Session 2B Grid Forming
Introduction about the need: Essence from Europe / GB

Focus on High Penetration of Power Electronic Interfaced Power Sources

17th Wind Integration Workshop
Stockholm, Sweden 17-19 October 2018

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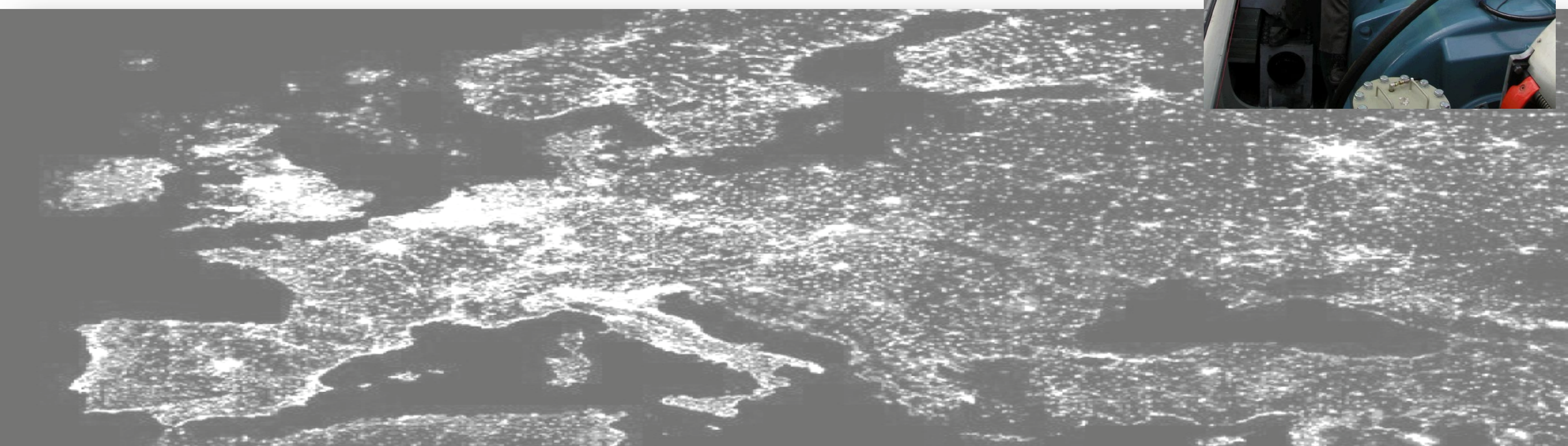

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Contents

- What is Grid Forming Converter Control?
  - As defined in ENTSO-E's IGD HPoPEIPS
- Diminishing System Strength
  - Including Total System Inertia
- What evidence exist of need for a change from BAU?
- Cost of limiting instantaneous penetration of PEIPS
- System Stability Studies with low System Strength using GF / VSM based converter controls approaching 100% penetration
- Wider stability challenges & system needs during high penetration (HP)
- Real experiences, laboratory activity and study activity
- Summary of high penetration challenges & potential solns in GB
- HP Expert Groups in Europe and in GB
- Key questions to for discussion

What is Grid Forming Converter Control?

As defined in ENTSO-E's IGD HPoPEIPS*, the Guidance for 34 countries implementing the European Network Codes

* Implementation Guidance Document "High Penetration of Power Electronic Interfaced Power Sources"

Capabilities of Class 1 / Grid Forming Converters

- Class 1 Converters shall be capable of supporting the operation of the ac power system (from EHV to LV) under normal, disturbed and emergency states without having to rely on services from synchronous generators.
- This shall include the capabilities for stable operation for the extreme operating case of supplying the complete demand from 100% converter based power sources.
- Grid Forming Converters provide an inherent performance resulting from presenting to the system at the Connection Point a voltage behind an impedance (true voltage source).
- The support services expected are limited by boundaries of defined capabilities (such as short term current carrying capacity and stored energy).
- Transient change to defensive converter control strategy is allowed (if it is not possible to defend the boundaries), but immediate return is required.

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Diminishing System Strength including Total System Inertia

- System strength is an important indicator for stability. It is expressed in different ways, dependent upon the users
  - TSI - Total System Inertia - Used for Frequency management
  - FL - Fault Level - Used in Protection context
  - SCR - Short Circuit Ratio - Used in Converter control context
- Availability of TSI data across Europe
  - TSI data for 2030 scenarios is available for all 5 European Synchronous Areas (SAs)
  - Data also for TSI contributions from each country to its SA
  - TSI expressed as H (pu). Prior to RES, H was typically 5-6 s.
  - If TSI is reduced, the impact increases of step changes in power. Less time to take counter measures before it is too late
  - Low TSI usually associated with low FL/SCR

Penetration of Wind & Solar in Europe's 2030 Energy Scenarios

The wind and PV installations continue to grow in GB & Europe

2018 scenarios (by ENTSO-E's in TYNDP) suggests an expansion of RES in EU28 to achieve an electricity share of

41% in 2020,
50-58% by 2030
and between 62 and 77% by 2040
(with a CO_2 reduction by 2040 between 60 and 70%),

Highest Instantaneous penetration >> average annual penetration (3-5 times)
Many countries > 100% penetration for significant numbers of hours in a year.

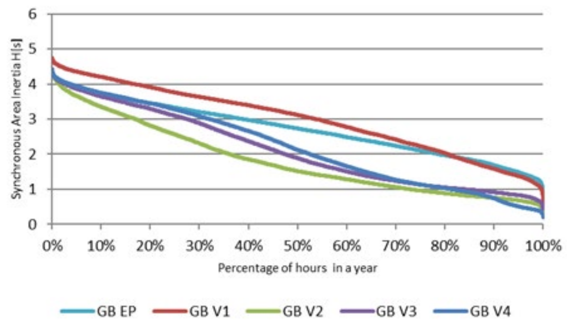
Management of system technical challenges needs to be substantially elevated to deliver stable operation with high penetration

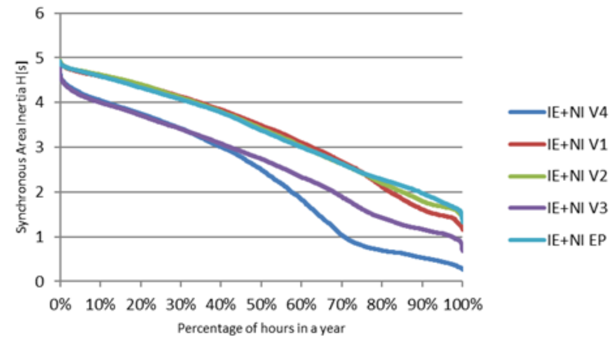
Duration Charts for Total System Inertia (H) in Europe's 5 Synchronous Areas (SAs)
Three SAs Ok'ish while two SAs have big concerns

From IGD HPoPEIPS with 2016 market study results for all synchronous areas for 2020 and 4 different visions for 2030

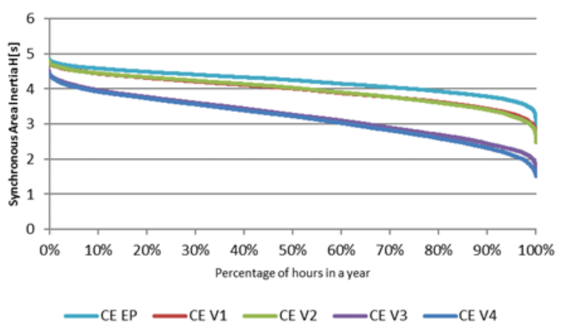
GB & IE+NI have BIG CONCERN at SA level.

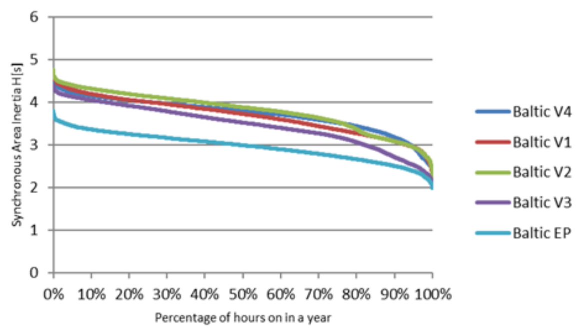
Some scenarios with H<1s for 30% of time! Dramatic reduction in H

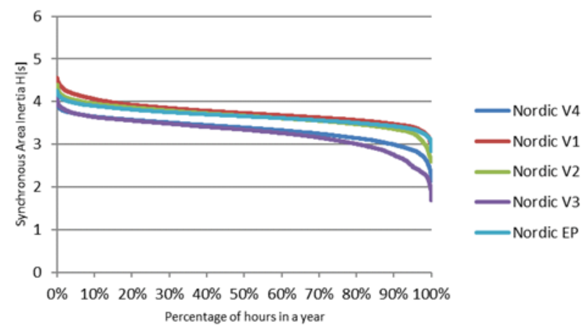




Three SAs ok'ish at SA level with modest reductions in H in all scenarios.







National per unit contributions to Synchronous Area TSI at time of minimum TSI for the SA - INDICATIVE

Inertia contribution colouring code:

- Green H>4s contribution — Very good
- Black 3s<H<4s contribution — Good
- Purple 2s<H <3s contribution — Marginal
- Red H <2s contribution. — Limited Action needed?

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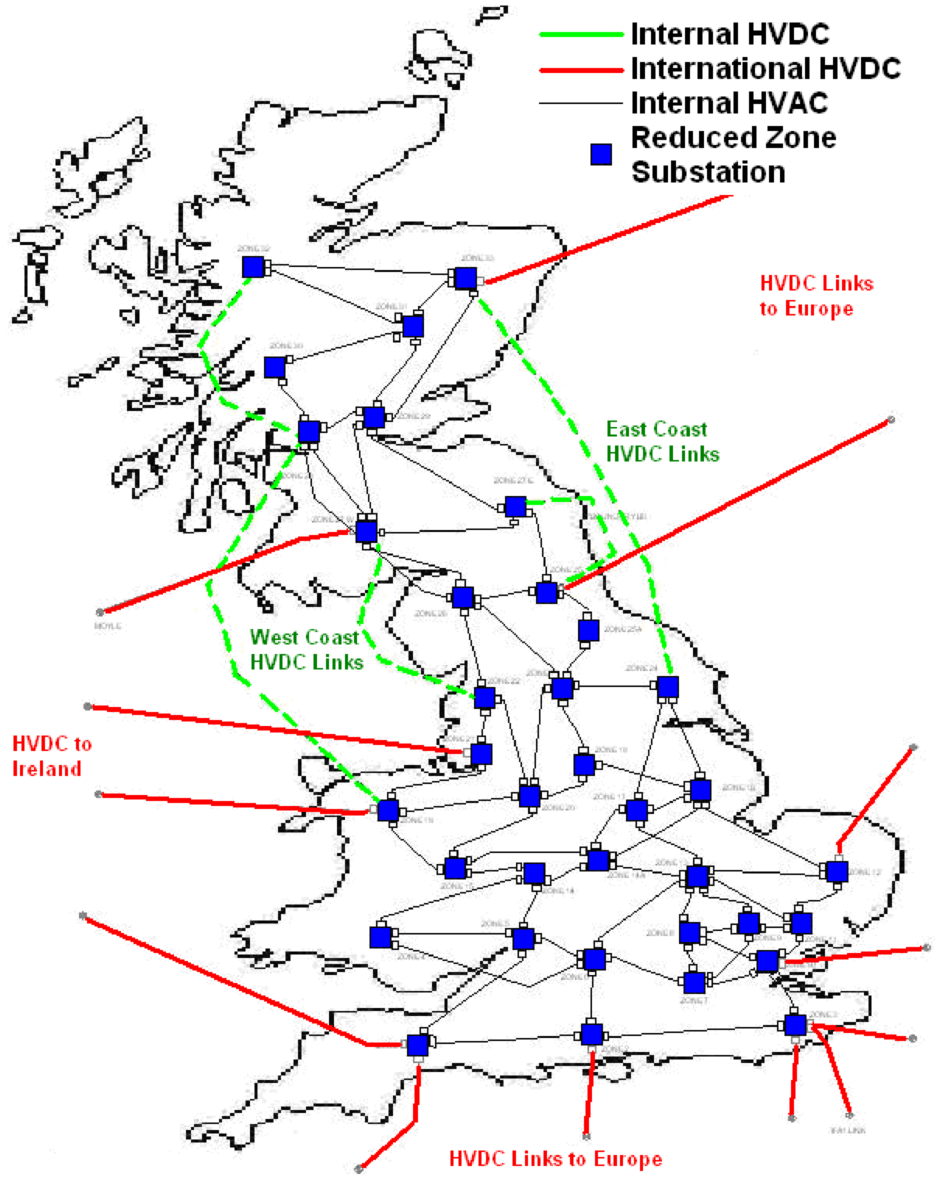
System Stability Studies with low System Strength using PLL based converter controls approaching 100% penetration

- PLL Phase Locked Loops – following externally provided system voltage
- By 2013 operational impact of high RES penetration had emerged in GB with wind farms tripping for high RoCoF.
- Concerns over various stability aspects with future weaker power system
- TSO need for system wide dynamic studies
- What is the limit of stable system wide operation with higher level of penetration of power electronic interfaced power sources?
- Are the models including generic models fit for purpose?

- Penetration levels predicted for 2030 based on hourly recorded weather data for 3 years for 36 zones including offshore, main focus wind.
- RES in 2030 could deliver 165% of demand in most challenging hour
- Need to be prepared in all operational aspects to come close to 100% RES at times and at other times close to 0%

Angular stability analysis for NSG >50%; network used

Reduced GB 2030 - 36 Node Transmission System Model



- Network reinforced to accommodate the high levels of NSG in 2030, including current and proposed works e.g. the series capacitors between England and Scotland and East and West Coast HVDC links. Absence of voltage support in the central parts of the system was first remedied by blocks of 2GVA STATCOMs
- Included dynamic controllers for Statcoms, Convertors, Governors, AVRs and PSSs.
- The case chosen was a double circuit 3 phase fault of 100ms duration on 2 of the 4 HVAC links between Scotland and England.
- **Dispatching > 65% NSG (on MW) created angular instability**
- Reduced model including dynamic data available on request by e-mailing Richard.Ierna@nationalgrid.com

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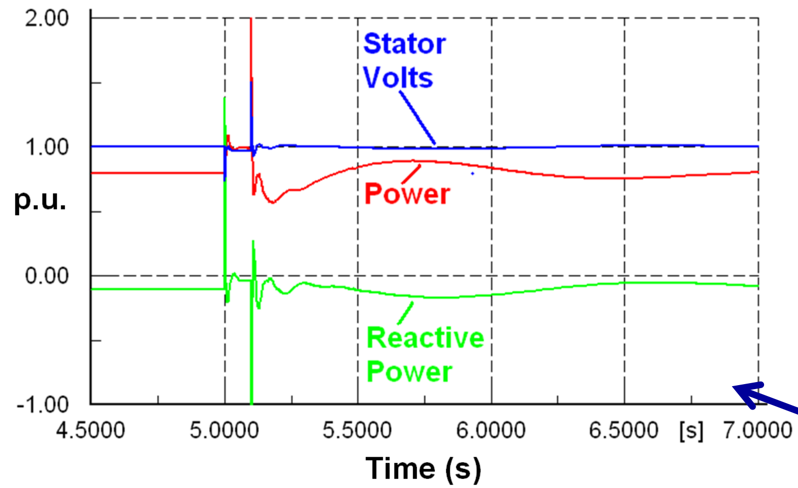
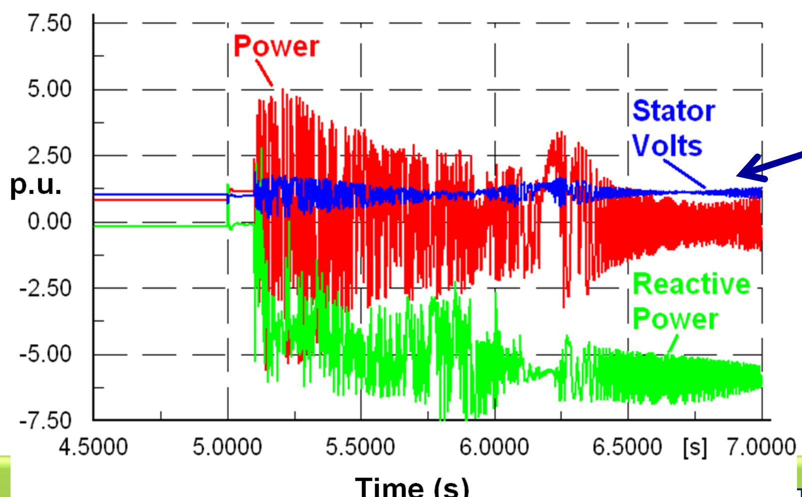
2013 Results

2013 – Stable Result



2013 – Unstable Result

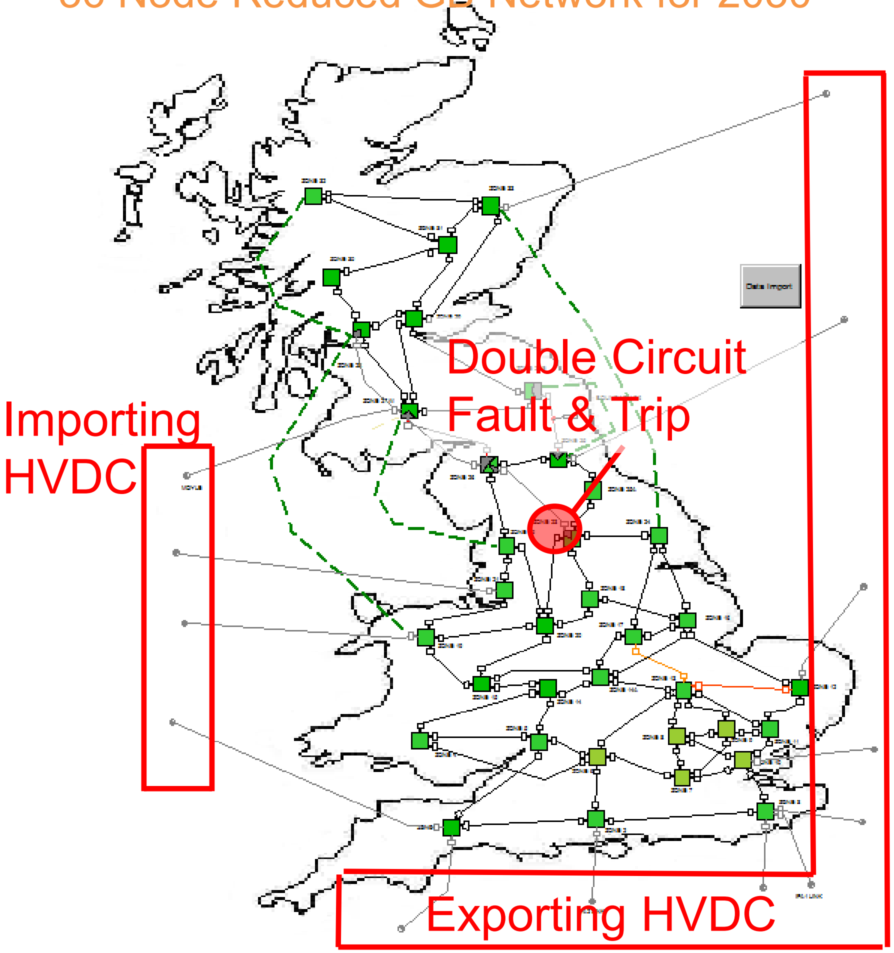


NSG	0 Import HVDC 0 Export HVDC			3GW Import HVDC 10GW Export HVDC			0 Import HVDC 10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	OK			OK	OK		OK	OK	OK
Mid				OK			OK	OK	
High			N/A						

2013 Studies

Only 9/26 high NSG scenarios ok

36 Node Reduced GB Network for 2030



NSG	0 Import HVDC 0 Export HVDC Load (GW)			3GW Import HVDC 10GW Export HVDC Load (GW)			0 Import HVDC 10GW Export HVDC 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

Brown cells ok in 2013
Grey cells produced HF instability

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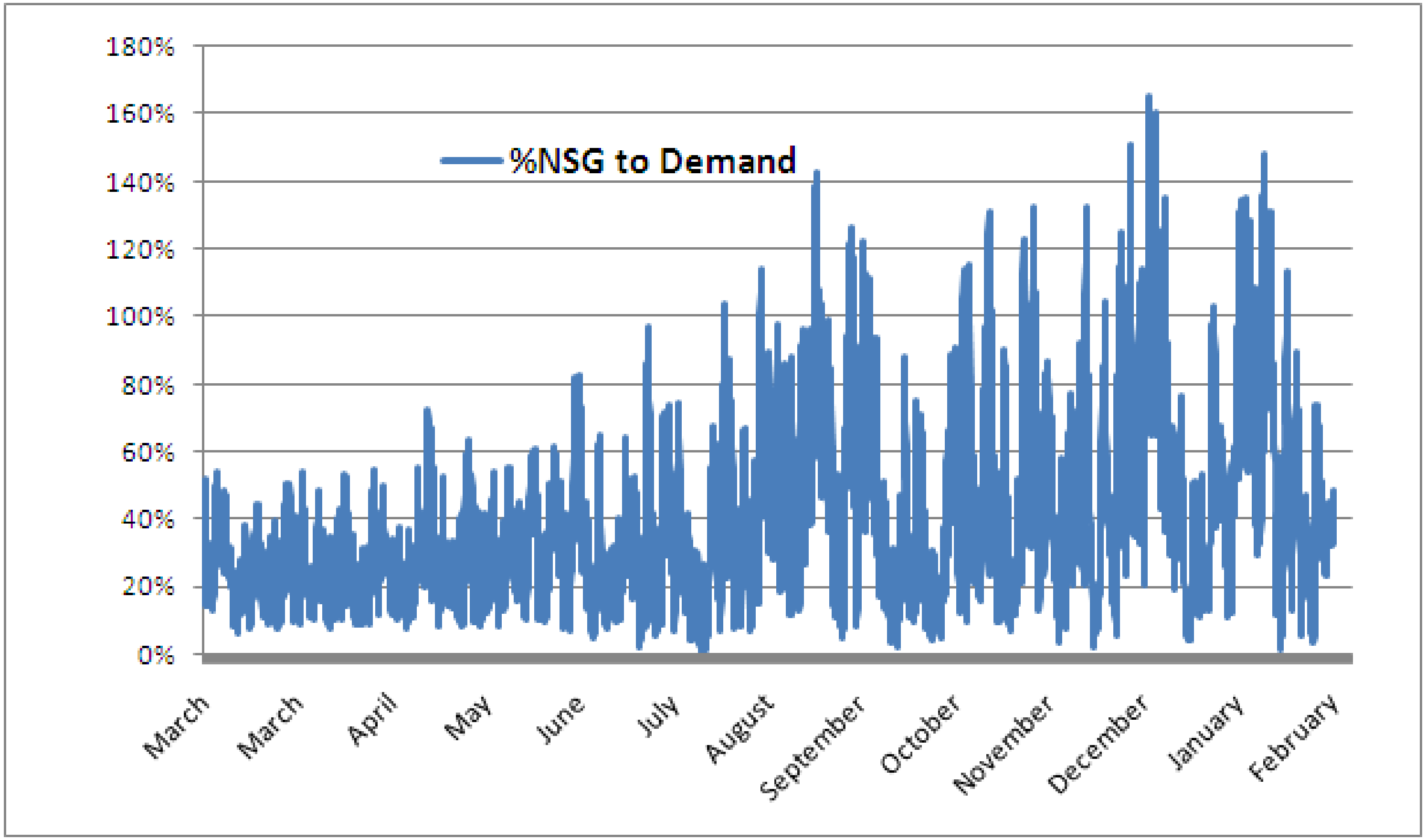
Hourly % Non Synchronous Generation

2030 Gone Green (in 2013) – GB in isolation



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Level of RES substitution (TWh) needed with different penetration limits. Improvements from raising GB limit from 50% to 95% NSG/PEIPS

Indicative Annual costs of substitution. Based on £100/MWh substituted. This gives 1TWH=£100M

Red R>£500M/Y

Amber £100<A<£500

Green G<£100M/Y

	Worse Import	Base case	Better	Best Export
NSG% (TWh)	3GW Imp. 0 Exp.	No Imp./Ex.	3GW Imp. 10GW Exp.	0 Imp. 10GW exp.
50	31.04	23.14	18.81	13.54
60	21.04	15.25	10.74	7.22
75	10.99	7.46	3.81	2.29
80	8.66	5.68	2.59	1.49
85	6.71	4.31	1.72	0.94
90	5.16	3.27	1.11	0.55
95	3.95	2.45	0.68	0.28

For base case:

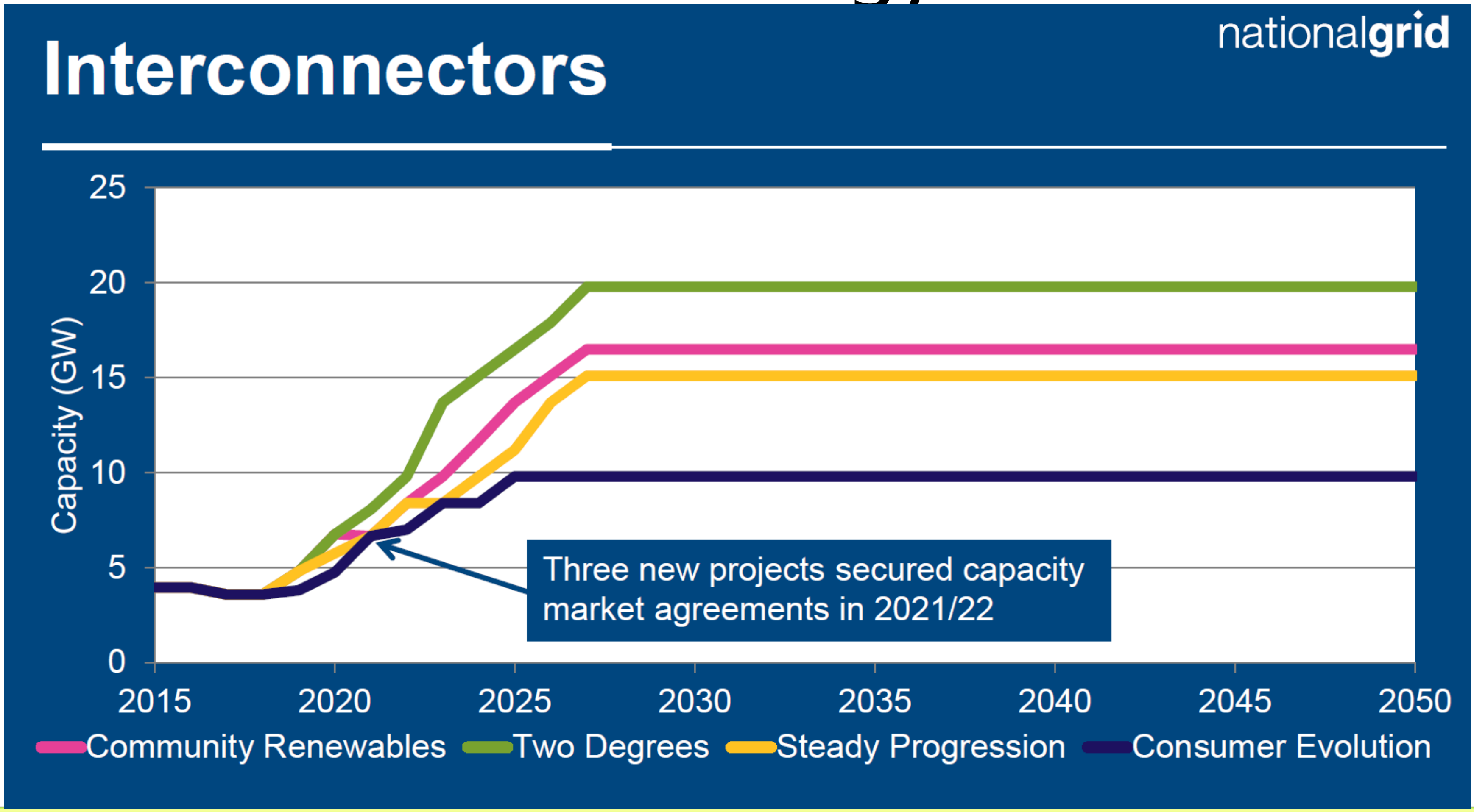
Raising NSG / PEIPS limit from 50 to 95 % reduces TWh substituted by a factor of ~10

Limit in System Operators’ freedom to operate at High Penetration of Power Interfaced Power Sources (HPoPEIPS)

- The GB 2013 economic analysis concluded that
  - On its own GB needs by 2030 to be stable for 95% PEIPS with respect to the load, in order to have a reasonable level of constraints (2TWh or £200M constraint payments)
  - With 10GW export to help, this falls to 85%
- These are both well above the level where super synchronous instabilities are predicted from rms studies.
- Recent further complex EMT extensive studies for Southern GB also show Sub-Synchronous Instability (at 6Hz). Seemingly similar to actual 4Hz instability experienced in Texas SA.

http://www.smarternetworks.org/project/nia_nget0187/documents

Interconnector capacities expected in 2018 Future Energy Scenarios GB



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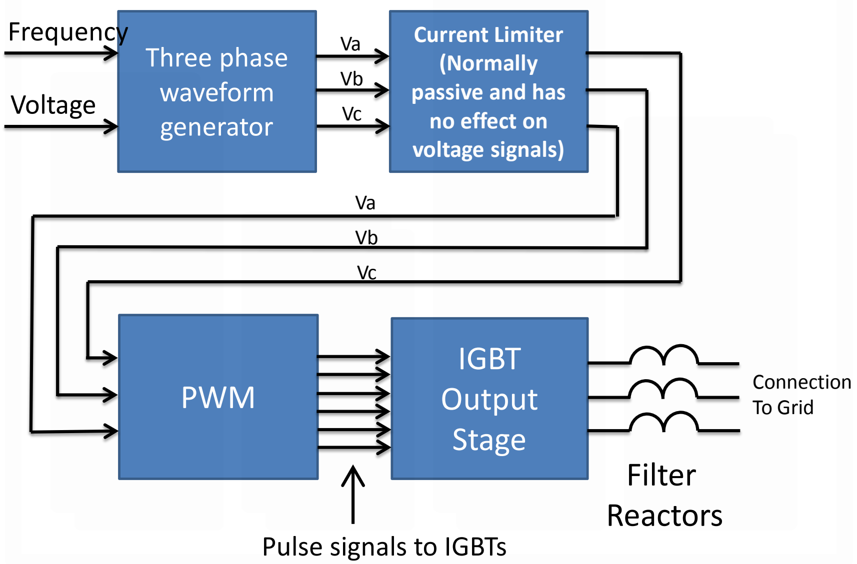
HP Studies with Grid Forming Converter Controls – VSM / VSM0H

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)

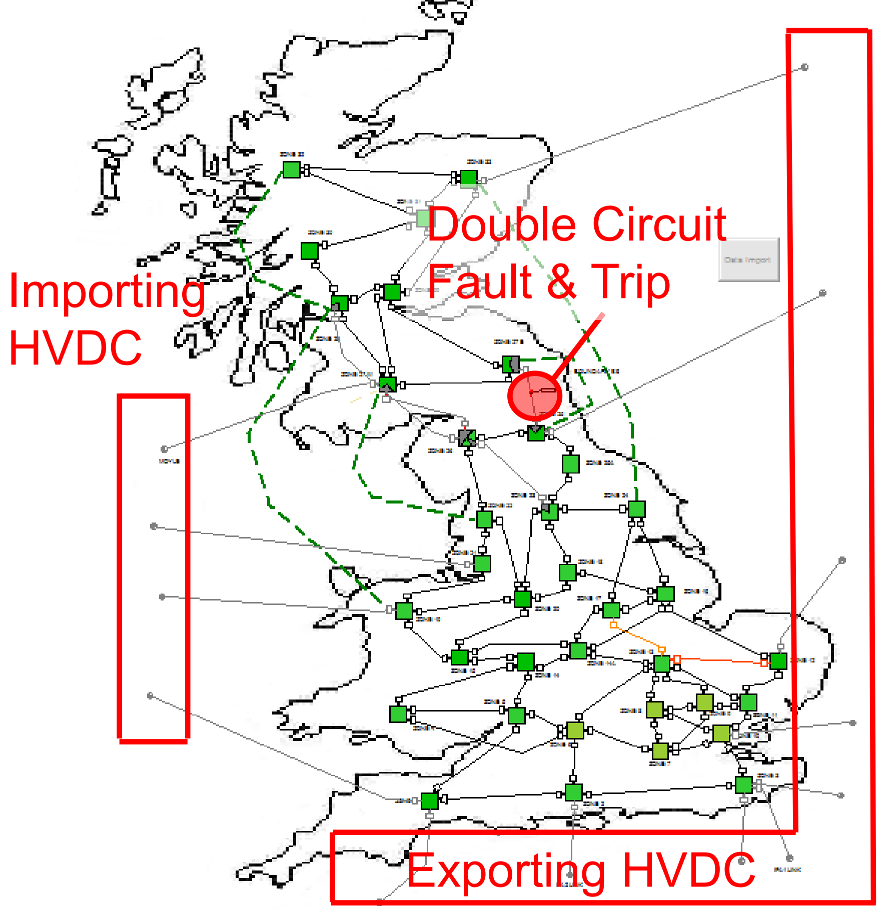
1. Contributes to RoCoF
2. Compatible with SG
3. Reduced interaction and HF instability risks
4. Can be modelled in RMS system studies

Disadvantages

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

2016 Studies
All high NSG scenarios stable

36 Node Reduced GB Network for 2030



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

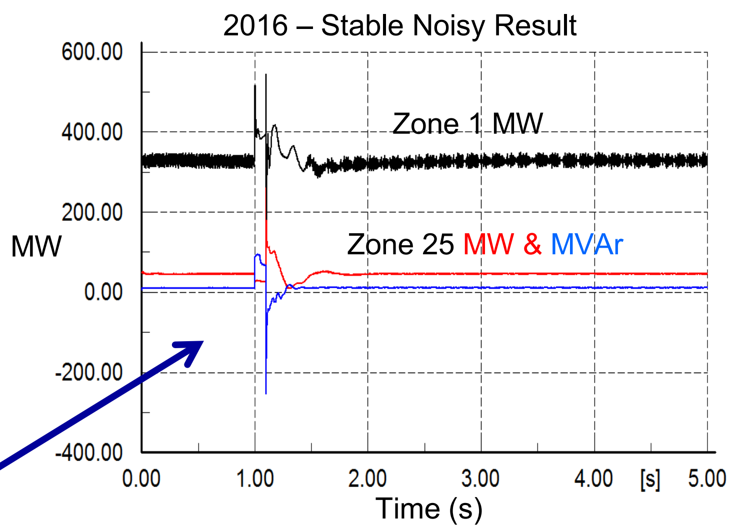
NSG	0 Import HVDC			3GW Import HVDC			0 Import HVDC		
	0 Export HVDC			10GW Export HVDC			10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	1% 60%	10% 25% 69%	10% 25% 80%	1% 54%	1% 60%	10% 68%	1% 48%	1% 15% 53%	1% 60%
Mid	5% 25% 73%	5% 83%	10% 97%	1% 64%	10% 25% 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%

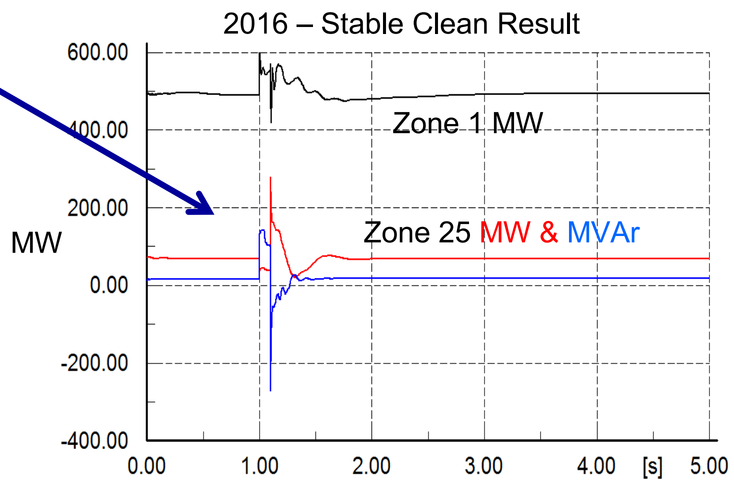
NSG is 8GW Solar +
Low: 16.0GW Wind
Mid: 20.5GW Wind
High: 28.5GW Wind

Brown 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)

Typical results from 2016 studies

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	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%





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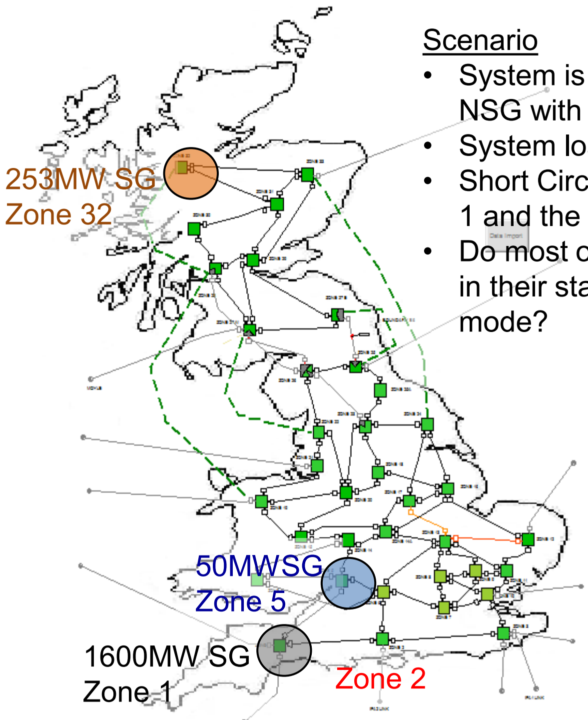
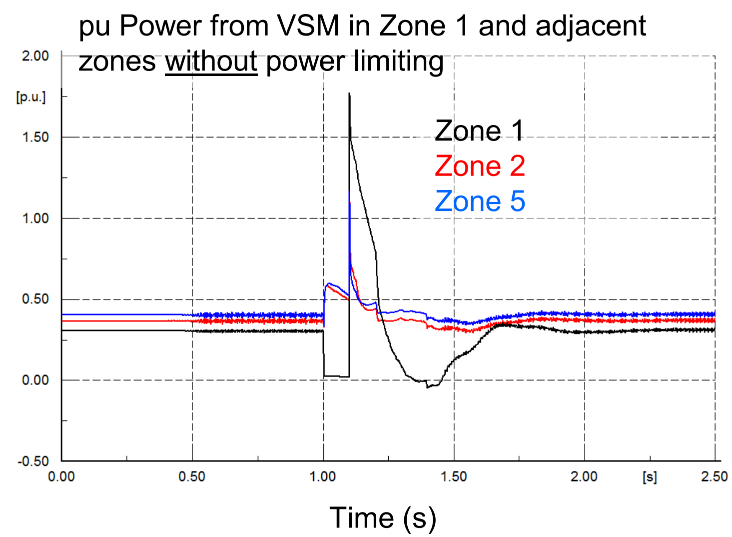
Time (s)

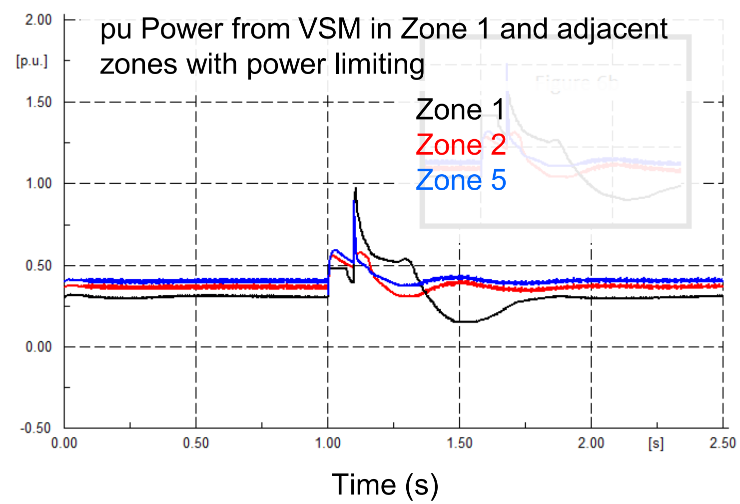
1600MW Trip at 97% NSG with 30GW of Load



Scenario

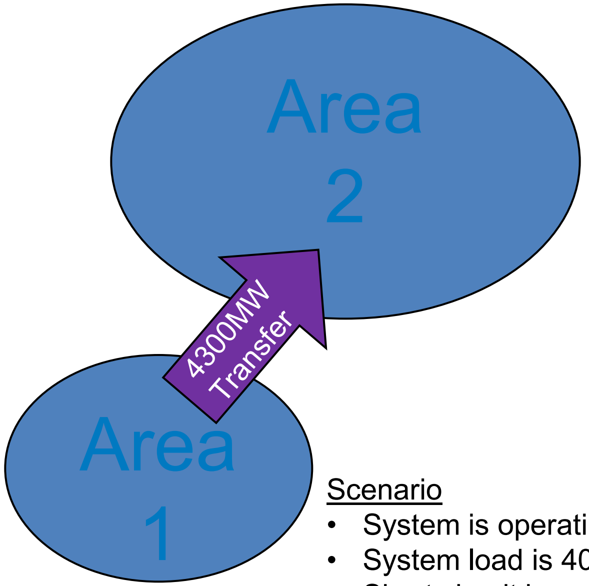
- System is operating at 97% NSG with SG as shown
- System load is 30GW
- Short Circuit is applied at Zone 1 and the 1600MWSG is tripped
- Do most of the VSM remain with in their stable region i.e. VSM mode?





System Islanding at 93% NSG with 40GW load

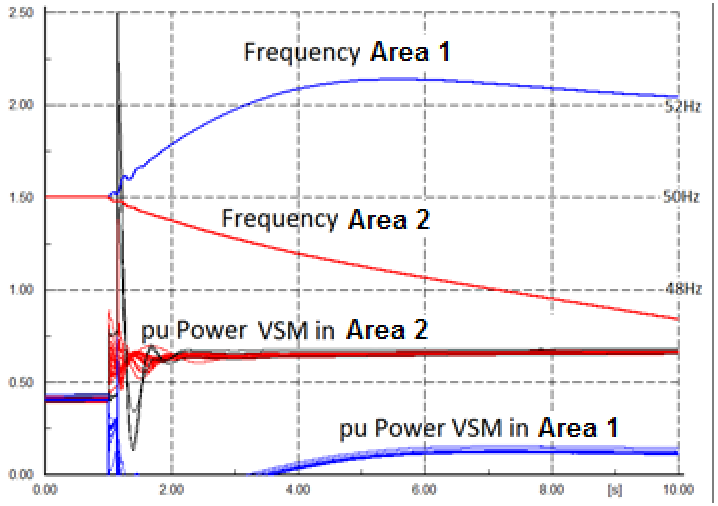
CC.6.3.7 and CP.A.3.6



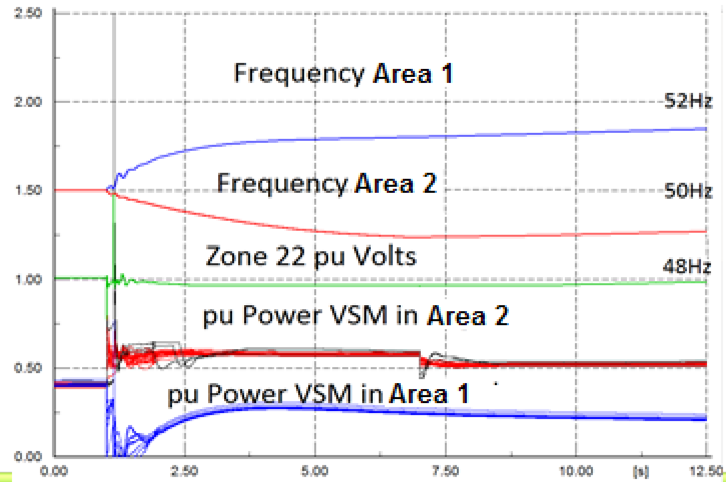
Scenario

- 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) without power limiting



pu Power from VSM (all zones) with power limiting



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Wider stability Challenges & system Needs during high penetration (HP)

Challenges with low System Strength

C1 Lack of synchronising torque with distorted voltage

C2 Inadequate system inertia

C3 Failure to survive major disturbances (allow time for LFDD + support system restoration)

C4 Adverse control system interactions, sub & super synch + simplify dynamic analysis

C5 Absence of sinks for harmonics & unbalance without synch gens

System Needs to cope even at high penetration

N1 Need converters to lead, shape voltage (PLLs just follow)

N2 RES contribute to TSI

N3 Aid system stability by locking frequency & angle during fault

N4 Limit f bandwidth of active controls, e.g. <5Hz avoiding high frequency analysis

N5 Converters act as sinks to harmonics & unbalance, act as a voltage behind an impedance

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Real experiences, laboratory activity and study activity

Actual experience of HP problems

- High df/dt (RoCoF) – GB experienced, WTGs tripping off
- Sub-synchronous instability – Texas SA
- Island systems
  - HVDC connected offshore – German sector – Early instabilities
  - Marine transport sector & small islands – experience + solns

Lab activity with multiple converters, in progress, to report

- MIGRATE – Europewide in France
- GB – Work continuing at Strathclyde, Nottingham & other Univs.

Large scale studies

- MIGRATE – see session 4B

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Summary of high penetration challenges & potential solns in GB

With current technology/models, the system may become unstable when more than 65% of generation is Non-Synchronous (PEIPSs)
For FES2017 in three scenarios, forecast 65% 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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HP Technical/Expert Groups in Europe and in GB

European HP TG: Stage 1 done: Produced two IGDs, including HPoPEIPS

https://consultations.entsoe.eu/system-development/entso-e-connection-codes-implementation-guidance-d-3/user_uploads/igd-high-penetration-of-power-electronic-interfaced-power-sources.pdf

Stage 2 Aim to have a draft report in Dec 2018, final report Summer 2019

- Describe individual aspects of grid forming capability
- Describe design/sizing consequences for Power Electronic interfaces
- Describe possibilities and limits of grid forming with respect to size of storage and/or current headroom
- Set up benchmarks for evaluation of compliance including testing

GB Expert Group on HP

- Develop Option 1 from previous details during Consultation Summer 2017
- Analysis to-date shows Grid Forming capabilities needed by 2021
- Aim to complete Grid Code proposal by end 2018 with study based CBA

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- System Stability Studies with low System Strength using GF / VSM based converter controls approaching 100% penetration
- Wider stability challenges & system needs during high penetration (HP)
- HP Studies with Grid Forming Converter Controls – VSM
- Summary of high penetration challenges & potential solns in GB
- HP Expert Groups in Europe and in GB
- Key questions for our session discussion

Key questions for our end of session 2B discussion

- Q1 Has the case been made yet for a change from BAU (Converter controls based on PLLs):
  Q1 a In highest PEIPS Synchronous Areas (GB & Ireland)? Yes / No
  Q1 b For HP countries within "ok" SA (e.g. Germany)? Yes / No
- Q2a Do realistic means for TSO Grid wide stability studies at HP exist? Yes / No
  Q2b Is bandwidth limitation on active converter controls essential for this? Yes / No
- Q3 Is Grid Forming converter control practical for each of
- Q3a For wind? Yes / No,
- Q3b For PV? Yes / No
- Q3c For HVDC? Yes / No
- Q4 Has economic alternatives to Grid Forming converter controls been brought forward, which can holistically deal with all the HP challenges? Yes / No
- Q5 Countries could move forward at their own pace, depending on need.
  Should High Penetration (>2/3 of load via converters) and Low-Medium Penetration (say ok for <2/3) converter versions of converters co-exist for some years? Yes / No

Questions

deferred to end of session discussion

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