Stability Modelling and Analysis of Converter Driven Power System

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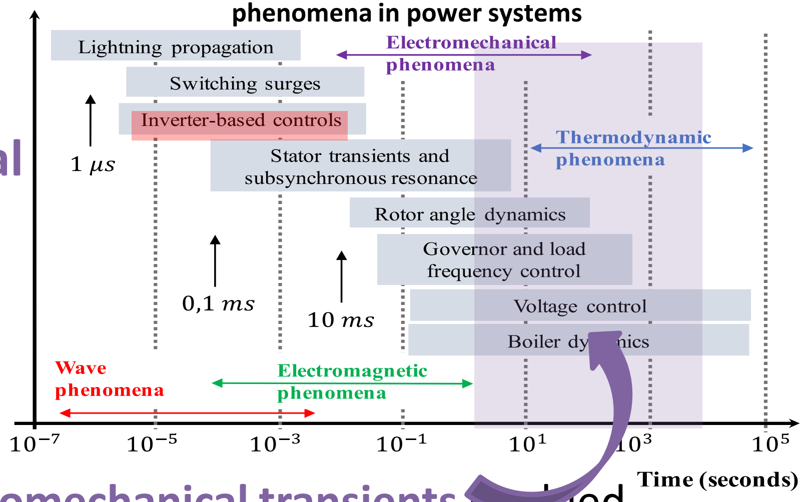
Overview

- Stability in recent context
- Modelling
- Analysis
- Insight
- Recommendations

Time Scales of Power System Dynamic Phenomena

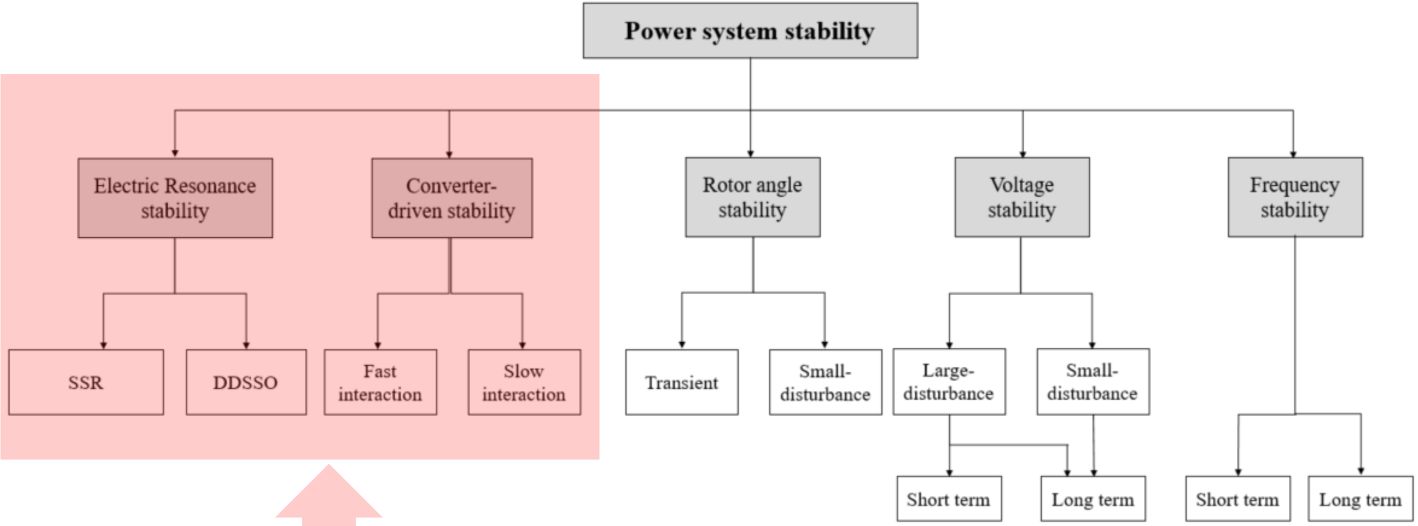
- electromagnetic phenomena
- electromechanical phenomena

Time scales for various classes of dynamic phenomena in power systems



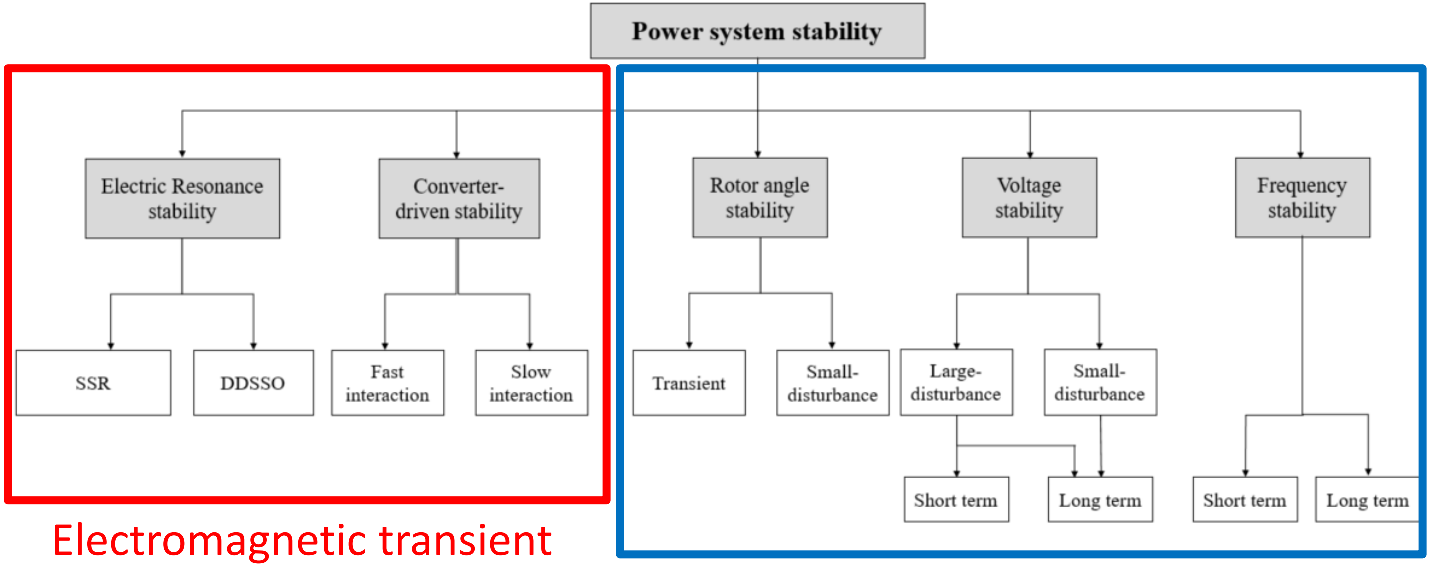
- electromechanical transients enabled several simplifications in characterization and analysis of the related phenomena
  - Phasors approach

New classification diagram



New (in)stability categories motivated by the increasing use of converter-interfaced generators

Time-scale representation aspects

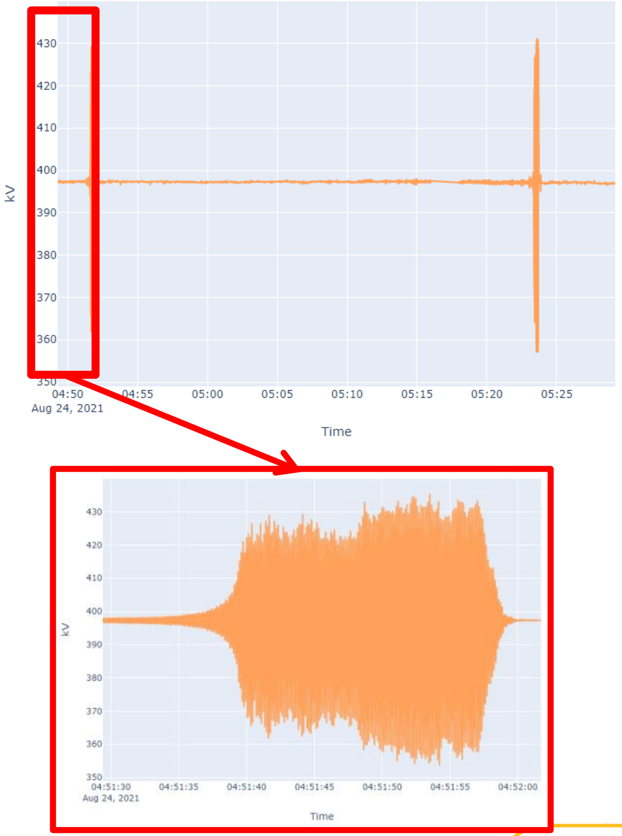


Electromagnetic transient modeling required

Phasor domain modeling is appropriate

Recent incidence in UK Transmission

- On 24/08/2021 severe voltage disturbances were observed on the SSEN-T and SPEN transmission systems.
- Major disturbance lasted 20-25 seconds on two occasions, approx. 30 minutes apart
- Investigation of available data suggests:
    - The oscillations with the largest magnitude were in the north of Scotland
    - The oscillations had a frequency of ≈8 Hz
- Some Users tripped off during the disturbances



Impedance approach to stability modelling: frequency-domain

$$\begin{bmatrix} V_d(s) \\ V_q(s) \end{bmatrix} = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix} \begin{bmatrix} I_d(s) \\ I_q(s) \end{bmatrix}$$

Real transfer functions

$$\begin{bmatrix} V_a(s) \\ V_b(s) \\ V_c(s) \end{bmatrix} = Z_{abc}(s) \begin{bmatrix} I_a(s) \\ I_b(s) \\ I_c(s \end{bmatrix}$$

Complex transfer functions

$$\begin{bmatrix} V_p(s + j\omega_i) \\ V_n(s - j\omega_i) \end{bmatrix} = \begin{bmatrix} Z_{pp}(s) & Z_{pn}(s) \\ Z_{np}(s) & Z_{nn}(s) \end{bmatrix} \begin{bmatrix} I_p(s + j\omega_i) \\ I_n(s - j\omega_i) \end{bmatrix}$$

Impedance approach

$$\begin{bmatrix} V_a(s) \\ V_b(s) \\ V_c(s) \end{bmatrix} = Z_{abc}(s) \begin{bmatrix} I_a(s) \\ I_b(s) \\ I_c(s \end{bmatrix}$$

$$\begin{bmatrix} V_d(s) \\ V_q(s) \end{bmatrix} = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix} \begin{bmatrix} I_d(s) \\ I_q(s) \end{bmatrix}$$

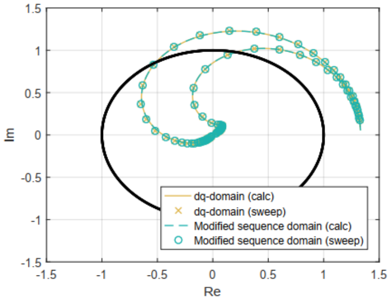
Real transfer functions

$$\begin{bmatrix} 1 & -j \\ 1 & j \end{bmatrix} \qquad \begin{bmatrix} 1 & -j \\ 1 & j \end{bmatrix}^{-1}$$

Complex transfer functions

$$\begin{bmatrix} V_p(s+j\omega_i) \\ V_n(s-j\omega_i) \end{bmatrix} = \begin{bmatrix} Z_{pp}(s) & Z_{pn}(s) \\ Z_{np}(s) & Z_{nn}(s) \end{bmatrix} \begin{bmatrix} I_p(s+j\omega_i) \\ I_n(s-j\omega_i) \end{bmatrix}$$

Objective

Measure	Use for stability	Limitation
Complex transfer functions $\begin{bmatrix} Z_{pp}(s) & Z_{pn}(s) \\ Z_{np}(s) & Z_{nn}(s) \end{bmatrix}$		Limited to only a single converter to infinite-bus scenario
Real transfer functions $\begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix}$	$\dot{x} = Ax + Bu$ $y = Cx + Du$	System identification problem is “not trivial”

Impedance estimation

Real transfer functions

$$\begin{bmatrix} V_d(s) \\ V_q(s) \end{bmatrix} = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix} \begin{bmatrix} I_d(s) \\ I_q(s) \end{bmatrix}$$

$$\begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix} = \begin{bmatrix} V_{1d}(s) & V_{2d}(s) \\ V_{1q}(s) & V_{2q}(s) \end{bmatrix} \begin{bmatrix} I_{1d}(s) & I_{2d}(s) \\ I_{1q}(s) & I_{2q}(s) \end{bmatrix}^{-1}$$

4 unknowns

2 equations

At least 2 measurements tests

Test 2

$$\begin{bmatrix} V_{2d}(s) \\ V_{2q}(s) \end{bmatrix} = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix} \begin{bmatrix} I_{2d}(s) \\ I_{2q}(s) \end{bmatrix}$$

Test 1

$$\begin{bmatrix} V_{1d}(s) \\ V_{1q}(s) \end{bmatrix} = \begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix} \begin{bmatrix} I_{1d}(s) \\ I_{1q}(s) \end{bmatrix}$$

G. Francis, R. Burgos, D. Boroyevich, F. Wang and K. Karimi, "An algorithm and implementation system for measuring impedance in the D-Q domain," *2011 IEEE Energy Conversion Congress and Exposition*, Phoenix, AZ, 2011, pp. 3221-3228, doi: 10.1109/ECCE.2011.6064203.

Impedance estimation: approximation

Real transfer functions

$$\begin{bmatrix} Z_{dd}(s) & Z_{dq}(s) \\ Z_{qd}(s) & Z_{qq}(s) \end{bmatrix}$$

4 unknowns

At least 2 measurements tests

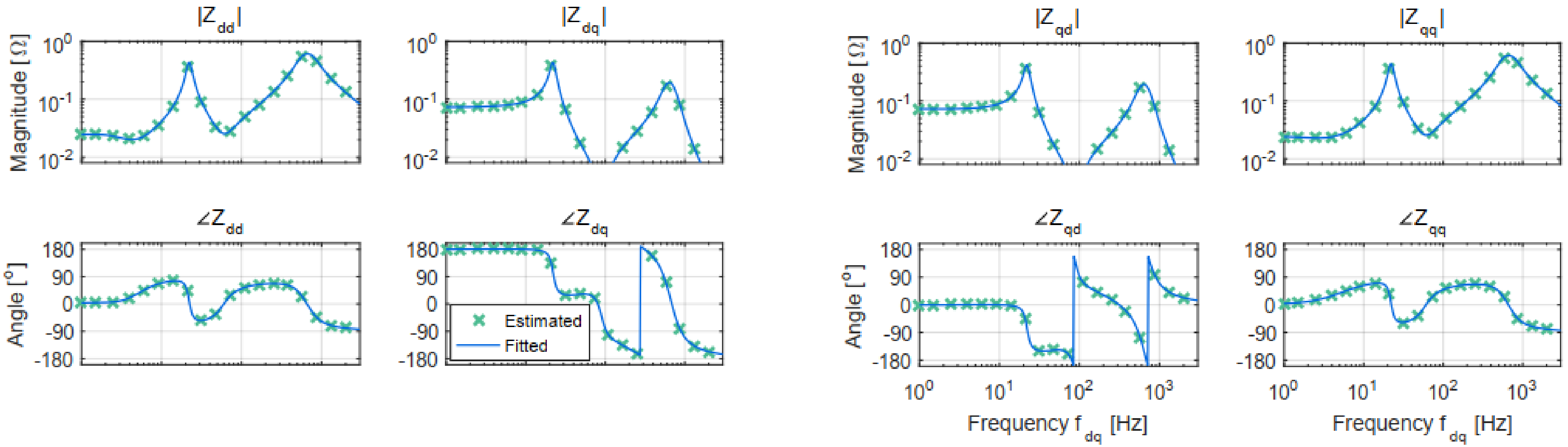
Vector fitting

$$G(s) \approx \sum_{i=1}^{N} \frac{r_i}{s - p_i} + d$$

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

Impedance estimation: Vector fitting

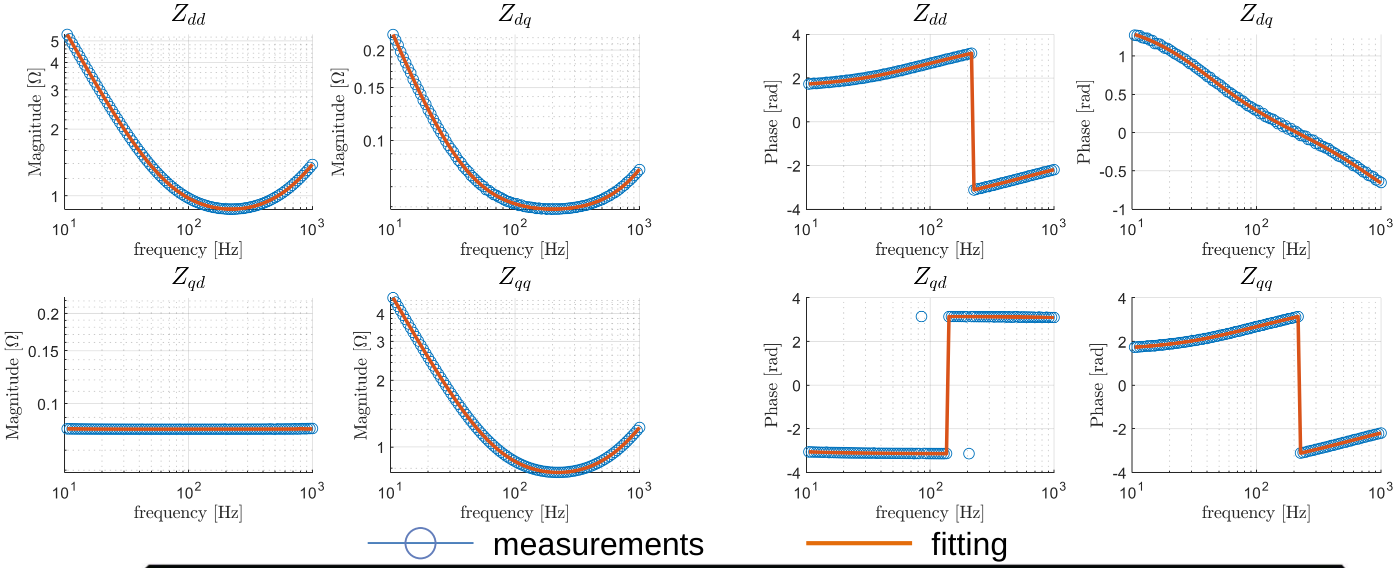
Example: average model of VSC with PLL and current control



A. Rygg and M. Molinas, "Apparent Impedance Analysis: A Small-Signal Method for Stability Analysis of Power Electronic-Based Systems," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 4, pp. 1474-1486, Dec. 2017

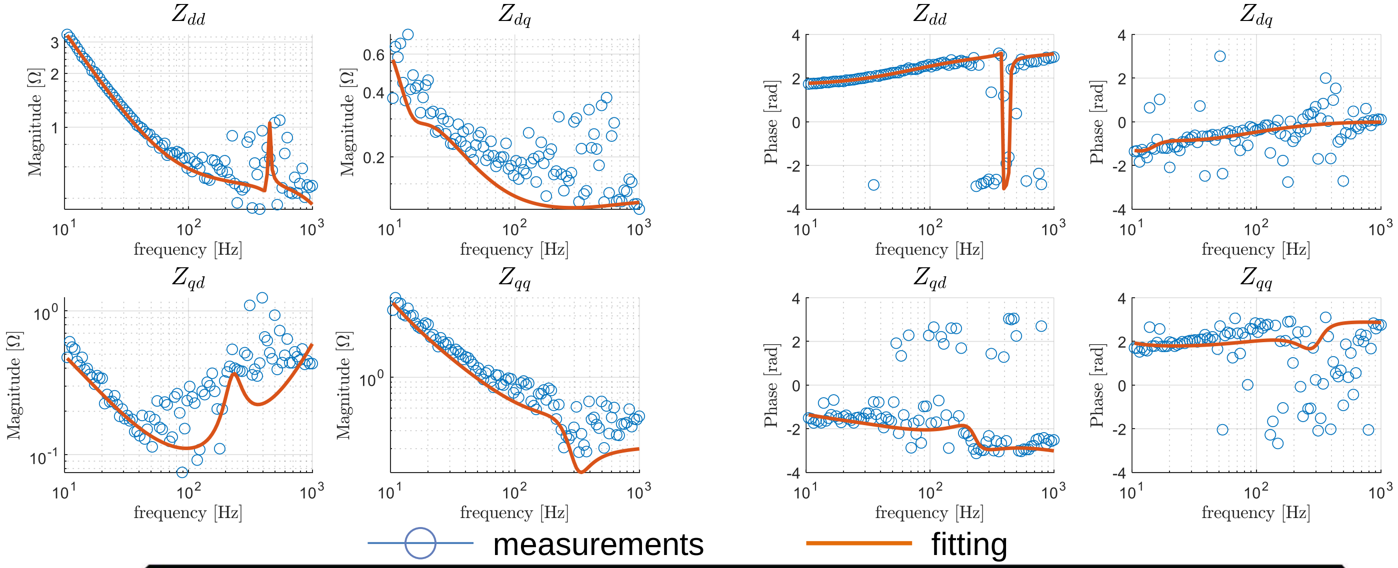
Impedance estimation: Vector fitting

Example reproduced in PSCAD: average model of VSC with PLL and current control



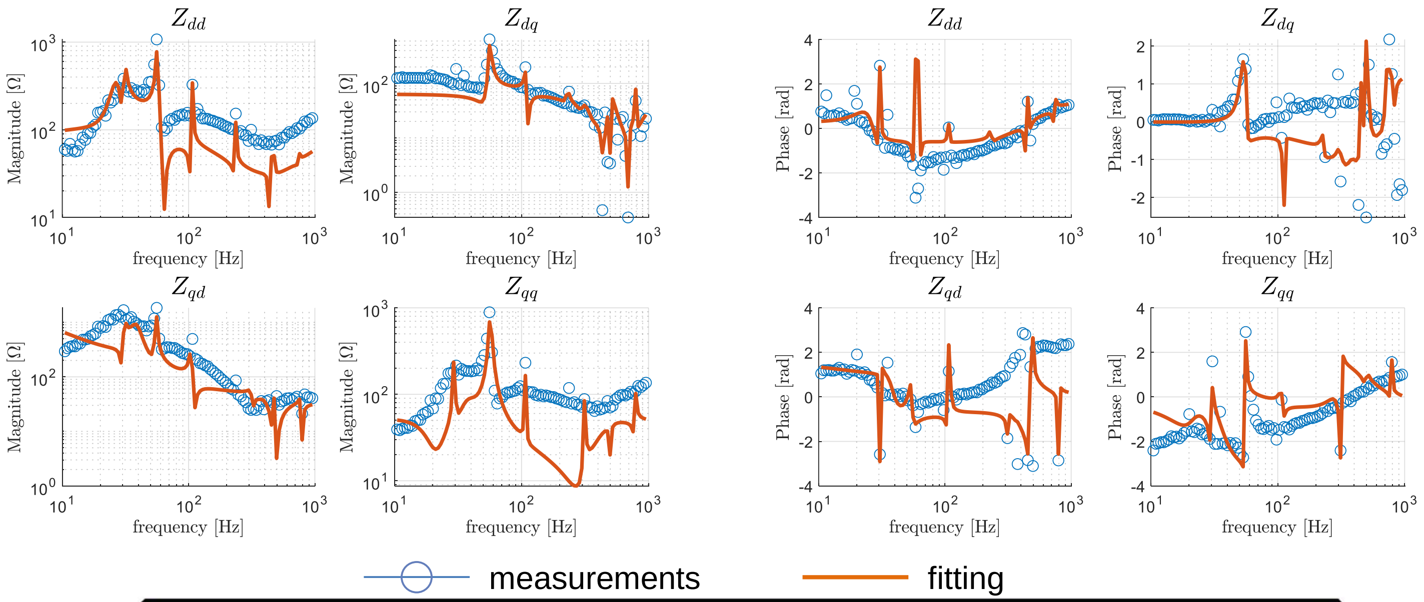
Impedance estimation: Vector fitting

Example reproduced in PSCAD: average model of VSC with PLL and current control including delay



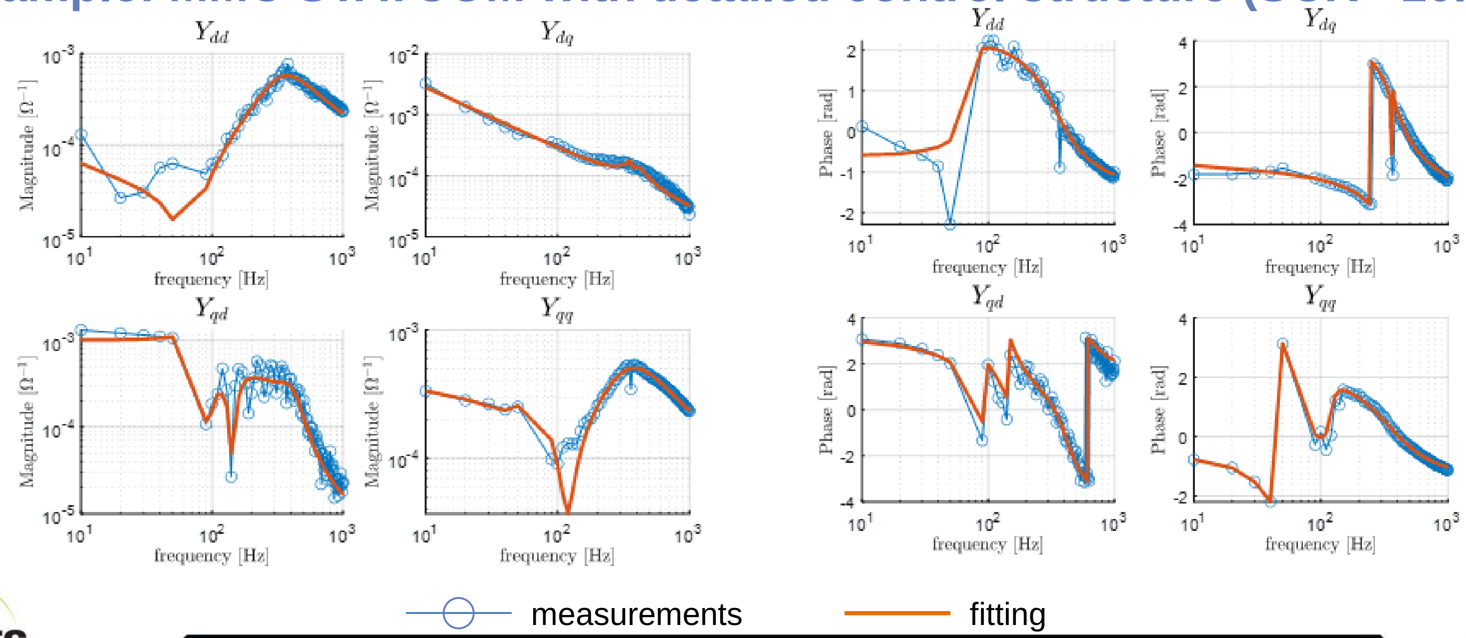
Impedance estimation: Vector fitting

Example: MMC STATCOM with detailed control structure



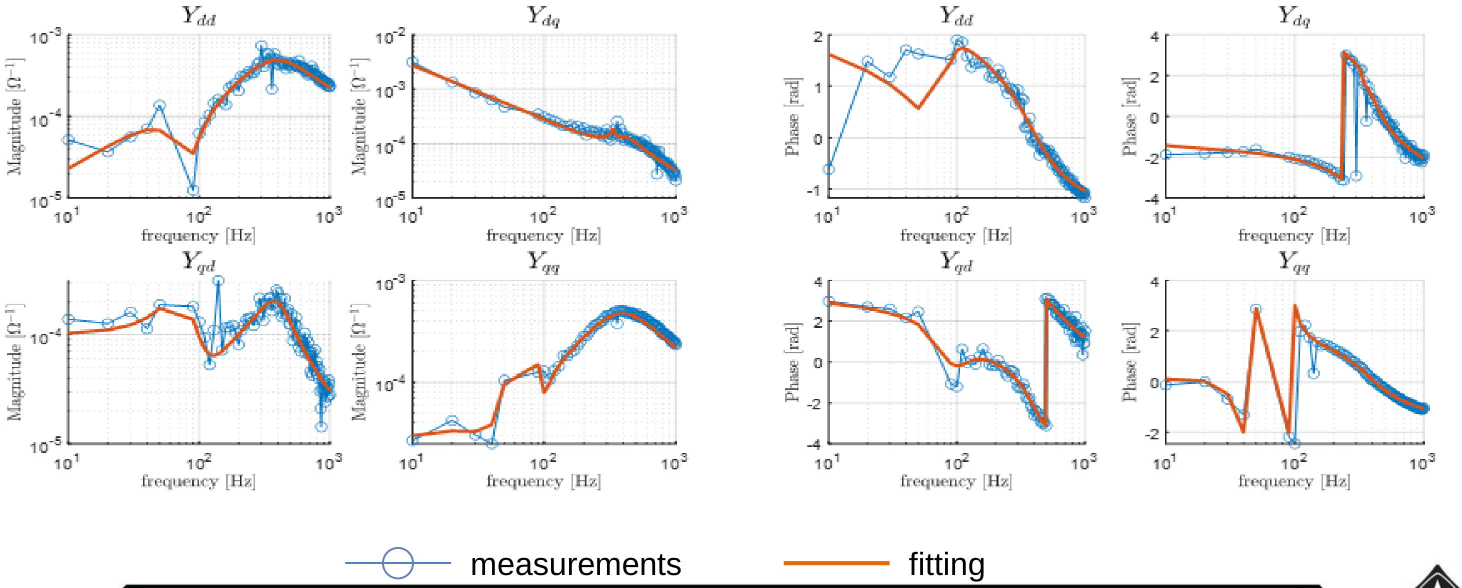
Admittance estimation: Vector fitting

Example: MMC STATCOM with detailed control structure (SCR =10.0)



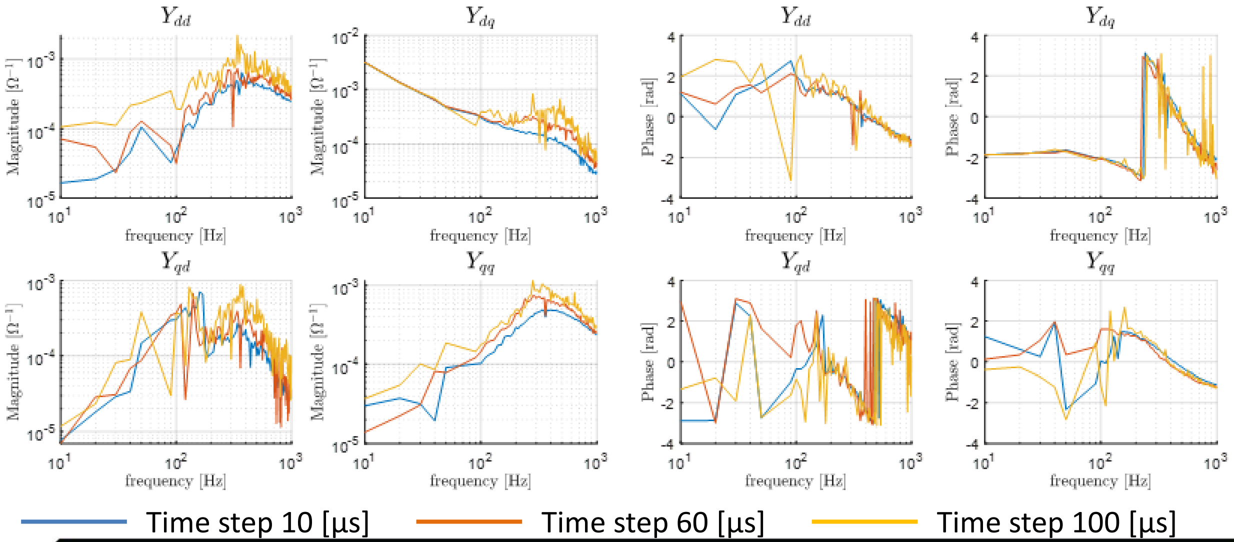
Admittance estimation: Vector fitting

Example: MMC STATCOM with detailed control structure (SCR =1.0)



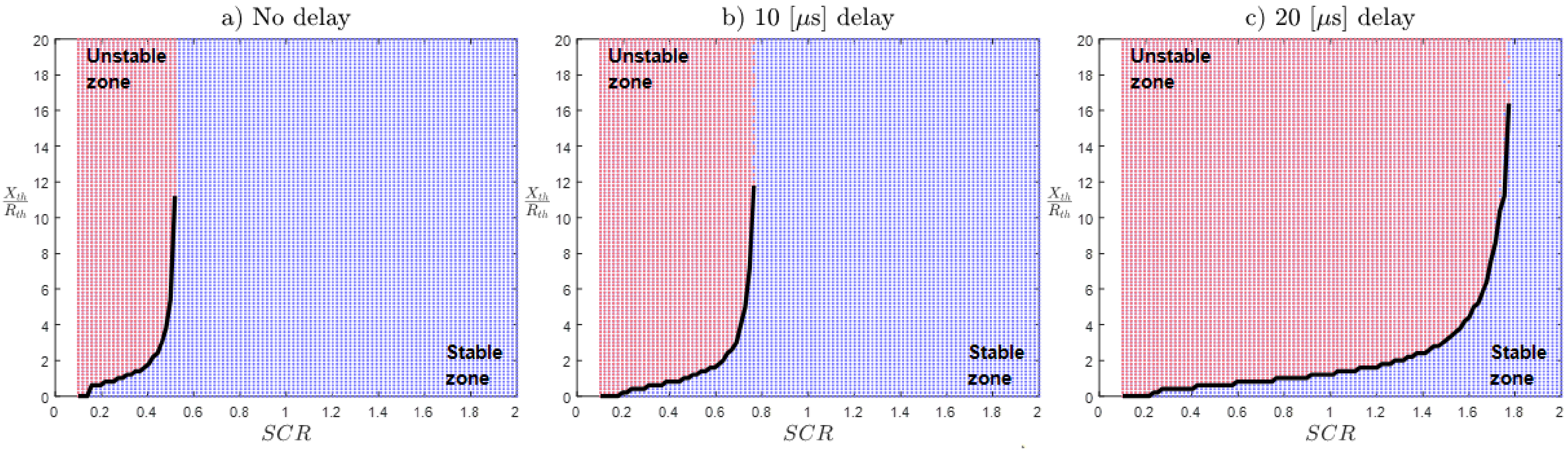
Impact of Time step for frequency sweep on admittance

- The MMC STATCOM model uses a carrier with a frequency of 360 [Hz], and each arm has 44 power modules, the effective update frequency is 15,840 [Hz]. In this case, the solution time-step should be at most **63 [μs].**



Impact of Measurement delay on stability margin

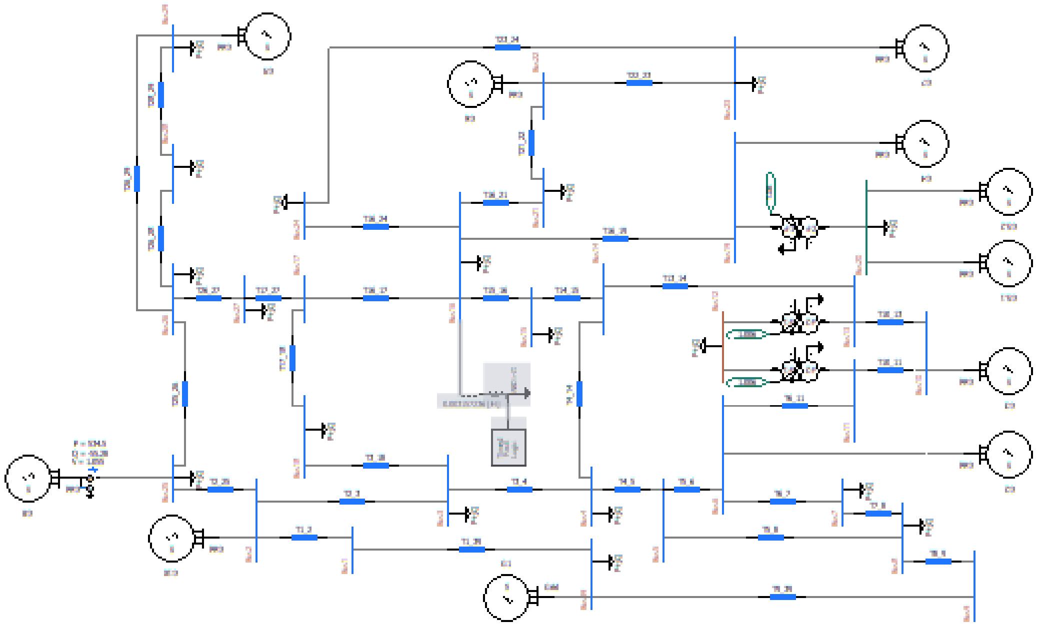
- Measurement delays reduce significantly the stability margin of the STATCOM module



Stability analysis of power systems

- Synchronous machines
- STATCOM (MMC)
- Wind Farm (VSC)
- Networks
- Loads

39 Bus system in PSCAD

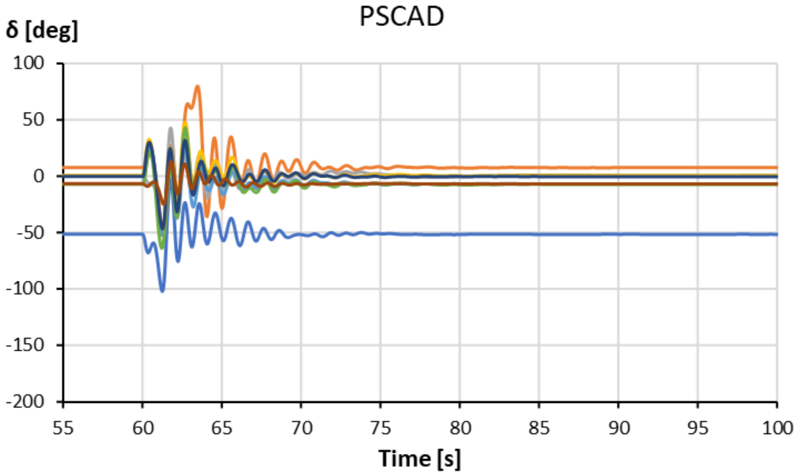


- 39 Bus system in 345 [kV]
- Analogue to the DigDILENT PowerFactory system
- Synchronous machines with AVR, Governor and steam turbine dynamics
- Lines modelled as π-circuits

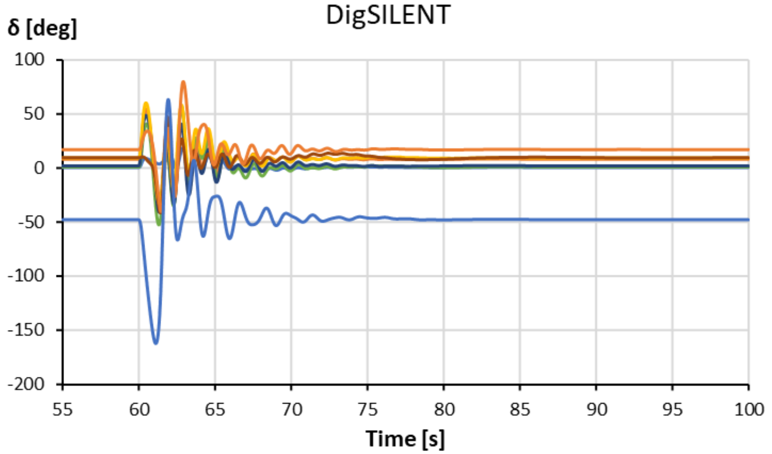
39 Bus system in PSCAD

- Dynamic response for fault on Bus 16 cleared after 180 [ms]

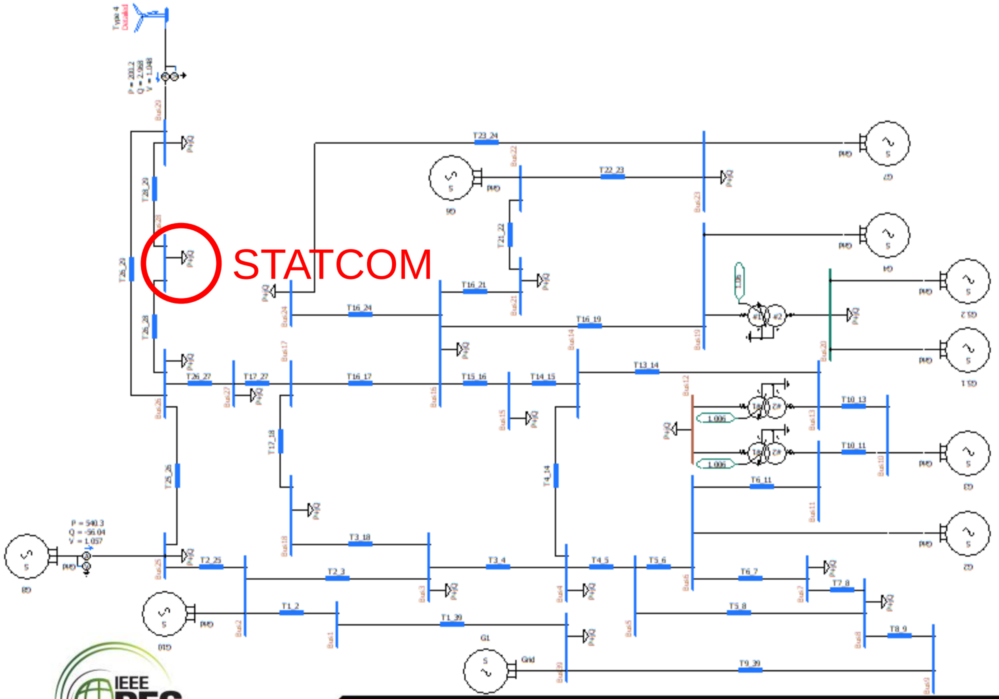
EMT simulation



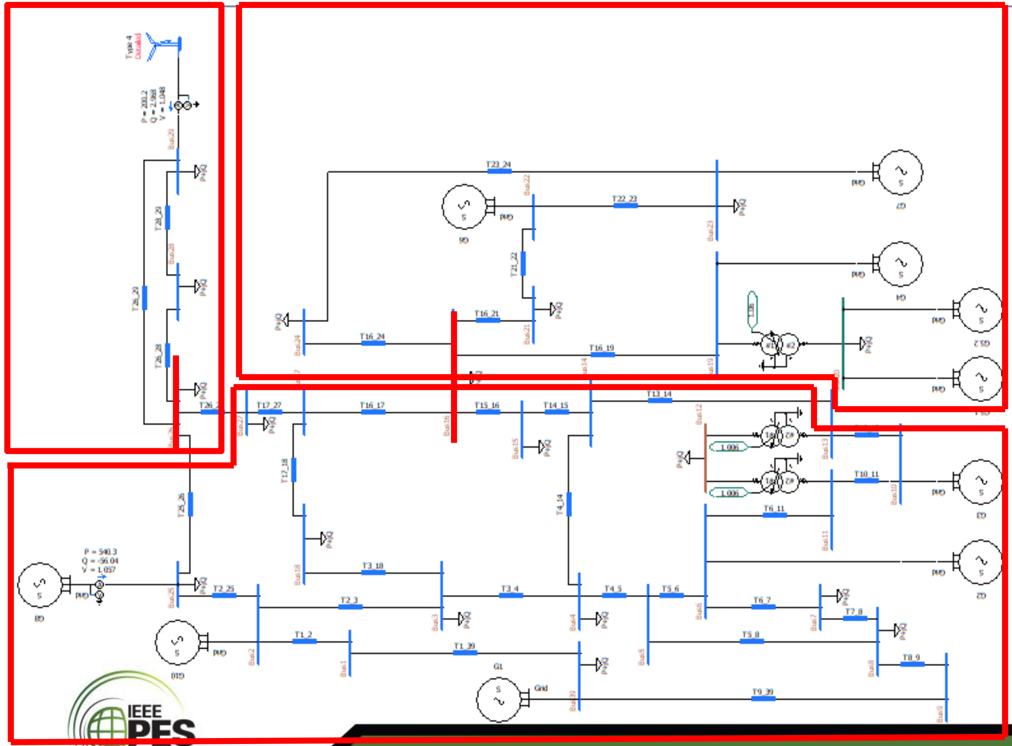
RMS simulation



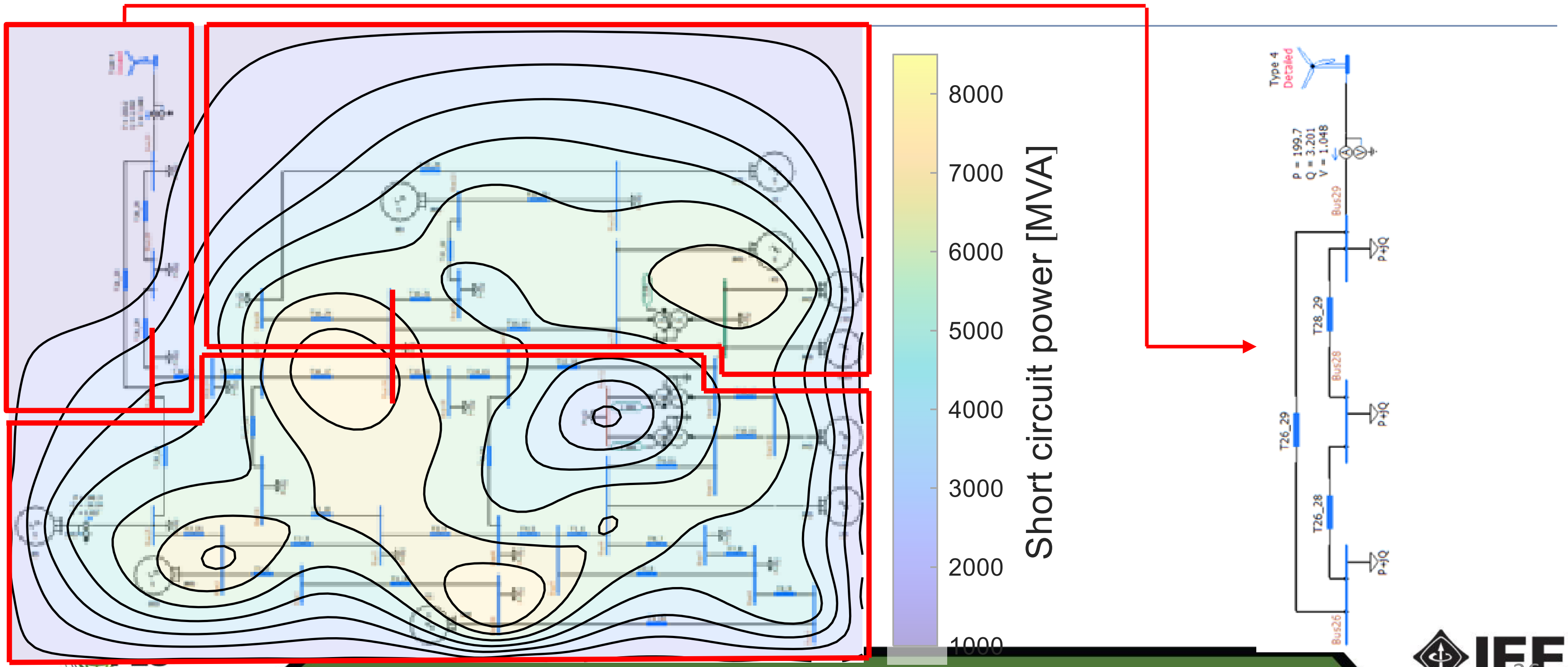
39 Bus system in PSCAD



39 Bus system in PSCAD : Test case for stability analsys

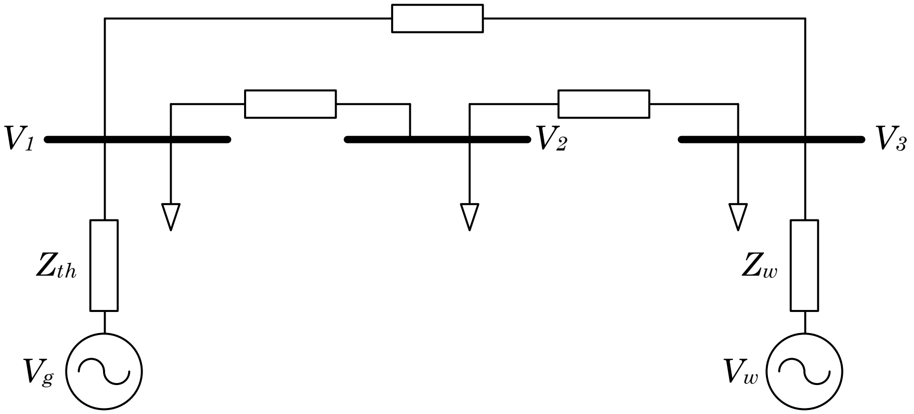


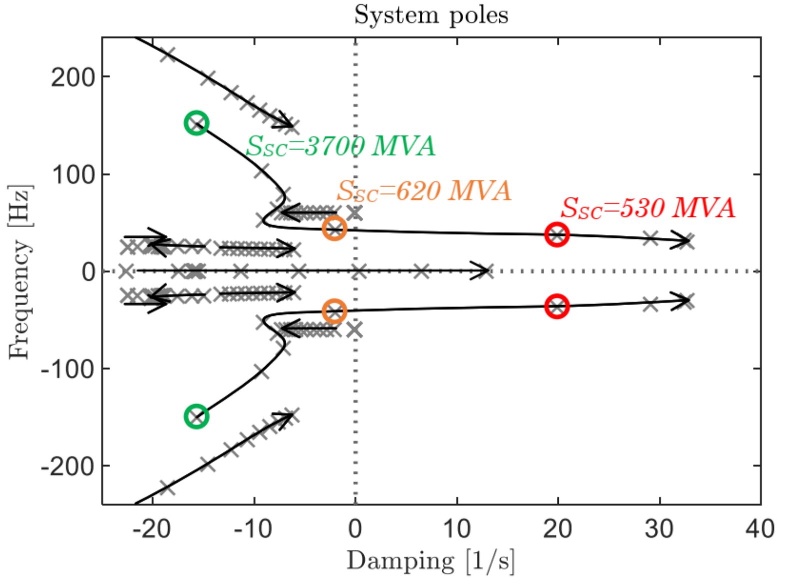
39 Bus system in PSCAD



Stability analysis for varying grid strength (WF only)

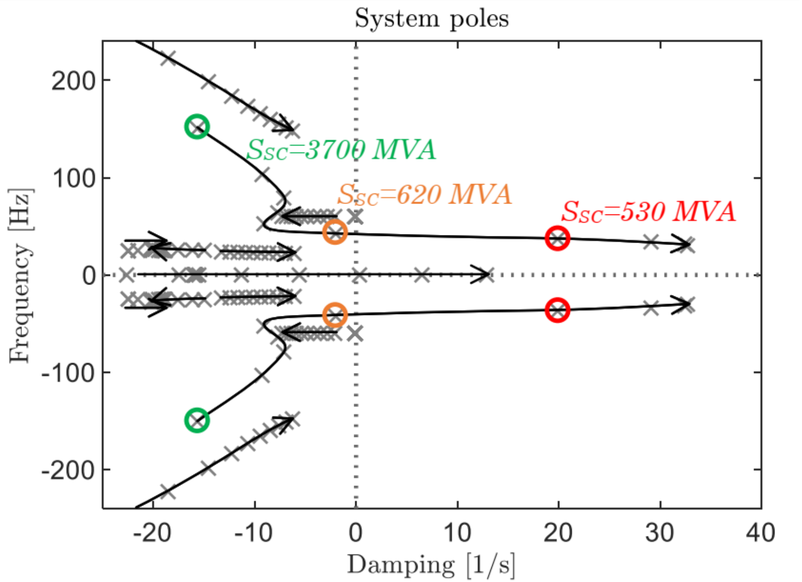
Sensitivity over the grid strength at V1 by varying Z_{th}

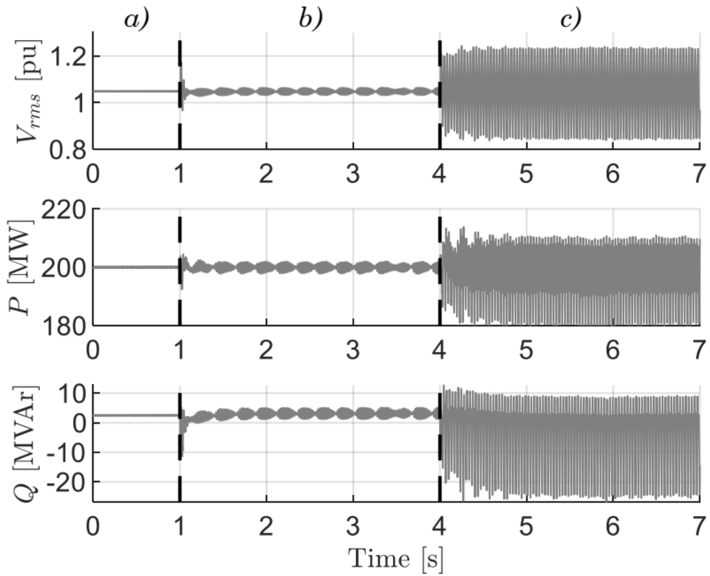




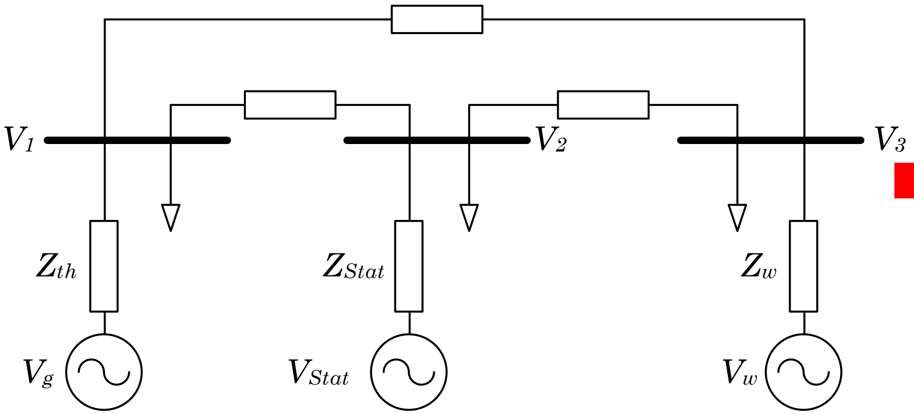
Stability analysis for varying grid strength (WF only)

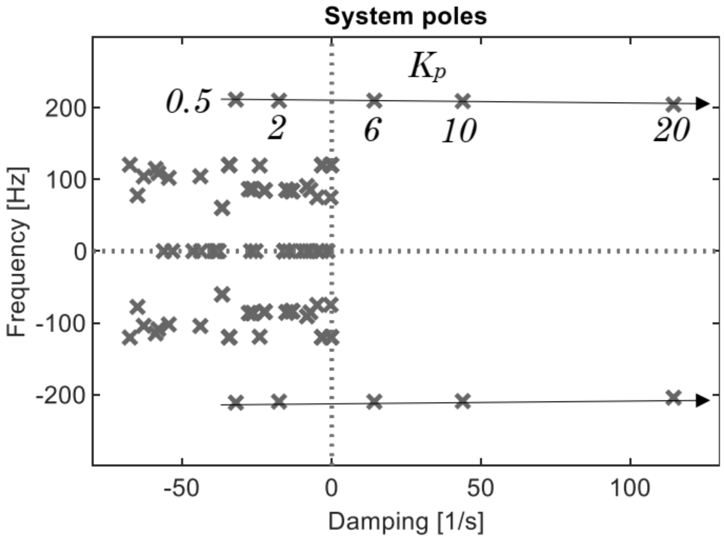
Results in reduced system



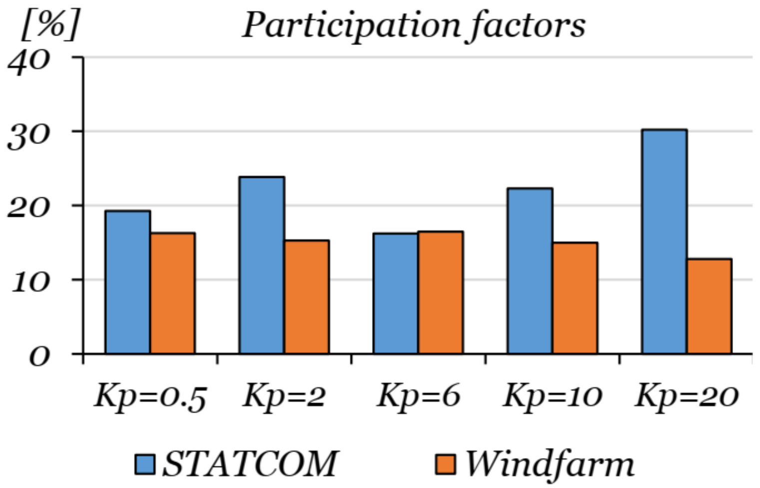


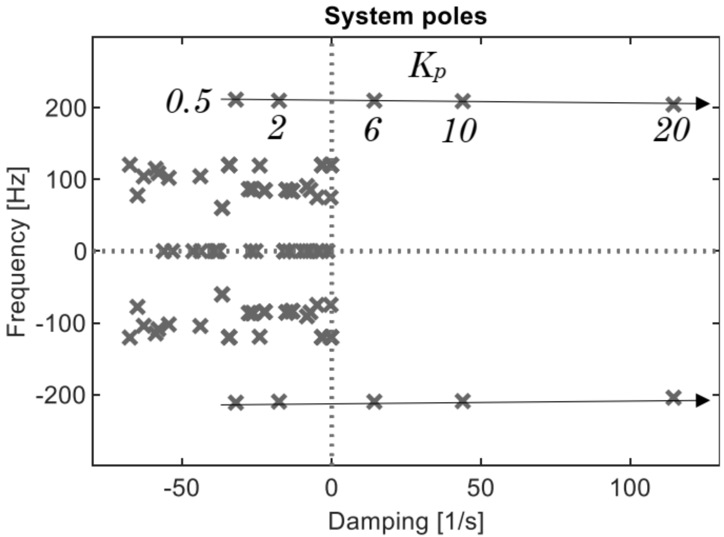
Impact of STATCOM AC voltage loop gain k_{pv} on stability





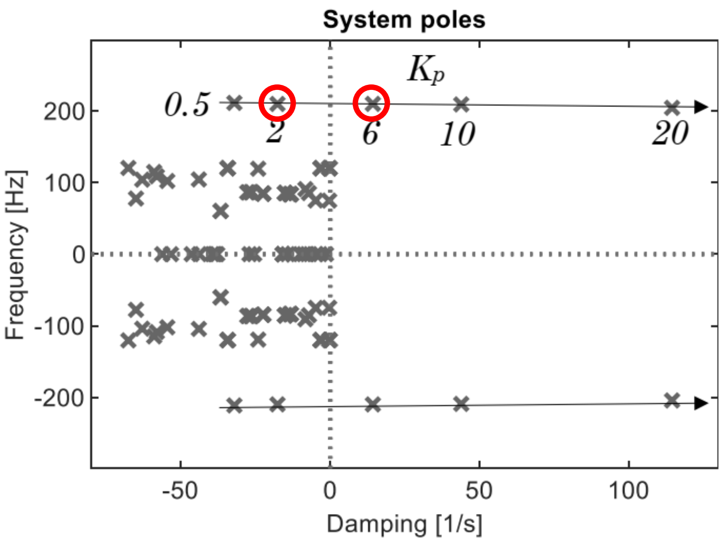
STATCOM loop gain Kpv on relative contribution to stability

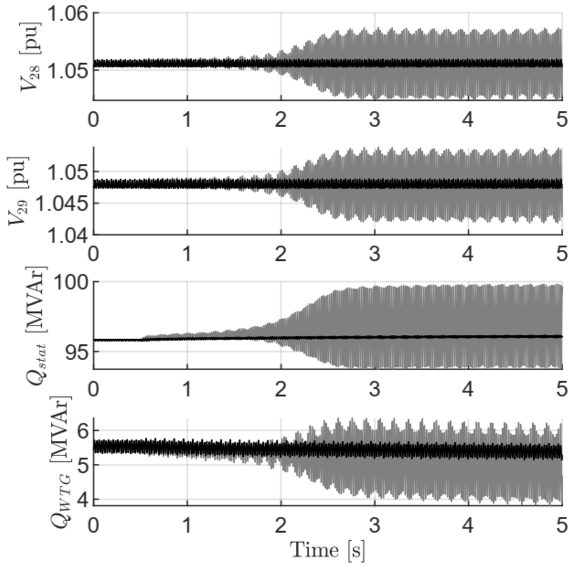




Validation in full 39 bus PSCAD model

PSCAD results full 39 bus system, changes on proportional gain





Insights

- Impedance estimation-based stability assessment tool takes care of the detail dynamic model of MMC technology used in all dynamic reactive power support devices
- The model is comprehensive in assessing the network stability impact of control delay, varying network short circuit capacity and fault ride through (FRT) capability of these devices during network events.

Insights

- The approach has demonstrated that real network operability margin is significantly lower in low short circuit cases when compared to the same obtained through time average simplified model of these devices.
- The control delay associated with these devices further shrink the stability margin.

Recommendations

- It is very much required to have detailed models of converter-based devices when performing grid connection studies in Electro-Magnetic Transient (EMT) time scale
- Stability assessment studies need to be performed for varying grid strengths/short circuit level at the point of connection as well as transmission voltage levels.

Recommendations

- TNO should insist on various other parametric sensitivity studies regarding key control schemes, interface PLL technologies etc.
- The grid connection study specification should be amended with these requirements so that any connection study adheres to these specifications.

Researcher

- Dr Nicolas Cifuentes
  - MEng , Universidad de Chile
  - PhD , Imperial College London

1. N. A. Cifuentes Otto, M. Sun, R. Gupta and B. C. Pal, "Black-Box Impedance-Based Stability Assessment of Dynamic Interactions Between Converters and Grid," in *IEEE Transactions on Power Systems*
2. N. Cifuentes and B. C. Pal, "A New Approach to the Fault Location Problem: Using the Fault's Transient Intermediate Frequency Response," in *IEEE Open Access Journal of Power and Energy*, vol. 8, pp. 510-521, 2021,

Researchers

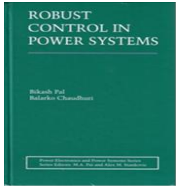

Diptargha

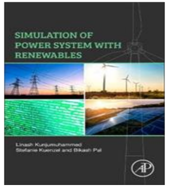
Onyema

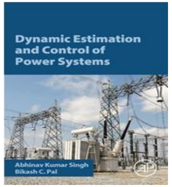
Ali

Adeyemi

Control



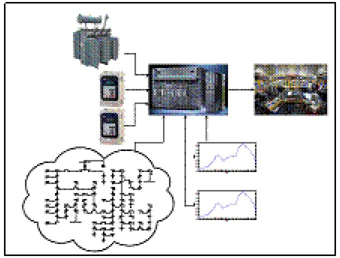




Modelling

Monitoring

Estimation

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Comments or Questions