Effects of VSM / Option 1 (Grid Forming) Convertor Control on Penetration Limits of Non-Synchronous Generation (NSG) in the GB Power System

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From Zero to 100% NSG using a reduced GB model

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Agenda   (35 Minutes Total)

- Future of the GB Network and Anticipated Issues

- Project History and Development of Ideas

- Overview of the Models and Techniques Used

  - Infinite Bus Model

  - 36 Node GB Model

- Technical Requirements for Grid Code

  - Fault Ride Through Work Group GC0048 & GC100

  - Other Requirements

High Convertor Penetration - Options

With current technology/models, the system may become unstable when more than 65% of generation is Non-Synchronous

For the FES 2Degrees, Consumer Power and Slow Progression scenarios, it is currently forecast this level could be exceeded for 800-1800Hrs p.a. in 2023/24 and for 2100-2750Hrs p.a.in 2026/27.
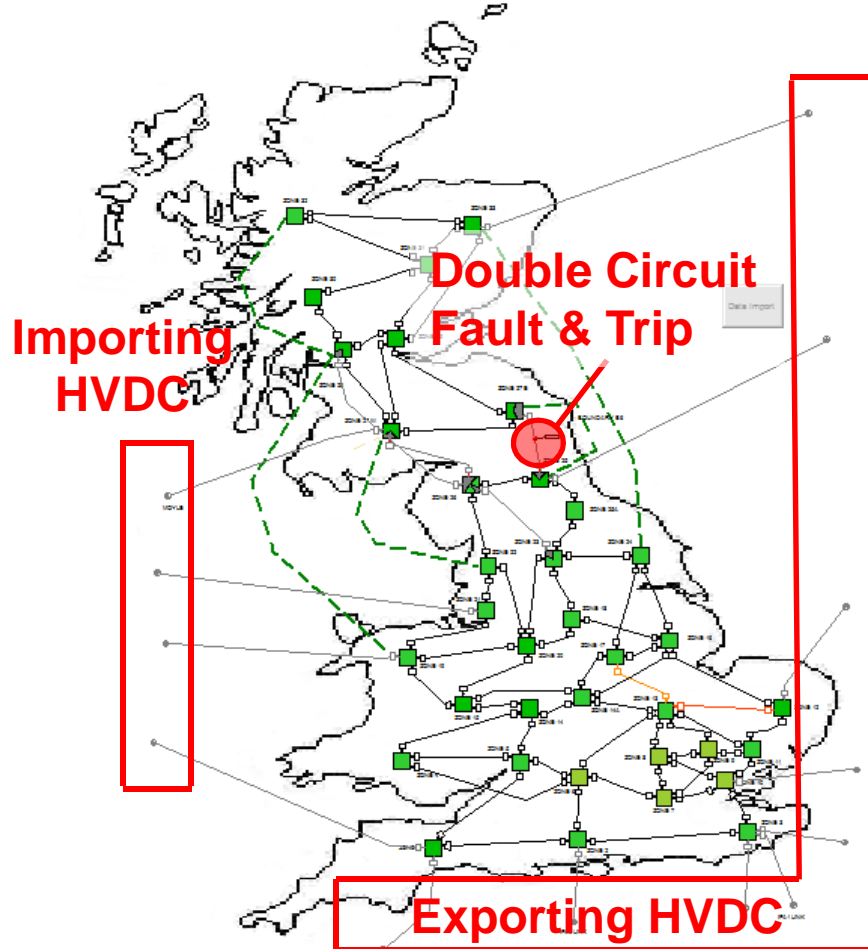
Key

No	Doesn't Resolve Issue
P	Potential
I	Improves
Yes	Resolves Issue

Solution	Estimated Cost	RoCoF	Sync Torque/Power (Voltage Stability/Ref)	Prevent Voltage Collapse	Prevent Sub-Sync Osc. / SG Compitable	Hi Freq Stability	RMS Modelling	Fault Level	Post Fault Over Volts	Harmonic & Imbalance	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	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	

Timescale (Based on work by SOF team)		Now	2019	2019	Now	2020	Now	Now	2025	2025

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2013 Studies – Only 9/26 high NSG scenarios ok

36 Node Reduced GB Network for 2030

Importing HVDC

Double Circuit Fault & Trip

Exporting HVDC

NSG	0 Import HVDC			3GW Import HVDC			0 Import HVDC		
	0 Export HVDC			10GW Export 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

2013 Results

2013 – Stable Result

2013 – Unstable Result

NSG	0 Import HVDC			3GW Import HVDC			0 Import HVDC		
	0 Export HVDC			10GW Export 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						

Step 1 – Add Synthetic Inertia (SEBIR)

Anticipated Outcome:

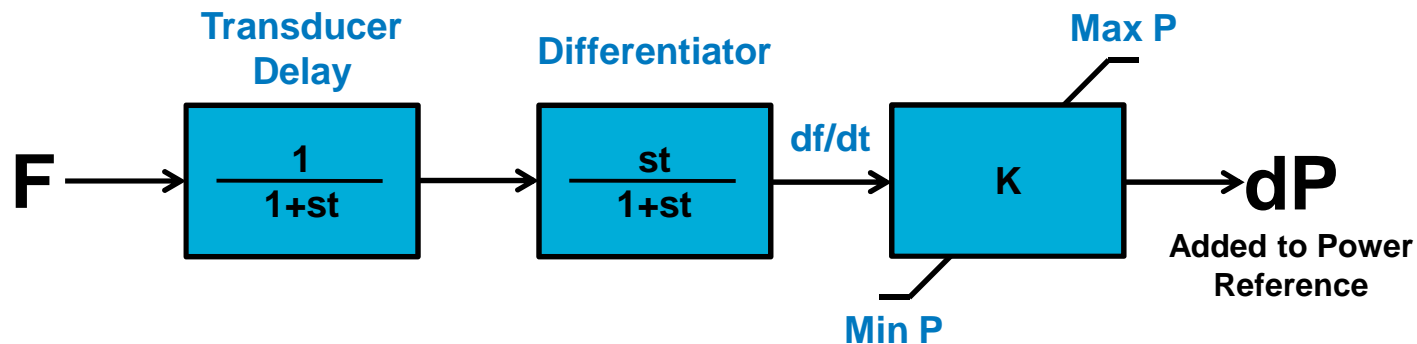Improves RoCoF

A – Solves the problem

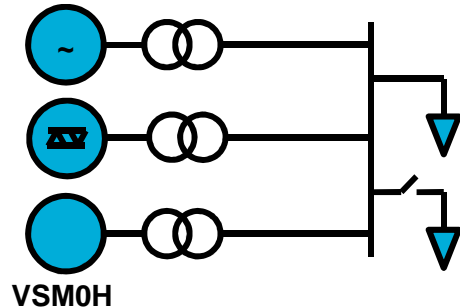**B – Higher % NSG before instability occurs**

C – Has no effect

Actual Outcome:

Improves RoCoF

D – Makes the system more unstable in some circumstance

Transducer Delay   Differentiator   Max P

$$F \rightarrow \boxed{\dfrac{1}{1+st}} \rightarrow \boxed{\dfrac{st}{1+st}} \xrightarrow{df/dt} \boxed{K} \rightarrow dP$$

Min P

Added to Power Reference

Step 2 – Implement Virtual Synchronous Machine Zero Inertia (VSM0H)

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VSM0H

MATLAB Model used to evaluate VSM0H stability limit

Commonly used in Marine Industry & Micro Grids
Provides stable control & 100% NSG possible
Voltage Source Convertor with no PLL
Droop Frequency and Voltage Control

For 100% Convertor Network with zero inertia, a load step change results in a frequency change which occurs in one AC cycle (assuming BOXCAR measurements taken over one cycle)

Step 3 – Implement Virtual Synchronous Machine (VSM)

Both VSM & VSM0H use similar output stages

3 Phase VSM / VSM0H Output Stage
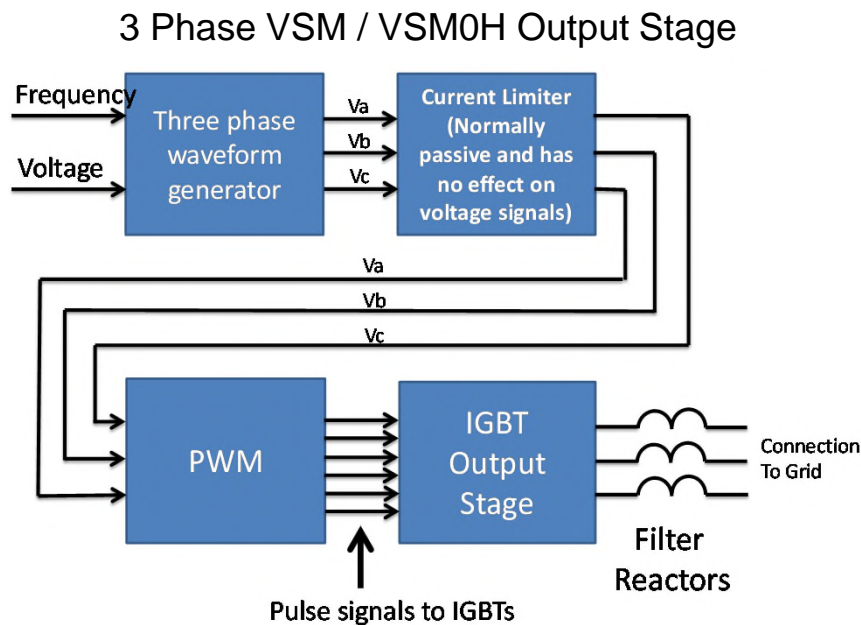
Changes for VSM
1. **Simulate inertia**
2. **Reduce the bandwidth of F and V to 5Hz**

Advantages (main)
1. **Contributes to RoCoF**
2. **Compatible with SG**
3. **Reduced interaction and HF instability risks**
4. **Can be modelled in RMS system studies**

Disadvantages
1. **Requires additional energy**
2. **Possibility of traditional power system instability**

Step 4 / 5 – Implement VSC in the GB Model / Build an Infinite Bus Model

- Step 4 – Change some convertors in the 36 node model to VSC without dynamic controls

  - Fixed the problem with high frequency instability

  - However this isn't really representative as its equivalent to connecting an infinite bus at multiple point through out the model

- Step 5 – Build a small M/C model and prove it swings / behaves like a synchronous machine model

  - This established that it was possible to model a voltage source convertor which behaved like a synchronous machine

# Key Features of the Option 1 Convertor Controller

- Similar voltage step response

- Without dynamic breaking, swings like SG.

- Can it ride through 500ms Distribution Faults?

- Provides inertial response to df/dt

- Similar frequency sweep characteristic

- Provides immediate energy input without needing to measure changes in volts, power or reactive power

Step 6 – Put the VSM model into the 36 Node Network

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- Demonstrate Option 1 (VSM / GF):

  - Stabilises the system

  - That convertors can temporarily come out of VSM mode under overload conditions

  - Network impedances limit the effect of VSM overload propagating across the network and therefore

  - Supports RoCoF & LFDD Relays

- The above provides Network Operators the potential to manage the key differences between Option 1 (VSM / GF) and conventional synchronous machines using RMS models.

2016 Studies – All high NSG scenarios stable

36 Node Reduced GB Network for 2030

Importing HVDC

Double Circuit Fault & Trip

Exporting HVDC
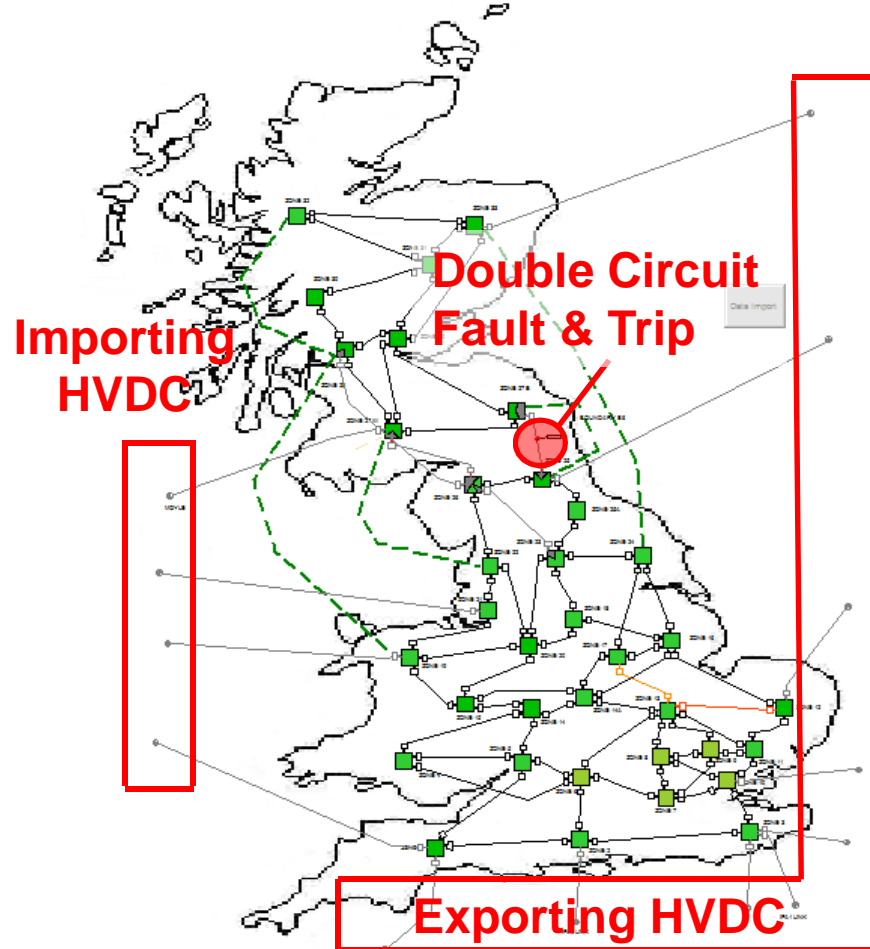
With VSM all scenarios are stable & 100% NSG is possible

NSG	0 Import HVDC			3GW Import HVDC			0 Import HVDC		
	0 Export HVDC			10GW Export HVDC			10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	1% 60%	10% 25% 69%	10% 25% 80%	1% 54%	1% 60%	10% 68%	1% 48%	1% 15% 53%	1% 60%
Mid	5% 25% 73%	5% 83%	10% 97%	1% 64%	10% 25% 71%	10% 80%	1% 58%	1% 20% 64%	10% 73%
High	15% 97%	20% 30% 103%	N/A	10% 80%	10% 89%	15% 35% 100%	10% 25% 74%	10% 82%	10% 30% 93%

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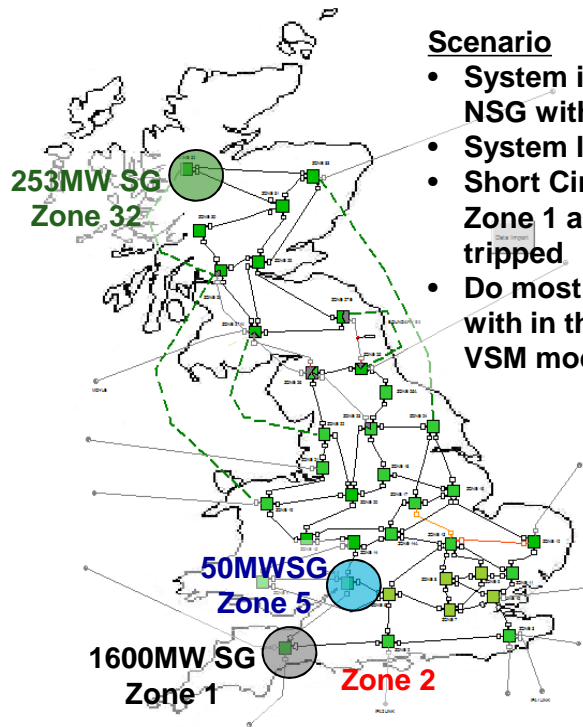**Low: 16.0GW Wind**
Mid: 20.5GW Wind
High: 28.5GW Wind

Green cells ok in 2013
All cells now ok with VSM
% of NSG which is VSM
10% VSM for stability
30% VSM for low noise
93% NSG (7%SG)

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Typical results from 2016 studies

NSG	0 Import HVDC			3GW Import HVDC			0 Import HVDC		
	0 Export HVDC			10GW Export HVDC			10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	1% 60%	10% 25% 69%	10% 25% 80%	1% 54%	1% 60%	10% 68%	1% 48%	1% 15% 53%	1% 60%
Mid	5% 25% 73%	5% 83%	10% 97%	1% 64%	10% 25% 71%	10% 80%	1% 58%	1% 20% 64%	10% 73%
High	15% 97%	20% 30% 103%	N/A	10% 80%	10% 89%	15% 35% 100%	10% 25% 74%	10% 82%	10% 30% 93%

2016 – Stable Noisy Result

Zone 1 MW

Zone 25 MW & MVAr

MW

2016 – Stable Clean Result

Zone 1 MW
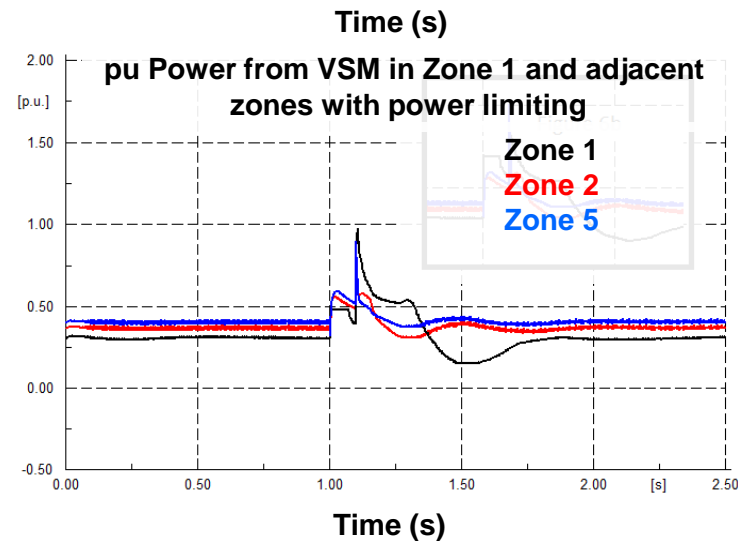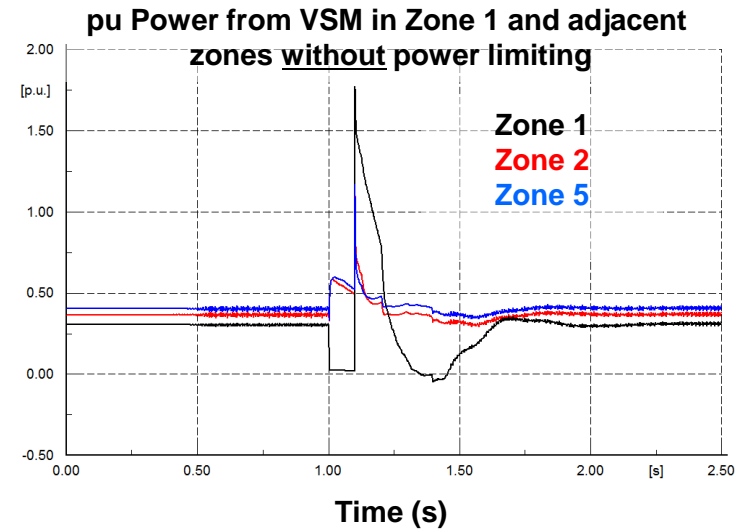
Zone 25 MW & MVAr

MW

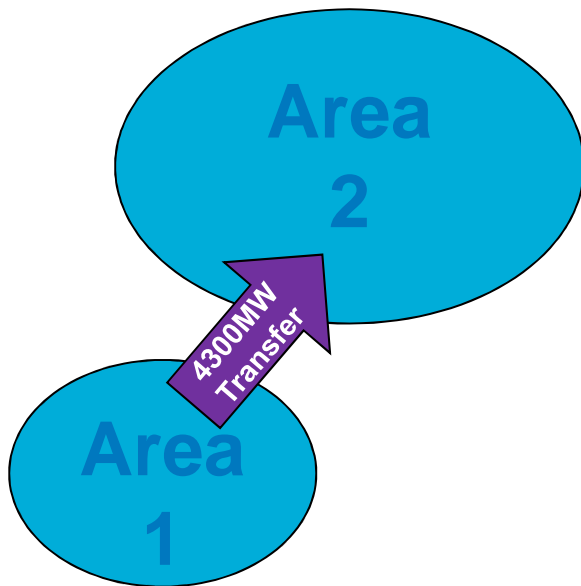13

1600MW Trip at 97% NSG with 30GW of Load

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?**

Map labels:
- **253MW SG Zone 32**
- **50MWSG Zone 5**
- **1600MW SG Zone 1**
- **Zone 2**

pu Power from VSM in Zone 1 and adjacent zones without power limiting

- **Zone 1**
- **Zone 2**
- **Zone 5**

Time (s)

pu Power from VSM in Zone 1 and adjacent zones with power limiting

- **Zone 1**
- **Zone 2**
- **Zone 5**

Time (s)

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System Islanding at 93% NSG with 40GW load
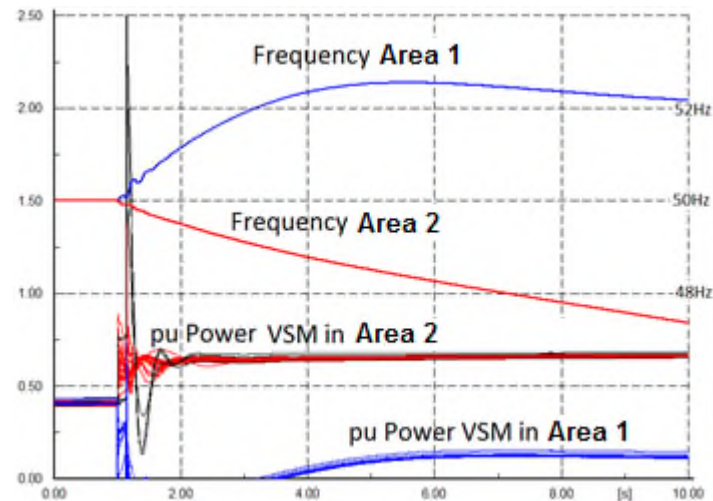
CC.6.3.7 and CP.A.3.6

Area 2

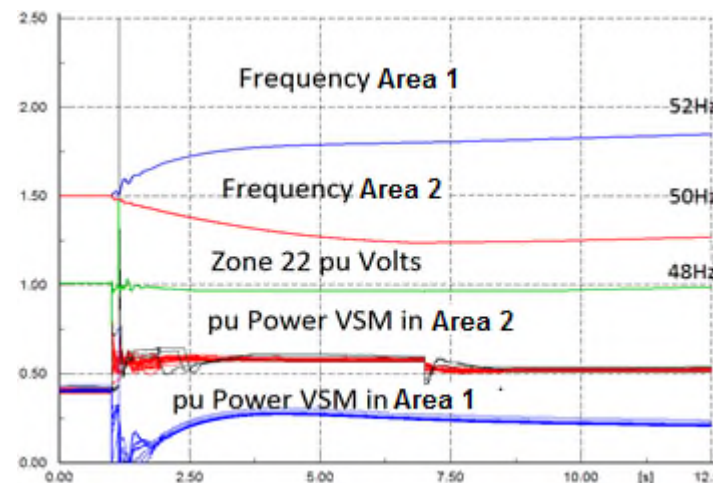Area 1

4300MW Transfer

Scenario
- **System is operating at 93% NSG**
- **System load is 40GW**
- **Short circuit is applied to AC interconnection**
- **Loss of AC interconnection between exporting Area 1 and importing Area 2**
- **Does LFDD work?**

**pu Power from VSM (all zones) <u>without</u> power limiting**

pu Power from VSM (all zones) <u>with</u> power limiting

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Requirement Proposal for Option 1 (Grid Forming Convertors - Initial Thoughts)

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Steady State Capability

- $\pm$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
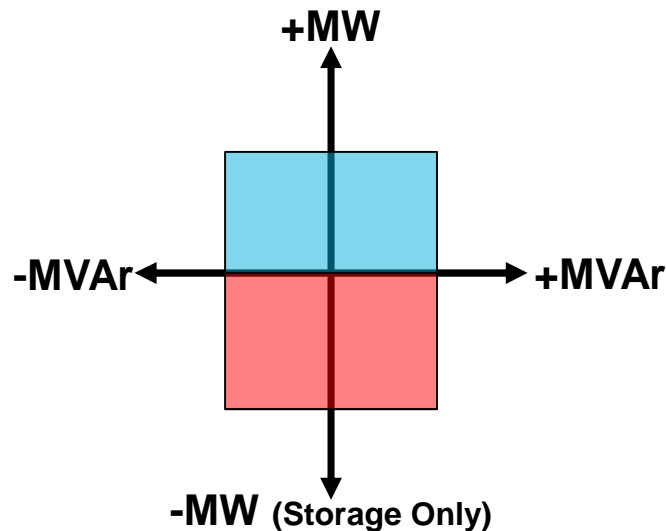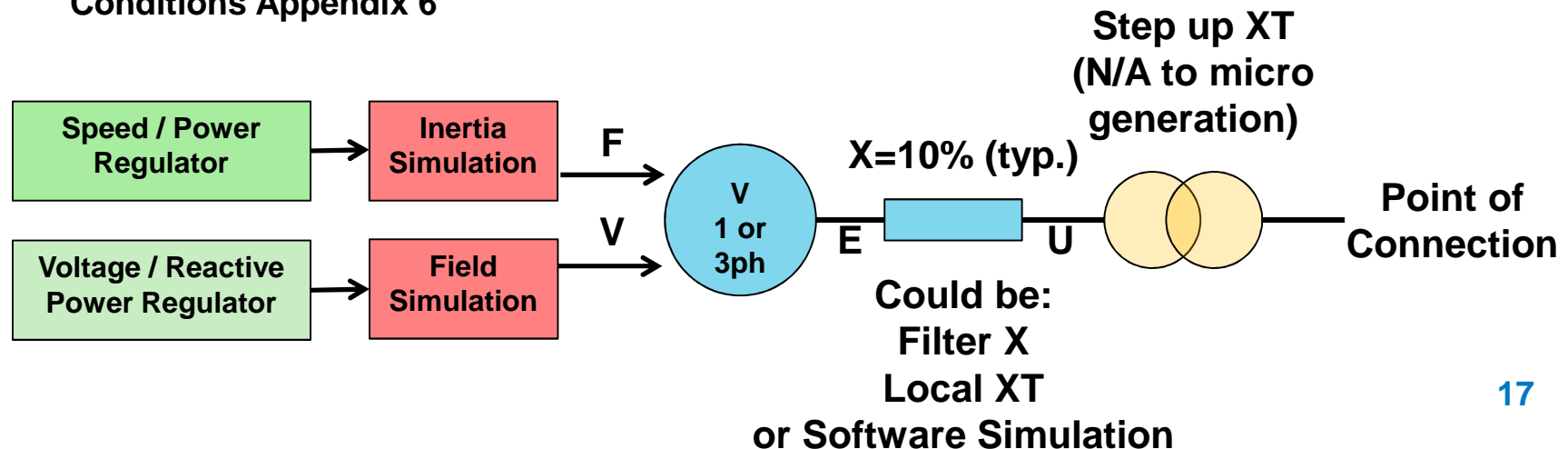
Extended Capability

- Available for 20Secs

- Harmonics & Imbalance as GBGC CC6.1.5, CC6.1.6 & CC6.1.7

- 1.33pu Rated Power (33% on rated power > current operating point)

- 1.5pu current (on rated MW)
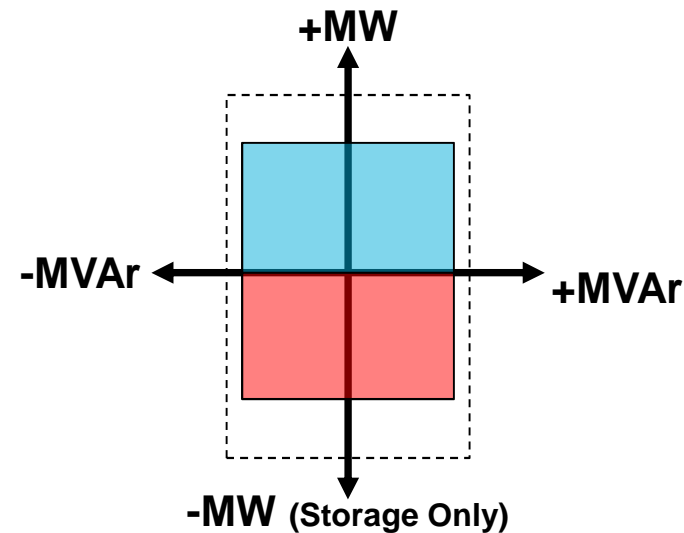
Please Note: Values (e.g. 1.33pu) quoted in these or the following slides are based on the preliminary studies presented here but maybe subject to change if further studies indicate changes are required.

Requirement Proposal for Option 1 (Grid Forming Convertors - Initial Thoughts)

- Should _behave_ like a balanced 3ph voltage source behind a constant impedance over the 5Hz to 1kHz band

- Rate of change of frequency should be limited by an equivalent inertia of H=2 to 7s on rated power

- Rapid change to the phase voltages (V), frequency (F) and phase angle in the >5Hz Band are not permitted whilst the operating point remains within the extended capability zone

- Harmonics and / or unbalanced currents will be as GB Grid Code CC6.1.5, CC6.1.6 and CC6.1.7. If the levels stated are exceeded they may be reduced by adjusting the wave shape or phase voltages. The speed at which this occurs may depend on the level.

- Dynamic performance requirements similar to those for GB Grid Code Connection Conditions Appendix 6

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Requirement Proposal for Option 1 (Grid Forming Convertors - Initial Thoughts)

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Operation Outside Extended Zone

- If the extended capability zone is breached the device may rapidly reduce real or reactive power, volts or current by reducing pulse width, phase angle, frequency, volts etc. to bring the device back within but not below the extended rating (for 20secs) then normal rating.

- It is anticipated that operation within the extended rating would be followed by operation at less than the previous rating allowing recharging of storage and cooling of power components and that extended rating would be available again after this period. Subsequent cycles would be available on a continuous on going basis provided that on average the device has only operated at full rating.

- Fast Fault Current Injection and Fault Ride Through for Convertors is currently being discussed in Grid Code (GC0048 / GC100) RfG / HVDC Implementation formal working group and can be followed through that forum.

FFCI Option 1 for RfG implementation

Under GB RfG adoption, it is necessary to augment the existing Grid Code definition of current injection. EU RfG requirements drive more robust specification of NSG to address the trends described in the SOF:-

- SOF (System Operability Framework – see National Grid website) illustrates extent of short circuit level decline and its impact upon stability, the ability of generation to ride through faults and for network protection to operate.

- Our studies illustrate the importance of new forms of replacement fault injection to support proposed fault ride through curves which address the issue today. This can be delivered by traditional convertor design choices, to ensure current injection is maximised and not out of phase but relies on a population of Grid Forming Generation.

- However, our studies also illustrate that in order to ensure that across the next 8 years the capability to support fault ride through and voltage against time performance does not degrade, grid forming capability is required from 1st January 2021 onwards. This is the "**FFCI Option 1**" requirement - requiring a short term 1.5p.u. capability and an equivalent inertia of at least 2-7MWs/MVA (for 20s) operating against the principles of VSM as discussed.

Conclusions

- Implementation of VSM requires additional energy source e.g. storage or operate with headroom

- A higher percentage of VSM convertors results in greater stability and reduces the additional energy / storage requirement for each VSM

- VSM is about power management on a millisecond timescale – Network operators must ensure enough resource is dispatched so that the majority of devices remain in VSM mode

- Next Step – Develop VSM to proof of concept

References

A. Roscoe, M. Yu, R. Ierna, H. Urdal, A. Dyśko, et al., " A VSM (Virtual Synchronous Machine) Convertor Control Model Suitable for RMS Studies for Resolving System Operator / Owner Challenges " in 15th Wind Integration Workshop, Vienna, 2016.

R. Ierna, A. Roscoe, M. Yu, H. Urdal, A. Dyśko, et al., "Effects of VSM Convertor Control on Penetration Limits of Non-Synchronous Generation in the GB Power System," in 15th Wind Integration Workshop, Vienna, 2016.

H. Urdal, R. Ierna, J. Zhu, C. Ivanov, A. Dahresobh, et al., "System strength considerations in a converter dominated power system," IET Renewable Power Generation, 2015.

M. Yu, A. J. Roscoe, A. Dyśko, C. D. Booth, R. Ierna, et al., "Instantaneous Penetration Level Limits of Non-Synchronous Generation in the British Power System," IET Renewable Power Generation, 2016.

M. Yu, A. Dyśko, C. Booth, A. J. Roscoe, J. Zhu, et al., "Investigations of the Constraints relating to Penetration of Non-Synchronous Generation (NSG) in Future Power Systems," in Protection, Automation & Control World Conference (PACWorld), Glasgow, UK, 2015.

M. Yu, A. Dysko, A. J. Roscoe, C. Booth, R. Ierna, et al., "Effects of Swing Equation-Based Inertial Response (SEBIR) Control on Penetration Limits of Non-Synchronous Generation in the GB Power System," in IET Renewable Power Generation (RPG), Beijing, China, 2015.

M. Yu, A. J. Roscoe, C. Booth, A. Dysko, R. Ierna, et al., "Use of an Inertia-less Virtual Synchronous Machine within Future Power Networks with High Penetrations of Converters," in 19th Power Systems Computation Conference (PSCC), Genoa, Italy, 2016.

Thank you for Listening

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