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Is “Grid Forming” enough: what do electricity grids need from IBR?

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G-PST and ESIG Webinar, May 2021

Key Issues

Growth of IBR at expense of Synchronous Machines are causing us to think again about:

- System Services/Needs – working toward mandatory services (grid codes) and procured services (SO market) but needing to do this in technology neutral way that thinks about the cost burdens
- How stability is ensured and the tools we need to analyse and synthesise our systems

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Inverter-Based Resource (IBR) and Variable Renewable Energy (VRE)

IBR are becoming prevalent

- Wind (variable-speed generators)
- Solar (DC generators)
- Batteries (DC resources)
- Regulated loads such EV battery chargers and variable speed motor drives are IBR
- Network equipment such Statcoms and HVDC terminals

- No synchronized inertia
- No short-term current rating
- Require high-bandwidth control which is complex and propriety

- Amenable to new control configurations and functions

VRE are becoming prevalent

- Wind and solar
- (hydro, geothermal and biomass not variable to the same extent)
- VRE are often IBR

- Run at maximum power point. Zero marginal cost generation, turn-down of power loses all revenue but does not save fuel cost
- No upward-power services while at maximum power point.

- Can run at low/no power (no minimum stable generation limit)
- Can provide non-energy services even when no energy resource is available

Other IBR

- Batteries earn from services on top of arbitrage in energy market. Will reserve capacity for this.
- STATCOM could provide range of services beyond reactive power.

Fueled Synchronous Machine

- SM also has to de-rate to provide reserve and reactive power
- But have large thermal mass and useful short-time rating
- Minimum stable generation means power must be taken to obtain the services (synchronous compensator apart)

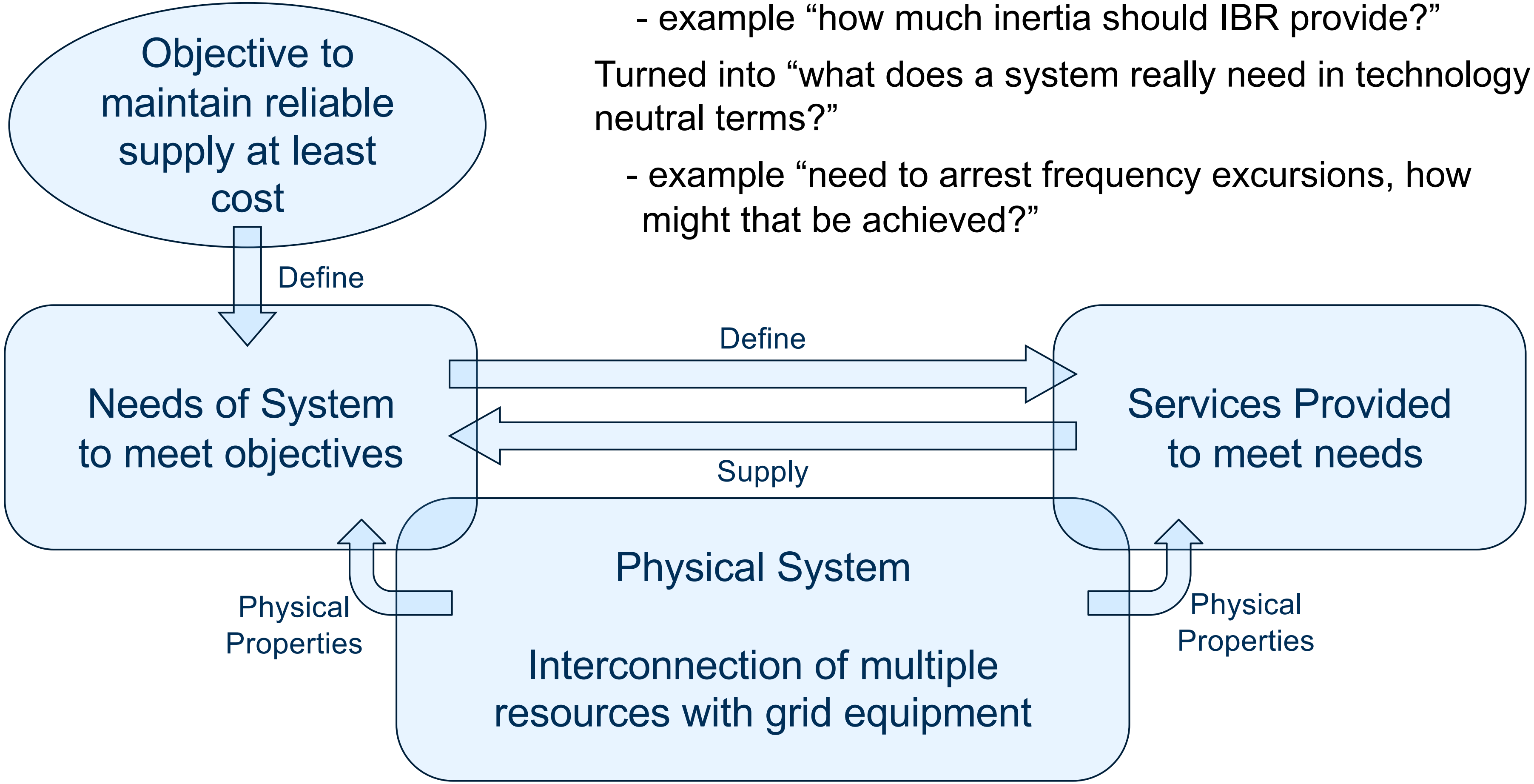
G-PST Working Group on System Needs and Services

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?"



Broad Categories of System Need

Power Quality & Stability

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

Service Quality & Security

- Energy
- Capacity
- Protection
- Restoration

IBR & VRE Limitations

- Phase-Lock Limits
- Absent Mechanical Inertia
- Power Availability
- Energy Availability
- Black-Box Dynamics
- Absent Short-Term Rating

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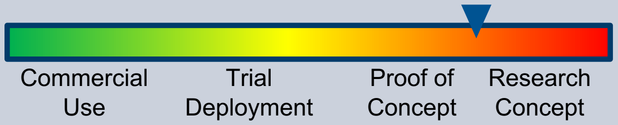
Needs in Frequency Regulation

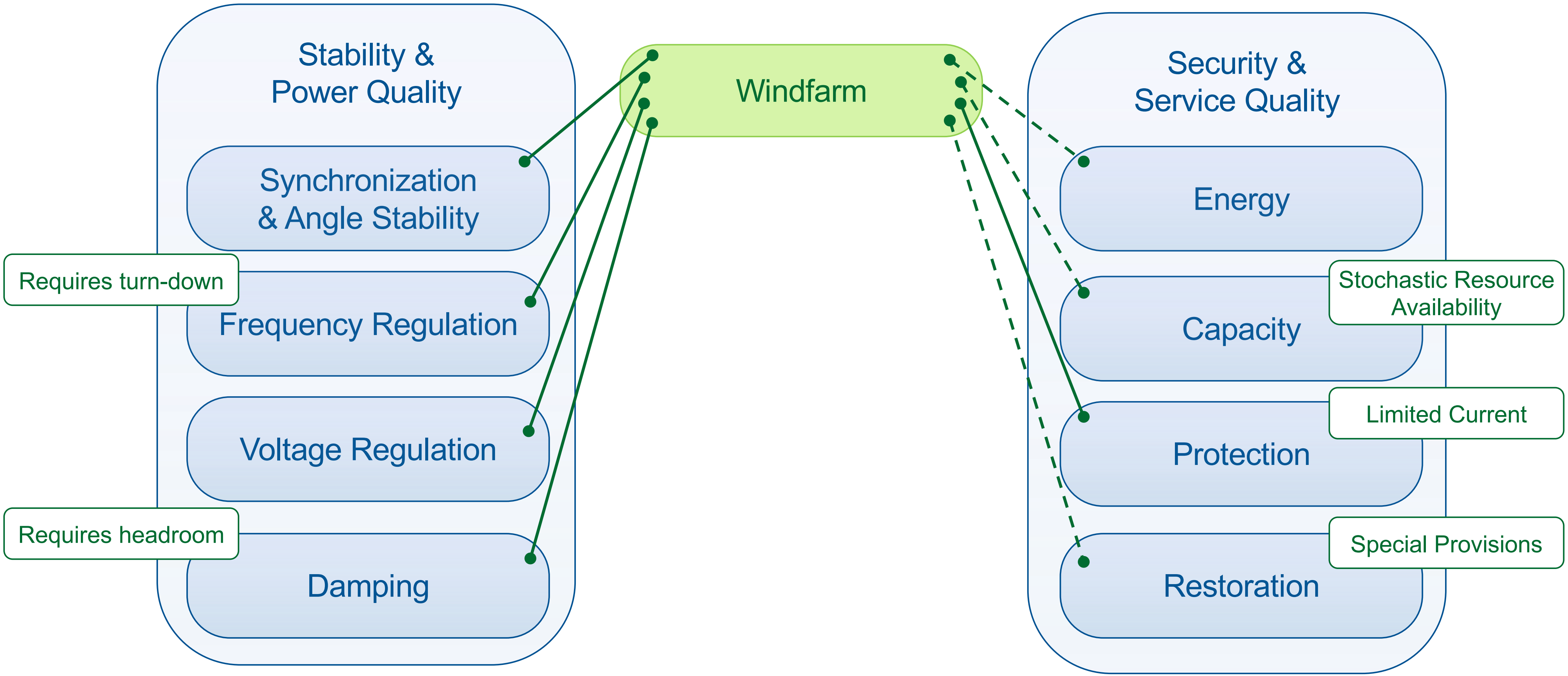
Need Type	Reason for Need
Frequency Regulation	Power fluctuation of VRE or load causing drift of frequency (Maps to frequency response.)
Containment within Frequency Limits	Loss of load/infeed causing large increase/decrease of frequency to the outside limits defined and causing equipment malfunction or loss of service.
RoCoF Limitation	Loss of load/infeed causing rapid change of frequency and protection malfunction or unwanted triggering of protection. (Maps to inertia and fast frequency response features of traditional system.)
Frequency Settling	Following major event immediate containment of frequency, settle (or stabilise) the frequency. (Maps to primary frequency response in traditional system.)
Frequency Recovery	Reserve services to restore frequency following large disturbance (Maps to secondary frequency response and short-term reserve in traditional system.)

Example System Need

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	

Mapping Resources to System Needs



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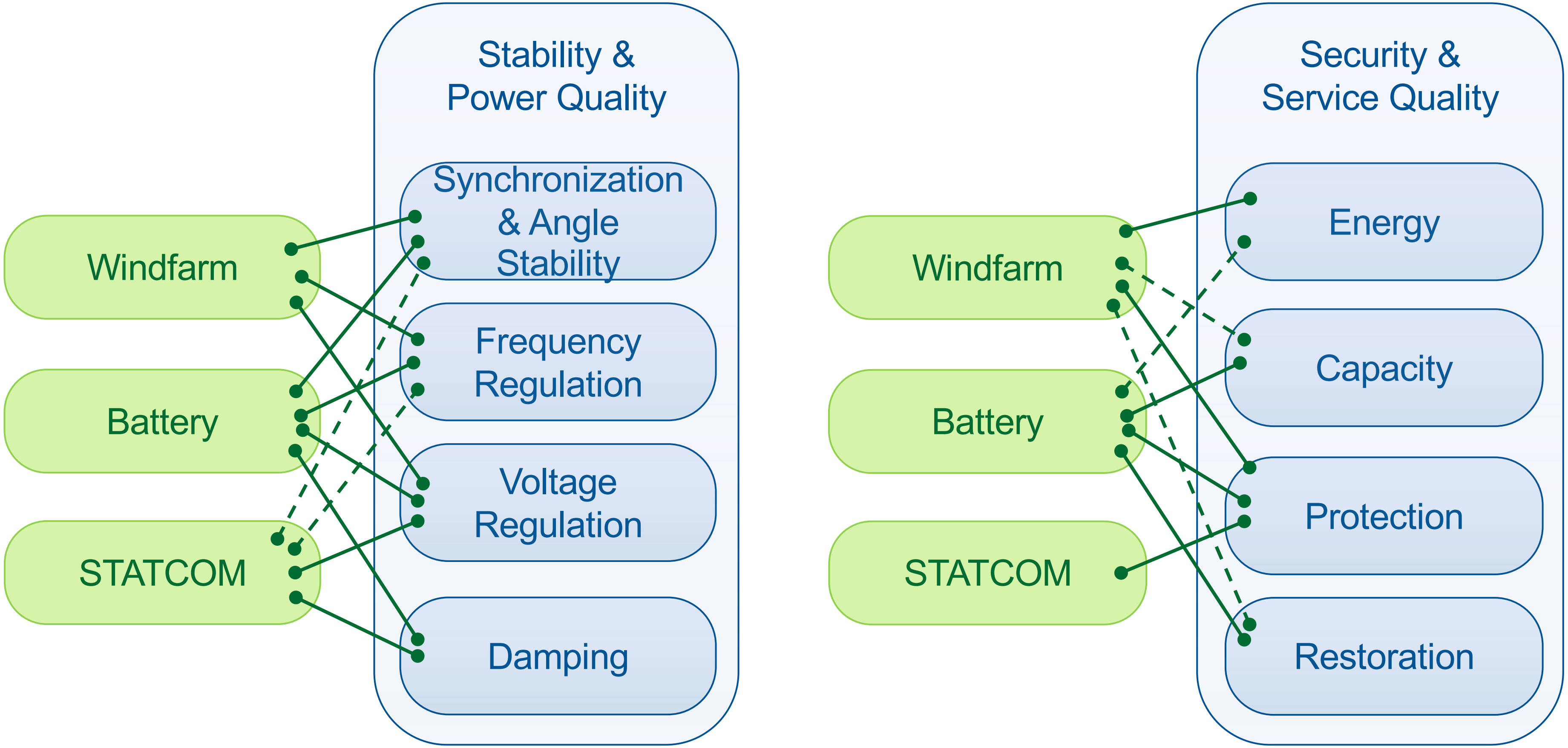
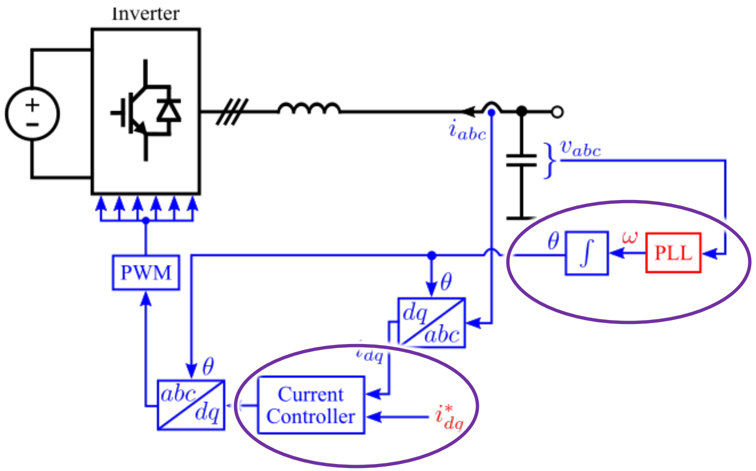
Mapping Multiple System Needs to Multiple Resources

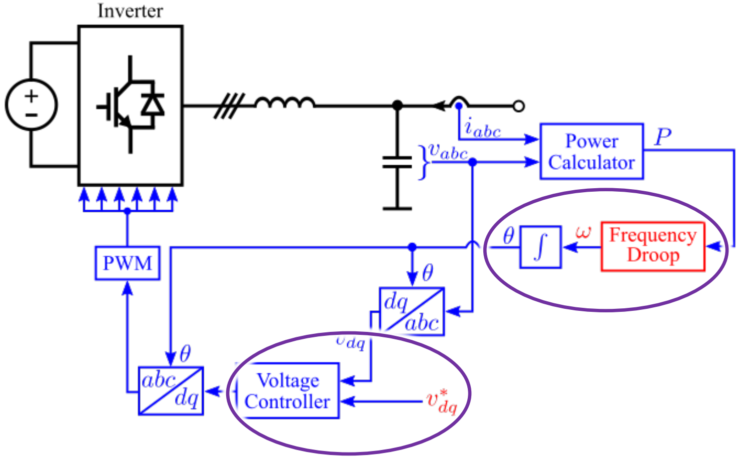


Overlaps and Co-actions in Services to meet Needs

- SM come with a consistent set of properties and abilities to deliver services.
- IBR are flexible ***but*** need definitions to configure services tailored to each need
- Needs and services are a not a one-to-one mapping:
  - one service might meet more than one need,
  - one need might be met by several services.
- For example, controlling frequency after a sudden loss of power in-feed:
  - We need to contain the maximum frequency deviation
  - This helped by limiting the rate-of-change of frequency because it reduces the frequency extreme and provides time over which to provide other services
- The services could be
  - Virtual 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)
  - Blends of these or other relationships not possible with synchronous machine.
- Loss-of-infeed may also cause a phase-jump and a voltage sag.
  - If reactive power and synchronising power are needed at the same time, how is the limited current rating of the inverter prioritised between services.

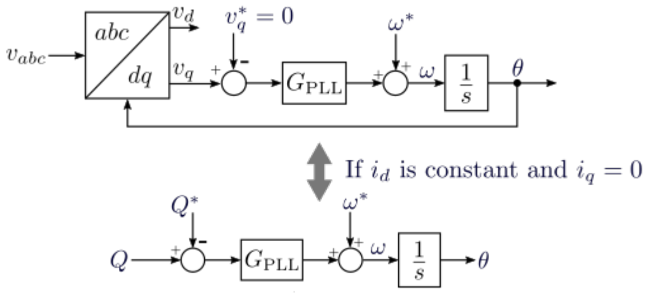
Grid Following and Grid Forming Inverters: Configurations





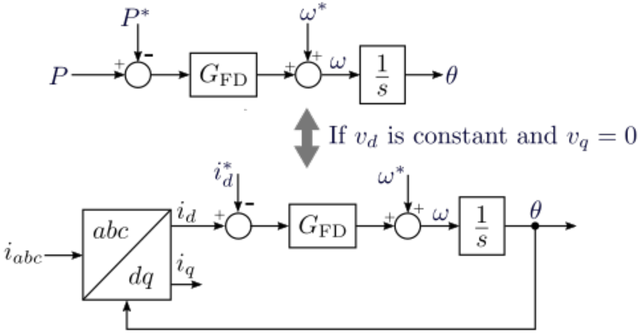
Grid Following (GFL)

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



Grid Forming (GFM)

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



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 network voltage 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
Swing Characteristics	$V-\delta$ or $Q-\delta$ swing	$I-\delta$ or $P-\delta$ swing

GFL and GFM Stability Features

View Point	Grid Following	Gird Forming
Synchronisation Stability	PLL unstable for high PLL bandwidth	Unstable for large droop gain
Control-Loop Stability	Super-synchronous (harmonic) instability when **current**-loop bandwidth is **high** Synchronisation instability when **current**-loop bandwidth is **low**	Super-synchronous (harmonic) instability when **voltage**-loop bandwidth is **high** Synchronisation instability when **voltage**-loop bandwidth is **low**
Grid Strength Stability	Unstable when grid impedance is high	Unstable when grid impedance is low

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Why GFL thus far?
Why GFM in future?

- Wind, solar and battery IBR arranged to a follow power reference and GFL achieves this.
- GFM require adjustable prime mover which does not suite VRE (batteries are different!)
- IBR were too small to exert influence on network or disbarred from exercising voltage control so GFL was sufficient or even necessary.

- GFL have not been required to provided services to meet grid needs
- Standing down of SM is leaving grid short of the services to meet its needs.

- GFM inverter is somewhat like a SM and meets some basic needs by creating a “stiff” node in a gird
  - Voltage is “stiff” or source “strength” is high.
  - Frequency changes little when real power is drawn so frequency is “stiff”.
  - Requires a ready supply of power and energy, that is, storage or de-rating below MPP etc.
  - Stiffness comes from over-provision of capacity and a foregoing revenue, so this is a service with a cost.
  - Stiffness also requires capacity for extra current for both reactive power and short-circuit current which is also a cost.
- GFM have been a feature of microgrids for 20 years

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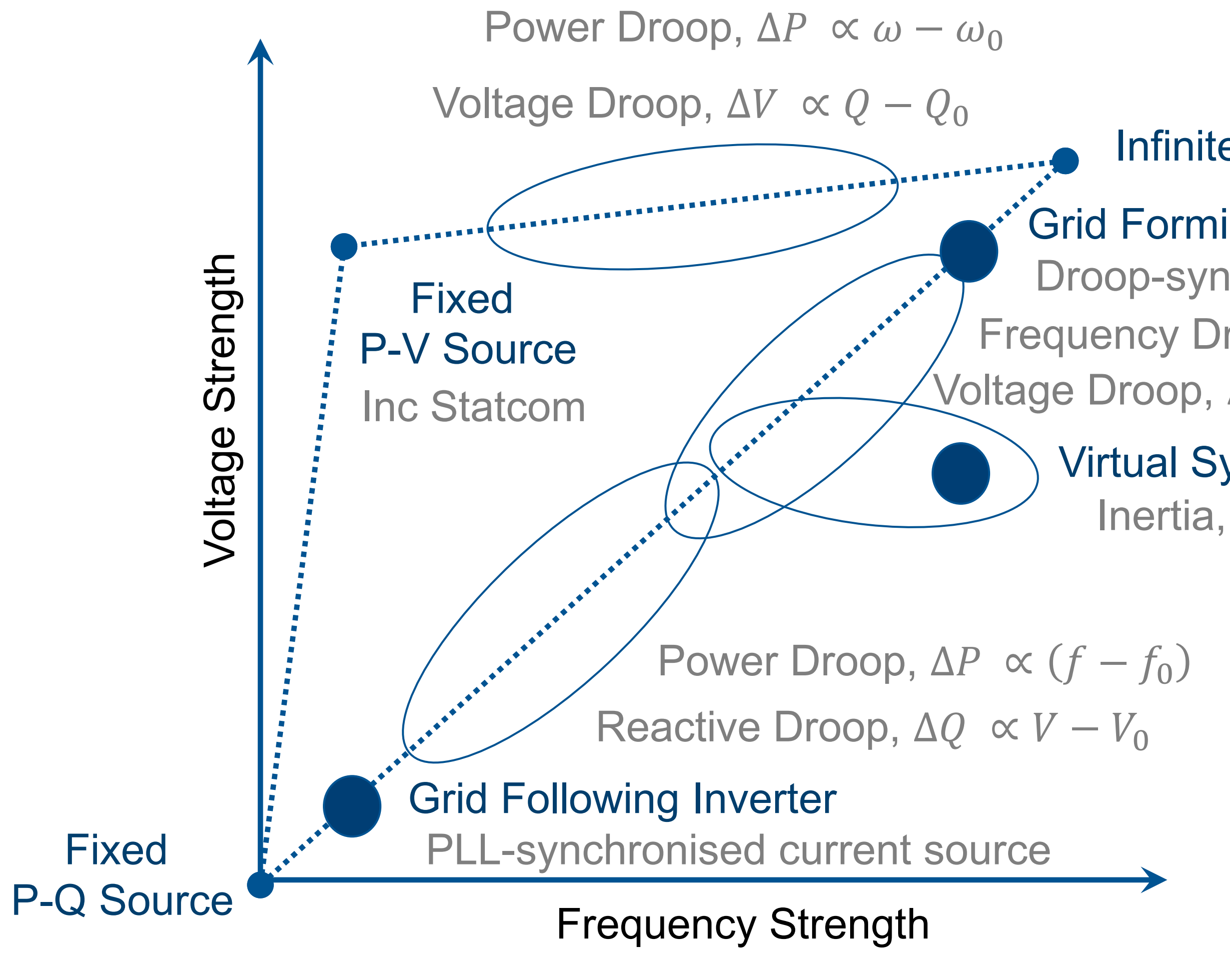
Two aspects of grid strength: GFM and GFL Context



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?

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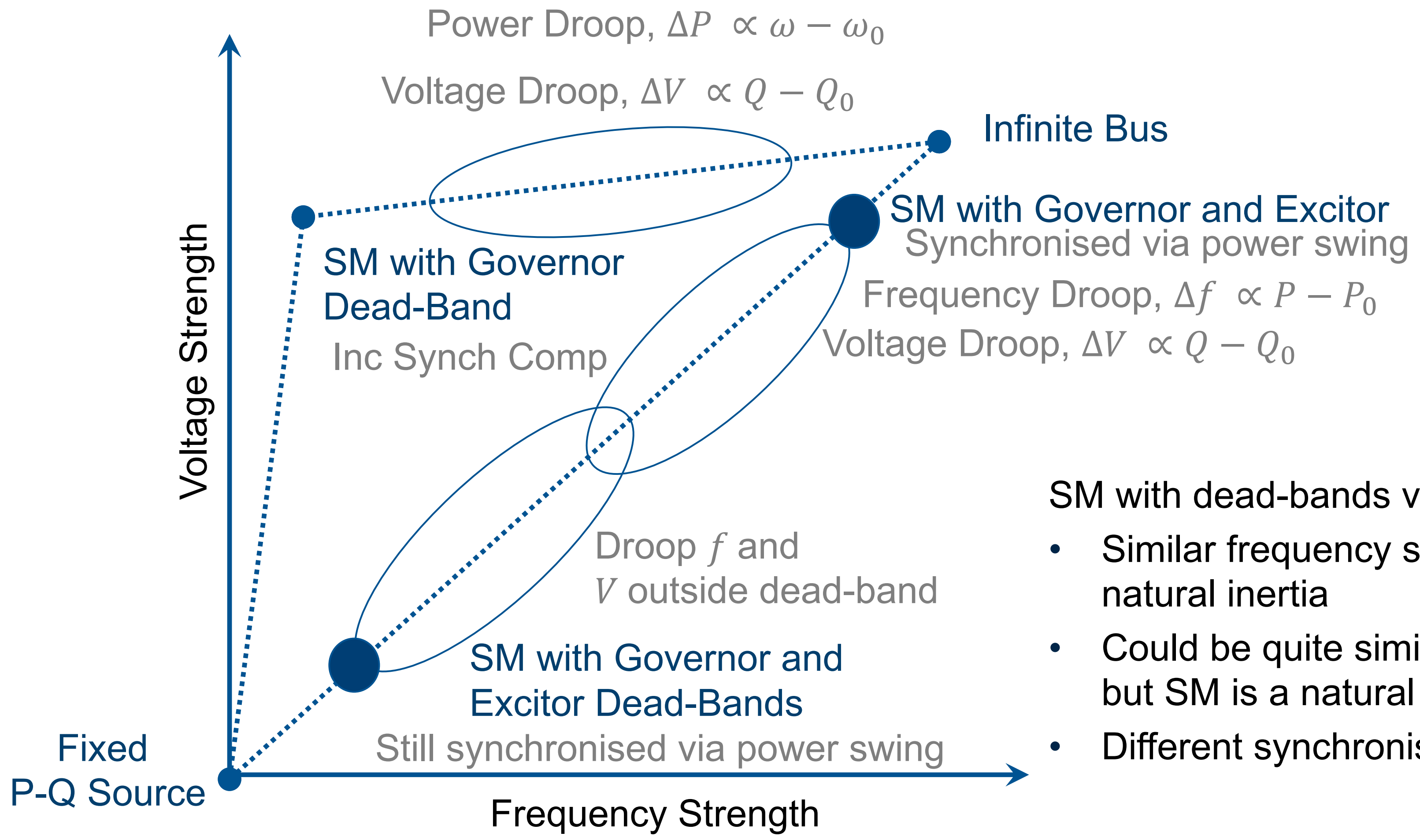
Two aspects of grid strength: SM



SM with dead-bands versus GFL 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 and angle stability

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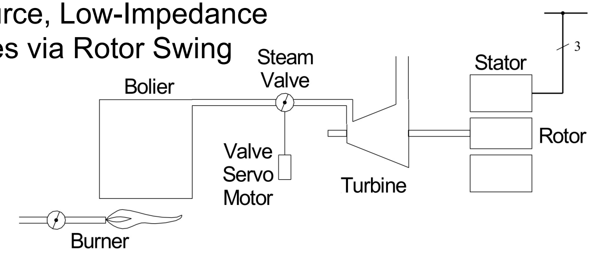
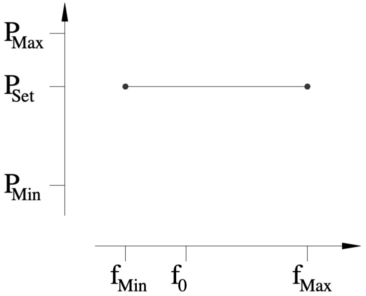
Governors, Dead-bands and IBR

No Governor
- Constant Power
- Voltage Source, Low-Impedance
- Synchronises via Rotor Swing
- Inertia

$$P = \frac{E\,V}{X}\sin(\delta) \Rightarrow J\frac{d\delta^2}{dt^2} = \frac{p}{\omega}\left(P - \frac{E\,V}{X}\sin(\delta) - D\frac{d\delta}{dt}\right)$$



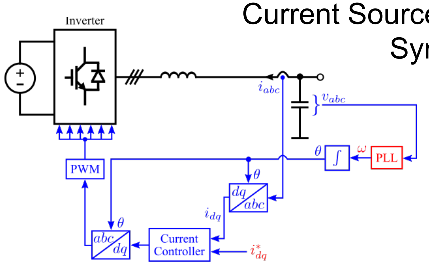


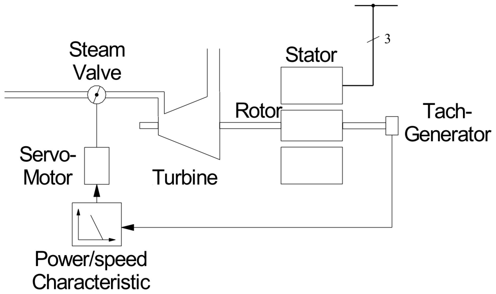
Constant Power

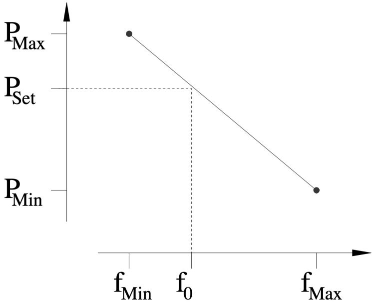
Current Source, High-Impedance

Synchronises via PLL

No Inertia





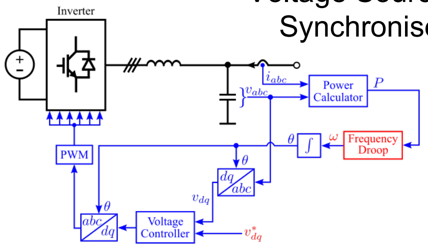


Drooped Power

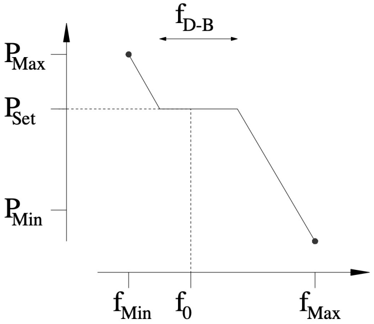
Voltage Source, Low-Impedance

Synchronises via Angle Swing

Virtual Inertia



Add Governor
- Drooped Power
- Voltage Source, Low-Impedance
- Synchronises via Rotor Swing
- Interia



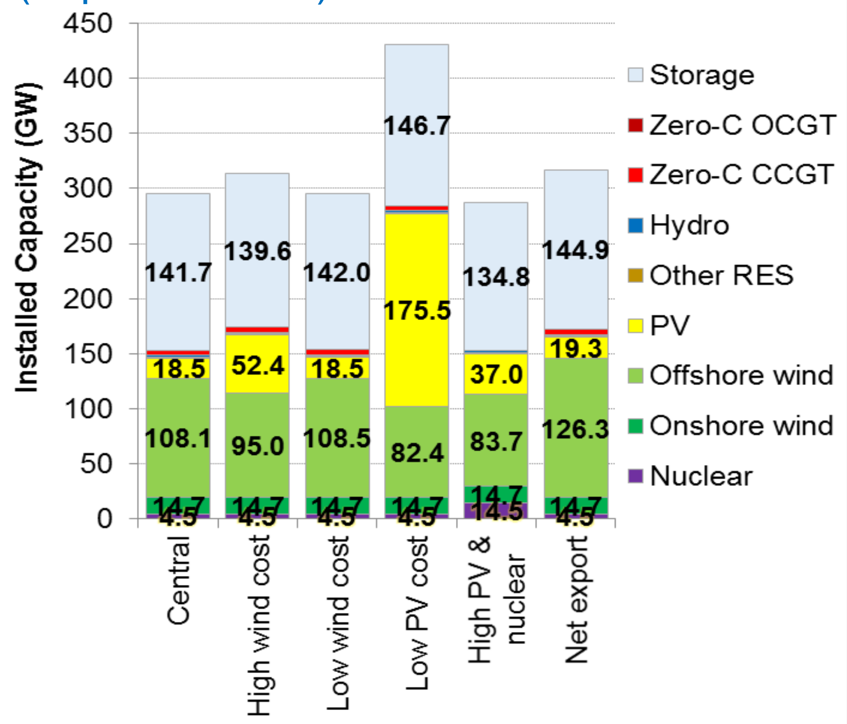
- Voltage Source, Low-Impedance
- Synchronises via Rotor Swing
- Inertia
- Constant Power except in Extremes
- May utilize short-term rating for under-frequency response

- Voltage Source, Low-Impedance
- Synchronises via Angle Swing
- Virtual Inertia
- Drooped Power except in Extremes
- *How is underfrequency-response accommodated? Is this from storage?*

?

Generation Mix and Service Provision

GB Generation Mix for Net-Zero (Expected 2035)



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

- Presence of some nuclear and hydrogen/biogas OCGT mean that this is still a synchronous system
- Just like today, only a subset of resources provide governor, excitor and black-start
- Wind (on- and off-shore) will have to provide wide variety of services but maybe not all
- Batteries can provide services needing short-term energy (frequency containment, peak capacity etc.)
- Statcoms needed for regional voltage stiffness
- An enhanced Statcom (Statcom+): add battery and short-term over-current rating to provide:
  - Synchronisation services
  - Frequency services
  - Voltage services
  - Protection services

Energy Futures Lab White Paper to be launched 8th June, https://www.imperial.ac.uk/energy-futures-lab/reports/

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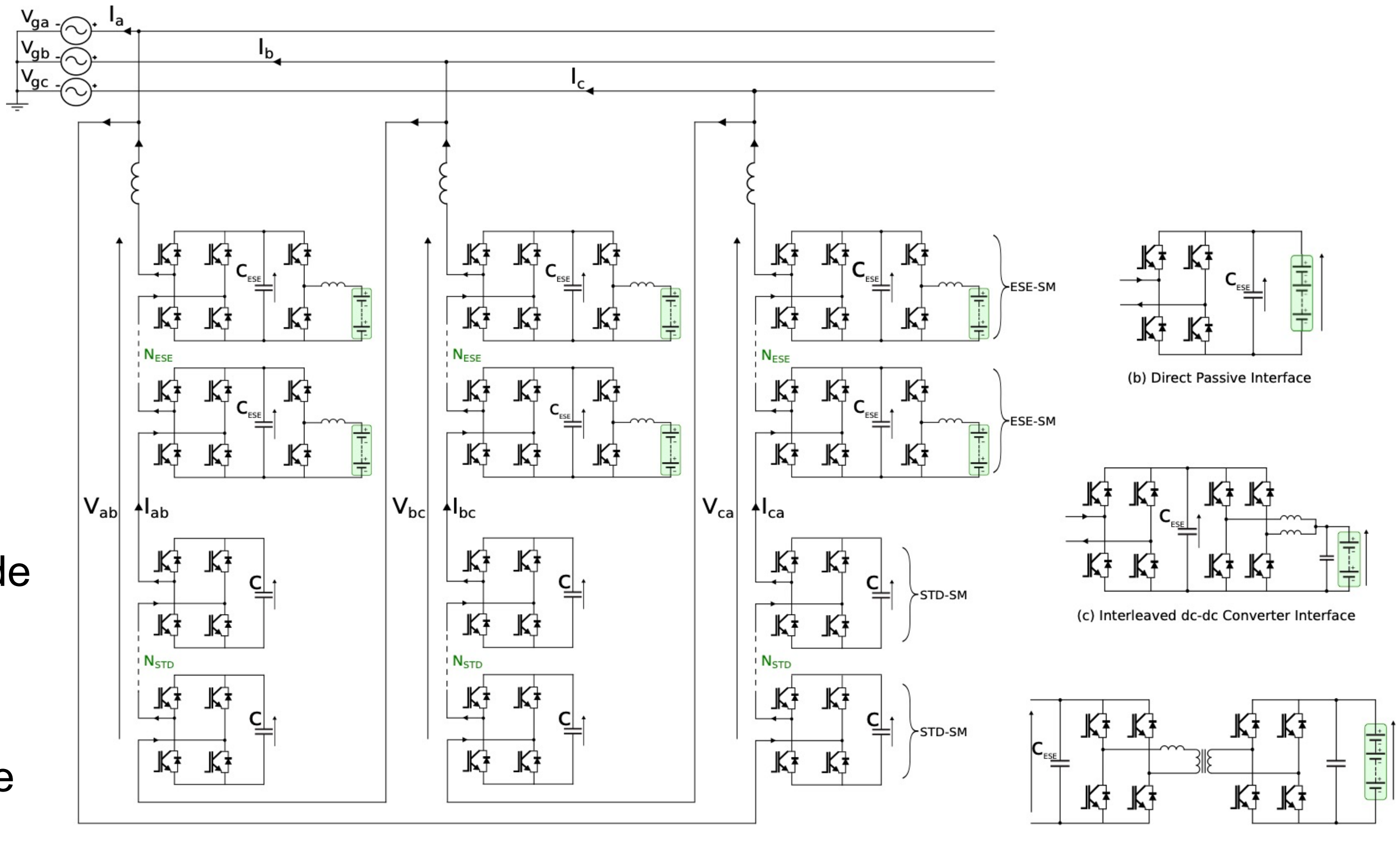
Statcom Plus

Modular Multi-Level Statcom to provide
- Voltage regulation
- Active filtering
- Damping

Battery Energy Storage added to fraction of the sub-modules to provide
- Frequency regulation
- RoCoF services

Short-Term Current Rating to provide
- Fault Current



(a) Single Delta Bridge Cell Converter with Partial Rated Battery Storage

(b) Direct Passive Interface

(c) Interleaved dc-dc Converter Interface

(d) Dual Active Bridge dc-dc Converter Interface

Sohail G. Mian, Paul D. Judge, Adria Junyent-Ferre and Tim C. Green, "Delta Connected Modular Multilevel STATCOM with Partially Rated Energy Storage for Intended Provision of Ancillary Services" IEEE trans PD, 2021

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.

Approaches to Stability Analysis

- Time-domain simulations might reveal the presence of a problem but are not good at pin-pointing root-causes or offering guidance on tuning parameters without a great deal of trial-and-error experimentation.
- Lots of challenges remain in performing time-domain simulations such as identifying limits to phasor simulation methods and speeding-up transient analysis of large systems.

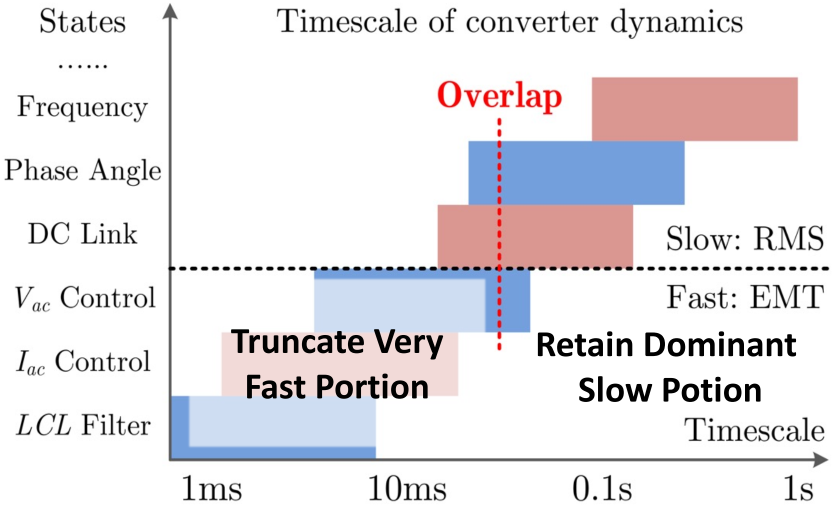
- Systematic methods are needed, building on and extending existing methods to accommodate IBR-dominated networks
  - State-space models and eigenvalue analysis
  - Transfer function models and mode shaping
  - Impedance/Admittance models and root-cause analysis
  - Extension to non-linear features and large-signal stability
  - Other …
- Time-domain simulations still very useful for confirmation of analysis.

Model Order Reduction for State-Space Analysis

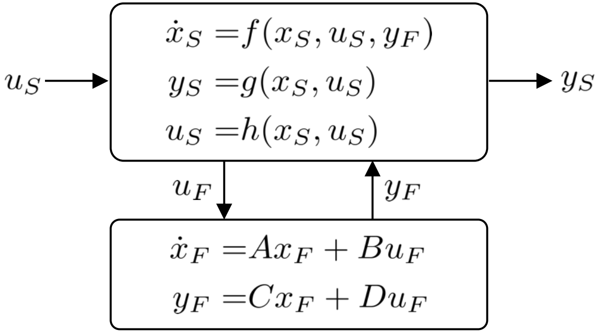
In a synchronous machine, the dynamics of governor, electromechanical modes and damper windings happen in well-separate timeframes.

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

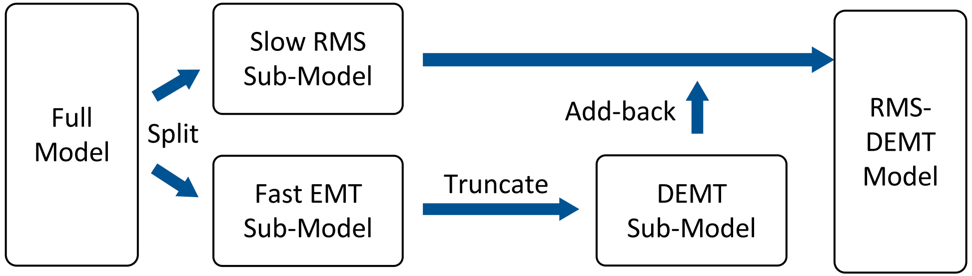
In an inverter, the modes of various control-loops are in overlapping timeframes and simply leaving a feature out of consideration breaks the coupling.



Slow (& Nonlinear)

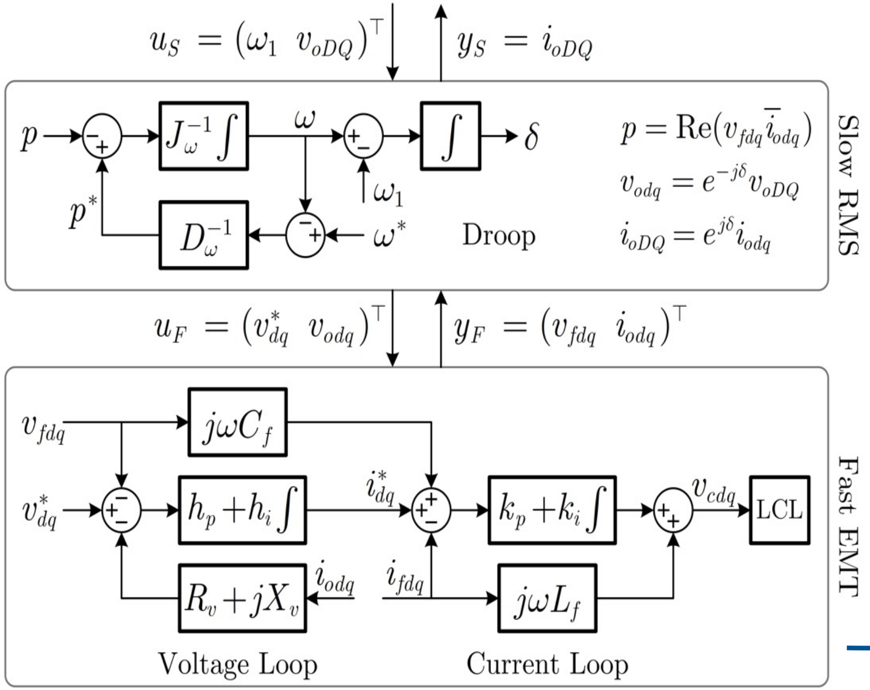


Fast (& Linear)



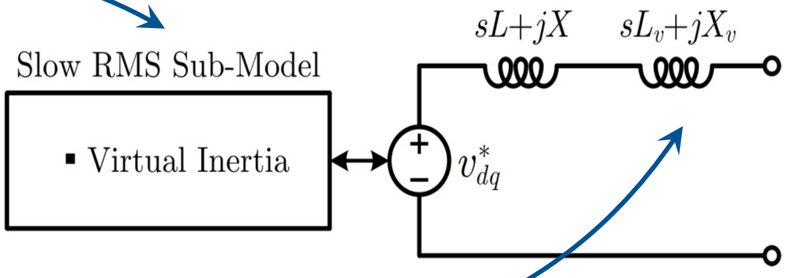
Solution is to identify the Dominant part of the EMT dynamics and combine this with an RMS model

RMS + Dominant EMT for GFM IBR



Droop control is equivalent to virtual inertia

Filter inductance is retained

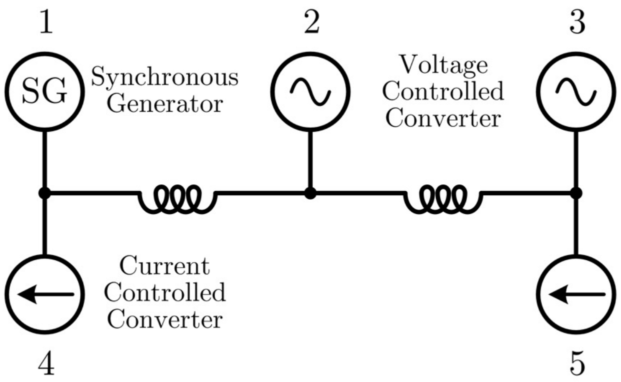


Voltage control induces virtual flux dynamics that appears as a virtual inductive term

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

Reduced IBR Models in Multi-Machine Interaction Study

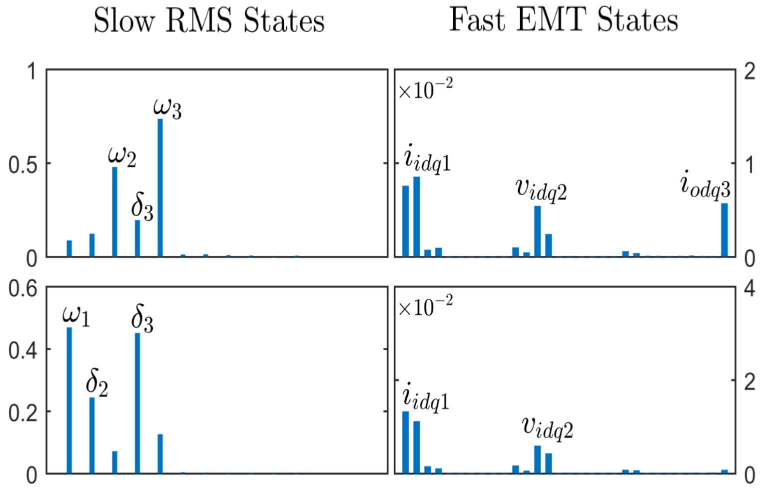
Unstable test system with large droop gain



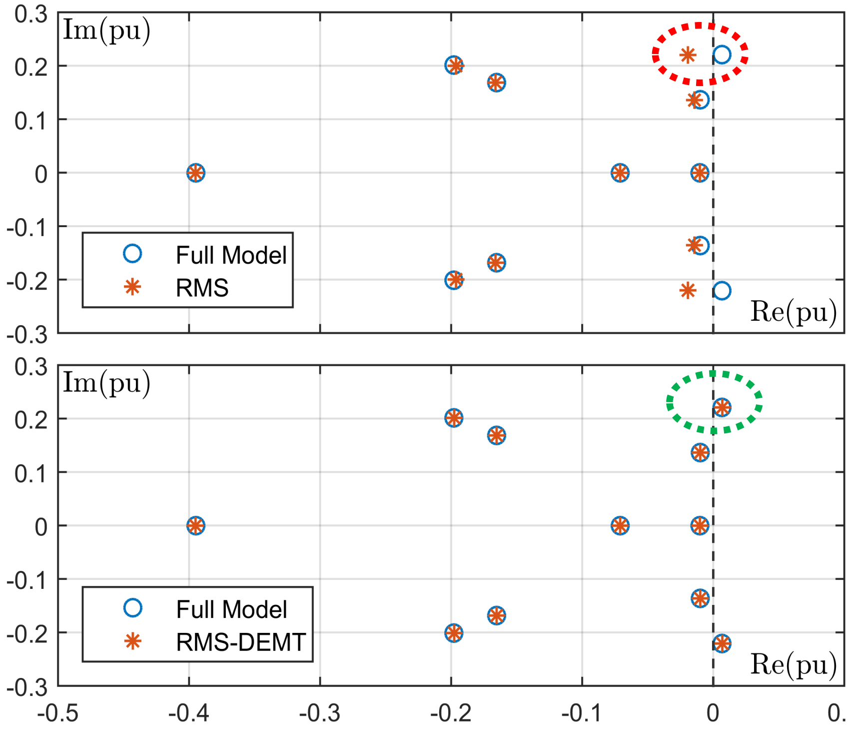
Participation-factor analysis shows role of current-loop states

Mode A: Swing 2-3

Mode B: Swing 1-(2,3)



RMS model alone appears stable



RMS + Dominant EMT correctly shows unstable mode

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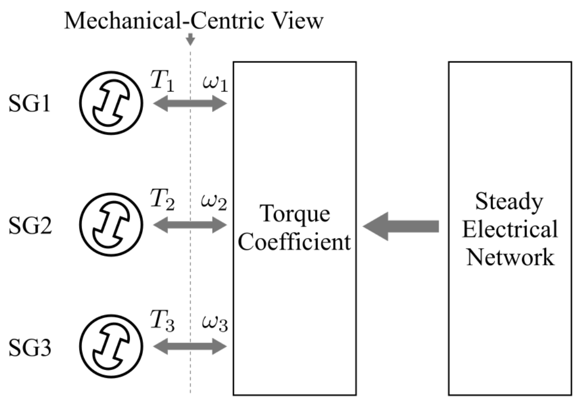
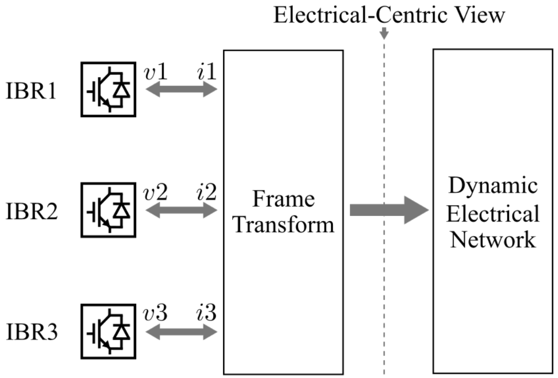
Framework for Combining Mechanical-Centric and Electrical-Centric Models

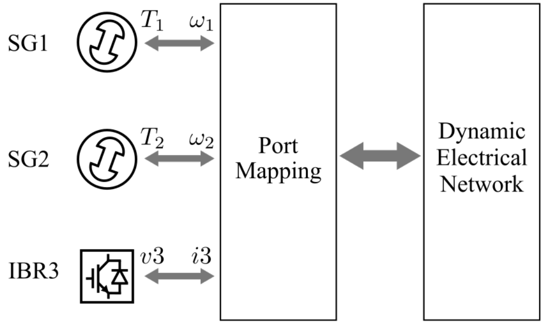
Mechanical-centric analysis arose because of dominance of synchronous machines.
Dynamics expressed in terms of torque-speed relationships.
Electrical gird of static impedances.

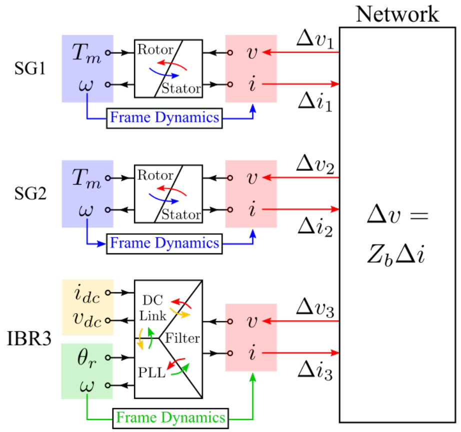


Electrical-centric analysis found in inverter-based microgrids.
Dynamics expressed in terms of voltage-current relationships
Electrical of inductive/capacitive dynamics.



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





Whole-System Models via Ports

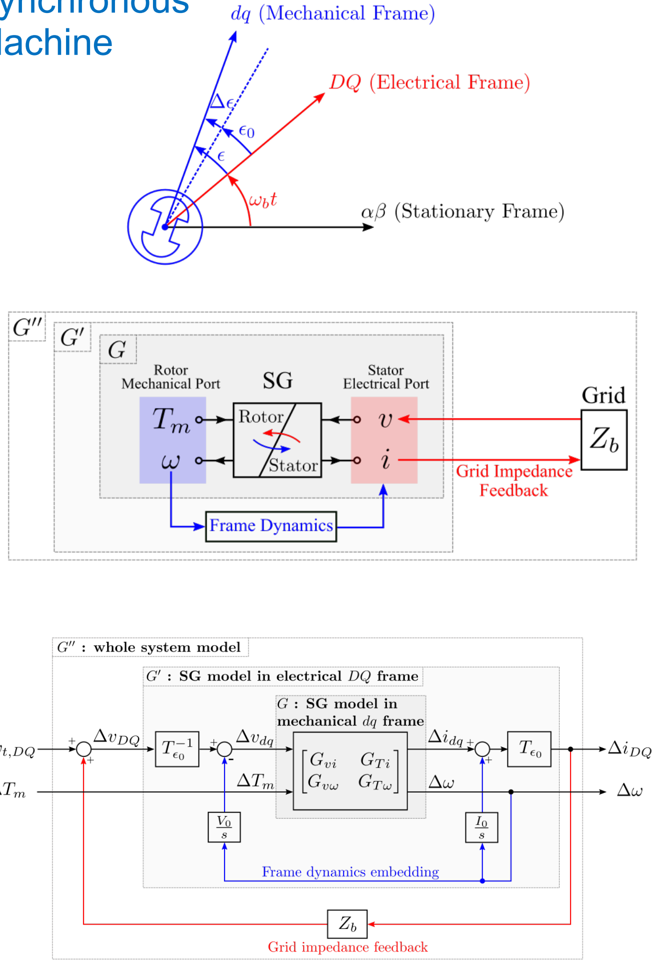
Reference frame of each SM and IBR is defined relative to a common frame (DQ), offset by a static angle, ε_0, from the operating point and a dynamic angle, $\Delta\varepsilon$, arising from swing of the device.

Machine can be modelled in its own reference frame with dynamics G,

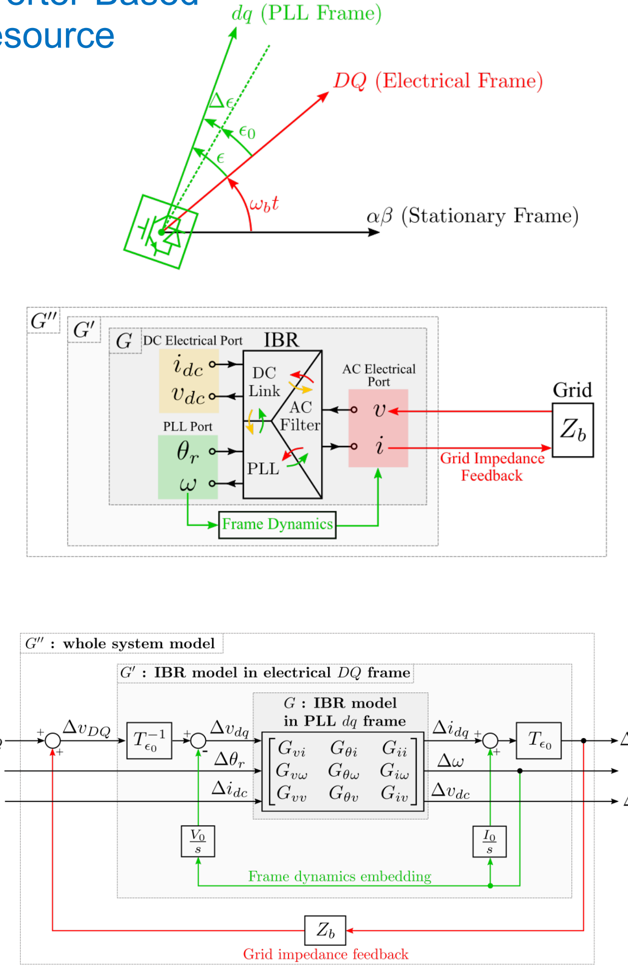
With the frame dynamics included it becomes G'

When combined with the rest of the system becomes G''

Synchronous Machine



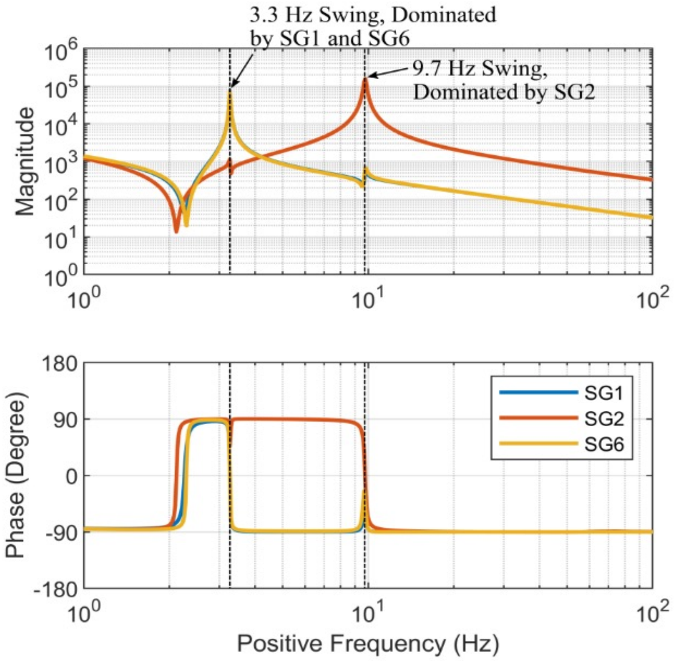
Inverter-Based Resource



Impedance Analysis at Mechanical-Ports

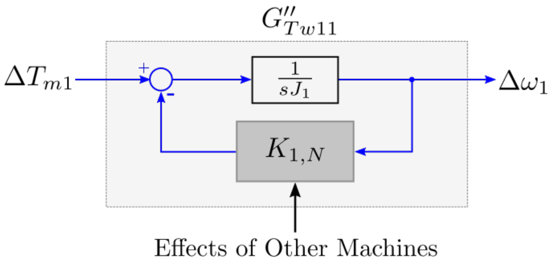
A port can be used to look at the interaction between a selected machine/inverter and the rest of the system.

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



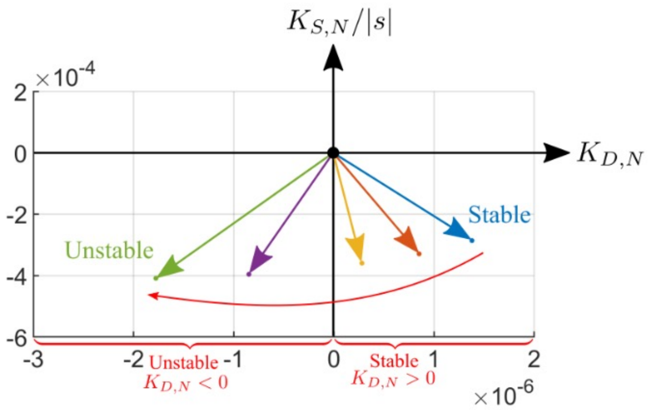
Torque coefficient of each machine can can be found from element of transfer function matrix G''

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



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, Under Review.

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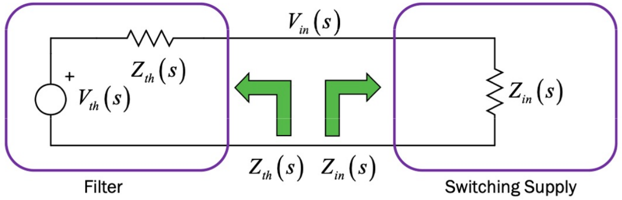
Impedance Spectrum Methods

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.



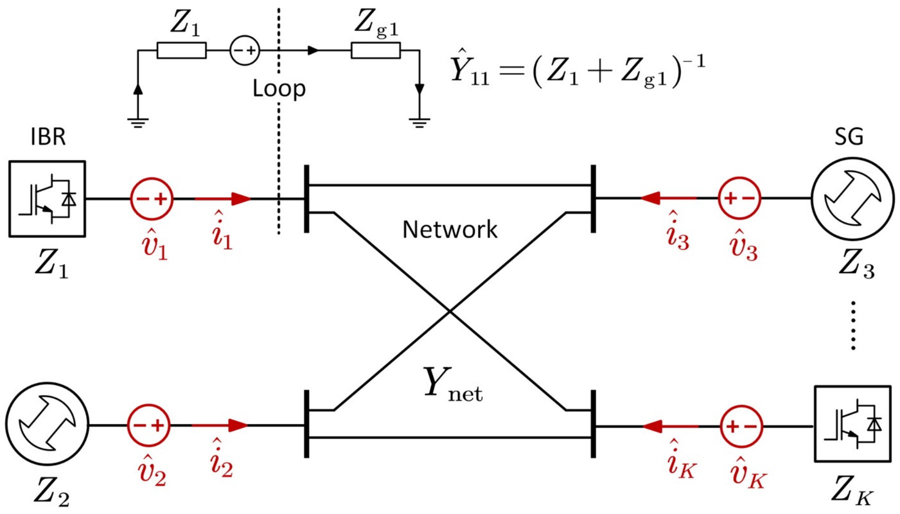
Input voltage of SMPS is

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

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

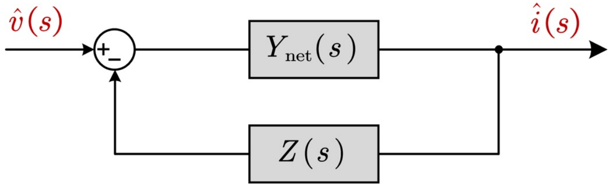
This can be extended to AC grids but it is not realistic to partition the grid into sources and load.

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



Impedance Models can be Black-Box

- An IBR Vendor can disclose an impedance spectrum, $Z(s)$, as
  - A series of impedance measurements at various frequency points
  - A series of poles and zeros
  - A set of R, L, C values and gains
- This does not disclose the underlying control algorithms so is a black-box model
- This a System Operator can compile a whole-system model from black-box resource models and its own grid model. It can then check for poorly damped modes.

- But what if a poorly damped mode is found,
  - How does one know which equipment and which feature of it is participating in the mode?
  - How does one know what to do in order to stabiles the mode?

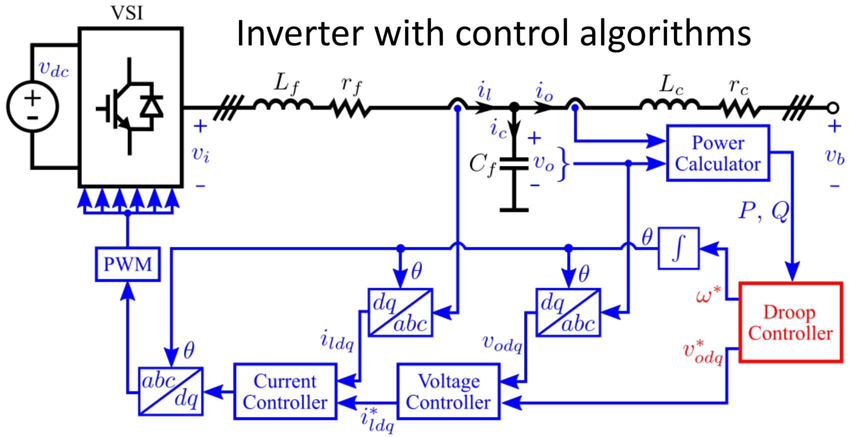
Representing Inverters Like Traditional Machines
Inverter as a Source behind an Impedance

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

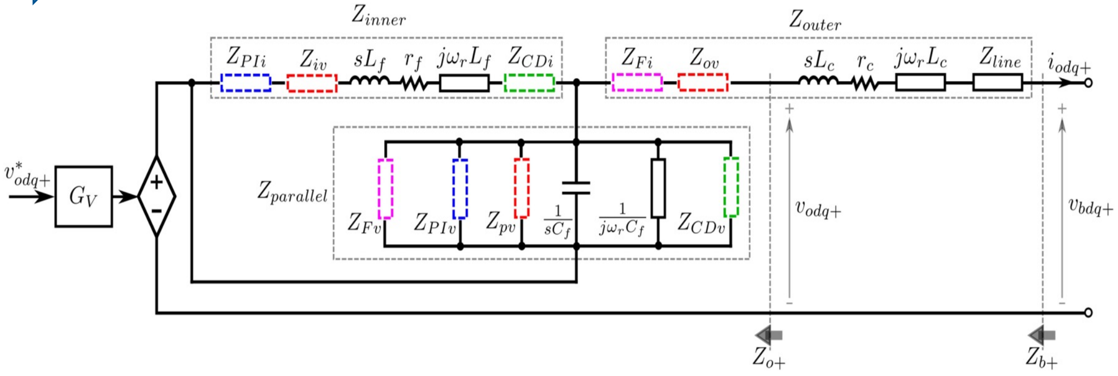
Each property can be expressed as a relationship between voltage and current.

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.

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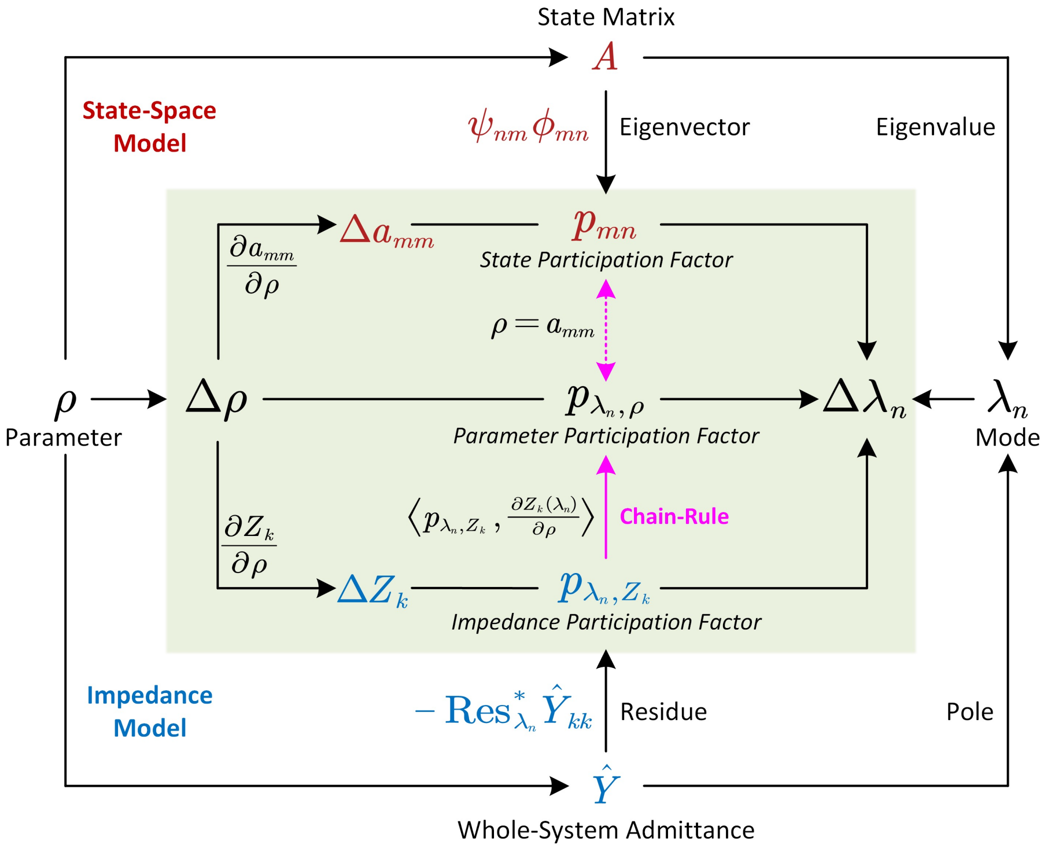
Looking Inside a Black Box to Create Grey Box Participation Analysis



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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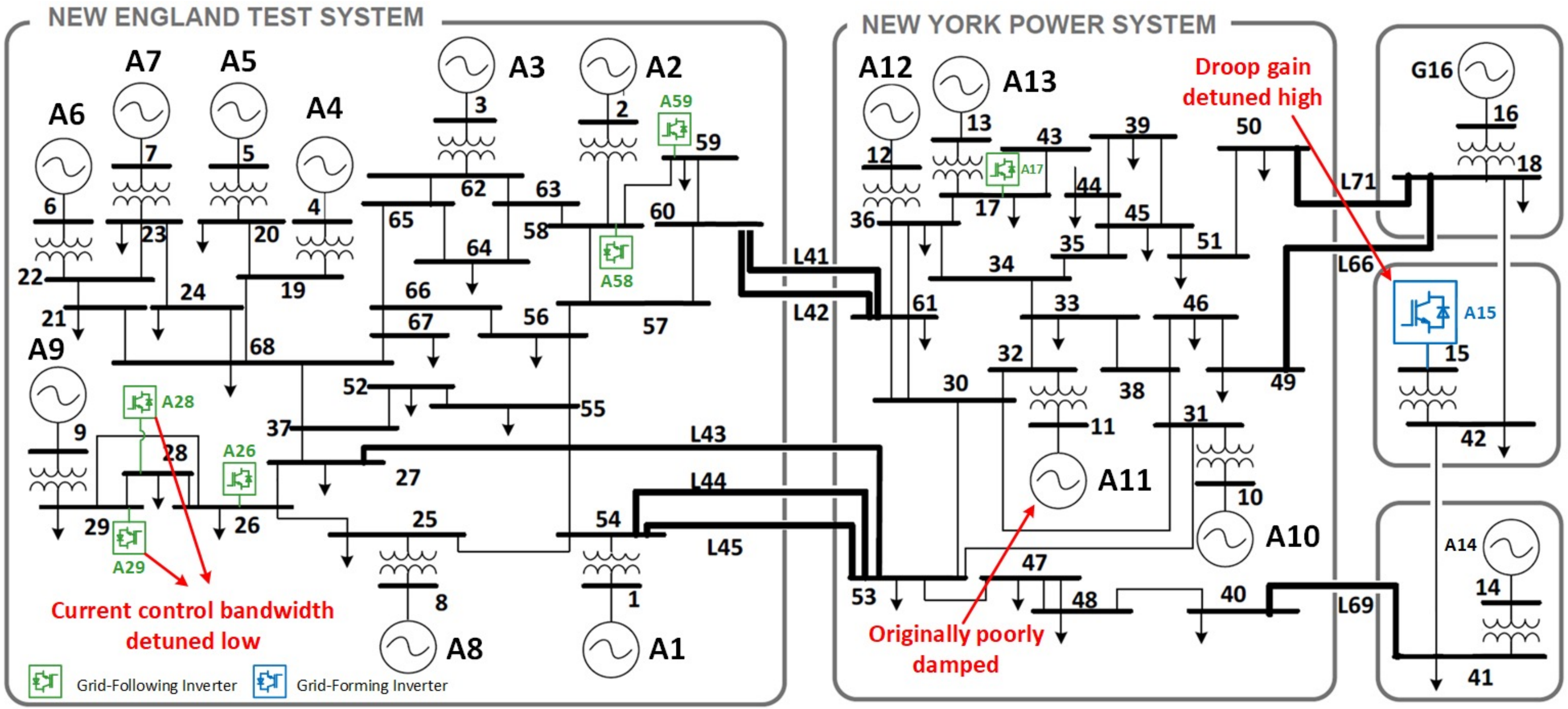
Illustration with modified NETS-NYPS

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, Under Review.

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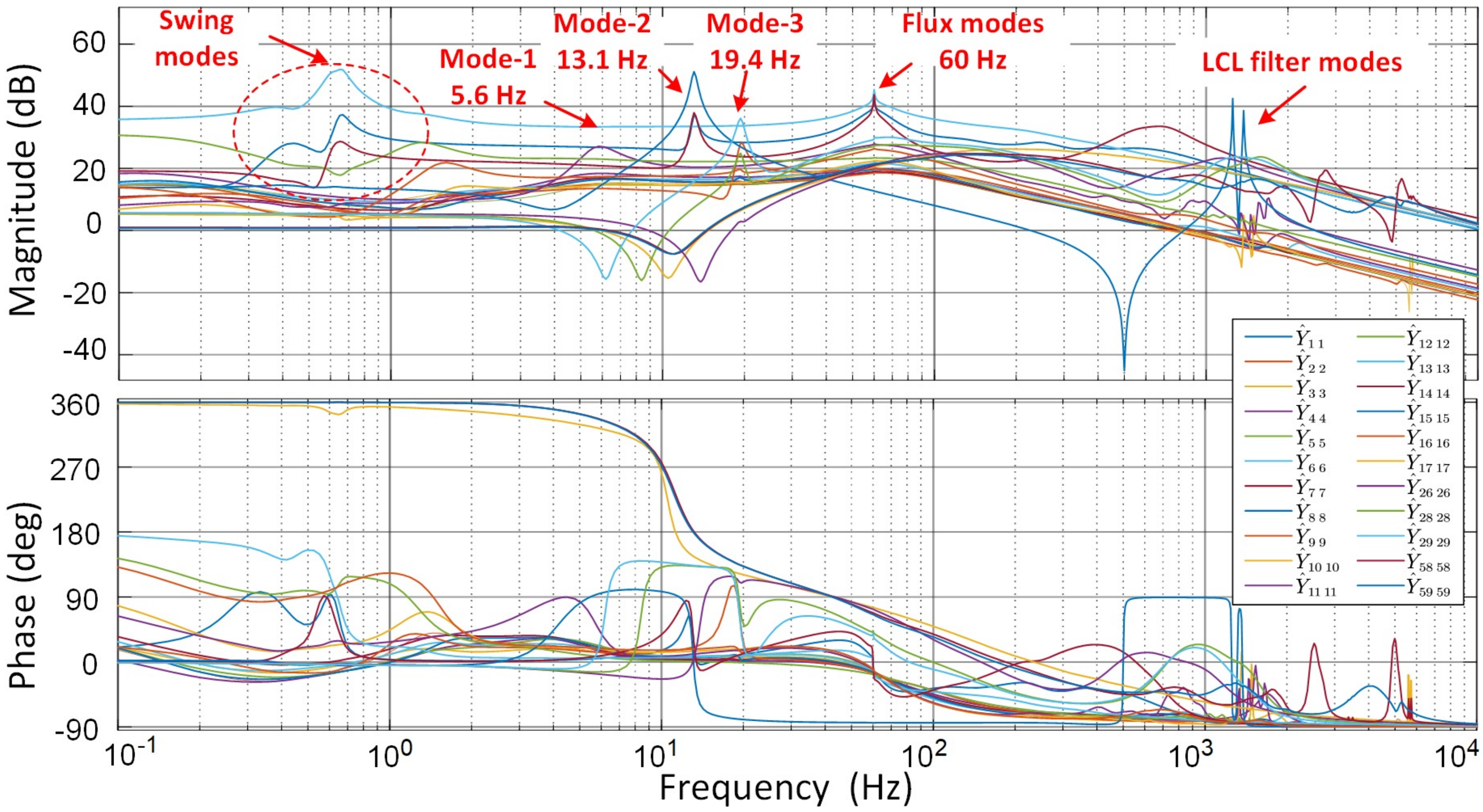
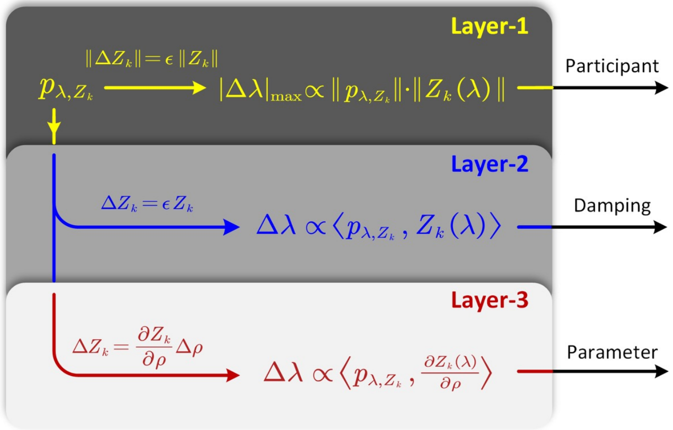
Identification of Modes in Elements of the Whole-System Admittance Matrix



Tuning Via Layer-3 Parameter Participation



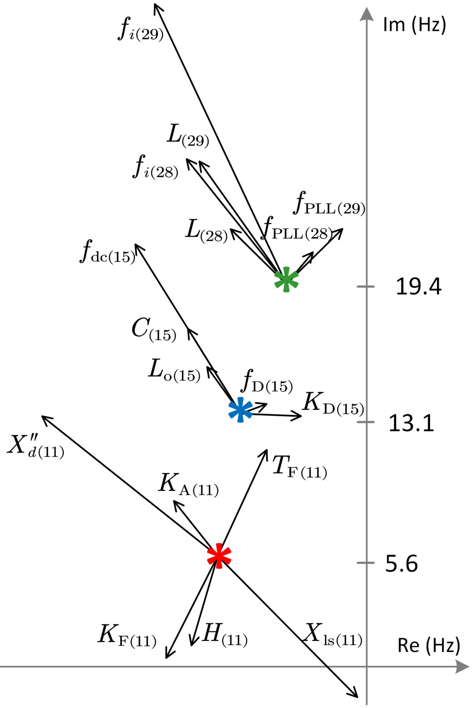
Residues of impedance at mode indicate whether large or smaller machine would improve damping

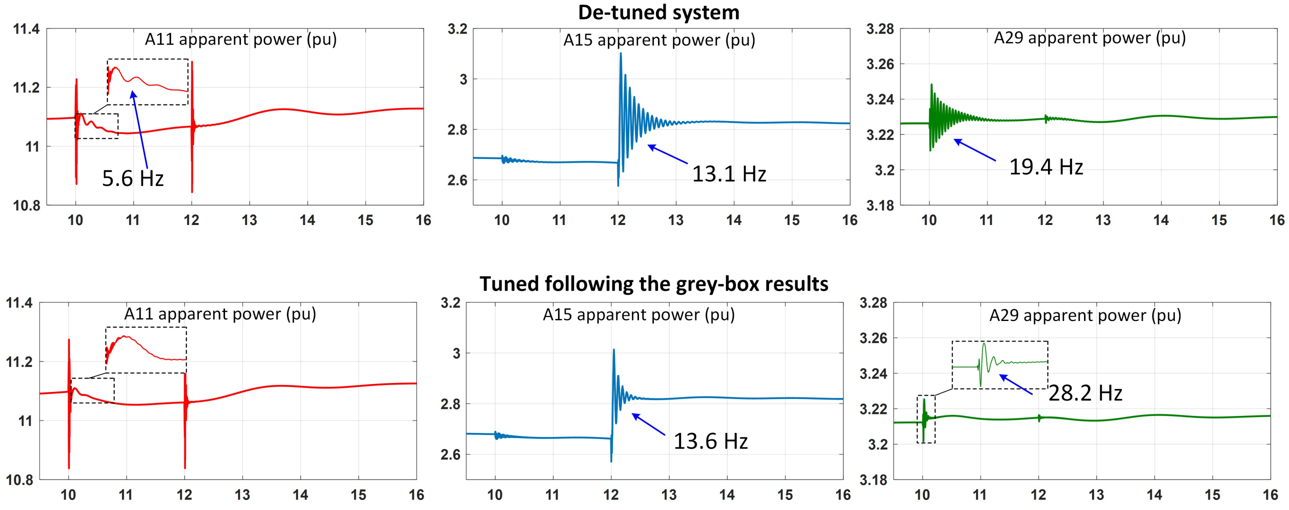
Chain-rule combination of residues and sensitivity of impedance to parameter indicate which direction to tune each parameter

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

- Mode-3 (19.4 Hz) (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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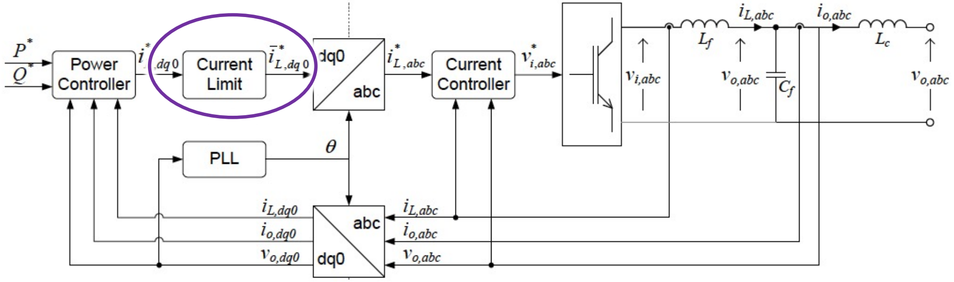
Fault Current Models and Protection Design

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 detection/location needs more work, and so do analysis tools

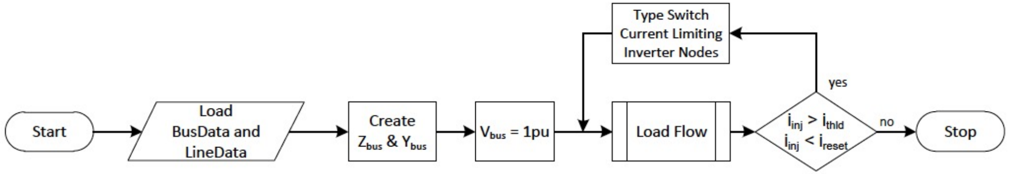
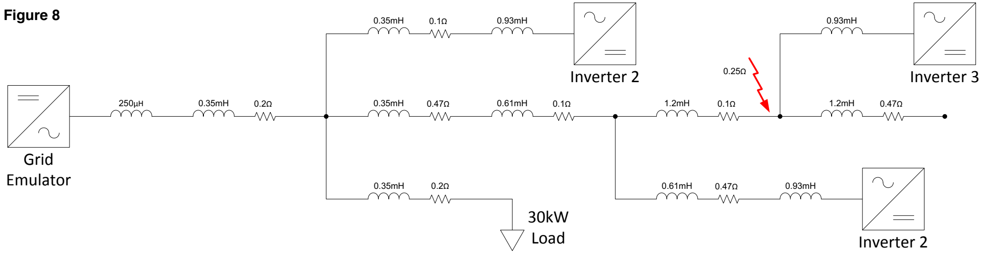
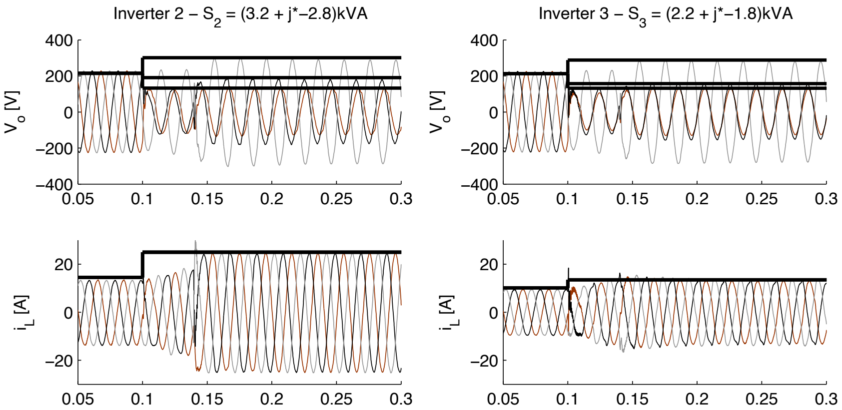


Figure 8





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/Needs in an IBR World

- Needs need to be met in aggregate not my every IBR
- Not all IBR can 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)
- Co-design of protection and IBR current-limits needed
- New network equipment (Statcom+) needed in place of the old (Synchronous Compensators)
- Responses to the G-PST Services/Needs white paper will help the debate

Tools/Models in an IBR World

- We need to analyse and synthesise (avoid trial-and-error synthesis)
- Guidelines on modelling adequacy and model reduction needed
- Time-domain simulation needs enhancement through new computational and model reduction techniques
- Black-box IBR models can be turned Grey and root cause analysis of small-signal stability performed
- Large-signal stability with non-linear causes under researched
- Tools to support dispatch of IBR services needed