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Addressing Oscillations In Planning and Connection Studies

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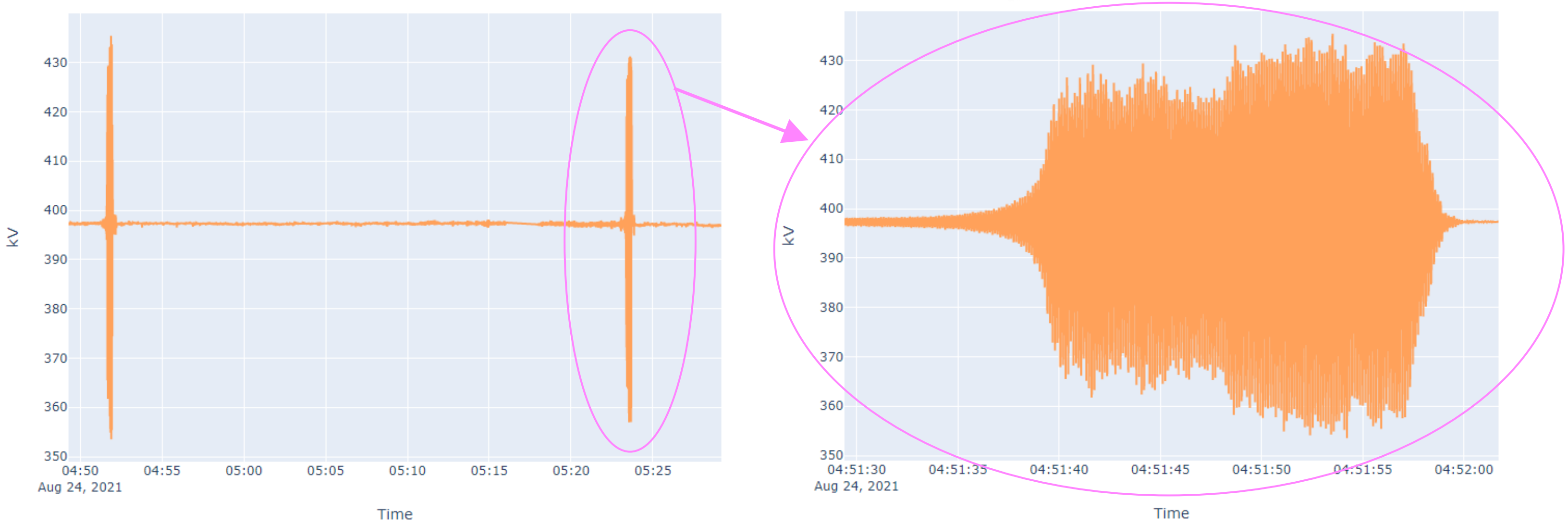
ESIG/G-PST Workshop 2024

Emergence of New Power System Oscillations

Example voltage oscillation in wind converters in Scotland in 2021.
Bursts of 8 Hz Oscillation of 30 kV at irregular intervals[1].

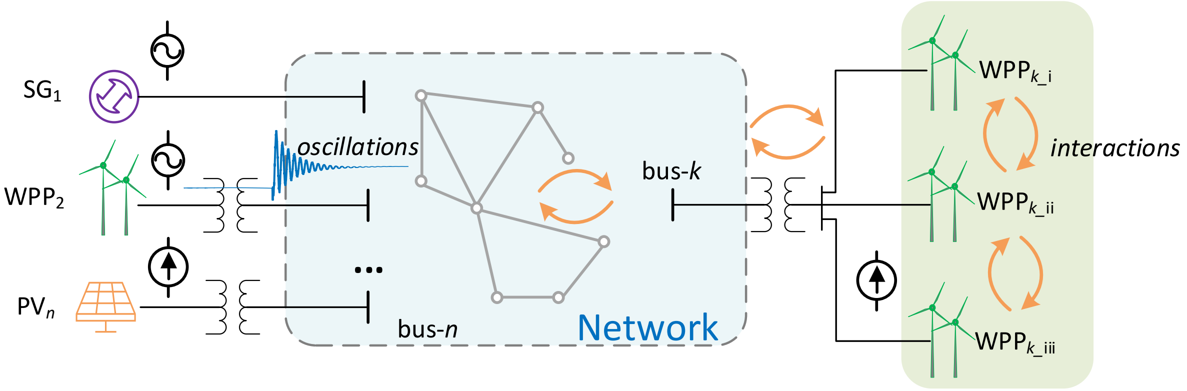


Ideally, one would have caught this in a connections study.

Second best, one would identify the root-cause post-event and re-tune as necessary.

[1] Nilesh Modi, Marta Val Escudero, Ken Aramaki, Xiaoyao Zhou and Pauli Partinen, “High Inverter-Based Resource Integration: The Experience of Five System Operators”, IEEE PES Magazine 2024

The Problems (in our experience)



The task is to identify risk of oscillation of IBR with closely located IBR and with other resources deeper in the networks

- IBR are complex, with dynamics on many overlapping time-scales and multiple mode-switch and saturation non-linearity features
- IBR vendors are extremely cautious about revealing details of controls
- For connection studies, System Operator gives Developer an overly-simple grid representation – perhaps only a single reactance.
- For system modelling, Developer gives System Operator either a generic model tuned for one condition or a black-box EMT models.
- EMT models require exhaustive testing against many operating conditions
- Simple metrics such as Short Circuit Ratio are over-used

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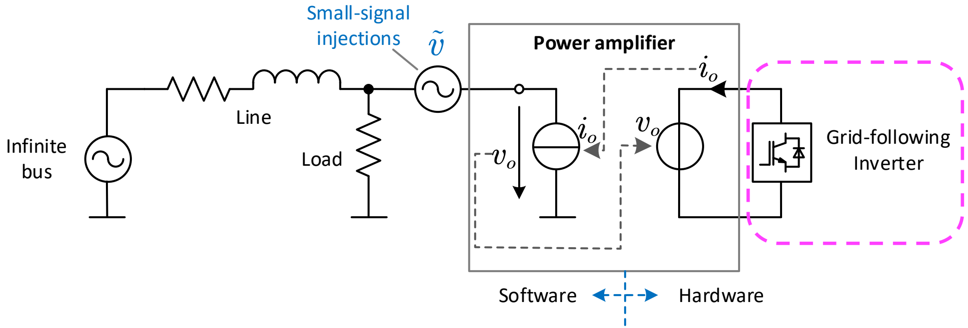
Over Coming Obscure Controls:
Grey-Box Models

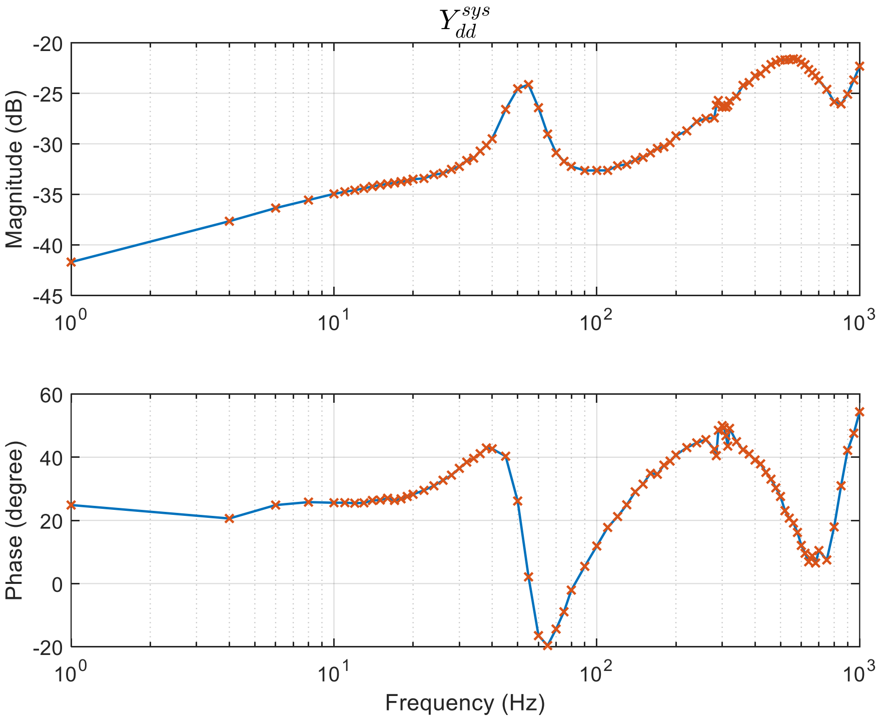
Impedance Spectra Methods to Overcome Control Obscurity

Impedance spectra are essentially transfer functions between current and voltage at the terminals of apparatus $Z(j\omega) = {}^{v(j\omega)}/_{i(j\omega)}$.

They exhibit the observable dynamics at point of connection but don’t disclose the internal structure.

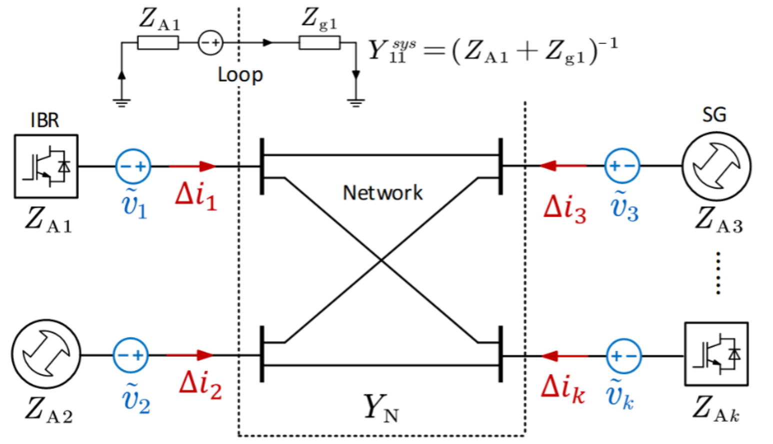
They can be measured physically or in EMT simulation of vendor-supplied black-box models.



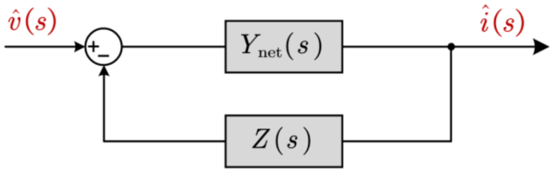


Whole-System Impedance Models

The system is partitioned between impedance of apparatus at nodes, $Z_A(s)$, and admittance of the network lines and cables, $Y_N(s)$.



$Y_N(s)$ and $Z_A(s)$ form a feedback loop from which we can define a "whole-system" admittance matrix mapping all voltages to all currents



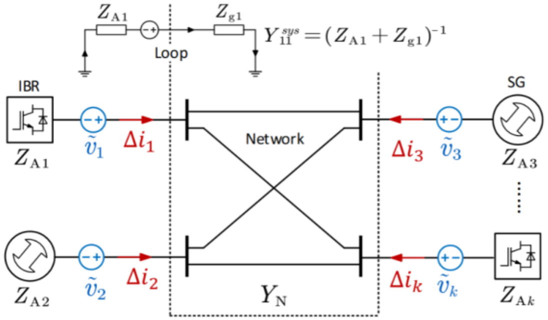
Diagonal terms like ${Y^{sys}}_{kk}$ relate voltage and current at same node, k, accounting for both the local equipment and all the rest of the network ${Y^{sys}}_{kk} = (Z_{Ak} + Z_{gk})^{-1}$.

$$Y^{sys} = (I + Y_N\, Z_A)^{-1}\, Y_N$$

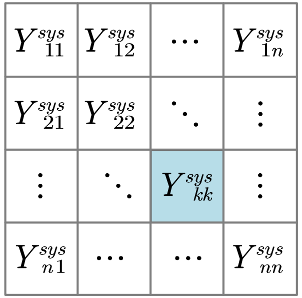
Y_{11}^{sys}	Y_{12}^{sys}	$\cdots$	Y_{1n}^{sys}
Y_{21}^{sys}	Y_{22}^{sys}	$\ddots$	$\vdots$
$\vdots$	$\ddots$	Y_{kk}^{sys}	$\vdots$
Y_{n1}^{sys}	$\cdots$	$\cdots$	Y_{nn}^{sys}

Small-Signal Stability from Whole-System Admittance Model

(Virtual) Voltage Injection

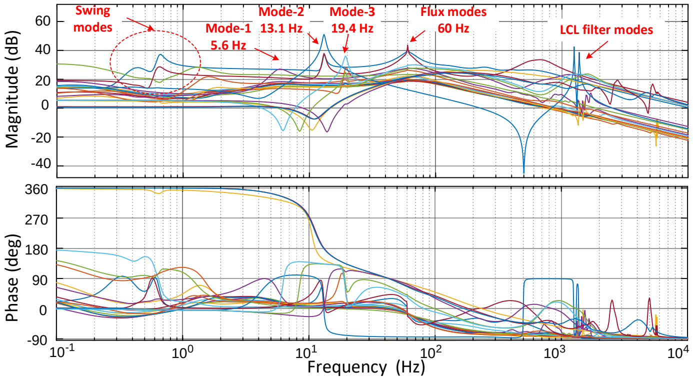


Whole-System Admittance



$$\begin{array}{|c|c|c|c|}\hline Y_{11}^{sys} & Y_{12}^{sys} & \cdots & Y_{1n}^{sys} \\ \hline Y_{21}^{sys} & Y_{22}^{sys} & \ddots & \vdots \\ \hline \vdots & \ddots & Y_{kk}^{sys} & \vdots \\ \hline Y_{n1}^{sys} & \cdots & \cdots & Y_{nn}^{sys} \\ \hline \end{array}$$

Admittance Spectra



Factorization or Vector Fitting

$$Y_{kk}^{sys}(s) = \frac{R_1}{s-\lambda_1} + \frac{R_2}{s-\lambda_2} \cdots + \frac{R_n}{s-\lambda_n}$$

← Residue

← Pole (Mode)

Impedance Participation

$$\Delta\lambda = \left\langle -\mathrm{Res}_{\lambda}^{*} Y_{kk}^{sys}, \Delta Z_{Ak}(\lambda) \right\rangle$$

Change in oscillatory mode

Residue

Chang in local impedance

Y. Zhu, Y. Gu, Y. Li, T.C. Green, “Participation Analysis in Impedance Models: The Grey-Box Approach for Power System Stability”, IEEE TPWRS 2022

Advantages of Whole-System Impedance Methods

- Impedances of equipment can be measured from
  - real plant
  - or from vendor-supplied EMT models
- Impedances do not disclose the internal control details
- The whole-system impedance captures the interactions of an IBR with both the network impedances and the impedances of other close and remote IBR
- The residues of the poles of a whole-system impedance model give useful information for identifying the root-cause of an oscillation and for subsequent re-tuning

- **But** impedance models are linear models valid only for a small region around the operating point at which they were obtained.

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Connection Strength Study

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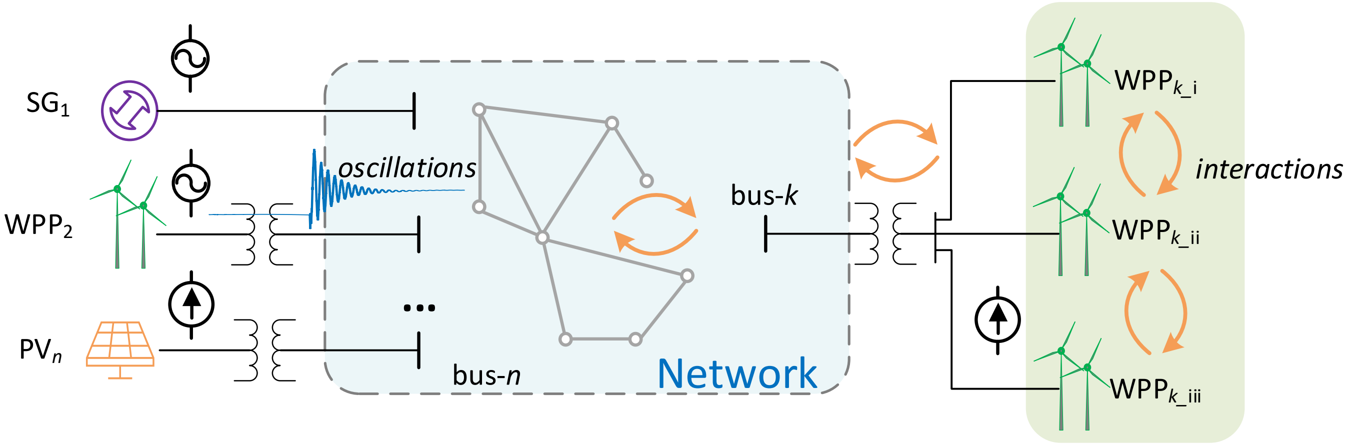
Descriptions of “System Strength”

18-month study “Strength to Connect” supported by National Grid ESO



Potential problems are:

- potential instability of grid-following inverters,
- inadequate voltage regulation,
- increased recovery times from voltage dips,
- mal-operation of protection.

SCR (short-circuit ratio) has been used as a universal metric

- Equivalent $^1/_{Z_{th\,pu}}$
- Thevenin impedance at connection point was good indicator for synchronous machine world
- But not for IBRs (different synchronisation, prominent non-linearities, actual fault current not the issue, etc.)

Small-Signal Stability of GFM and GFL

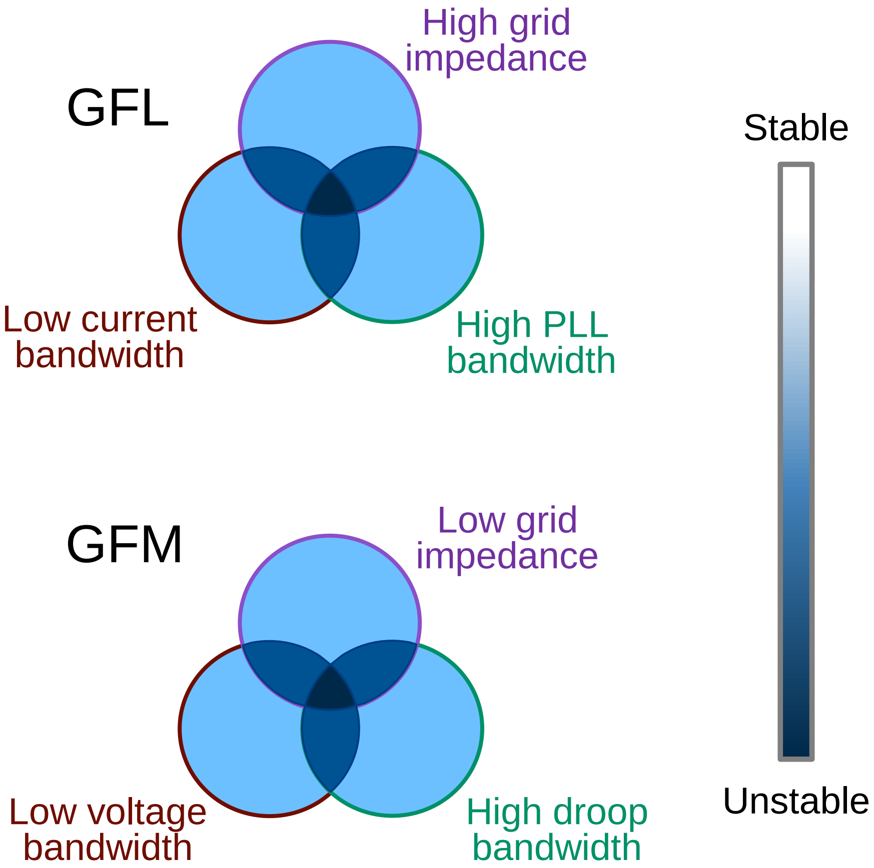
Local interactions can occur between

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

For instance,

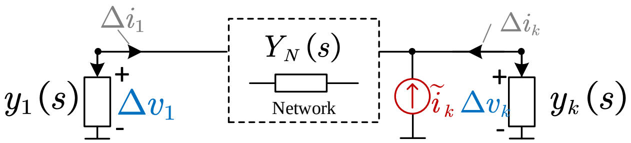
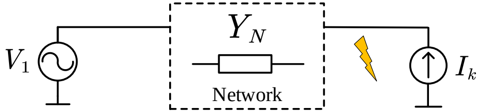
- disturbance of PLL angle perturbs current controllers
- changes injected current of GFL inverter
- voltage drop over grid impedance is disturbed
- voltage couples back into PLL.

SCR is not a sufficient indicator of small-signal stability because it reflects only one of the several local factors and ignores interactions deep in networks



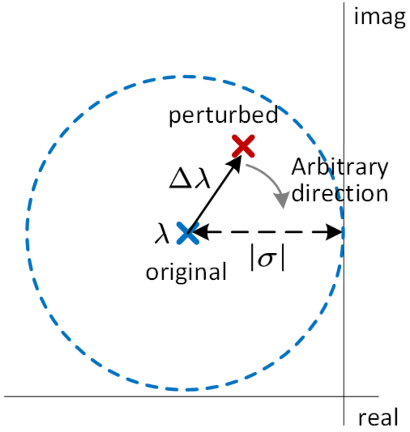
Y.Li, Y. Gu, T.C Green, “Revisiting Grid-Forming and Grid-Following Inverters: A Duality Theory”, IEEE Trans PWRS 2022.

Classification of System Strength Metrics

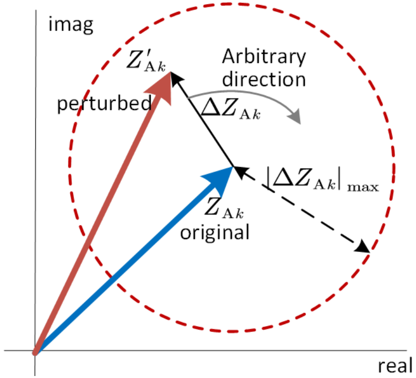
	Small-Signal Strength	Large-Signal Strength
		
Use Cases	• Potential poorly damped oscillations and potential instability caused by interactions between inverters	• Inadequate voltage regulation, • Poor recovery from voltage dips, • Low fault current or false fault current injection.
Features	• Small perturbations around operating point • Frequency-domain analysis • Small-signal models of IBRs are used	• Large perturbations such as faults • Fundamental frequency analysis (extension of SCR) • Nonlinear system when IBRs are used
Possible Metrics	• Grid strength impedance metric (GSIM) • Generalized short-circuit ratio (gSCR) • Impedance Margin Ratio (IMR)	• Composite short-circuit ratio (CSCR) • Weighted short-circuit ratio (WSCR) • Equivalent short-circuit ratio (ESCR) • Voltage sensitivity • Actual fault current calculation.

Impedance Margin Ratio (IMR)

Mode margin (complex plane)



Impedance margin ($s=\lambda$)



Principle is:

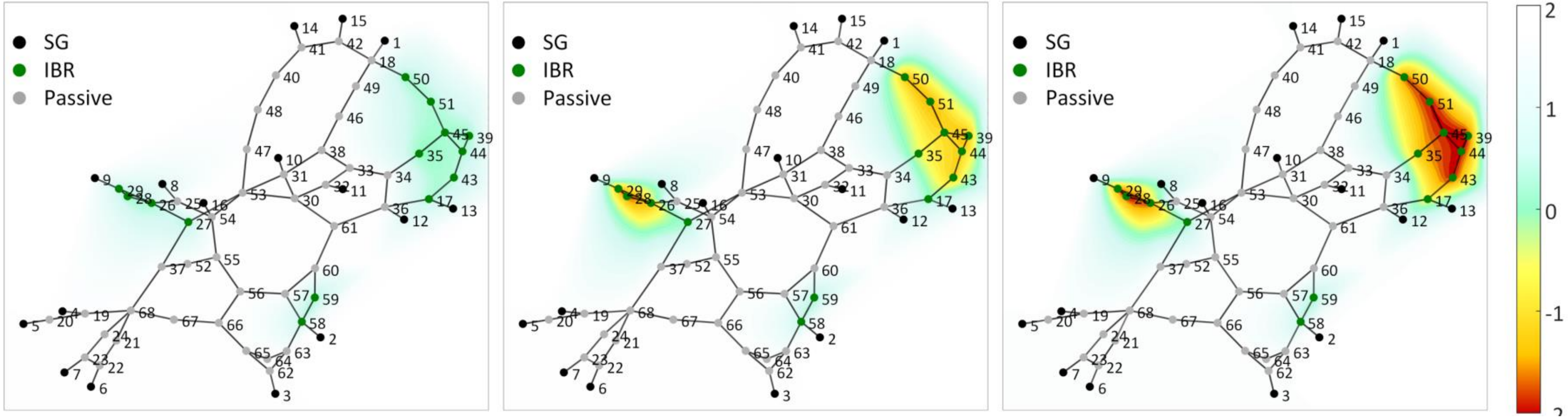
- Define how much the least stable mode can be allowed to change as $\Delta\lambda_{max} = |\sigma|$
- Map allowed max change of mode to change in impedance of the apparatus using grey-box method: $\Delta\lambda = \langle -Res_{\lambda}^{*} Y_{kk}^{sys}, \Delta Z_{Ak}(\lambda) \rangle$
- This is the Impedance Margin $\Delta Z_{Ak}(\lambda) = \frac{|\sigma|}{\|Res_{\lambda}^{*} Y_{kk}^{sys}\|}$
- Define the ratio of max allowed change to original value of impedance, $IMR = \frac{\|\Delta Z_{Ak}(\lambda)\|_{max}}{\|Z_{Ak}(\lambda)\|} = \frac{|\sigma|}{\|Res_{\lambda}^{*} Y_{kk}^{sys}\| \|Z_{Ak}(\lambda)\|}$

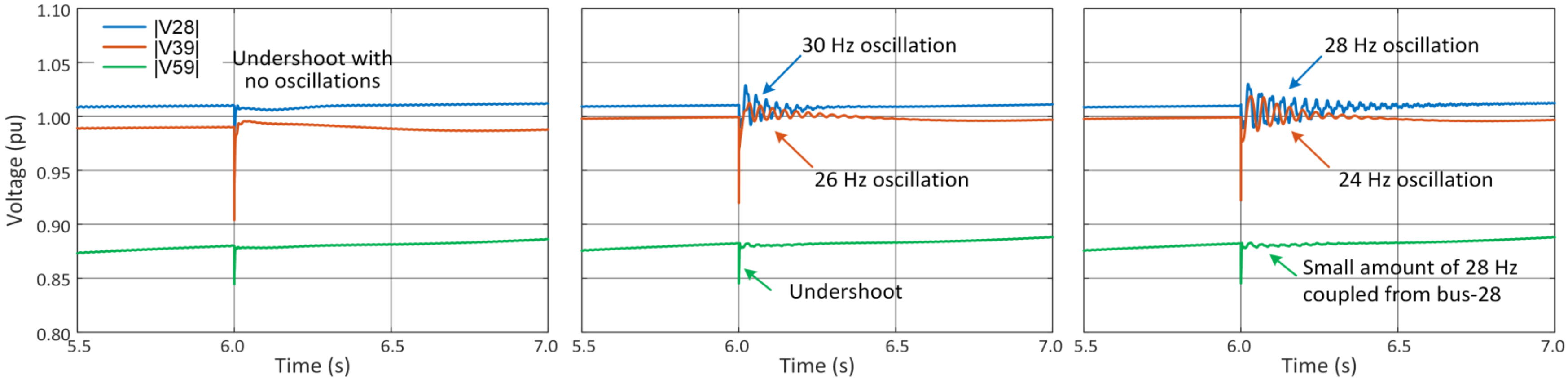
- A large IMR means the mode is relatively insensitive to the connected apparatus, *i.e.*, system is strong at given location.
- A small IMR means the system is prone to be unstable when the IBR at that location is varied, *i.e.*, system is weak at given location.
- When multiple modes are present, the small-signal strength is determined by the critical (minimum) IMR.

Y. Zhu, T. C. Green, X. Zhou, Y. Li, D. Kong and Y. Gu, “Impedance Margin Ratio: a New Metric for Small-Signal System Strength”, IEEE TPWRS, 2024

IMR Heat Map of IBR-dominated IEEE 68-Bus System

IBR Well Tuned → IBR Badly Tuned → IBR Very Badly Tuned





Undershoot with no oscillations

30 Hz oscillation

26 Hz oscillation

Undershoot

28 Hz oscillation

24 Hz oscillation

Small amount of 28 Hz coupled from bus-28

How are buses without apparatus assessed?

With no apparatus impedance ($Z_A = \infty$), IMR is undefined.

Swap to considering apparatus admittance ($Y_A = 0$) and use residue of whole-system impedance.

Change in mode can be expressed as $\Delta\lambda = \langle -Res_{\lambda}^{*} Z_{kk}^{sys}, \Delta Y_{Ak}(\lambda) \rangle$

Set maximum change of mode to real part of the mode, $|\Delta\lambda|_{max} = |\sigma|$

Worst-case (angle unknown) change is $|\Delta\lambda|_{max} = \left\| Res_{\lambda}^{*} Z_{kk}^{sys} \right\| \cdot \|\Delta Y_k\|_{max}$

Now define the admittance margin, $AM = \|\Delta Y_k(\lambda)\|_{max} = \frac{|\sigma|}{\left\| Res_{\lambda}^{*} Z_{kk}^{sys} \right\|}$

We don’t normalise (not expressed as ratio)

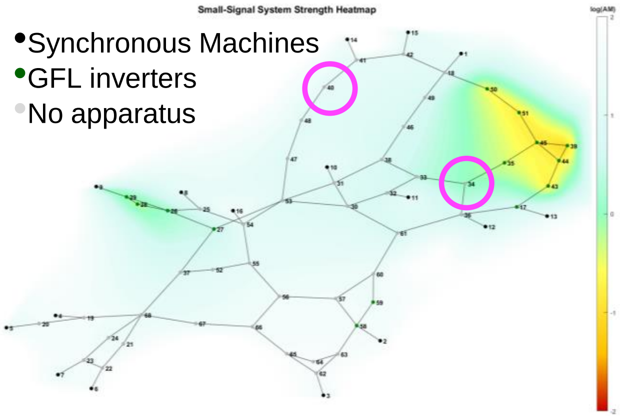
Admittance margin (AM) shows the maximum allowed change in the admittance at bus *k* at $s = \lambda$ for which it is guaranteed that mode λ will remain at the left-hand plane.

A larger AM value indicates high small-signal “strength”

AM Heatmaps for Modified IBR-Dominated IEEE 68-bus system

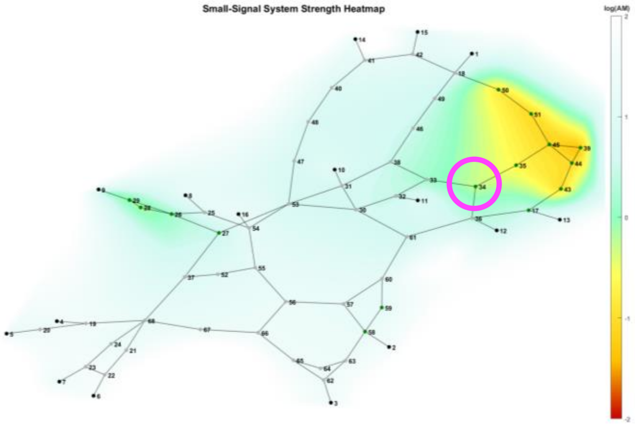
Initial Configuration

● Synchronous Machines
● GFL inverters
● No apparatus



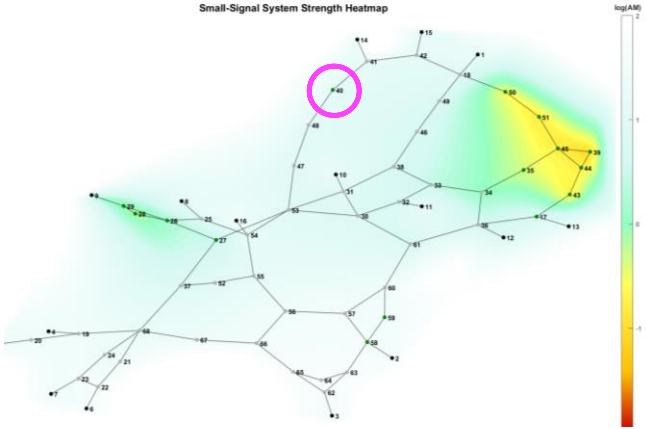
- AM can be assessed at all busses
- Bus 34 has lower strength than bus 40
- There is a higher risk of instability for adding equipment at bus 34 than at 40

GFL inverter added to bus 34



- AM at bus 34 reduces with addition of a GFL inverter
- AM of nearby buses reduced as well

GFL inverter added to bus 40

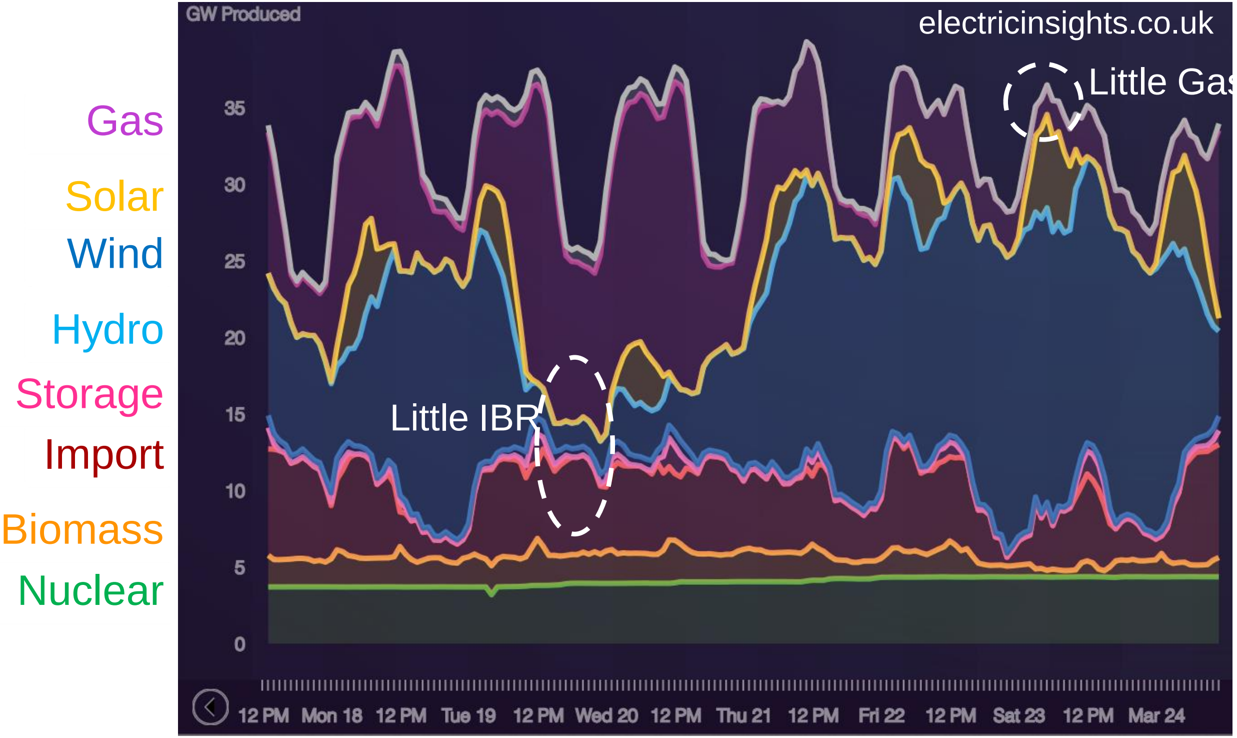


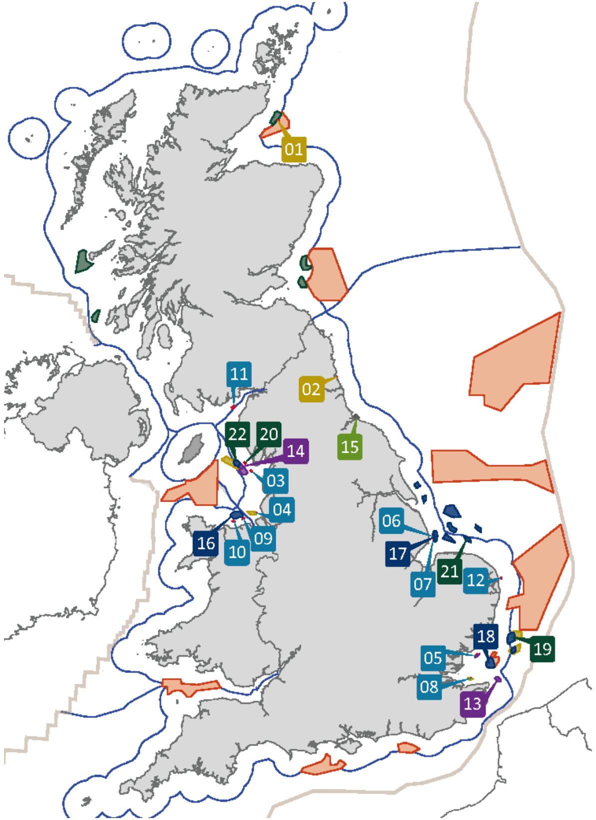
- AM at bus 40 reduces slightly but location remains “strong”
- AM of nearby buses not significantly affected

Operating Point Variation
and
Grid Evolution

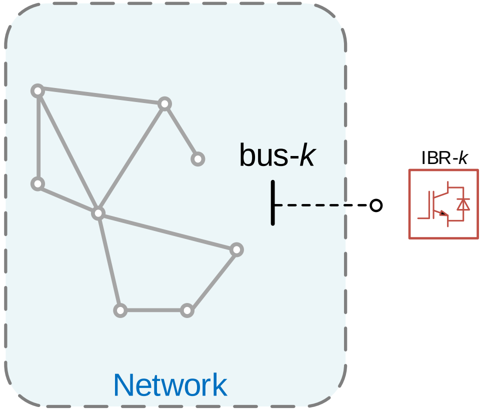
IBR Dominance – Sometime, Somewhere

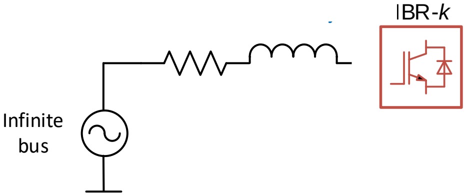
Generation (GW) in Great Britain w/b 18th March 2024





How is Variability of System Dynamics Captured for Connection Studies





- A Thevenin equivalent impedance (diagonal element of whole-system impedance) can capture all the small-signal features for one operating point and is a compact representation.
- Could exhaustively identify all operating conditions.
- We are exploring clustering methods methods to reduce number of representations and produce a “model bank” for connection studies

- Still need to address grid evolution during lifetime of an IBR through both addition of new IBR and retirement of other resources.

- Competing approaches:
  - Local stability guarantees – tend to be very conservative
  - Standardised envelopes for IBR impedances in critical frequency ranges

Conclusions

Conclusions

- Black-box IBR models can be turned into grey-box models and root cause analysis of small-signal stability performed.
- Impedance spectra can be obtained from measurements or EMT models
- Impedance Margin Ratio (IMR) good for capturing risk of interaction instability of a given IBR in a complete network
- Admittance Margin (AM) good for indicating small-signal strength before specified IBR connection but does not capture new interaction modes.

Open Issues

- For small-signal stability assurance, time-varying operating points need to be tracked
- Connection studies need a wide range of consideration and still aren't fit-and-forget

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Publications Details

Title	Journal	OA Link
Impedance Margin Ratio: a New Metric for Small-Signal System Strength	IEEE Trans PWRS 2024	https://doi.org/10.36227/techrxiv.24196386.v1
Analytical Design of Contributions of Grid-Forming & Grid-Following Inverters to Frequency Stability	IEEE Trans PWRS 2024	http://hdl.handle.net/10044/1/109112
The intrinsic communication in power systems: a new perspective to understand synchronisation stability	IEEE Trans CAS 2023	https://arxiv.org/abs/2103.16608
Injection Amplitude Guidance for Impedance Measurement in Power Systems	IEEE Trans PELS 2023	http://hdl.handle.net/10044/1/103480
Power System Stability with a High Penetration of Inverter Based Resources	IEEE Proc 2023	http://hdl.handle.net/10044/1/105983
Impedance-based Root-cause Analysis: Comparative Study of Impedance Models and Calculation of Eigenvalue Sensitivity	IEEE Trans PWRS 2023	http://hdl.handle.net/10044/1/97635
Revisiting Grid-Forming and Grid-Following Inverters: The Duality Theory	IEEE Trans PWRS 2022	https://arxiv.org/abs/2105.13094
Mapping of Dynamics between Mechanical and Electrical Ports in SG-IBR Composite Power Systems	IEEE Trans PWRS 2022	http://arxiv.org/abs/2105.06583
Participation Analysis in Impedance Models: The Grey-Box Approach for Power System Stability	IEEE Trans PWRS 2022	http://hdl.handle.net/10044/1/90192
Impedance Circuit Model of Grid-Forming Inverters: Visualizing Control Algorithms as Circuit Elements	IEEE Trans PELS 2021	http://hdl.handle.net/10044/1/82204

Thank You