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Rethinking System Services with GFM

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Key Issues

Growth of Inverter-Based Resources at expense of Synchronous Machines are causing us to think again about:

- System Needs and System Services
  - how are these defined in a technology neutral way for grid codes or services markets to bring forward cost-effective system solutions
- System Stability
  - how is stability, broadly defined, ensured and what tools do we need to analyse and synthesise our systems

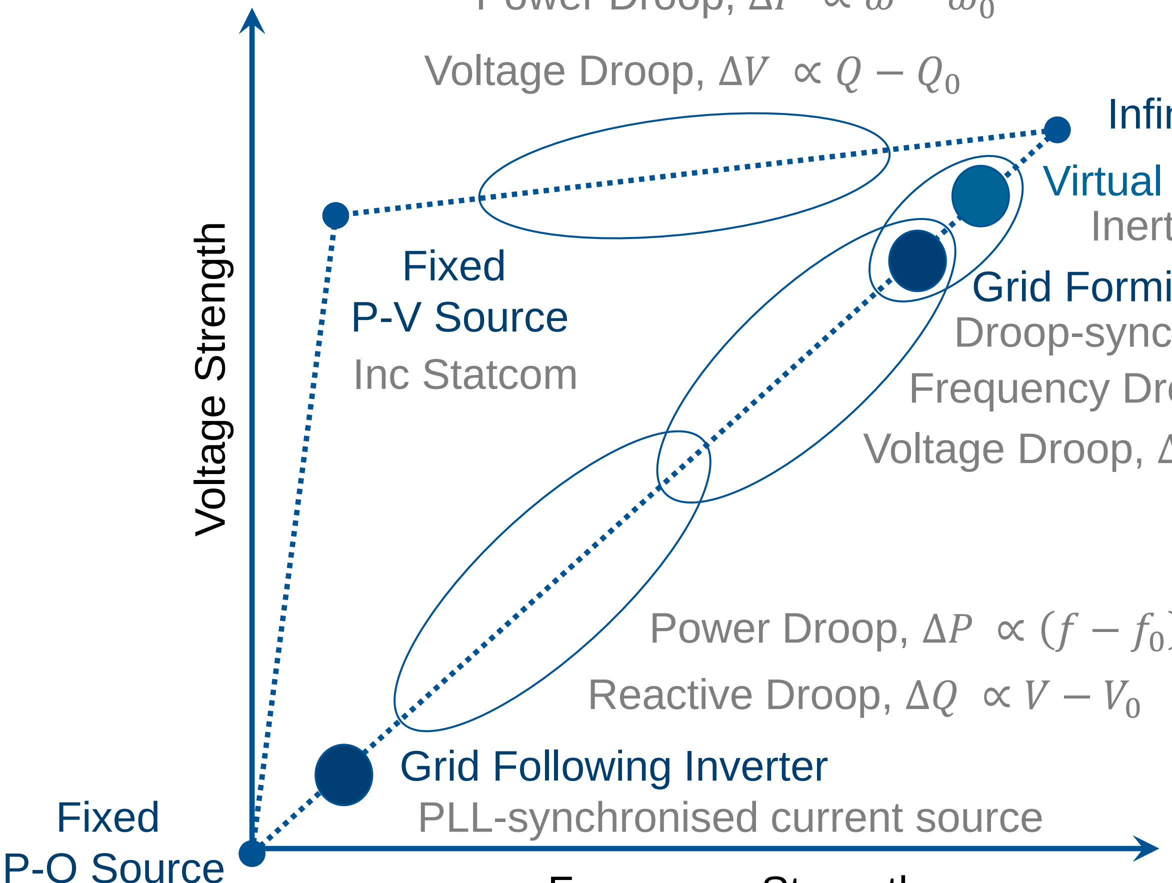
These considerations depend on how IBR present themselves to the grid: are they Grid-Following or Grid-Forming?

Grid-Forming and Grid-Following Inverters

- Grid-following IBR (GFL)
  - Synchronise to an existing AC grid voltage
  - Inject power according to their own needs (such as maximum power point operation)
  - May have some basic services (reactive power at fixed power factor, reactive current injection into faults

- Grid-forming IBR (GFM)
  - Create an AC voltage with frequency and magnitude that adjust to local conditions
  - Provide power according to combination of local set-points and grid conditions
  - Contribute directly to frequency and voltage regulation
  - Additional services should be provided to meet full range of grid needs
  - GFM require a ready supply of power and energy which means a reliance on storage or de-rating the source (operating below MPP etc.).
  - It also requires capacity for extra current for both reactive power and short-circuit current.

Two aspects of grid strength: GFM and GFL Context



Power Droop, $\Delta P \propto \omega - \omega_0$

Voltage Droop, $\Delta V \propto Q - Q_0$

Infinite Bus: V-δ Source

Virtual Synchronous Machine (GFM+?)

Inertia, Fault current

Fixed P-V Source

Inc Statcom

Grid Forming Inverter

Droop-synchronised voltage source

Frequency Droop, $\Delta f \propto P - P_0$

Voltage Droop, $\Delta V \propto Q - Q_0$

Power Droop, $\Delta P \propto (f - f_0)$

Reactive Droop, $\Delta Q \propto V - V_0$

Grid Following Inverter

PLL-synchronised current source

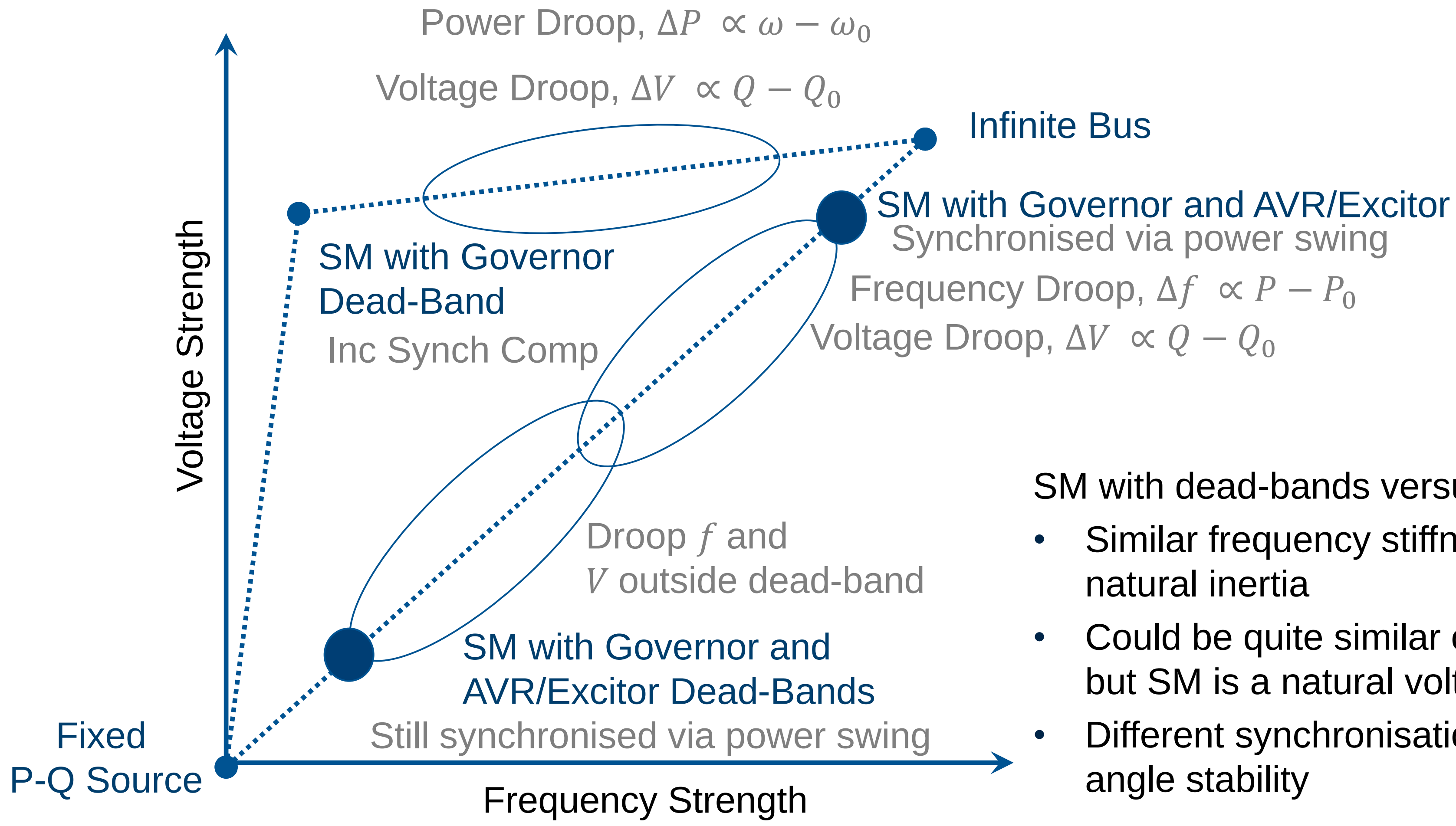
Fixed P-Q Source

A binary divide between GFM and GFL does not recognise the subtleties.

Not all inverters can offer all services; but we don’t need them to. We just need the right combination across the grid.

So how much of each service does a grid need?

Two aspects of grid strength: SM



Power Droop, $\Delta P \propto \omega - \omega_0$

Voltage Droop, $\Delta V \propto Q - Q_0$

Infinite Bus

SM with Governor Dead-Band
Inc Synch Comp

SM with Governor and AVR/Excitor
Synchronised via power swing
Frequency Droop, $\Delta f \propto P - P_0$
Voltage Droop, $\Delta V \propto Q - Q_0$

Droop f and
V outside dead-band

SM with Governor and AVR/Excitor Dead-Bands
Still synchronised via power swing

Fixed P-Q Source

SM with dead-bands versus GFM IBR

- Similar frequency stiffness but SM has natural inertia
- Could be quite similar on voltage stiffness but SM is a natural voltage source
- Different synchronisation dynamics and angle stability

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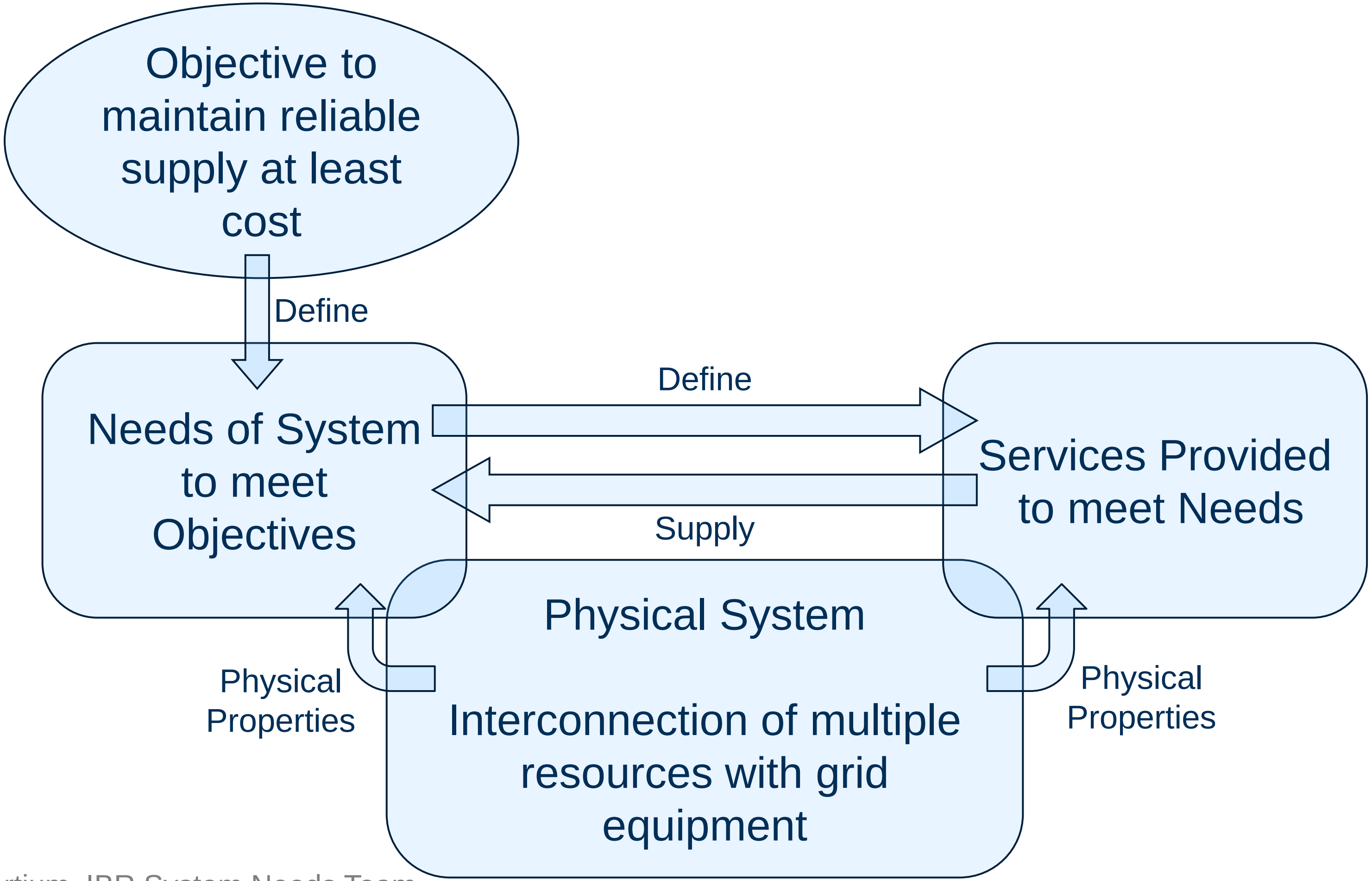
G-PST Working Group on System Needs and Services

Started as “what services should IBR provide?”

- example “how much inertia should IBR provide?”

Turned into “what does a system really need in technology neutral terms?”

- example “need to arrest frequency excursions, how might that be achieved?”



Global Power System Transformation Consortium, IBR System Needs Team
https://globalpst.org/what-we-do/system-operator-research-peer-learning/pillar-1-inverter-based-resources-research-team/

System Needs and IBR Restrictions

Global Power System Transformation Consortium https://globalpst.org/resources/

Power Quality & Stability

- Synchronization & Angle Stability
- Frequency Regulation
- Voltage Regulation
- Damping

Service Quality & Security

- Energy
- Capacity
- Protection
- Restoration

IBR Limitations

- Absence of Short-Term Rating
- Absence of Synchronized Inertia
- Phase-Lock Limits
- Complex Dynamics

VRE Limitations

- Power Availability
- Energy Availability

Needs in Frequency Regulation

Need Type	Reason for Need	Traditional Services	IBR Service
Frequency Regulation	Power fluctuation of VRE or load causing drift of frequency need to be mitigated	Primary frequency response from part-load generators	Primary frequency response from part-load renewables and batteries
Containment within Frequency Limits	Loss of load/infeed causing large increase/decrease of frequency to the outside limits defined and causing equipment malfunction or loss of service.	Inherent inertia and primary frequency response	Dynamic containment – block power triggered by threshold
RoCoF Limitation	Loss of load/infeed causing rapid change of frequency leading to protection malfunction or unwanted triggering of protection.	Inherent inertia	Virtual and synthetic inertia plus fast frequency response
Frequency Settling	Following major event and immediate containment of frequency, need to settle (or stabilise) the frequency.	Primary and second frequency response	Response from batteries, DSR, and part-loaded renewables
Frequency Recovery	Reserve services to restore frequency following large disturbance	Secondary frequency response and short-term reserve	Response from batteries, DSR, and part-loaded renewables

Overlaps and Co-actions in Services to meet Needs

- Inverters give us huge choice to configure services tailored to each need
- Frequency related services could be
  - Synthetic inertia (*P* proportional to *df/dt*)
  - Fast frequency response (*P* proportional to ($f - f_0$) with or without dead-band)
  - Frequency containment (Fixed *P* triggered by ($f - f_0$) threshold, as a positive service not “shedding”)
  - Blends of these or other relationships not possible with synchronous machines
- All of these services help meet needs for Containment, RoCoF Limitation, Settling and Recovery after loss-of-infeed
- Loss-of-infeed may also cause a phase-jump and a voltage sag with further needs for synchronising services and voltage regulation.
- The real and reactive power needed for the group of services must fit withing the operating envelope and so complete and must be prioritised.

Angle Stability and Synchronisation

Need Type	Reason for Need
Synchronising torque	Loss of synchronisation of SM from angle instability in low inertia or low synchronising torque cases.
PLL instability mitigation	PLL instability in GFL IBR arising from high-impedance (low strength) at connection point causing loss off IBR through.
First-swing mitigation	Loss of synchronisation from large voltage disturbance causing acceleration of SM.
Phase-jump mitigation	Loss of synchronisation from abrupt change of angle from loss-of-infeed or loss of line.

Double-sided responsibility

- *IBR must be compatible with grid (be able to synchronise);*
- *grid needs to be good environment for IBR (facilitate synchronisation)*

Voltage Regulation

Need Type	Reason for Need
Containment within Voltage Limits	Heavy line loading and/or absence of reactive power sources leading to voltage excursions outside limits.
Mitigation of Unbalance and Harmonics	High impedance presented to equipment sourcing distortion leading to power voltage quality.
Voltage Collapse Mitigation	Sudden and large increase in line loading or grid impedance due to loss of line causing non-linear behaviour and collapse of voltage beyond bifurcation point.
Low-Voltage Ride Through (aka fault ride through)	Deep voltage dips leading to tripping of generation and consequent frequency regulation problem

Damping

Need Type	Reason for Need
Sub-synchronous mode/resonance mitigation (power oscillation damping)	Poorly damped local or inter-area mode causing instability
Super-synchronous mode/resonance mitigation (“harmonic” instability correction)	Control interactions between IBRs in high frequency range causing instability

Protection and Restoration

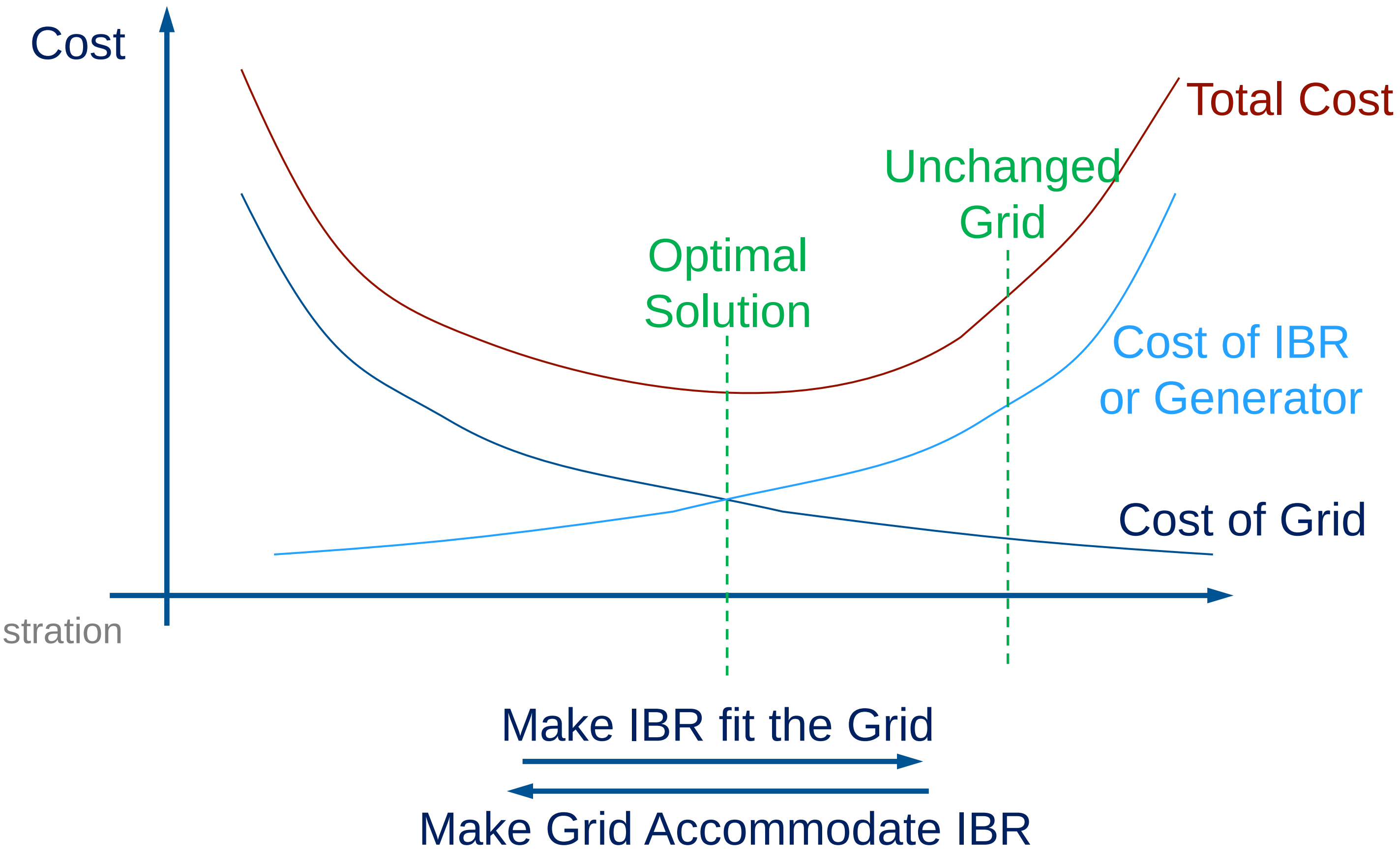
Need Type	Reason for Need
Detection of Faults	Rapid detection needed for safety of people and equipment. Traditionally based on flow of large fault current from SM.
Location of Faults	As above but with fault current magnitude and fault impedance used to locate fault.
Isolation of Faults	Not really an SM or IBR service – here for completeness
Cold-load Pick-up	Need to maintain voltage and provide additional power flow during “in-rush” of network segments being returned to supply
Black Start	Need to self-start then (i) establish voltage to which other IBR and SM can synchronise (ii) provide cold-load pick-up and (iii) synchronise and close onto adjacent areas
Island Operation	Need to maintain core functions (frequency and voltage regulation) within an area after a system split. Need ability to synchronise to an adjacent area as in Black-Start.

Example System Need – Synchronising Torque

Need	**Synchronisation and Angle:** **Synchronising Torque**
Importance / Consequence if Unmet	Existing fleet of rotating machines are coupled to each other through magnetic flux linkages, EMFs and current flows. Synchronising strength can be approximated by the magnitude of synchronizing torque. When the magnitude of this torque reduces their ability to exert a positive stabilizing influence on each other reduces. Happens when synchronous machines are connected to each other via a long transmission line. A low synchronizing torque result in large swings between machines and large fluctuations in voltage and power transfer.
Influence on relevance or scale	Number of machines in service, impedance of transmission path, angle spread across the network (read as magnitude of power transfer)
Expected Volume	Qualification of the volume is not straightforward, because they are related to parameters and design of rotating machines. The quantification is locational and system dependent.
Physical Limits on Availability	The impedance of transmission path and the angle spread across the network influence the synchronizing torque a lot and limit its value, which are also related to the power transfer limit/capacity and power flow of the whole systems.

Need	**Synchronisation and Angle:** **Synchronising Torque**
Coaction or Competition for Service	Provision of synchronising torque can co-act with provision of services for needs in frequency response.
Supporting Tools	Small-signal stability evaluation (either Eigen values or impedance diagrams), improved and robust positive sequence models, EMT analysis.
Market, Mandatory or Inherent Service	This service has to be an inherent service as it operates in a time frame that is too small for market operations. Further, since it is a service that will improve system stability, it has to be inherent.
Legacy, enduring or new need	This need is for rotating machines rather than power converters. But the synchronization loops of converters may show similar dynamics and have similar needs even though the converters have more control flexibilities. This needs more insight and research.
Readiness for IBR Supply	

Balancing Costs of Compatibility



This is only an illustration of the principle

The control and operation of IBR dominated grids demands some new and deep thinking across power electronics and grids.

Summary

System Services and Needs in an IBR World

- A set of needs have to be met across the system but not by every IBR
- Not all IBR can readily provide all services – depends on prime-mover etc.
- GFM and GFL have many flavours and can be more similar than the binary debate allows
- Several systems needs require co-design of the grid and the IBR
  - Co-design of grid impedance and IBR synchronisation
  - Co-design of protection and IBR current-limits needed
  - Etc.
- A single view of grid strength (e.g. short-circuit ratio) is not sophisticated enough for an IBR dominated grid
- Responses to the G-PST Services/Needs white paper will help the debate