Imperial College London

Observability of Modes in Power Systems Through Signal Injection

Final Year Project Presentation

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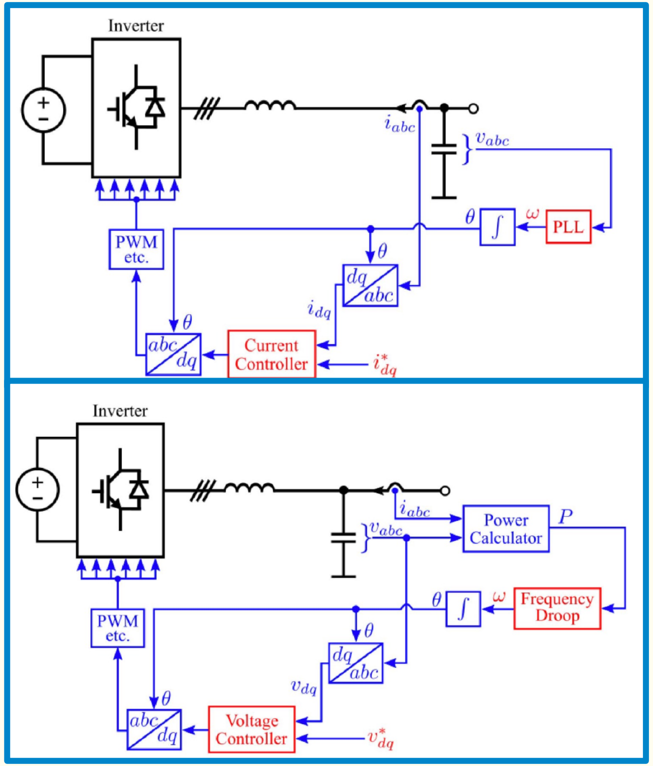
Contents

Inverter-based Resources

- Generation based on AC-to-DC converters.
- E.g. solar, wind, some tidal.
- Used for DC-DC links.
- Two modes: grid following (GFL) and grid forming (GFM).
- Control systems kept secret by manufacturers – models may be inaccurate.

GFL inverter

GFM inverter



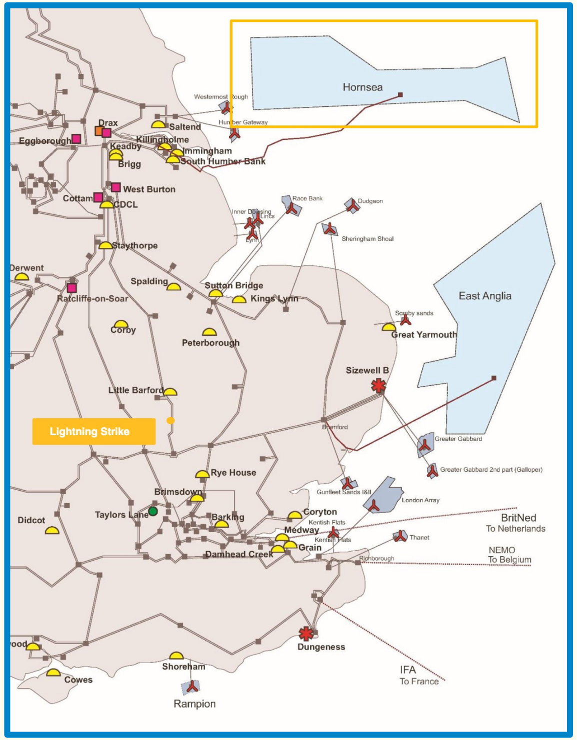
Grid Oscillations

- Grid simulated with no instability.
- Tests pass = commissioned.
- Texas (Oct 2009)
  - lack of damping caused resonance between DFIG and series compensation
  - damage to WTG due to overcurrent
- China (Dec 2012, Feb 2013)
  - same suspected cause
  - unstable oscillation
  - don’t always show up: dependent on number of WTGs in service, wind speed, power outputs

[2] [3]

9th August 2019 – Hornsea One

- Lightning causes fault and voltage sag.
- Circuit breakers disconnect line.
- Hornsea One reactive power injection rises to maintain system voltage.
- WTGs enter oscillation and trip.
- Loss of 737 MW of generation from Hornsea One.
- Total loss of 1,878 MW leads to load shedding.
- 3.2% disconnected.



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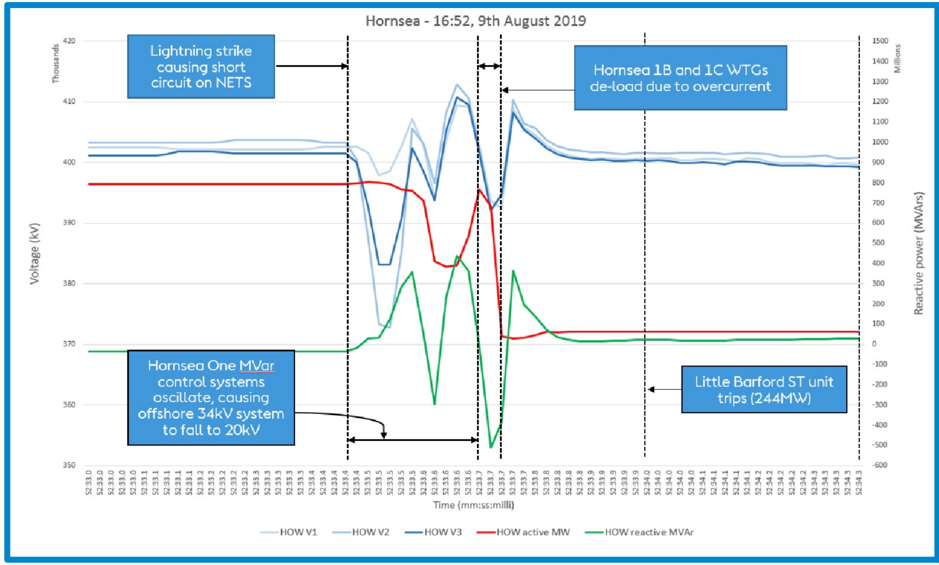
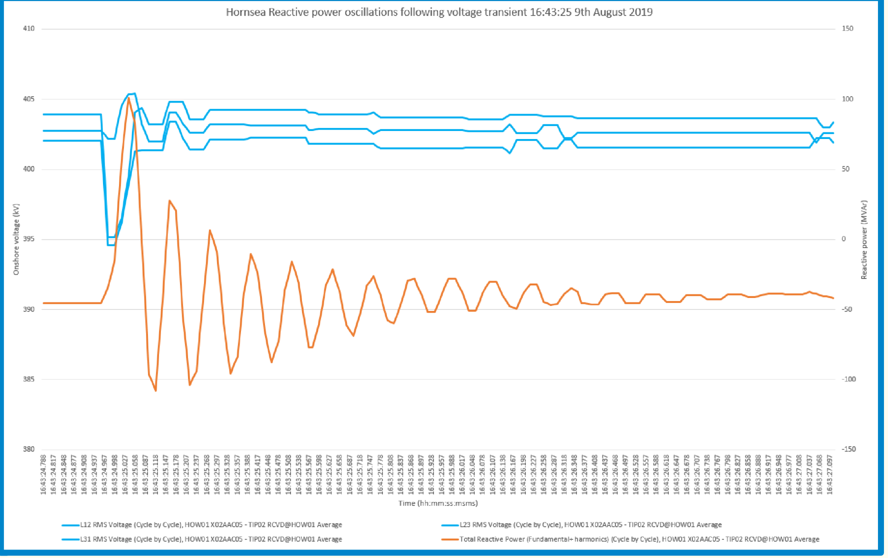
9th August 2019 – Hornsea One





Impedance and System Poles

- Can express system impedance in matrix form.
- Nodal admittance matrix Y_N and apparatus admittance matrix Y_A as elements.

$$Y_N = \begin{bmatrix} Y_{N,11}(s) & \dots & Y_{N,1n}(s) \\ \vdots & \ddots & \vdots \\ Y_{N,n1}(s) & \dots & Y_{N,nn}(s) \end{bmatrix}$$

$$Y_A = \begin{bmatrix} Y_{A,1}(s) & 0 & \dots & 0 \\ 0 & Y_{A,2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & Y_{N,n}(s) \end{bmatrix}$$

Impedance and System Poles

$$Y^{nodal} = Y_N + Y_A$$

$$Z^{sys} = Z_A(I + Y_N Z_A)^{-1}$$

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

$$(Z^{sys})^{-1} = \left((I + Y_N Z_A)^{-1}\right)^{-1} Y_A = Y_A + Y_N$$

$$Y_A = (Z_A)^{-1}$$

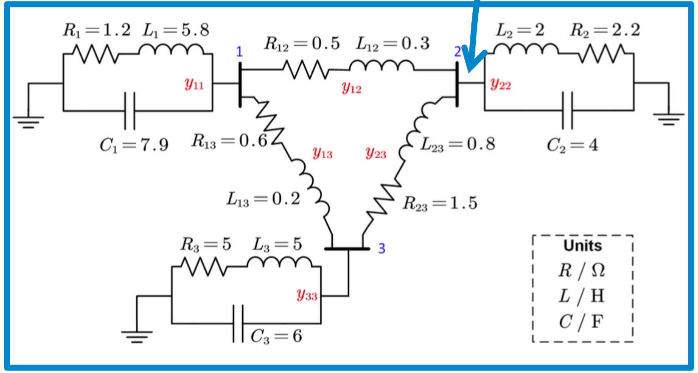
$$Z^{sys} \neq (Y^{sys})^{-1}$$

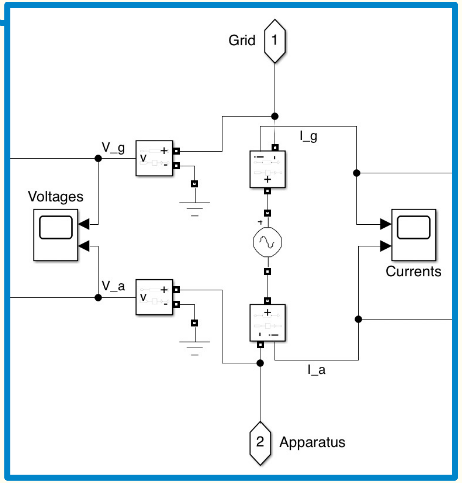
- **Poles of Z_{kk}^{sys} = poles of system.**
- **Zeros of $\det(Y^{nodal})$ = poles of system.**
- Interested in complex conjugate poles – sources of oscillations.

System Tuning

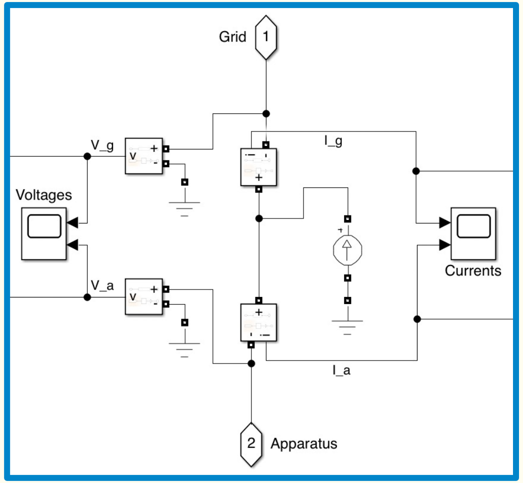
- Multiple methods for analising system modes and how to change them.
- Grey Box Approach:
  - Layer 1: identify most significant contributors to a particular mode.
  - Layer 2: analyse how changes in impedance of a particular apparatus move the pole.
  - Layer 3: quantify impedance changes in terms of parameter variations of the apparatus in question.

Single-phase Impedance Measurement





voltage injection,
current measurement



current injection,
voltage measurement

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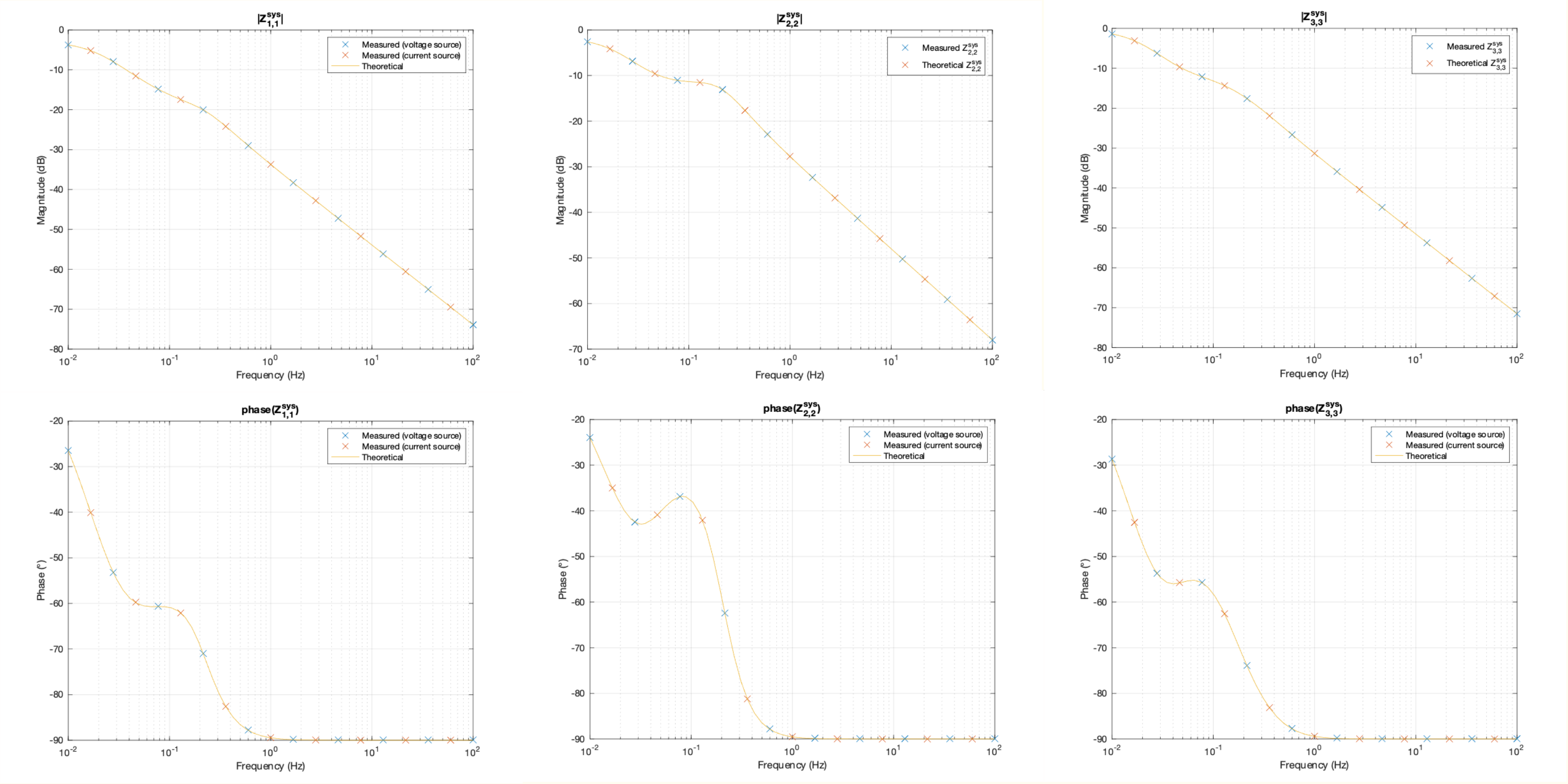
Observability of Modes in Power Systems Through Signal Injection



Vector Fitting

- Reconstruct transfer function of a system based on data points.
- Specify number of poles to fit to.
- Better to specify high number of poles – higher chance of identifying actual system poles.

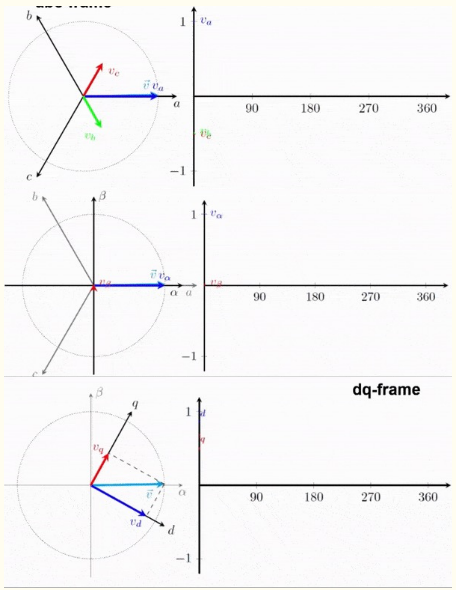
Eigenvalue (pole)	Value
λ_1	-2.4973
λ_2	-1.4524
λ_3	-1.0769
$\lambda_{4,5}$	$-0.8366 \pm 0.9678i$
$\lambda_{6,7}$	$-0.9447 \pm 0.2697i$
$\lambda_{8,9}$	$-0.1297 \pm 0.0451i$

Vector fitting conditions	**Complex conjugate poles**		
Analytical poles	$-0.8366 \pm 0.9678i$	$-0.9447 \pm 0.2697i$	$-0.1297 \pm 0.0451i$
92 samples, 9 poles	$-0.8366 \pm 0.9678i$ $-1.7402 \pm 1.8309i$	$-0.9447 \pm 0.2697i$ -6321.5 ± 9214.3	$-0.1297 \pm 0.0451i$
92 samples, 15 poles	$-0.8366 \pm 0.9678i$	$-0.9447 \pm 0.2697i$	$-0.1297 \pm 0.0451i$
92 samples, 30 poles	$-0.8366 + 0.9678i$	$-0.9447 \pm 0.2697i$	$-0.1297 \pm 0.0451i$
	8 more complex conjugate poles		
20 samples, 7 poles	$-0.7520 \pm 0.9130i$		
20 samples, 8 poles	$-0.8369 \pm 0.9676i$	$-0.9459 \pm 0.2719i$	$-0.1298 \pm 0.04485i$
20 samples, 9 poles	$-0.8366 \pm 0.9683i$	$-0.9439 \pm 0.2717i$	$-0.1296 \pm 0.0452i$
20 samples, 15 poles	$-0.8329 + 0.9696i$ $-8055.5 \pm 1830.6i$	$-0.9281 \pm 0.2632i$	$-0.1281 \pm 0.04676i$

Three-phase Impedance Measurement – Basics

- 3 x 3 matrix of impedances for each node.
- Use transformation from *abc* to *dq0* – Clarke and Park transforms.
- Balanced system leads to 0 component being 0.
- Impedance reduces to 2 x 2 matrix of “DC” system.

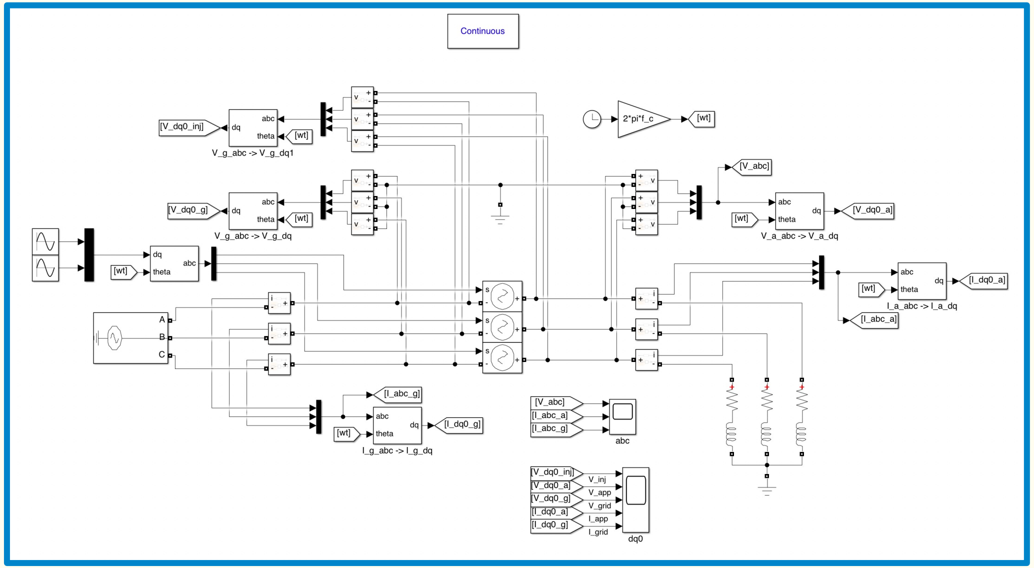
$$\begin{bmatrix} v_d(s) \\ v_q(s) \end{bmatrix} = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix} \begin{bmatrix} i_d(s) \\ i_q(s) \end{bmatrix}$$

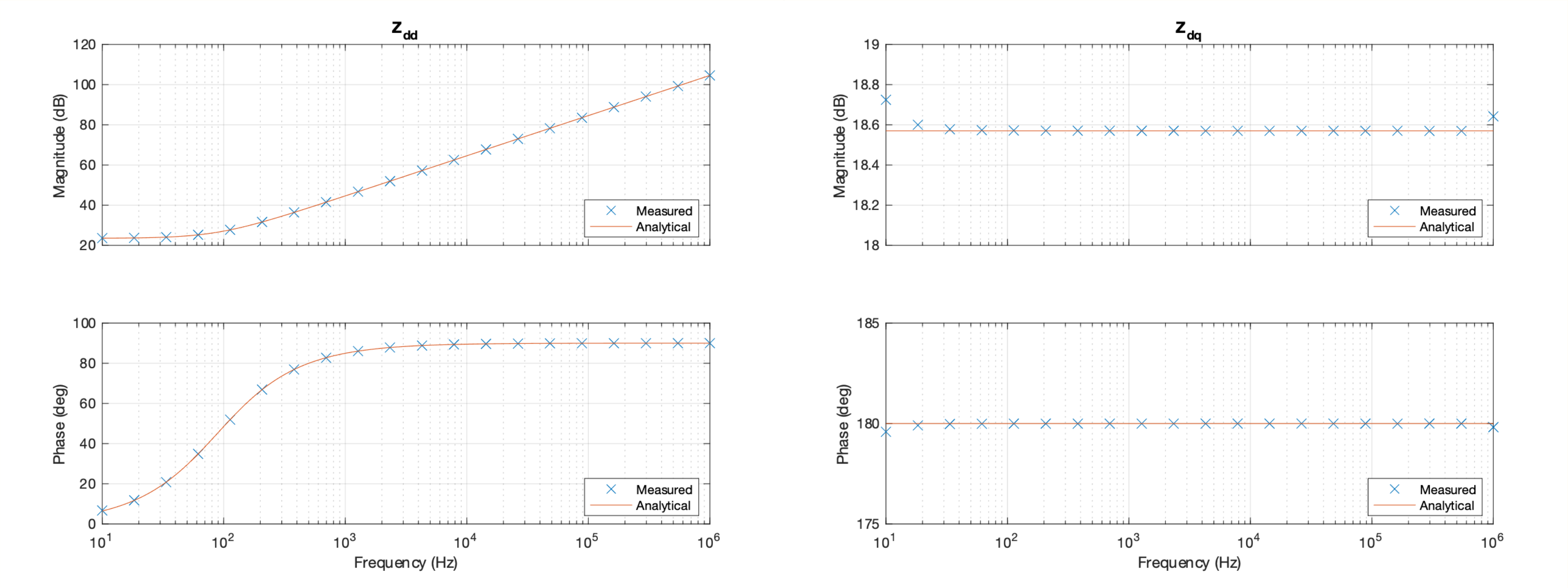


Three-phase Impedance Measurement – System 1

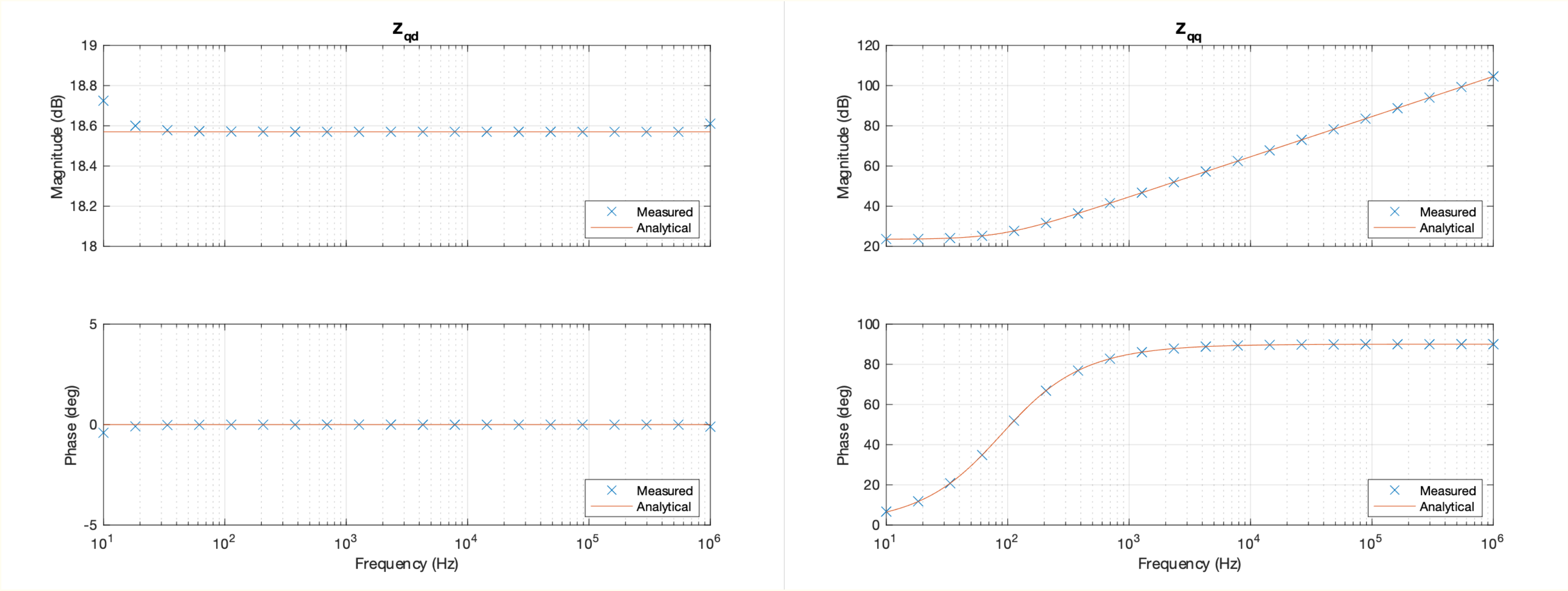
- 2 equations with 4 unknowns.
- Need to take 2 measurements with independent injections.
- Solve the resultant 4 equations with 4 unknowns.

$$\begin{bmatrix} i_{d1}(s) & i_{q1}(s) \\ i_{d2}(s) & i_{q2}(s) \end{bmatrix}^{-1} \begin{bmatrix} v_{d1}(s) & v_{d2}(s) \\ v_{q1}(s) & v_{q2}(s) \end{bmatrix} = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix}$$




Z dd
Z dq
Magnitude (dB)
Phase (deg)
Frequency (Hz)
Measured
Analytical
120
100
80
60
40
20
0
19
18.8
18.6
18.4
18.2
18
185
180
175
10^1
10^2
10^3
10^4
10^5
10^6

R = 15 Ω, L = 27 mH


Z_{qd}
Magnitude (dB)
19
18.8
18.6
18.4
18.2
18
Measured
Analytical
Phase (deg)
5
0
-5
Measured
Analytical
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hz)
Z_{qq}
Magnitude (dB)
120
100
80
60
40
20
Measured
Analytical
Phase (deg)
100
80
60
40
20
0
Measured
Analytical
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hz)

R = 15 Ω, L = 27 mH

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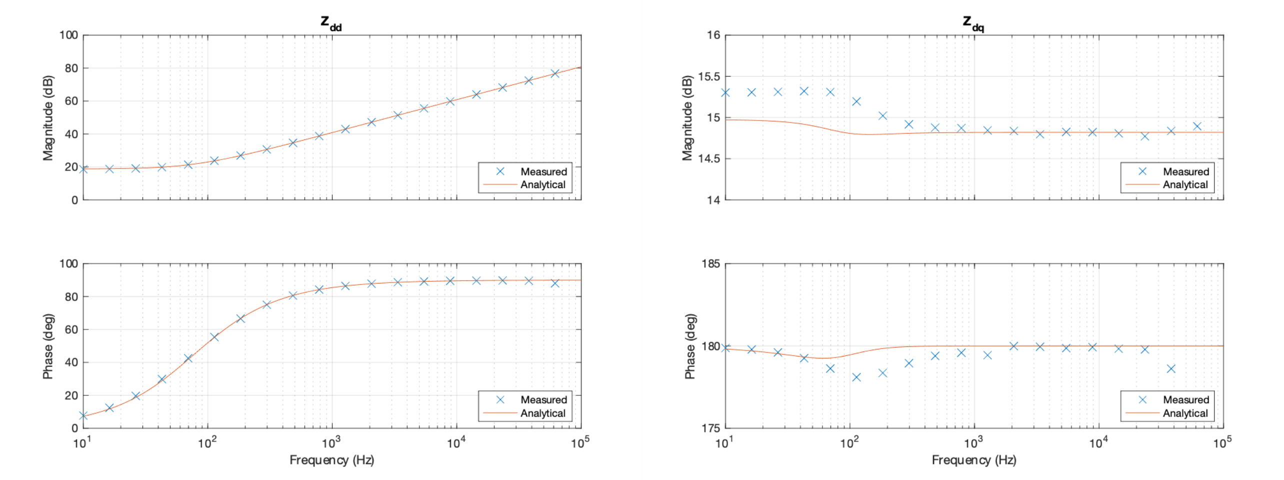
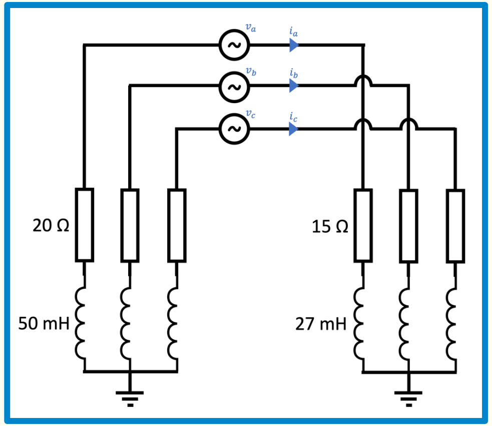
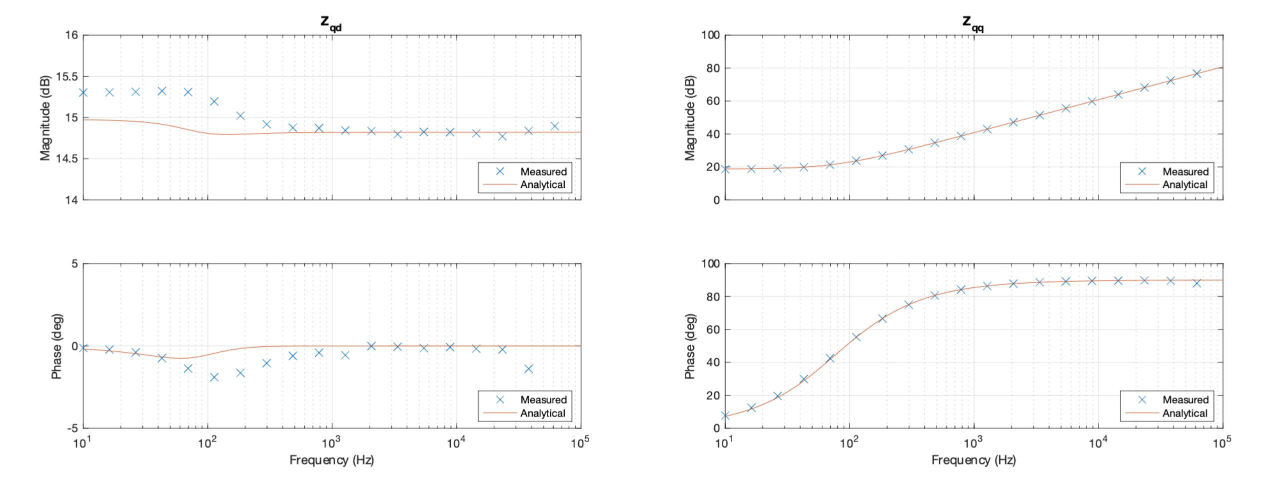
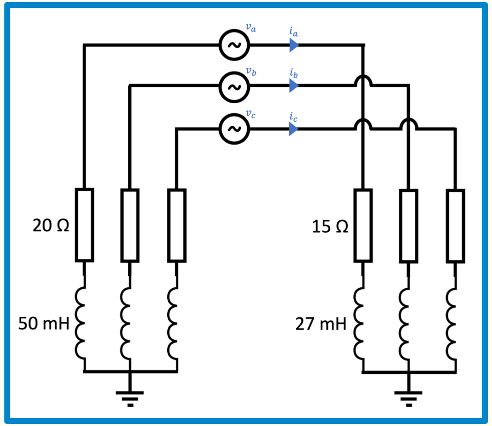
Three-phase Impedance Measurement – System 2



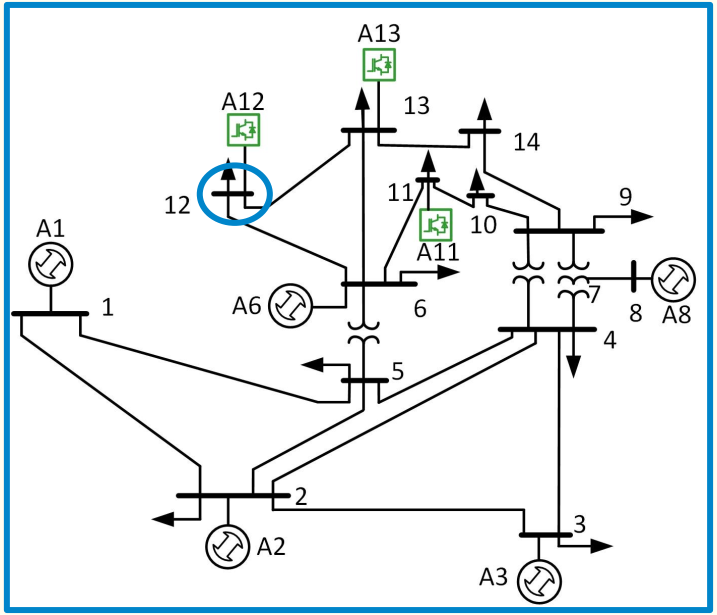


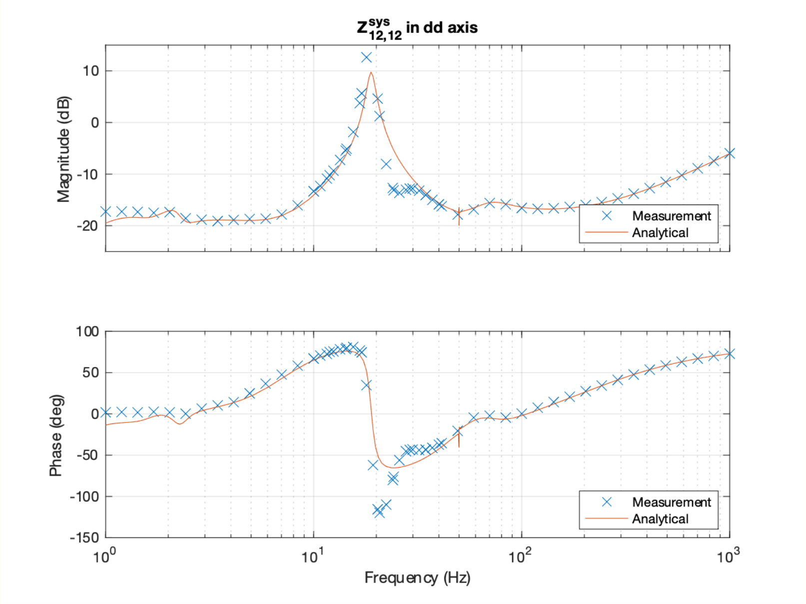
Three-phase Impedance Measurement – System 2





Three-phase Impedance Measurement – IEEE 14 Bus





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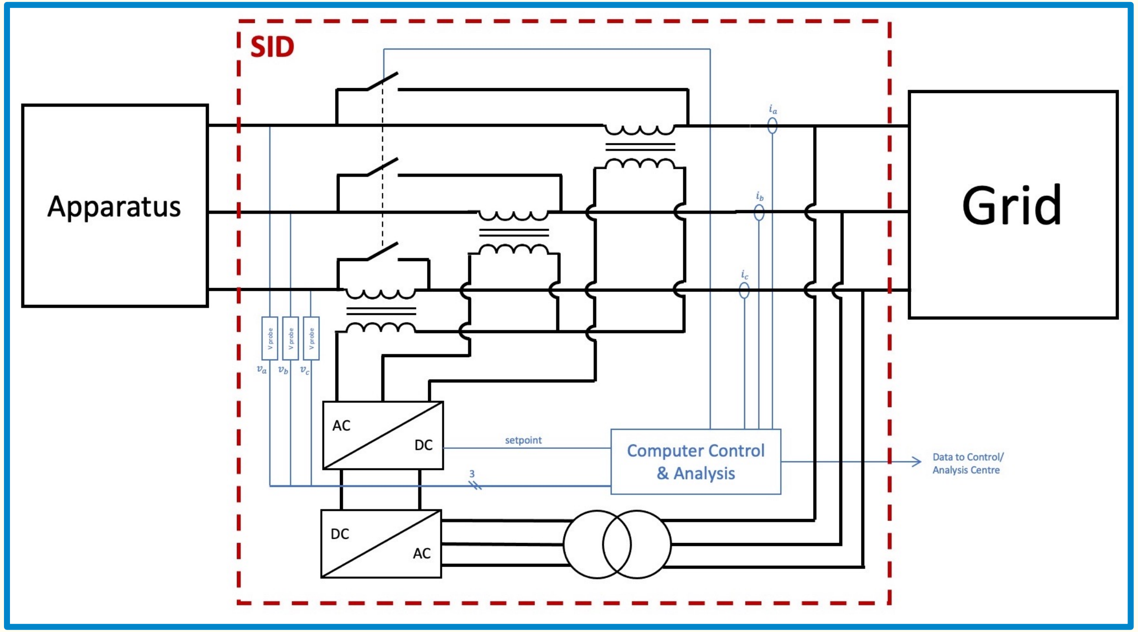
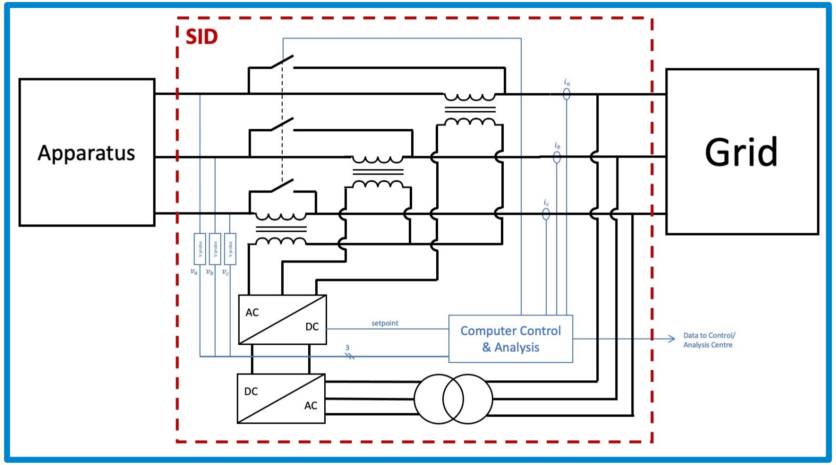
Signal Injection Device



Design Considerations

- Number of MMC stages
- IGBT ratings
- Transformer turns ratio
- MMC bandwidth
- Example: 400 kV, 2 kA steady state line.
  - 5% amplitude injection = 20 kV
  - 1:10 turns ratio
  - MMC rated for 200 kV, 200 A



Conclusions

- Impedance measurement of grid systems is possible and can be done online.
- Online impedance measurement identifies system modes, including peaks due to oscillatory modes.
- A signal injection device can be implemented in real life using available technologies and components.
- With some data known by system operators (e.g. impedance values between nodes), the rest can be measured to reconstruct an accurate system model.
- New model can be used for tuning using e.g. the Grey Box Approach.

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