Stability Challenges & Solutions for Power Systems Close to 100% Penetration of Power Electronic Interfaced Power Sources

Exchange of Experience between Hybrid and Major Power Systems

3rd International Hybrid Power System Workshop
Tenerife, Spain 8-9 May 2018

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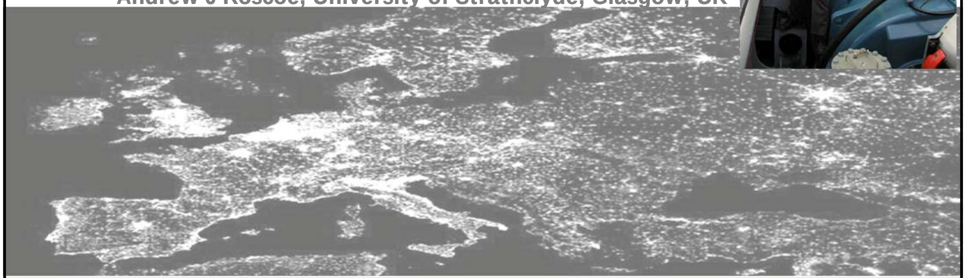

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Objective of paper & presentation

- Share status of analysis of High Penetration stability issues from Synchronous Areas in Europe
- Initiate greater cooperation between converter control experts supplying Hybrid Power Systems and the equivalent experts supplying converters for large Synchronous Areas.
- Ask Questions to Hybrid experts related to challenges which may already have been faced and solved in the hybrid world

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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 60and 70%),

Highest Instantaneous penetration >> average annual penetration
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

European Network Codes

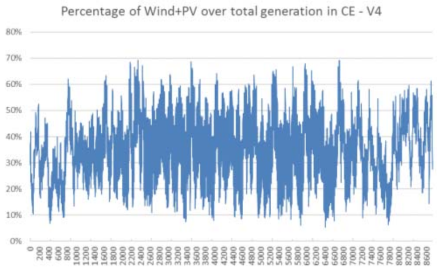
Implementation Guidance Document
High Penetration of Power Electronic Interfaced Power Sources

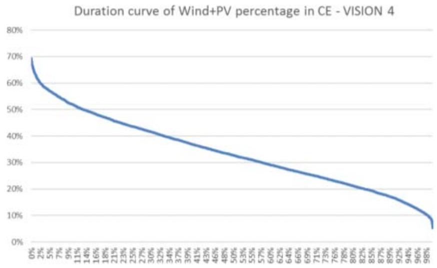
IGD HPoPEIPS

Guidance for 34 European countries

Contains analysis and a decision process related to:
Do you have a HP problem / need to act?

Variability & penetration data for Continental Europe from IGD HPoPEIPS with 2016 Wind + PV penetration data (by ENTSO-E) – Vision 4 scenario 2030.





Penetration getting high even in CE

Smallest synchronous areas, Ireland and GB much higher penetration still. These will soon hit 100% for some hours in the year, unless constrained.

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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
  - 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

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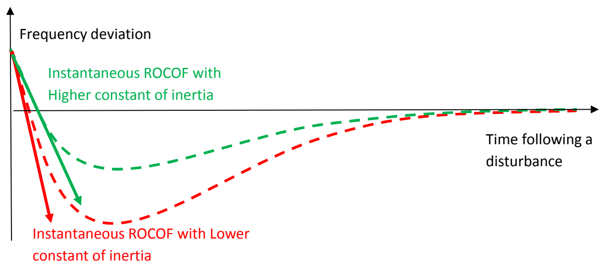
Importance of inertia to frequency stability

- Rate-of-change-of frequency (RoCoF) critical in systems with high percentage of non-synchronous generation.
- High RoCoF occurs immediately after a sudden imbalance in generation and demand.
- Concerning the ROCOF, the system performance is mainly dependent on the available system inertia (for the synchronous area, the TSI).
- Short duration angular movements between machines and between regions result in RoCoF not being uniform across an interconnected system



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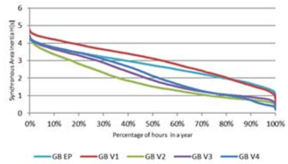
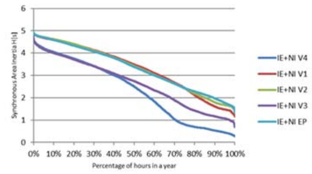
Duration Charts for Total System Inertia (H) in Europe's 5 Synchronous Areas (SAs)
Three SAs Ok'ish while two SAs have big concerns

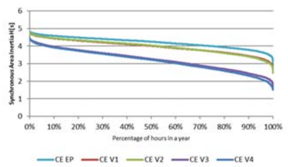
From IGD HPoPEIPS with 2016 market study results for all synchronous areas for 2020 and 4 different visions for 2030

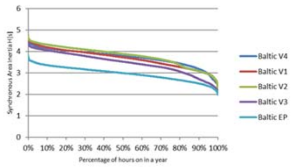
GB & IE+NI have BIG CONCERN at SA level.
Some scenarios with H<1s for 30% of time! Dramatic reduction in H

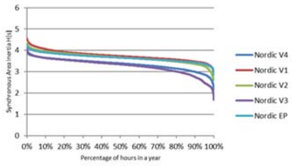




Three SAs ok'ish at SA level with modest reductions in H in all scenarios.







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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%

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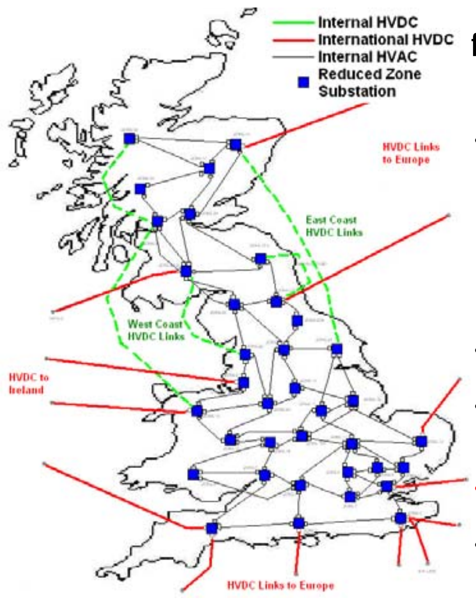

Angular stability analysis for NSG >50%; network used

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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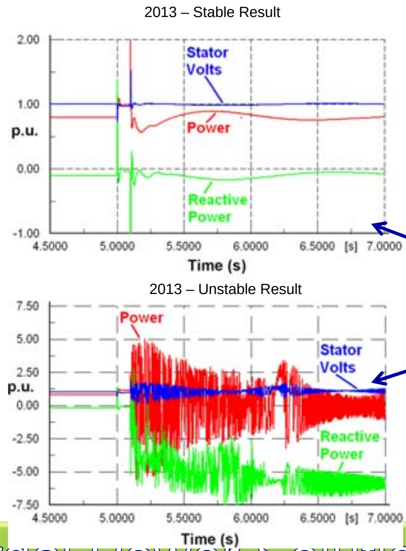
2013 Results



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						

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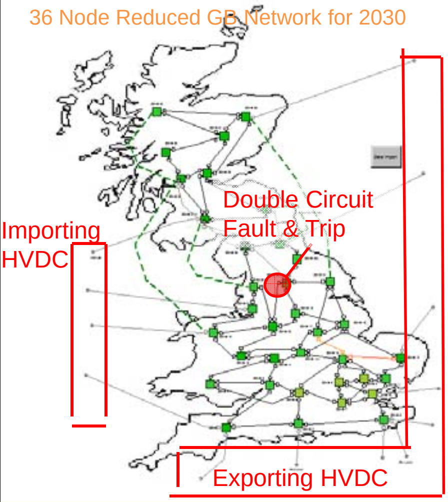
2013 Studies
Only 9/26 high NSG scenarios ok



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

Brown cells ok in 2013
Grey cells produced HF instability

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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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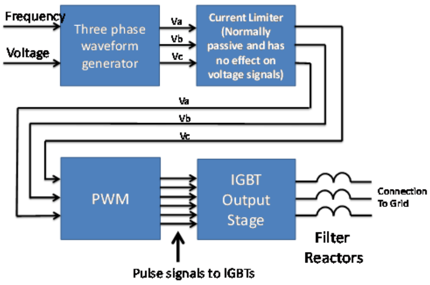
HP Studies with Grid Forming Converter Controls – VSM / VSM0H

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

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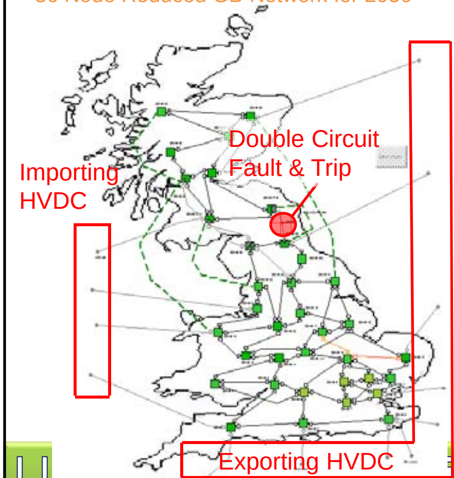
2016 Studies
All high NSG scenarios stable

36 Node Reduced GB Network for 2030



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

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

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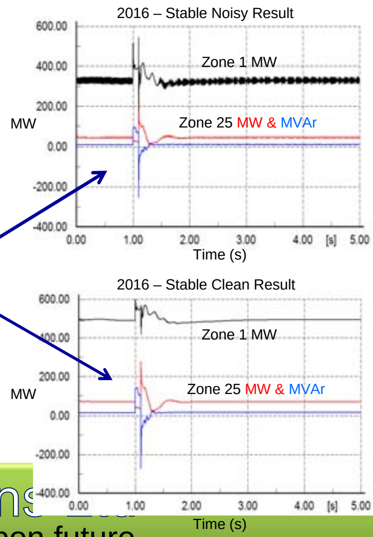
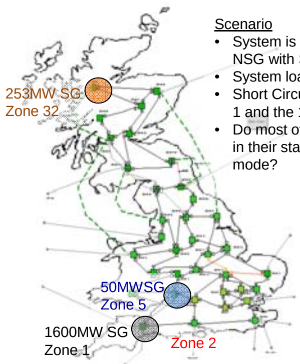
Typical results from 2016 studies

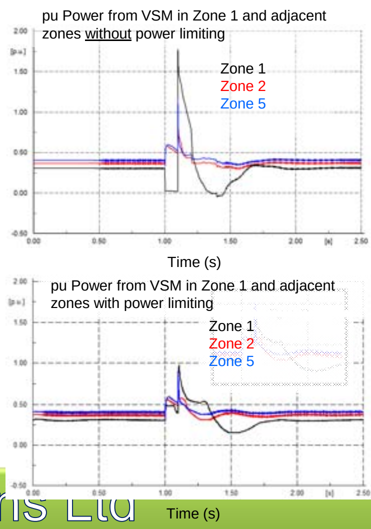
NSG	0 Import HVDC			3GW Import HVDC			0 Import HVDC		
	0 Export HVDC			10GW Export HVDC			10GW Export HVDC		
	Load (GW)			Load (GW)			Load (GW)		
	40	35	30	40	35	30	40	35	30
Low	1% 60%	10% 25% 69%	10% 25% 80%	1% 54%	1% 60%	10% 68%	1% 48%	1% 15% 53%	1% 60%
Mid	5% 25% 73%	5% 83%	10% 97%	1% 64%	10% 25%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



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?



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System Islanding at 93% NSG with 40GW load

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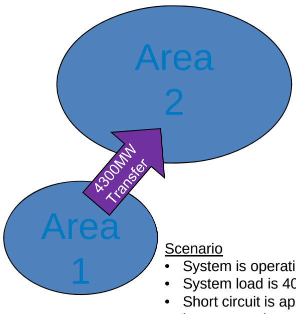
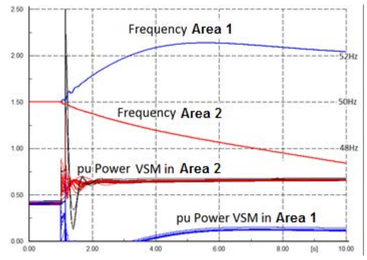
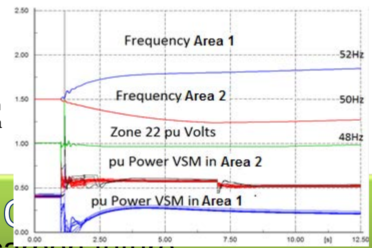


Scenario
- System is operating at 93% NSG
- System load is 40GW
- Short circuit is applied to AC interconnection
- Loss of AC interconnection between exporting Area 1 and importing Area 2
- Does LFDD work?

pu Power from VSM (all zones) without power limiting



pu Power from VSM (all zones) with power limiting



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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

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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Grid Forming option – what can it achieve? - holistic approach?

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First the basics or even advanced capabilities

IGD HPoPEIPS identifies:

Basic expectations for converters – calling it Class 3, already common

Advanced capabilities for converters – calling it Class 2, on its way in

Focuses on needs for Class 1 – to be self sufficient where, when and under which circumstances needed

Why a holistic approach for Class1?

- The TSO analysis of fast dynamics associated with extremely low System Strength show strong inter relations between different topics.
- Management of one issue is bound to affect management of several others.
- A holistic approach is needed to prepare a path towards full RES penetration.

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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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HP Expert Groups in Europe and in GB

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

Stage 2 Draft report due 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
- Publish results

GB Expert Group
- Develop Option 1 from previous details during Consultation Summer 2018
- Analysis todate shows Grid Forming capabilities needed by 2021
- Aim to complete Grid Code proposal (refining Option 1) by end 2018

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Process extract from draft IGD HPoPEIPS (abbreviated) Steps for Synchronous Area & Individual Countries

Step 1 - Define extent of the challenge.

Establish penetration of PEIPS in area at least to 2030.

Step 2A - If PEIPS > 75% for the SA for >10% of the hours in the year. →
A strategy needed to make improvements to contributions from PEIPS.

If the SA H is < 1s for more than 10% of time consider urgently to implement the converter control capabilities defined as Grid Forming.

If 2A conditions do not apply:
Step 2B - If PEIPS > 50% for your COUNTRY, discuss within SA.
If your country inertia <1s for >10% of time, consider if your inertia contribution is acceptable, and resilience for system splits is adequate.
Consider the possibility of implementing Grid Forming capabilities.

Step 3 - Detail requirements including parameters for the implementation and models to study the effectiveness as well as compliance tests → Introduce new requirements at national level

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Questions

To Hybrid Power Systems from Large Synchronous Areas

Is there room for wider collaboration / sharing of experience in context of stability associated with high penetration and weak power systems?

- Q1: What experience exist with operation some times at 100% PEIPS?
  - Experience of hybrid power systems (HPS) operating stably with 100% PEIPS, at times without diesel generators / other synchronous generators.
- Q2: Does such operation rely on VSM type converters?
- Q3: Converters used to give seamless transition when separating from Grid. Are they Grid Forming / VSM?
- Q4: If so, roughly in % of converter cost, how much has this added to cost?
- Q5: How long was needed to develop and then deliver the new solutions?

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Conclusions

- Total system strength is reducing as Synchronous Generators (SGs) are increasingly being replaced by Power Electronic Interfaced Power Sources (PEIPS)
- Unless restriction applied / market intervention taken, hours of operation with total absence of SGs will become common place in Europe.
- The largest Synchronous Areas (SAs) have more time to prepare than the smallest SAs, such as GB & Ireland.
- Analysis has identified a range of services needed from PEIPS in the future, the foremost candidate being Grid Forming (true voltage source) / VSM
- The longer delay in introduction of Grid Forming requirements, the more severe parameters will be needed (as a smaller part of PEIPS has to deliver)
- Hybrid Power Systems (HPS) are considered to be similar to, but more extreme than the smallest SAs. Access is sought to early experience of challenges for HPS, as well as solutions applied. What can be exchanged?
- Aware that VSM was installed as early as 1996.
- Main focus is dealing with novel stability aspects associated with operation close to 100% PEIPS.
- Is Grid Forming capabilities (e.g. VSM) the optimal answer?

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Questions




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