Challenges from increased Electricity Generation from Wind in Ireland

Meeting of the Energy Group of the European Physical Society

Royal Academy, Brussels – Belgium 11.10.2022

Dr Marios Zarifakis, ESB E&MP – Generation Engineering, Electrical Assets

Wind Mill and Wind Pump vs Wind Turbine

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    a) RoCoF - Rate of Change of Frequency: Increase of Frequency Volatility in Low Inertia Power Systems
        - Oscillations
        - Trips
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5. Synchronous Condensers and the Increase of Inertia in the System
6. SSR – Sub Synchronous Resonance: Damping of a synchronous condenser
7. Delivery through people
8. Commercial Challenges => Technical Challenges
9. Emerging Technologies

DRIVEN TO MAKE A DIFFERENCE

NET ZERO BY 2040

MAJOR EXTERNAL DEVELOPMENTS SINCE OUR PREVIOUS 2017 STRATEGY

Radical Shifts in Direction in Post-2017 Period

NET ZERO	Consensus on tackling climate change, with clearer commitment, accountability and a more ambitious end point
TRANSFORMED AND EXPANDED ROLE OF NETWORKS	New growth opportunities alongside a greater delivery imperative
SEM OFFSHORE	Creation of a large but hyper-competitive new market
ENERGY SERVICES	Rapidly-evolving landscape requiring a sharper focus to enable future profits
GB ENERGY POLICY AND MARKET	Advanced market with evolving competitive and regulatory challenges, including Brexit
STAKEHOLDER EXPECTATIONS	Sharpening – and rapidly shifting – stakeholder expectations, including increased focus on Environmental, Social and Governance (ESG)

Accelerated Trends

INCREASED COMPETITION	Wall of cheap money and entry at scale by oil majors
DIGITALISATION AND DATA	Faster pace but with new major use cases (e.g. Smart Working, Active System Management for networks)

AT ESB WE'RE DRIVEN TO MAKE A DIFFERENCE DELIVERING A BRIGHTER FUTURE

7 AFFORDABLE AND CLEAN ENERGY

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

13 CLIMATE ACTION

Creating and connecting sustainable, reliable affordable energy

Supporting the customers and communities we serve to achieve net zero

NET ZERO BY 2040

WE'VE ALWAYS BEEN DELIVERING A BRIGHTER FUTURE, FOR THE CUSTOMERS AND COMMUNITIES WE SERVE

TODAY, THAT MEANS WE'RE DRIVEN TO MAKE A DIFFERENCE - TO ACHIEVE NET ZERO BY 2040

DECARBONISED ELECTRICITY

RESILIENT INFRASTRUCTURE

EMPOWERED CUSTOMERS

OUR PEOPLE • DIGITAL & DATA DRIVEN • FINANCIALLY STRONG • SUSTAINABLE & SOCIALLY RESPONSIBLE

OUR VALUES

WE'RE COURAGEOUS

WE'RE CARING

WE'RE DRIVEN

WE'RE TRUSTED

OUR ROLE

PURPOSE

At ESB, we're driven to make a difference.
Delivering a brighter future; creating and connecting sustainable, reliable, affordable energy; and supporting the customers and communities we serve to achieve net zero.

WHAT WE WILL DO

DECARBONISED ELECTRICITY

Develop and connect renewables to decarbonise the electricity system by 2040

RESILIENT INFRASTRUCTURE

Provide resilient infrastructure for a reliable low carbon electricity system

EMPOWERED CUSTOMERS

Empower, enable and support customers and communities to achieve net zero

FOUNDATIONAL CAPABILITIES

OUR PEOPLE

Ensure we have the people capability to deliver our strategic objectives with a strong values-based and inclusive culture

DIGITAL & DATA DRIVEN

Leveraging data and technology, transform ESB to a data driven digital utility

FINANCIALLY STRONG

Maintain the financial performance and strength required to deliver our purpose

SUSTAINABLE & SOCIALLY RESPONSIBLE

Step forward on social and environmental responsibility, cultivating a safe, sound and sustainable ethos in line with our values

HOW

OUR VALUES

- WE'RE COURAGEOUS
- WE'RE CARING
- WE'RE DRIVEN
- WE'RE TRUSTED

THE SCALE OF OUR AMBITION

These are the most significant changes in strategic ambition from our previous 2017 strategy

Decarbonise ESB: Science Based Target 2030, Net Zero 2040

Higher renewable targets

Faster, steeper reduction in carbon intensity

Increased focus on Island of Ireland / GB investment for specific purposes

Transform ESB to a data driven digital utility

Position for large scale storage and renewable balance

Transition to reliable low carbon electricity system

Step forward on social and environmental responsibility – cultivating a safe, sound and sustainable ethos in line with our values

Scaled up ambition for electrification of heat and transport

Refocused approach to energy services

Ensure we have the people capability to deliver our strategic objectives, with a strong, values based and inclusive culture

STRATEGIC AMBITION - ESB IN 2030 - KEY METRICS

	TODAY	2030
ESB renewable generation	976MW	> 5,000MW
Wind connected to networks (ROI + NI)	6.5GW	> 15GW
Share of ESB generation from zero carbon	~ 20%	63%
Networks asset base regulated (ROI + NI)	~ €11bn	> €16bn
EVs and heat pumps connected networks (ROI + NI)	~ 100k	~ 2m
Carbon intensity of generation fleet	414 gCO_2/kWh	<140 gCO_2/kWh
Home retrofits	Start up	35k
Satisfied customers	79-85%	> 85%
Premises passed with SIRO infrastructure	420k	770k

Strong alignment with Climate Action Plan

OUR VALUES

WE'RE COURAGEOUS

Each of us is prepared to challenge the way we've always done things, stand up for what we feel is right and try better ways of working.

WE'RE CARING

We're putting customers current and future needs at the heart of what we do and we keep ourselves and others safe and healthy.

WE'RE DRIVEN

We bring passion and persistence to what we do everyday, innovating and collaborating to meet the challenges and opportunities ahead.

WE'RE TRUSTED

We each play our part, taking ownership of our responsibilities, seeing the job through and protecting our own health and safety, as well as others'.

ESB’s Vision

Wind Energy

At ESB, we want our wind farm investments to deliver long-term social, economic and environmental benefits for everyone. We believe in the power of wind energy and the potential it holds to change our world. As such, wind energy infrastructure is a core component of ESB's sustainability strategy.

A challenging Week - 2-8 October 2022

LATEST WIND GENERATION
1,046 MW

TODAY'S FORECAST PEAK WIND
2,802 MW

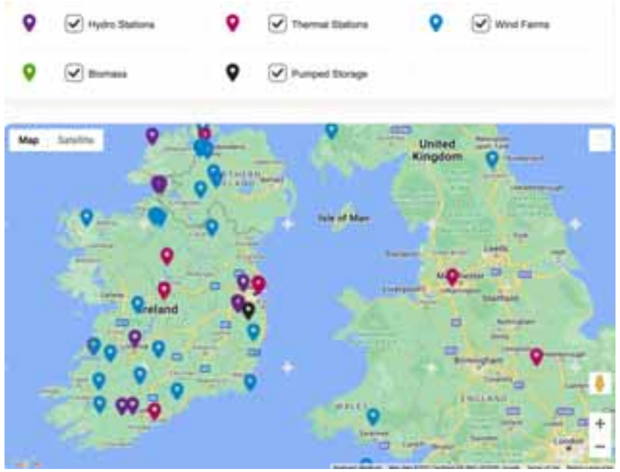
MAX WIND OUTPUT ALL TIME
4,585 MW

Actual and Forecast Wind Generation

Wind Generation is an estimate of the total electrical output of all wind farms on the system. Actual and Forecast Wind Generation are shown in 15 minute intervals.

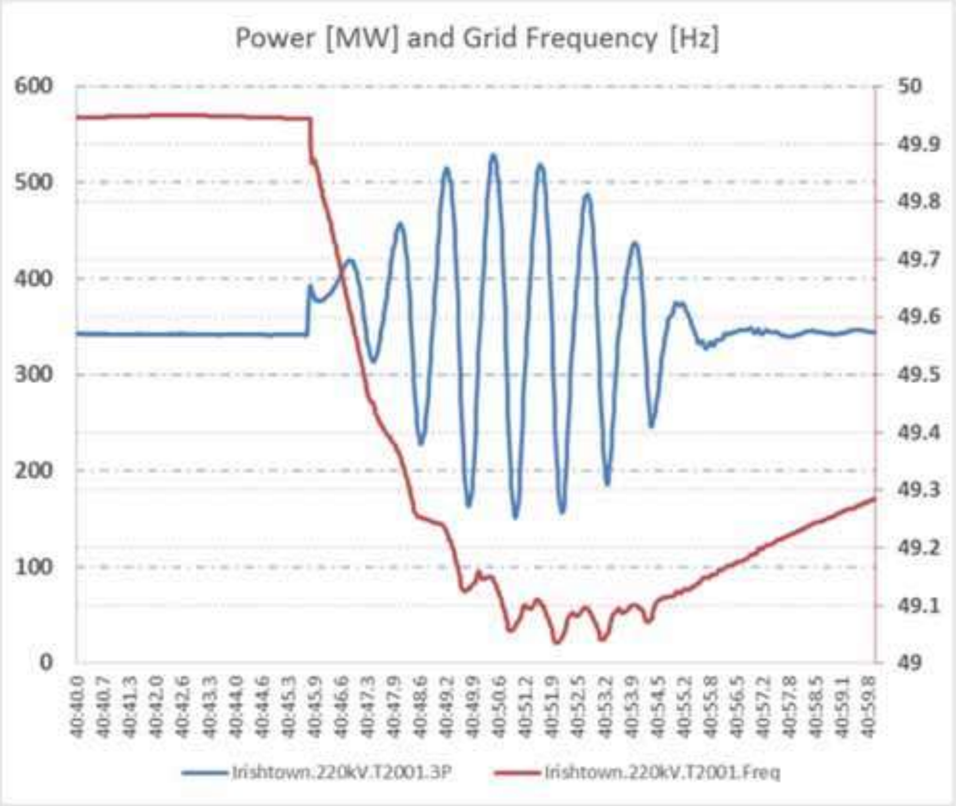
This Week (02/10/2022 - 8/10/2022)

- High volatility in Wind Generation
- Challenging System Margins:
    - Some Units are out of service on planned overhauls
    - Demand on high availability and reliability of conventional generation capacity



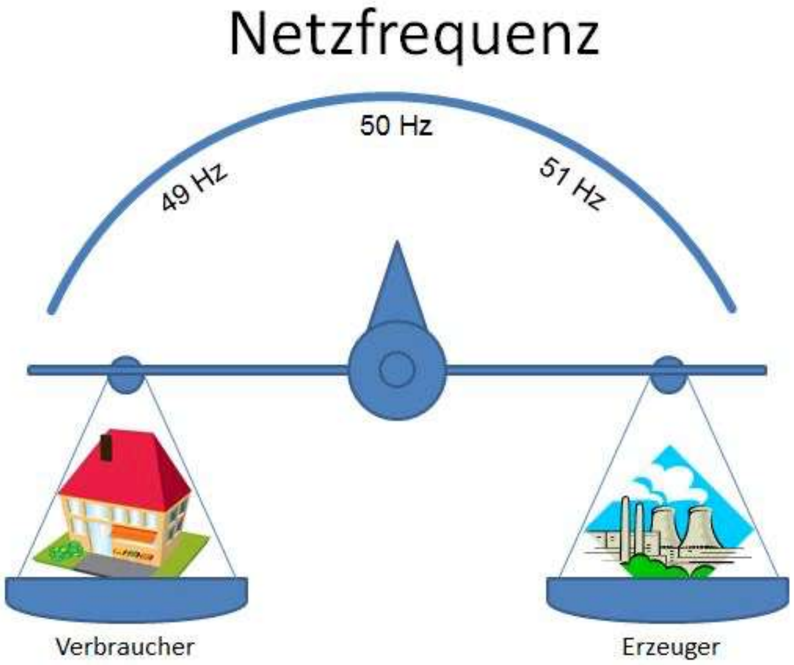
ESB Fleet

Real Event, Frequency Drop, DBP

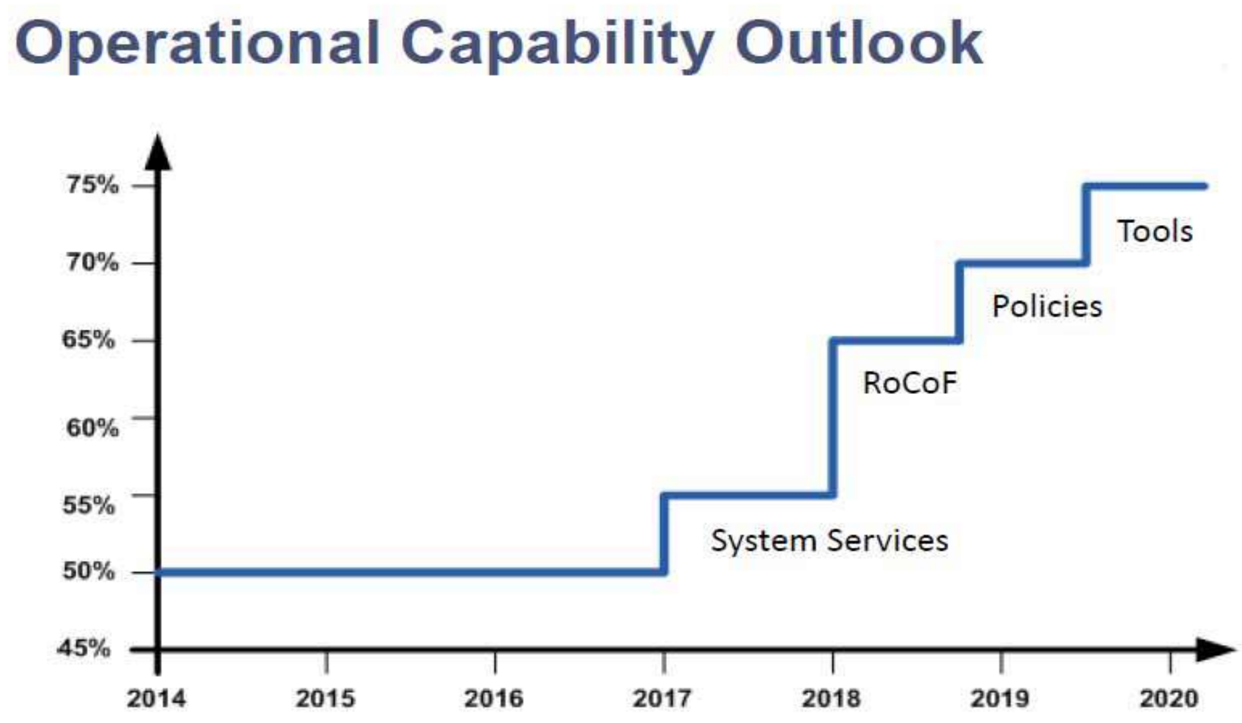


Fuel: Natural gas
Capacity: 410MW
Commissioned: 2002
Technology: Combined Cycle Gas Turbine (CCGT)

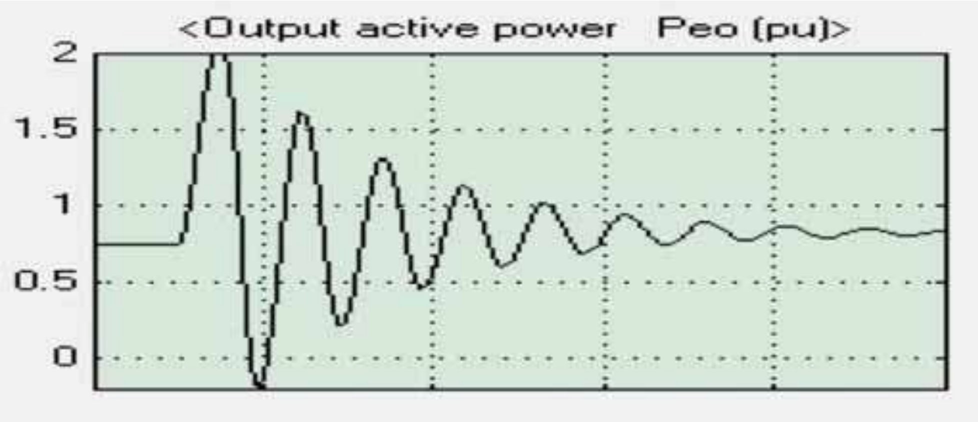
Electricity System Analogy

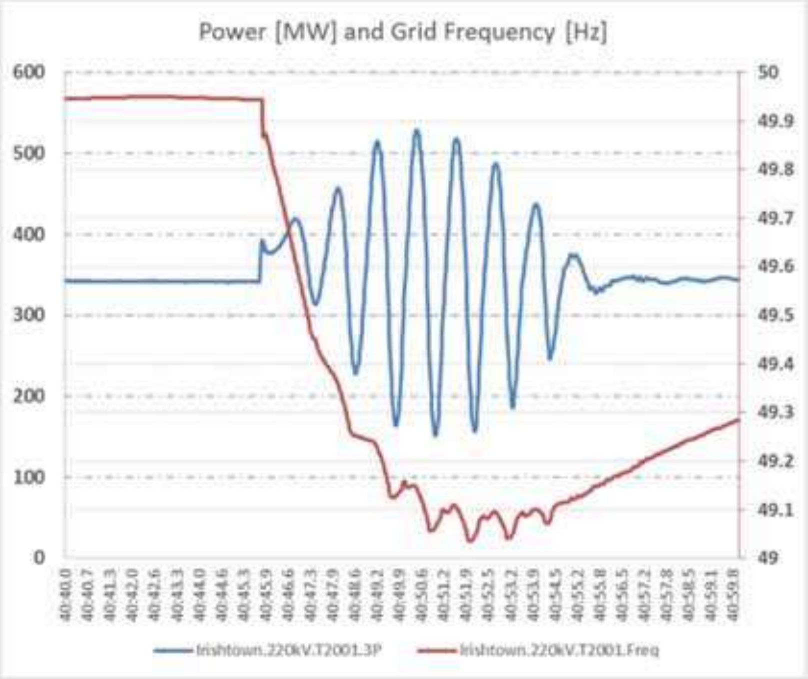


SNSP – Timeline (System Non Synchronous Penetration)

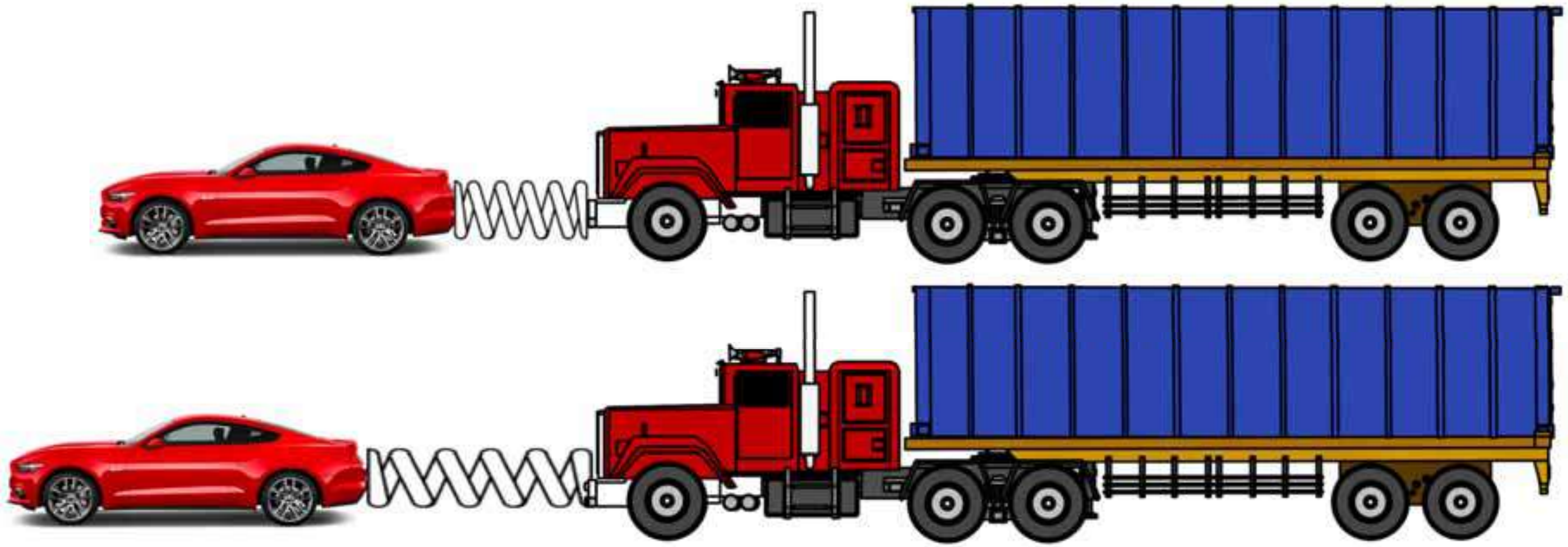


“Continental Model” – Infinite Inertia vs “Island Model” – Finite Inertia





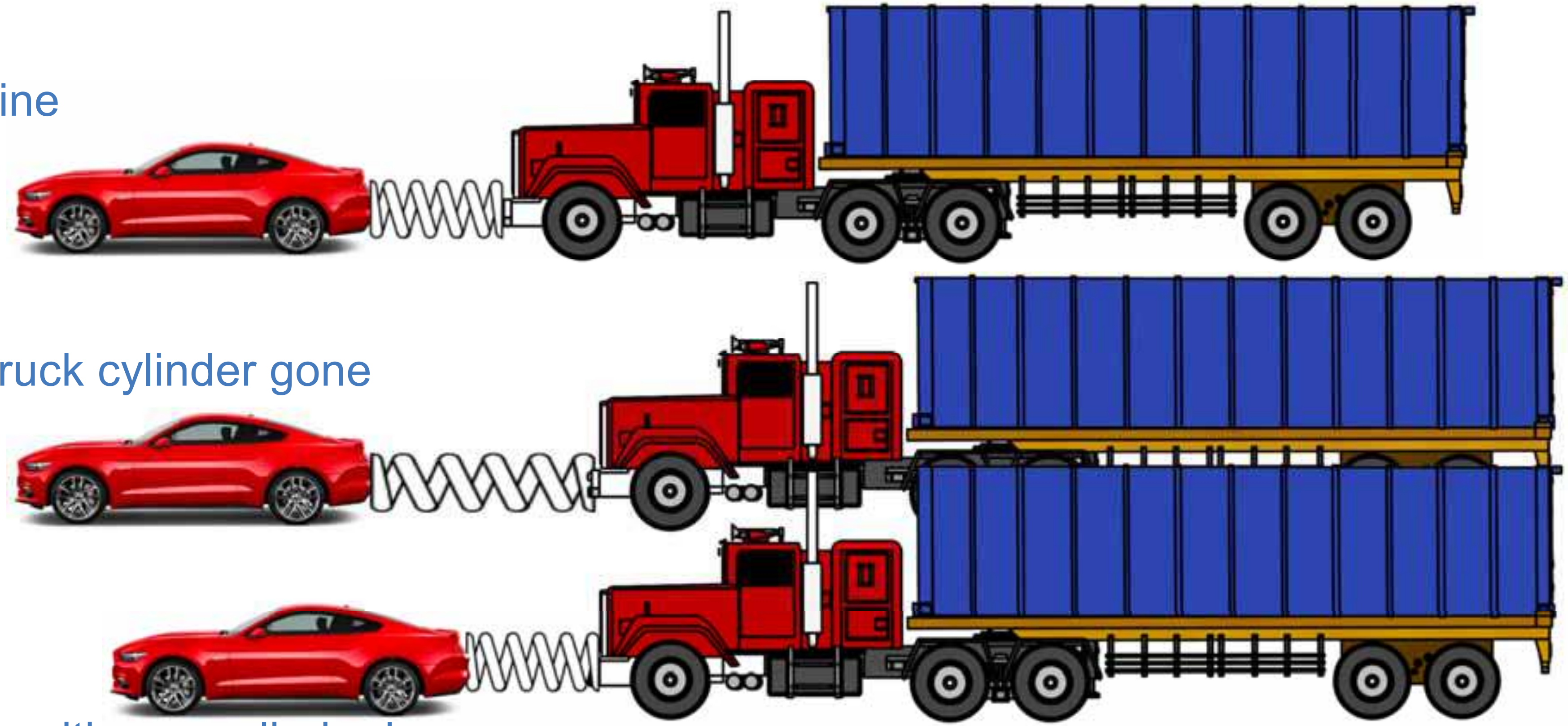
Car floors the Gas Pedal



Truck and Car drive at 100km/h, constant

Distance between Car and Truck indicates the power of car (how strong you push the gas)

Motorway analogy

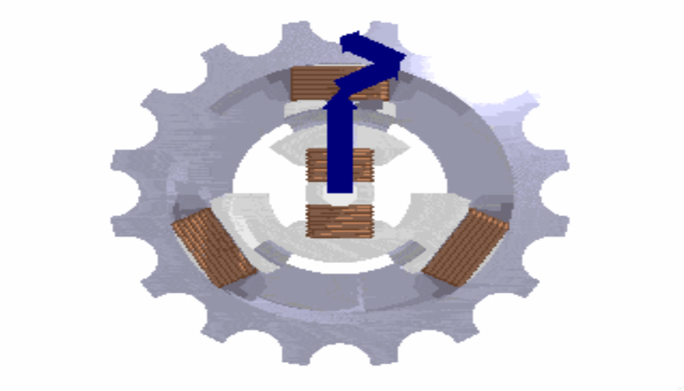


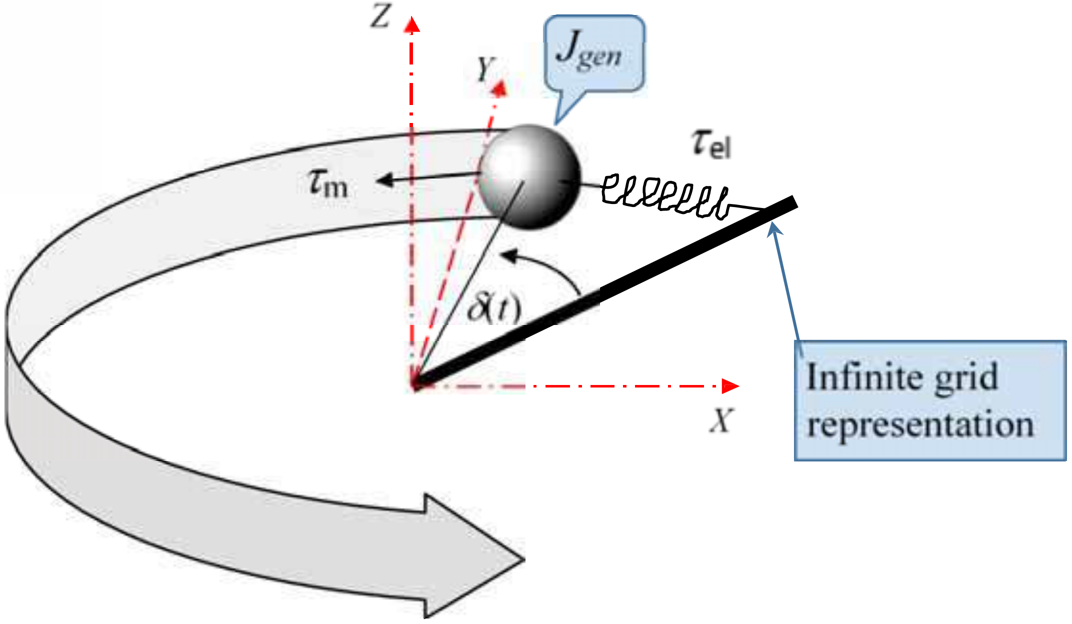
All fine

One truck cylinder gone

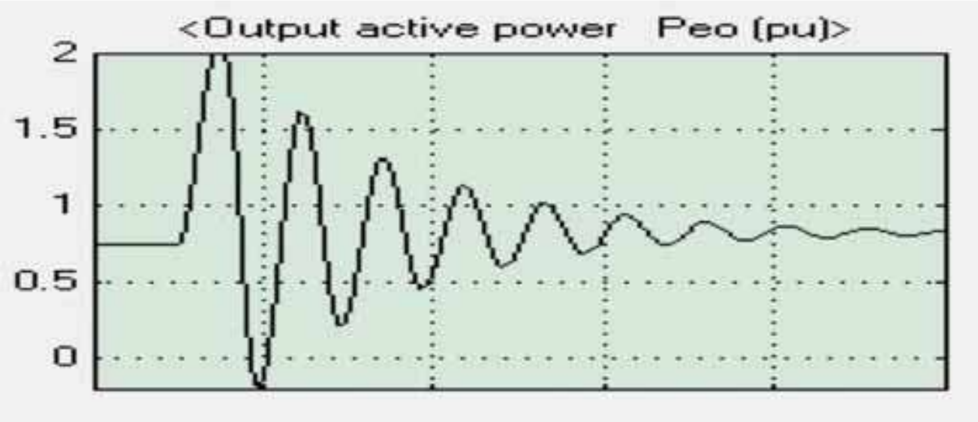
Stable with one cylinder less

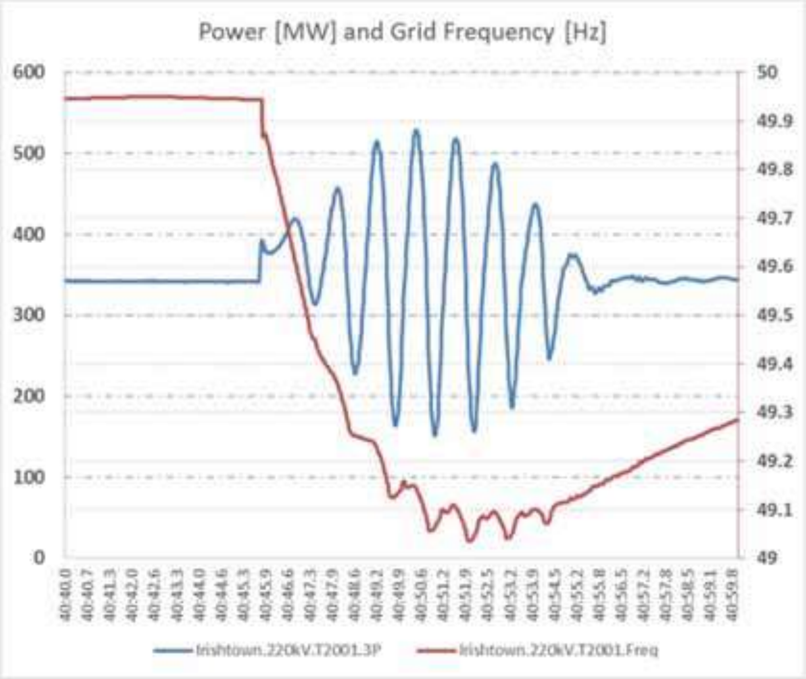
Infinite Grid



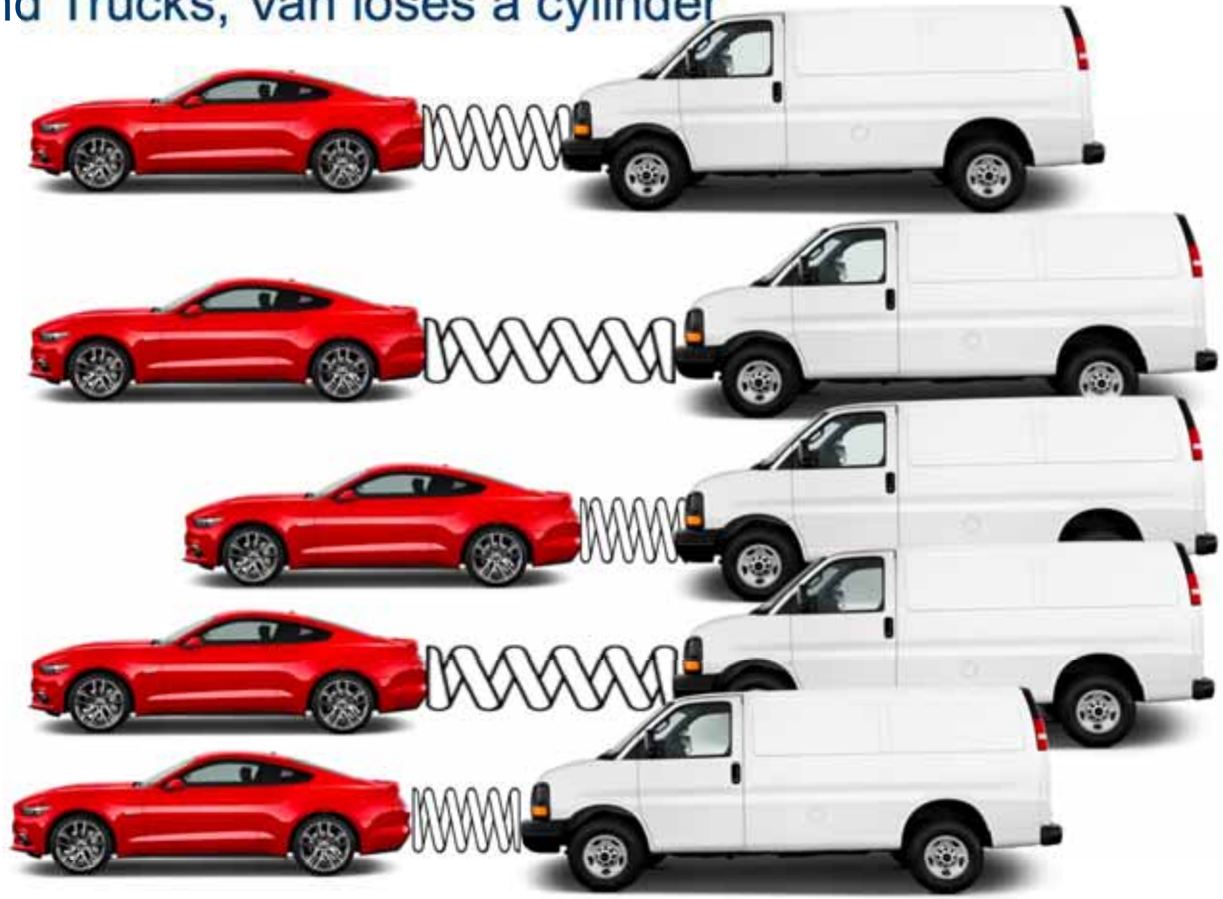


“Continental Model” – Infinite Inertia



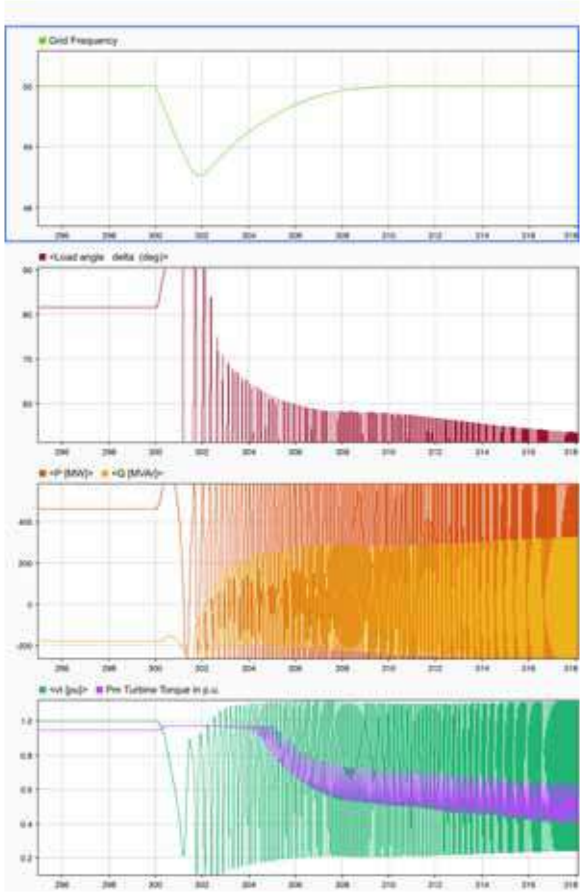


Cars and Trucks, Van loses a cylinder

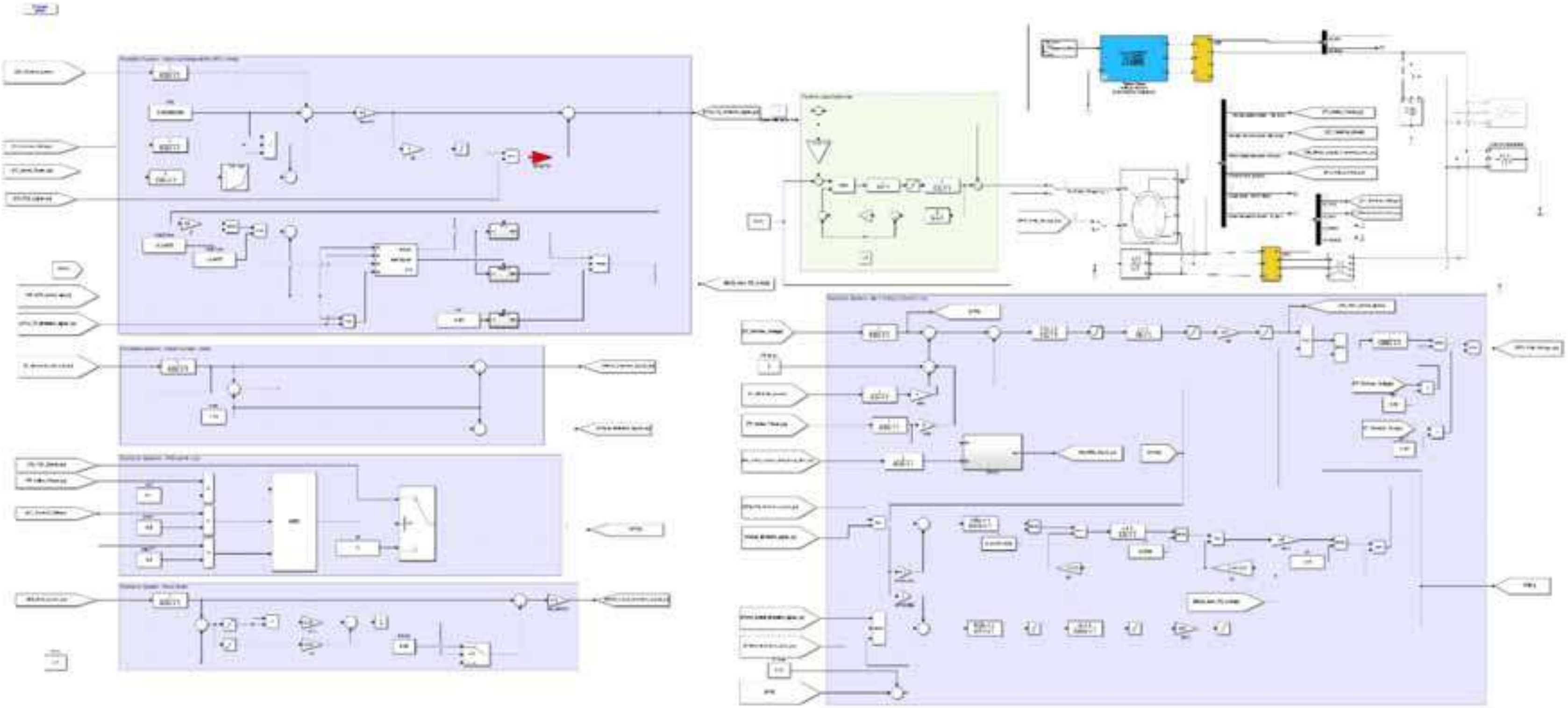


Trip due to Generator Pole Slip, Simulation after MXL2

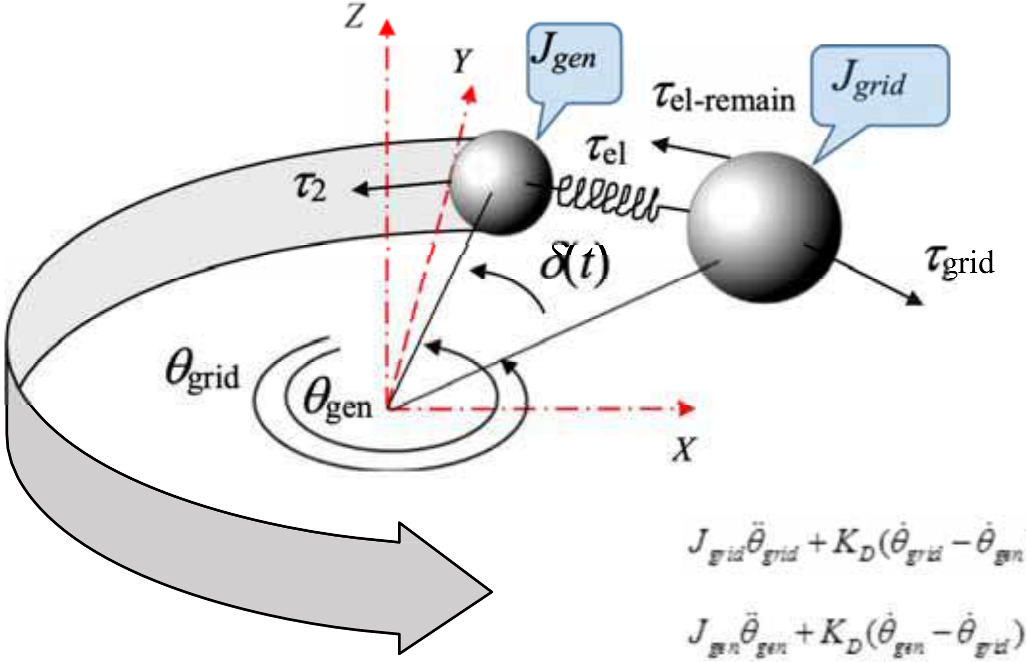
Aghada Unit 2, Single shaft CCGT
461 MW at generator terminals, 2010

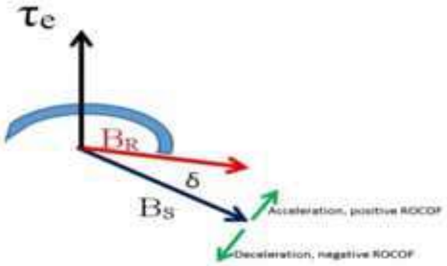


Modelled Turbine Governor and Voltage Controller



Equations of motion

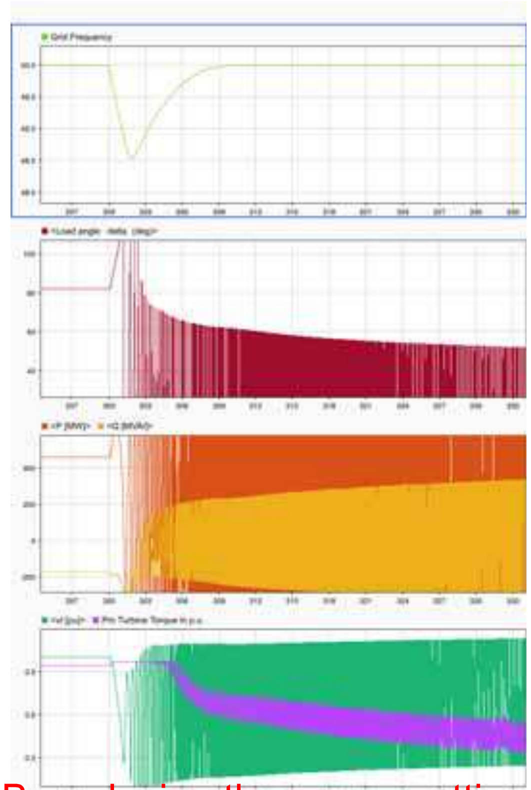


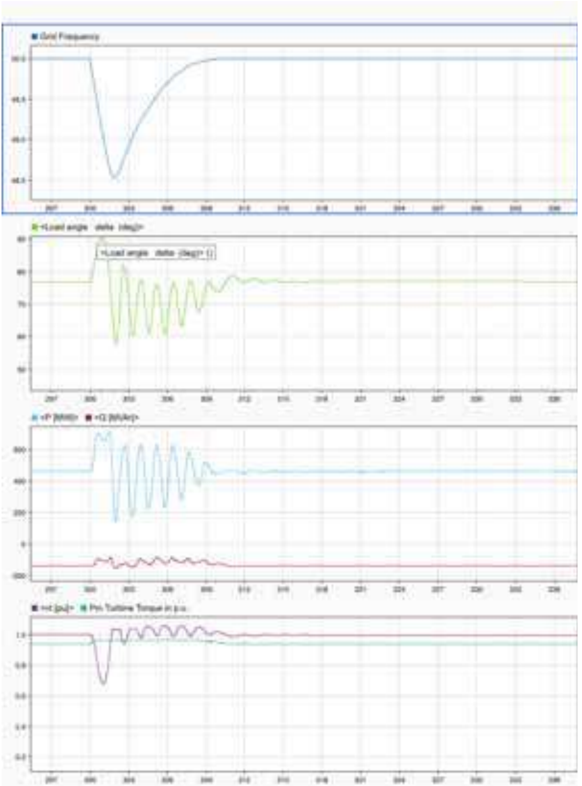


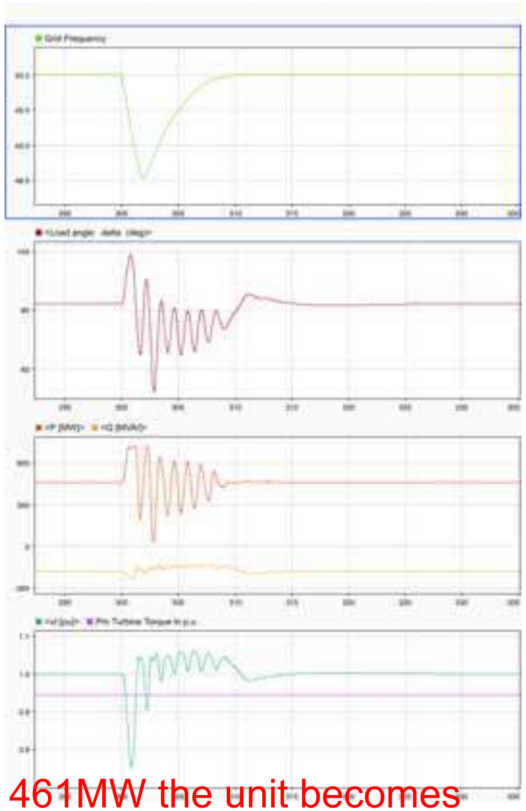
$$J_{grid}\ddot{\theta}_{grid} + K_D(\dot{\theta}_{grid} - \dot{\theta}_{gen}) + \tau_{el\max}\sin(\theta_{grid} - \theta_{gen}) = \tau_1 = \tau_{grid} - \tau_{el-remain}$$

$$J_{gen}\ddot{\theta}_{gen} + K_D(\dot{\theta}_{gen} - \dot{\theta}_{grid}) + \tau_{el\max}\sin\left(\theta_{gen} - \theta_{grid}\right) = \tau_2 = \tau_{gen}$$

Trip due to Generator Pole Slip (Simulated)



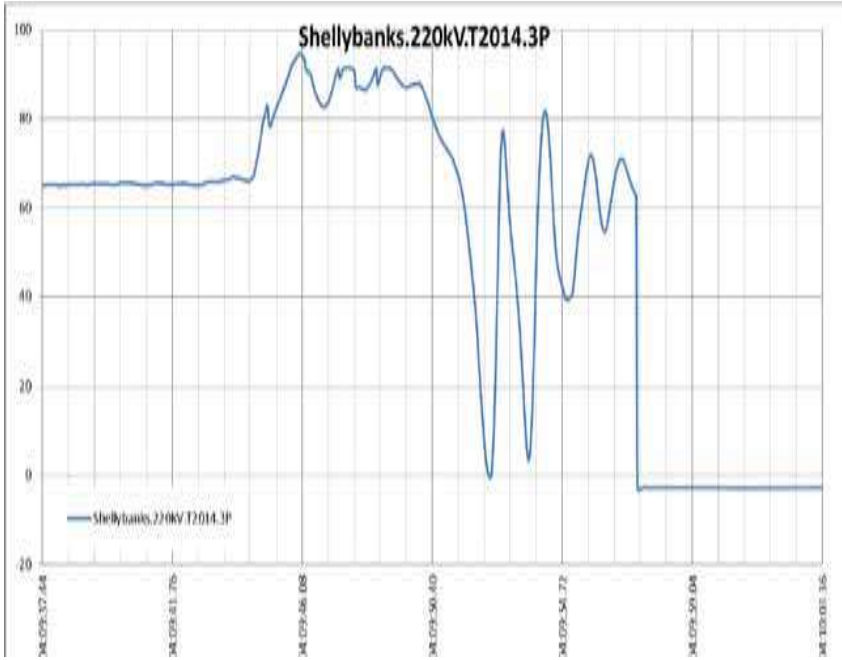




By reducing the wrong setting of the maximum load from 470MW to 461MW the unit becomes compliant to the grid code. Unfortunately, until this modification is done the Under-Excitation Limits had to be reduced by 45MVAr which costs €2700 per day!

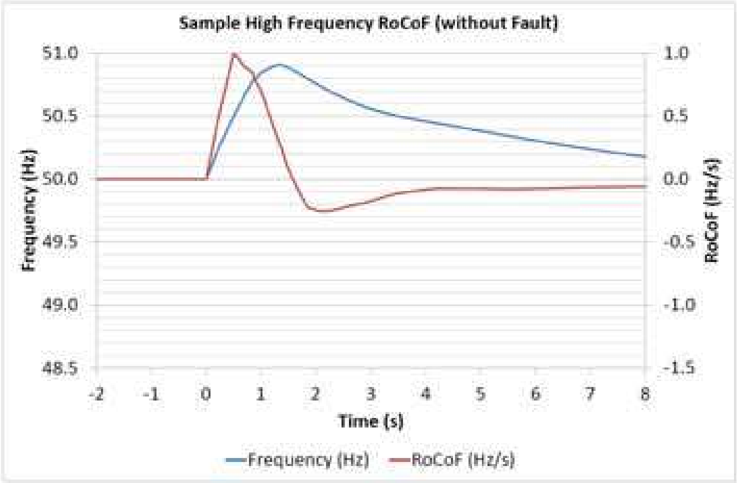
Real Event, Poolbeg CT 15 @ 65 MW

Fuel: Natural gas
Capacity: 480MW
Commissioned: 1994, 1998-99
Technology: Combined Cycle Gas Turbine (CCGT)



Real Event, North Wall, Trip on reverse power

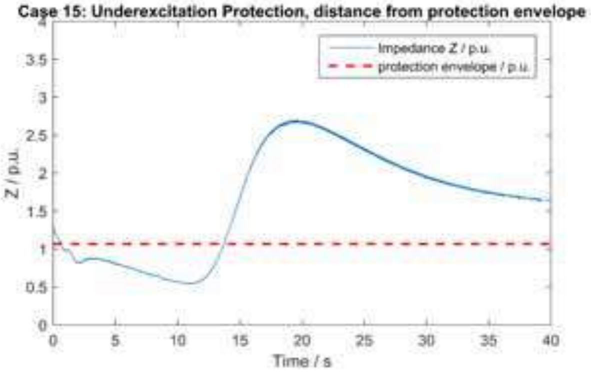
County: Dublin
Fuel types: Oil; Gas
Capacity: 106 MW
Commissioned: 1982



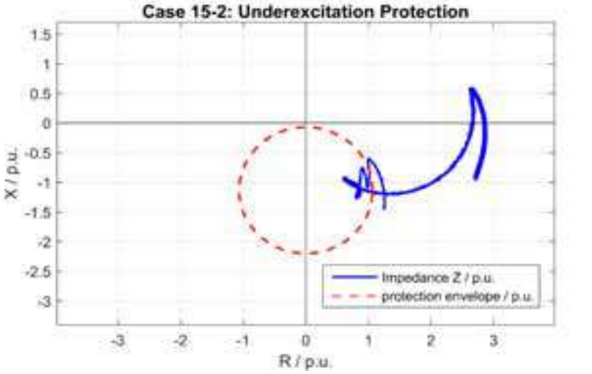
During RoCoF tests a frequency rise signal was injected. The unit, seeing a frequency rise closed the controlvalves and went into reverse power and tripped

Trip on Under excitation Protection (Simulation by Injection)

Lough Ree Power, Peat burning boiler, Steam Turbine, 100MW



Case 15: Underexcitation Protection, distance from protection envelope

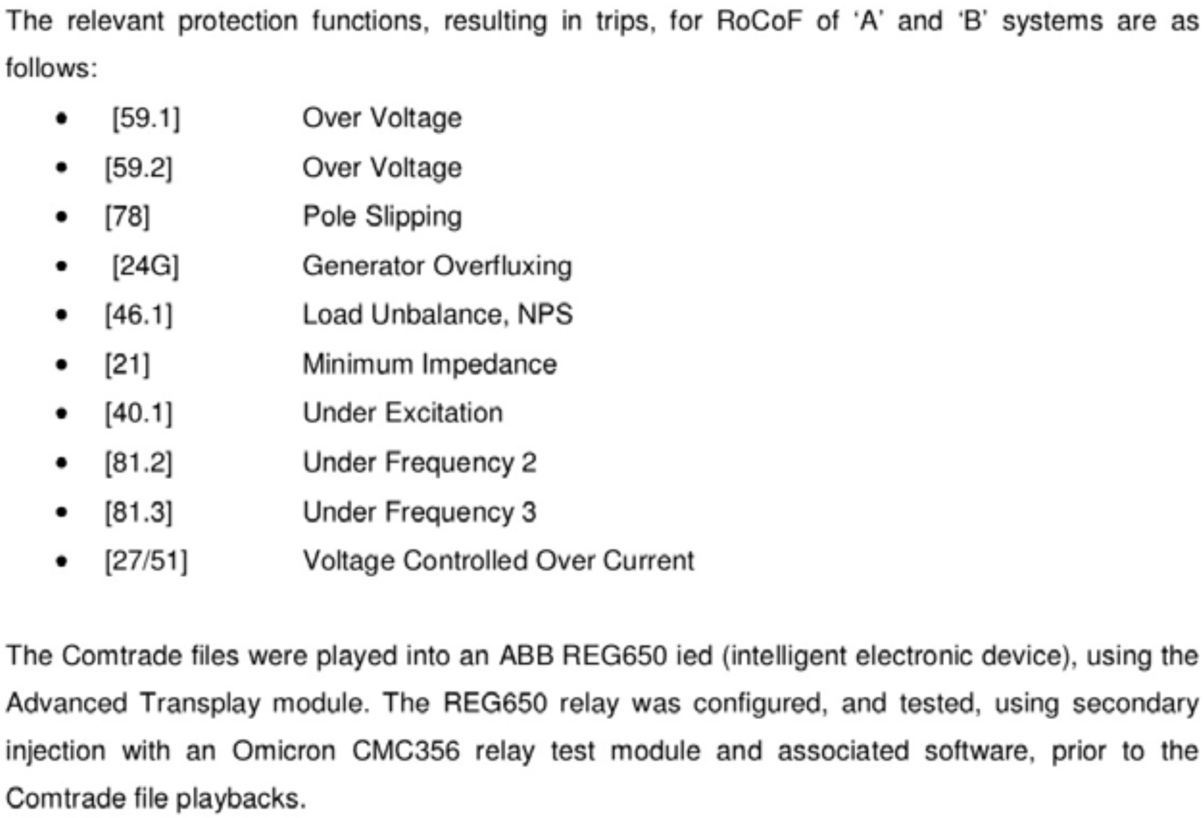


Case 15-2: Underexcitation Protection

Enerlyzer Software with CMC356

https://www.omicronenergy.com/fileadmin/_processed_/d/b/csm_Protection-Troubleshooting-CMC-TU-EnerLyzer-gallery_c616a4c1b0.jpg

Generator Protection Study

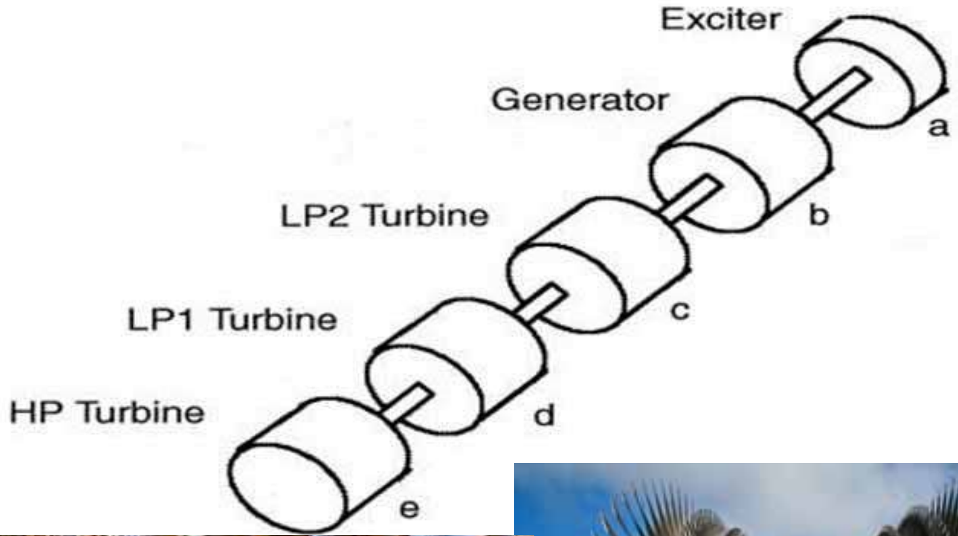


The relevant protection functions, resulting in trips, for RoCoF of ‘A’ and ‘B’ systems are as follows:

[59.1]	Over Voltage
[59.2]	Over Voltage
[78]	Pole Slipping
[24G]	Generator Overfluxing
[46.1]	Load Unbalance, NPS
[21]	Minimum Impedance
[40.1]	Under Excitation
[81.2]	Under Frequency 2
[81.3]	Under Frequency 3
[27/51]	Voltage Controlled Over Current

The Comtrade files were played into an ABB REG650 ied (intelligent electronic device), using the Advanced Transplay module. The REG650 relay was configured, and tested, using secondary injection with an Omicron CMC356 relay test module and associated software, prior to the Comtrade file playbacks.

Mechanical Components

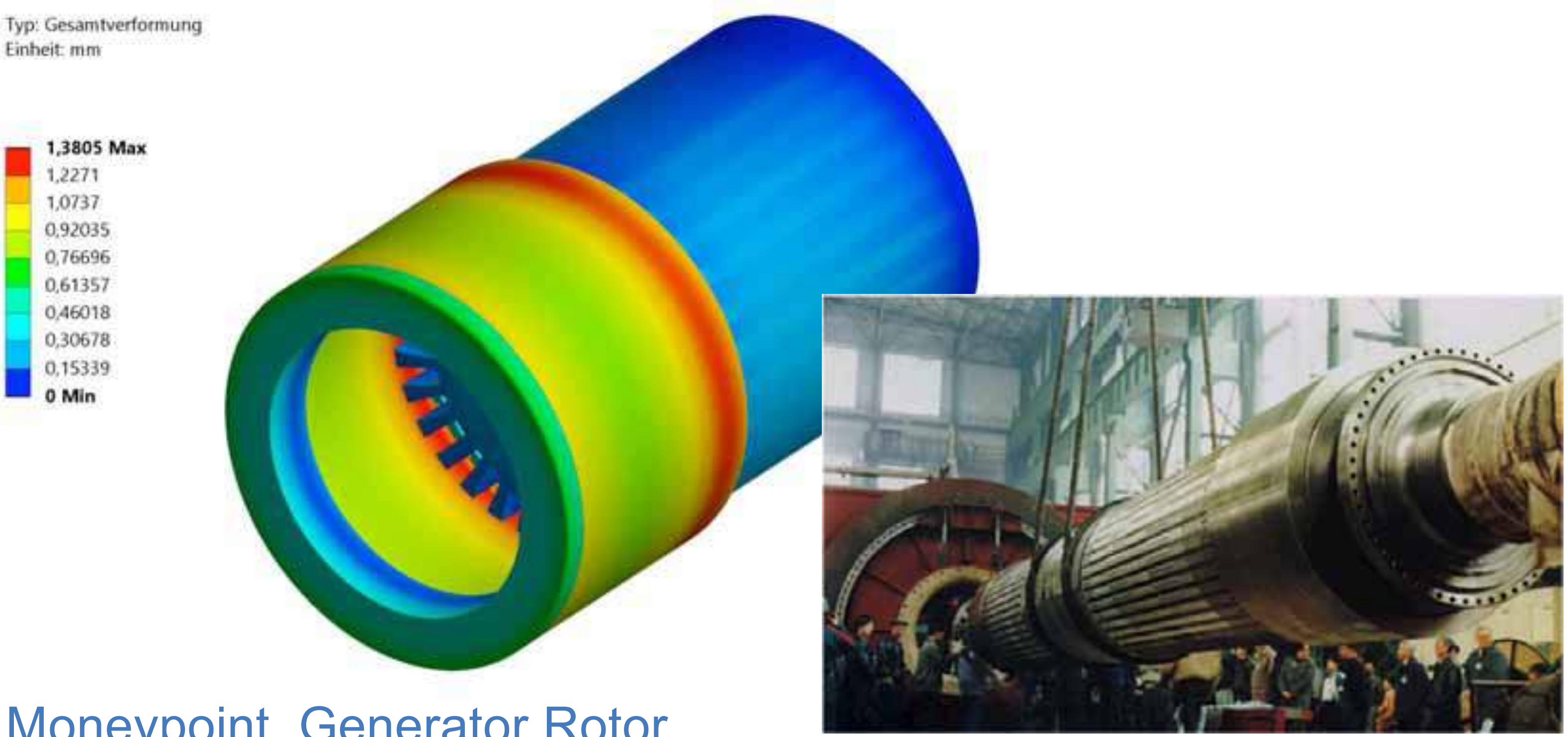


- Couplings
- Rotors and shafts
- Turbine blades and roots
- Generator rotor end bells

Mechanical Analysis, Moneypoint Generating Station

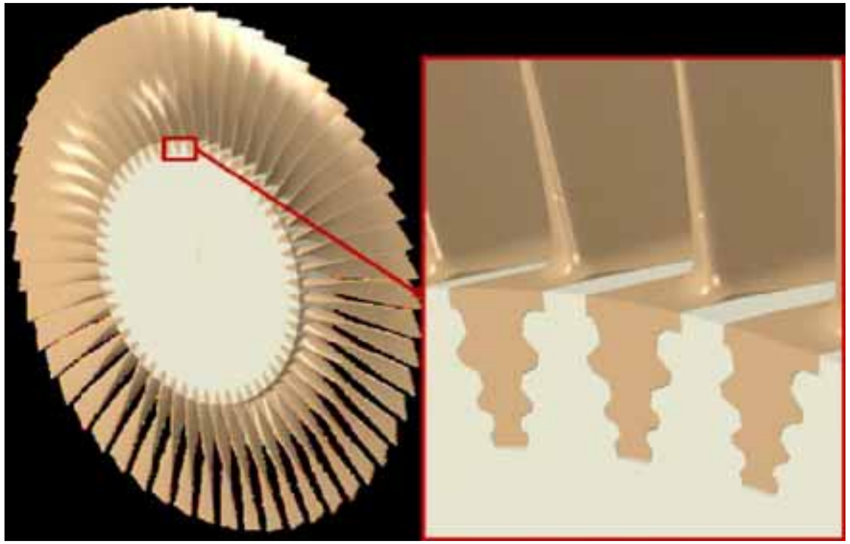
Fuel: Coal and Oil
Capacity: 915 MW
Commissioned: 1985, 1986 and 1987
Technology: 3 x Steam Turbines

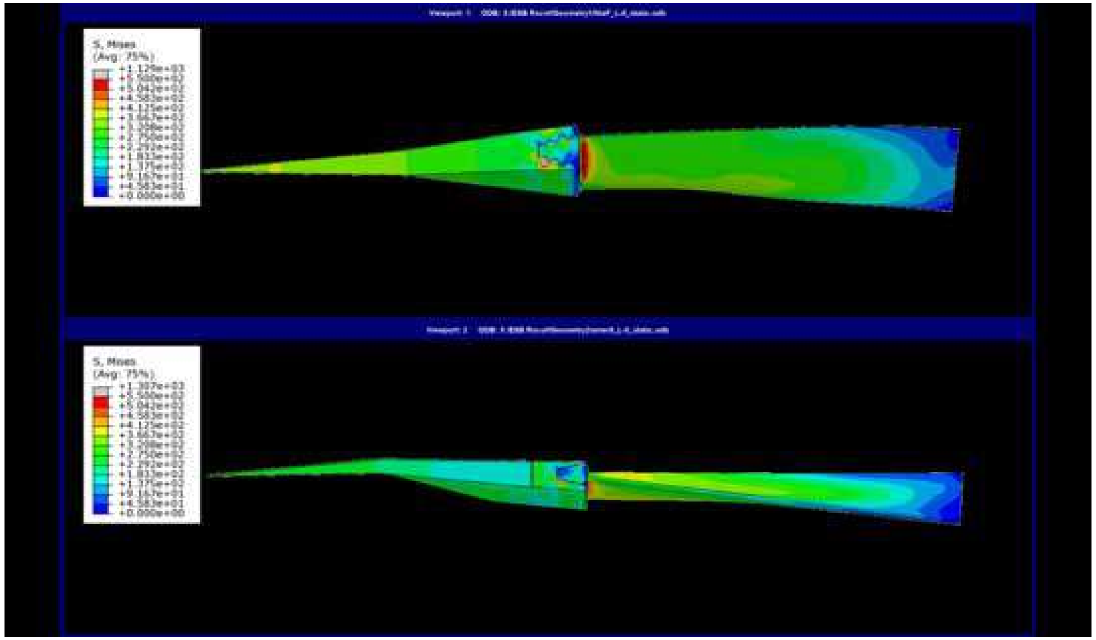
Stress on Rotor End Bell



TUV Report, Moneypoint, Generator Rotor

Mechanical analysis: Blade oscillations and stresses





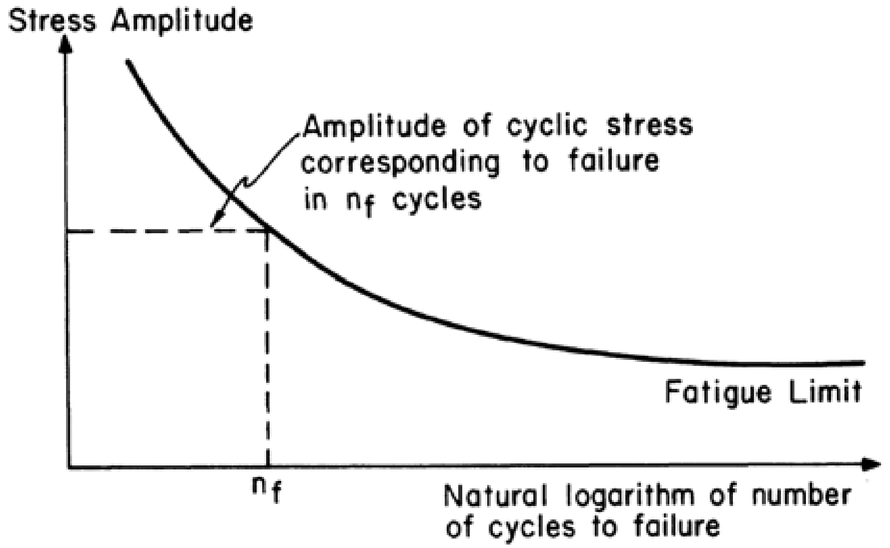
TUV Report, Moneypoint Steam Turbine 305MW

Risks related to mechanical integrity

Torsional oscillations can create stresses to:

- Couplings
- Rotors and shafts
- Turbine blades
- Generator rotor end bells
- Generator stator end windings

Woehler Curve (SN Curve):



Operational Consequences

ROCOF Event

Further loss of Electrical Power Generations

↓

Cascade Tripping Event

↓

Load Shedding in the system

↓

System Brown/Black Out

↓

Mech/Elec Integrity Consequences

RoCoF Event

Reduced Component Life Time

Consequential Machine Damage

Decreased overhaul intervals and

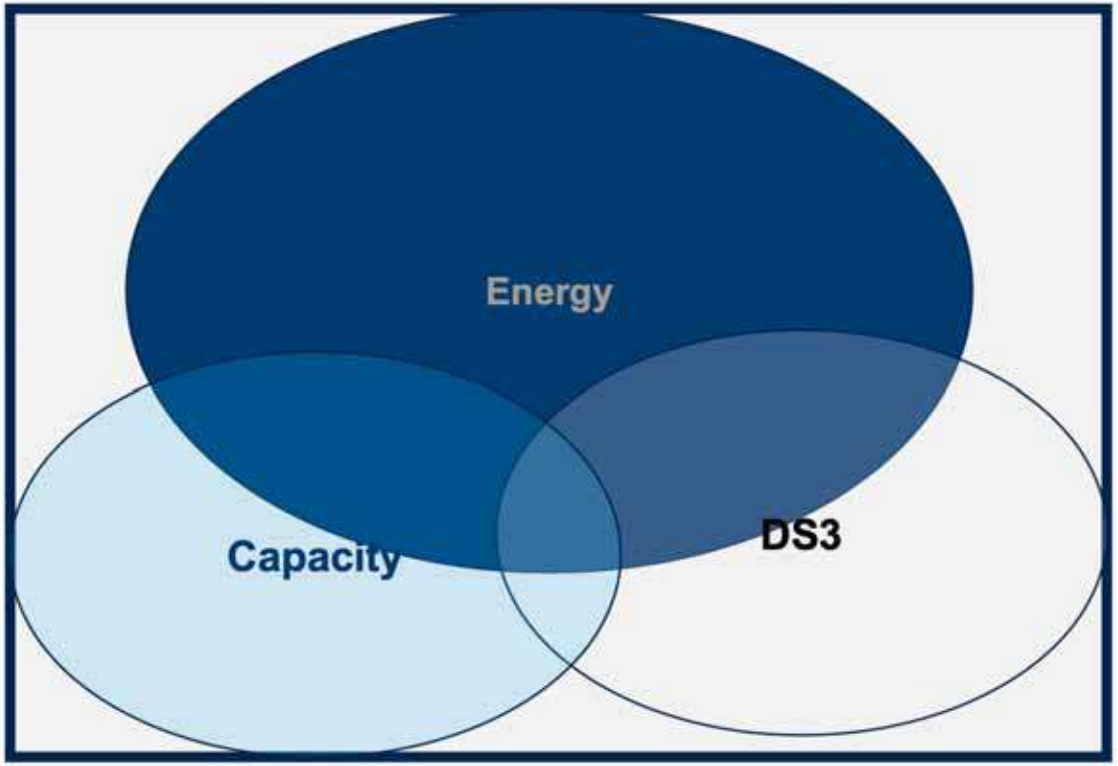
Increased Inspection Requirements

Forced Outage

RoCoF is a System Challenge

We need inertia

Introduction of a System Services Market



Performance Categorization

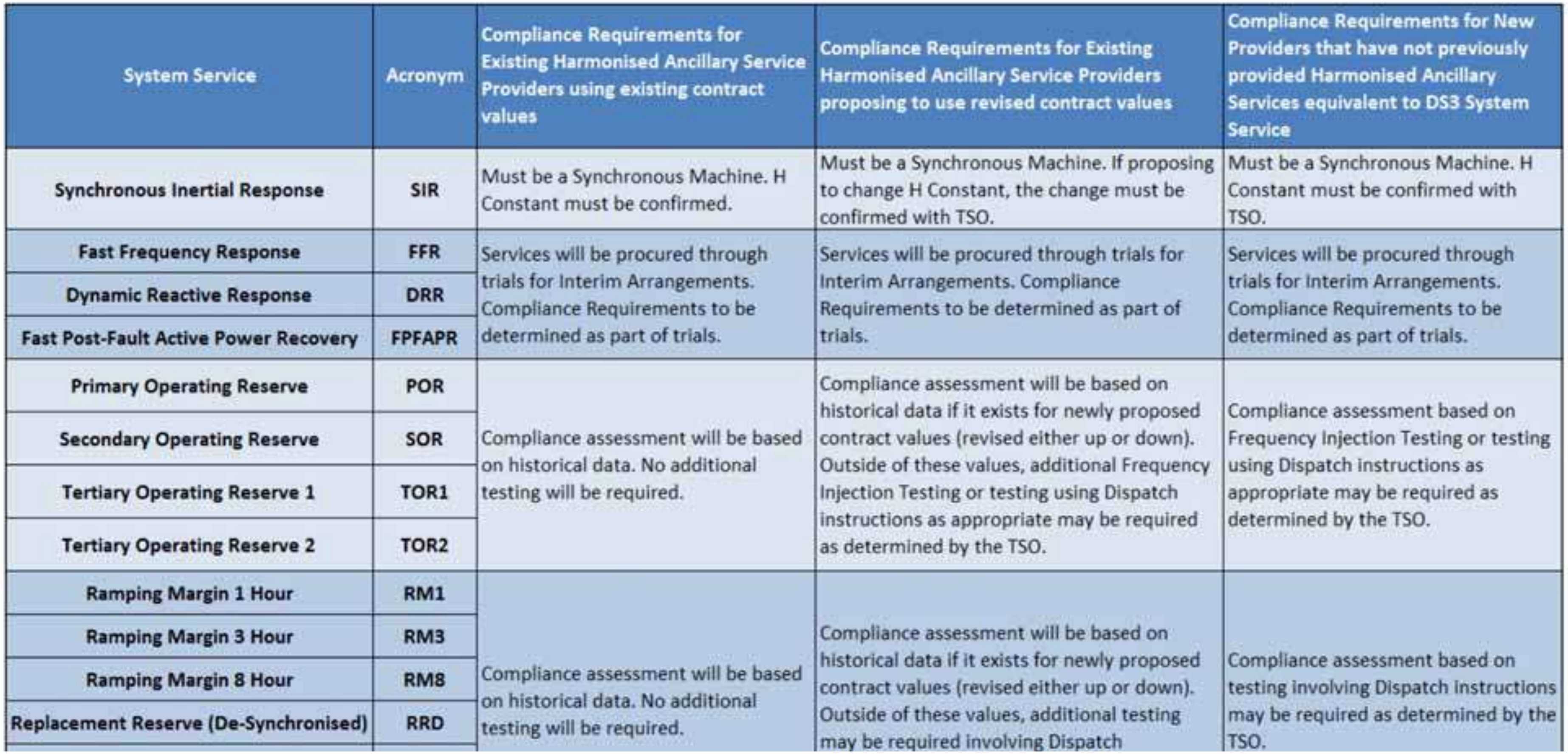
Reserve	POR	SOR	TOR1	TOR2	RRS
Ramping	RM1	RM3	RM8	RRD	
Inertia	SIR				
Fast-acting	FFR	FPFAPR	DRR		
Reactive Power	SSRP				

Delivering a **Secure, Sustainable Electricity System**" (DS3)

- www.eirgridgroup.com/site-files/library/EirGrid/DS3-System-Services-Interim-Protocol-Document-Version-2.1.pdf

Declaration	Fast Frequency Response	Ramping Margin 1 Hour	Ramping Margin 3 Hour	Ramping Margin 8 Hour	Dynamic Reactive Response	Fast Post Fault Active Power Recovery	Automatic Voltage Regulation	Current Fuel
EDIL Acronym	FFR	RM1	RM3	RM8	DRR	FPFAPR	AVR	FUEL
Description	Fast Frequency Response in MW	Ramping Margin 1-3 Hours in MW	Ramping Margin 3-8 Hours in MW	Ramping Margin 8-16 Hours in MW	Ability to provide Dynamic Reactive Response	Ability to provide Fast Post Fault Active Power Recovery	Ability to Act Under AVR	Current Fuel Being Used
Framework Agreement term	Declared FFR	Declared RM1	Declared RM3	Declared RM8	Declared DRR	Declared FPFAPR	Declared Automatic Voltage Regulator Status	No standalone term – used in average Availability calculation

DS3 - System Services



System Service	Acronym	Compliance Requirements for Existing Harmonised Ancillary Service Providers using existing contract values	Compliance Requirements for Existing Harmonised Ancillary Service Providers proposing to use revised contract values	Compliance Requirements for New Providers that have not previously provided Harmonised Ancillary Services equivalent to DS3 System Service
Synchronous Inertial Response	**SIR**	Must be a Synchronous Machine. H Constant must be confirmed.	Must be a Synchronous Machine. If proposing to change H Constant, the change must be confirmed with TSO.	Must be a Synchronous Machine. H Constant must be confirmed with TSO.
Fast Frequency Response	**FFR**	Services will be procured through trials for Interim Arrangements. Compliance Requirements to be determined as part of trials.	Services will be procured through trials for Interim Arrangements. Compliance Requirements to be determined as part of trials.	Services will be procured through trials for Interim Arrangements. Compliance Requirements to be determined as part of trials.
Dynamic Reactive Response	**DRR**			
Fast Post-Fault Active Power Recovery	**FPFAPR**			
Primary Operating Reserve	**POR**	Compliance assessment will be based on historical data. No additional testing will be required.	Compliance assessment will be based on historical data if it exists for newly proposed contract values (revised either up or down). Outside of these values, additional Frequency Injection Testing or testing using Dispatch instructions as appropriate may be required as determined by the TSO.	Compliance assessment based on Frequency Injection Testing or testing using Dispatch instructions as appropriate may be required as determined by the TSO.
Secondary Operating Reserve	**SOR**			
Tertiary Operating Reserve 1	**TOR1**			
Tertiary Operating Reserve 2	**TOR2**			
Ramping Margin 1 Hour	**RM1**	Compliance assessment will be based on historical data. No additional testing will be required.	Compliance assessment will be based on historical data if it exists for newly proposed contract values (revised either up or down). Outside of these values, additional testing may be required involving Dispatch	Compliance assessment based on testing involving Dispatch instructions may be required as determined by the TSO.
Ramping Margin 3 Hour	**RM3**			
Ramping Margin 8 Hour	**RM8**			
Replacement Reserve (De-Synchronised)	**RRD**			

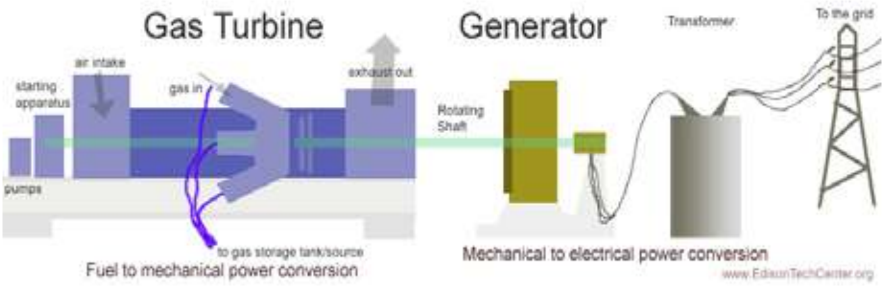
Moneypoint Synchronous Condenser

Katie Wall, Lead Engineer

June 2022

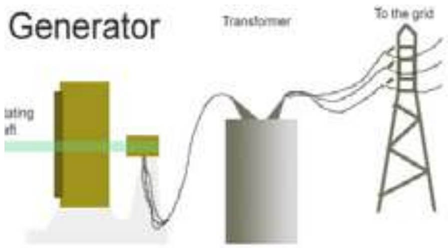
What is a Synchronous Condenser

IN
Fuel
Power (MW)



OUT
Power (MW)
Emissions
System Services (DS3)

IN
Power (MW)



OUT
System Services (DS3)

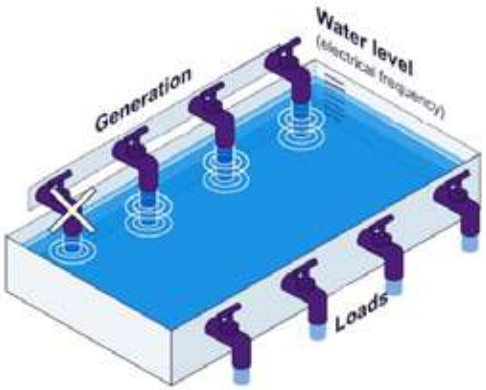
NO FUEL, NO COMBUSTION, NO EMISSIONS

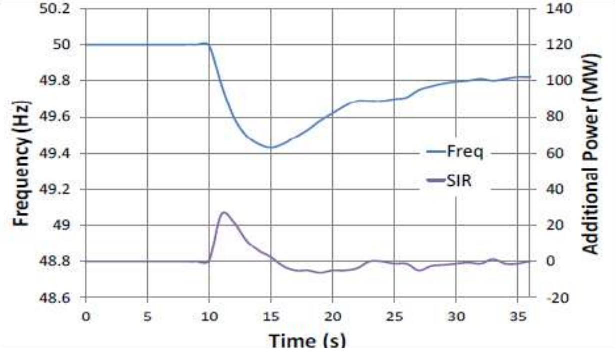
Images Reference: EdisonTechCentre.org

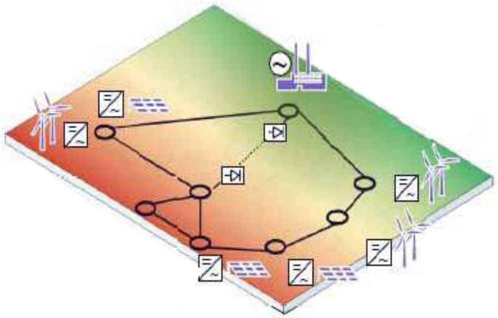
System Services

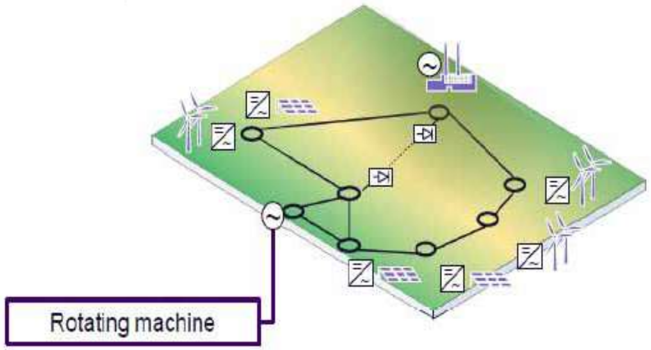
- Inertia (SIR)

- Reactive Power (SSR



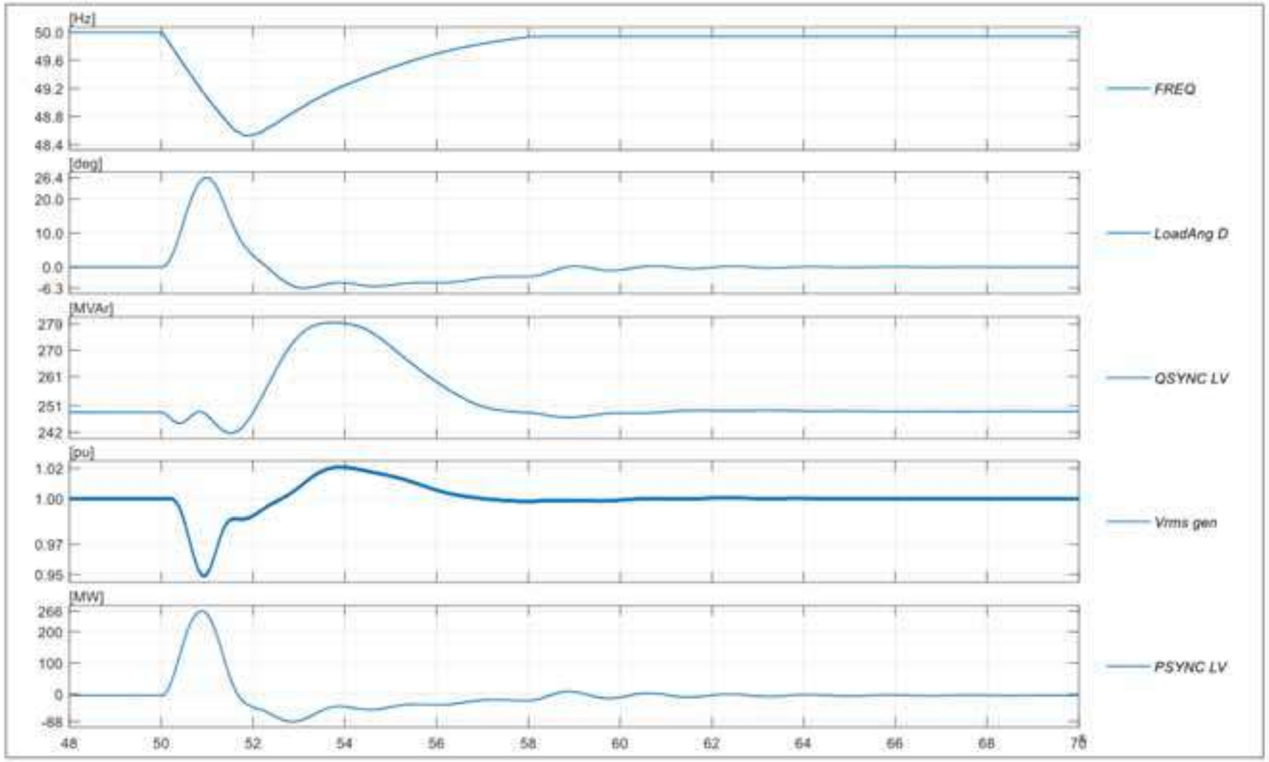






Images Reference: Siemens Energy, 2020

Response of Synchronous Condenser to a frequency event



Synchronous Condenser & Flywheel

Synchronous Condenser

- Inertia 512 MWs

Flywheel

- Inertia 3488 MWs

Total Inertia = 4000 MWs
= 2 x existing MP units

Images Reference: Siemens Energy, 2020

Synchronous Condenser

Siemens SGen5 1200A 2P

- +260 MVAr (capacitive/lagging), -111MVAr (inductive/leading)
- 970 MVA short circuit power
- Air Cooled
- Rotor weight = 67,160 kg

Syncon Rotor

Flywheel

Design based on existing gen rotors / LP turbines

- 4 m long, 2.2 m diameter
- Monoblock metal
- Rotor weight = 126,300 kg
- Water cooled
- Operates in Vacuum

Largest flywheel installation in world

Delivery to site

Flywheel forged in Italy, final machining & assembly in Mulheim, Germany

SynCon manufactured in Erfurt, Germany

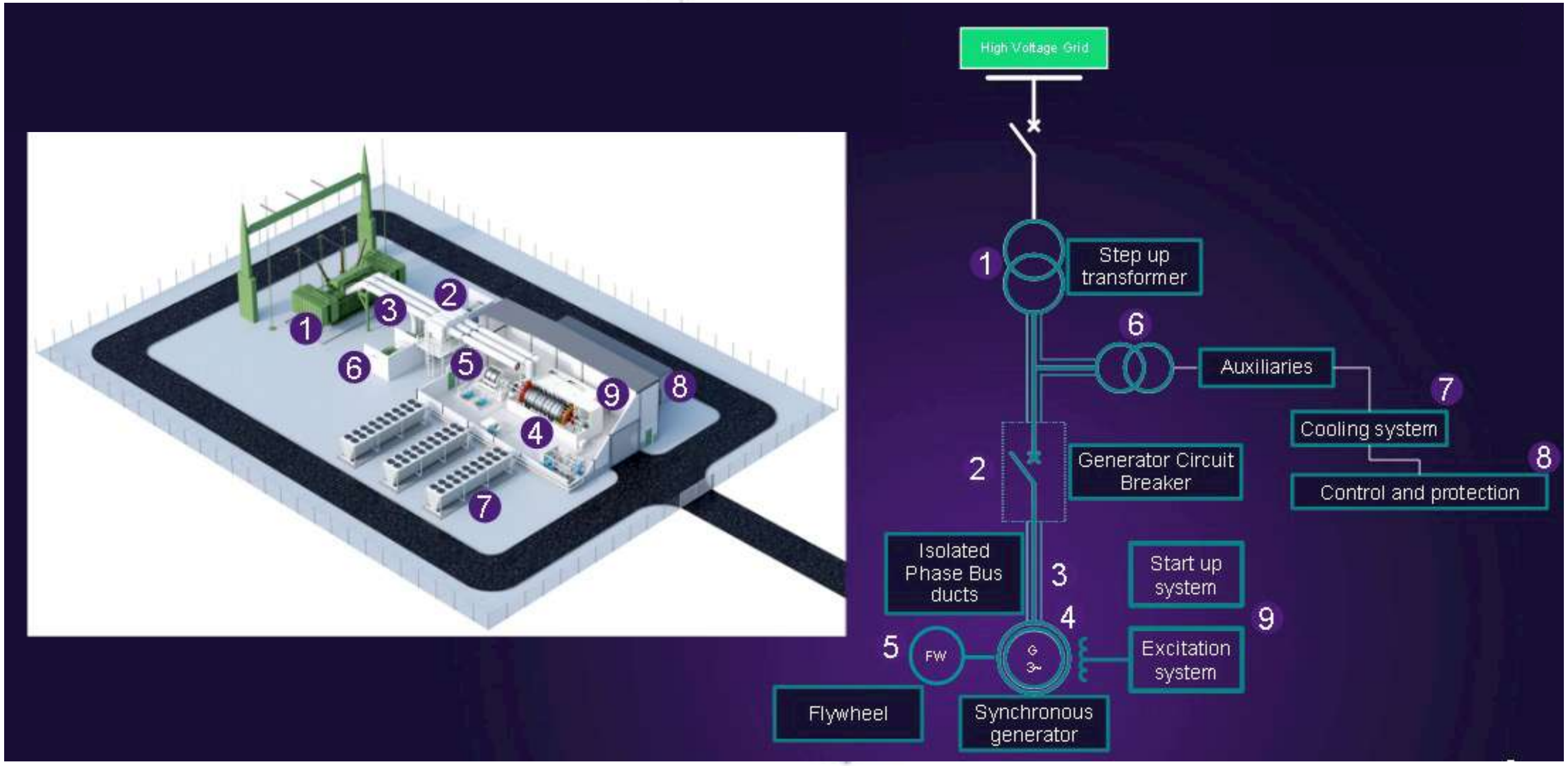
Barge to Rotterdam

Cargo ship to Foynes, Co. Limerick

Barge to Moneypoint jetty

Delivery to site

Moneypoint SynCon Layout

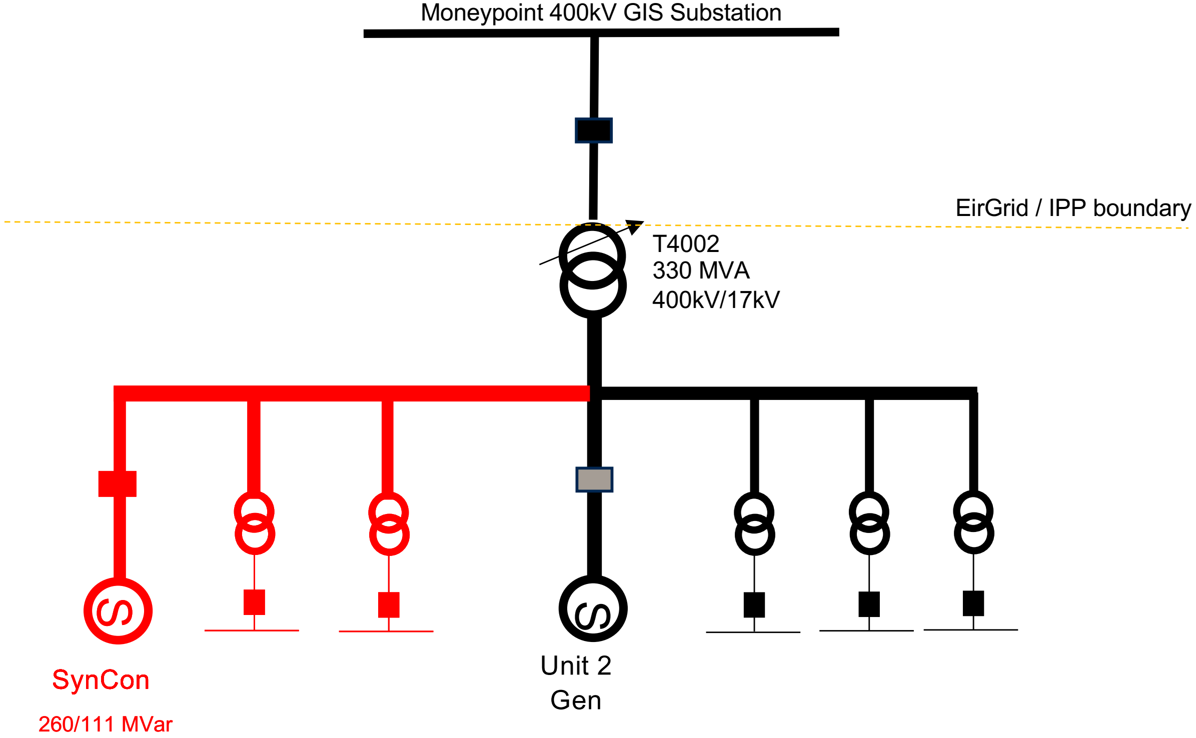


Images Reference: Siemens Energy, 2020

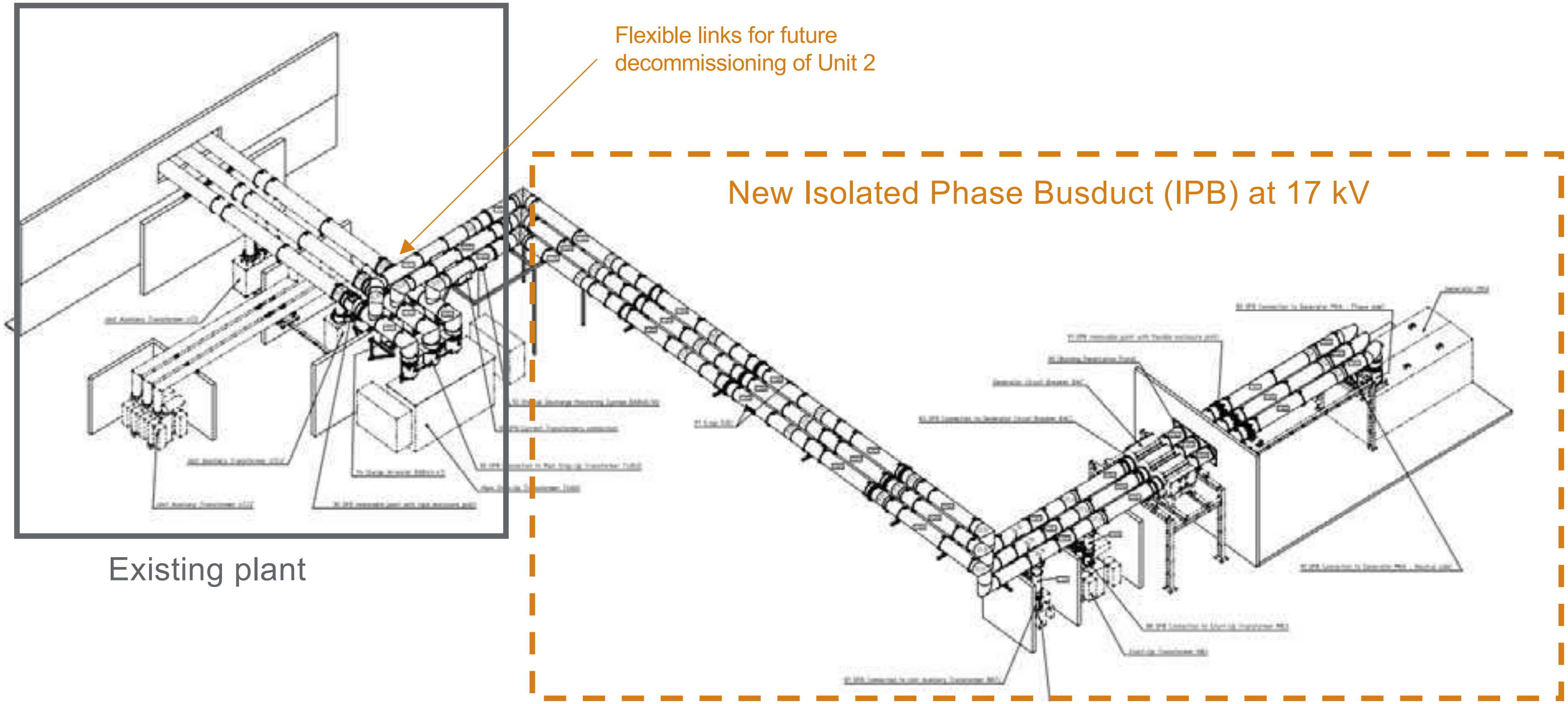
Shared Grid Connection with MP Unit 2

Note: MP2 & SynCon interlocked

Parallel Operation not permitted



Shared Grid Connection with MP Unit 2

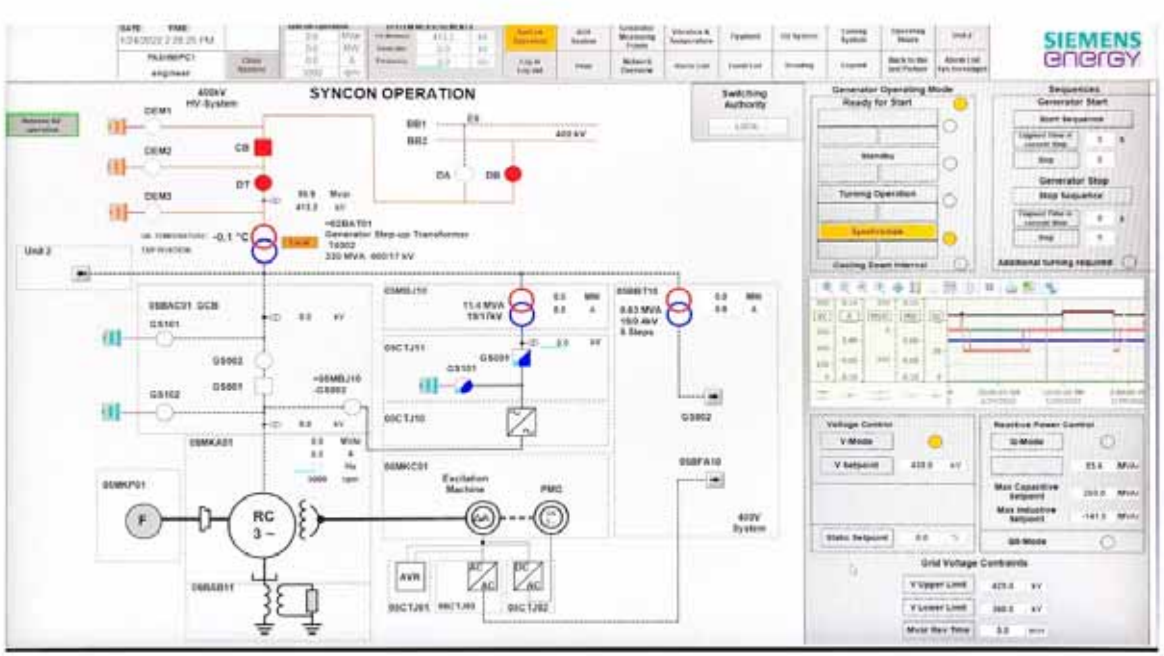


Flexible links for future decommissioning of Unit 2

New Isolated Phase Busduct (IPB) at 17 kV

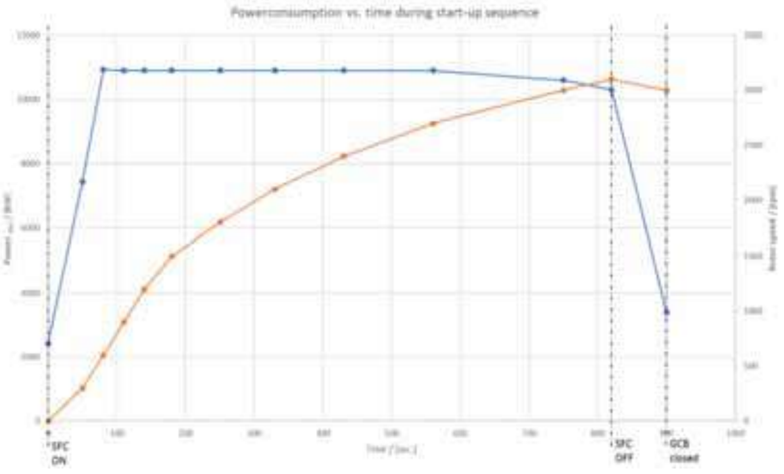
Existing plant

Remotely Operated from Dublin



15 mins start-up (11 MW import)

4 MW – 5 MW continuous operation depending on MVAr output



De-sync & coast down = 8 hours
(can use SFC for braking to reduce this)

Progress & Programme

Planning
Permission Aug '20 ✓

SIEMENS
energy

EPC Contract
April '21 ✓

Detailed Design
May '21 – April
'22 ✓

Site Mobilisation
Sept '21 ✓

SynCon & Flywheel
delivery
April '22 ✓

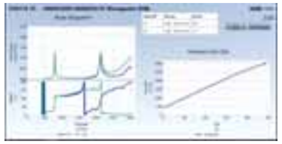
14 FATs completed
Sept '21 - April '22 ✓

Centreline
Concrete Pour
March '22 ✓

Piling
Dec
'21 ✓

Civil work finalising
May '22 ✓

Cold commissioning
June – July '22 ✓



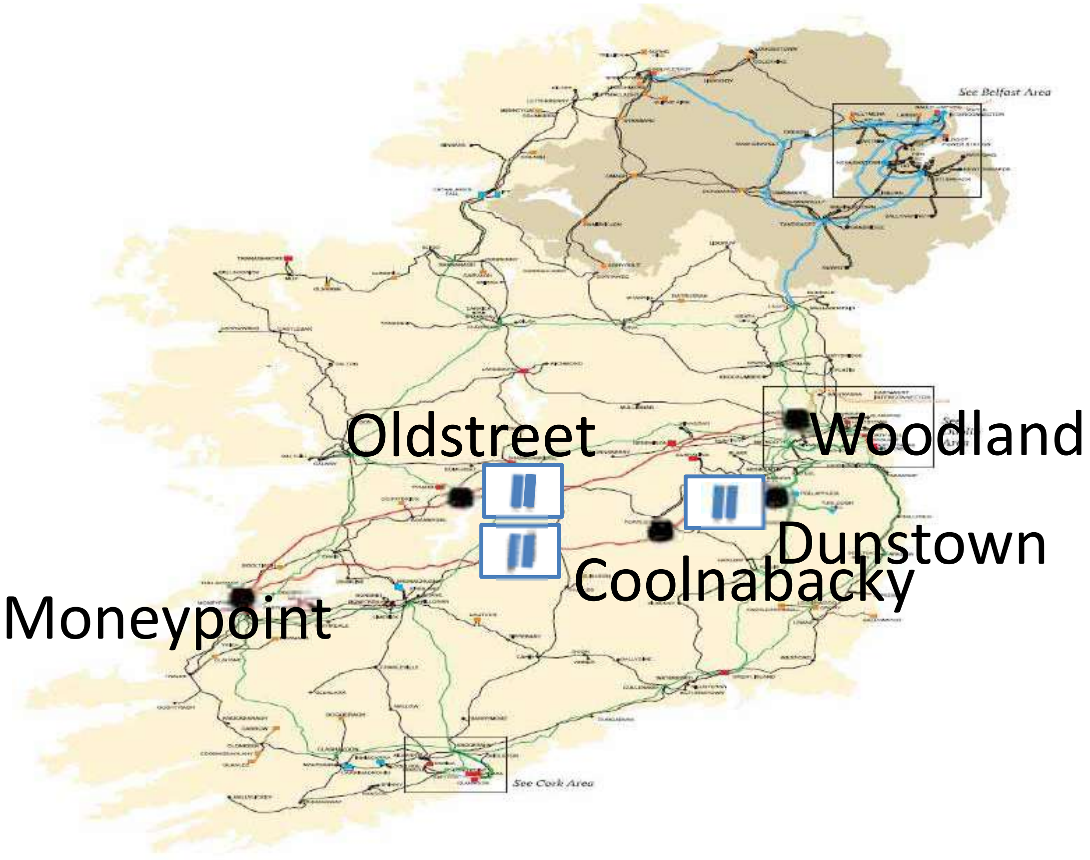
Hot commissioning
& Grid Code
Testing

Commercially Operational
Oct

Conclusion

[Siemens Energy Ireland & Siemens Energy Germany, Time-lapse - April 2022 (vimeo.com)]

Three 400kV Series Capacitors close to MP, Tender Issue Q1 2023; Energisation 2025



Oldstreet - Woodland 400kV Series Capacitor

Compensation Level		70%
Location	Oldstreet substation	
Capacitance	µF	111
Impedance	Ω	28.6
Reactive Power Rating	Mvar	676

Moneypoint - Coolnabacky 400kV Series Capacitor

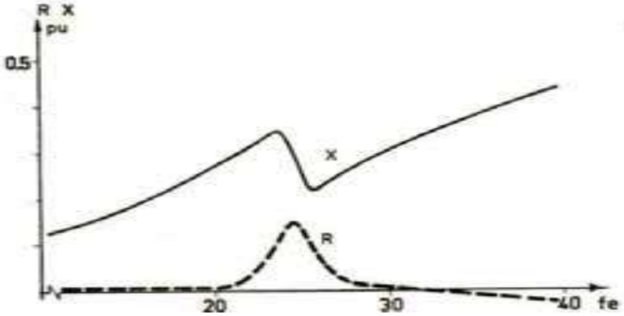
Compensation Level		54%
Location	127km from Moneypoint	
Capacitance	µF	111
Impedance	Ω	28.6
Reactive Power Rating	Mvar	676

Coolnabacky - Dunstown 400kV Series Capacitor

Compensation Level		70%
Location	Dunstown substation	
Capacitance	µF	315
Impedance	Ω	10.1
Reactive Power Rating	Mvar	239

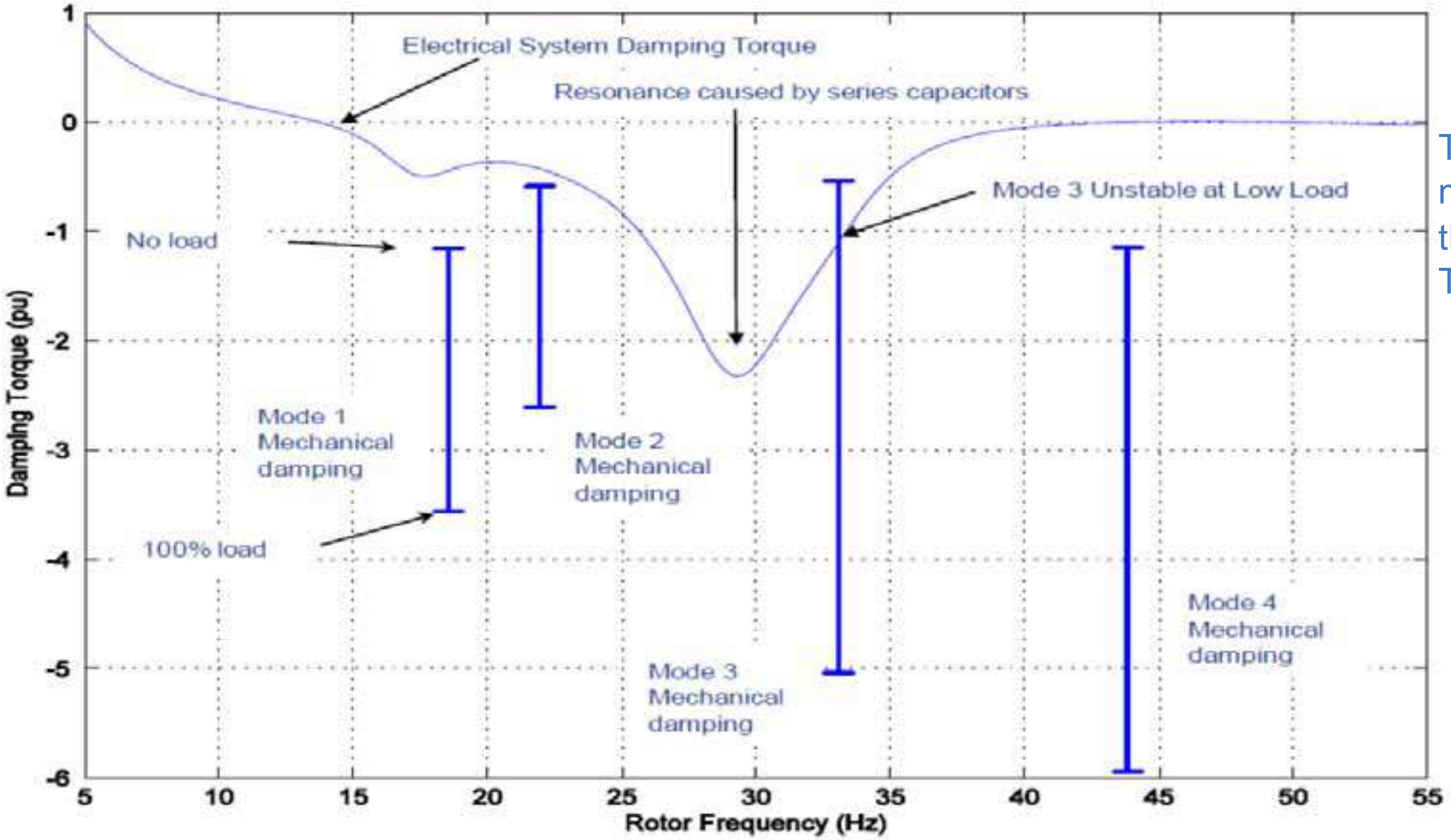
Sub Synchronous Resonance (SSR) Series capacitors change ‘impedance quality’ of electrical system

- Series capacitors introduce series and parallel resonances in the sub-synchronous range (less than 50Hz)
- The resonances can interact with shafts of turbines, or the control system of converters



- Risk of interaction depends also upon mechanical and electrical characteristics of the generator

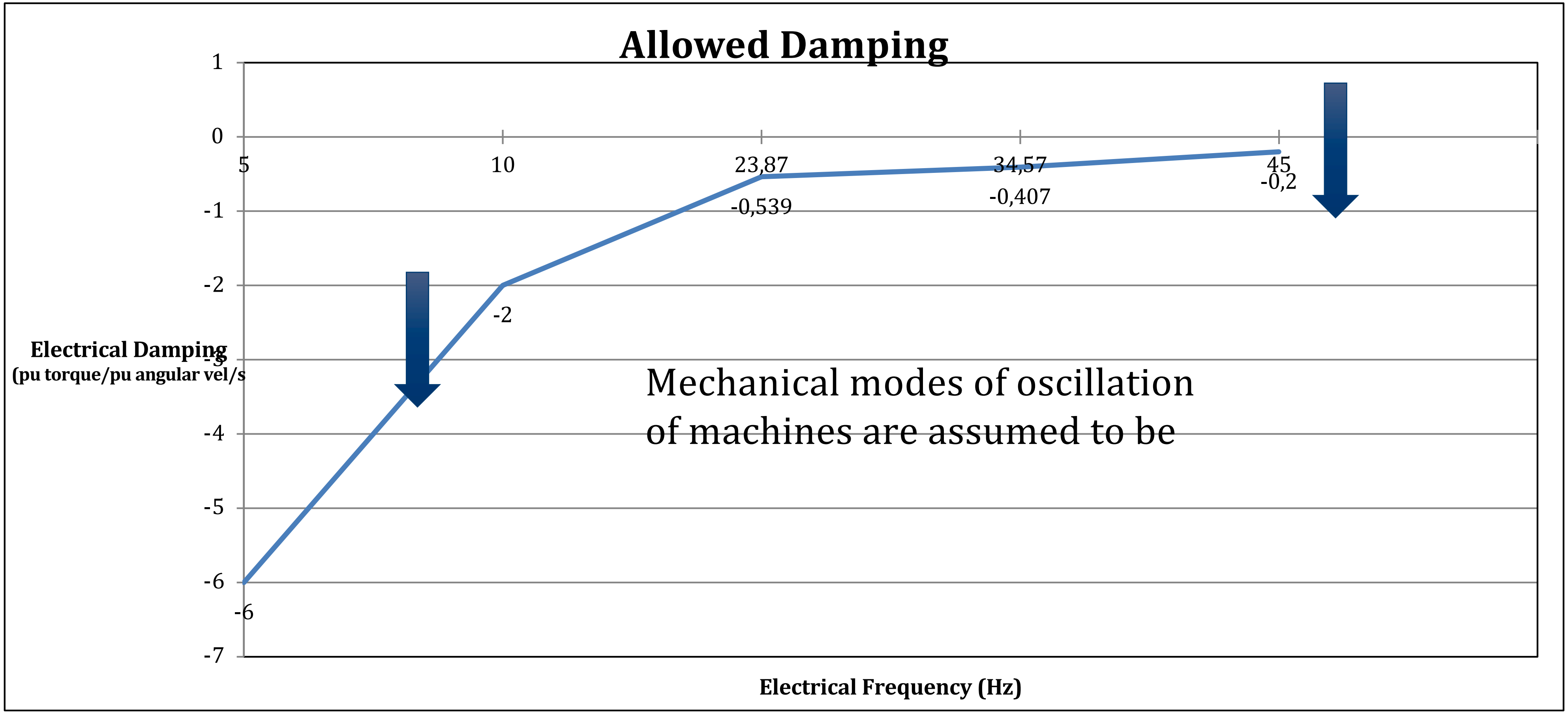
SSR Interaction depends on mechanical characteristics of machines



These Generator modes shown are of the MP Steam Turbine units

TSO Criteria for SSR Mitigation

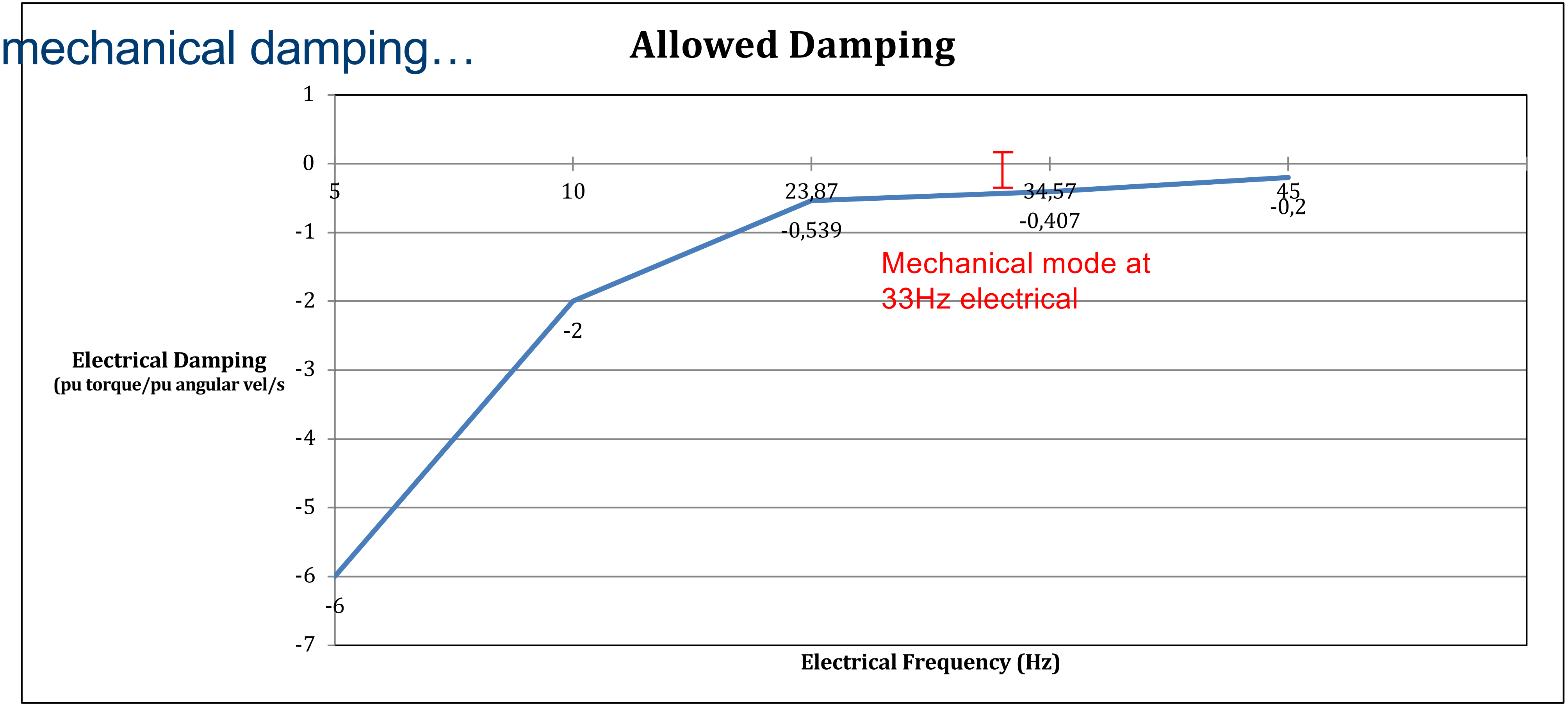
Controls negative electrical damping due to series capacitors…



Mechanical modes of oscillation of machines are assumed to be

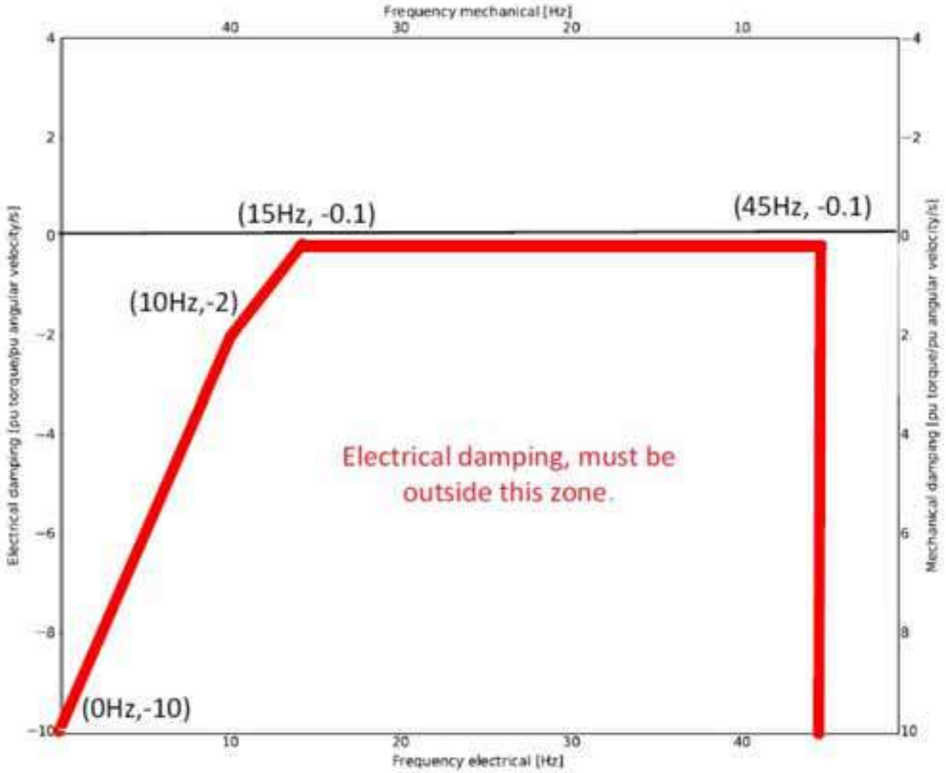
MP Synchronous Condenser

One mechanical mode of oscillation of concern reported at 33Hz with low mechanical damping…



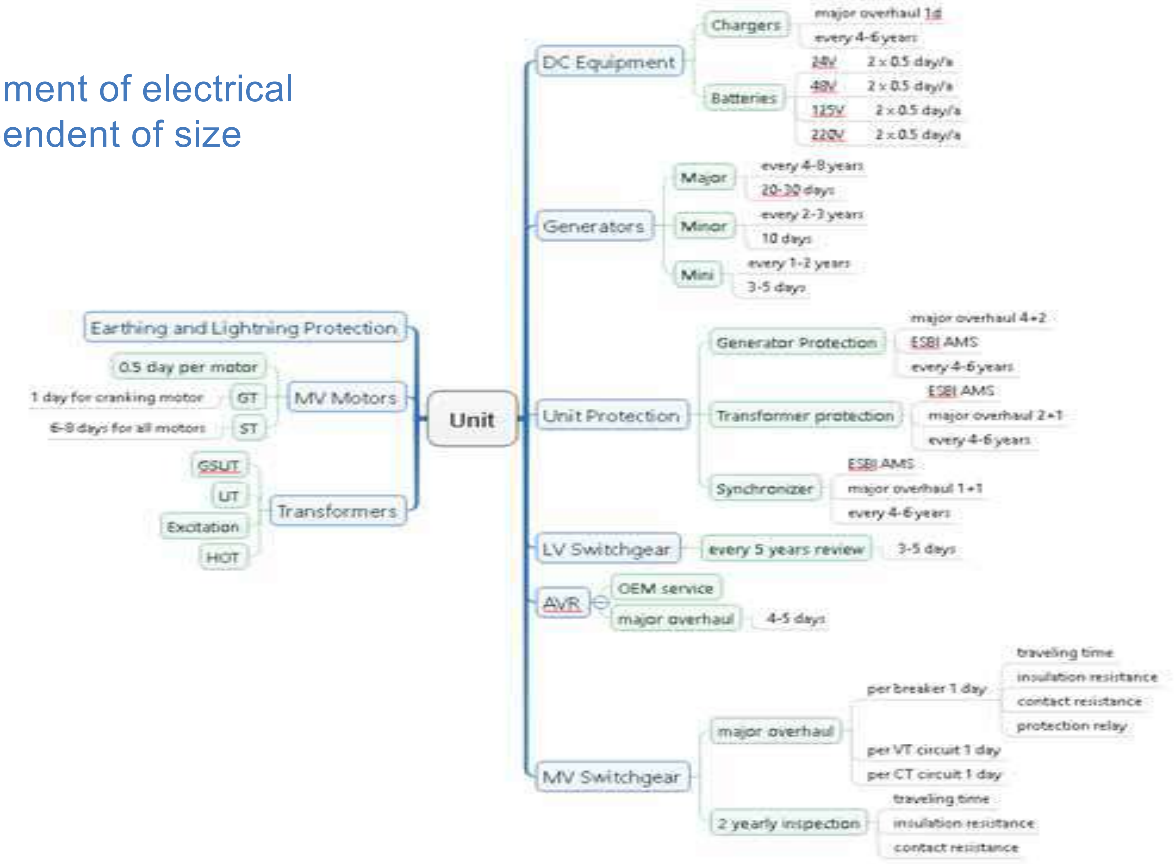
Mechanical mode at 33Hz electrical

Series Compensation, Damping

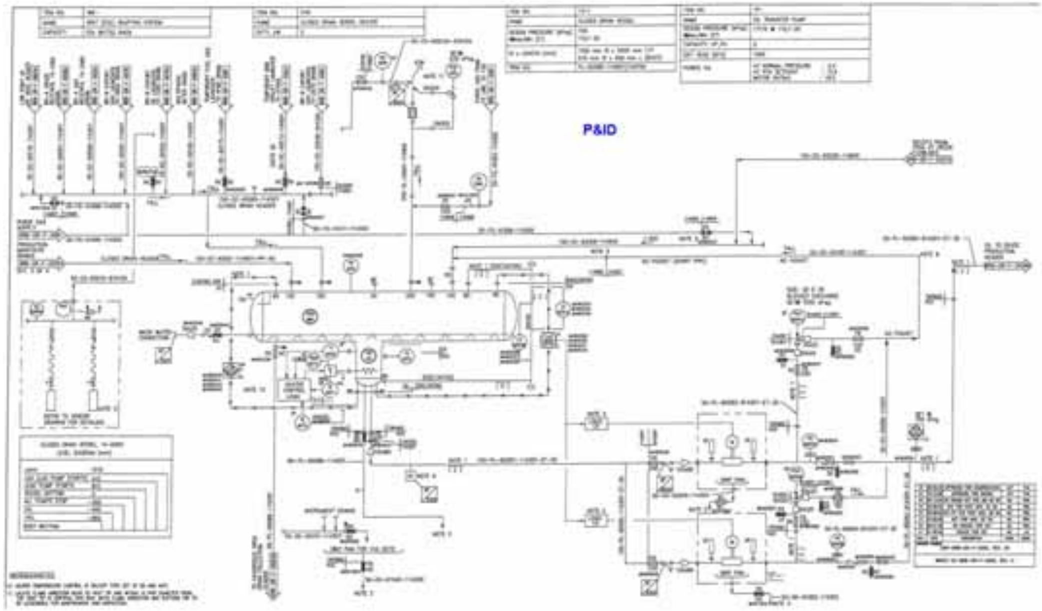


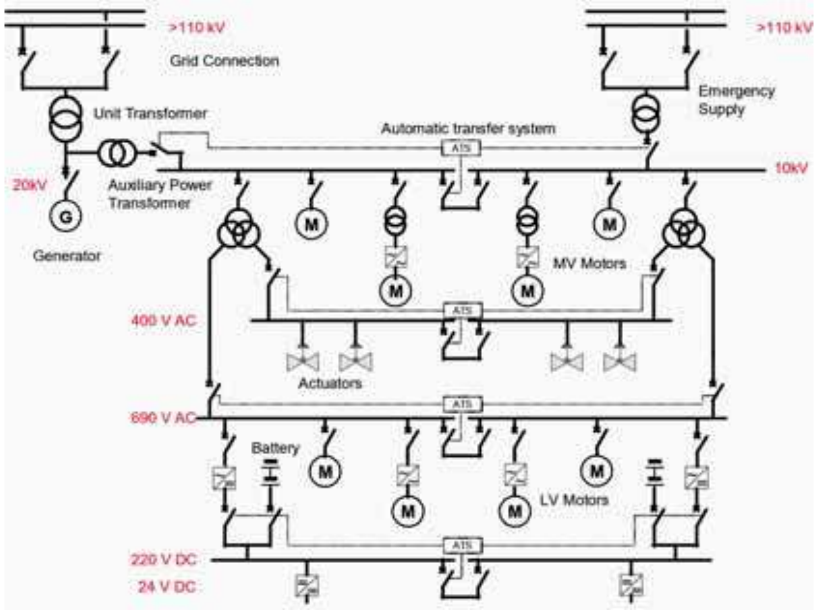
Additional Assets require Skilled Personnel:

Maintenance requirement of electrical assets is often independent of size



Personnel Development: Understanding of components within Generating Assets





Personnel Development: Understanding of theory

Models for the transient stability of conventional power generating stations connected to low inertia systems

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[2] Department of Electronic and Electrical Engineering, Trinity College, Dublin 2, Ireland

[3]Laboratoire de Mathématiques et Physique (EA 4217), Université de Perpignan Via Domitia, F-66860, Perpignan, France

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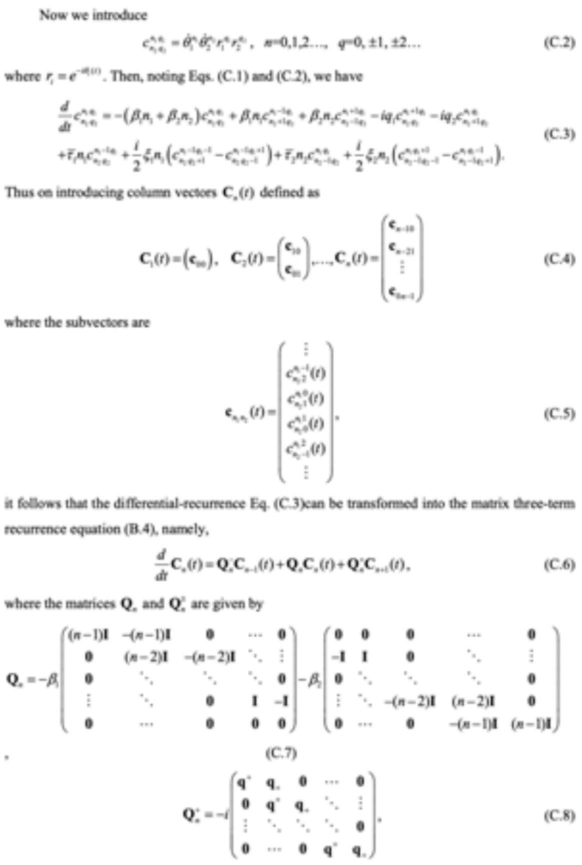
Abstract

An ever-increasing requirement to integrate greater amounts of electrical energy from renewable sources especially from wind turbines and solar photo-voltaic installations exists and recent experience in the island of Ireland demonstrates that this requirement influences the behaviour of conventional generating stations. One observation is the change in the electrical power output of synchronous generators following a transient disturbance especially their oscillatory behaviour accompanied by similar oscillatory behaviour of the grid frequency, both becoming more pronounced with reducing grid inertia. This behaviour cannot be reproduced with existing mathematical models indicating that an understanding of the behaviour of synchronous generators, subjected to various disturbances especially in a system with low inertia requires a new modelling technique. Thus two models of a generating station based on a double pendulum described by a system of coupled nonlinear differential equations and suitable for analysis of its stability corresponding to infinite or finite grid inertia are presented. Formal analytic solutions of the equations of motion are given and compared with numerical solutions. In particular the new finite grid model will allow one to identify limitations to the operational range of the synchronous generators used in conventional power generation and also to identify limits, such as the allowable Rate of Change of Frequency which is currently set to ±0.5Hz/s and is a major factor in describing the volatility of a grid as well as identifying requirements to the total inertia necessary, which is currently provided by conventional power generators only, thus allowing one to maximise the usage of grid connected non-synchronous generators e.g. wind turbines and solar photo-voltaic installations.



Now we introduce

$$c^{n_1 n_2}_{q_1 q_2} = \dot{\theta}_1^{n_1}\dot{\theta}_2^{n_2} r_1^{q_1} r_2^{q_2}, \quad n=0,1,2\ldots, \quad q=0, \pm 1, \pm 2\ldots \qquad \text{(C.2)}$$

where $r_i = e^{-i\theta_i(t)}$. Then, noting Eqs. (C.1) and (C.2), we have

$$\begin{aligned}\frac{d}{dt}c^{n_1 n_2}_{q_1 q_2} &= -(\beta_1 n_1 + \beta_2 n_2)c^{n_1 n_2}_{q_1 q_2} + \beta_1 n_1 c^{n_1-1 n_2}_{q_1+1 q_2} + \beta_2 n_2 c^{n_1+1 n_2}_{q_1-1 q_2} - i q_1 c^{n_1+1 n_2}_{q_1 q_2} - i q_2 c^{n_1 n_2}_{q_1+1 q_2}\\ &+ \bar{\tau}_1 n_1 c^{n_1-1 n_2}_{q_1 q_2} + \frac{i}{2}\xi_1 n_1\left(c^{n_1-1 n_2-1}_{q_1 q_2+1} - c^{n_1-1 n_2+1}_{q_1 q_2-1}\right) + \bar{\tau}_2 n_2 c^{n_1 n_2}_{q_1-1 q_2} + \frac{i}{2}\xi_2 n_2\left(c^{n_1 n_2+1}_{q_1-1 q_2-1} - c^{n_1 n_2-1}_{q_1-1 q_2+1}\right).\end{aligned} \qquad \text{(C.3)}$$

Thus on introducing column vectors $\mathbf{C}_n(t)$ defined as

$$\mathbf{C}_1(t) = \left(\mathbf{c}_{00}\right), \quad \mathbf{C}_2(t) = \begin{pmatrix}\mathbf{c}_{10}\\ \mathbf{c}_{01}\end{pmatrix}, \ldots, \mathbf{C}_n(t) = \begin{pmatrix}\mathbf{c}_{n-10}\\ \mathbf{c}_{n-21}\\ \vdots\\ \mathbf{c}_{0n-1}\end{pmatrix} \qquad \text{(C.4)}$$

where the subvectors are

$$\mathbf{c}_{n_1 n_2}(t) = \begin{pmatrix}\vdots\\ c^{n_1,-1}_{n_2,2}(t)\\ c^{n_1,0}_{n_2,1}(t)\\ c^{n_1,1}_{n_2,0}(t)\\ c^{n_1,2}_{n_2,-1}(t)\\ \vdots\end{pmatrix}, \qquad \text{(C.5)}$$

it follows that the differential-recurrence Eq. (C.3)can be transformed into the matrix three-term recurrence equation (B.4), namely,

$$\frac{d}{dt}\mathbf{C}_n(t) = \mathbf{Q}_n^-\mathbf{C}_{n-1}(t) + \mathbf{Q}_n\mathbf{C}_n(t) + \mathbf{Q}_n^+\mathbf{C}_{n+1}(t), \qquad \text{(C.6)}$$

where the matrices $\mathbf{Q}_n$ and $\mathbf{Q}_n^{\pm}$ are given by

$$\mathbf{Q}_n = -\beta_1\begin{pmatrix}(n-1)\mathbf{I} & -(n-1)\mathbf{I} & \mathbf{0} & \cdots & \mathbf{0}\\ \mathbf{0} & (n-2)\mathbf{I} & -(n-2)\mathbf{I} & \ddots & \vdots\\ \mathbf{0} & \ddots & \ddots & \ddots & \mathbf{0}\\ \vdots & \ddots & \mathbf{0} & \mathbf{I} & -\mathbf{I}\\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{0} & \mathbf{0}\end{pmatrix} - \beta_2\begin{pmatrix}\mathbf{0} & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0}\\ -\mathbf{I} & \mathbf{I} & \mathbf{0} & \ddots & \vdots\\ \mathbf{0} & \ddots & \ddots & \ddots & \mathbf{0}\\ \vdots & \ddots & -(n-2)\mathbf{I} & (n-2)\mathbf{I} & \mathbf{0}\\ \mathbf{0} & \cdots & \mathbf{0} & -(n-1)\mathbf{I} & (n-1)\mathbf{I}\end{pmatrix}$$

, (C.7)

$$\mathbf{Q}_n^+ = -i\begin{pmatrix}\mathbf{q}^+ & \mathbf{q}_- & \mathbf{0} & \cdots & \mathbf{0}\\ \mathbf{0} & \mathbf{q}^+ & \mathbf{q}_- & \ddots & \vdots\\ \vdots & \ddots & \ddots & \ddots & \mathbf{0}\\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{q}^+ & \mathbf{q}_-\end{pmatrix}, \qquad \text{(C.8)}$$

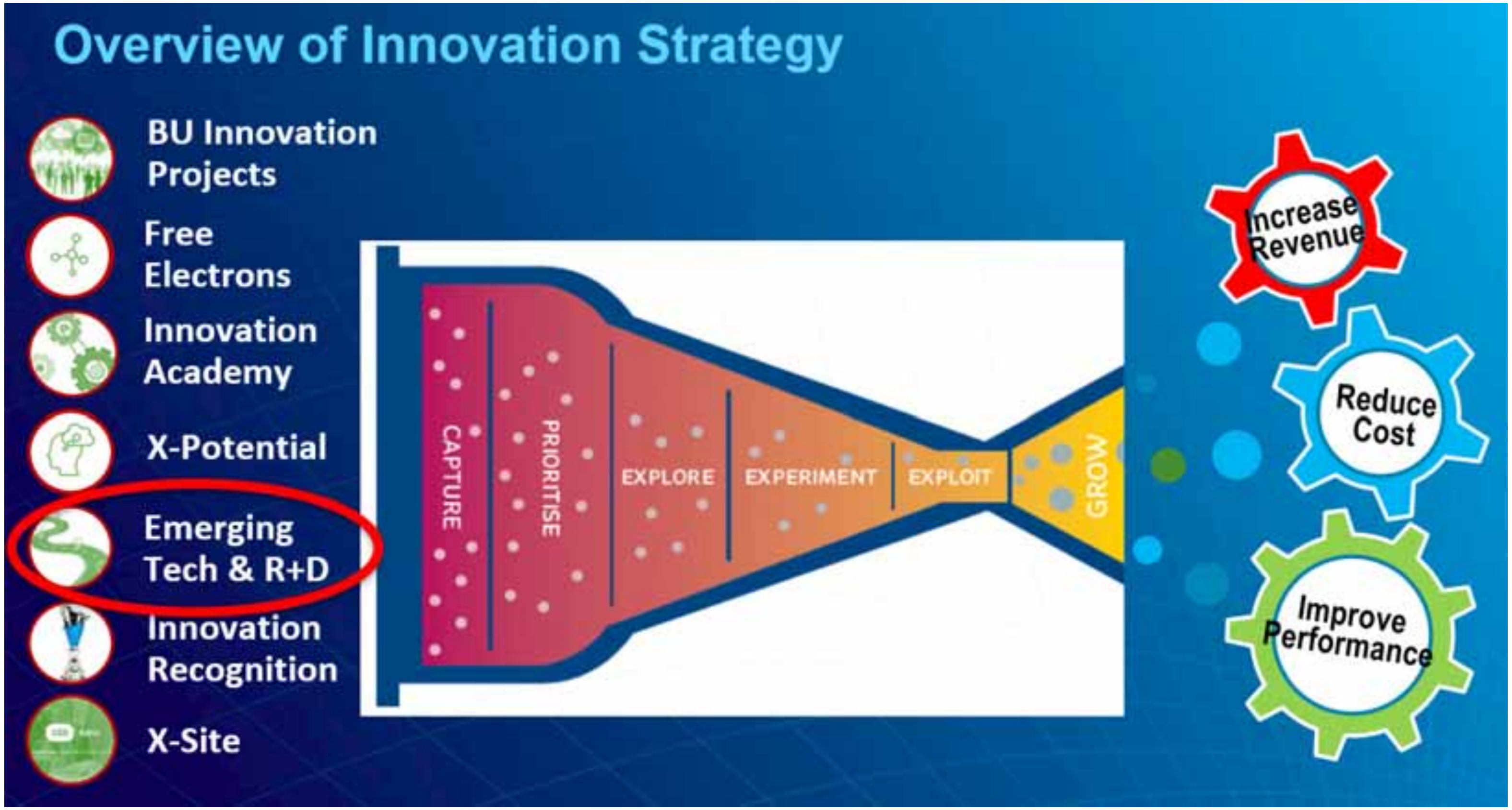
Commercial Challenges – Price Volatility and Predictability

High Wind => Low Prices
Low Wind => High Prices

=> Caused by non-availability of conventional generation

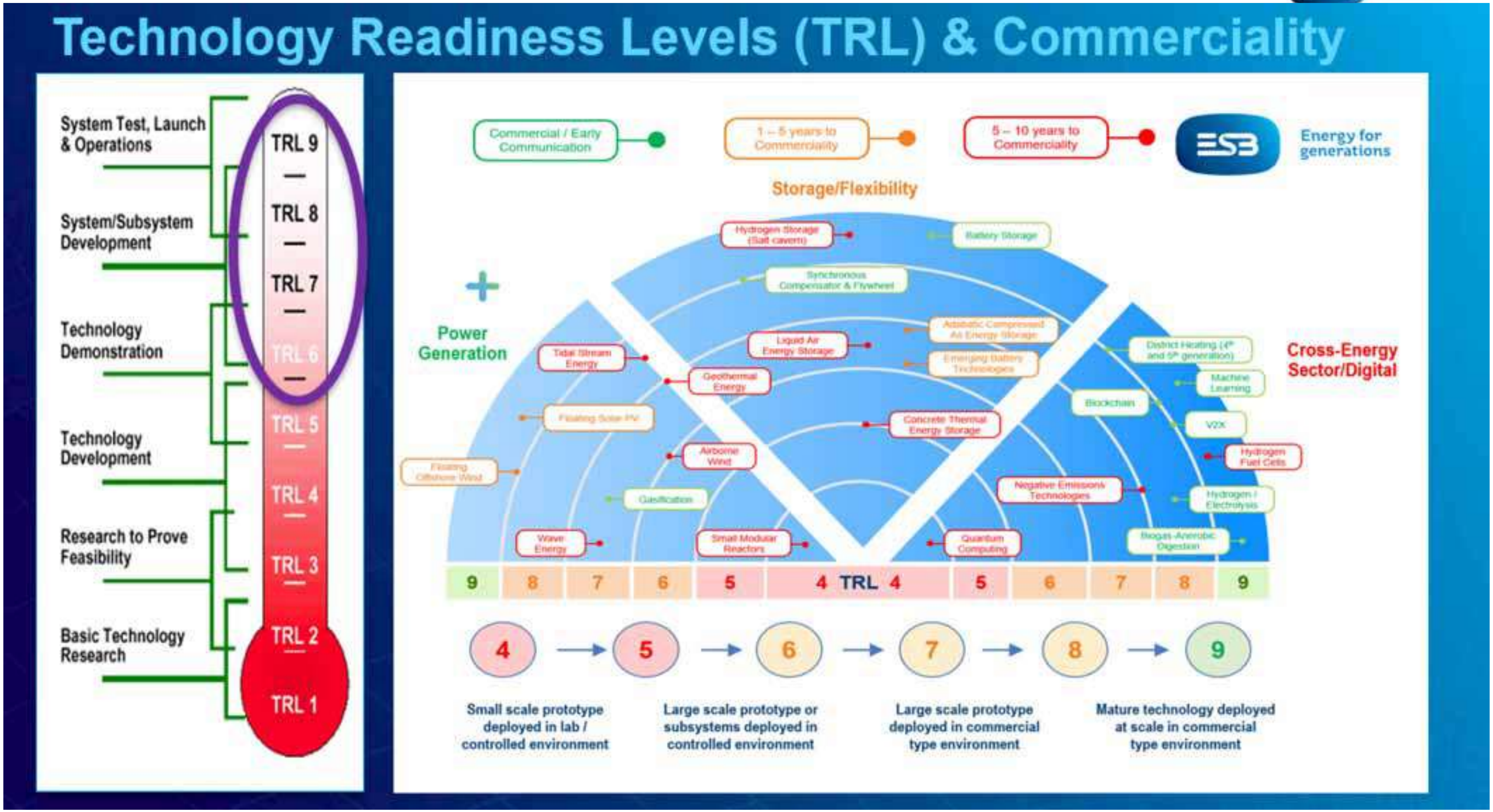
=> Technical challenge to increase availability and reliability

Last, but not least



Overview of Innovation Strategy

- BU Innovation Projects
- Free Electrons
- Innovation Academy
- X-Potential
- Emerging Tech & R+D
- Innovation Recognition
- X-Site



Technology Readiness Levels (TRL) & Commerciality

Small scale prototype deployed in lab / controlled environment

Large scale prototype or subsystems deployed in controlled environment

Large scale prototype deployed in commercial type environment

Mature technology deployed at scale in commercial type environment

Power Generation

Floating Wind TRL8-9

Floating Solar TRL9

Tidal Stream TRL8-9

Wave Energy TRL7

Airborne Wind TRL6-7

Small Modular Reactor TRL 4

Geothermal TRL5-9

Gasification TRL7

Storage and Flexibility

Storage & Flexibility Technologies

Grid Scale Batteries TRL9

Flywheel + Synch-comp TRL9

Emerging battery technologies TRL7

Liquid Air Storage TRL 7

Concrete Storage TRL5-6

Hydrogen Storage TRL9

A-CAES TRL7

Crosse Energy sector Technologies

Cross Energy Sector Technologies

Industrial Heat Pumps TRL7

Vehicle to X TRL8-9

Negative Emissions TRL7-8

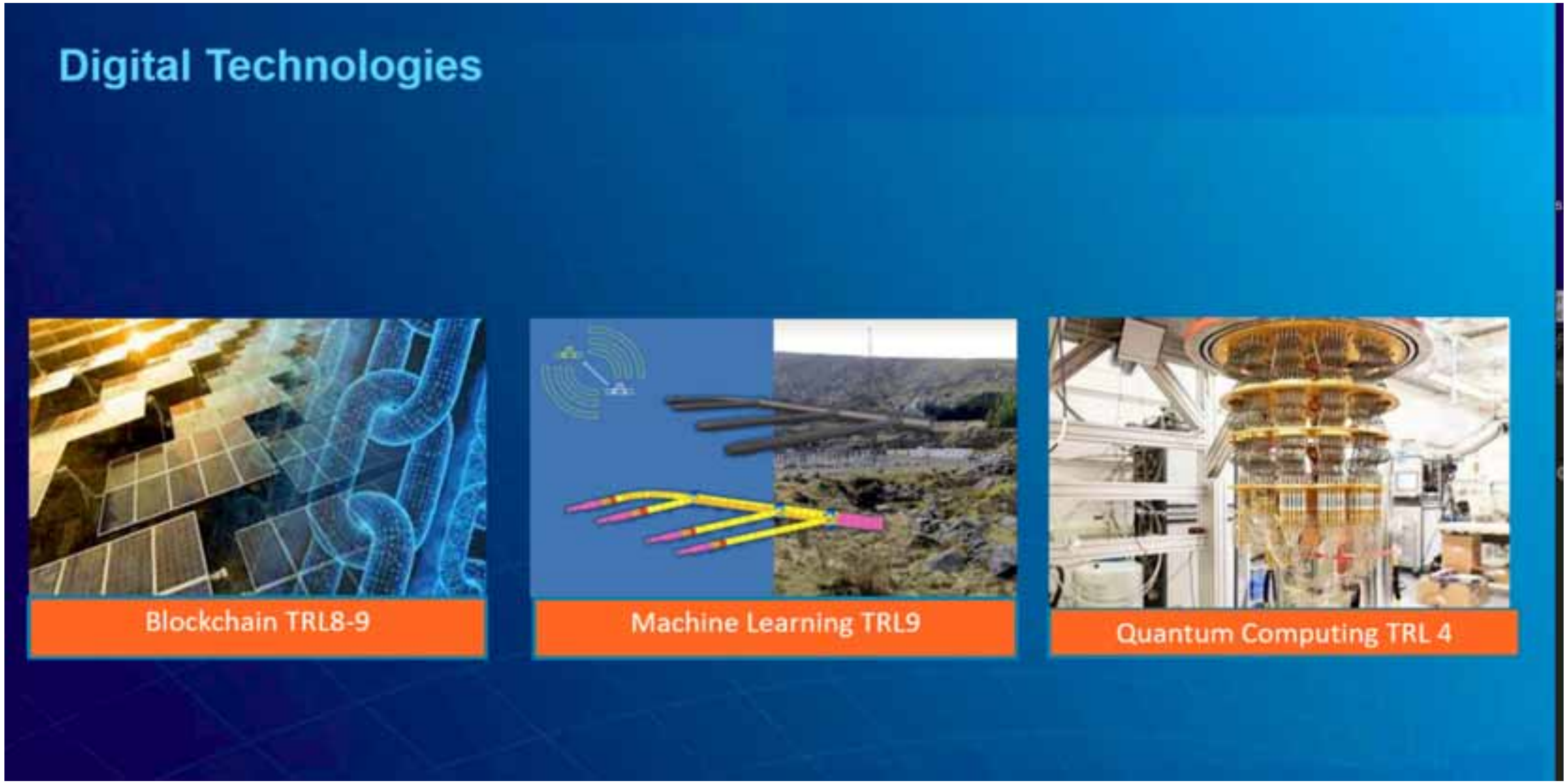
Biogas / AD TRL7-9

Hydrogen / Fuel Cells TRL7-9

Hydrogen / Electrolysis TRL6-9

District Heating (4G & 5G) TRL 8-9

Digital Technologies



Digital Technologies

Blockchain TRL8-9

Machine Learning TRL9

Quantum Computing TRL 4

Conclusions

- Further increase of renewable energy generated from Wind Turbine Generators is challenging
- Resilience of older generators to more dynamic grid events is challenging
- Introduction of new technologies is necessary but challenging
- The introduction of the largest flywheel in the world is challenging
- New market is challenging
- Empowering the work force is challenging

John F. Kennedy: “We choose to go to the Moon, we choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too.”