Energy for generations

IRELAND

Update on RoCoF

Marios Zarifakis, ESB G&WM

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1. **Analysis of Eirgrid's KEMA Study**
    1. Stability – Mechanical Impacts
    2. Limitations in the under excited area – Operational Issues
    3. Time window in definition of Rocof. 500ms vs. 100ms sec duration of a RoCoF Event – Unknown Requirement –> Compliance Impossible
2. **Analysis of Study currently being undertaken by DNV GL (former KEMA) for ESB GWM**
    1. Ability to operate at Minimum Load – Potentially unavailable at night i.e. when most required
3. **Next Steps**

Stable Operation

Generation Units Result Summary					1 Hz total frequency drop			
Generator Set	Unit Size	Inertia Constant H	Xd	Terminal Voltage	Stable	during	RoCoF	
[name]	[MW]	[Sec.]	[p.u.]	[kV]	[@ 0.5 Hz/s]	[@ 1.0 Hz/s]	[@ 1.5 Hz/s]	[@ 2.0Hz/s]
CCGT Single-shaft	400	5.5	1.9	20	Y	Y*	Y*	N
CCGT Dual-Shaft	260	6	2.3	17	Y	N	N	N
CCGT Dual-Shaft	140	9	2.1	17	Y	N	N	N
Steam Thermal (Reheat)	300	5	1.7	17	Y	Y*	Y*	N**
Steam Thermal (Once Through)	250	4.5	2.3	20	Y*	Y*	N	N
Steam Thermal (Fluidized bed peat)	150	8	2.2	11	Y*	N	N	N
OCGT	50	1.5	2.9	11	Y*	Y*	Y*	Y*
Salient-pole Hydro	30	2.7	1.4	11	Y	Y	Y	Y

The tables give a general overview of the findings where:

Y is used to indicate stable operation

Y* is used where a pole slip is only observed for a 0.93 leading power factor operation mode;

N is used when a pole slip is also observed for power factors of 1 unity or/and 0.85 lag;

N** is used when no pole slip is observed for power factors of 1 unity or/and 0.85 lag but negative power generation is detected.

Stable: Y; Interpretation of Stability

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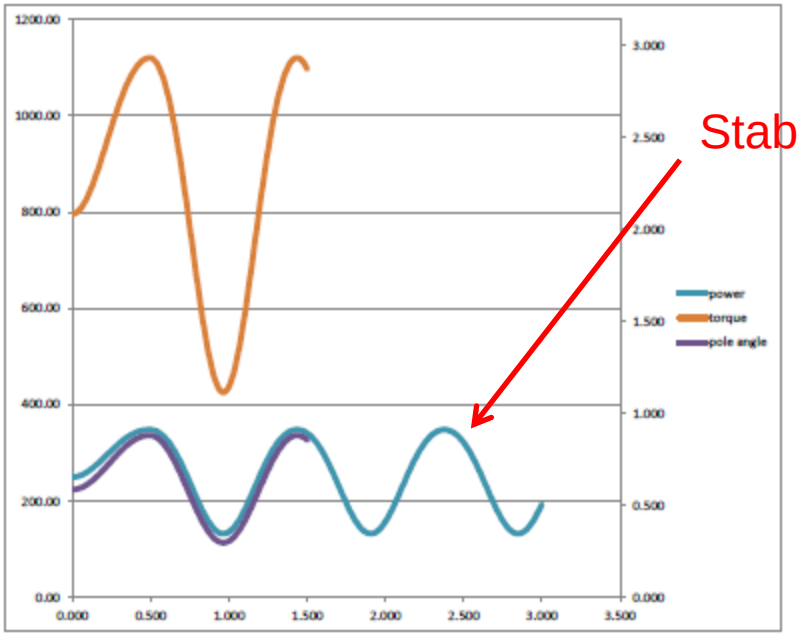
Calculation ID: E

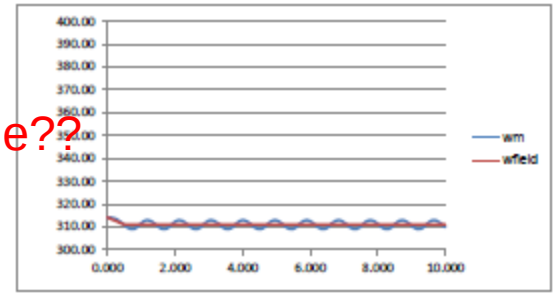
Torque Calculation Synchronous Generator

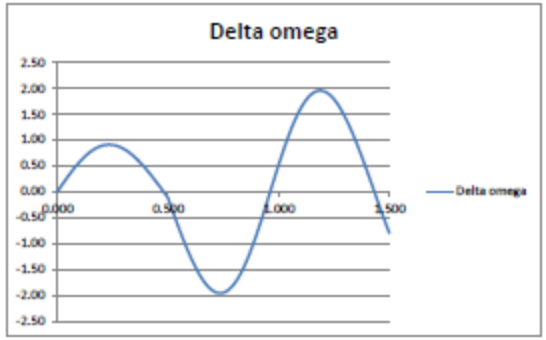
Quantity/ Dimension [Name/ Symbol]	Value [Number]	SI Unit [Symbol]	Quantity/ Dimension [Name/ Symbol]	Value [Number]	SI Unit [Symbol]
Rated power	250	[MW]	Reference reactance	1.360	[Ω]
Rated power factor	0.85		Synchronous reactance	3.128	[Ω]
Rated voltage	20000	[V]	ω_N	314.2	[rad/s]
Synchronous reactance	2.3	[p.u.]	δ	0.59	[rad] 33.59 °
f_e	50	[Hz]	P_{basis}	250.0	[MW]
p (pole pair number)	1		Cpower	451.9	
H (stored energy constant)	4.5	[s]	T_{basis}	796	[kNm]
Rated power	294	[MVA]	J	26820	[kgm²]
Rated current	8490	[A]	Max. torque (500 ms)	141	[%]
Rated torque	796	[kNm]	Max. torque (1 s)	141	[%]

ID	oocφ [-]		load [%]	RoCoF [Hz/s]	Stable	MaxTorque [%]	Limit [Hz/s]
E	0.85	lag	100	-1	y	141	
	φ		$\alpha_{fo,start}$				
	31.78833 °		0.59				

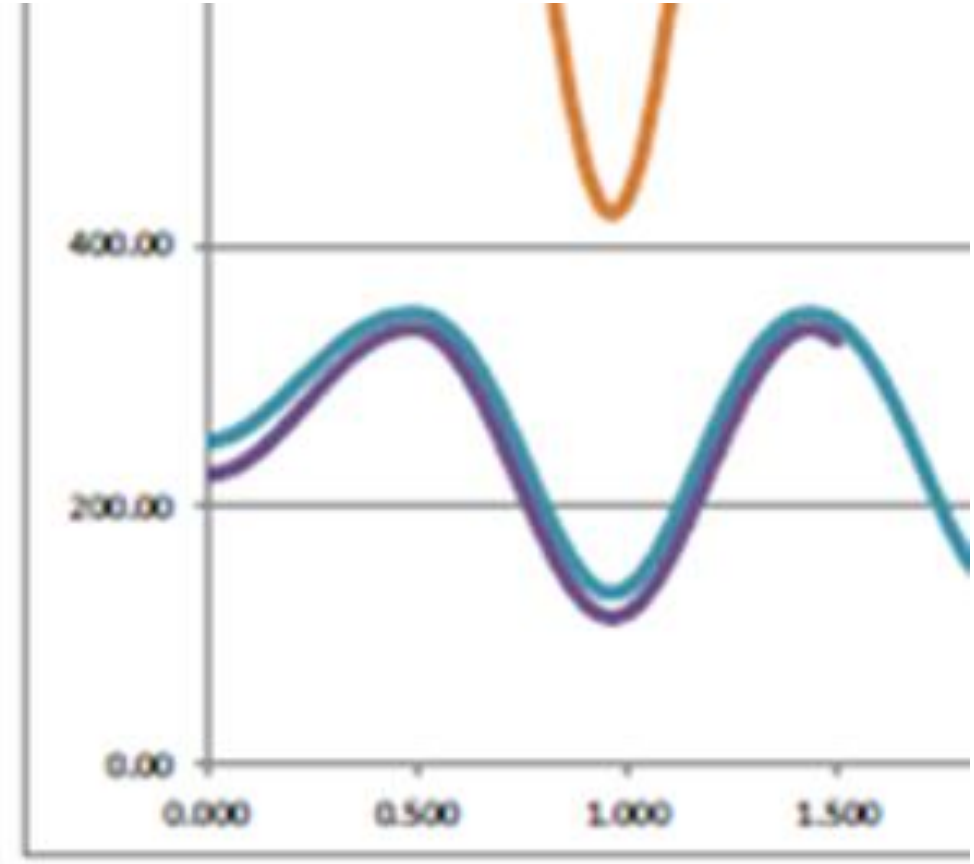


Stable??





Power Oscillations



In this example, the power, even considered stable oscillates within parts of seconds 100MW

Stability

- The term stable is used in relation to Rotor Angle Stability, i.e. Rotor does not pole slip.
- It does not mean that the generator is able to operate with such power and torque oscillations
- Further Studies are required to determine if Turbine Controller would be stable (frequency response logics)
- No review of mechanical stresses undertaken
- No review of AVR and PSS undertaken (PSS: right model?)

Operation at 0.93 leading

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Generation Units Result Summary					1 Hz total frequency drop			
Generator Set	Unit Size	Inertia Constant H	Xd	Terminal Voltage	Stable	during	RoCoF	
[name]	[MW]	[Sec.]	[p.u.]	[kV]	[@ 0.5 Hz/s]	[@ 1.0 Hz/s]	[@ 1.5 Hz/s]	[@ 2.0Hz/s]
CCGT Single-shaft	400	5.5	1.9	20	Y	Y*	Y*	N
CCGT Dual-Shaft	260	6	2.3	17	Y	N	N	N
CCGT Dual-Shaft	140	9	2.1	17	Y	N	N	N
Steam Thermal (Reheat)	300	5	1.7	17	Y	Y*	Y*	N**
Steam Thermal (Once Through)	250	4.5	2.3	20	Y*	Y*	N	N
Steam Thermal (Fluidized bed peat)	150	8	2.2	11	Y*	N	N	N
OCGT	50	1.5	2.9	11	Y*	Y*	Y*	Y*
Salient-pole Hydro	30	2.7	1.4	11	Y	Y	Y	Y

The tables give a general overview of the findings where:

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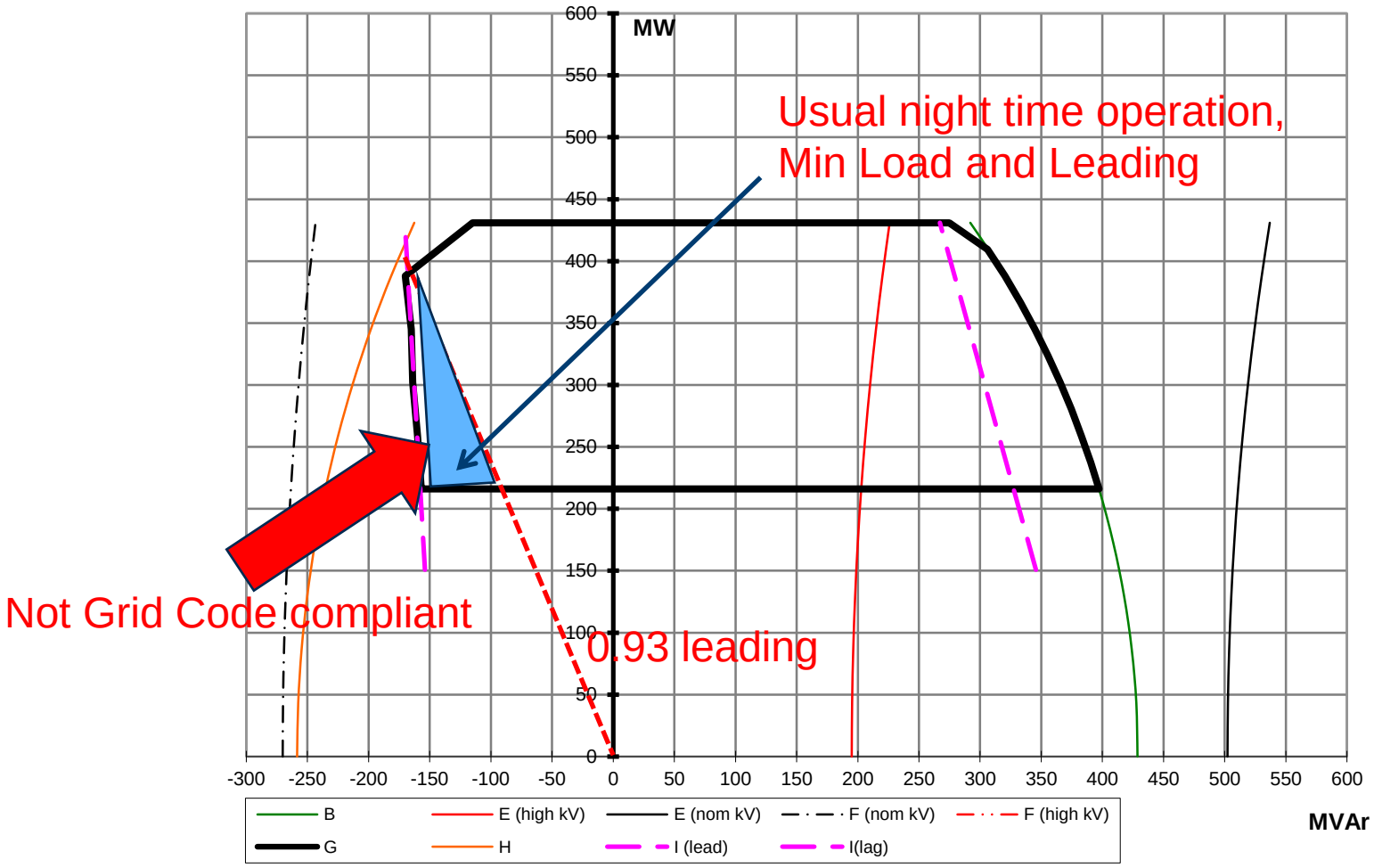
N** is used when no pole slip is observed for power factors of 1 unity or/and 0.85 lag but negative power generation is detected.

0.93 leading, example single shaft CCGT



0.93 Leading

- Operation below 0.93 leading could be restricted especially at night time which means non-compliance to the grid code
- Further Studies are required to determine exact line of rotor instability during RoCoF events.

500ms window vs 200ms window (Eirgrid)

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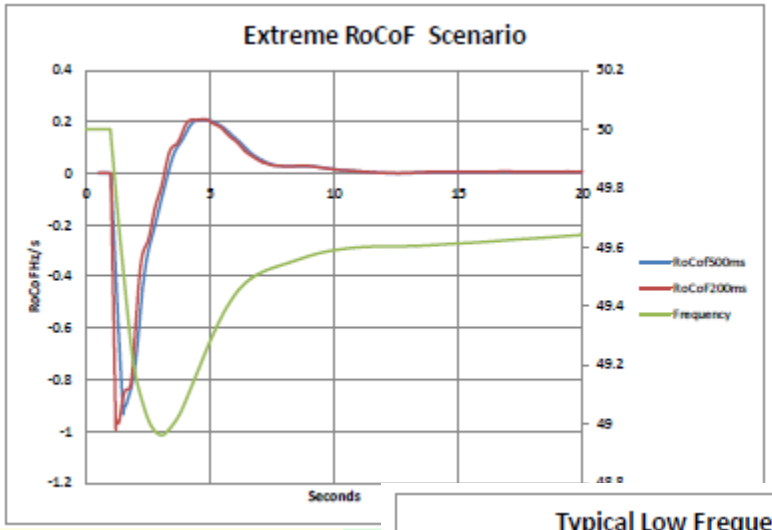
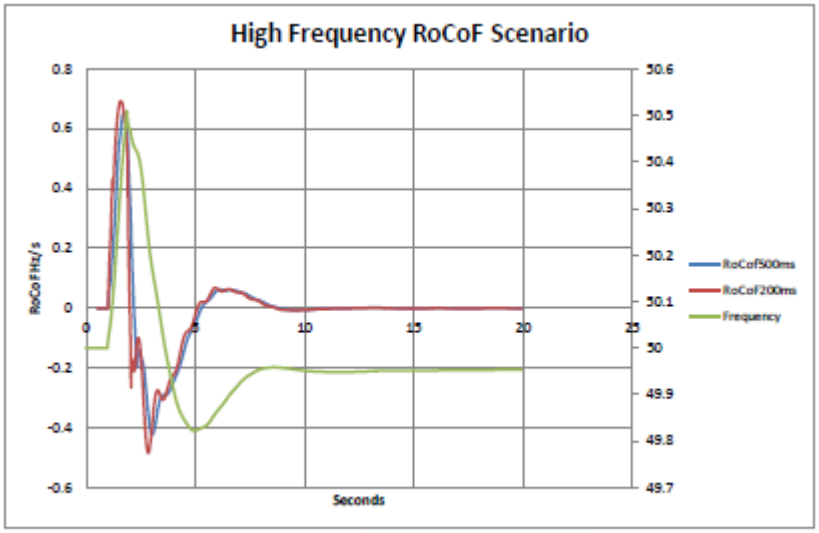
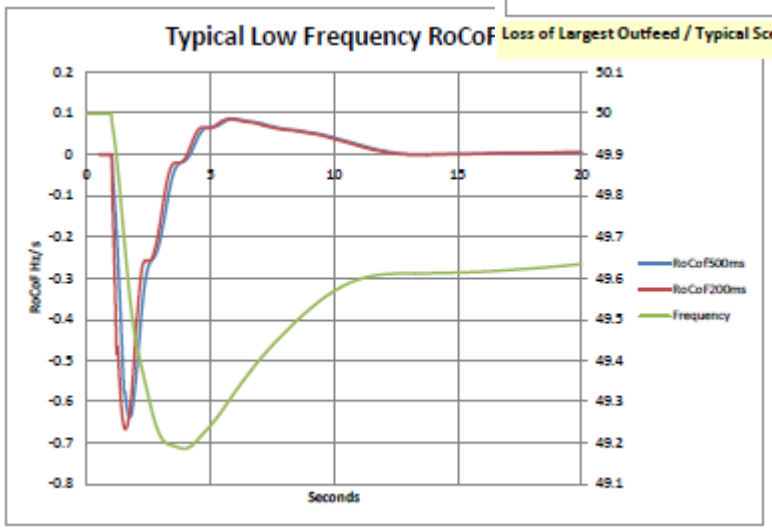


Loss of Largest Infeed / Extreme Scenario

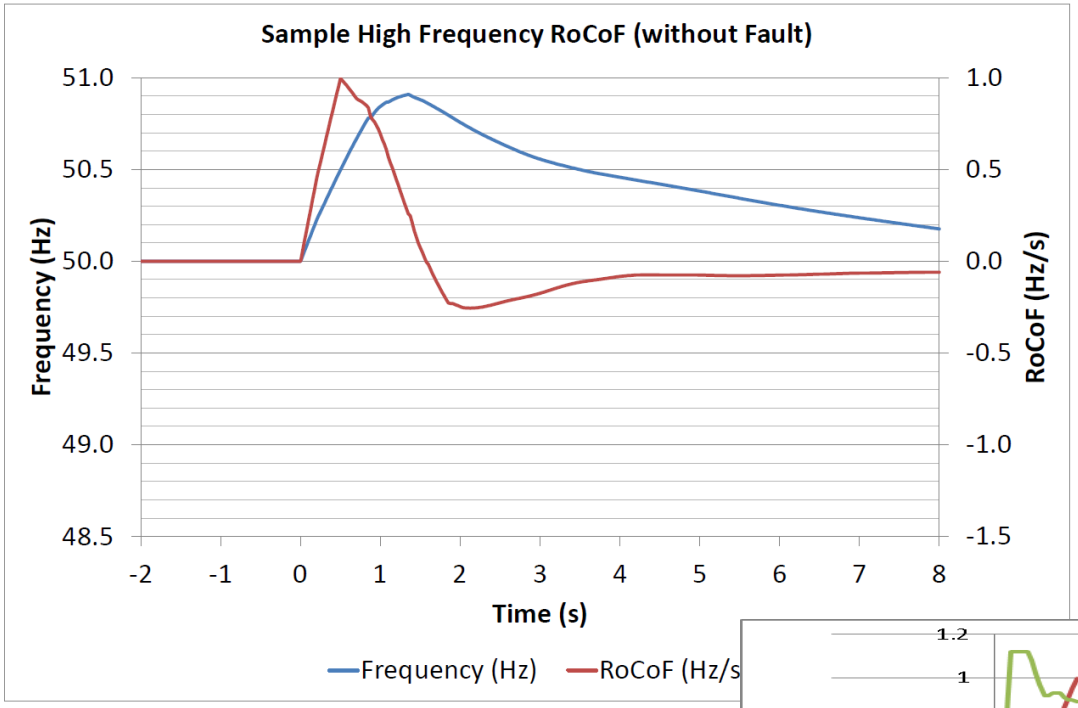


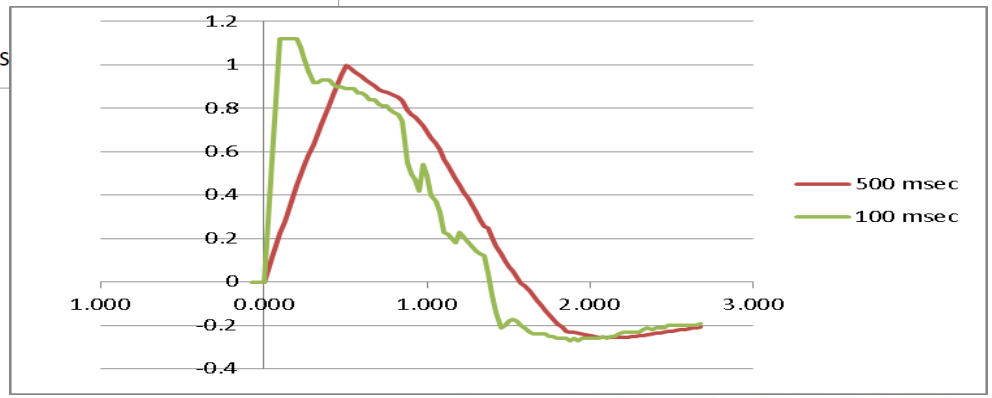
Loss of Largest Outfeed / Typical Scenario



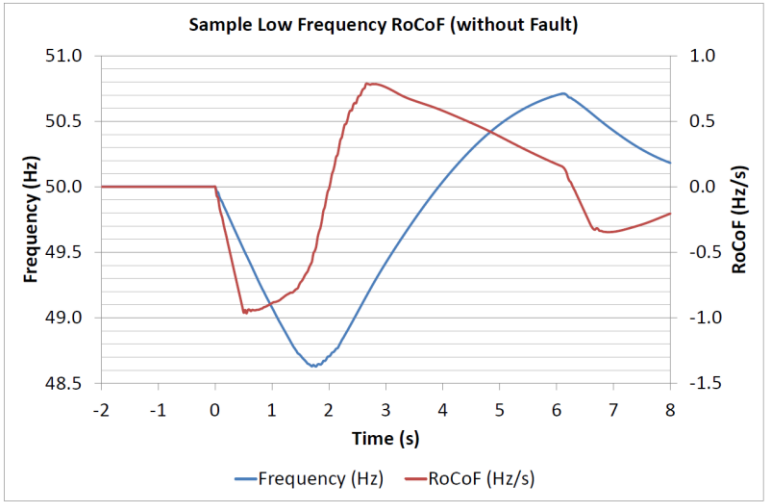
Loss of Largest Infeed / Typical Scenario

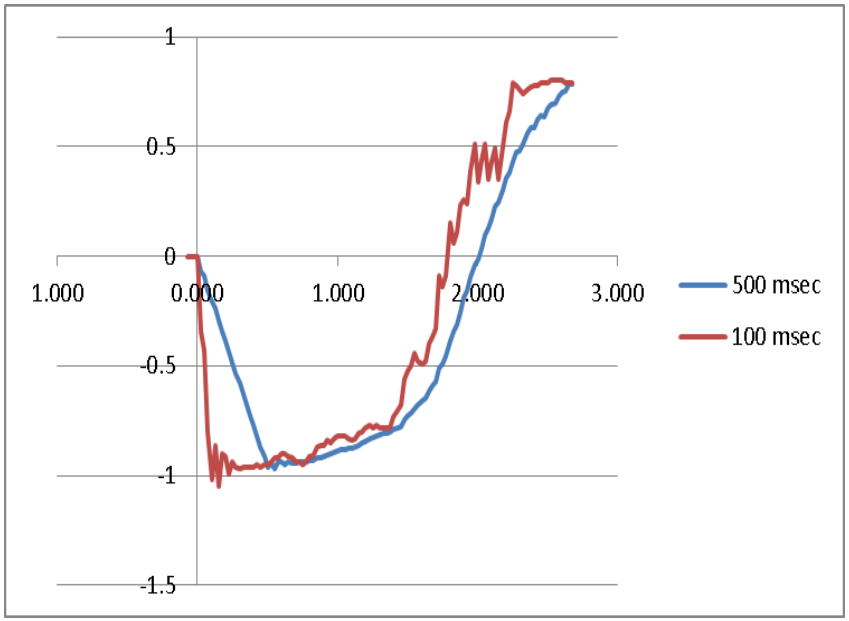
500ms window vs 100ms window





Duration of high RoCoF
Is longer when time window
Is decreased.





Duration of high RoCoF
Is longer when time window
Is decreased

Duration of fault and it's impact

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Generation Units Result Summary					500 ms v		1 Hz total frequency drop			
Generator Set	Unit Size	Inertia Constant H	Xd	Terminal Voltage	Stable	during	Stable	during	RoCoF	
[name]	[MW]	[Sec.]	[p.u.]	[kV]	[@ 0.5 Hz/s]	[@ 1.0 Hz/s]	[@ 0.5 Hz/s]	[@ 1.0 Hz/s]	[@ 1.5 Hz/s]	[@ 2.0Hz/s]
CCGT Single-shaft	400	5.5	1.9	20	Y	Y*	Y	Y*	Y*	N
CCGT Dual-Shaft	260	6	2.3	17	Y	Y*	Y	N	N	N
CCGT Dual-Shaft	140	9	2.1	17	Y	Y*	Y	N	N	N
Steam Thermal (Reheat)	300	5	1.7	17	Y	Y*	Y	Y*	Y*	N**
Steam Thermal (Once Through)	250	4.5	2.3	20	Y	Y*	Y*	Y*	N	N
Steam Thermal (Fluidized bed peat)	150	8	2.2	11	Y	Y*	Y*	N	N	N
OCGT	50	1.5	2.9	11	Y	Y*	Y*	Y*	Y*	Y*
Salient-pole Hydro	30	2.7	1.4	11	Y	Y	Y	Y	Y	Y

Definition of RoCoF is masking the real duration. Machine sees real time.
More generators will not be compliant

Definition of RoCoF (500ms window)

RoCoF values at various substations (EWIC problems)

Maximum RoCoF measurements for different time windows

Bus	T = 100 ms	T = 500 ms
AA	0.23	0.41
AD	1.07	0.41
CF	1.34	0.42
LOU	2.09	0.43
CKM	1.91	0.43
GI	1.56	0.42
BALLY	1.55	0.43
PB	2.71	0.53
AVG	**1.59**	**0.43**

Ardnacrusha (AA), Aghada (AD), Cathaleen's Fall (CF), Louth (LOU), Carrickmines (CKM), Great Island (GI), Ballylumford (BALLY) and Poolbeg (PB) (*1)

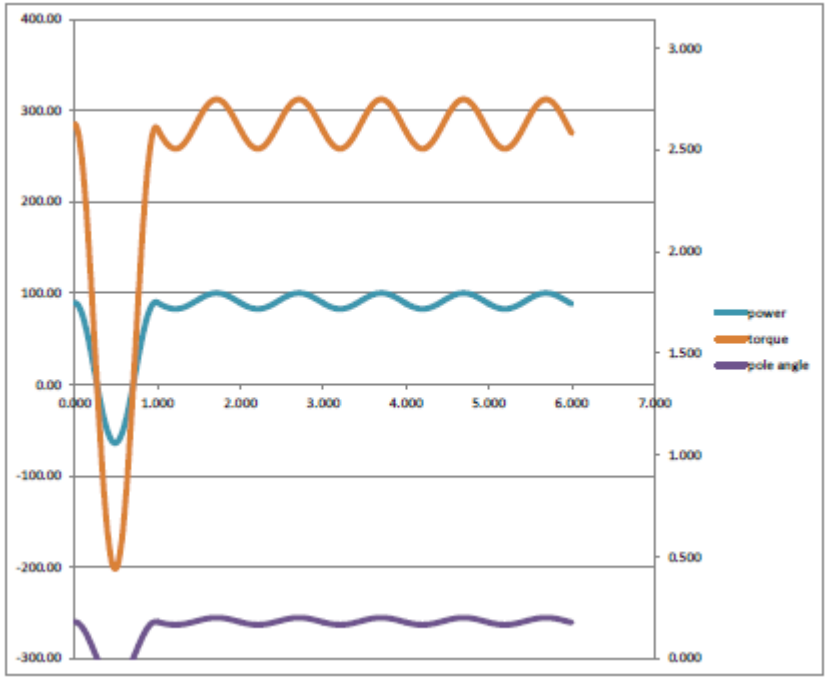
Problem: Generator sees actual values…

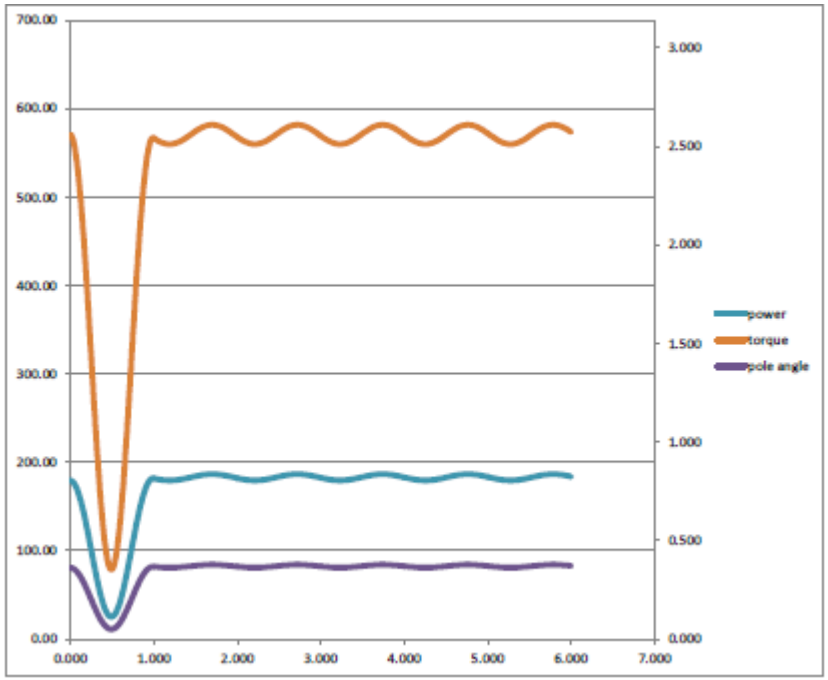
500ms vs 100ms Time Window

- Definition of RoCoF is questionable as the generator sees real time rather than windows
- Generators in Poolbeg will experience higher RoCoF values
- Compliance to the grid code can not be guaranteed without **exact** traces and an available model of the entire network or even a simplified model

ESB Study, undertaken by DNV GL(former KEMA)

Min Load Operation, Steam Turbine 25 and 50% Load, 50->51Hz, +1Hz/sec (KEMA Study commissioned by ESB)





Problems with Minimum Load to be anticipated (usual at night time)

* Eirgrid-KEMA study did not analyse min load capability

ESB Study, real values, example: Steam Turbine

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RoCoF Calculations For Synchronous Generator Regarding Torque And Stability

Generator 4, Poolbeg 16, Steam Turbine connected at 2 HRSG's fed by Gas Turbines

Quantity/ Dimension [Name/ Symbol]	Value [Number]	SI Unit [Symbol]
Rated power	170	[MW]
Rated power factor	0.85	
Rated voltage	15,750	[V]
Synchronous reactance	2.25	[p.u.]
f_e	50	[Hz]
p (pole pair number)	1	
H (stored energy constant)	10	[s]
Rated power	200	[MVA]
Rated current	7,331	[A]
Rated torque	541	[kNm]
Reference reactance	1.240	[Ω]
Synchronous reactance	2.791	[Ω]
ω_N	314.2	[rad/s]
J	40528	[kgm^2]

ID	oocφ	load	RoCoF 1	RoCoF 2	Stable	MaxTorque	Limit 1	Limit 2
	[-]	[%]	[Hz/s]	[Hz/s]		[%]	[Hz]	[Hz]
A	1	25	-1.00	0.00	N**	118	49.0	50.0
B	1	50	-1.00	0.00	N**	142	49.0	50.0
C	1	75	-1.00	0.00	N**	151	49.0	50.0
D	1	100	-1.00	0.00	N	150	49.0	50.0
E	1	25	1.00	0.00	N**	29	51.0	51.0
F	1	50	1.00	0.00	N**	59	51.0	51.0
G	1	75	1.00	0.00	N**	88	51.0	51.0
H	1	100	1.00	0.00	N	118	51.0	51.0
I	1	25	-0.50	0.00	N**	76	49.0	50.0
J	1	50	-0.50	0.00	Y	104	49.0	50.0
K	1	75	-0.50	0.00	Y	132	49.0	50.0
L	1	100	-0.50	0.00	Y	150	49.0	50.0
M	1	25	0.50	0.00	N**	29	51.0	51.0
N	1	50	0.50	0.00	Y	59	51.0	51.0
O	1	75	0.50	0.00	Y	88	51.0	51.0
P	1	100	0.50	0.00	Y	118	51.0	51.0

**) Reverse Power and therefore assumed instability

Currently compliant with 0.5Hz/sec. With 1Hz/sec problems with compliance

Energy for generations

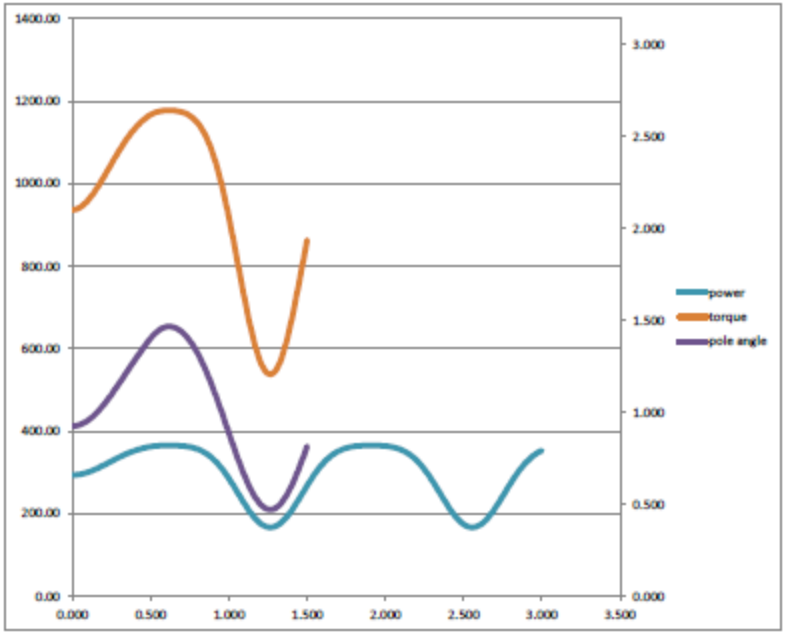
Calculation ID: K

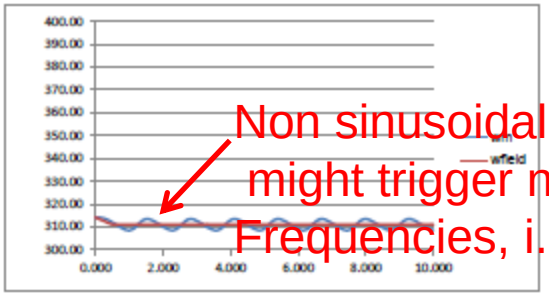
Torque Calculation Synchronous Generator

Quantity/ Dimension [Name/ Symbol]	Value [Number]	SI Unit [Symbol]	Quantity/ Dimension [Name/ Symbol]	Value [Number]	SI Unit [Symbol]
Rated power	250	[MW]	Reference reactance	1.360	[Ω]
Rated power factor	0.85		Synchronous reactance	3.128	[Ω]
Rated voltage	20000	[V]	ω_N	314.2	[rad/s]
Synchronous reactance	2.3	[p.u.]	δ	0.93	[rad]
f_e	50	[Hz]	P_{back}	294.1	[MW]
p (pole pair number)	1		Cpower	368.2	
H (stored energy constant)	4.5	[s]	T_{back}	936	[kNm]
Rated power	294	[MVA]	J	26820	[kgm²]
Rated current	8490	[A]	Max. torque (500 ms)	147	[%]
Rated torque	796	[kNm]	Max. torque (1 s)	148	[%]

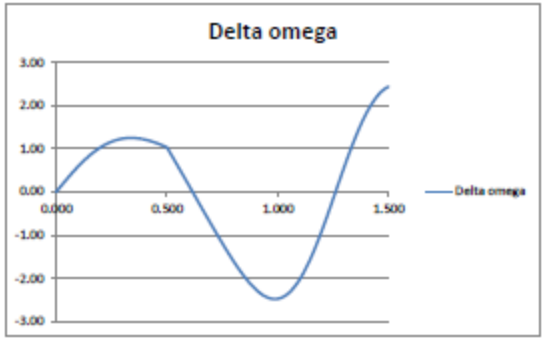
ID	cosφ		load	RoCoF	Stable	MaxTorque	Limit
	[-]		[%]	[Hz/s]		[%]	[Hz/s]
K	1	0	100	-1	Y	148	
	φ		$\alpha_{fo,start}$				
	0	°	0.93				

53.02 °





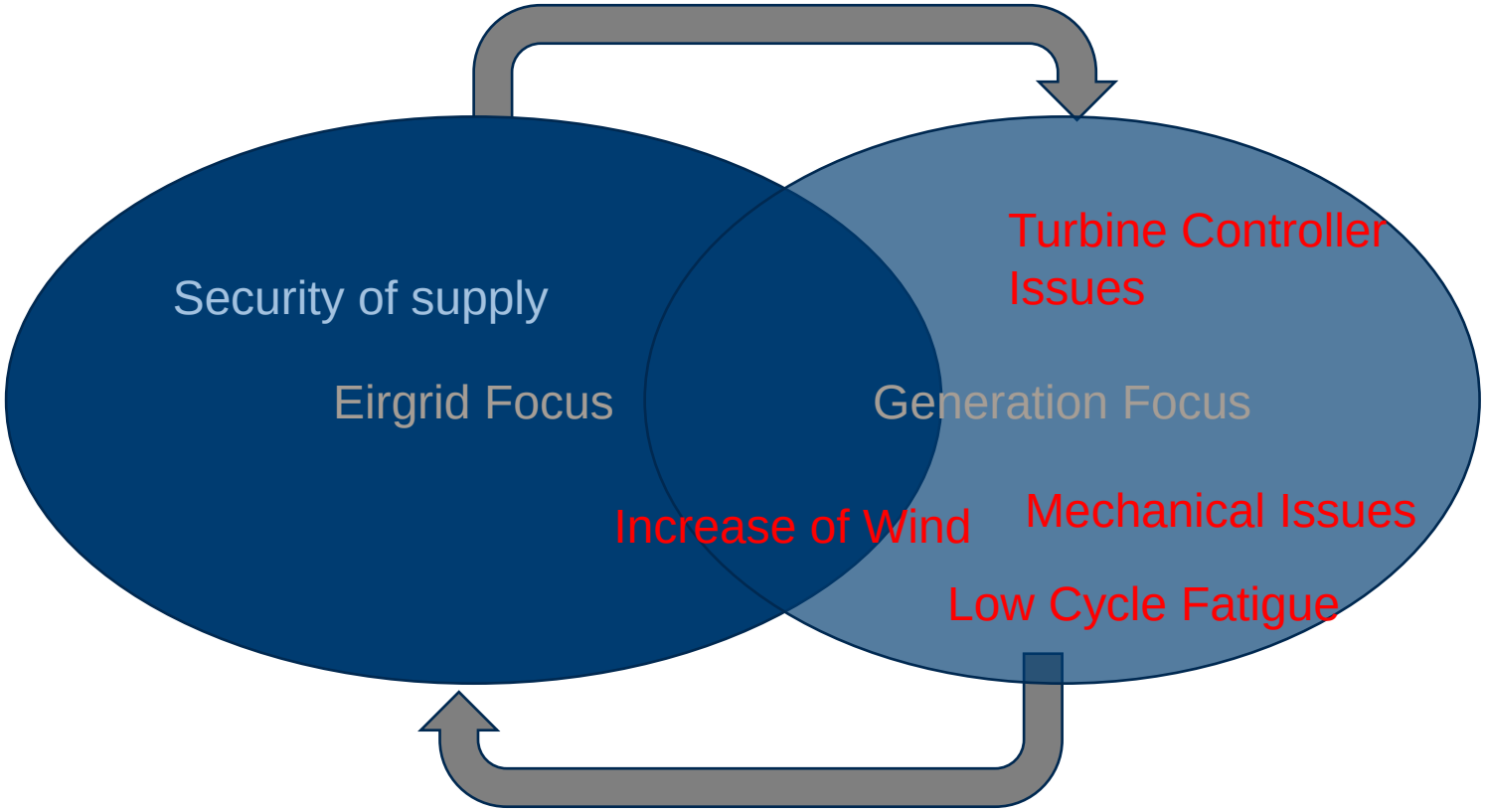
Non sinusoidal oscillations might trigger natural Frequencies, i.e. blades



ESB Study (DNV GL), main points

- **Minimum Load Problematic**
- **Compliance of existing machines especially with high inertia at 1Hz/s**
- **Further investigations required due to problems with non-sinusoidal oscillations**

Perspectives and dependencies



Shaft line, modelling required for all stations

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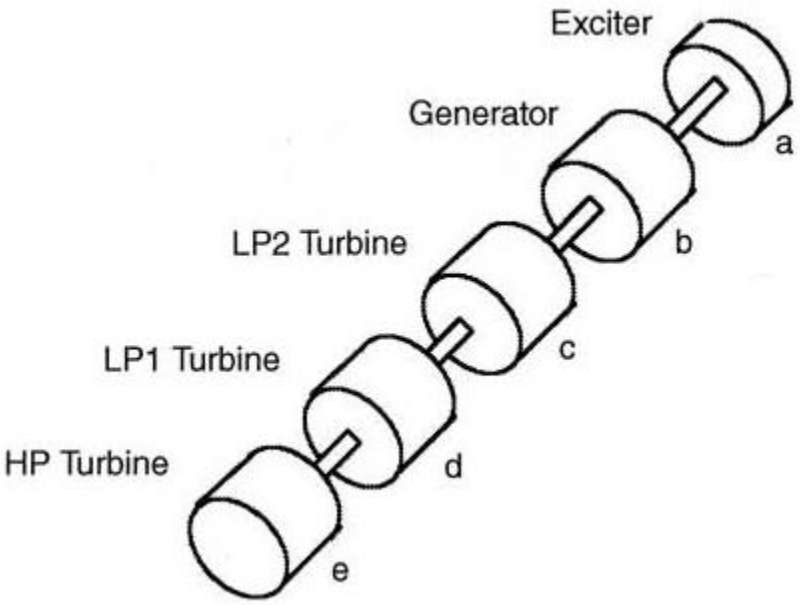
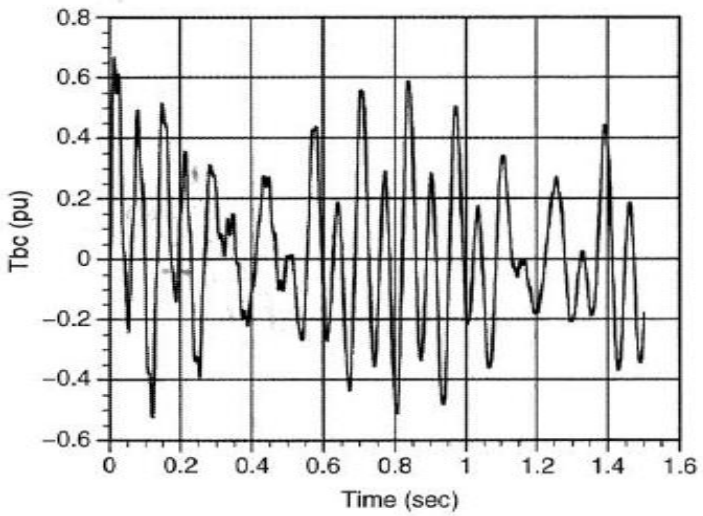
Analysis for impact at mechanical components

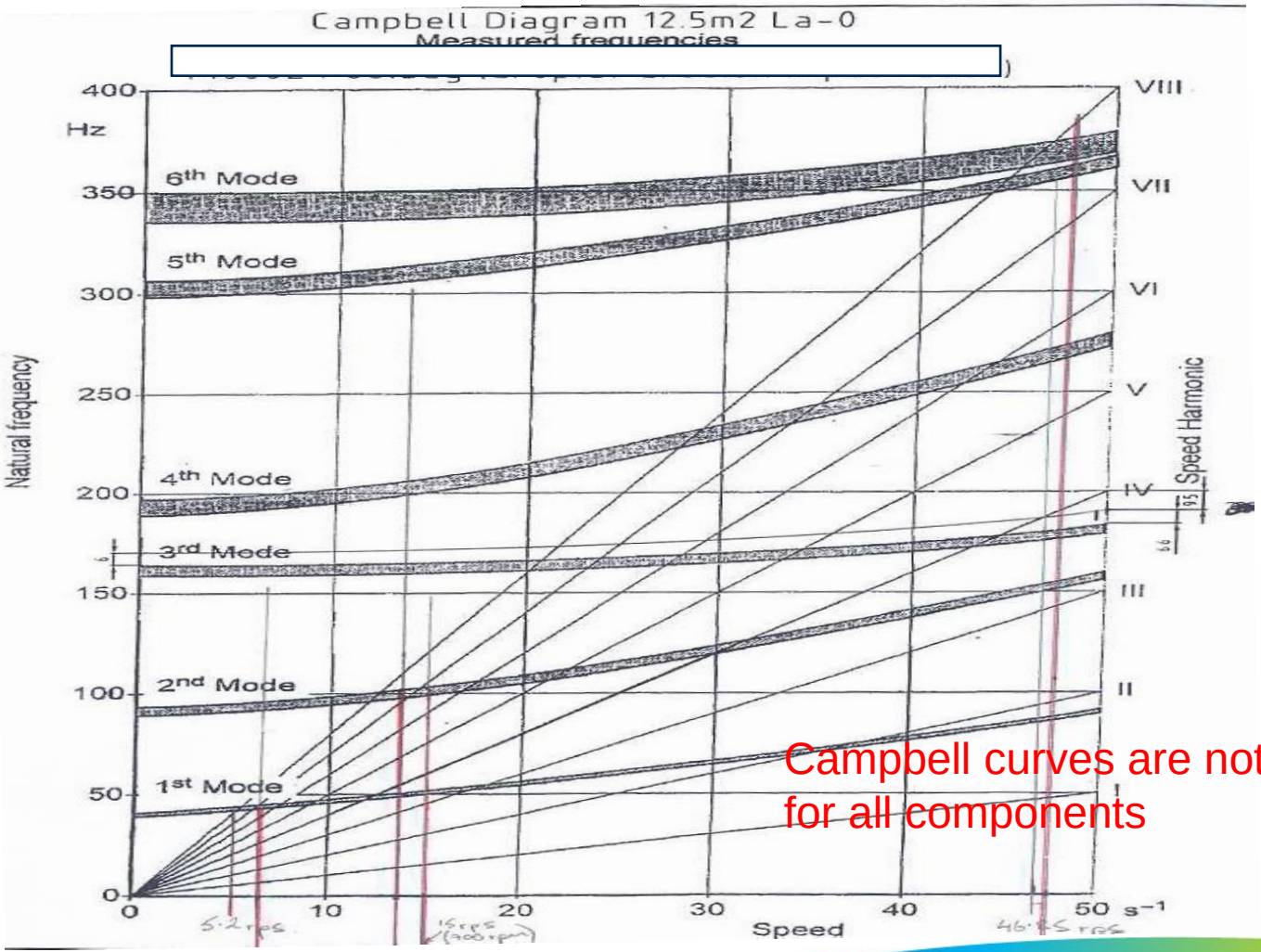




Shaft section b–c torque for three-phase fault.

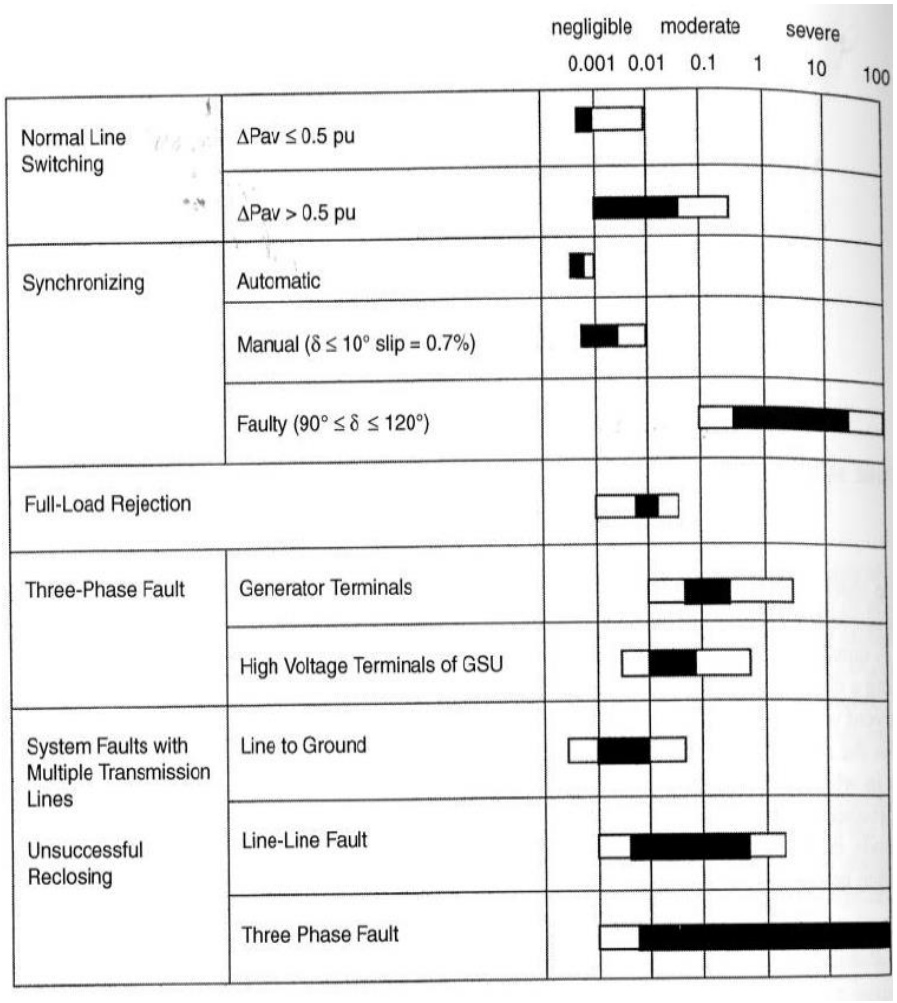
Higher RoCoF values might trigger Eigen-Frequencies

Natural Frequencies of Components, Example LP-Blades row 0 (Last stage blades)



Campbell curves are not available for all components

Impact on lifetime



Life time and maintenance analysis to be undertaken

Next Steps

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Further analysis of RoCoF events is required:

> …….Therefore the increase of 153 % in torque of the nominal value will not cause immediate failure of the synchronous machines currently compliant with the Ireland and Northern Ireland grid code. Considerations however may need to be made regarding lifetime reduction/ maintenance intervals. Allowing multiple RoCoF events each year could effect lifetime.

RoCoF, An independent analysis on the ability of Generators to ride through Rate of Change of Frequency values up to 2Hz/s. (8.2.2013 KEMA)

Next steps

- Dynamic analysis with accurate models is required. Digsilent models to be developed
- Information collection, especially mechanical components
- Life time analysis and crack and failure mechanisms need to be investigated

Areas of concern

1. **Stability - > Mechanical Issues**

2. **Definition of RoCoF (500ms) – >Suitable Trace required to check compliance**

3. **Operation at leading power factors - >Operational Issues**

4. **Issues at Min Gen - > Capability unavailable when most required i.e. at night**

References

1. “DNV_KEMA_Report_Rocof_20130208v3.pdf”, commissioned by Eirgrid
2. “Summary of Studies on Rate of Change of Frequency events on the All-Island System”, August 2012, Salim Temtem & Karen Creighton (Eirgrid)
3. “Protective Relaying for Generation Systems”, Donald Reimert

Final Messages

- Major doubt over feasibility of 1Hz/s
  - Mechanical issue
  - Operational issues
  - Min Gen
- Data Requirements
- Eirgrid unsuitable for PM Role
- Unrealistic timelines for OEM’s to meet
- Cost Recovery