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Inverter-Dominated Electricity Grids

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with

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West Burton A (Coal) & B (Gas) Power Stations (2,000 MW and 1,270 MW)

Chiddingley Solar Farm (5MW)

Toreness Nuclear Power Station (1,360 MW)

Rampion Wind Farm (400 MW)

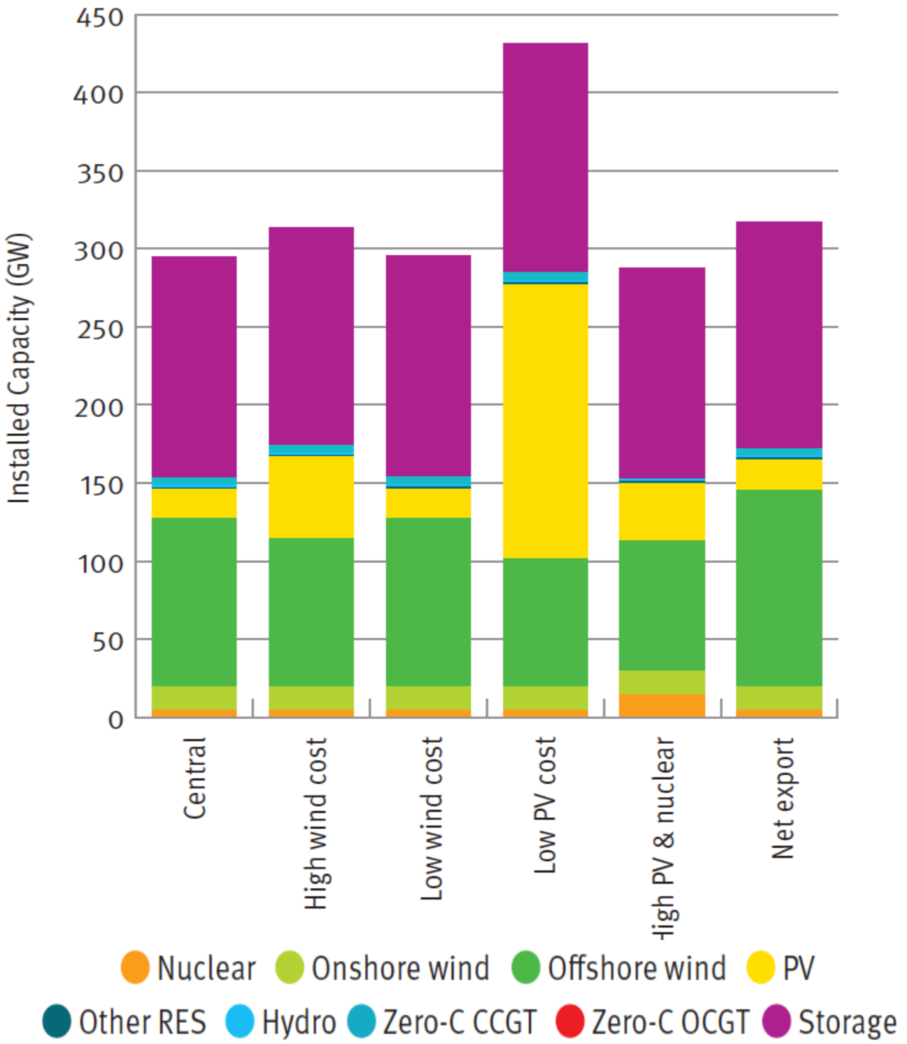
Generation Mix: United Kingdom in 2035 as an Example

Cost-optimising system planning tool used to find zero-carbon generation mix. Variations of technology costs also examined.

In all cases, system is dominated by
- offshore wind (~100 GW)
- battery storage (~140 GW / ~280 GWh)

with some nuclear (4.5 GW) and occasional use of hydrogen back-up.

There will be very few synchronous machines, almost all resources will be inverter (power electronics) interfaced because the resources are DC or variable frequency.



Energy Futures Lab White Paper June 2021, https://www.imperial.ac.uk/energy-futures-lab/reports/white-papers/

Variable Renewable Energy (VRE)

- Often inverter-based
- VRE run at maximum power point
- Zero marginal cost: turn-down of power loses all revenue but does not save fuel cost
- No upward-power services while at maximum power point.

Inverter-Based Resource (IBR)

- Not only wind, PV but also EV chargers and HVDC
- No synchronized inertia
- No short-term current rating
- High-bandwidth control which is complex and propriety
- Flexibility in control configurations and functions

Challenges for Systems Dominated by Inverter-Based Resources

- How will IBR dominated grids be operated – what what “services” should IBR contribute to that operations?
- What tools do we need to analyse and synthesise our systems so that they are stable and secure?

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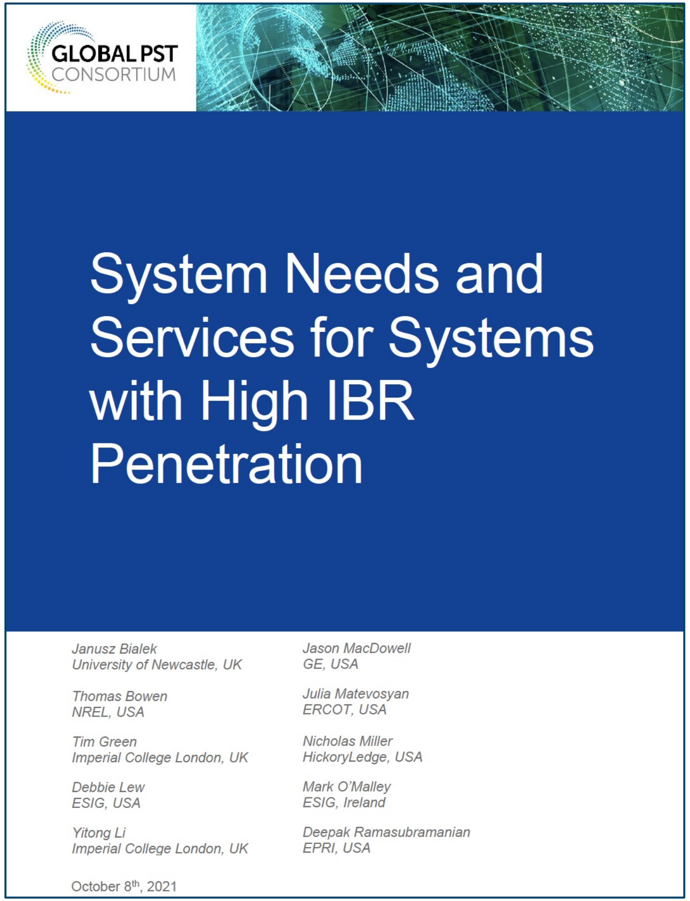
System Needs and Services



GLOBAL PST CONSORTIUM

System Needs and Services for Systems with High IBR Penetration

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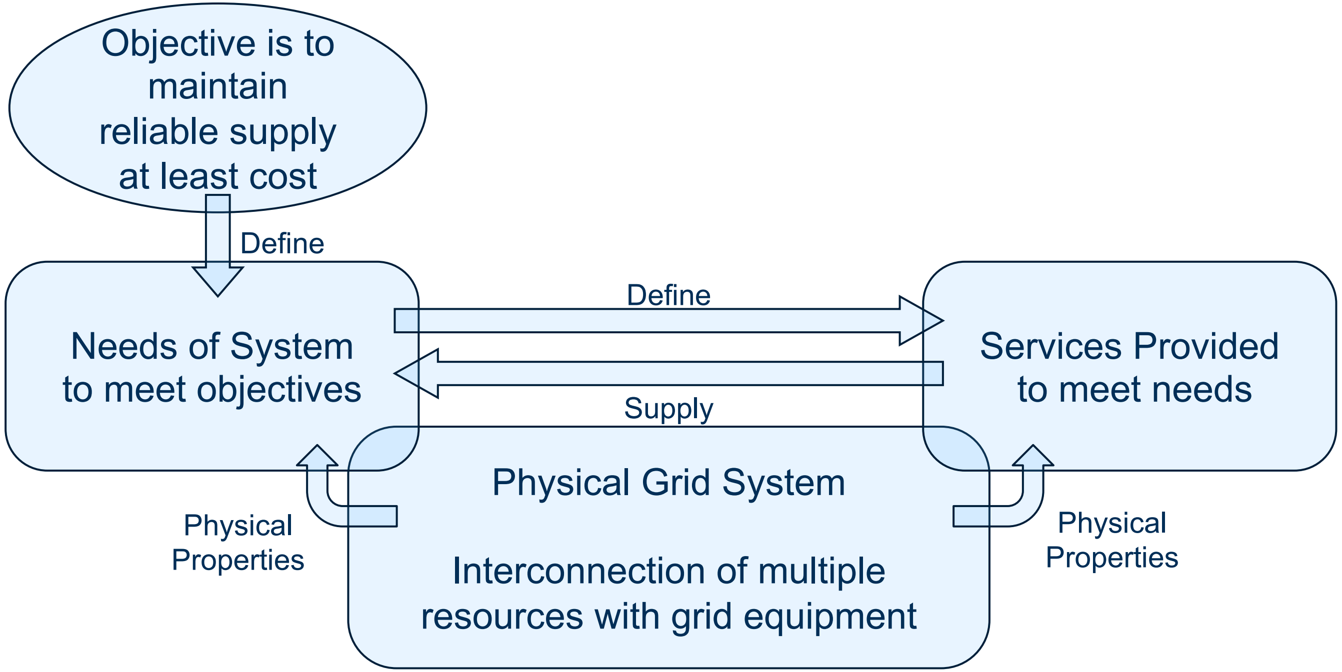
October 8th, 2021

We could ask "what services should IBR provide?"

It is better to ask "what does a grid system really need?"



https://globalpst.org/wp-content/uploads/GPST-IBR-Research-Team-System-Services-and-Needs-for-High-IBR-Networks.pdf

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What Does an Electricity System Need to Keep Operating Reliably?

Power Quality & Stability

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

Service Quality & Security

- Resource Adequacy
- Protection
- Restoration

VRE Limitations

- Power Availability
- Energy Availability

IBR Limitations

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

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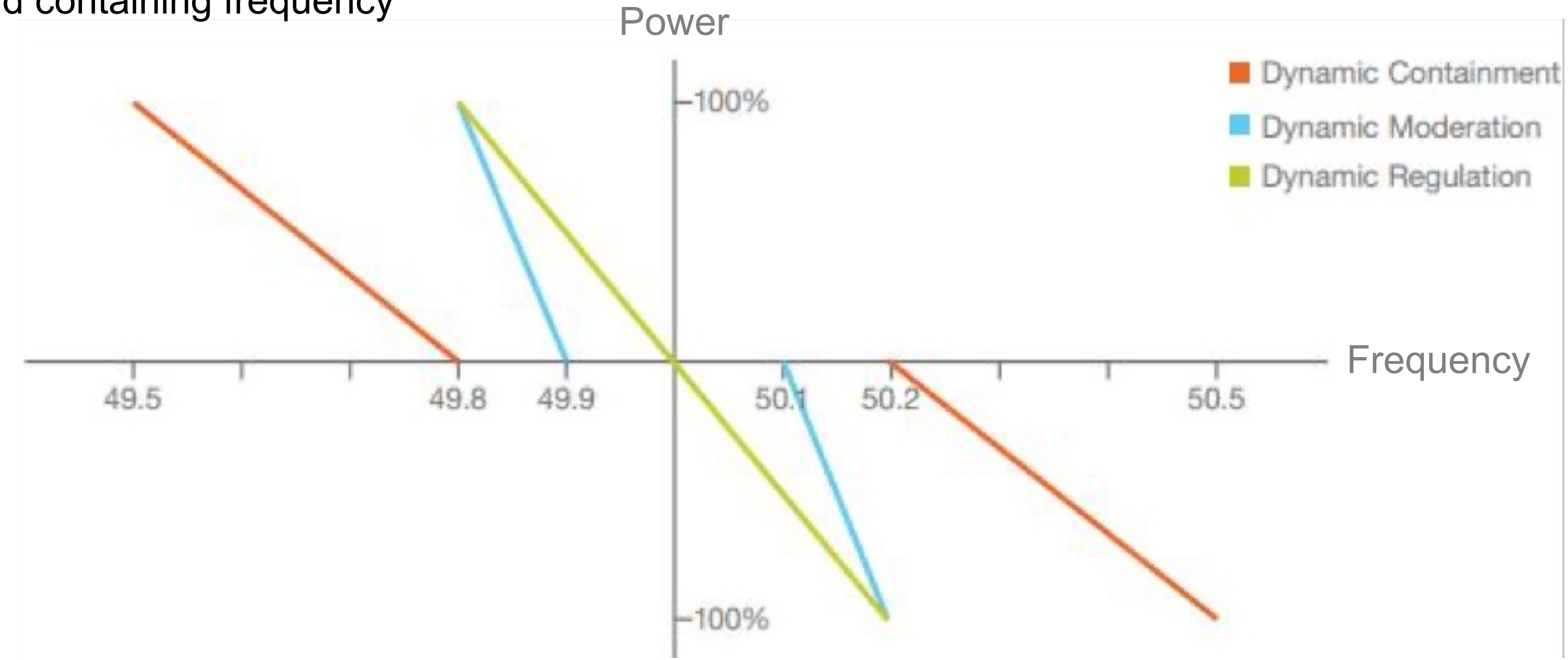
Needs in Frequency Regulation

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 dynamic containment
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

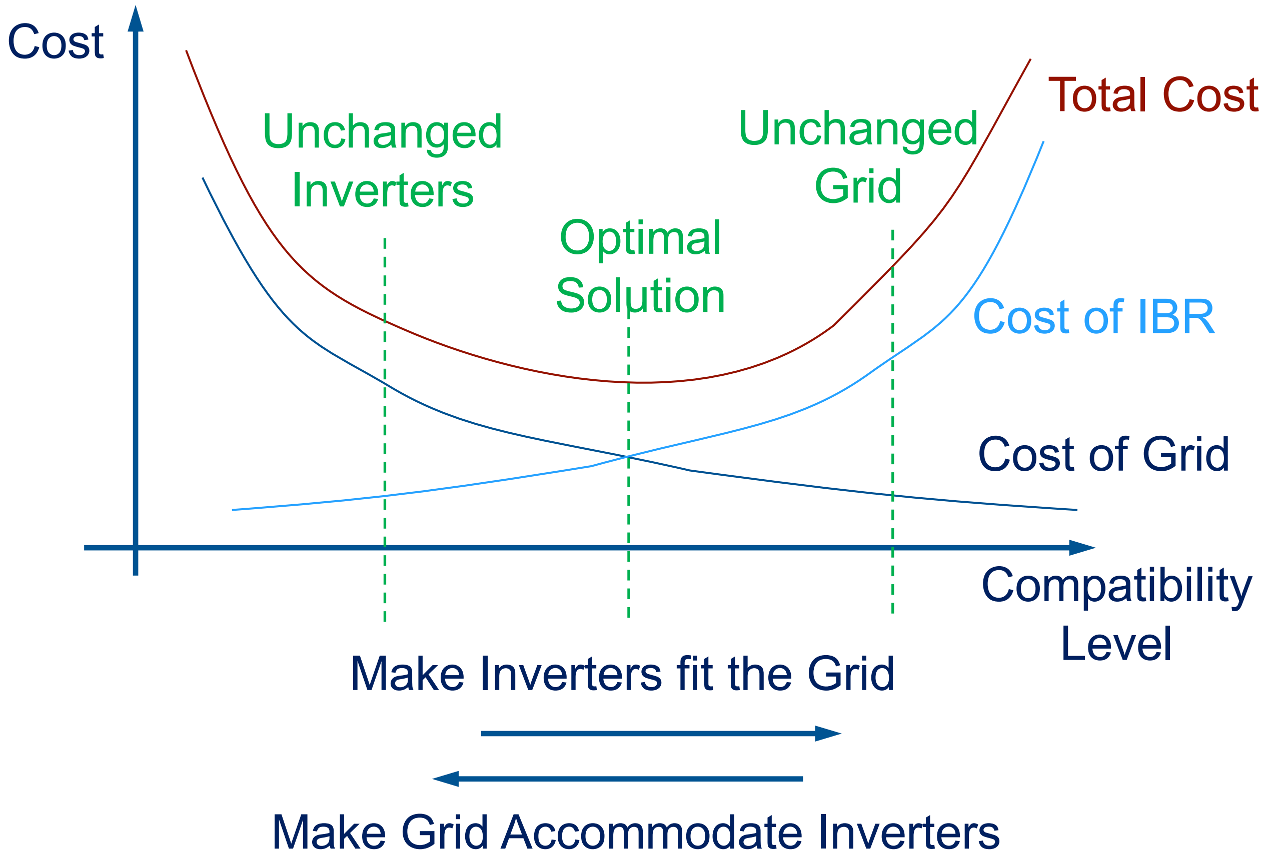
New System Service Definitions from National Grid ESO

Three new services for regulating and containing frequency



https://www.nationalgrideso.com/industry-information/balancing-services/frequency-response-services

Compatibility between Inverters and Grids



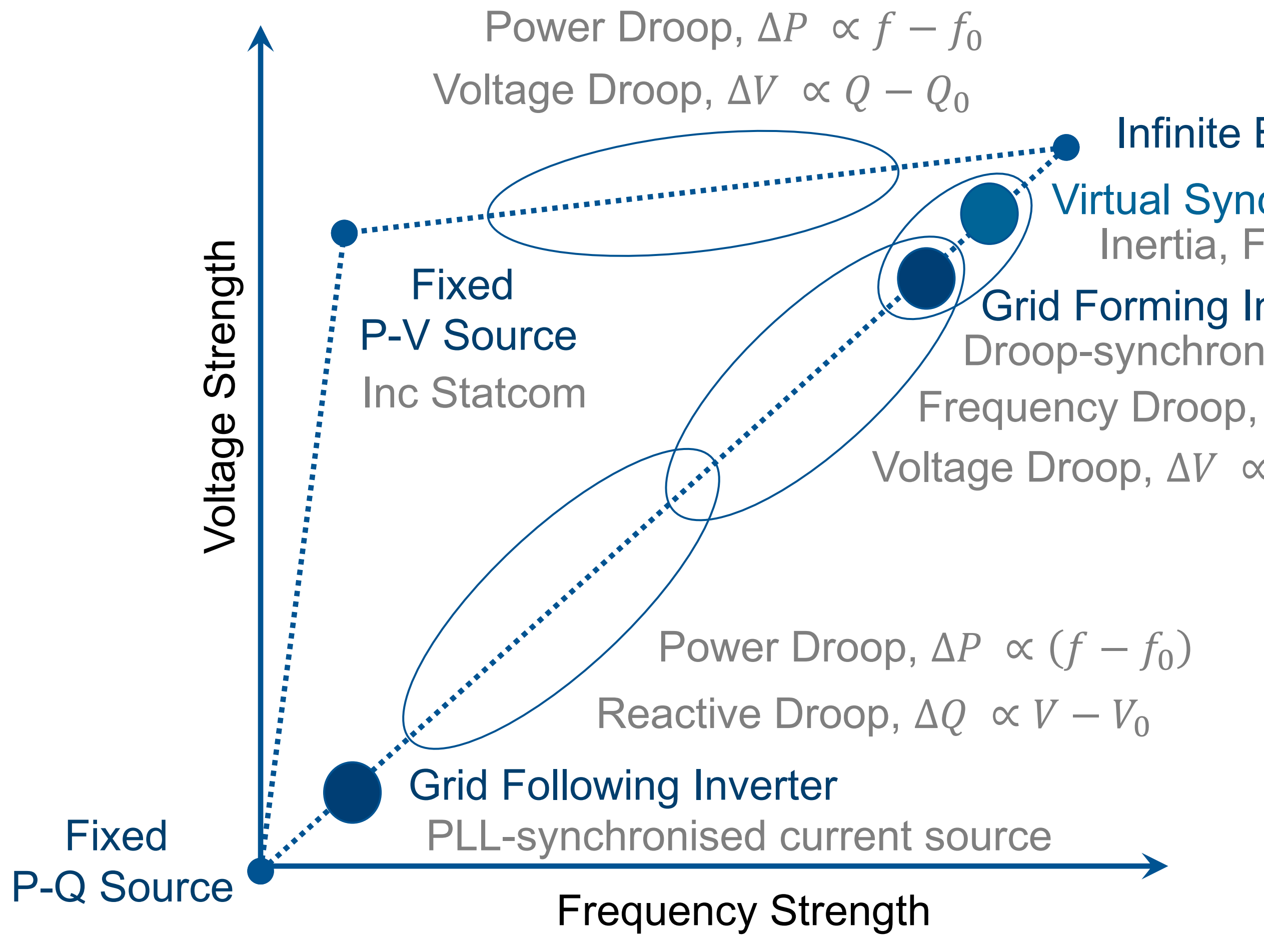
Grid-Forming and Grid-Following Inverters

- Emphasis on services, not just energy, means that the control arrangements of IBR need to change
- This is often expressed as IBR becoming Grid-Forming rather than Grid-Following

- Grid-following IBR
  - Synchronise to an existing AC grid voltage
  - Inject power according to their own needs (such as maximum power point operation)

- Grid-forming IBR
  - Create an AC voltage with frequency and magnitude that adjust to local conditions
  - Provide power according to grid conditions via droop characteristics
  - Contribute directly to frequency and voltage regulation

Two aspects of grid strength: GFM and GFL Context



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

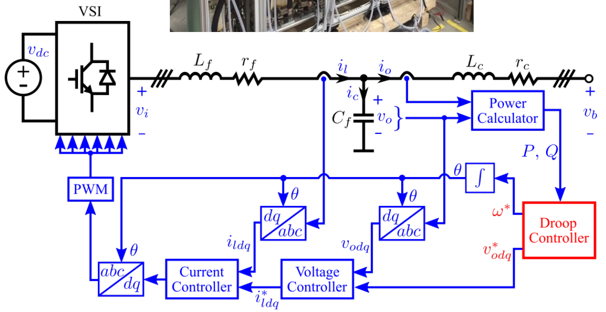
Some partial-GFM exist – providing voltage strength or frequency strength only.

Models and Tools for System Studies with IBR

- Synchronous machines have consistent physical form across scales and between manufacturers:
  - Models are open (white-box) in non-linear state-space format.
  - Models can also be used for eigenvalue analysis and participation factors can be used to find root-causes of instabilities.

$$\frac{d^2\delta}{dt^2} = \frac{p}{J}\left(T_{Mech} - \frac{E_S V_G}{\omega_{Rotor} X_S}\ sin(\delta) - D\,\frac{d\delta}{dt}\right)$$

- Inverters take very many forms with wide range of design choices in control loop format and tuning:
  - Inverter control systems are proprietary and are not disclosed.
  - Manufacturer's models are black-box as either binary code or impedance spectrum.
  - Models can also be used impedance stability test but further analysis is limited.



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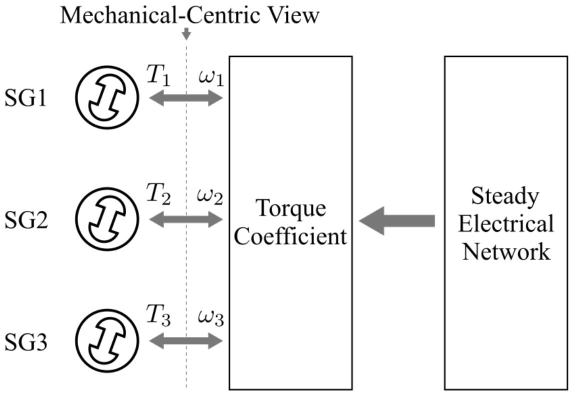
Framework for Combining Mechanical-Centric and Electrical-Centric Models

Mechanical-centric analysis arose because of dominance of synchronous machines.

Dynamics expressed in terms of torque-speed relationships.

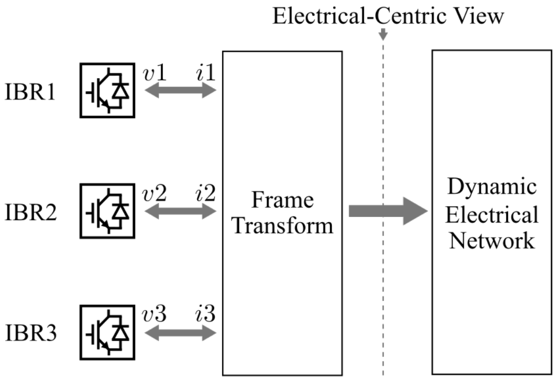
Electrical gird of static impedances.



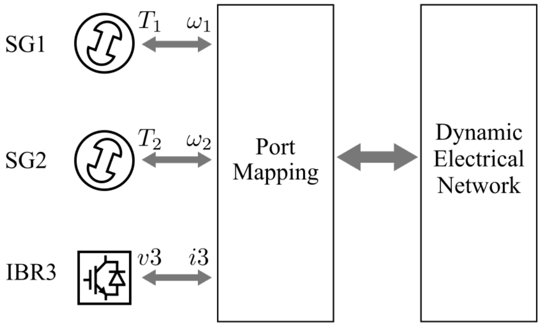
Electrical-centric analysis found in inverter-based microgrids.

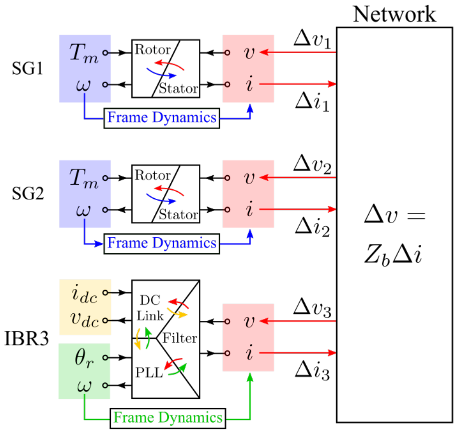
Dynamics expressed in terms of voltage-current relationships

Electrical gird of inductive/capacitive dynamics.



Mapping dynamics through ports can be used to form composite, unified system models.





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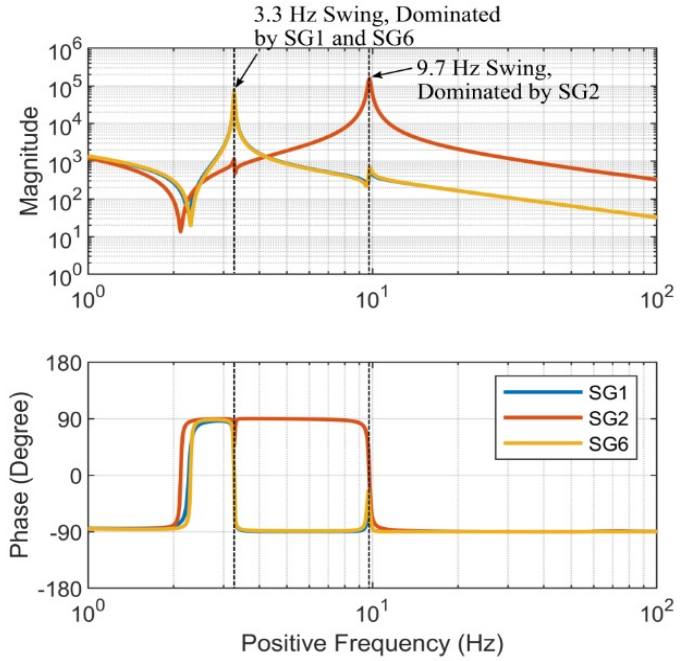
Impedance Analysis at Mechanical-Ports

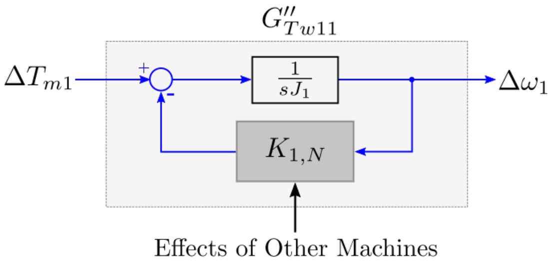
A port can be used to look at the interaction between a selected machine/inverter and the rest of the system.

Resonant peaks in mechanical transfer function from torque to speed reveal modes and indicate the participation.



Torque coefficient of each machine can can be found from element of transfer function matrix G''

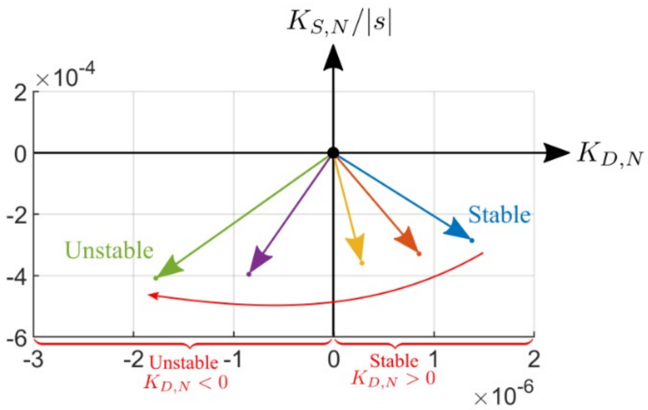
$$K_{1,N} = {G''_{T\omega 11}}^{-1} - sJ_1$$



Imaginary part of torque coefficient is synchronizing torque

Real part is damping torque

The sign of damping torque at the mode frequency indicates the stability



Yitong Li, Yunjie Gu, Tim Green, "Mapping of Dynamics between Mechanical and Electrical Ports in Generator-Inverter-Composite Power Systems", IEEE Trans Power Systems, Early Access.

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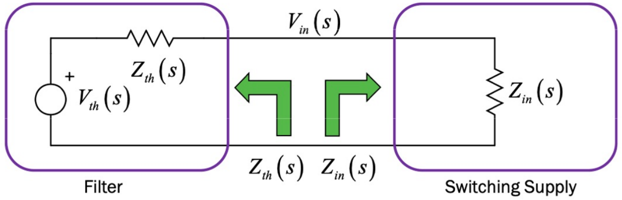
Whole-System Impedance Spectrum Methods

Original work by Middlebrook in 1970s was for DC/DC SMPS with source-side filter.

Established Nyquist-style criteria for stability based on output impedance and input admittance.



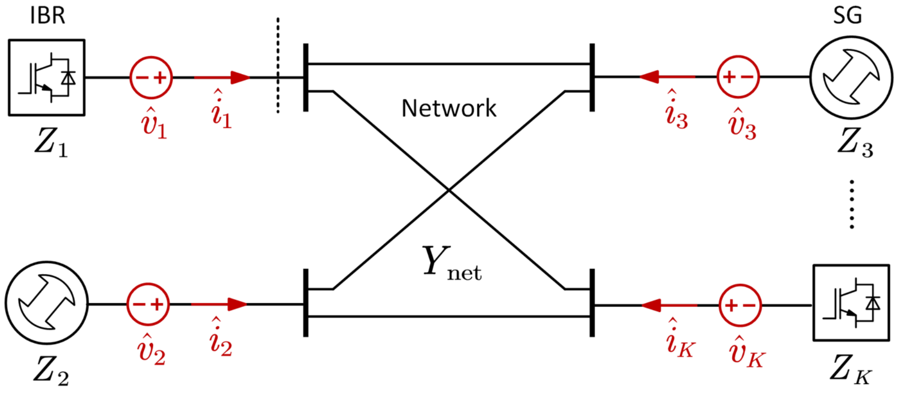
Input voltage of SMPS is

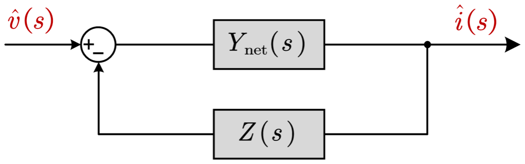
$$V_{in}(s) = V_{th}(s)\frac{1}{1+Z_{th}(s)Y_{in}(s)}$$

which is unstable if $Z_{th}(s)Y_{in}(s)$ encircles -1

This can be extended to AC grids but it is not realistic to partition the grid into sources and load.

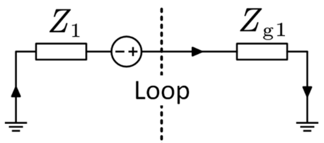
Instead of partition the grid between between impedance of equipment at nodes, $Z_n(s)$, and admittance of the network lines and cables, $Y_{net}(s)$.





We also define a "whole-system" admittance matrix mapping all voltages to all currents, $\hat{Y} = (I + Y_{net}\,Z)^{-1}\,Y_{net}$.

Diagonal terms like $\hat{Y}_{kk}$ relate voltage and current at same node, k, accounting for both the local equipment and all the rest of the network $\hat{Y}_{kk} = \left(Z_k + Z_{g\,k}\right)^{-1}$.



$\hat{Y}_{11} = (Z_1 + Z_{g1})^{-1}$

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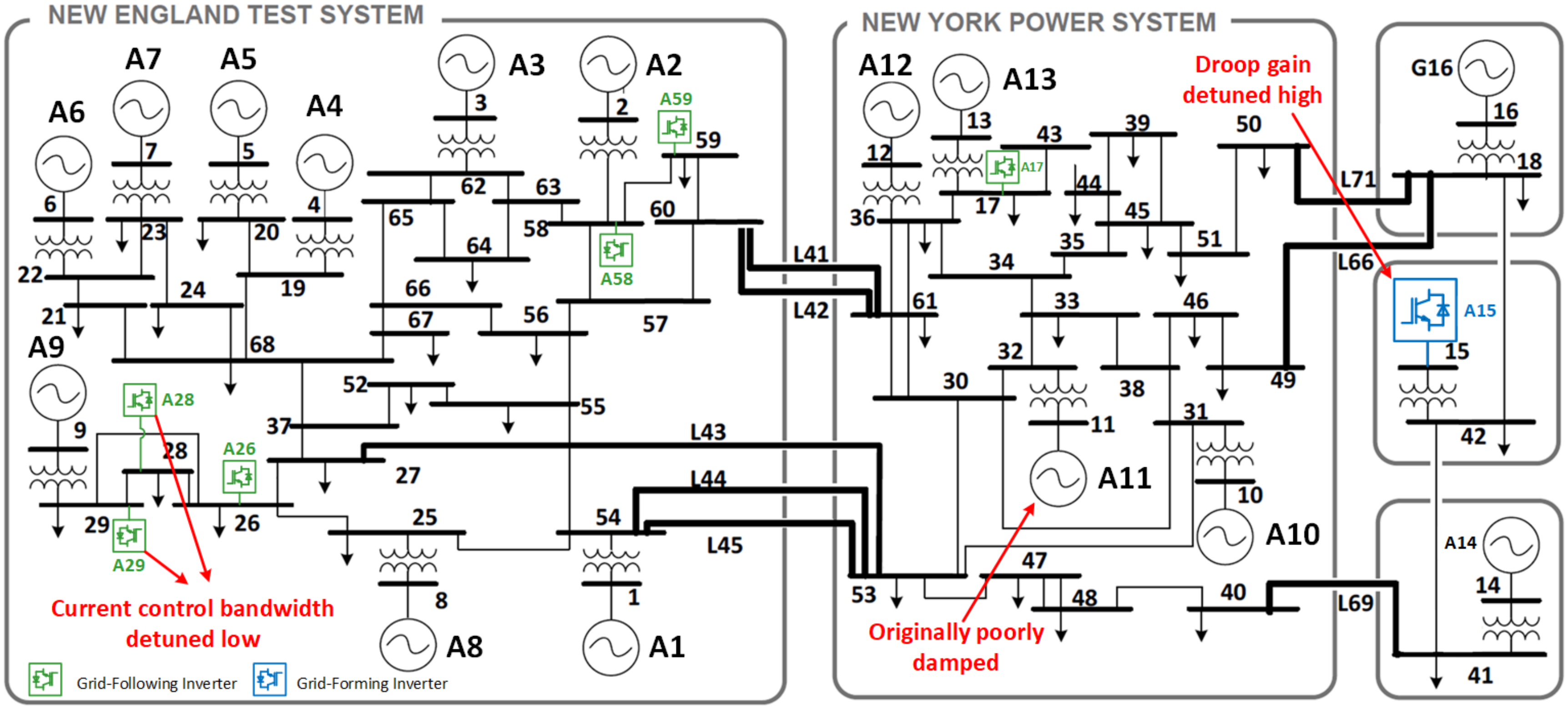
Illustration with modified NETS-NYPS

68 Buses, 16 SM (one poorly damped), 6 GFL-IBR, 1 GFM-IBR



Models and Toolbox at https://github.com/Future-Power-Networks/Publications

- Yunjie Gu, Yitong Li, Yue Zhu, Tim Green, "Impedance-Based Whole-System Modeling for a Composite Grid via Embedding of Frame Dynamics", IEEE Trans PS, 2021.
- Yue Zhu, Yunjie Gu, Yitong Li, Tim Green, "Participation Analysis in Impedance Models: The Grey-Box Approach for Power System Stability", IEEE Trans PS, 2021.

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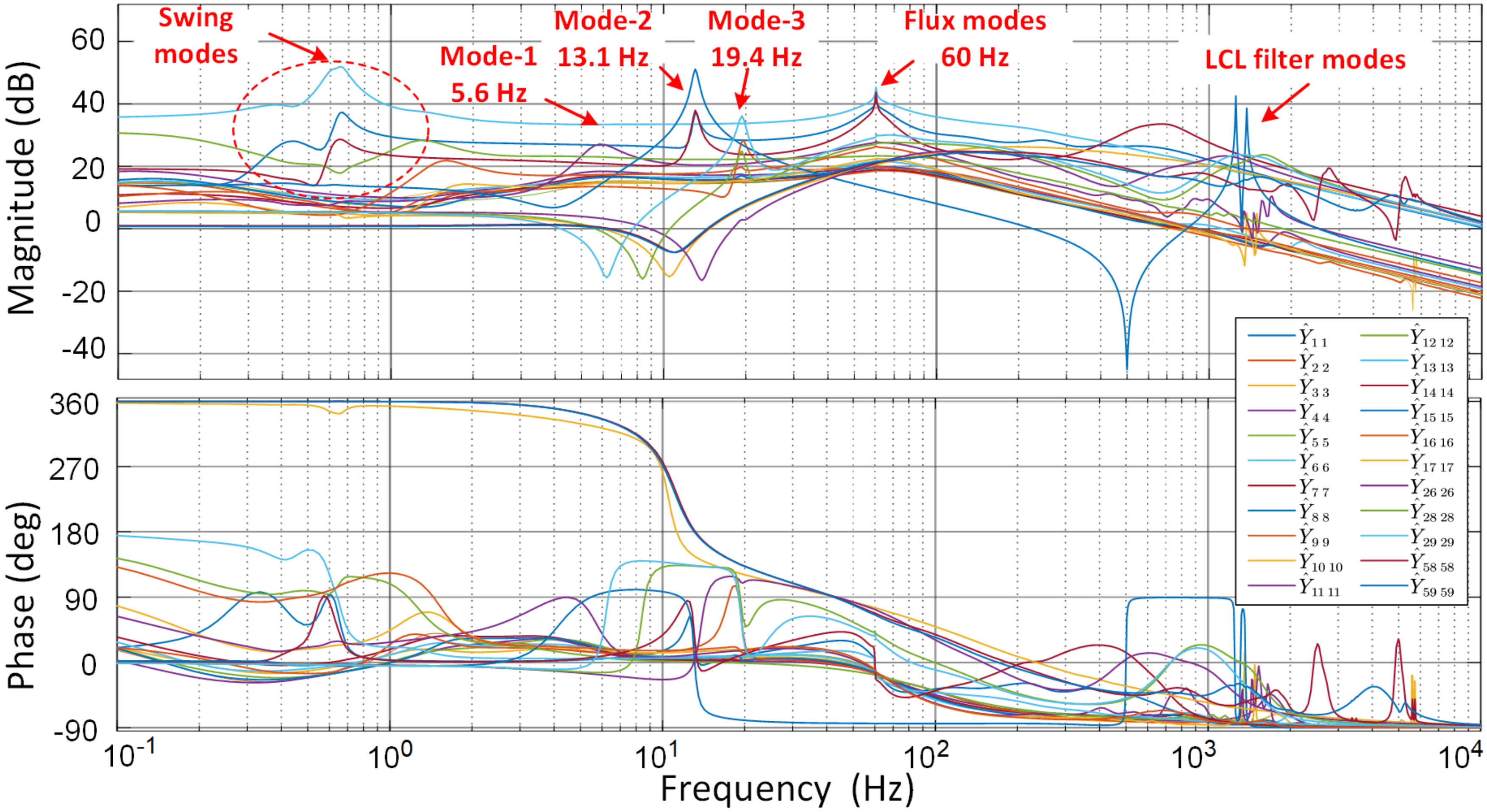
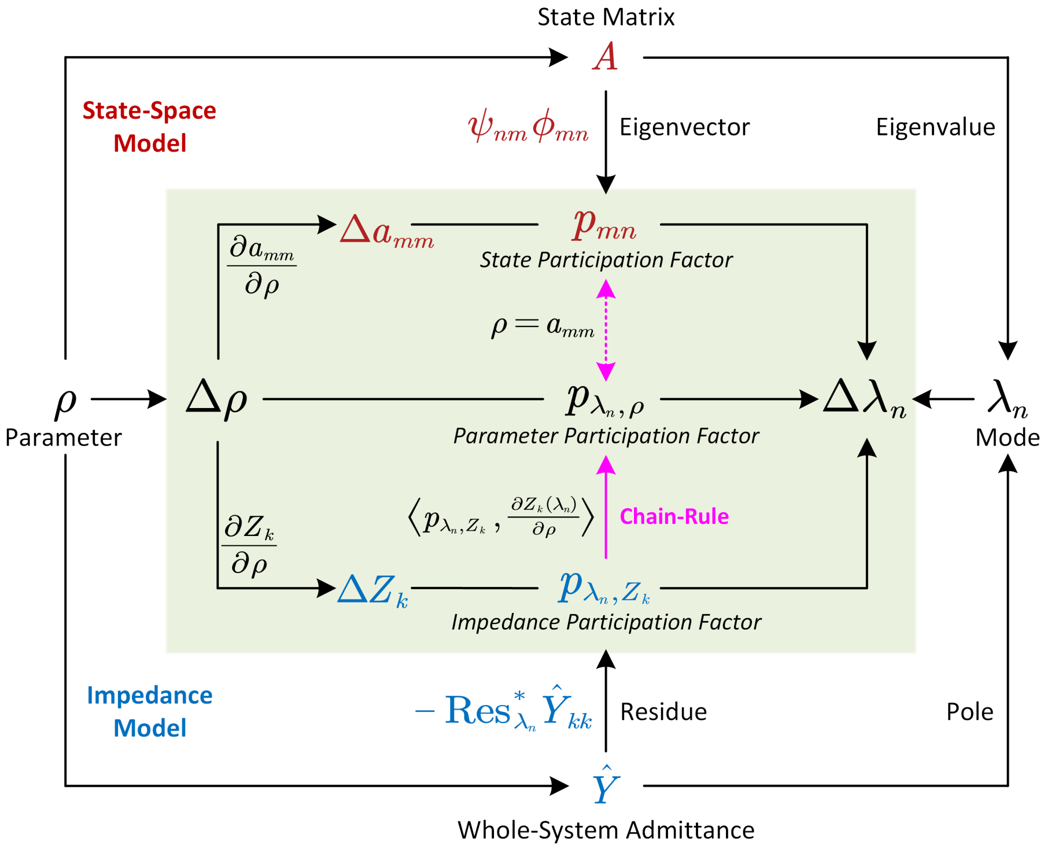
Identification of Modes in Elements of the Whole-System Admittance Matrix



Looking Inside a Black Box to Create Grey Box Participation Analysis



If you know the parameters, ρ, you can:

- Build the state-space matrix A
- Find the eigenvalues, λ, and identify poorly damped modes
- Find the participation factors, p_{mn}, and determine which states, n, participate in a given mode, m.
- Find the sensitivity of the mode to a parameter, $^{\partial\lambda}/_{\partial\rho}$, (parameter participation) and re-tune

If you only know the equipment and network impedances, you can numerically:

- Find modes, λ, by observation of impedance spectrum, $\hat{Y}_{kk}$,
- Find, numerically, the residues, Res, of the modes which are impedance participation factors, $p_{\lambda Z}$, (sensitivity of mode to changes in a given impedance, $^{\partial\lambda}/_{\partial Z}$)
- Use a chain-rule to identify sensitivity to a mode to a parameter, $^{\partial\lambda}/_{\partial\rho}$

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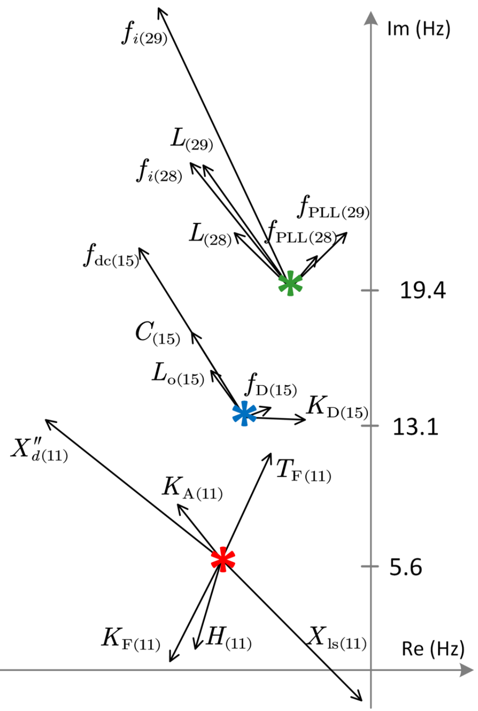
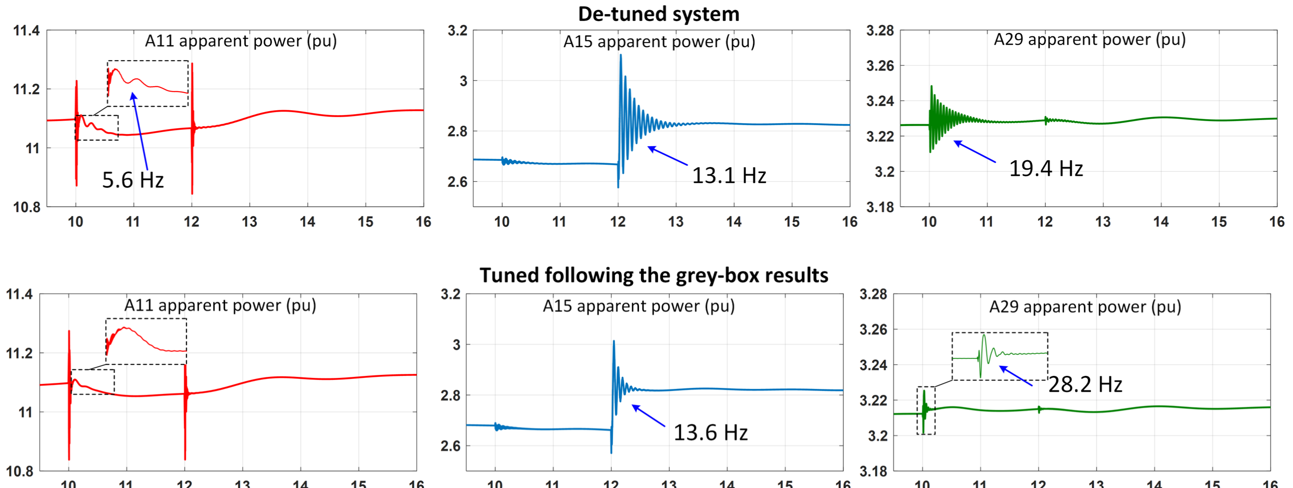
Tuning Via Parameter Participation

Layer-3: $\Delta\lambda \leftarrow \Delta\rho$

Mode-3 (19.4 Hz)	green *
Mode-2 (13.1 Hz)	blue *
Mode-1 (5.6 Hz)	red *

H	inertia
X''_d	*d*-axis sub-transient reactance
X_{ls}	armature leakage reactance
K_{F}	AVR feedback gain
T_{F}	AVR feedback time constant
K_{A}	AVR dc regulator gain
C	filter capacitor
L	filter inductor
L_{o}	output inductor (*LCL*)
K_{D}	frequency droop gain
f_{D}	droop control bandwidth
f_{PLL}	PLL bandwidth
f_{dc}	dc-link control bandwidth
f_i	current control bandwidth





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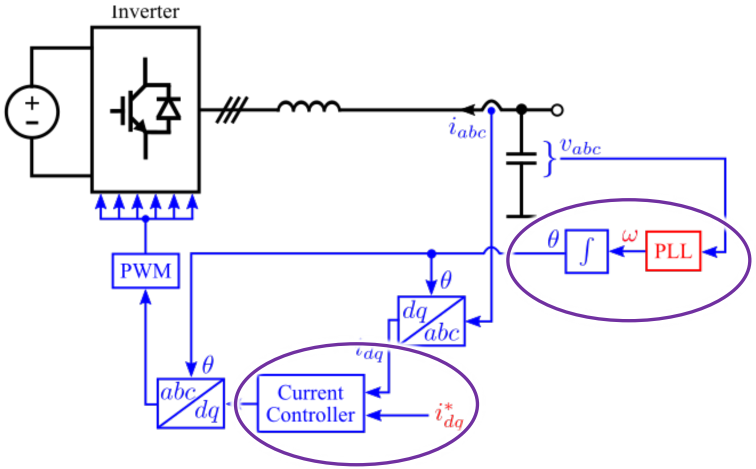
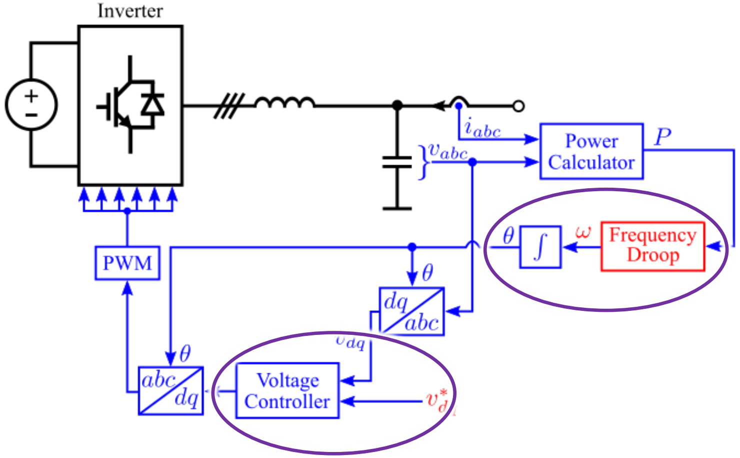
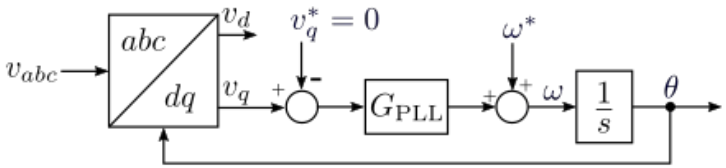
Dynamics of Grid Following and Grid Forming Inverters





Grid Following (GFL)

- Inverter is controlled as a current source
- Frequency set by phase-locking to existing grid

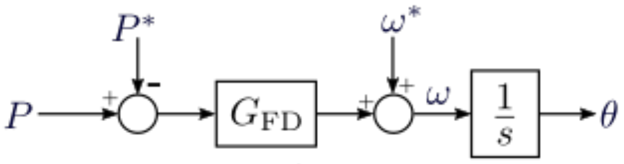


$Q = v_q\, i_d \;- v_d\, i_q$

If i_d constant and $i_q = 0$ then $v_q \propto Q$

Grid Forming (GFM)

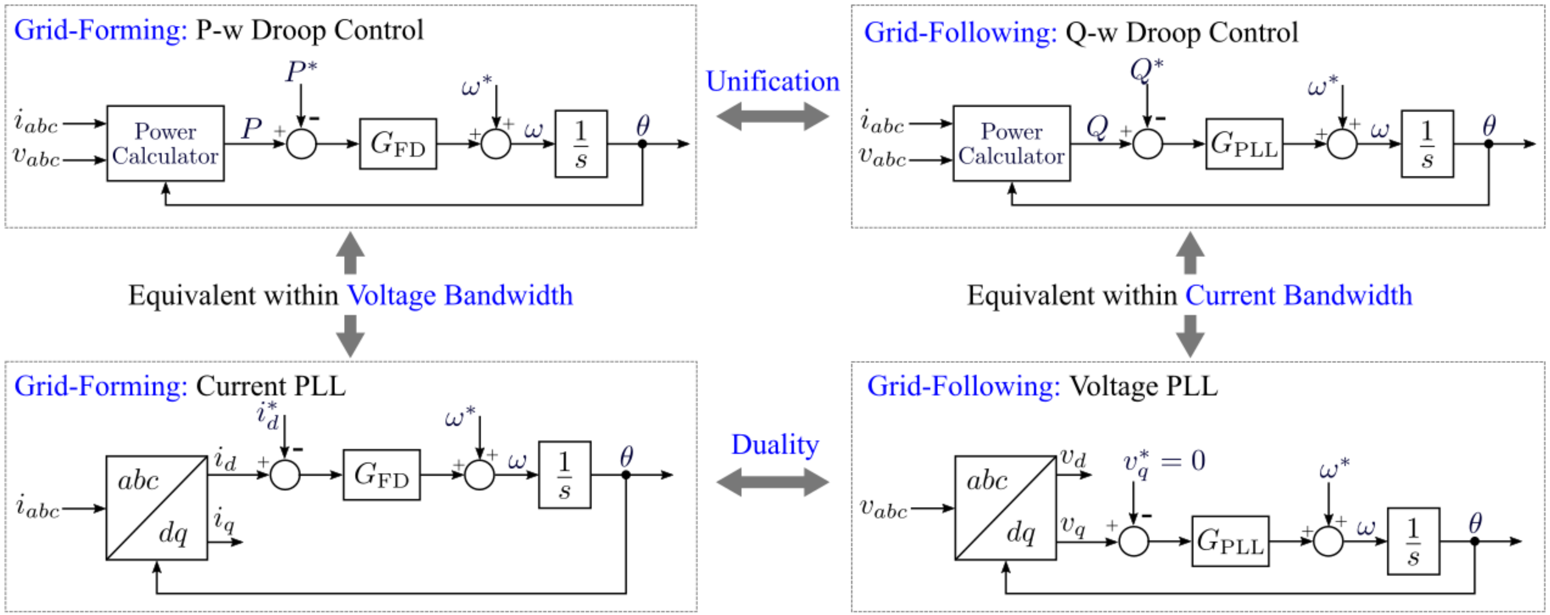
- Inverter is controlled as a voltage source
- Frequency set by droop function of exported power



$P = v_d\, i_d \;+ v_q\, i_q$

If v_d constant and $v_q = 0$ then $P \propto i_d$

A New Perspective on Inverter Dynamics: GFM-GFL Duality Theory



GFM

- Forms grid voltage
- Follows grid current
- $P - \omega$ droop or i_d PLL
- $P - \delta$ or $I - \delta$ swing

GFL

- Forms grid current
- Follows grid voltage
- v_q PLL or $Q - \omega$ droop
- $V - \delta$ or $Q - \delta$ swing

GFMs and GFLs are not so different, if seen as duals of each other

Yitong Li, Yunjie Gu, Tim Green, “Revisiting Grid-Forming and Grid-Following Inverters: A Duality Theory”, IEEE Trans Power Systems, 2022.

Duality of Stability

Small-Signal Stability

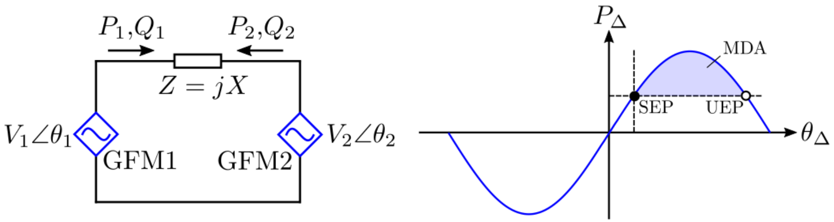
Interactions occur between grid impedance, synchronization control (droop or PLL), inner-loop control (voltage or current).

Inverters become unstable when:

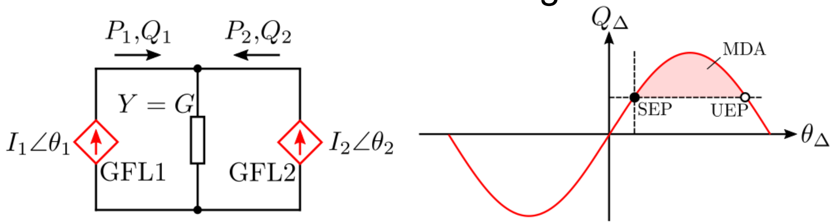
GFL
- Weak grid
- (high grid impedance)
- Large PLL bandwidth
- Low current bandwidth
- High current bandwidth

GFM
- Strong grid
- (low grid impedance)
- Low droop bandwidth
- Low voltage bandwidth
- High voltage bandwidth

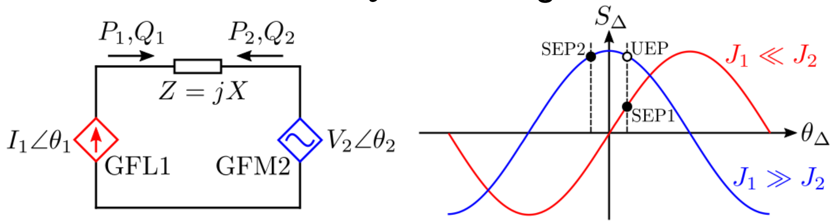
Large-Signal (Transient) Stability



GFM: $P - \delta$ swing



GFL: $Q - \delta$ swing



GFM-GFL: Dynamics are dominated by inertias

Yitong Li, Yunjie Gu, Tim Green, "Revisiting Grid-Forming and Grid-Following Inverters: A Duality Theory", IEEE Trans Power Systems, 2022.

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IBR Dominated Grids: Summary

System Services/Needs in an IBR World

- System needs should be described in technology neutral way so that IBR and Synchronous Machines can contribute
- Not all IBR will be able to provide all services
- Services should be defined with minimum system cost as the objective
- GFM and GFL have many flavours and are more similar than the binary debate allows
- Guidelines for service configurations needed (grid strength, droop settings, damping)

Tools/Models in an IBR World

- We need to analyse and synthesise (avoid trial-and-error synthesis)
- Black-box IBR models can be turned into Grey-box and root cause analysis of small-signal stability performed
- Duality between GFM and GFL may help understand how to achieve stability of mixed grids
- Tools are need to identify how much grid forming is needed for frequency stability, voltage stability etc.