.
Ceiling current	Ifp	3000	A
Ceiling voltage	Ufp	300	V
Ceiling time		10	s
Short-circuit ratio	SCR	0.5	-

SCR: Ratio of the field current required to generate rated voltage on an open circuit to the field current required to circulate rated armature current on a short circuit.

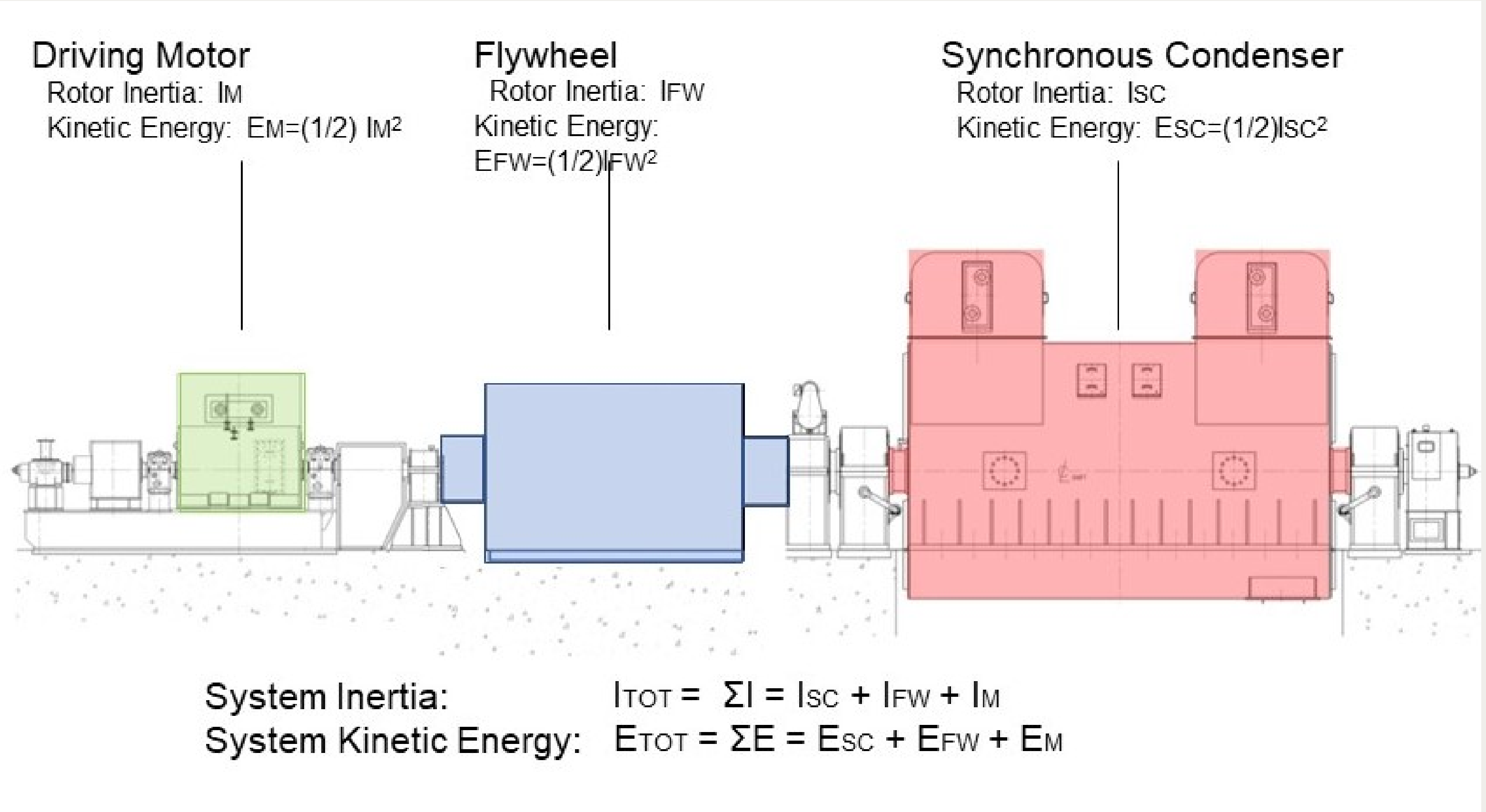
Specifications technical data requirements

- Indoor/Outdoor Solution
- Step-up transformer technical requirements
- Starting system (Pony Motor or Static Frequency Converter)
- Applicable standards (for components) or grid codes
- Support at Point of connection:
  - Reactive Power at Point of Connection in MVAR
  - Inertia/kinetic Energy in MWs
  - Short Circuit Contribution at the Point of connection in MVAR
- **Excitation System** – Static or brushless
  - Excitation System response ratio and response time
  - Excitation system ceiling voltage

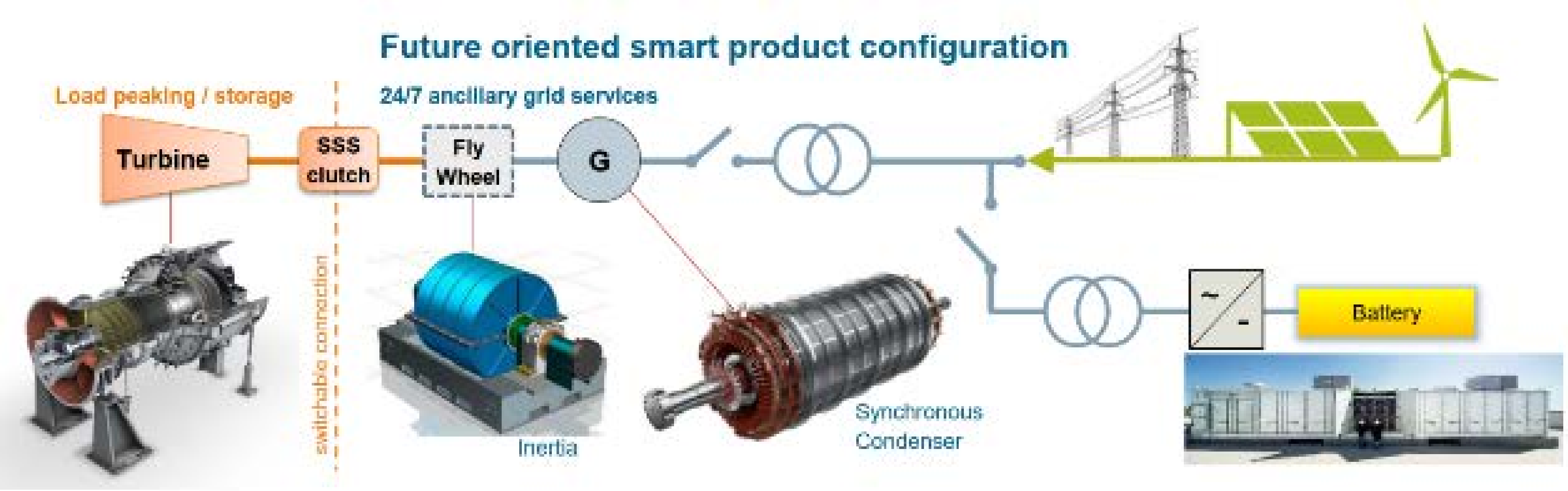
Synchronous Condenser Configuration



Synchronous Condenser with flywheel are provided to meet system inertia requirements



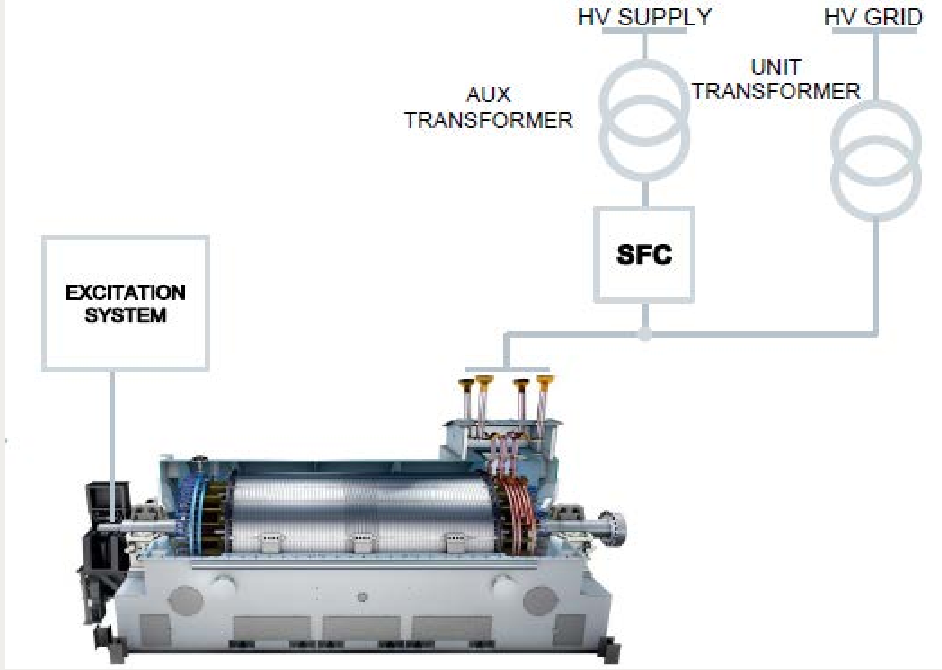
Clutch are provided to operate machine as generator or synchronous condenser



- This concept involve connecting the gas turbine to the generator by a clutch.
- When active power is required, the clutch is closed, and active power is delivered to the grid.
- When no active power is required, the clutch is opened after synchronization and the generator remains connected to the grid as a synchronous condenser.

Synchronous Condenser starting using Static Frequency Converter

- Static Frequency Converters (SFC) are similar as variable speed drive and are connected between Synchronous condenser and generator circuit breaker.
- The SFC voltage and frequency is raised to maintain flux as required to ensure smooth start-up of synchronous condenser.
- Once the rated speed of machine is reached, the SFC is re-accelerated over the rated speed, such as 103% speed. After that, SFC is switched off.
- The machine excitation increases the field voltage to achieve rated voltage at machine terminals, during free rotating condition.
- The machine voltage, speed and phase are matched to that of the network, synchronization is done.



Starting of Synchronous Condenser using pony motor

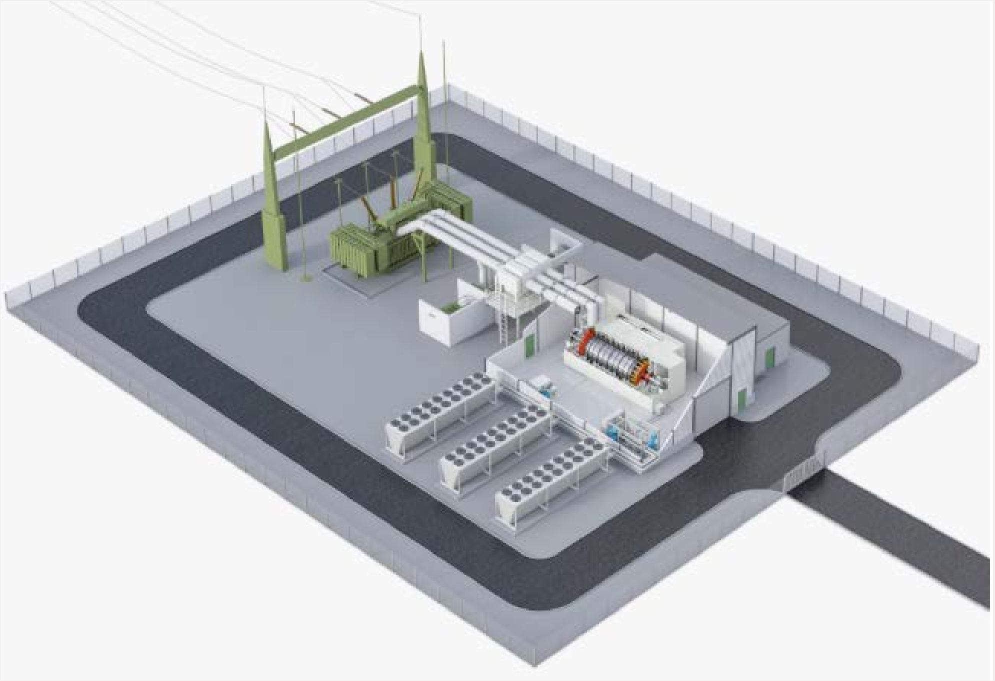
- The Pony motor used to start the Synchronous Condenser.
- The pony motor is soft start using variable speed drive.
- As the network synchronous speed is achieved, the machine voltage is increased with the help of excitation system.
- As rated voltage is match to the bus voltage, the synchronization panel matches the machine output voltage, frequency, and phase with that of the network and close the breaker.
- After successful synchronization, the pony motor is switched off and it continues to run in de-energized condition coupled with the synchronous condenser.

Synchronous Condenser starting using pony motor

Synchronous condenser placement criteria

The synchronous condenser placement criteria should include:

- The power system remote area where the inverter-based resource is located, but far away from existing synchronous generators.
- Locations where fault level needs to be increased to operate protection system effectively.
- The remote end of the transmission line due to voltage compensation.
- Synchronous Condensers must offer voltage regulation and short-circuit power at the right places in the grid.
- To enhance inertial support.



Synchronous condenser layout

SYNCHRONOUS CONDENSER RETROFIT SOLUTIONS

By D K Chaturvedi

For power system expertise

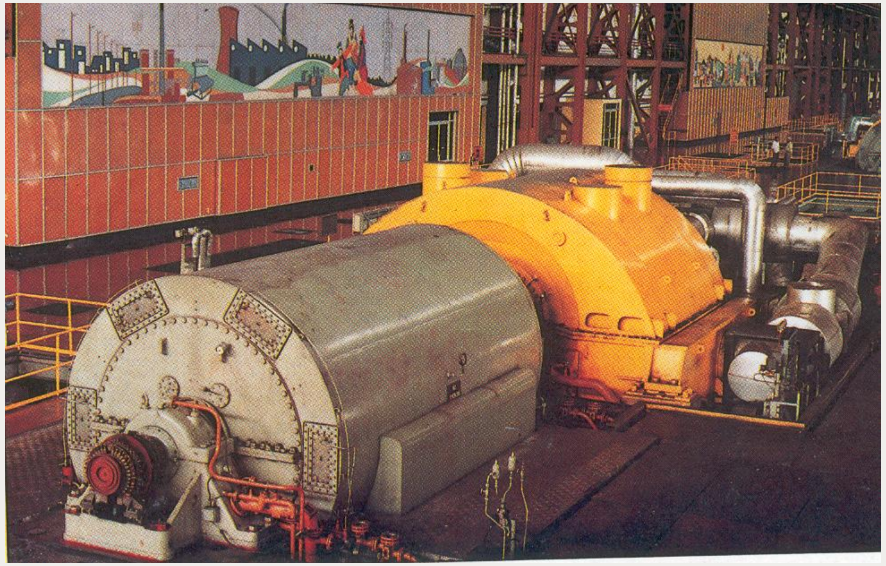
Synchronous condenser retrofit solution

Old thermal power plant unit can be converter into synchronous condenser. While planning a conversion of a turbo generator unit, the following factors needs to be reviewed:

- Who will plan and initiate the conversion of old turbo generator unit,
- Relationship of conversion initiator agency with plant owner,
- Does ownership need be transferred,
- Who will run the plant after conversion to Synchronous Condenser?
- Who will bear capital expenses involved in conversion?
- Who will do the O&M after conversion and who will bear the O&M expenses?

Conversion to SynCon - Residual life analysis

- Based on decision on commercial aspects one should plan Residual Life Analysis (RLA) of major electrical equipment and system to be used after the conversion.
- The scope of RLA will include major electrical equipment
  - Turbo Generator (TG) and auxiliary system (lube oil, seal oil and cooling water).
  - TG excitation system,
  - Generator relay panels and control equipment,
  - Generator transformer and electrical bay equipment.
- The checks should establish:
  - ➢ What condition is the generator stator and rotor?
  - ➢ Are they in need of a rewind or significant repair, prior to conversion?



Short Circuit MVA Calculations						
Generator rating	Gen. impedance	Transf. Impedance	Gen. X_d"impedance with +tol.	Transf. Impedance with +tol.	Total Impedance	Fault rating
960	18.5	16	21.27	17.2	38.47	2500
776	24	15	27.6	16.12	43.7	1775
588	17.2	13.5	19.78	14.5	34.3	1700
294	16	13.5	18.4	14.5	32.9	900

The Short Circuit Power support during fault will be 4-5 times of machine rating as the machine is designed for Synchronous condenser application, instead of about 2.5 times of machine rating

Installation of New Synchronous Condenser (250 MVAR rating)

S. No.	Description	Price for 400 KV in million USD
1.	Synchronous Condenser (250 MVAR)	4.02
2.	Generator Transformer Bank	1.21
3.	Generator Circuit Breaker	0.67
4.	Static Excitation System and Generator Protection System	1.34
5.	Drive Motor with VFD	0.67
6.	Generator Busduct	0.4
7.	Generator Auxiliary System	0.13
8.	HV and LV System, Air Conditioning and Miscellaneous system	0.4
9.	EHV Bay	0.67
10.	Land Cost	0.4
11.	Civil Foundations and Building Cost	0.4
12.	Erection, Testing and Commissioning	1.34
13.	Technical Support	2.68
14.	Miscellaneous Expenses	0.67
	Total	**15**

Conversion of Retire Thermal Plant as Synchronous Condenser

S. No.	Description	Price in USD Million
1.	Generator Rewinding cost (250 MVAR)	2.01
2.	Modification in Excitation System & Generator Protection System (if required)	1.34
3.	Drive Motor with VFD	0.67
4.	Generator Auxiliary System	0.134
5.	Miscellaneous modifications including civil cost	0.67
6.	Erection, Testing and Commissioning	1,34
7.	Technical support	2.01
8.	Miscellaneous expenses	0.67
	Total	**8.84**

Advantages of Conversion

Synchronous Condenser provides three phase balance, pure sine wave out, and thus, has an advantage over static solution.

- Meet system MVAR requirements arising out of retiring generators,
- Low voltage ride through capability during fault,
- Facilitates dynamic compensation,
- Meet reactive MVA of HVDC,
- Improves network inertia,
- Improves system stability,
- Maintains power quality.

SYNCHRONOUS CONDENSER INSTALLATIONS

By Fabian Koehler

cigre

For power system expertise

Synchronous Condenser Installations

Chapter Intention:

- Provide an overview of various installations and retrofits
- Showcase the range of SynCon applications to address set of challenges
    - ➢ Provide system inertia
    - ➢ Provide short-circuit power
    - ➢ Provide reactive power
    - ➢ Reduce system harmonics

Synchronous Condenser Installations

Seven Synchronous Condenser Installations in Denmark

- Solution for high penetration of renewables on the network
- SynCons at or near HVDC converter stations
- Provision of short-circuit power, inertia and reactive power

- Fraudge & Herslev Units of +200/-120 MVAr reactive power, 1000MVA short-circuit power and 450MWs inertia (see photo)

  → Supporting LCC HVDC Stoerebelt 600MW

CIGRE Session 2022

Synchronous Condenser Installations

Seven Synchronous Condenser Installations in Denmark

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Synchronous Condenser Installations

Seven Synchronous Condenser Installations in Denmark

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Synchronous Condenser Installations

Seven Synchronous Condenser Installations in Denmark

Synchronous Condenser Installations

Synchronous Condensers in South Australia

2 x 2 synchronous condensers with flywheels to stabilize the grid by providing short-circuit power and inertia due to loss of conventional generation

Example: Robertstown 2x +125/-71 MVAR with 1100 MWs inertia and 580MVA short-circuit power

Synchronous Condenser Installations

Synchronous Condensers in South Australia

Source: https://www.siemens-energy.com/global/en/news/magazine/2021/flywheels-for-electranet-substation.html

Synchronous Condenser Installations

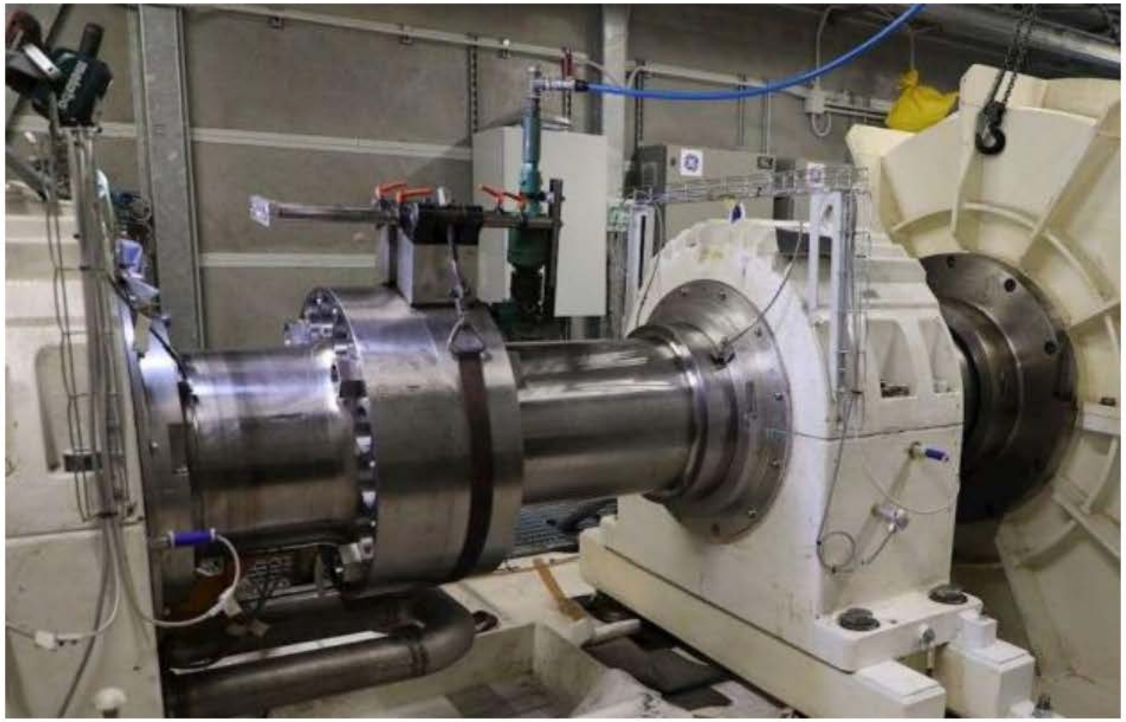
Several Synchronous Condenser Installations with Flywheel in Italy

- 20 synchronous condensers with flywheels to stabilize the grid by providing short-circuit power and inertia by 2022 (24 in total)
- first 7 synchronous condensers at LCC HVDC stations, +250/-125MVAr reactive compensation, 1750MWs inertia and over 1000 MVA short-circuit power

Source: G. M. Giannuzzi, F. Palone, C. Pisani*, R. Zaottini, R. Puddu, B. Aluisio, An innovative power system stabilization method with augmented inertia synchronous condensers, CIGRE Session 2022

Synchronous Condenser Installations

Several Synchronous Condenser Installations with Flywheel in Italy



CIGRE Session 2022

Source: G. M. Giannuzzi, F. Palone, C. Pisani*, R. Zaottini, R. Puddu, B. Aluisio, An innovative power system stabilization method with augmented inertia synchronous condensers, CIGRE Session 2022

Synchronous Condenser Installations

Layout of the 2 x 250 Mvar synchronous condenser / flywheel system in Matera (SC, aux and flywheel manufactured by Ansaldo, Step-up Transformer manufactured by Getra, GCB and BOP manufactured by ABB, Flywheel cryogenic system manufactured by Criotec)

Source: G. M. Giannuzzi, F. Palone, C. Pisani*, R. Zaottini, R. Puddu, B. Aluisio, An innovative power system stabilization method with augmented inertia synchronous condensers, CIGRE Session 2022

Synchronous Condenser Installations

Vacuum tight enclosure for the flywheel (Ansaldo / Criotec).

Source: G. M. Giannuzzi, F. Palone, C. Pisani*, R. Zaottini, R. Puddu, B. Aluisio, An innovative power system stabilization method with augmented inertia synchronous condensers, CIGRE Session 2022

THANKS