Generator Capability Envelope and Design Challenges to Accommodate Grid Code Requirements

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Kevin Chan	GE Power
Robert Cummings	NERC
Kevin Mayor	GE Power
John Yagielski	GE Power

Introduction

- Synchronous generators are designed according IEC60034 and IEEE C50.13 standards.
- In a deregulated electricity market varying interests of the market players demand clear connection requirements in order to ensure the stability of supply → defined in Grid Codes.
- All Grid Codes extend the technical requirements of equipment. Grid codes are not harmonized.
- Large scale integration of renewable energy sources leads to further flexibility requirements for conventional plants.

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Change — Affected Grid Performance

Generation Mix

- **System Inertia**
  - RoCoF
  - Frequency Containment
  - Generation Withstand Capability
  - System Stability
- **Short Circuit Level**
  - Protection
  - Voltage Dips
  - Voltage Management
  - Resonance and Harmonics
- **Conventional Generator Closures & Increase in DG**
  - Emergency Restoration
  - System Inertia and Short Circuit Level

New Technologies

- **Series Compensation & New CSC HVDC Links**
  - Subsynchronous Resonance
- **New VSC HVDC Links**
  - Control Systems

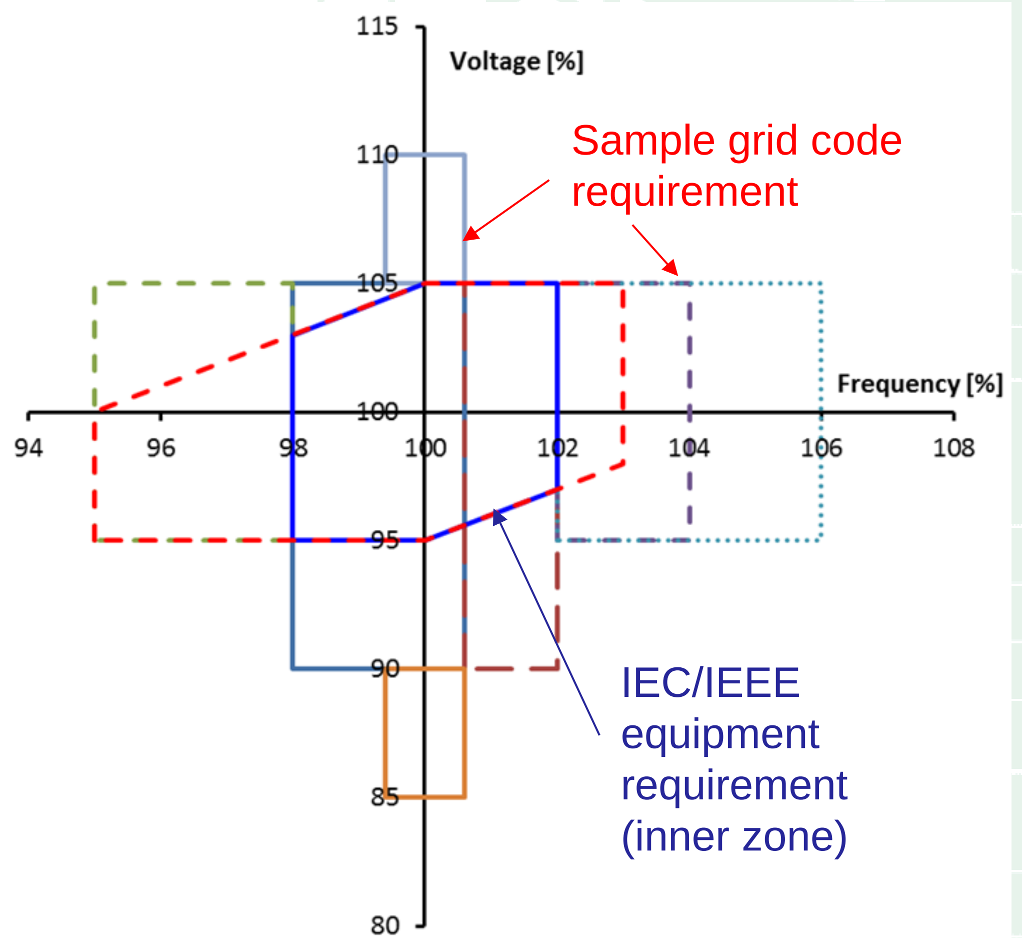
Image From National Grid System Operability Framework 2014

Typical Grid Code Requirements

- Voltage-frequency operating ranges and durations
- Reactive power capability
- Generator short-circuit ratio (SCR)
- Rate of Change of Frequency (RoCoF) withstand
- Fault ride through
- Excitation voltage ceiling factor
- Auto-reclosing
- Power output Vs Frequency

Voltage-Frequency Operating Range

- V-f ranges often significantly larger than in equipment standards
- Boundary conditions are often not defined (e.g. reactive load, duration of disturbance, frequency of occurrence)
- Voltage ranges usually defined for connection point → For OEM unclear without knowing:
  - Transformer reactance
  - Use of on-load tap changer (OLTC) transformer



From IEEE-PES-2012_WG8-Panel-paper_Grid Code Impact to Machine Design

V-F Range Design Challenges

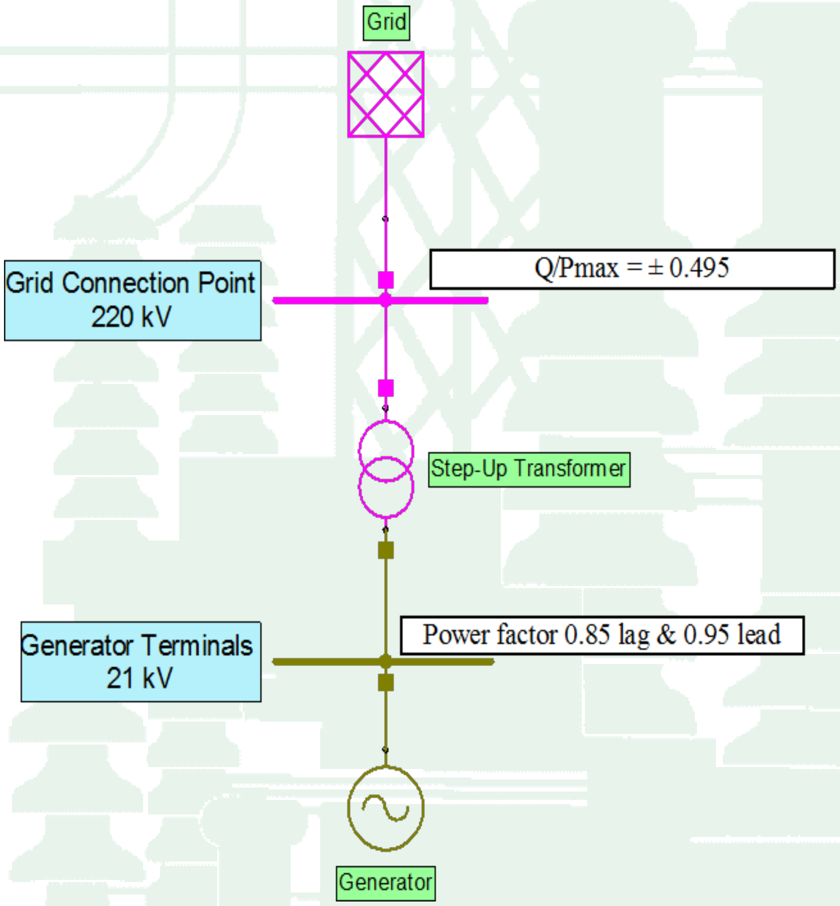
- V-f requirements not harmonized between grid codes
  - Difficult to design standard generators for standard turbines (engineering/manufacturing effort → cost impact)
- Enlarged V-f ranges lead to oversized machines (cost impact)

- **Possible solutions**:
  - Clear definition of operating conditions, expected duration and frequency of occurance of voltage-frequency excursions by TSO's
  - Equipment standards to allow short-term overheating during short term voltage and frequency excursions

Reactive Power Capability

Existing Equipment Standards:

- MVAr capability defined by standard rated power factors at the generator terminals of 0.8, 0.85 and 0.9 overexcited.
- The lower the power factor the larger will be the machine. → **Do not over-specify**
- **<u>Recommended</u>:** Grid codes to specify 0.95 underexcited power factor at rated MW, consistent with equipment standards.



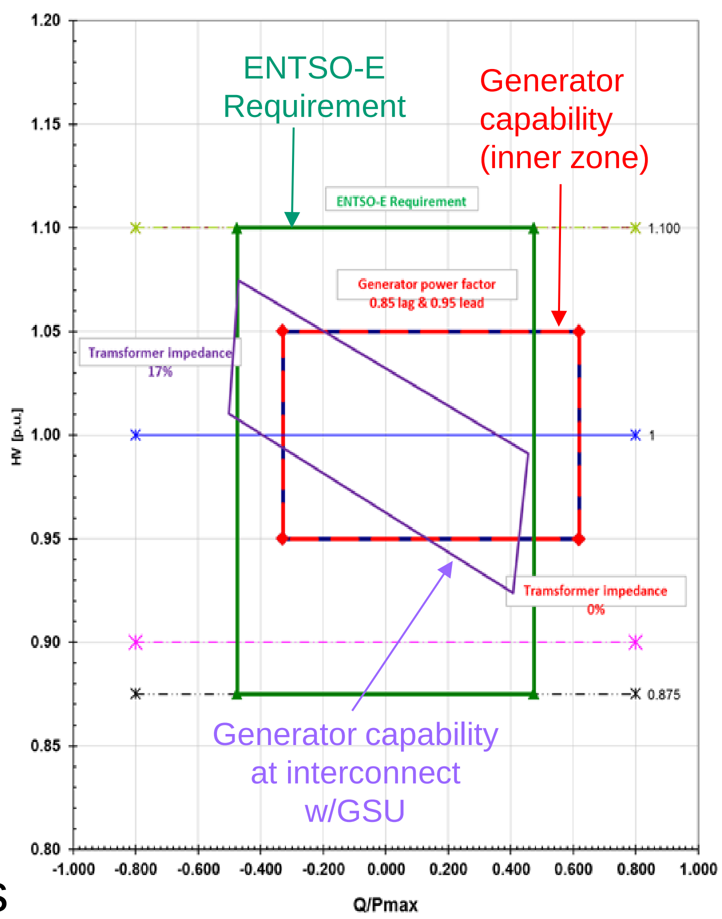
Typical one-line diagram denoting varying locations for capability requirements

MVAr Capability Design Challenges

Grid Codes:

- MVAr capability is often defined at grid connection point by Voltage vs. Q/P_{max} diagrams
  → Capability depends on generator AND step-up transformer design
- Without OLTC transformers, conventionally designed synchronous machines can hardly meet the requirements:
  → oversized, more expensive generators

Comparison of V vs Q/Pmax requirements



Possible solutions:

- TSO's to allow OLTC in all transmission grids
- Grid codes to consider requirements at generator terminals and harmonize with realistic V-f-MVAr conditions

Short-Circuit Ratio (SCR)

IEC 60034-3 / IEEE C50.13 specifies a minimum SCR of 0.35:

- Most generators designed to have SCR > 0.45
- Most grid codes require SCR ≥ 0.5
- A high SCR is believed to improve grid stability

IEC60034-4 SCR definition :

$$SCR = K_c = \frac{i_{f0}}{i_{fk}}$$

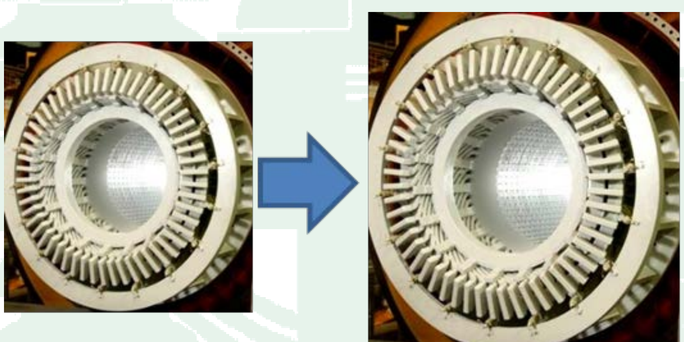
i_{f0} …field current at no-load and rated terminal voltage
i_{fk} …field current at 3-phase short-circuit and rated stator current

- Marginal improvement with SCR=0.5 compared with SCR=0.45
  - Insignificant difference with fast and high gain excitation systems
  - Increases generator size / cost & reduces efficiency
  - Effective only for certain grid configurations at the connection point

SCR Design Considerations

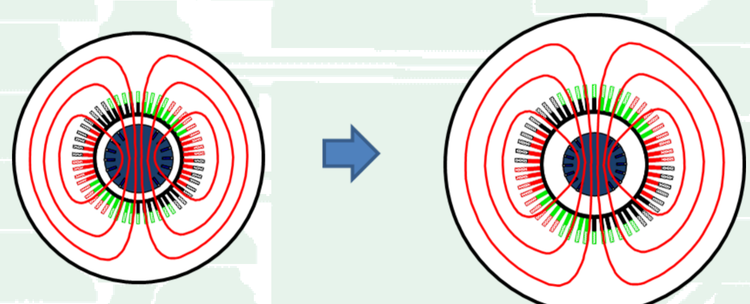
Selection of Larger Generator

- Weight increase ~0.6 times the percentage of SCR increase
- SCR: 0.45 → 0.5
  ⇒ Weight: 100% → 107%



Air Gap Increase

- Weight increase ~0.35 times the percentage of SCR increase
- SCR: 0.45 → 0.5
  ⇒ Weight 100% → 104%
- Field current increases with the air gap and leads to higher temperature and lower efficiency



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SCR Design Considerations

<u>Possible solutions</u>:

- Harmonization of grid code requirements for countries with similar grid topology (SCR ←→ reactive capability, V/f range)

- Flexibility of grid codes to allow lower SCR if grid study shows no significant benefit for stability

- Lower SCR requirements in grid codes for large generating units

Rate of Change of Frequency (RoCoF)

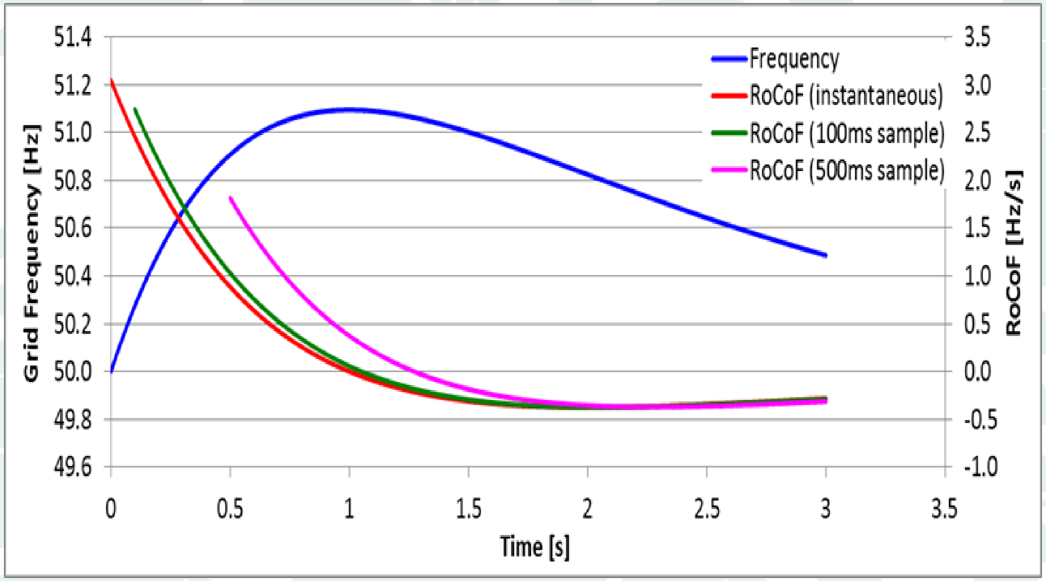
- Grid codes require Generators to stay connected during high gradients of grid frequency.
  - e.g.: Australian code requires up to 4Hz/s for up to 0.25s

- Usually only max. Gradients are defined, but boundary conditions are often unclear and do not allow an evaluation

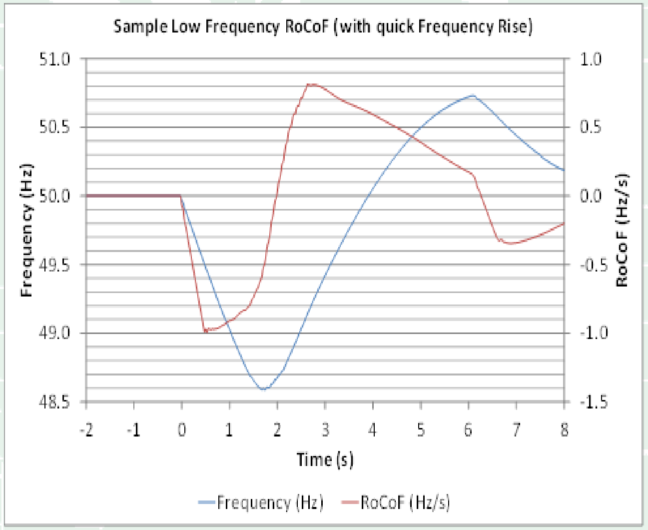
- Generator standards do not specify RoCoF withstand capability

RoCoF Requirements

- **Recommendation**: Grid codes to define:
  - Expected duration of the event for the required RoCoF
  - Expected wave shape(s) of the frequency excursion (right diagram)
  - Measurement conditions for the RoCoF value (left diagram)



Variation in measured RoCoF based on sampling rate



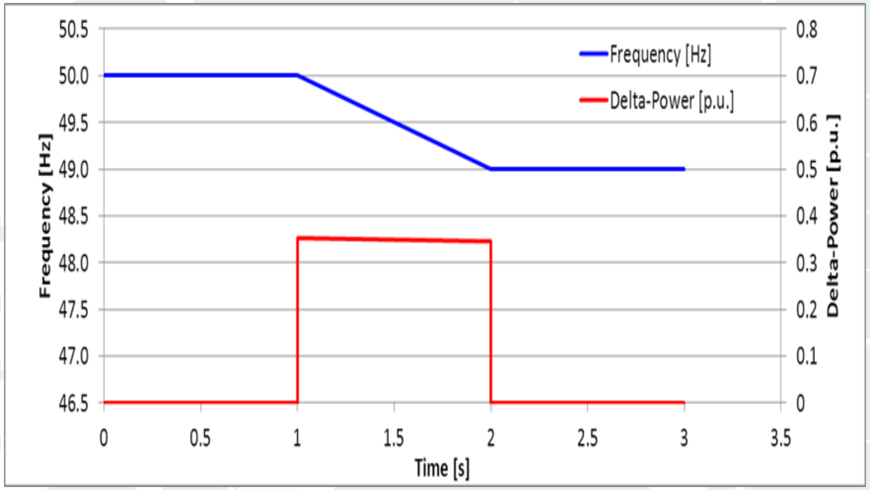
RoCoF – Effects on Generator

RoCoF general evaluation by simplified representation:

- Frequency changes with constant gradient
  → immediate power step request at generator terminals.
- Step is deceleration or acceleration power of shaft line
- **Negative frequency gradients are critical:**
  → generator load angle increase
  → exported power increase

Result: new balance or pole slip.

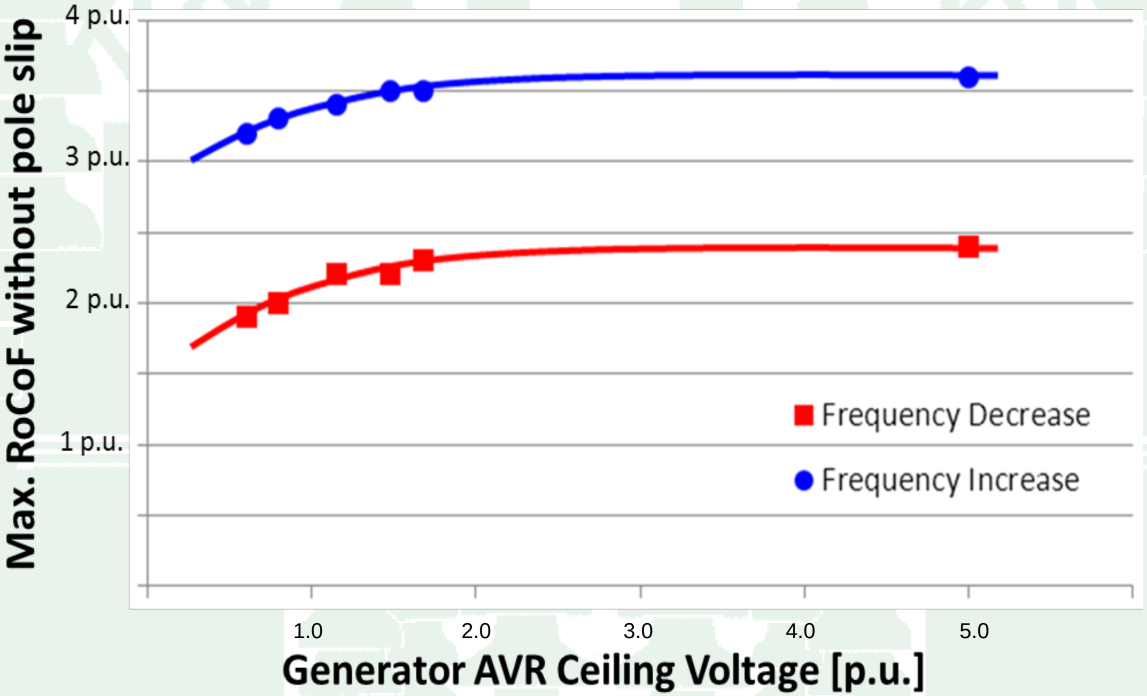
Rate of Change of Frequency	Resulting immediate Power Step ΔP (example, typical GT single drive shaft train)
0.5 Hz/s	17.5 %
1.0 Hz/s	35 %
2.0 Hz/s	70 %
3.0 Hz/s	105 %
4.0 Hz/s	140 %



<u>**Recommendation**</u>**:** Grid codes to allow for out-of-step protection

RoCoF Design Challenges

- Increased AVR ceiling voltage has limited effect on capability
- Above ceiling factors of 2, no significant increase in withstand capability



Fault Ride Through (FRT) Capability

- Generators designed (per IEC60034-3 / IEEE C50.13) to withstand sudden short-circuits may not comply with FRT requirements.

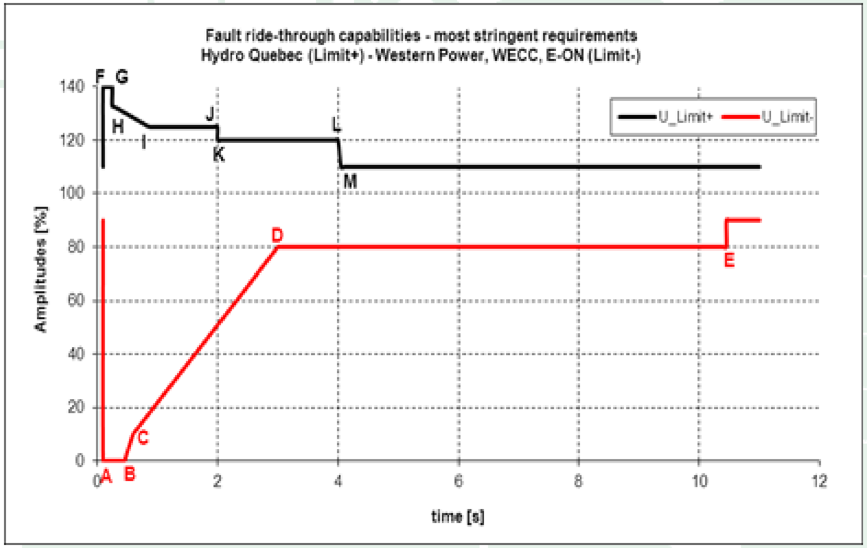
- FRT capability depends on generator characteristics <u>and</u> external factors:
  - system pre and post fault conditions,
  - transformer reactance

  → **System studies necessary!**

- Local grid codes give varying profiles
- FRT requirements may impact design parameters such as inertia, SCR, ceiling voltage, etc.

  → **Difficult to have a standard design**

Representative FRT requirement



	LVRT				HVRT	
Point	Time [s]	U_{PCC} [%]		Point	Time [s]	U_{PCC} [%]
A	0	0		F	0.1	140
B	0.45	0		G	0.2	140
C	0.55	6.46		H	0.25	133
D	3.00	80		I	0.85	125
E	10.45	90		J	2.00	125
				K	2.05	120
				L	4.00	120
				M	4.05	110

Excitation Voltage Ceiling Factor (CF)

- One possibility for improved FRT capability is excitation system with a higher excitation voltage CF.

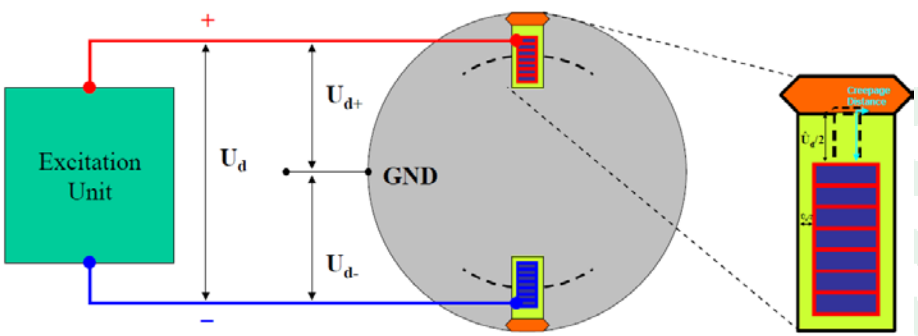
- IEEE 421.4 specifies a minimum excitation voltage CF of 1.5.

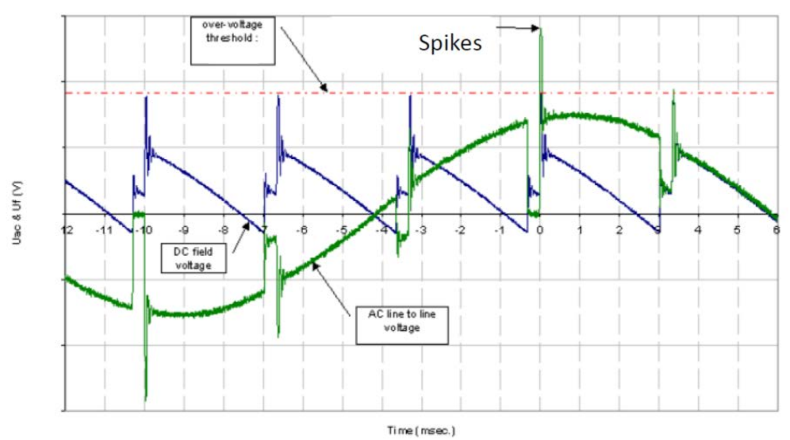
- Grid code requirements on voltage CF vary from 1.6 to 4. Current grid codes show tendency toward voltage CF ≥ 2.

Voltage CF Design Challenges

<u>Consequences of high voltage CF</u>:

- Rotor insulation systems are crucial to the reliability of a generator.
- High voltages impose additional duty on the field winding insulation system.
- The field winding is exposed to switching spikes that reach ceiling voltage several times per cycle and may exceed the allowable voltage level of the rotor winding insulation.





Typical static excitation voltage waveforms

Voltage CF Design Challenges

<u>High excitation voltage</u>:

- Higher pulse (12 or more) exciter to reduce over-voltages
  - → increased equipment costs.
  - → non industry standard solution.
  - → may require new development of converter bridges for large units.

<u>Alternative to high excitation voltage</u>:

- Separately sourced excitation system → increased equipment costs.
- Other means of improving FRT capability such as fast valving for steam turbines → increased equipment costs and more complex control systems.

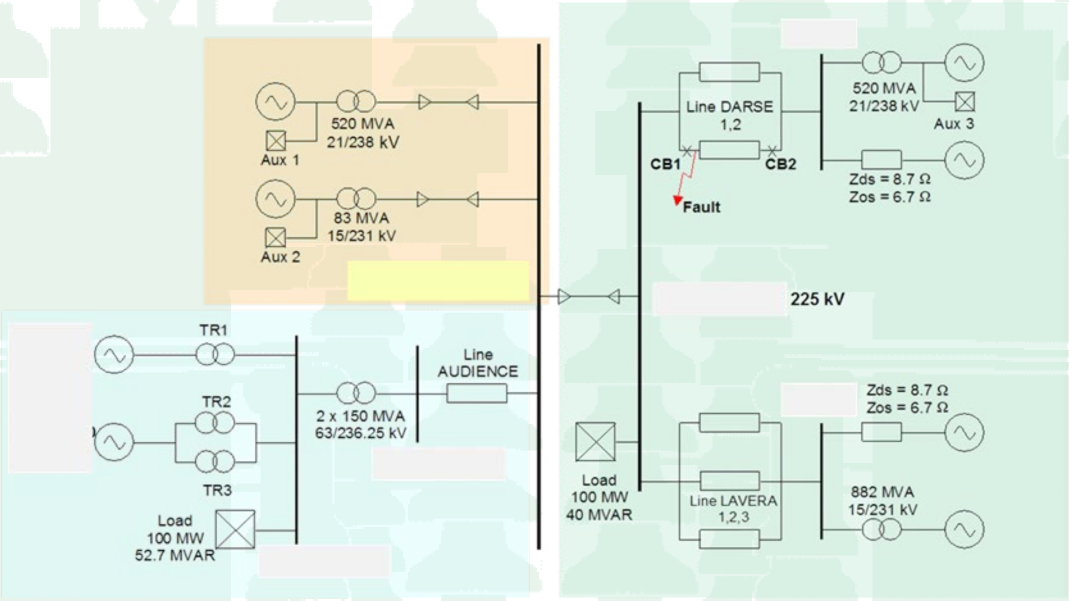
<u>Recommendation:</u>

- Given diminishing performance benefit → CF should not exceed 2.0.
- Employ other means for FRT as dictated by system simulations

Auto Re-Closing

IEEE C50.13 states that:

- Rapid reclosure (successful & unsuccessful) :
  - results in shaft torques which are statistical in nature
  - could lead to cumulative fatigue damage to shafts
- Generalized torsional stress requirements are not possible
- Unit-specific study is recommended to be performed



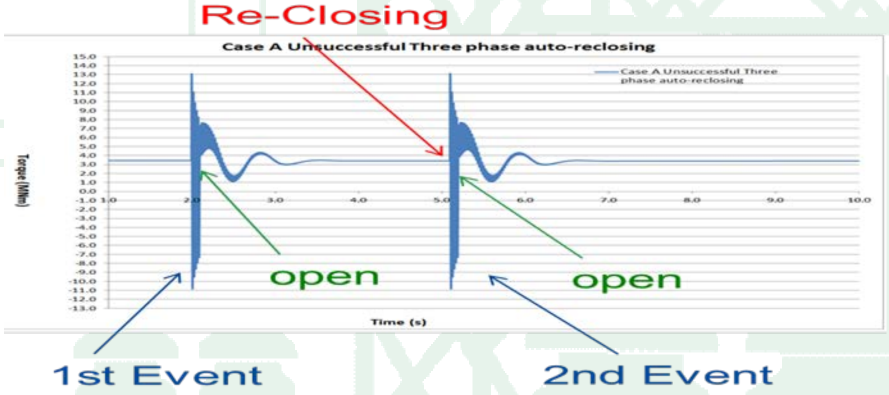
Typical system representation for modeling re-closing events

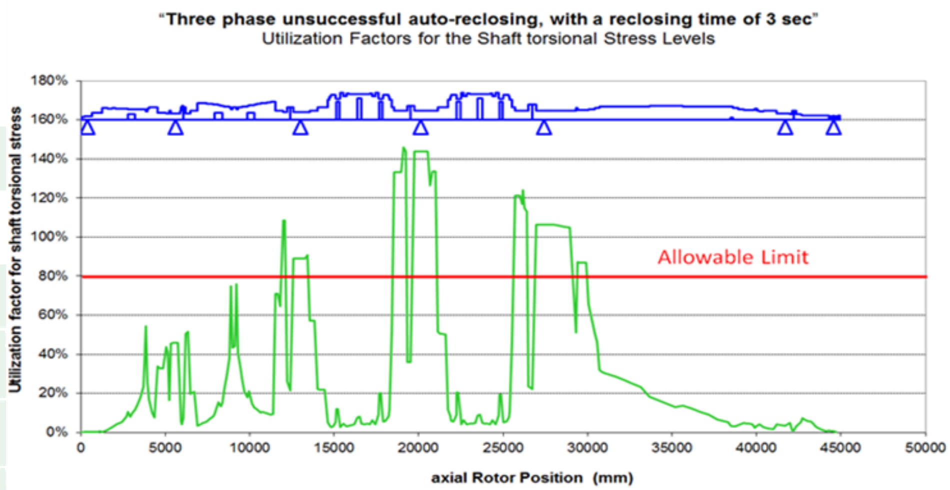
Auto Re-Closing

- Grid codes generally require units to withstand 1- or 3-phase auto-reclosures without tripping

- Protective measures:
  - Supervision by synchro-check relay to avoid reclosing onto a fault
  - Specific study needed, considering statistical nature of events vs. “worst” case

→ **Machine shaft integrity shall be considered 1st priority for grid reliability / availability**





Representative torque and shaft stresses due to re-closing

Power Output Vs. Frequency

- <u>EU grid code</u>
  - Below 49.5 Hz reduction rate of 10% per 1 Hz Frequency drop
  - Below 49 Hz: reduction rate of 2% per 1 Hz Frequency drop

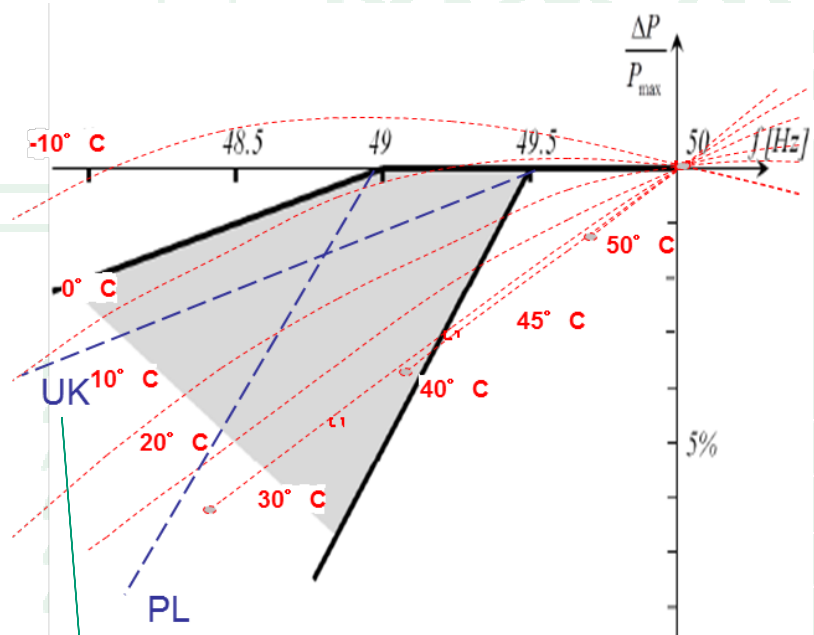
- <u>UK and Poland grid code</u>

  - requirements shown by dotted BLUE lines

Physical behavior of CGT

- Significantly decreased output with higher ambient temperature
- Therefore limitation of requirement to 25°C in UK

Sample Output vs Frequency Requirements



--- Typical GT power output (Unit specific)

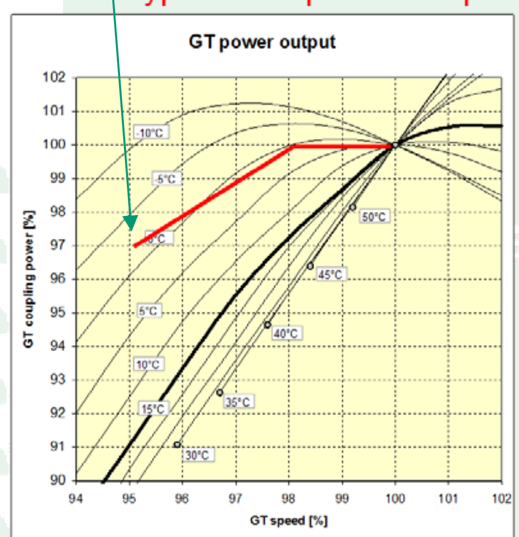


Image by EUTurbines

MW vs F Design Impact

- Need to “derate” units to provide headroom for an event that may never occur.
- Higher €/kW Capex for dead capacity, losing best efficiency. Creates a **0.5 B€ cost***
- Need to develop and install compensation mechanisms with inherent activation delay times. Creates **additional 0.1 B€ cost*.**

- **Recommendation:** Do not specify capability, but require submission of capability by manufacturers. Adjust load shedding schemes through simulations.

*Estimates by EUTurbines for subject market
(Brussels presentation 2013)

Summary

- Evolution in the power system is driving changes in the grid requirements for power generation equipment.
- Equipment designed to current machine standards does not necessary meet the grid code requirements.
- Grid operators must also consider the physical limitations and the cost impact when defining grid requirements for power generation equipment.
- There is an urgent need to identify existing gaps and harmonize design standards with grid code requirements.
- Industry consultations are important to ensure design standards and grid code requirements are harmonized.