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Challenges of running a national electricity system with a high penetration of inverter-interfaced resource

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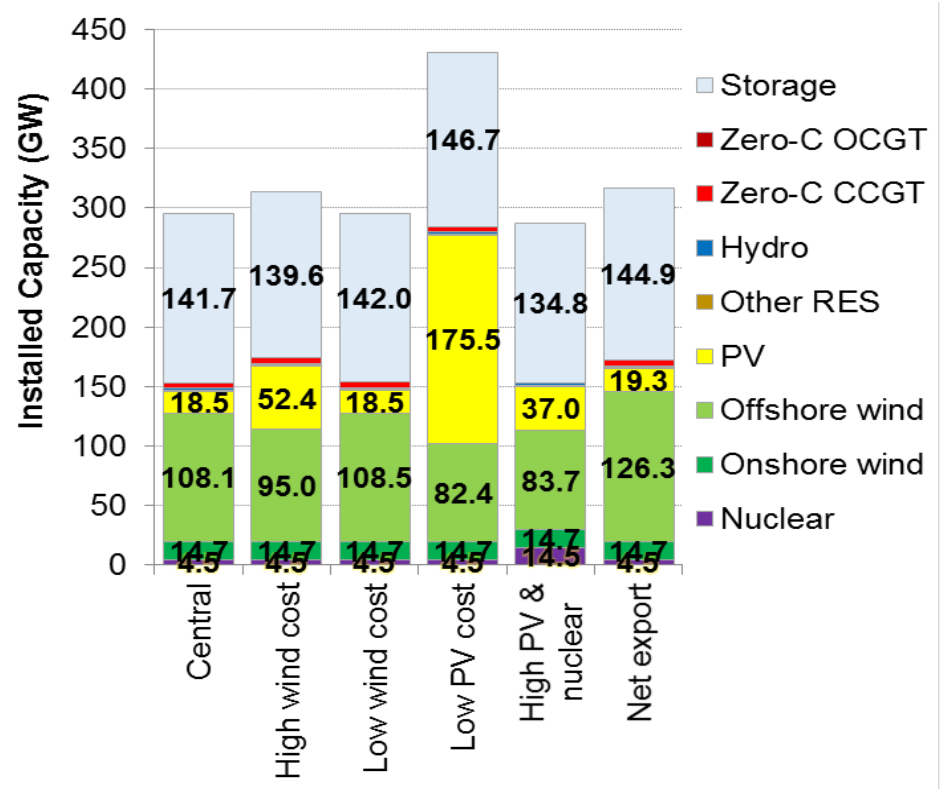
Centre for Power Electronics, July 2021

Generation Mix and Service Provision

GB Generation Mix for Net-Zero at 2035

System dominated by offshore wind (~100 GW) and battery storage (~140 GW / ~280 GWh) with some nuclear (4.5 GW) and occasional use of hydrogen back-up.



- Presence of some nuclear and hydrogen/biogas OCGT means that this is still a synchronous system
- Wind (on- and off-shore) not only provides most of the energy but will need to provide wide variety of “services” that regulate and control grid operation
- Batteries can provide services needing short-term energy (frequency regulation, system adequacy at peak etc.)
- Some network equipment, like Statcoms, needed for localised voltage regulation and other services
- Not all resources need to provide all services, only a subset of resources. Today, not all synchronous machines provide governor, excitor and black-start services but they all inherently provide inertia and fault current.

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

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

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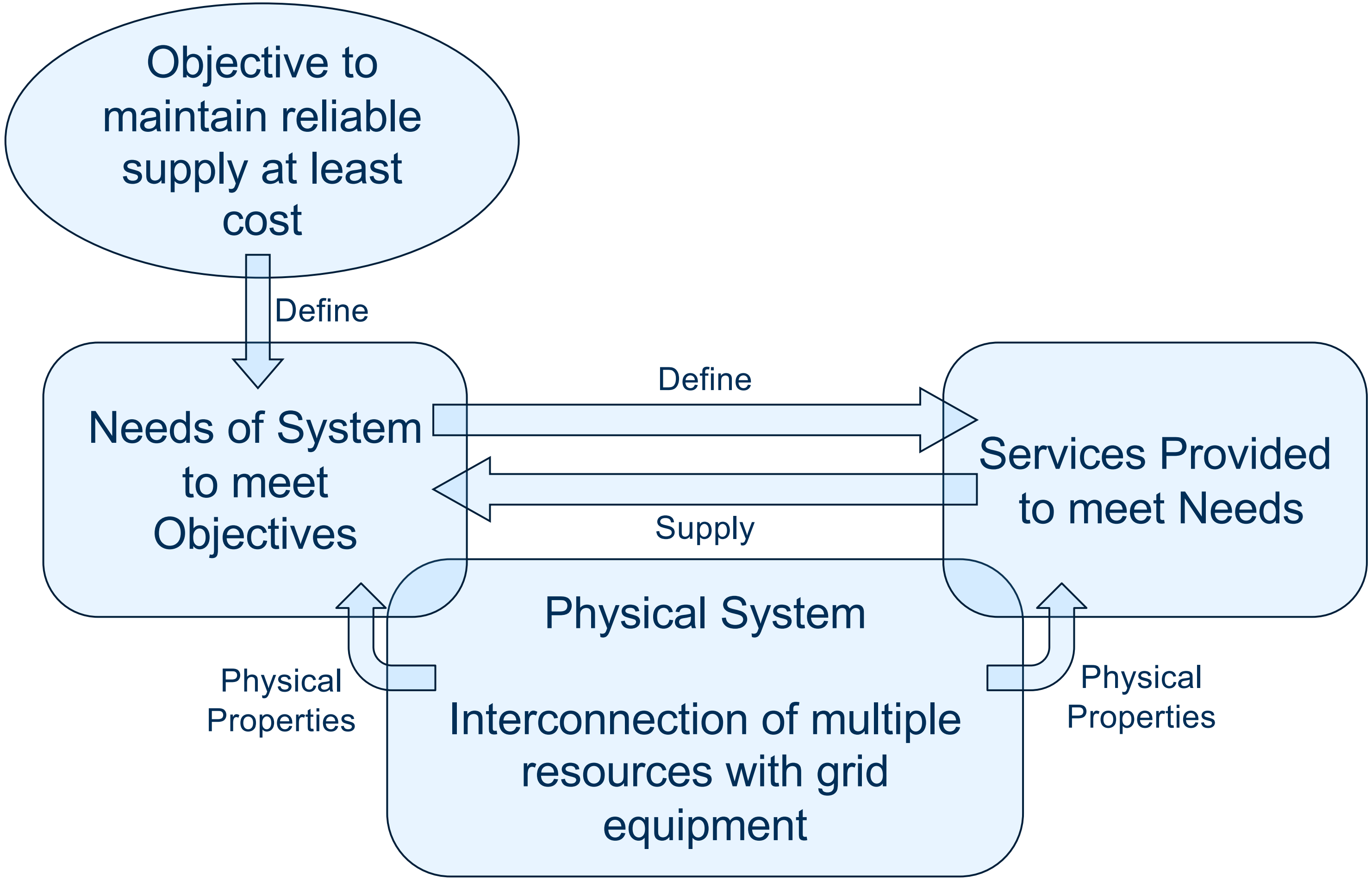
Working Group on System Needs and Services
(Global Power Systems Transformation Consortium)

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?"



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

Example System Need – Synchronising Torque

Need	**Synchronisation and Angle:** **Synchronising Torque**
Importance / Consequence if Unmet	Need is to support synchronisation of SM and GFM-IBR. Existing fleet of rotating machines are coupled to each other through the swing equations that relate acceleration of machine rotors to exchange of power through the network driven by angle differences between machine rotors. The flow of power that tends to close angle difference and maintain synchronism is known as the synchronising power or synchronising torque. Grid-forming inverters synchronising through a governor-like frequency droop have a broadly similar need for synchronising power or torque.
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 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	

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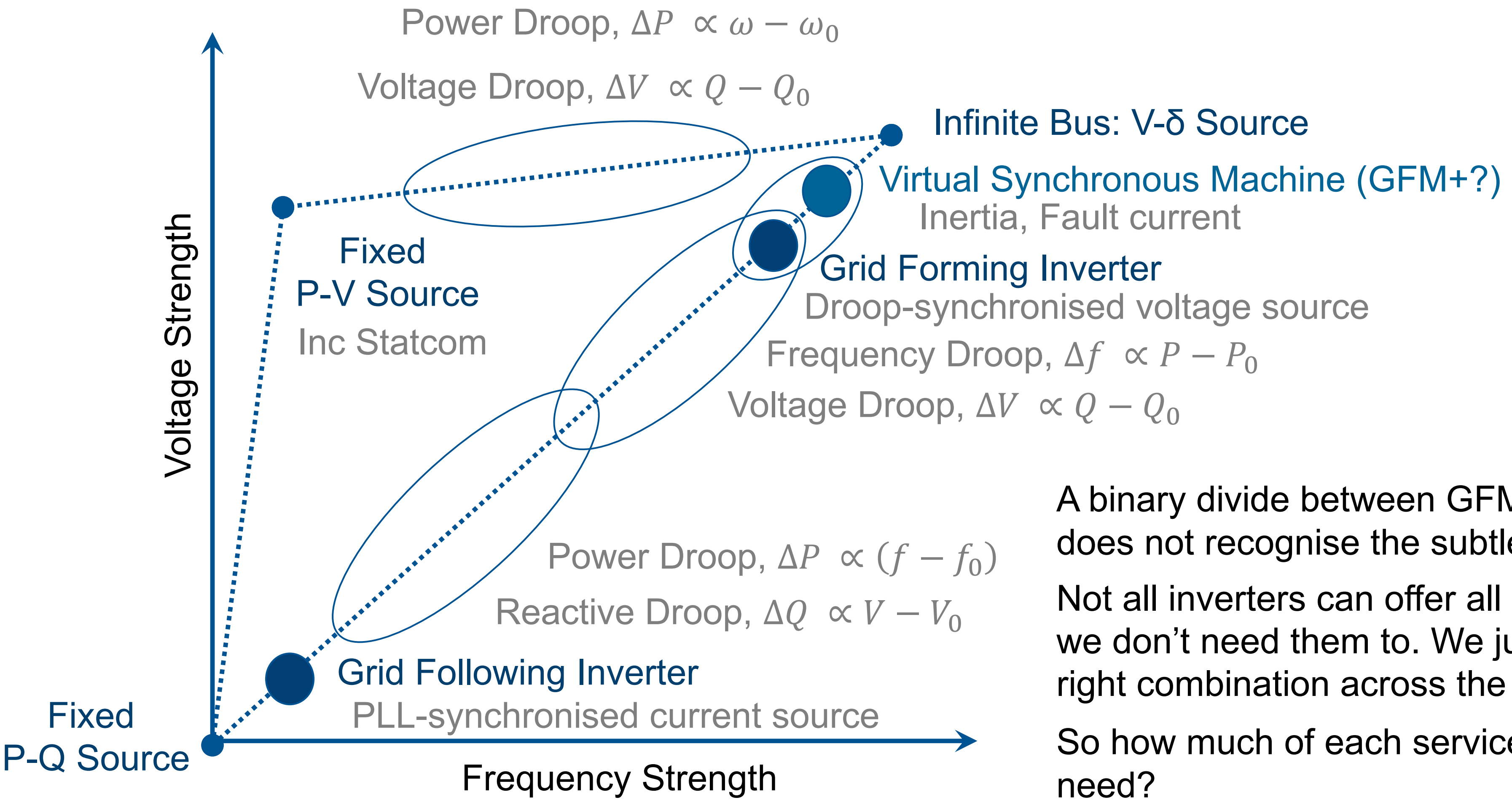
Grid-Forming and Grid-Following Inverters

- 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 not merely 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)
  - May have some basic services (reactive power at fixed power factor, reactive current injection into faults

- 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
  - Additional services should be provided to meet full range of grid needs

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

Grid Forming Inverter
Droop-synchronised voltage source

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

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

Fixed
P-V Source
Inc Statcom

Voltage Strength

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

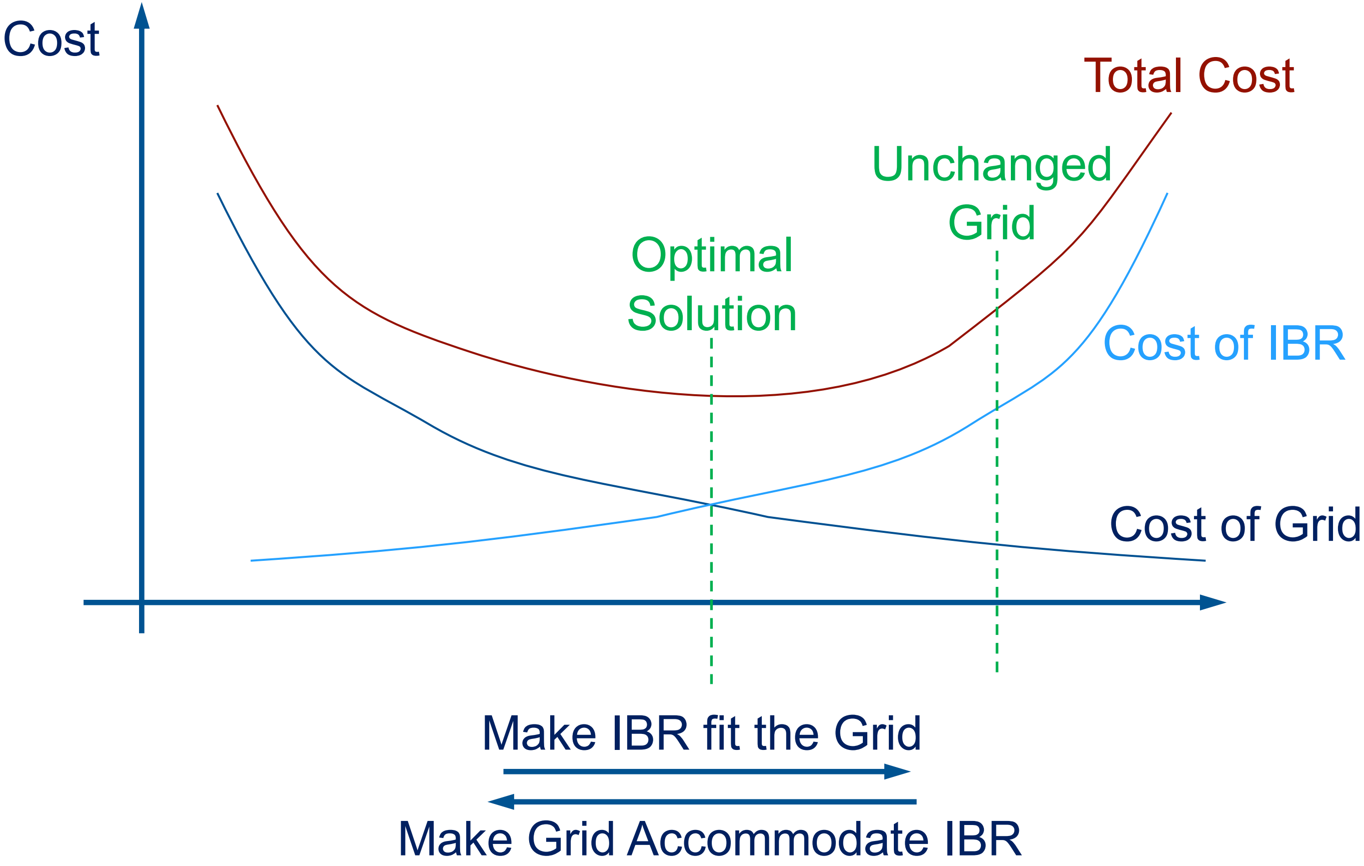
Frequency Strength

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.

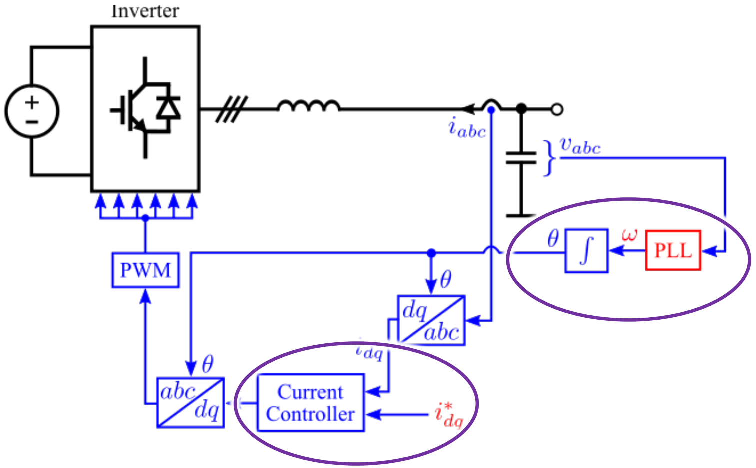
So how much of each service does a grid need?

Balancing Costs of Compatibility



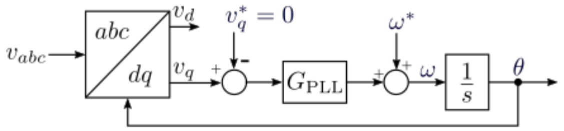
The control and operation of IBR dominated grids demands some new and deep thinking from people who understand power electronics and grids.

Grid Following and Grid Forming Inverters



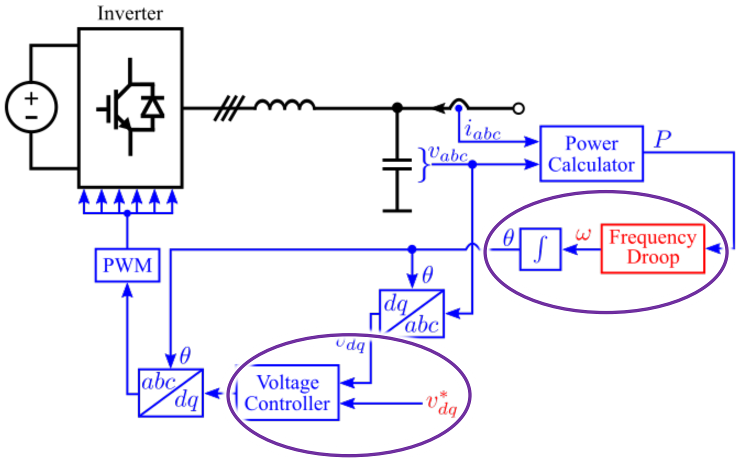
Grid Following (GFL)

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



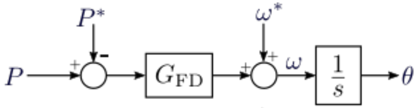
$Q = v_q\, i_d \; - v_d\, i_q$

If i_d is constant and $i_q = 0$



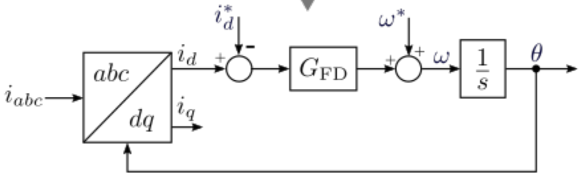
Grid Forming (GFM)

- 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 is constant and $v_q = 0$



Yitong Li, Yunjie Gu, Tim C Green, "Rethinking Grid-Forming and Grid-Following Inverters: The Duality Theory", https://arxiv.org/abs/2105.13094

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GFL and GFM Characteristics

View Point	Grid Following	Gird Forming
Synchronisation	Lock to voltage by adjusting internal frequency to close observed phase error	Adjust instantaneous frequency in response to observed power flow (frequency droop)
Voltage & Current Characteristics	**Follow voltage** via PLL **Form current** according to power reference	**Form voltage** according to V & f references **Follow current** via P and Q droop
Power Regulation	Power follows "prime mover" (dispatched or variable) Possible addition of P/f droop and prime mover adjustment	Power follows network loads "Prime mover" must follow inverter
Dynamics of synchronisation angle	$V-\delta$ or $Q-\delta$ swing	$I-\delta$ or $P-\delta$ swing

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 be used for time-domain simulation – EMT or Phasor.
  - Models can also be used for eigenvalue analysis and participation factors can be used to find root-causes of instabilities.

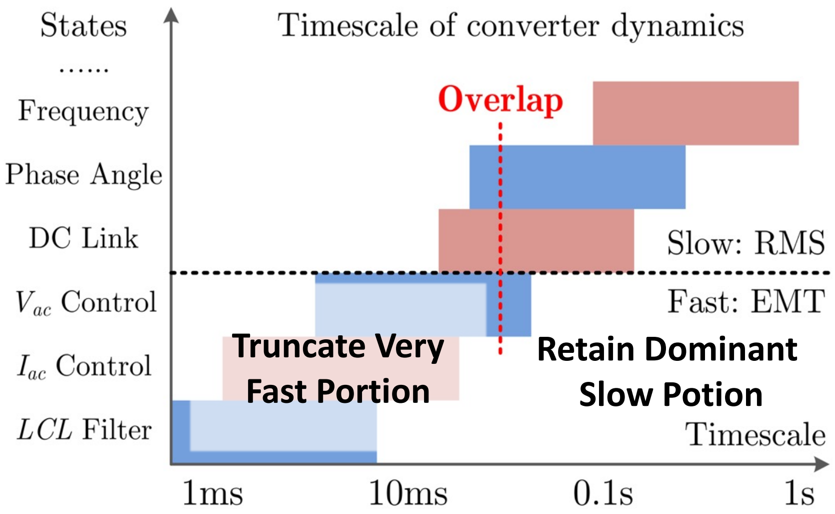
- Inverters take very many forms with wide range of design choices in control loop format and tuning:
  - Inverter control systems are proprietary and are not disclosed.
  - Manufacturer’s models are black-box as either binary code or impedance spectrum.
  - Models can be used for time-domain simulation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

Model Order Reduction for State-Space Analysis

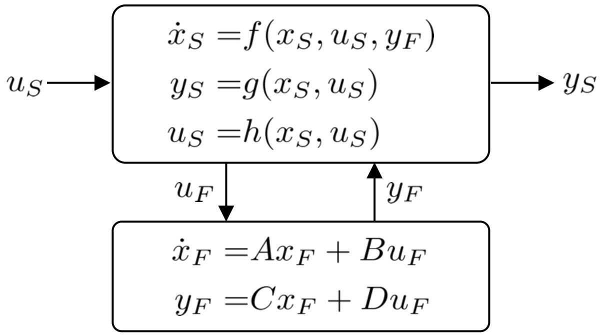
In a synchronous machine, the dynamics of governor, electromechanical modes and damper windings happen in well-separate timeframes.

Experience has taught us that not all elements need to be present in particular types of study.

In an inverter, the modes of various control-loops are in overlapping timeframes and simply leaving a feature out of consideration breaks the coupling.



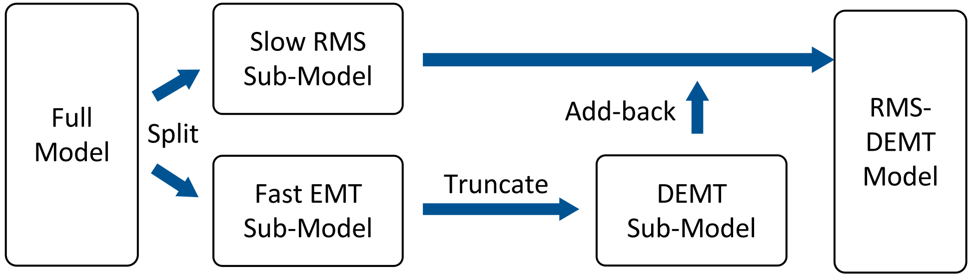
Slow (& Nonlinear)



$$\dot{x}_S = f(x_S, u_S, y_F)$$
$$y_S = g(x_S, u_S)$$
$$u_S = h(x_S, u_S)$$

$$\dot{x}_F = Ax_F + Bu_F$$
$$y_F = Cx_F + Du_F$$

Fast (& Linear)

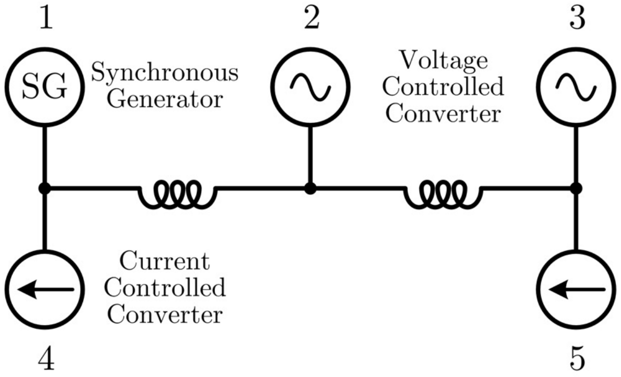


Solution is to identify the Dominant part of the EMT dynamics and combine this with an RMS model

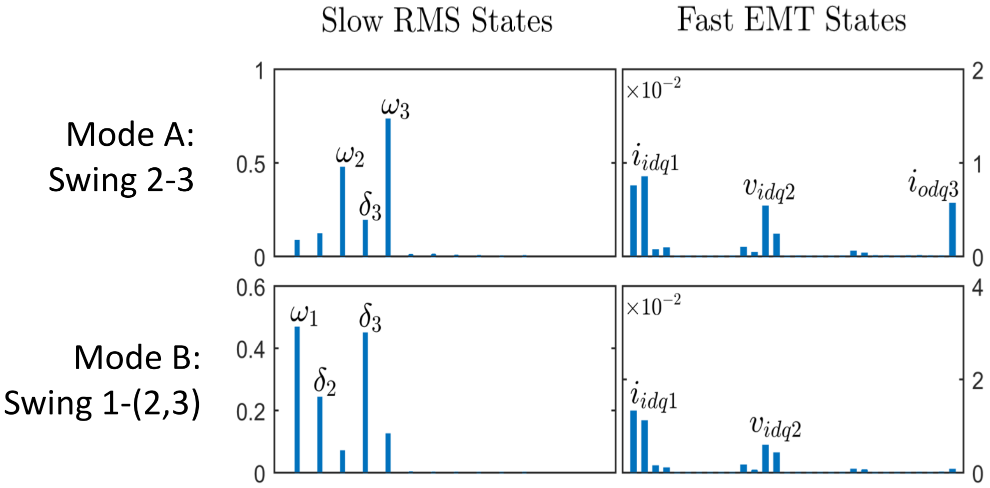
Y. Gu, N. Bottrell, T. C. Green, Reduced-Order Models for Representing Converters in Power System Studies, IEEE Trans PELS, 2017

Reduced IBR Models in Multi-Machine Interaction Study

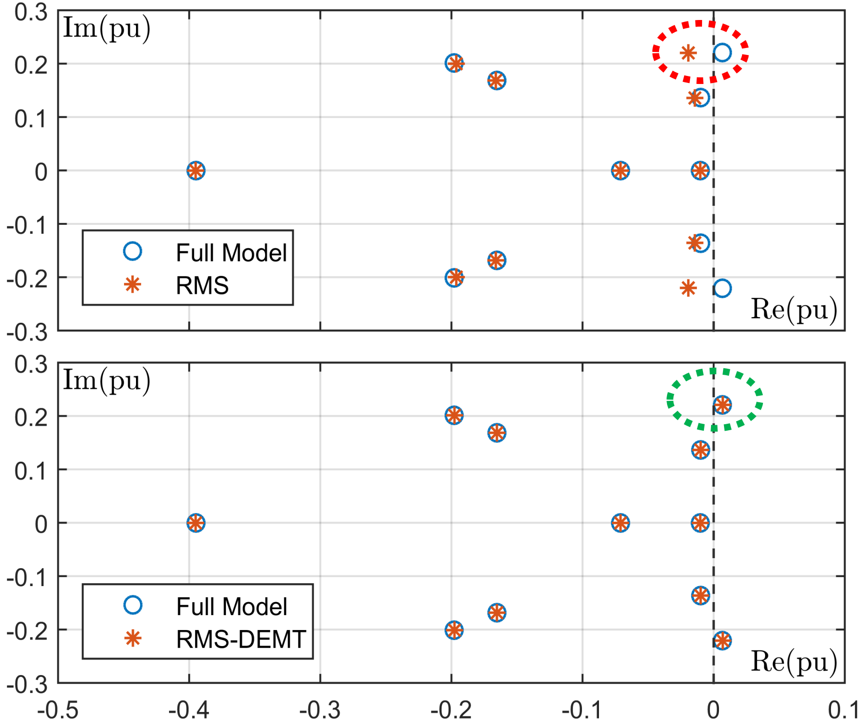
Unstable test system with large droop gain



Participation-factor analysis shows role of current-loop states



RMS model alone appears stable

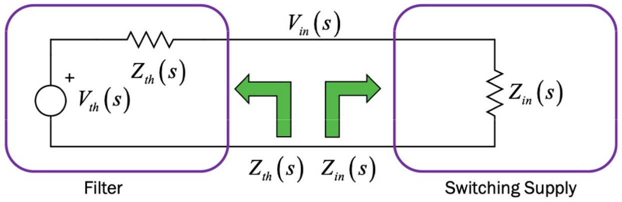


RMS + Dominant EMT correctly shows unstable mode

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.



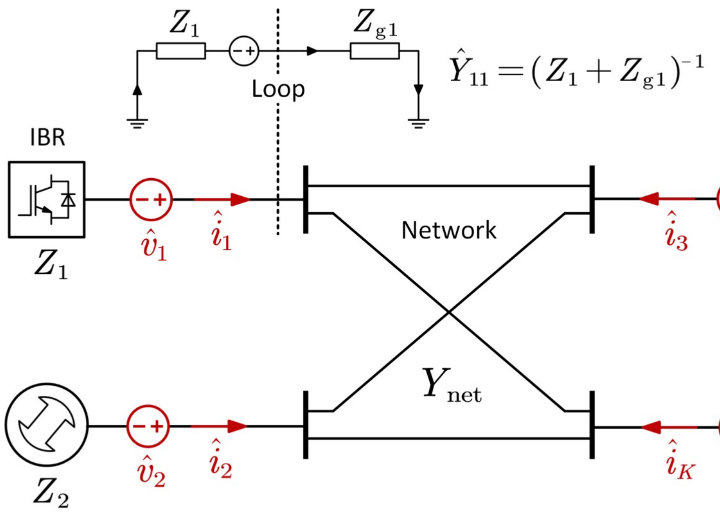
Input voltage of SMPS is

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

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

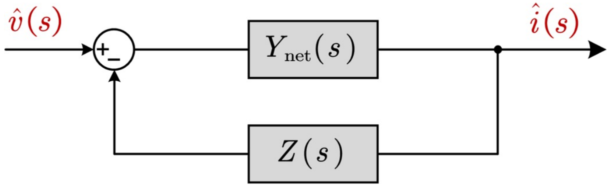
This can be extended to AC grids but it is not realistic to partition the grid into sources and load.

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 $\hat{Y}_{kk} = \left(Z_k + Z_{g\,k}\right)^{-1}$.



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Representing Inverter Controls as a Source behind an Impedance

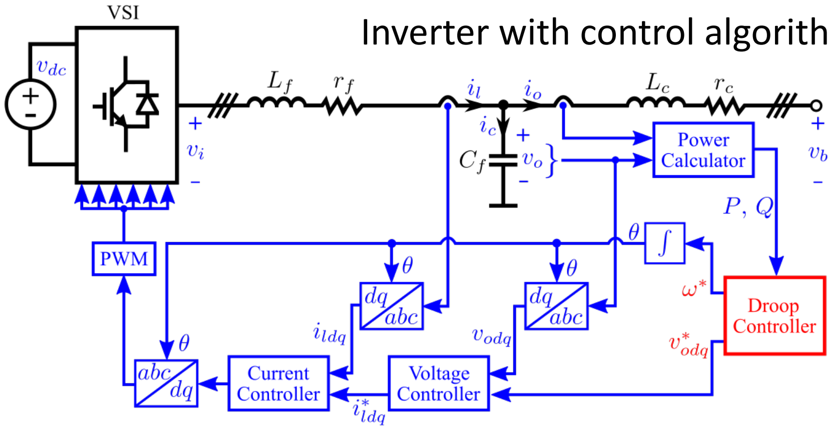
An inverter has:

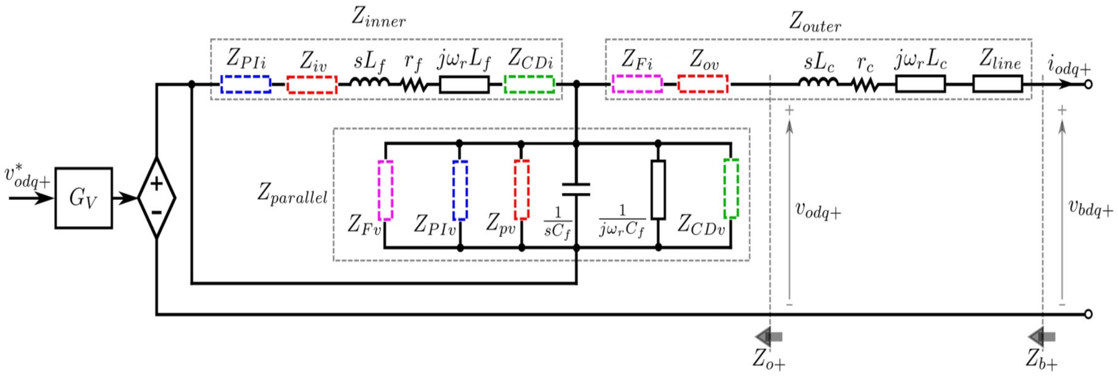
- Physical resistance, inductance, capacitance,
- Variation of voltage with current because of imperfect inner control loops
- Deliberate droop of voltage with reactive power
- Deliberate droop of frequency with real power

Each property can be expressed as a relationship between voltage and current.

Virtual Impedance	$Z_{iv} = (R_{iv} + jX_{iv})G_{del}$ $Z_{pv} = \frac{(R_{pv}//jX_{pv})}{G_I}$ $Z_{ov} = (R_{ev} + jX_{ev})G_V$
PI Controller	$Z_{PIi} = PI_i G_{del} = (K_{pi} + \frac{K_{ii}}{s})G_{del} = (K_{pi} + \frac{1}{s\frac{1}{K_{ii}}})G_{del}$ $Z_{PIv} = \frac{1}{PI_v G_I} = \frac{1}{(K_{pi}+\frac{K_{iv}}{s})G_I} = \frac{(\frac{1}{K_{pv}}//s\frac{1}{K_{iv}})}{G_I}$
Cross Decoupling	$Z_{CDi} = -j\omega_0 L_f G_{del}$ $Z_{CDv} = \frac{1}{-j\omega_0 C_f G_I}$
Feedforward	$Z_{Fv} = -\frac{Z_{inner}}{F_v G_{del}}$ $Z_{Fi} = -(Z_{inner}//Z_{parallel})F_i G_I$
Loop Gain & Delay	$G_{del} = e^{-1.5T_s s}$ $G_I = \frac{Z_{PIi}}{Z_{inner}}$ $G_V = \frac{Z_{inner}//Z_{parallel}}{Z_{PIv}}$

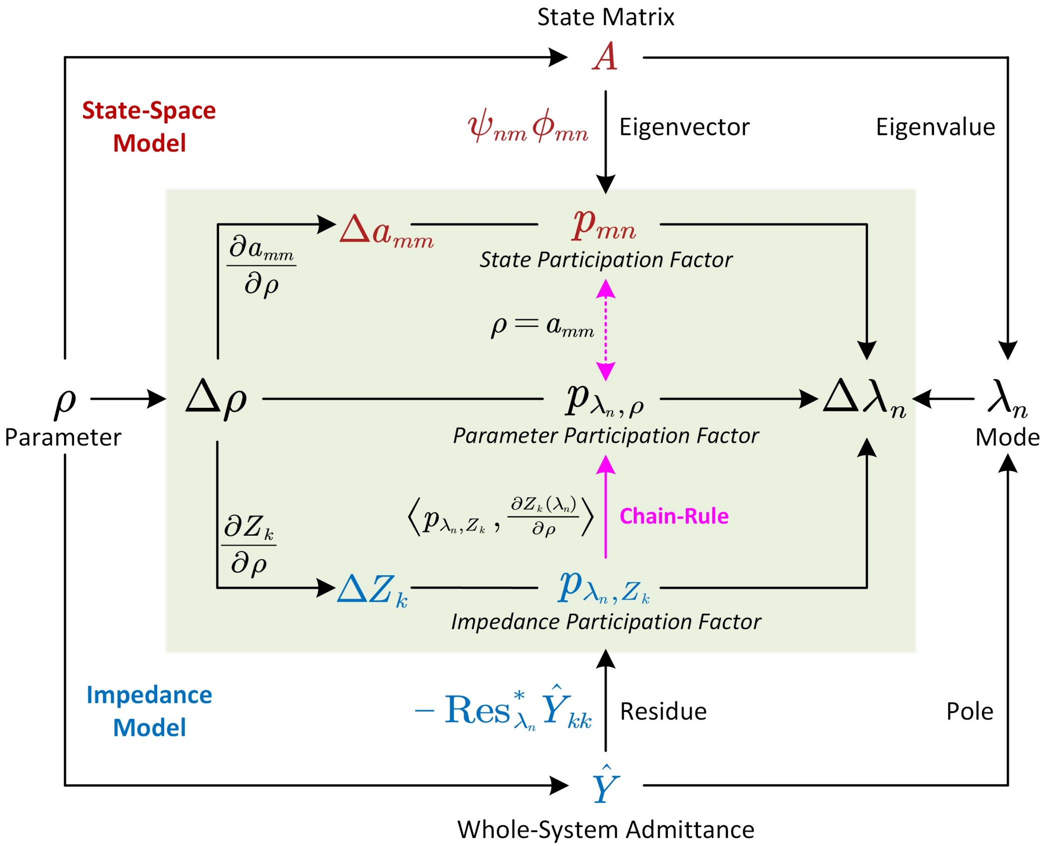
Inverter with control algorithms ⇨ Impedance circuit model





Yitong Li, Yunjie Gu, Yue Zhu, Adria Junyent-Ferre, Xin Xiang, Tim Green, “Impedance Circuit Model of Grid-Forming Inverter: Visualizing Control Algorithms as Circuit Elements,” IEEE Trans PELS, 2021.

Looking Inside a Black-Box to Create Grey-Box Participation Analysis



State Matrix

A

State-Space Model

$\psi_{nm}\phi_{mn}$ Eigenvector

Eigenvalue

Δa_{mm} p_{mn}

State Participation Factor

$\frac{\partial a_{mm}}{\partial \rho}$

$\rho = a_{mm}$

ρ $\Delta\rho$ $p_{\lambda_n,\rho}$ $\Delta\lambda_n$ λ_n

Parameter

Parameter Participation Factor

Mode

$\frac{\partial Z_k}{\partial \rho}$

$\left\langle p_{\lambda_n,Z_k}, \frac{\partial Z_k(\lambda_n)}{\partial \rho} \right\rangle$ **Chain-Rule**

ΔZ_k p_{λ_n,Z_k}

Impedance Participation Factor

Impedance Model

$-\mathrm{Res}^*_{\lambda_n}\hat{Y}_{kk}$ Residue

Pole

$\hat{Y}$

Whole-System Admittance

If you know the parameters, ρ, you can:

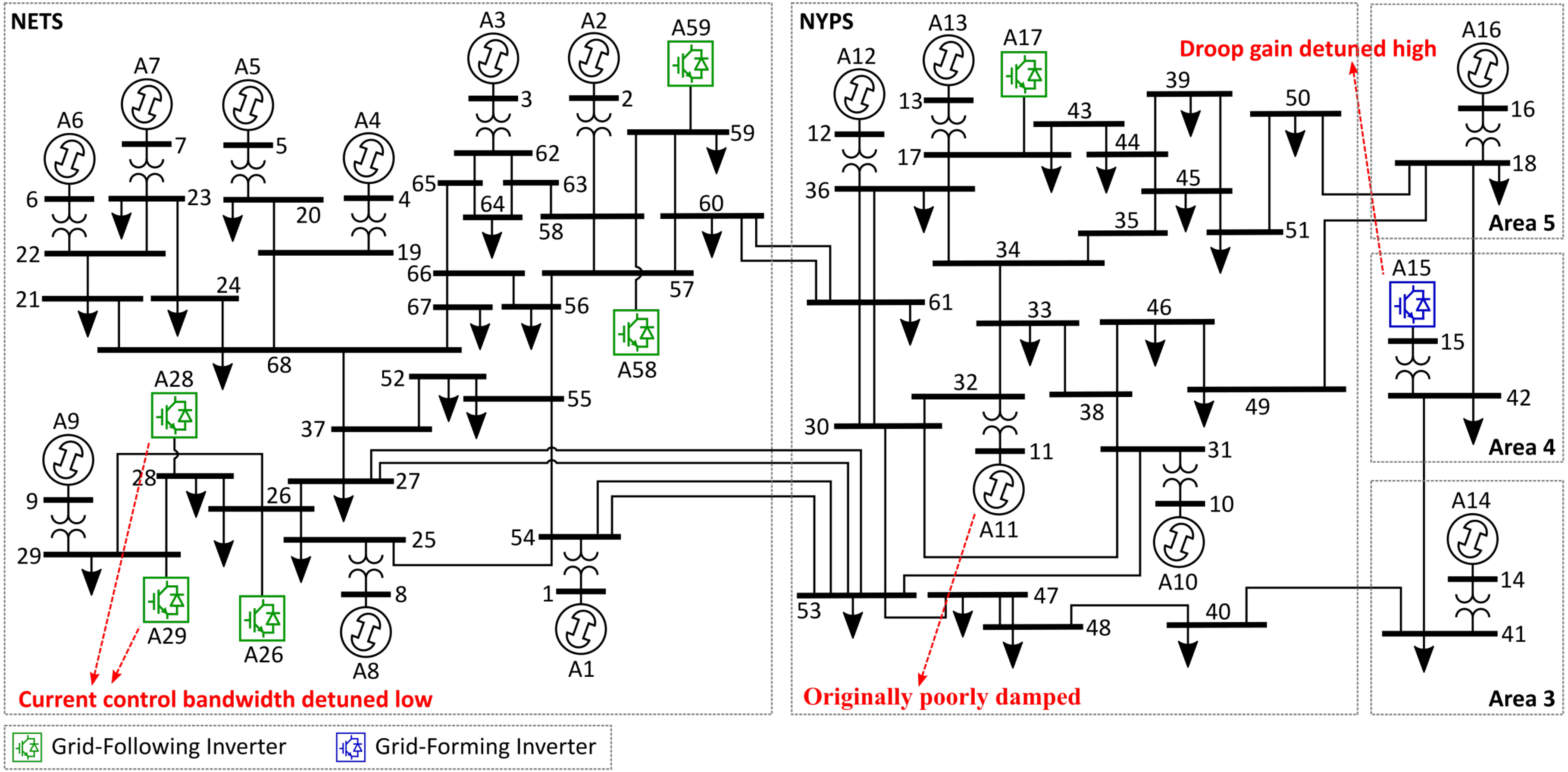
- Build the state-space matrix A
- Find the eigenvalues, λ, and identify poorly damped modes
- Find the participation factors, p_{mn}, and determine which states, n, participate in a given mode, m.
- Find the sensitivity of the mode to a parameter, $^{\partial\lambda}/_{\partial\rho}$, (parameter participation)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

Illustration with modified NETS-NYPS

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



Droop gain detuned high

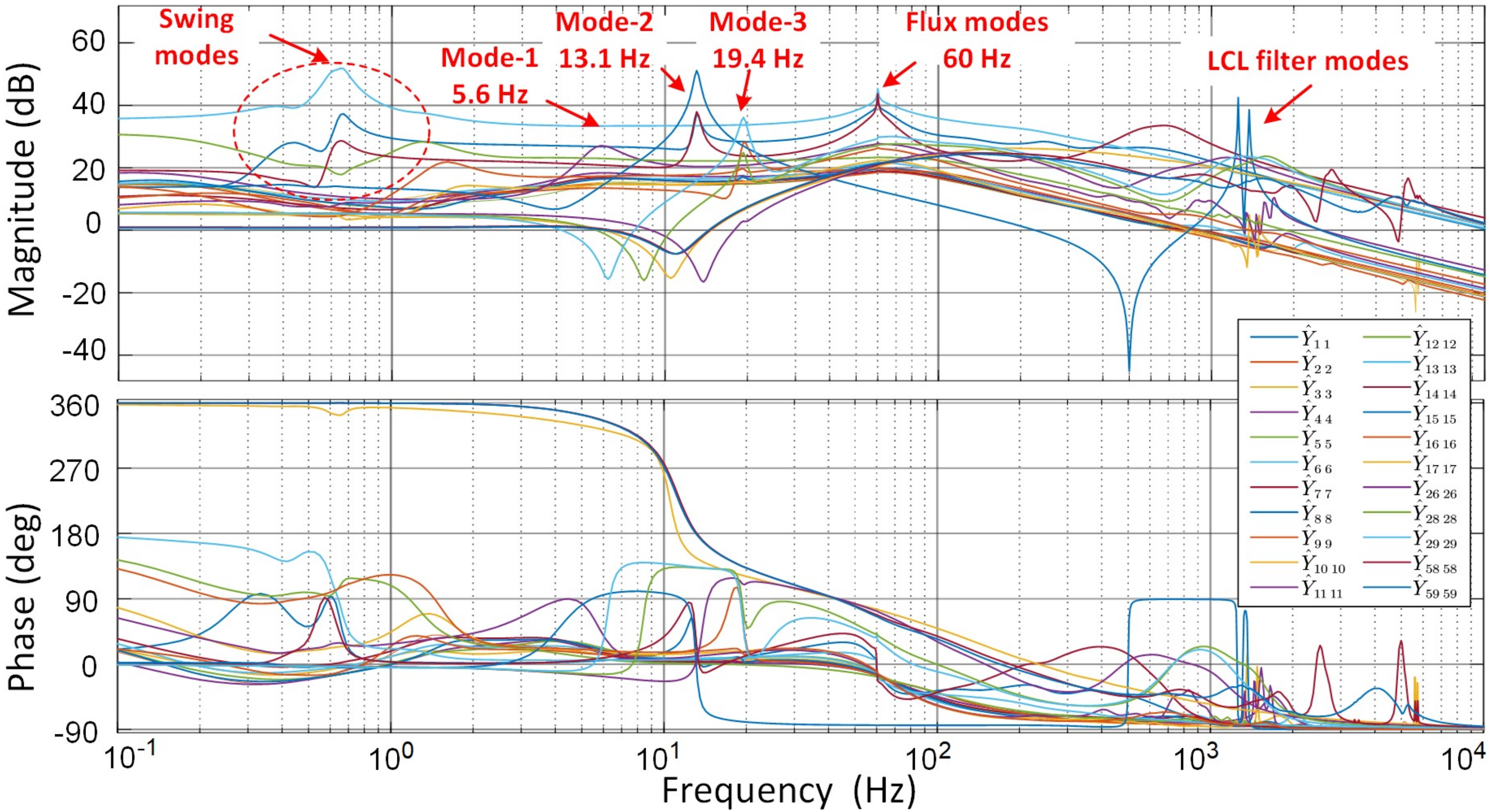
Current control bandwidth detuned low

Originally poorly damped

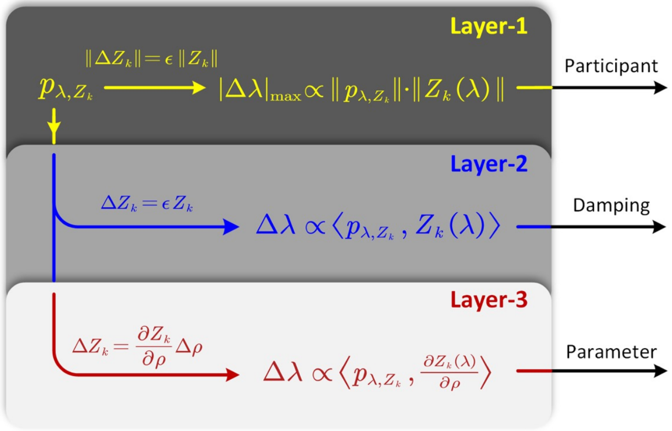
Models and Toolbox at https://github.com/Future-Power-Networks/Publications

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

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



Tuning Via Layer-3 Parameter Participation



Layer-1

$\|\Delta Z_k\| = \epsilon \|Z_k\|$

$p_{\lambda,Z_k} \longrightarrow |\Delta\lambda|_{\max} \propto \|p_{\lambda,Z_k}\| \cdot \|Z_k(\lambda)\|$

Participant

Layer-2

$\Delta Z_k = \epsilon Z_k$

$\Delta\lambda \propto \langle p_{\lambda,Z_k}, Z_k(\lambda) \rangle$

Damping

Layer-3

$\Delta Z_k = \frac{\partial Z_k}{\partial \rho} \Delta\rho$

$\Delta\lambda \propto \langle p_{\lambda,Z_k}, \frac{\partial Z_k(\lambda)}{\partial \rho} \rangle$

Parameter

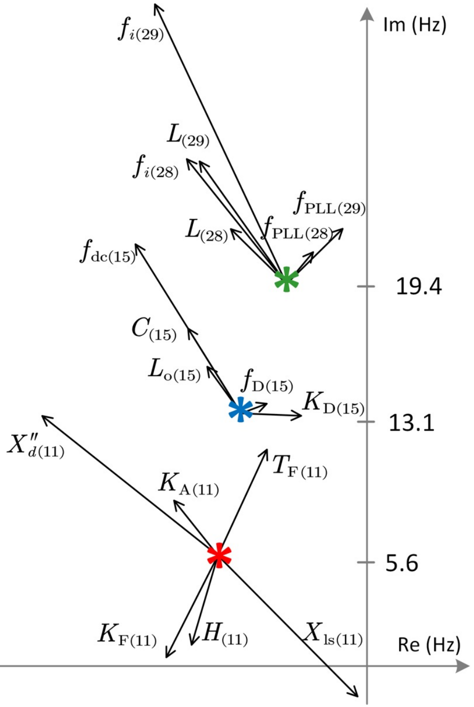
Residues of impedance at mode indicate whether large or smaller machine would improve damping

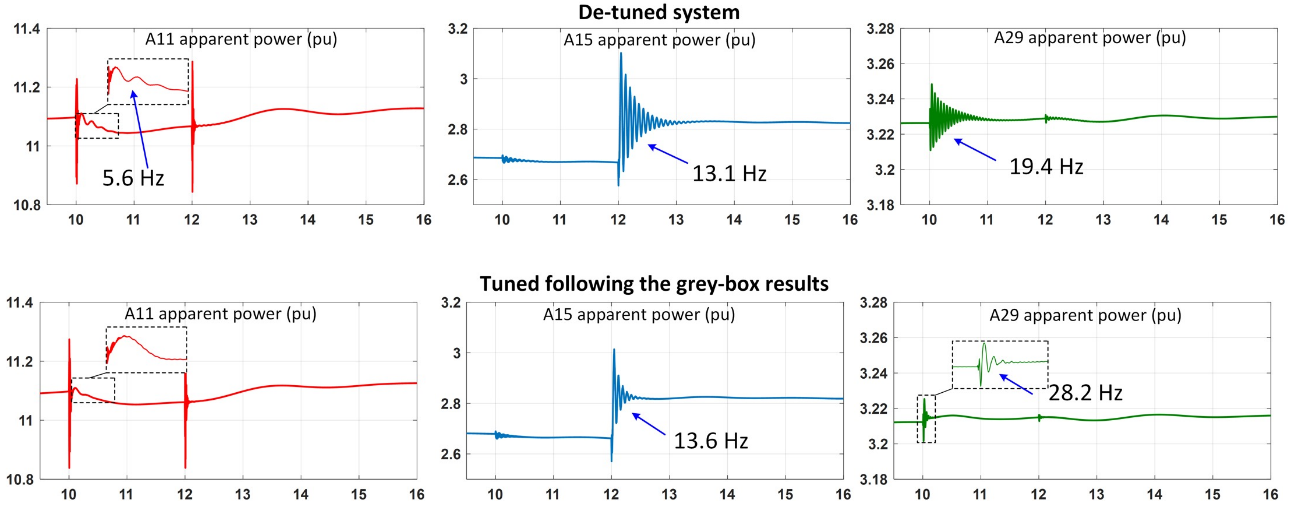
Chain-rule combination of residues and sensitivity of impedance to parameter indicate which direction to tune each parameter

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

Mode-3 (19.4 Hz)	✱
Mode-2 (13.1 Hz)	✱
Mode-1 (5.6 Hz)	✱

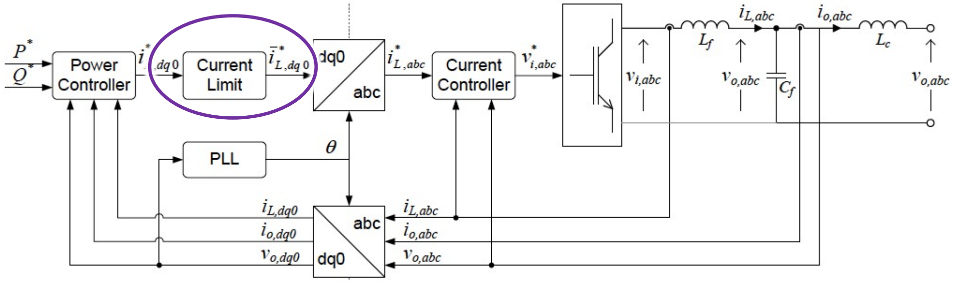
H	inertia
X''_d	*d*-axis sub-transient reactance
X_{ls}	armature leakage reactance
K_{F}	AVR feedback gain
T_{F}	AVR feedback time constant
K_{A}	AVR dc regulator gain
C	filter capacitor
L	filter inductor
L_{o}	output inductor (*LCL*)
K_{D}	frequency droop gain
f_{D}	droop control bandwidth
f_{PLL}	PLL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





Fault Current Models and Protection Design

Known that semiconductors have no useful short-time rating and need fast-acting current limitation to protect the devices.



Current limits can be applied per-phase or to *d*- and *q-axis* currents. We can choose the sequence component response to various types of asymmetric faults.

Difficulties we face:

- Faults currents beyond 1.5 pu unreasonable or expensive so differential or distance protection must replace simple over-current
- IBR close to fault current limit; those further away may not
- Sequence-circuit fault analysis complicated by multiple coupling points
- Distance protection algorithms must be designed in harmony with expected sequence response
- Definitions of needs and services around fault location require further thought by grid operators and equipment vendors

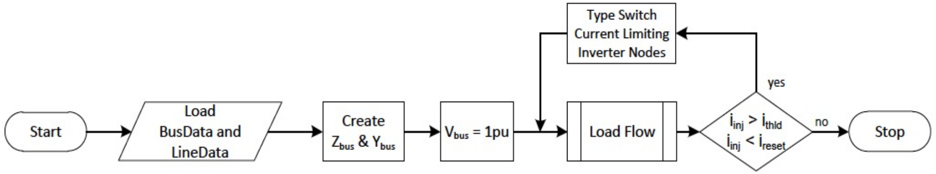
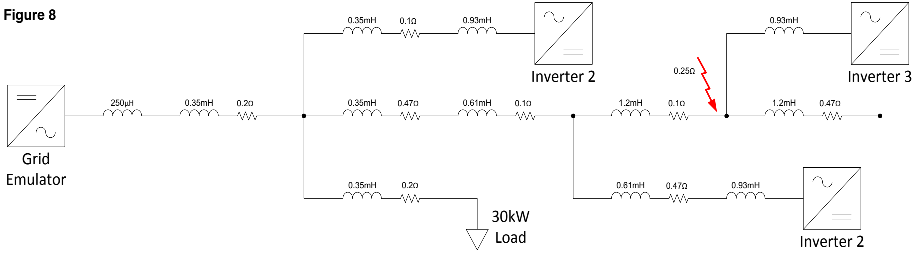
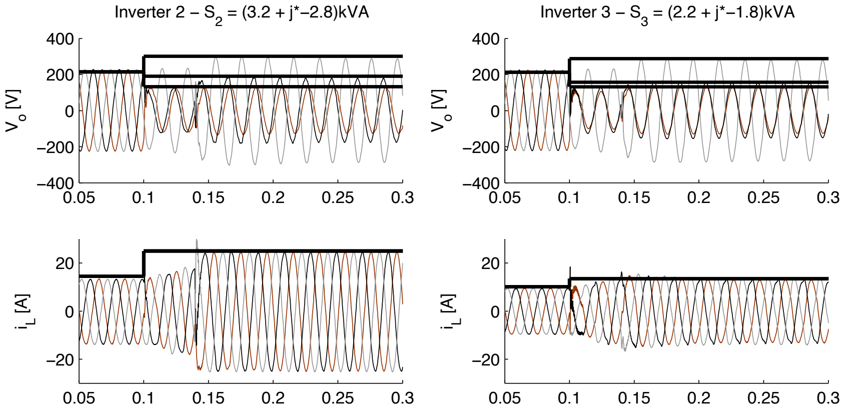


Figure 8





C. Plet and T.C. Green, “Fault response of inverter interfaced distributed generators in grid-connected applications”, Electric Power Systems Research, 2014

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
- Guidelines for service configurations needed (grid strength, droop settings, damping settings)
- This needs to be viewed as co-design of grid and IBR

Tools and Models in an IBR World

- We need to analyse and synthesise (avoid trial-and-error synthesis)
- Guidelines needed on modelling adequacy and model-reduction
- Time-domain simulation needs enhancement through new computational and model reduction techniques
- Black-box IBR models can be turned into Grey-box models and root cause analysis of small-signal stability performed
- Large-signal stability with non-linear causes is under researched
- Future of protection in a low fault-current grid is unclear