VSM Expert Group Meeting

21 Oct 2019

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Agenda

1. Recap from last meeting
2. Proposed VSM Specification
3. Stability Finder RFI Feedback
4. Richard Ierna – Feedback/Research
5. Eric Lewis - Enstore's review of RFI, VSM and synchronous machines
6. Further Discussion / AoB

Lunch to be served around 12:00

Meeting to close no-later than 15:00

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GB Grid Forming Converters / Virtual Synchronous Machines

Discussion of Proposed Specification

Summary October 2019

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Summary

Challenge: Operation of the system is becoming less stable mainly due to an increasing proportion of non-synchronous generation

Solutions: A range of potential solutions are being progressed under the stability pathfinder work, changing loss of mains protection, consideration of synchronous compensators and Virtual Synchronous Machines (VSM)/GB Grid Forming Converters

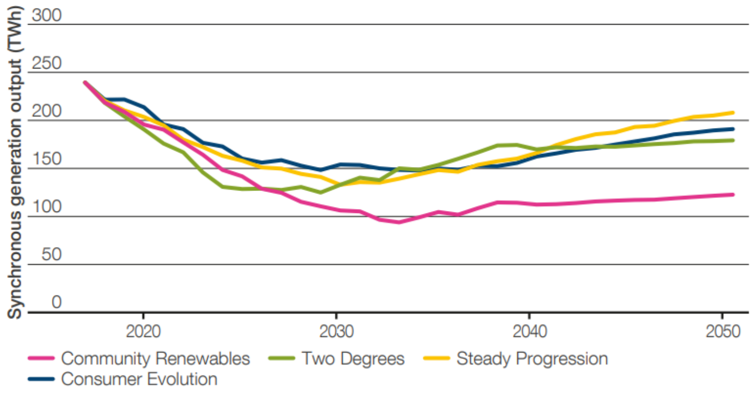
Next steps

- **Specification:**
  - Complete work to justify a Grid Code specification,
  - Move from expert group to formal Grid Code Working Group
  - Develop commercial treatment of specification
- **Innovation:** Progress innovation projects to inform solutions

What is the operability need?

The generation background is changing

- Synchronous generation capacity and output is decreasing
- More convertor based technologies are connecting to the system



We need to find alternative approaches to ensure stable operation

- Synchronous generators inherently deliver stabilising capabilities which are not inherently delivered from converter based generators:
  - Inertia – instantaneous frequency management
  - Fault current – instantaneous current injection
  - Dynamic voltage support – instantaneous reactive power

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What are Virtual Synchronous Machines/ GB Grid Forming Converters?

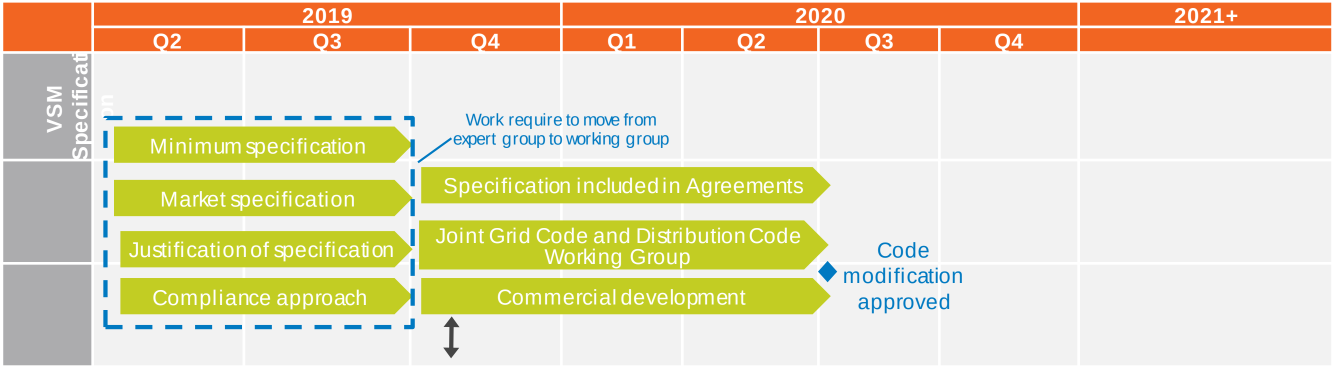
With investment, some convertor based technologies can offer stability

- Changes to the control system mimics the behaviour of synchronous generators
- Part loading of generation or combination with storage enables injection of current
- Approach can be applied to a range of different technologies (Eg. Converter based generators, interconnectors, batteries, electric vehicle charging)

We are developing a specification

- To ensure that the further connection of convertor based technologies doesn't make the system less stable we are writing a minimum specification to be included in the Grid Code
- We are considering the most suitable treatment of the Grid Cod specification
- The specification proposed in the stability pathfinder will allow innovative approaches such as VSM/GB Grid Forming to participate

Timeline



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Stakeholder Engagement

An Expert Group was established in April 2018 to:

- Engage with Manufacturers and developers with an interest in this area
- Establish if VSM/GB Grid Forming is feasible as a capability / product through a questionnaire
- Define a VSM/GB Grid Forming specification based on capability and the minimum requirements of the System
- Establish overall costs through a Cost Benefit Analysis – Being addressed through Stability Pathfinder – Costs expected later in the near future

Next steps: Grid Code Working Group

- Following the completion of the Expert Group objectives, the secondary stage is to establish a Grid Code Working Group so a VSM / GB Grid Forming type specification can be included within the Grid Code

Both of the above activities will require significant Stakeholder engagement. As part of the Expert Group excellent Stakeholder Engagement has already been established and this is expected to grow with the Grid Code Workgroup. Excellent feedback has also been received from the Stability Pathfinder work.

Stability Pathfinder

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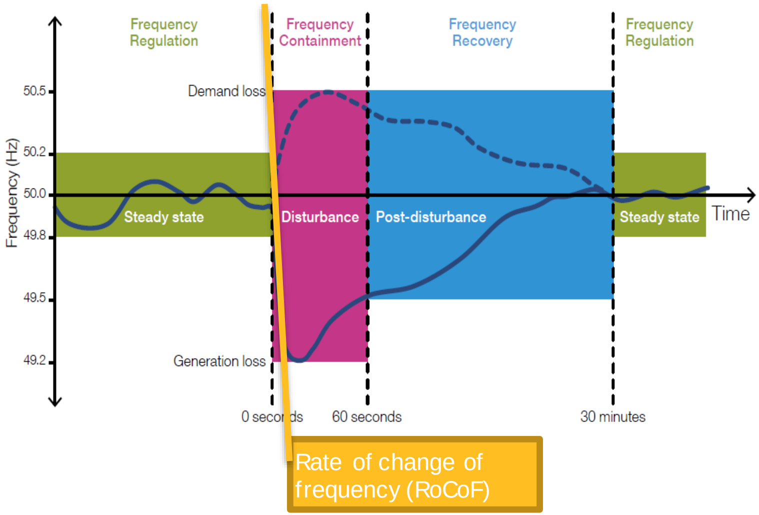
Stability Context

System Operator Obligations	- The System Operator has a statutory obligation to ensure a safe, secure and economic system. - The System Operator is required to maintain frequency within statutory limits and ensure safe, stable and economic operation of the transmission network. - The System Operator is required to maintain voltage within within statutory limits and ensure safe, stable and economic operation of the transmission network.
Stability Context	- By stability, we mean the stability of frequency and voltage, and the ability of a user to remain connected to and to act to support the system during normal operation, during a secured fault or after a secured fault, without any restriction in doing so that would relate to the strength of the system at that time. - Properties of synchronous generators such as short circuit level, fast fault current injection and inertia mean that decline in availability may impact stability of system voltage and frequency. - With decline of synchronous assets and increase of non-synchronous generation on both transmission and distribution networks, stability needs are evolving.

2.1. Stability Context

Stability Context – National	■ At national level, frequency is maintained within limits by consideration of frequency response/reserve market products. ■ At national level, Rate of Change of Frequency(RoCoF) is maintained within limits by consideration of largest generation/demand loss on the system and planning for national levels of inertia.
Stability Context – Regional	■ Based on the conditions at the time, regional levels and the distribution of regional inertia across GB has the potential to influence the scale of regional variations in RoCoF, or regional frequency variations- such that regional impacts could be beyond established National limits. ■ Voltage is a regional characteristic and it is maintained within limits by consideration of the balance of local/regional reactive power support both through TO assets or market products. ■ Voltage support must be provided across all times of regulation, the period of the fault/ disturbance, and the recovery period immediately following it. Whilst voltage can be supported statically as well as dynamically, only dynamic support can be provided across all periods of a disturbance. Support approaches may be unique, or layered across a variety of solutions to achieve this. ■ Short circuit level is a regional characteristic, influenced by local network elements (demand, generation) and is important in ensuring local voltage, frequency stability and control system integrity.

Frequency Stability Overview



- Figure illustrates frequency management at different network states.
- RoCoF, calculated in Hz/s, is a local measure of how fast frequency is changing following a network disturbance. This measure may be influenced regionally by the effect of the disturbance itself. Containing RoCoF contains the risk of embedded generation disconnection subject to disconnection under loss of mains relays.
- Synchronous machines and motor demand provide instantaneous energy or inertia in case of a network event which limits the rate at which frequency changes.
- During a disturbance, regional frequency can be different to national average, as explored in our NIC EFCC project.

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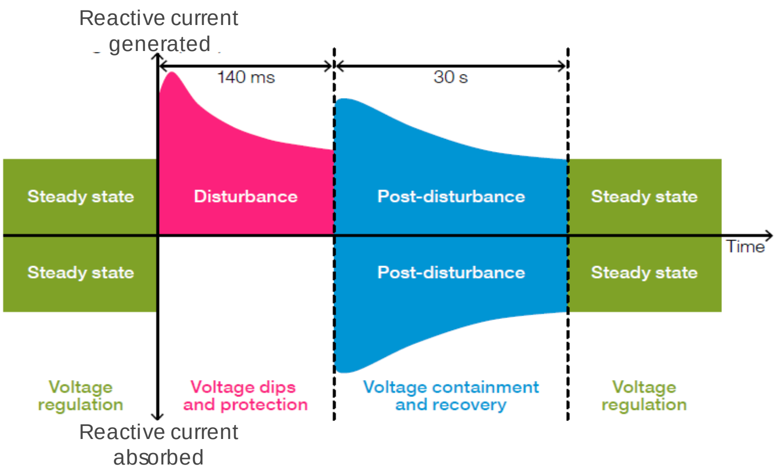
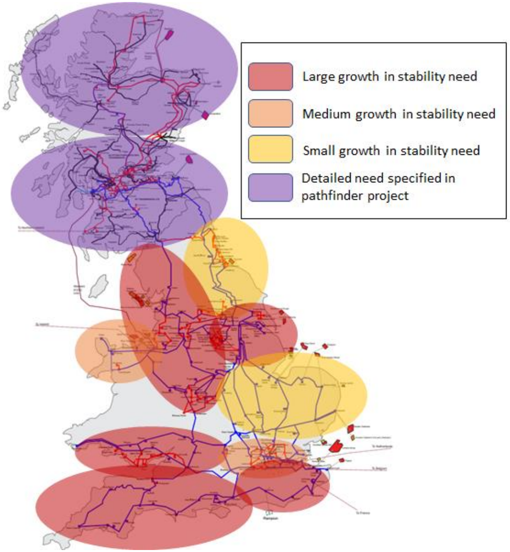
Voltage Stability Overview



- Figure illustrates voltage management at different network states.
- Voltage requirements vary regionally across different periods of a fault/disturbance.
- With more non-synchronous penetration in the electricity network
  - There is increased need of immediate reactive support during a disturbance and immediately after.
  - There is increased risk of combined voltage and frequency events. (Highlighted this in our SOF report on Voltage and frequency dependency)
- High voltage pathfinders in Mersey and Pennine are considering voltage regulation requirements during the steady state period.

GB Areas of Stability Focus

- Our assessment shows that our need for stability products is different across the country.
- High-Voltage pathfinders in Mersey and Pennine are addressing static high voltage requirement which is separate to our stability needs in these areas.
- For Stability Pathfinder, we have carried out detailed assessment of Scotland and high-level assessment of England & Wales (E&W)



New Stability Support Product

Stability support product description
Transient voltage dip, short circuit level and inertial support. Immediate post fault response to limit voltage deviation, and contain voltage angle movement.

Potential solution providers are expected to meet the technical specification specified in the Appendix 1 of the stability pathfinder RFI.

Some performance criteria are:

- Short circuit level contribution (MVA) ≥ 1.5 p.u. of MVA available in steady state operation
- Inertia (MVA.s) ≥ 1.5 p.u. of MVA available in steady state operation
- Transient voltage stabilisation and support capability
- Fast fault current injection
- Performance across range of minimum Short Circuit Levels

For more information

Network Development Roadmap Website:

https://www.nationalgrideso.com/publications/network-options-assessment-noa/network-development-roadmap

Richard Ierna

Wind Integration Workshop
Dublin 2019

Agenda

Paper 1 – National Grid

- Introduction to Paper & Projects
- Project History
- Grid Code Considerations
- Basic Convertor Algorithm (RMS)
- Dispatching Considerations

Paper 2 – Agusti Egea (UoS)

- HGFC & X Reduction Algorithm

Paper 3 & 4 – Mark Sumner (UoN)

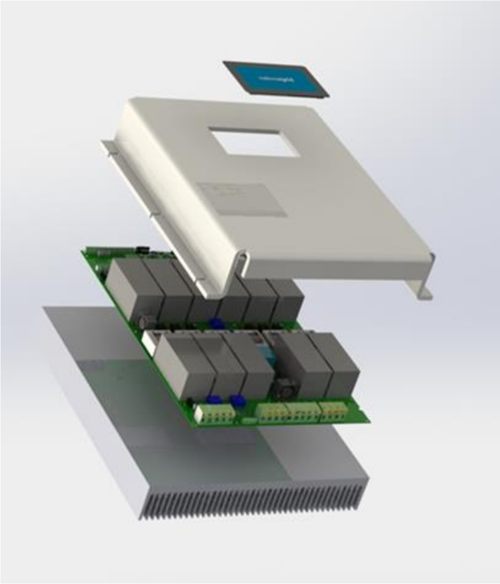
- Physical Implementation
- Power and Current Limiter
- Harmonics & Imbalance

Paper 5 – Adam Dysko (UoS)

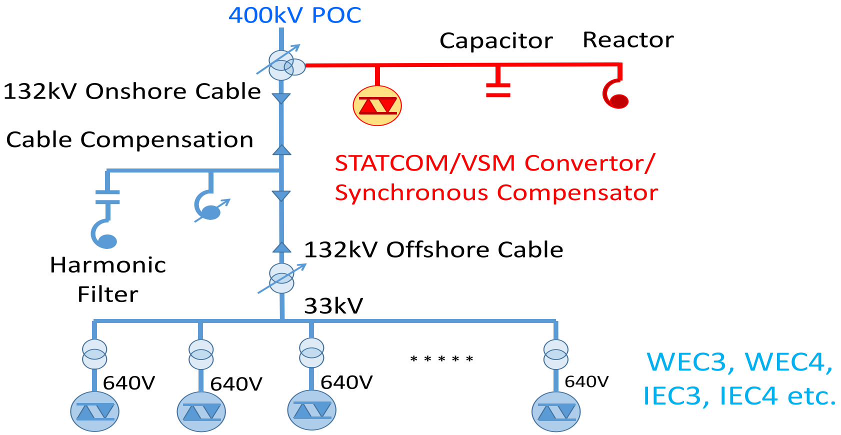
- Hybrid GF Convertors
- Sync Comp vs HGFC

Two NIA Projects Objectives

VSM Demonstrator
(University of Nottingham)



Hybrid Grid Forming Convertor
(University of Strathclyde)



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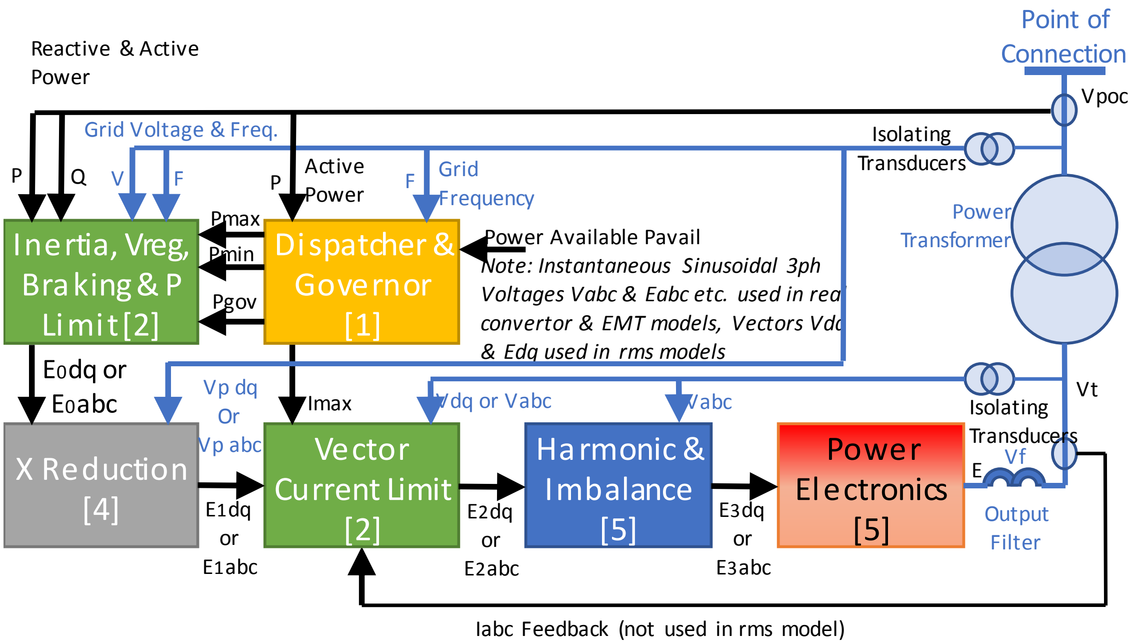
Projects Objectives

1. To design and test a VSM algorithm in line with general GFC/VSM principals such as GC0100 option 1.
2. To establish which plant control principals, parameters and tests are particularly relevant to grid stability.
3. To understand how grid forming performance affects one of the possible convertor designs and strategies which might mitigate any negative effects.
4. To establish whether it is possible to provide grid forming performance from hybrid solutions (for example STATCOMS) where not all of the converters are grid forming.

NB Many possible implementations of VSM / GFC – The SO is not seeking to prescribe a design but is seeking to capture the requirement which extends beyond the minimum ENTSO-E requirement.

Overall Algorithm and Structure of Presentation / Papers



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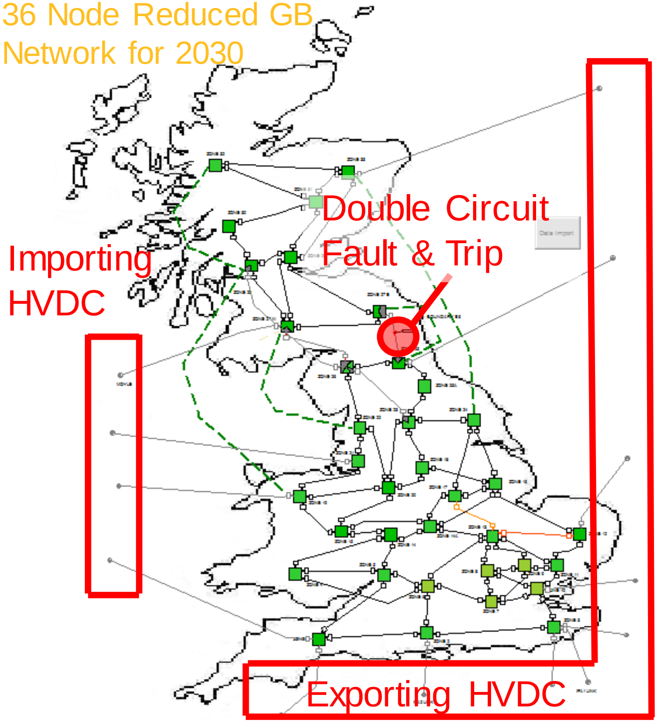
2013 Studies – Only 9/26 high NSG scenarios ok

36 Node Reduced GB Network for 2030

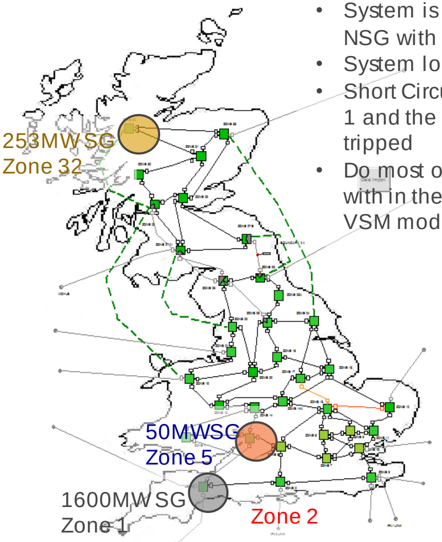


NSG	0 Import HVDC / 0 Export HVDC			3GW Import HVDC / 10GW Export HVDC			0 Import HVDC / 10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	OK			OK	OK		OK	OK	OK
Mid				OK			OK	OK	
High			N/A						

NSG is 8GW Solar +
Low: 16.0GW Wind
Mid: 20.5GW Wind
High: 28.5GW Wind

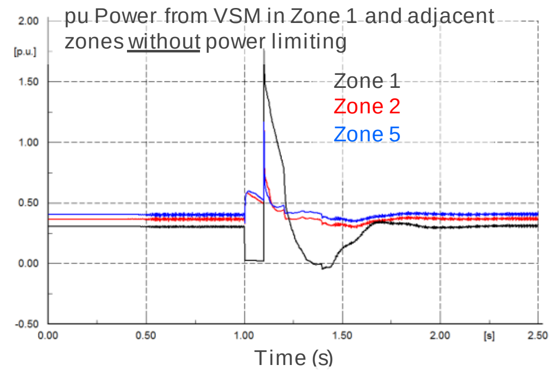
Green cells ok in 2013
Grey cells produced HF instability

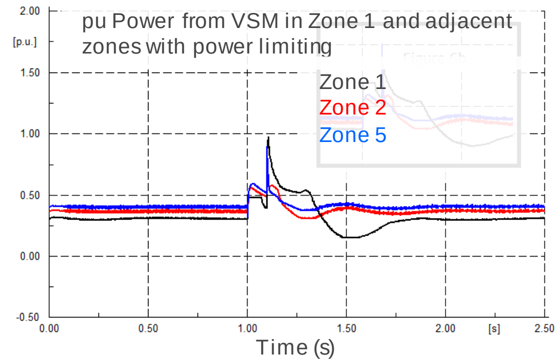
2016 – VSM Solution Demonstrated



Scenario

- System is operating at 97% NSG with SG as shown
- System load is 30GW
- Short Circuit is applied at Zone 1 and the 1600MWSG is tripped
- Do most of the VSM remain with in their stable region i.e. VSM mode?





Summary of 2016 Findings

- **Synthetic Inertia Doesn't Work**
- **Possible to Stabilise Systems 0 Inertia VSM**
- **Fundamentally it's a Voltage Stability Problem**
- **Need to add voltage sources back into the network**
- **These systems need headroom (additional current & power capability)**
- **VSM needs to get the additional energy from somewhere (storage?)**
- **33% extra power 50% extra current works**
- **Once you have added the extra capability you can use it to fix:**
  - Imbalance
  - Harmonics

Overview of Solutions to High Convertor Grid Stability

Solution	Estimated Cost	RoCoF [1] [2]	Sync Torque/Power (Voltage Stability/Ref) [2] [*] [4]	Prevent Voltage Collapse [2]	Prevent Sub-Sync Osc. / SG Compitable [2] [*]	Hi Freq Stability [2]	RMS Modelling [1] [2] [*] [4]	Fault Level [1] [2]	Post Fault Over Volts [2]	Harmonic & Imbalance [5]	System Level Maturity	Notes
Constrain Asyncronous Generation	Hgh	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	These technologies are or have the potential to be Grid Forming / Option 1
Syncronous Compensation or More Sync. Gens at lower load	High	I	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Proven	
VSM	Medium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	P	Modelled	
VSM0H	Low	No	Yes	Yes	No	P	P	P	Yes	P	Modelled	Has the potential to contribute but relies on the above Solutions
Synthetic Inertia	Medium	Yes	No	No	P	No	No	No	No	No	Modelled	
Other NG Projects	Low	Yes	P	Yes	No	No	No	P	P	No	Theoretical	

Summary of GC0100 Option 1 Grid Code proposals

- Voltage Source Behind and Impedance over 5Hz to 1kHz band
- Max Power Level of 1.33pu on rating
- Capable of sustaining 33% increase on rating of power initially proposed 20 seconds capability (now reduced to 0.5s for non LFSM-U plant)
- Max Fault Level of 1.5pu on rating
- Inertia of 2-7 Secs
- Minimum Filter Impedance of 10%
- Maintains voltage source behaviour during fault (current phase is determined by the fault impedance and not injected at 90degs to volts)
- For distribution systems – automated fault level management

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Stability Path Finder and VSM Working Group

Stability Path Finder

Request for Information:

- Conventional & Convertor Solutions
- TRL – Technology Readiness Level
- Cost

Grid Forming / VSM Working Group

New proposed VSM spec released on Wed 16/10/2019

- **Based on a combination of:**
  - GC0100 proposal
  - Stability Path Finder
  - NIA projects presented here

Stakeholder Questions with regard to GC0100

- *What do we mean V source from 5Hz to 1kHz*
- *What does the 10% impedance relate to*

Voltage Source behind an Impedance over 5Hz – 1kHz & 10% Impedance

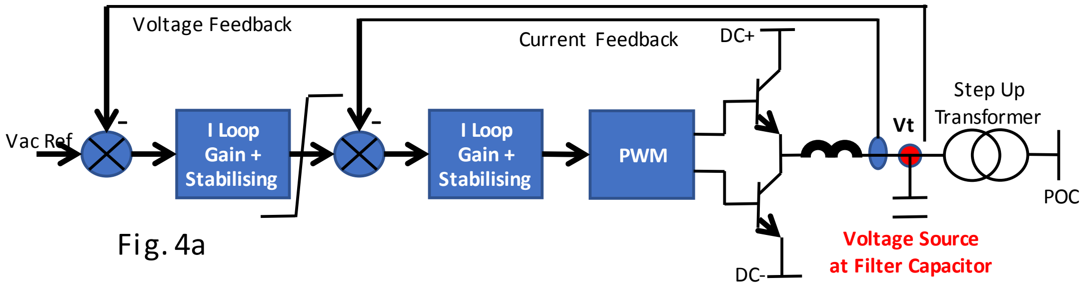


Fig. 4a

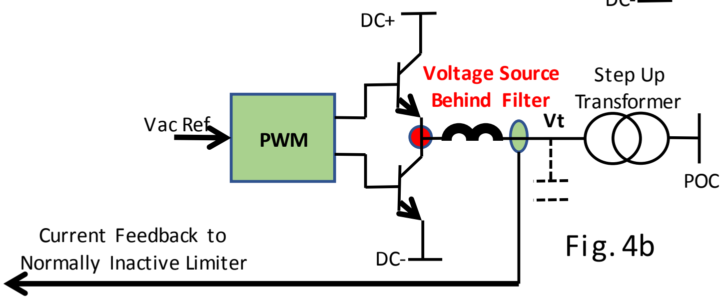


Fig. 4b

Grid Code Requirement

Steady State Capability

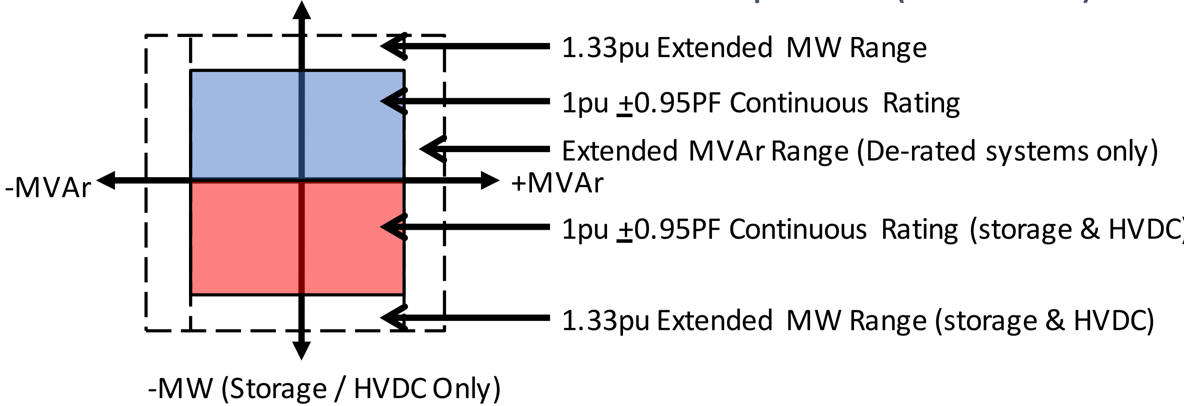
+0.95 Lead/Lag at 100% Rated Power

Red region applicable to storage and HVDC only

Many requirements in this region taking from existing Class 1 requirements

Extended Capability

- **Available for 20Secs**
- **1.33pu Rated Power (33% on rated power > current operating point)**
- **1.5pu current (on rated MW)**



Key Concerns of Stakeholders (We are listening)

- **Locating equipment offshore is very expensive and confidence building takes a long time**
- **Increased Convertor Rating**
- **Increased Energy Requirement (Storage and Derating)**
- **High Frequency event followed by Low Frequency event potentially requires additional energy storage**

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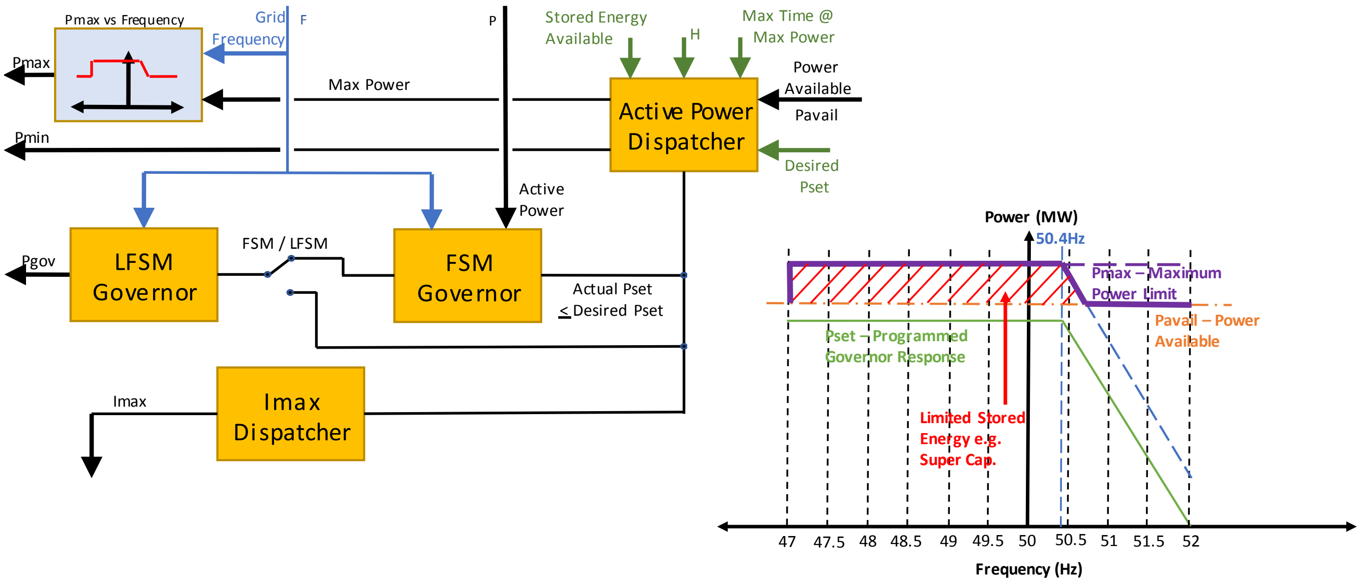
Dispatcher and Reduced Energy Requirement



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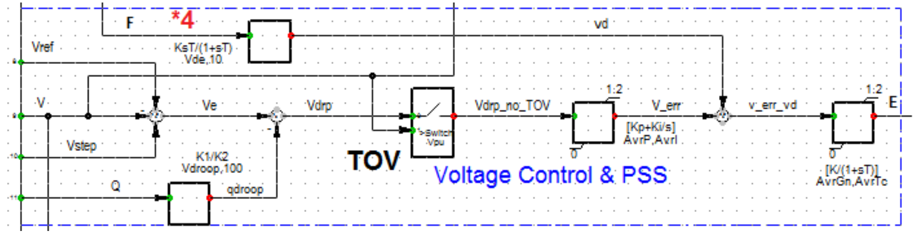
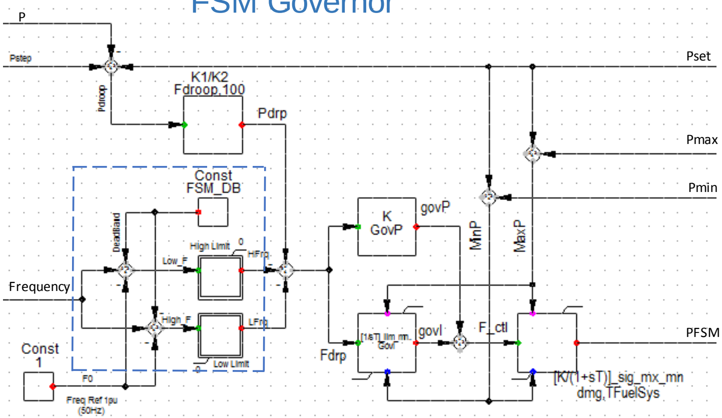
What's the same?

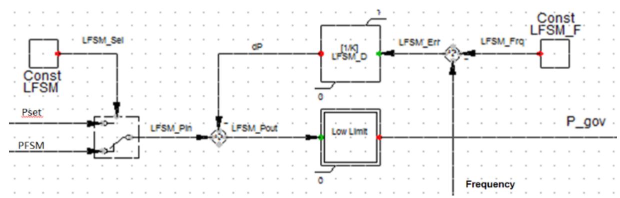


FSM Governor

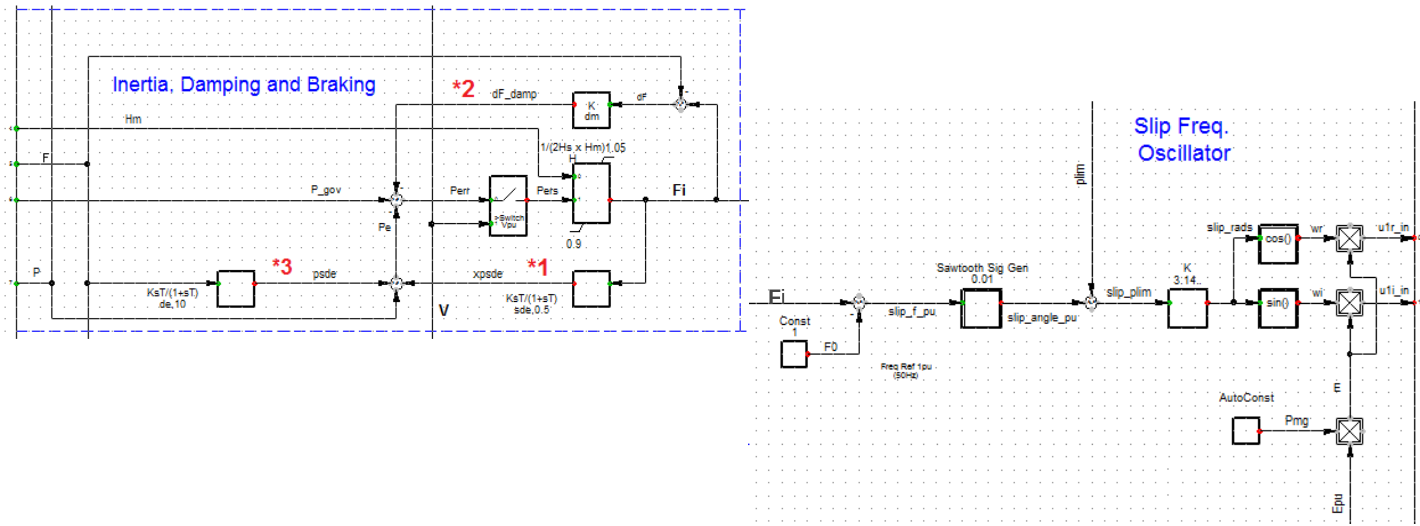


Fast

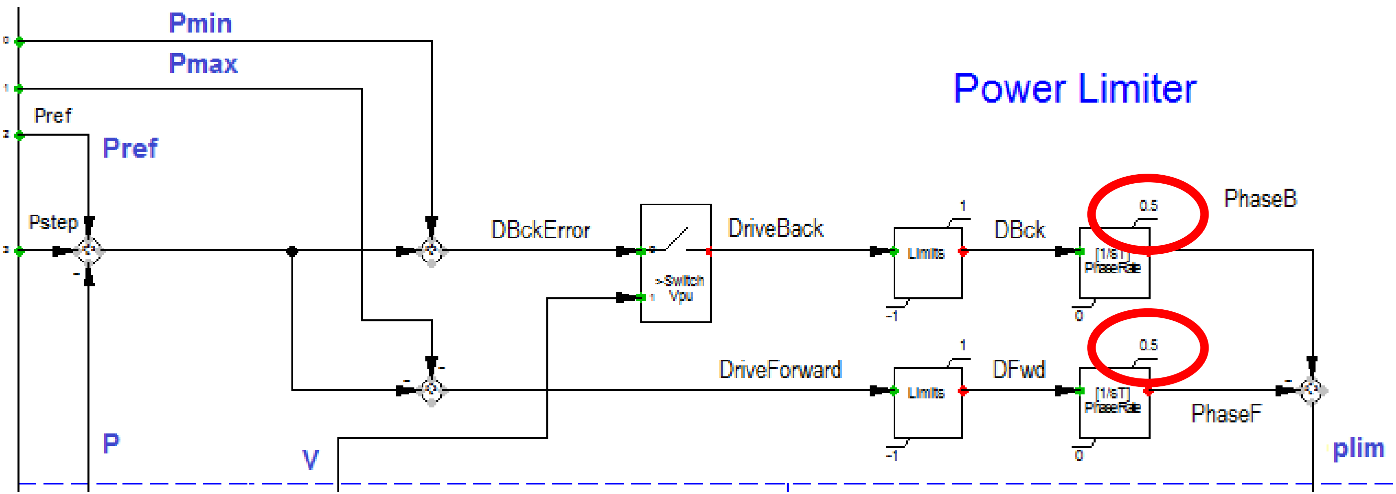
LFSM Governor



What’s different?



Power Limiter



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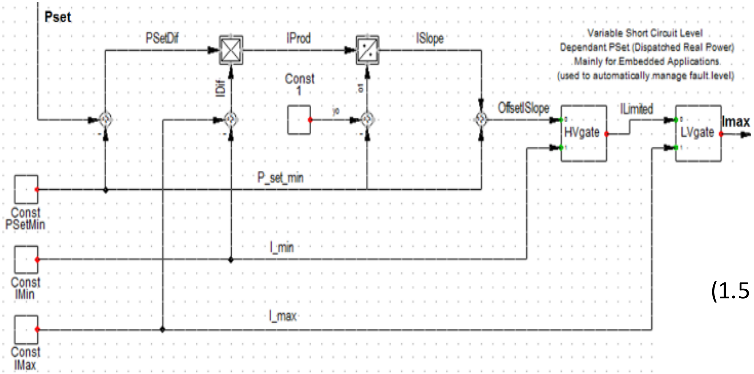
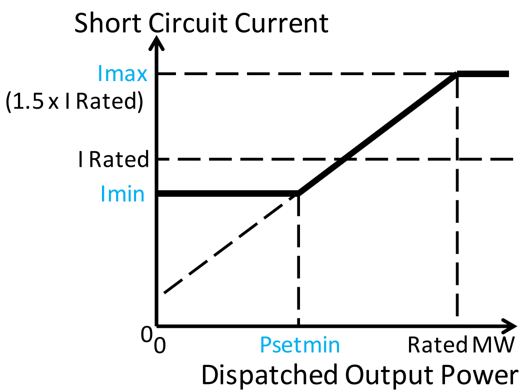
Semi-automatic Fault Level Management (GC0100)





Conclusion – Outcomes for Grid Code Proposal

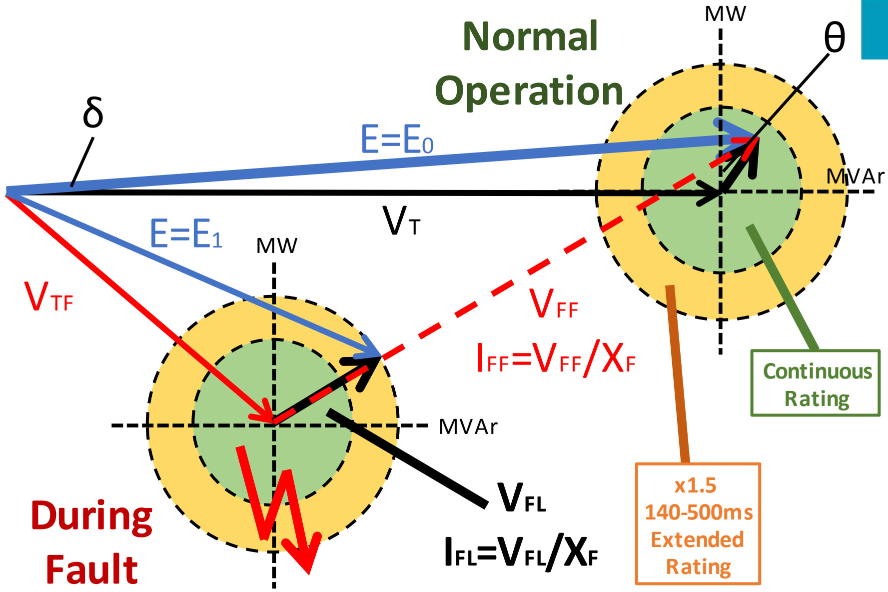
GC0100 Grid Code Modification:

1. **Instead of specifying Inertia – specify the minimum energy change relative to the RoCoF (Rate of Change of Frequency)**
2. **Instead of specifying the minimum impedance – Specify and impedance range and the energy change required relative to a vector shift / bus bar angle change**

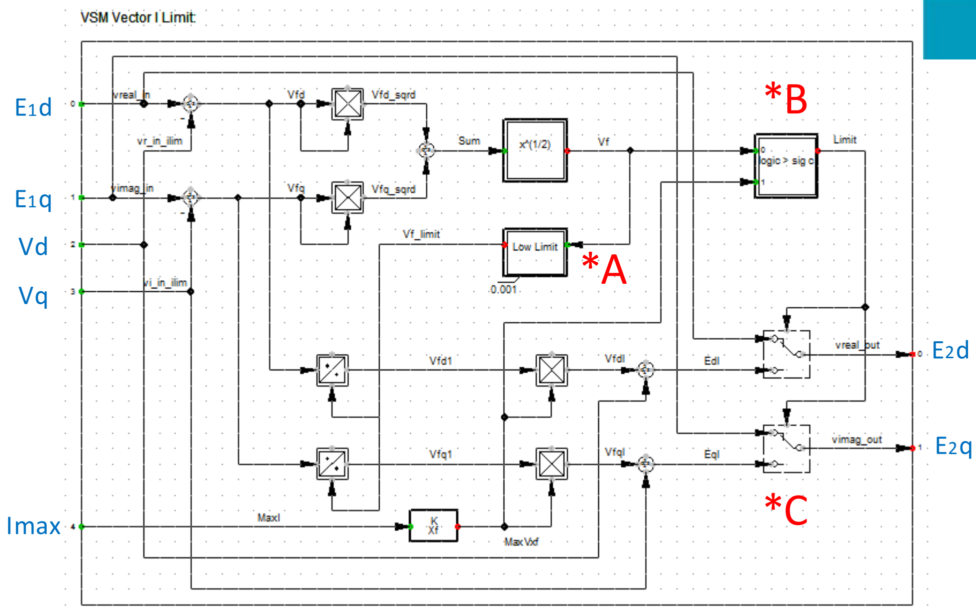
Other Outcomes:

1. **The manufacturer and generator can decide the proportions of additional energy provided by storage or/and curtailment**
2. **Only limited storage is required above 50Hz as fast governors allow automated curtailment and headroom for the inertial response**
3. **Hybrid Grid Forming Capability included**

Vector Current Limit



Vector Current Limit



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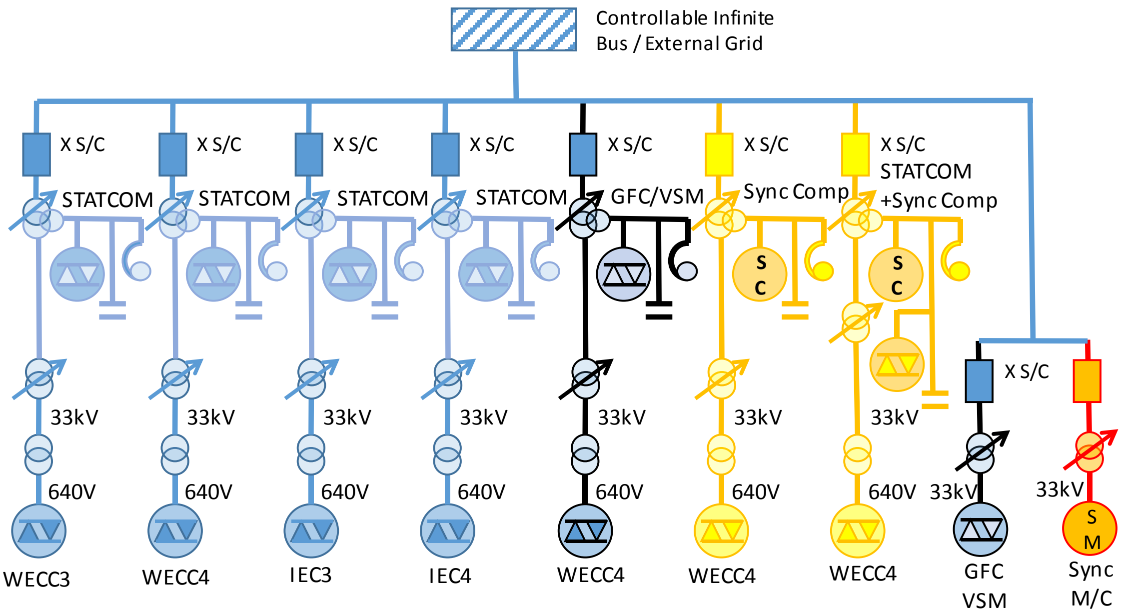
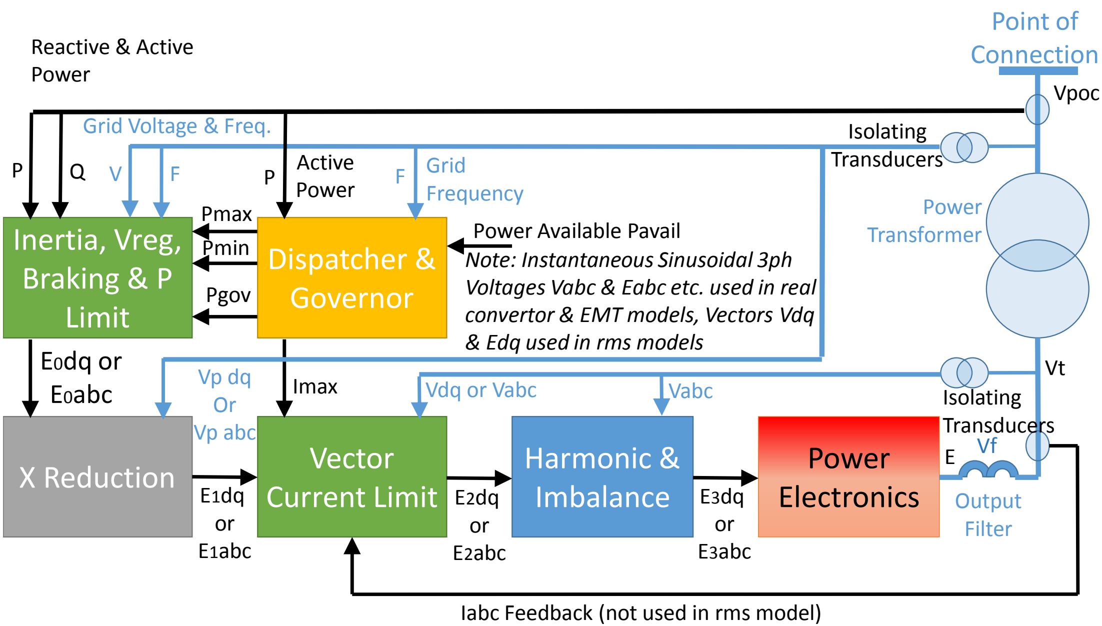
OFTO Network topology and study cases



VSM Implementation



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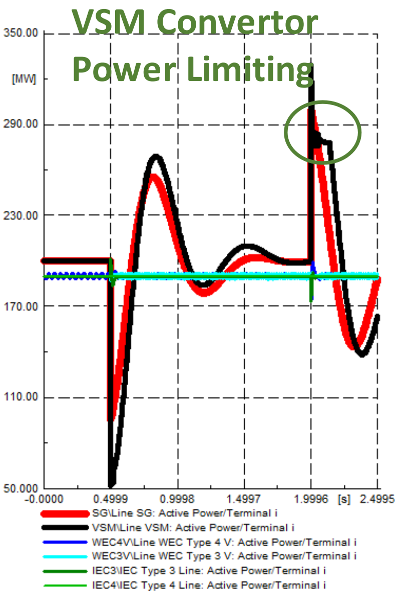
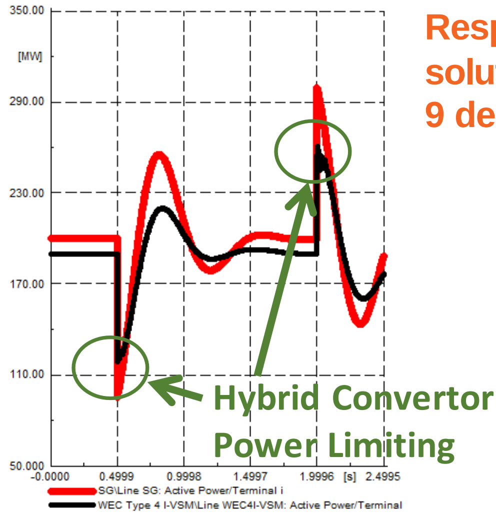
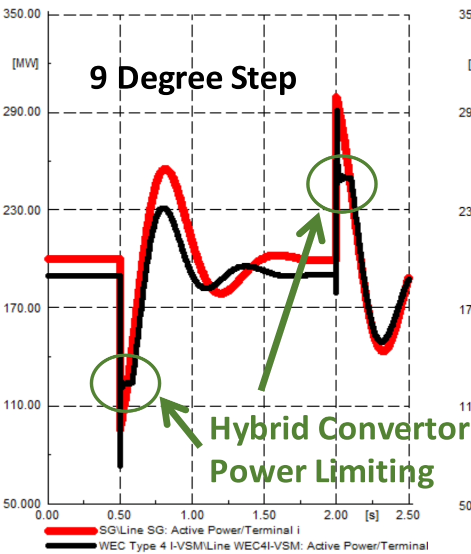
Results - Vectors shift of 9 deg

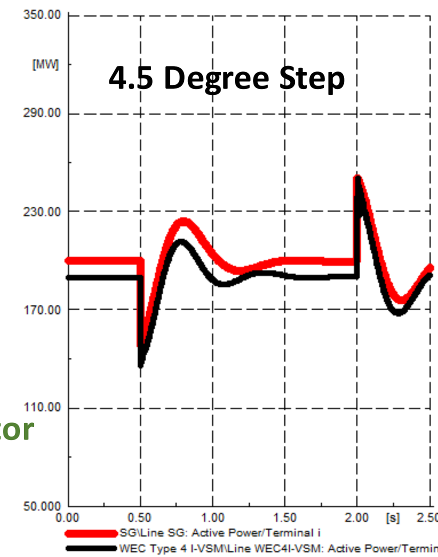




Responses of differing control solutions to a vector shift of 9 deg.

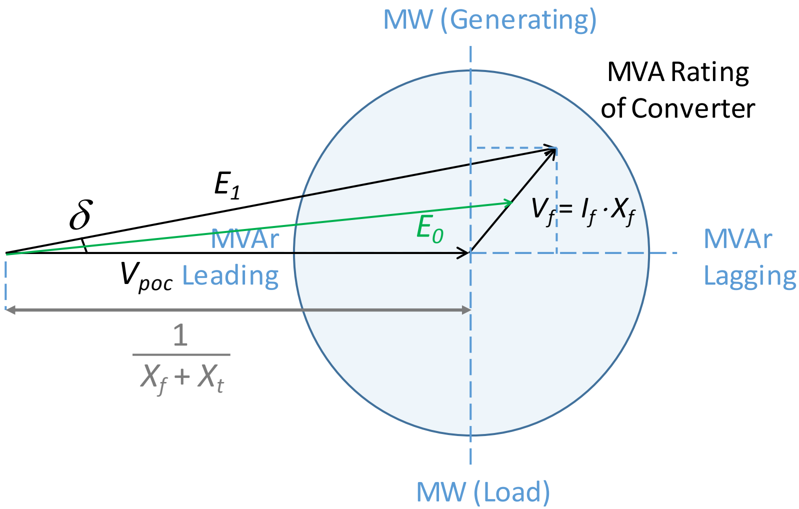
Results - Impedance Reduction





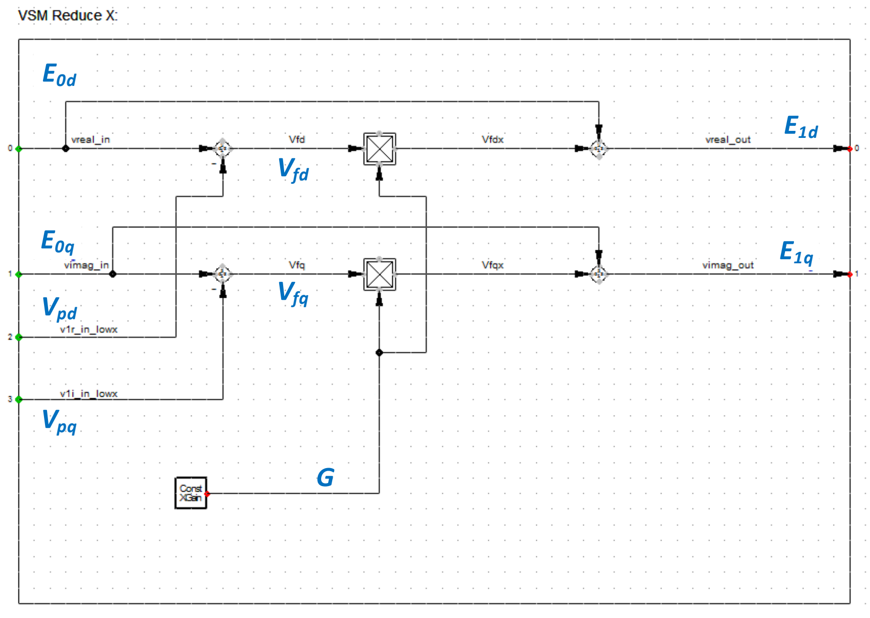
Vector shift response with filter impedance reduced from 10% to 1% & tertiary winding increased from 120MVA to 150MVA

Impedance Reduction Algorithm

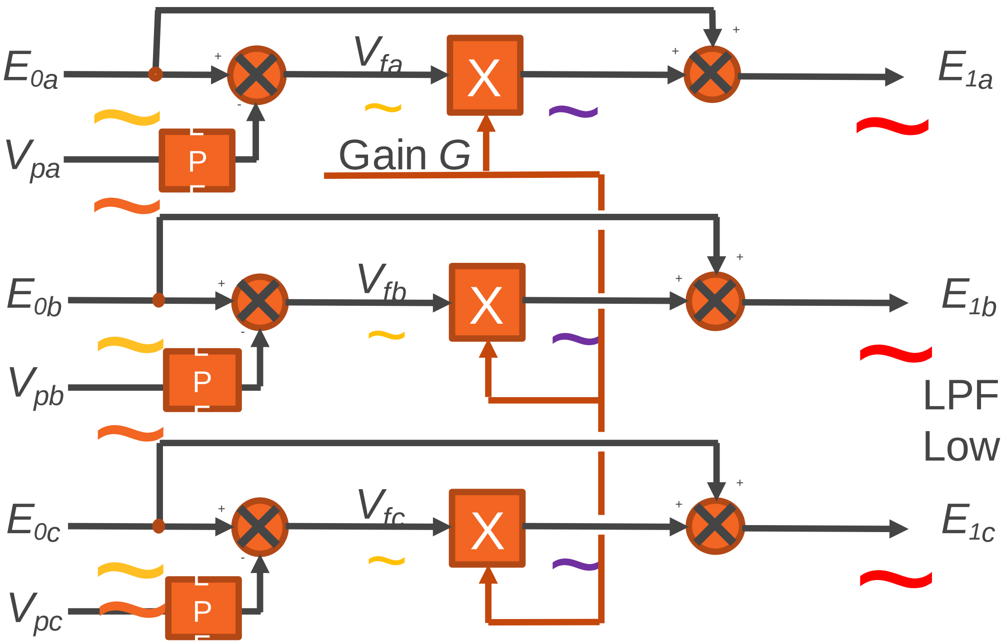


$$P = \frac{V_{poc} \cdot E \cdot \sin(\delta)}{X}$$

RMS Algorythm

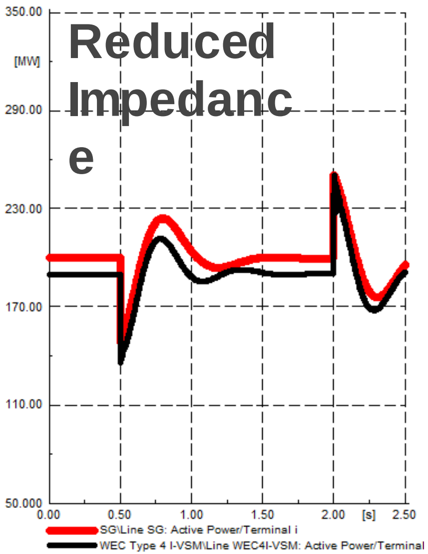


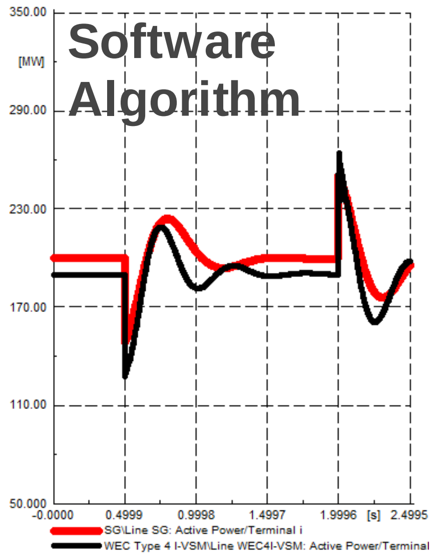
AC Algorithm



LPF is a ~75Hz Low Pass Filter

Results of Simulation



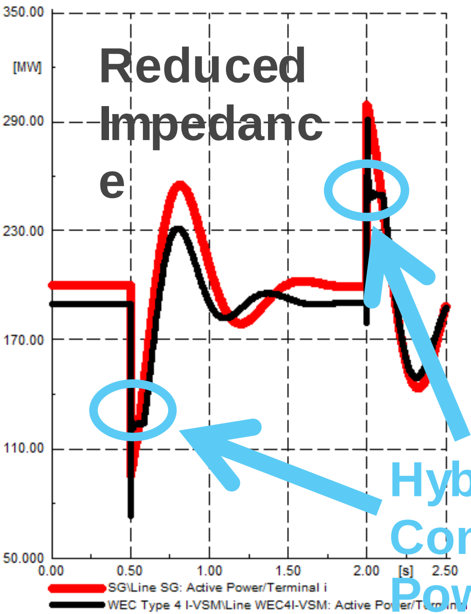


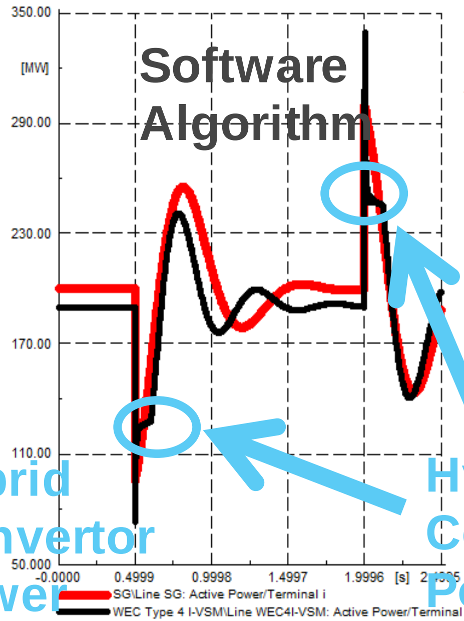
Vector shift response 4.5Degs with:

Filter impedance reduced from 10% to 1% & tertiary winding increased from 120MVA to 150MVA

X Reduction Algorithm

Results - Impedance Reduction





Vector shift response 9 Degs with:

Filter impedance reduced from 10% to 1% & tertiary winding increased from 120MVA to 150MVA

X Reduction Algorithm

Thank you for listening

VSM Capability Expert Group

Enstore's review of RFI, VSM and synchronous machines

Eric A Lewis **Enstore**

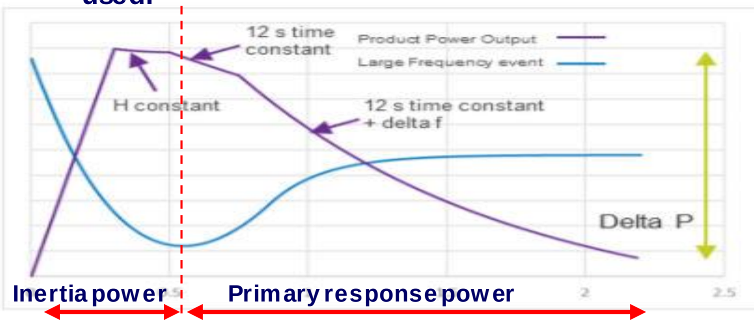
The power point can be freely used in the public domain.

RFI main requirements

1.1.1. Short circuit level contribution (MVA) ≥ 1.5 p.u. of MVA available in steady state operation.

1.1.2. Inertia (MVA.s) ≥ 1.5 p.u. of MVA available in steady state operation.

The inertia constant must not degrade faster than a 12s decay in capability. This is giving a fast primary response power to enable existing primary response power systems to be used to used.



Swing equation relationship to determine additional active power to allow df/dt of upto 1 Hz/s

12 s time constant

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Data from Webinar 14 / 08 / 2019 slide 11

Defining inertia for VSM systems :

In the Grid code the inertia H parameter is defined in many places as H = (MW.s) / (MVA).

The data below uses the definition, but this equation only works for synchronous machines with real rotating inertia. This equation is not valid for some VSM systems with large values of stored MW.s.

The alternation H1 and H2 equations are more useful.

H1 = (Inertia power of the inverter x Grid frequency) / (MVA x RoCoF x 2).

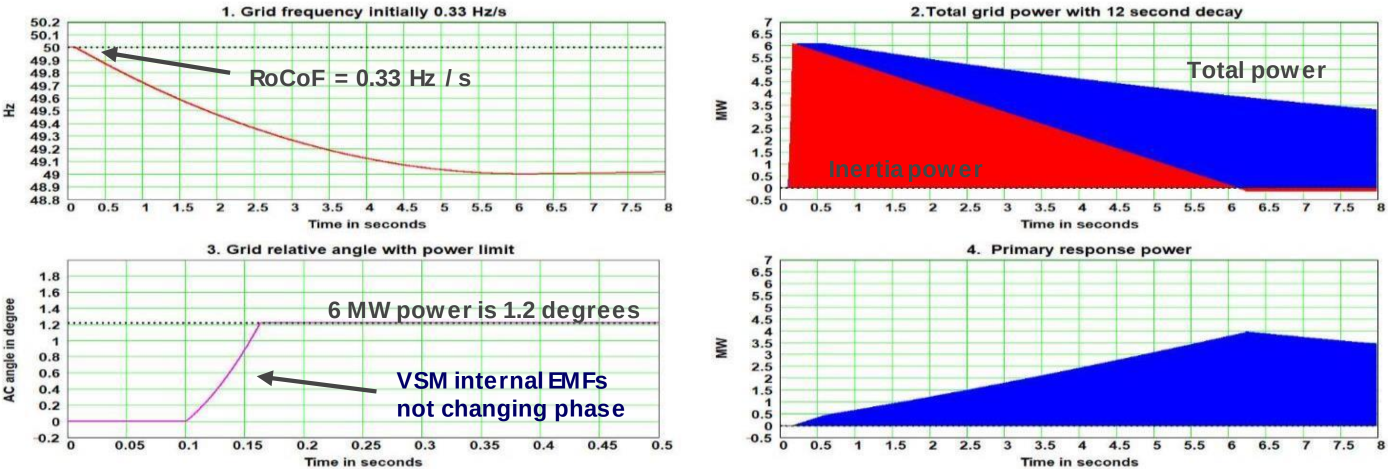
For a 50 Hz grid frequency and a maximum RoCoF of 1 Hz / second can use the simpler H2 equation.

H2 = (Peak inertia power of the inverter x 25) / (MVA) or can use.

Peak inertia power of the inverter = (H2 x MVA) / (25).

For a 100 MVA system with an H2 = 1.5 this gives a Peak inertia power of only 6 MW per 100 MW.

VSM with RFI ratings and control Type 1 using H = infinity control



- Design is a 100 MVA system with a Short circuit level contribution of 150 MVA and an H = 1.5 power rating producing 6 MW for a RoCoF of 1 Hz / s with 35% AC impedance.
- With Type 1 control the VSM internal EMFs track the grid frequency and phase with a slow response.
- When a RoCoF event happens the VSM internal EMFs do not change frequency and phase until the rated maximum power is reached, then the VSM internal EMFs frequency and phase change to stay synchronised to the grid with a phase difference to continue to produce the rated maximum power.
- This gives AC grid power proportional to the AC grid angle changes up to the maximum power limit.
- The grid power increases with the grid relative angle as shown on Trace 3 for a RoCoF of 0.33 Hz /s.
- Trace 2 shows the total grid power produced “Blue zone” with the inertia component “Red zone”.
- Trace 4 shows the extra primary response power needed to meet the RFI requirements.
- With this control a faster RoCoF produces power more rapidly but peak power is unchanged.

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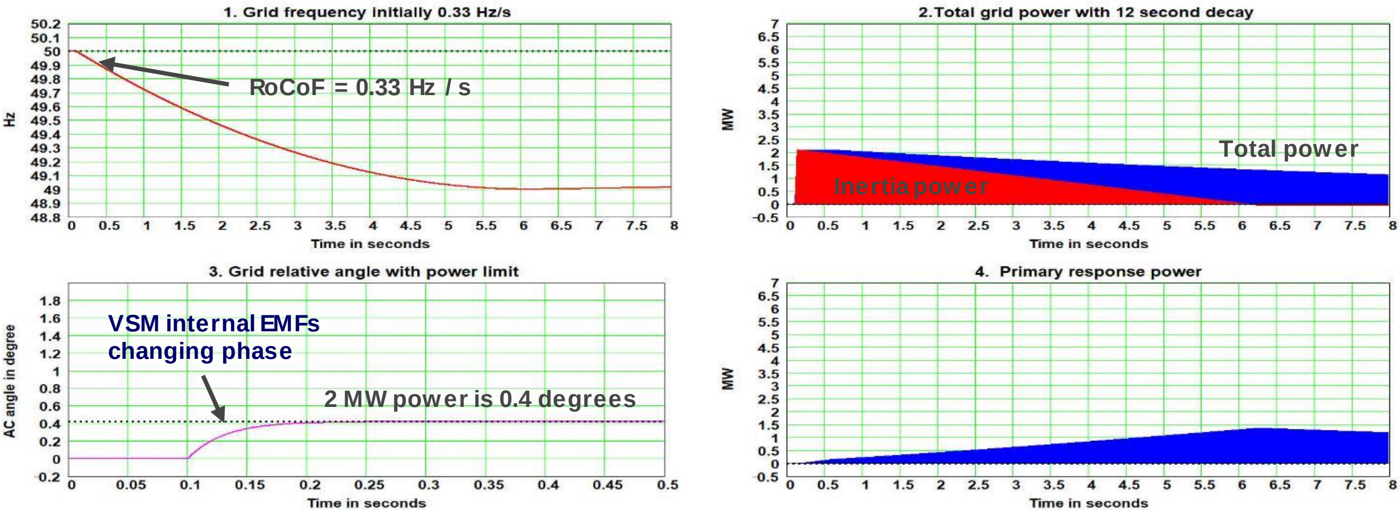
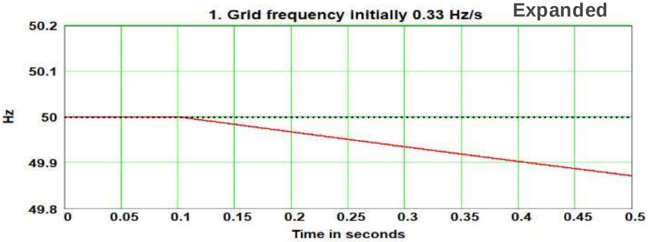
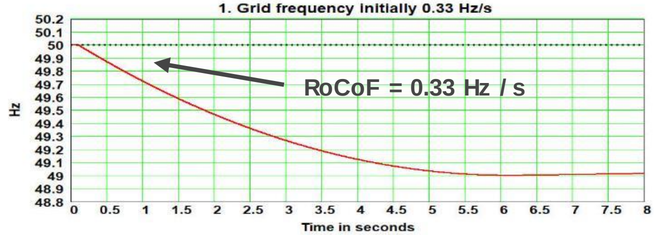
VSM with RFI ratings and control Type 2 using H = 1.5 control

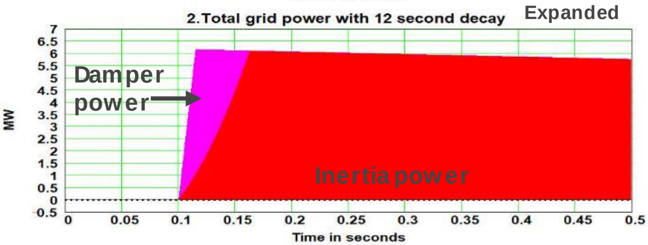


- Design is a 100 MVA system with a Short circuit level contribution of 150 MVA and an H = 1.5 power rating producing 6 MW for a RoCoF of 1 Hz / s with 35% AC impedance.
- With Type 2 control the VSM internal EMFs change frequency when real power is produced at a frequency rate equal to the set H value. Then the VSM internal EMFs frequency and phase changes to stay synchronised to the grid with a phase difference to continue to produce the required H power.
- This gives AC grid power proportional to the AC grid RoCoF up to the maximum power limit.
- The grid power increases with the grid relative angle as shown on Trace 3 for a RoCoF of 0.33 Hz /s.
- Trace 2 shows the total grid power produced “Blue zone” with the inertia component “Red zone”.
- The Trace 4 shows the extra primary response power needed to meet the RFI requirements.
- With this control faster RoCoF produces more power up to rated max. power.

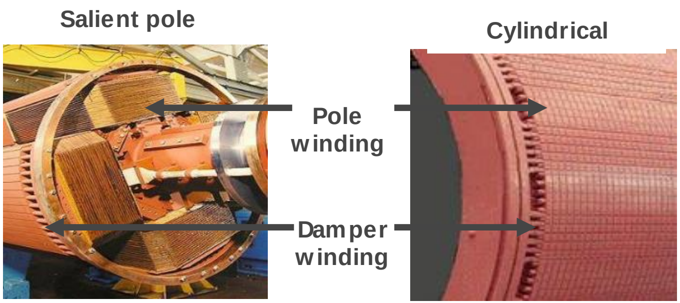
Synchronous machines like synchronous condensers





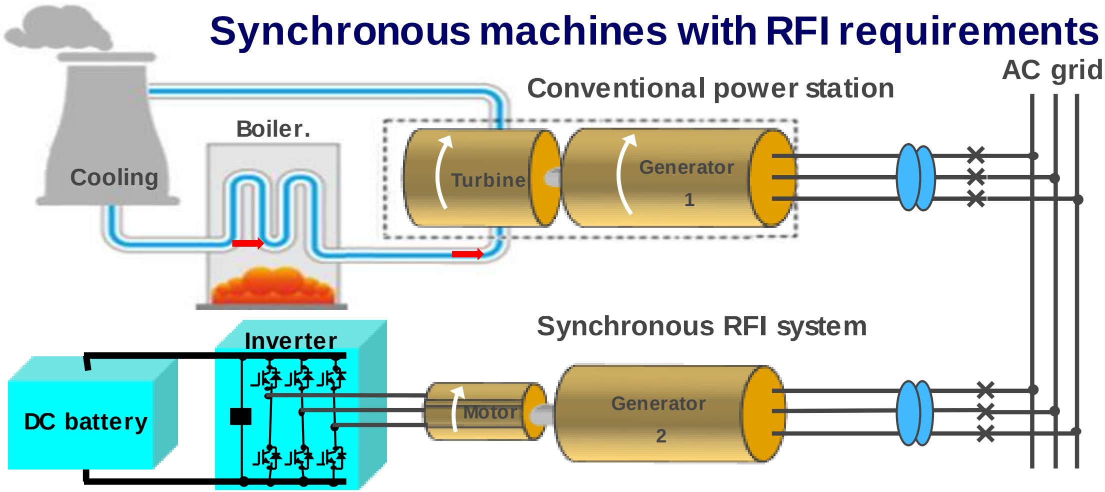


- **Design is a 100 MVA system with a Short circuit level contribution of 150 MVA and an H = 1.5 power rating producing 6 MW for a RoCoF of 1 Hz / s with 35% AC impedance.**



- **Enstore has a significant experience in using synchronous machines with and without damper windings in dynamic applications like rolling mills.**
- **The damper windings produce extra power very rapidly based on df/dt as shown by the Magenta area. This is then replaced by the angle based inertia power like a VSM design.**
- **These machines can not produce the RFI primary response follow up power to be RFI compliant.**

Synchronous machines with RFI requirements



- Design is a 100 MVA system with a Short circuit level contribution of 150 MVA and an H = 1.5 power rating producing 6 MW for a RoCoF of 1 Hz / s with 35% AC impedance.
- The motor can be an induction motor for the best time response for the primary response power.
- The motor, inverter and the battery only need to be rated for 6 MW with the correct storage time.
- The battery can do a soft start and can also be recharged from the AC grid via the motor and inverter.
- The design provides the same results as shown on slide 3 plus the damper power shown on slide 5.
- If the generator 2 inertia is to low to provide the H = 1.5 inertia power there are two main options:
  - Option 1. De-rate the Generator 2 to give the required inertia.
  - Option 2. Add advanced control to the Motor / inverter to give extra dynamic inertia.
- Enstore has supplied the Option 2 for several industrial contracts to raise the inertia by a factor more than 3:1 totally independent of the AC grid system with no AC power measurements.

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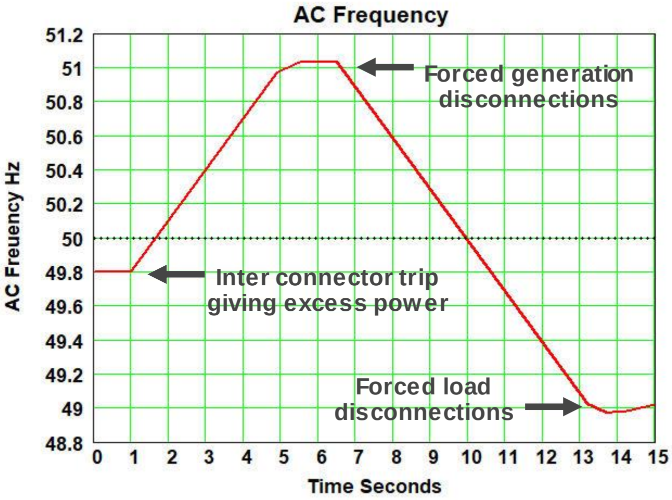
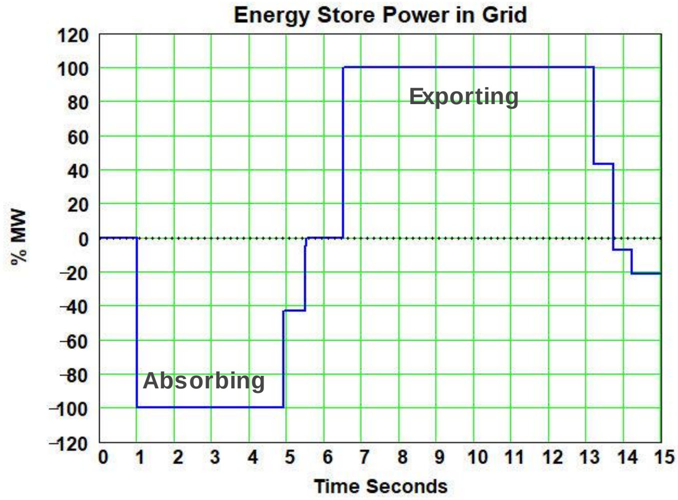
Other VSM requirements





Worst case event :

- **Must rate for a worst case event and maintain inertia to allow time for the backup systems to operate.**
- **This requires a bidirectional energy store rating and operation for the worst case frequency range.**

Other design considerations :

- **The VSM system needs to have damping of grid transients, this can be added but may not be needed for control Type 1 that has the maximum stability operation.**
- **VSM system produce inertia power very rapidly based on the grid phase changes.**
- **Adding a feature like the damper winding df/dt power of synchronous generators is very difficult to implement.**

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Thank you

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Further Discussion / AoB

Thank You for Your Participation

We welcome your feedback and wish you a safe journey home

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