



Automated Impedance Measurement Toolbox for Power System Stability Analysis

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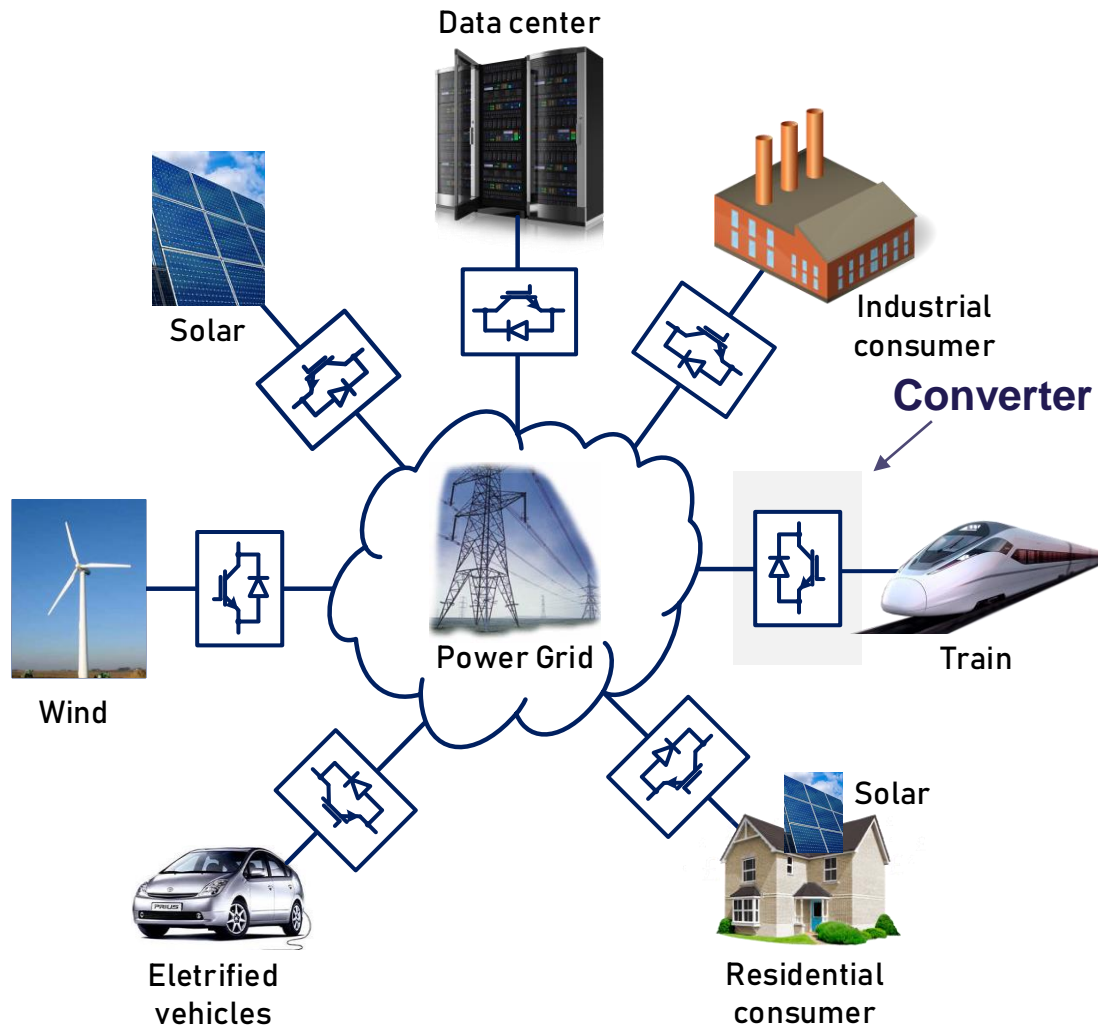
AAU Energy, Aalborg University, Denmark

eGRID
ELECTRONIC POWER GRID



AAU
ENERGY

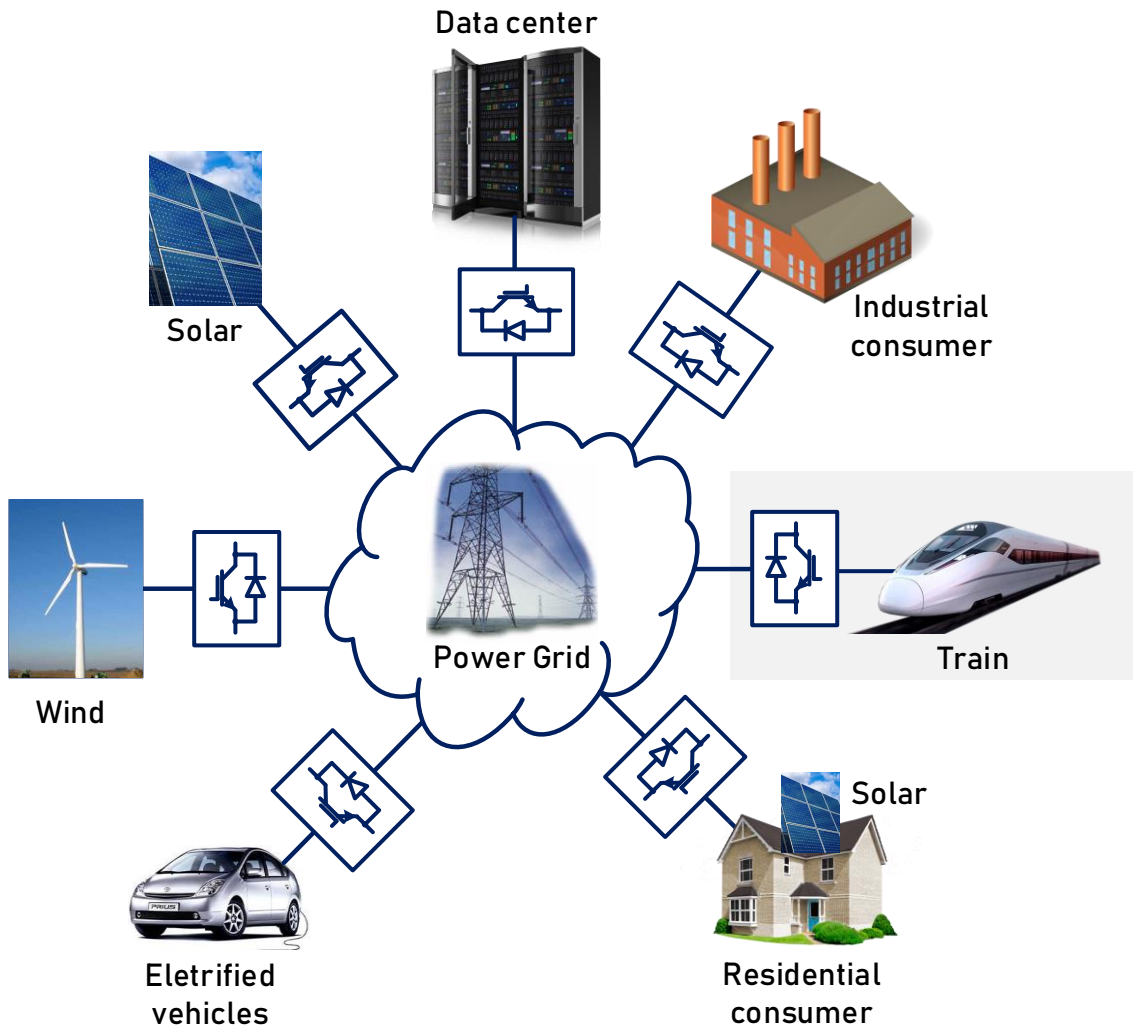
Converter-based power system



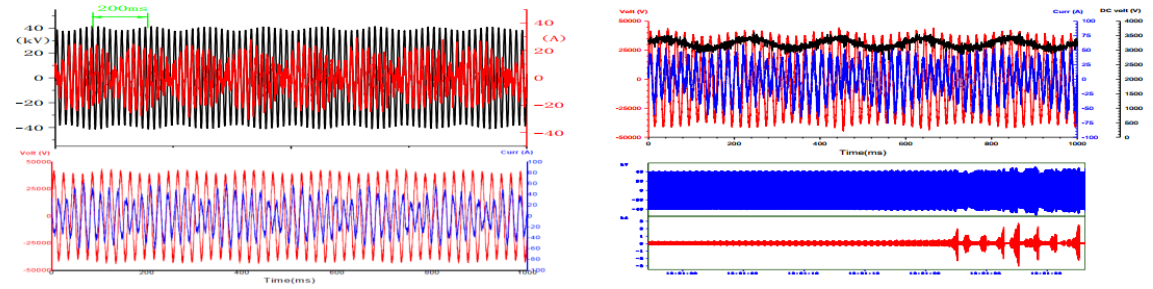
- Almost every electrical component is interfaced with power grid through **power converters**
- **Power converters can destabilize the power system**

Unstable operation

High-speed train



Cases of low frequency oscillations in high-speed railway



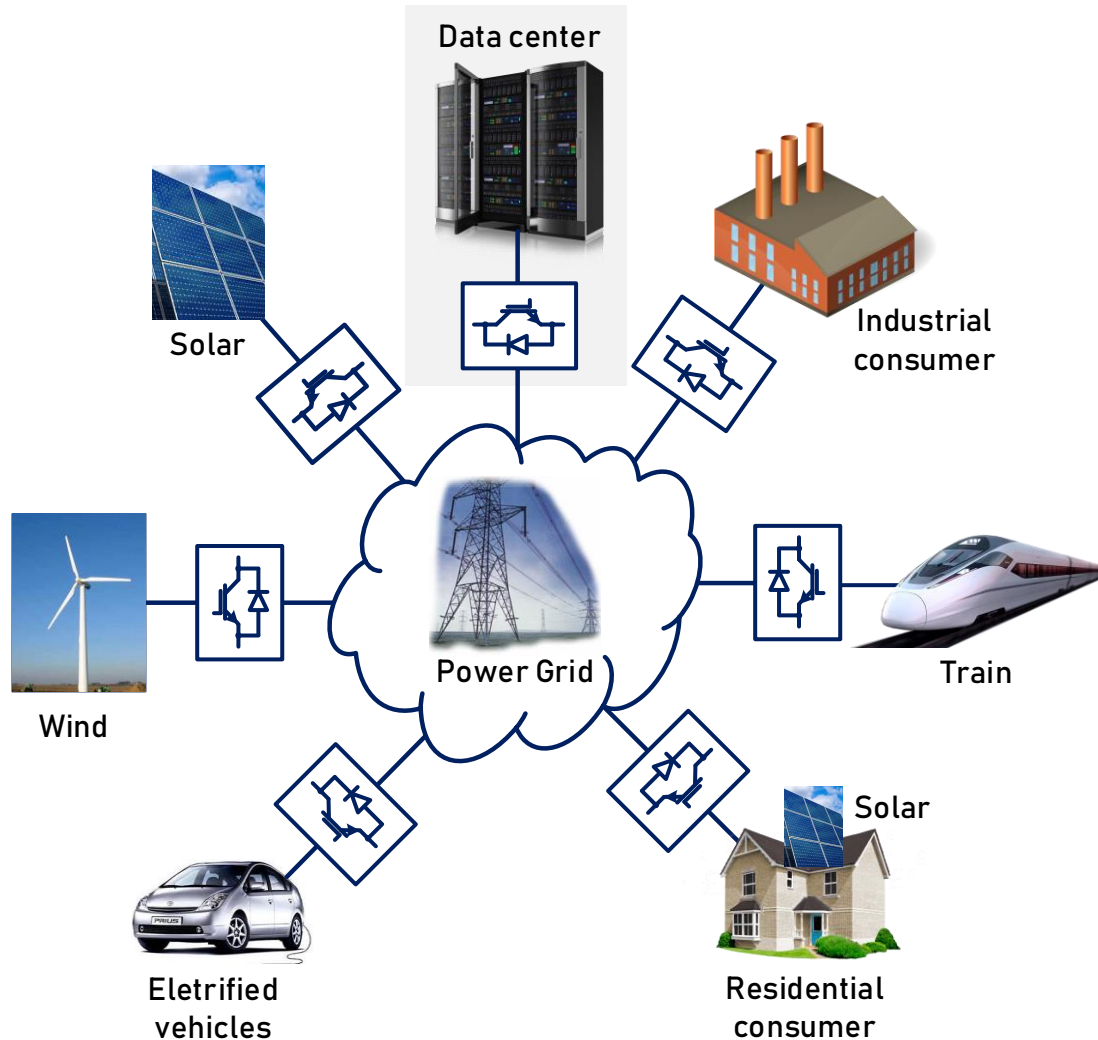
Cases of low-frequency oscillation

Vehicle type	Time	Place	Places overseas
HX _D 1	2008.01	Hudong locomotive depot	
CRH1	2010.01	Nanxiang station, Shanghai	
CRH5	2010.09	Qingdao	Switzerland, France, the USA, Germany
HX _D 2B	2011.06、2014.01	Xuzhou	
HX _D 3B	2011.11	Shanhaiguan	

[1] Z. Liu and Y. Liao. "Stability and Protection of Vehicle-Grid Systems in High-speed Railway". *IEEE et&d*, 2017

Unstable operation

Data center



Incidents in Facebook

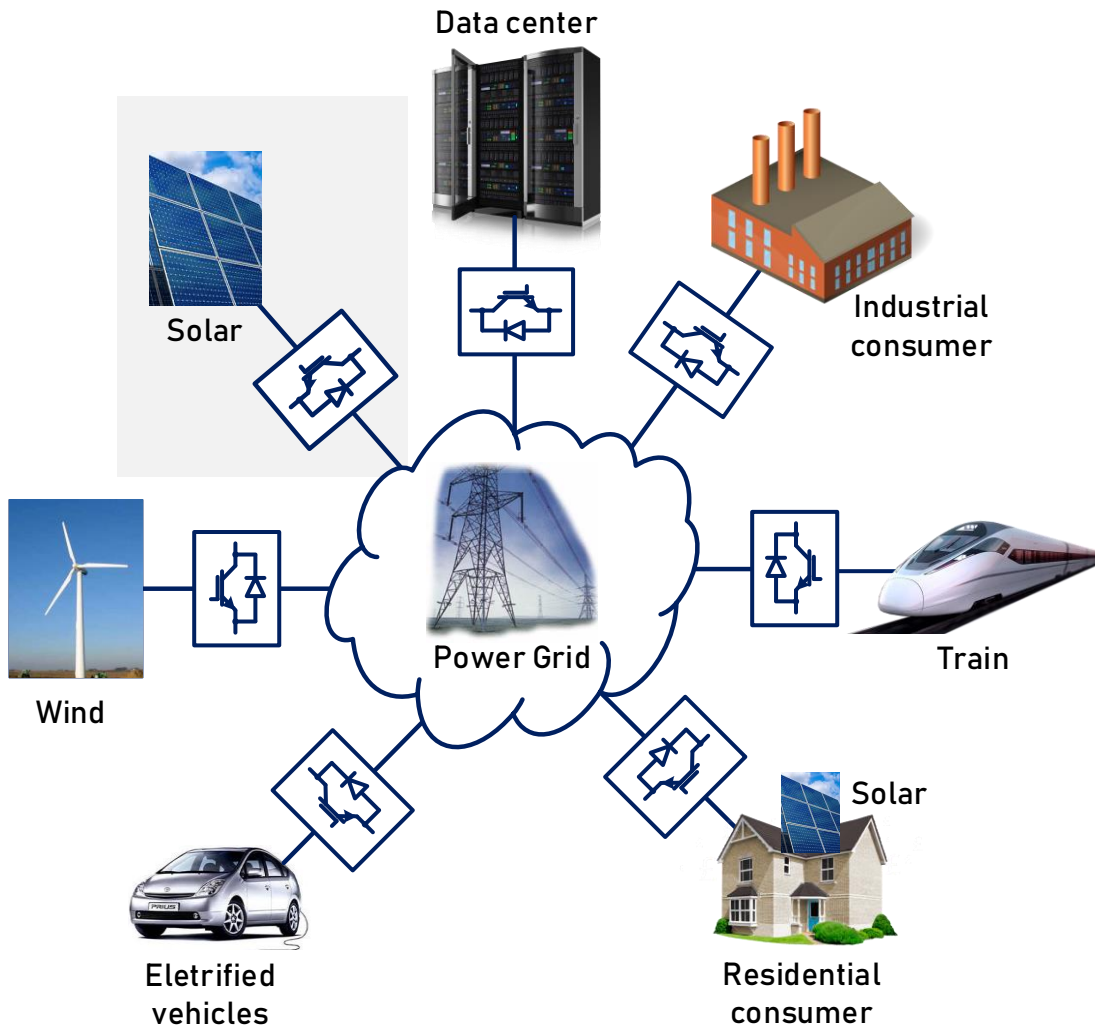


Fig. 1. Measured one PFC converter input current (upper) and voltage (lower) during a data center power system resonance.

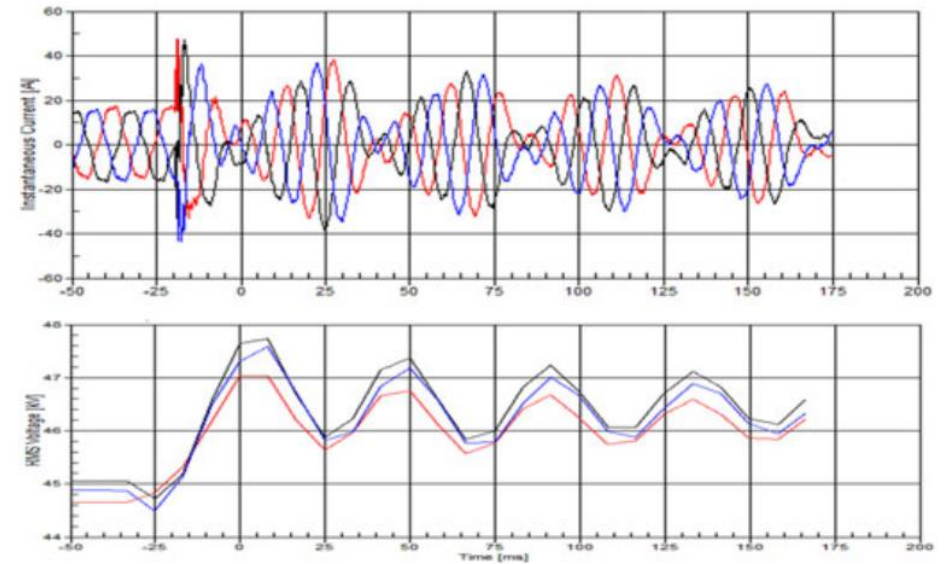
[1] J. Sun, M. Xu, M. Cespedes and M. Kauffman, "Low-Frequency Input Impedance Modeling of Single-Phase PFC Converters for Data Center Power System Stability Studies," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019, pp. 97-106, doi: 10.1109/ECCE.2019.8912862.

Unstable operation

Solar



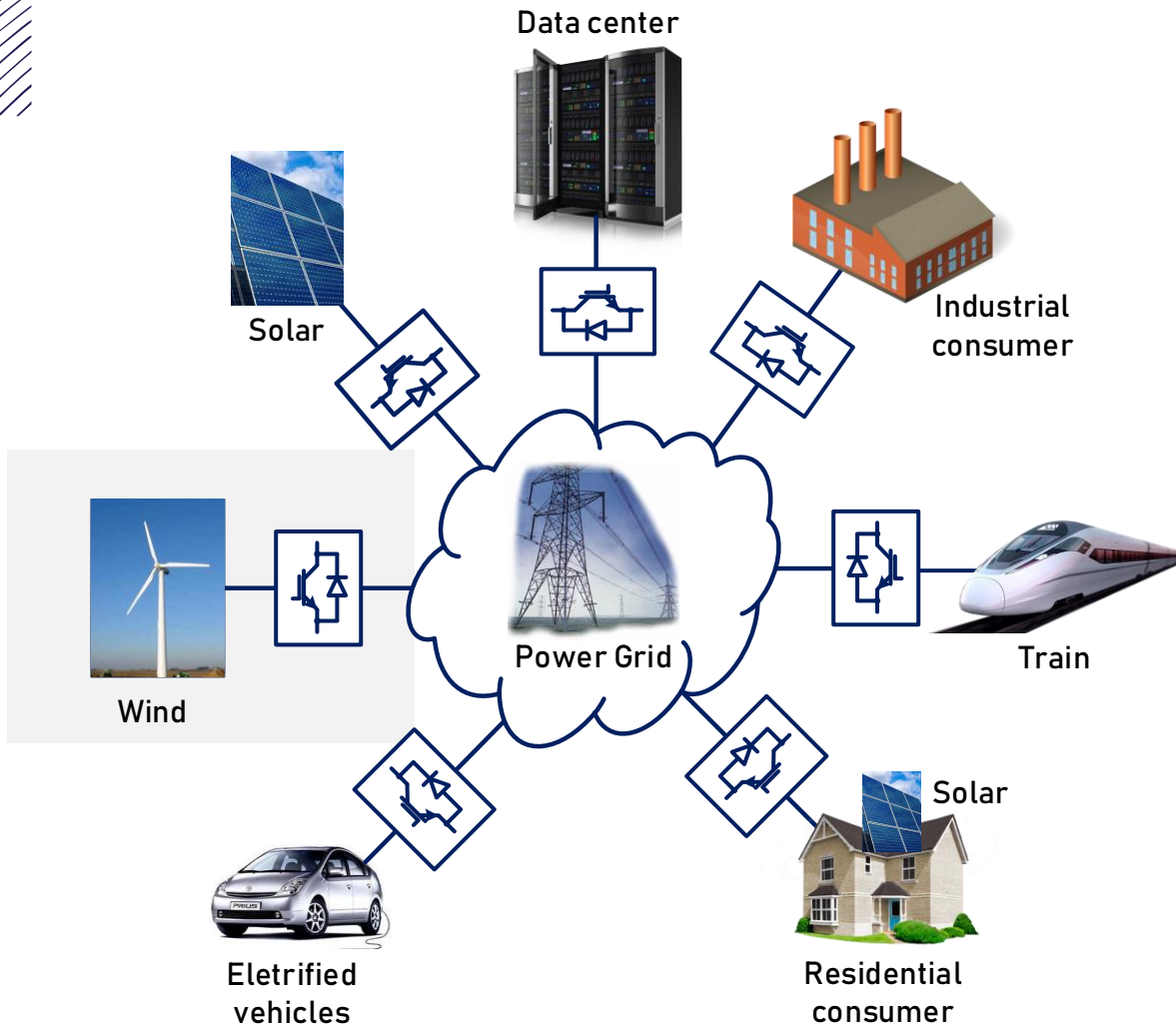
20Hz resonance occurs in a 1 MVA PV plant when a capacitor in the substation is energized [1]



[1] C. Li. "Unstable Operation of Photovoltaic Inverter From Field Experiences". *IEEE Transactions on Power Delivery*, 2018

Unstable operation

Wind



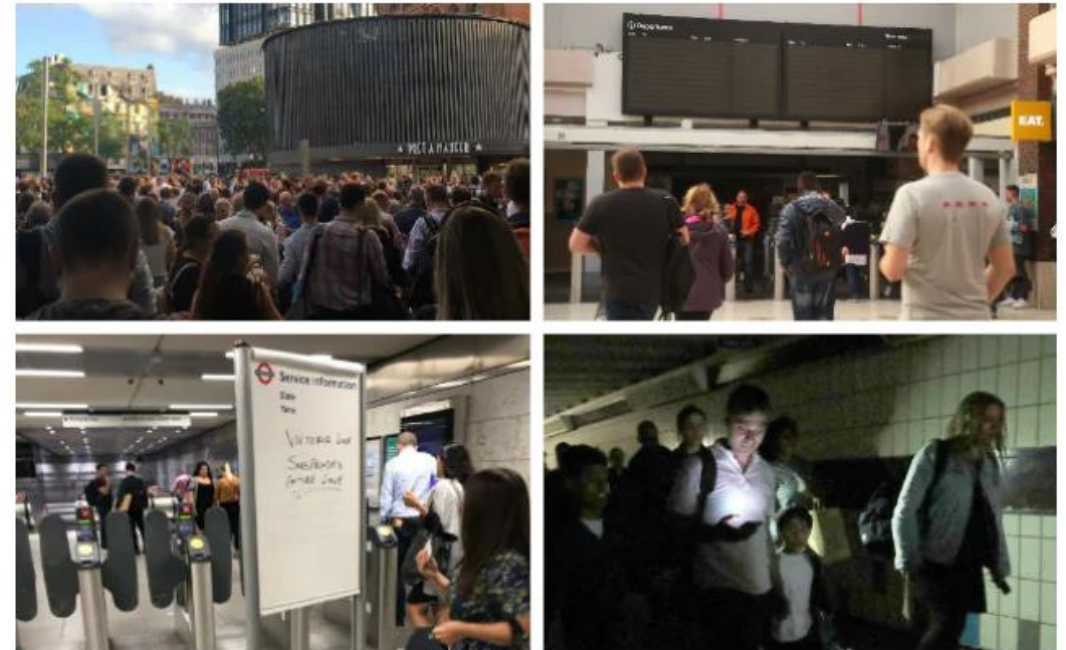
In 2019, the Trip of 700MW wind power plant lead to 1 million customers lose power in London

News

Major power cut across country as London goes dark after National Grid failure

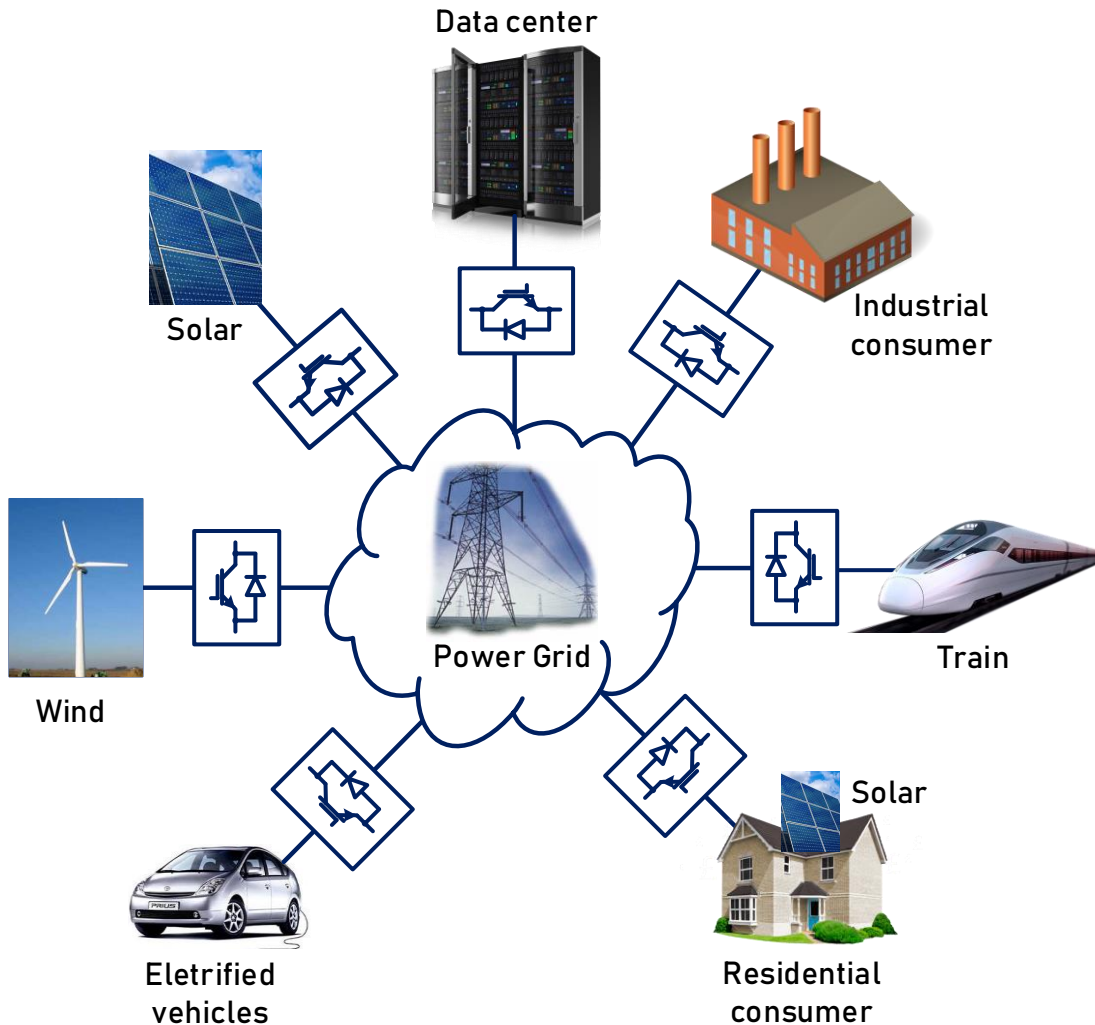


Save



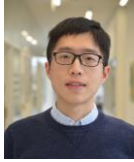
London experienced rush-hour chaos today when the power died across the country

Research topic



Stability analysis are mandatory of transmission system operator (TSO) before allowing converters to physically connect to the power system

Impedance-based stability analysis is most suitable for stability assessment for converter-dominated power system



Project: MTDC (2019~2021)

Assist. Prof. Heng Wu

MTDC = Multi-Terminal MMC-HVDC



AALBORG
UNIVERSITY



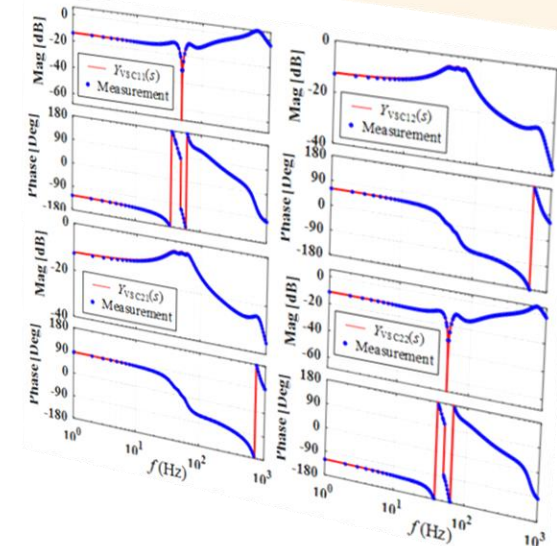
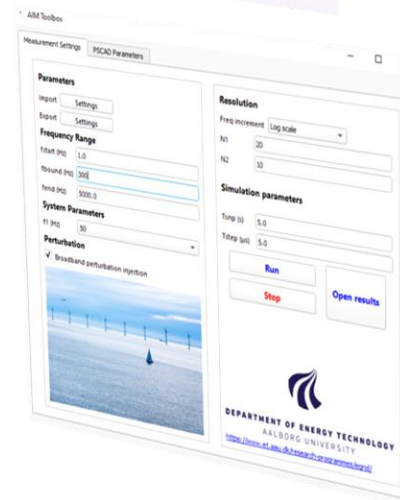
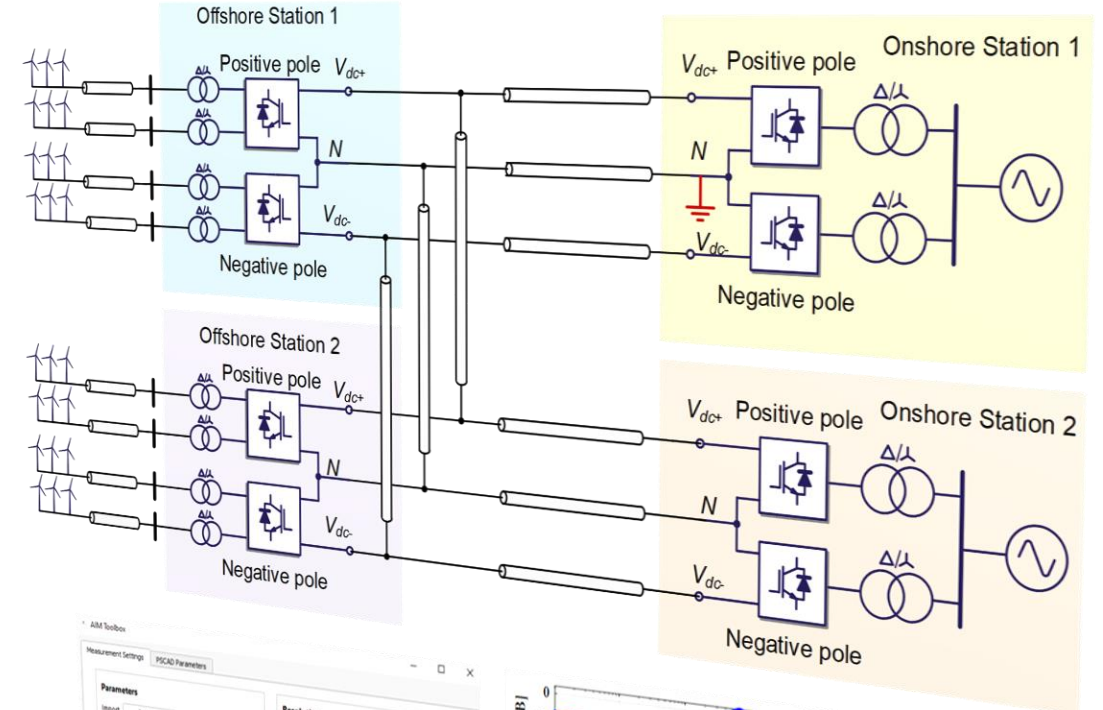
Objective

Impedance-based modeling and stability analysis of multi-vendor, multi-terminal MMC-HVDC systems

Deliverables

1. Theoretical model of ac/dc impedance matrix of the MMC.
2. Impedance-based stability analysis of the MTDC system.
3. Sensitivity analysis to identify the “trouble-maker” that destabilizing the system
4. PSCAD-compatible toolbox for automated ac/dc impedance matrix measurement.

Commercialized



Development of the toolbox

2019

Start software development in corporation with German TSO TenneT



Impedance Measurement



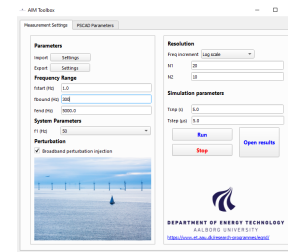
```
ImpedanceMeasurement.py - C:\Users\hewl\OneDrive - Aalborg Universitet\G...
File Edit Format Run Options Window Help
Python Shell
# Frequency Scan
fstart=1
fstop=200
fstep=5000
I_p_mag=0
I_p_ang=0.0041
V1_mag=400
# Magnitude of voltage perturbation (Unit: kV), 1k to 5k (Unit: Hz)
# Magnitude of current perturbation (Unit: kA), 1k to 5k (Unit: Hz)
# Magnitude of the fundamental voltage, L-L RMS (Unit: kV)
EN_Adaptive=1 #Enable signal of the adaptive frequency injection (1 or 0)
HEX_Adaptive=1 Adaptive Frequency Injection in log scale
HEX_Adaptive=0 Equal Distance Frequency Injection in log scale
#Adaptive Frequency Injection Parameters
MaxErr=0.7 # Maximum magnitude error of measured impedance model (0 PhaseErr=0.5 # Maximum phase error of measured impedance model (0)
#Equal Distance Frequency Injection Parameters
N1=30 # Number of measured points for MIM measurement
N2=40 # Number of measured points for SIS measurement. This d
```

2021. 01-2021.07

- AAU proof of concept (PoC) project is granted
- 1st commercial version



Imp_Toolbox



2021.07-2022.12

- Innoexplorer is granted
- Version 2 is expected



- ✓ Beta version of the software is developed
- ✓ Automatic impedance matrix measurement
- ✓ Tested by TenneT in the real HVDC project

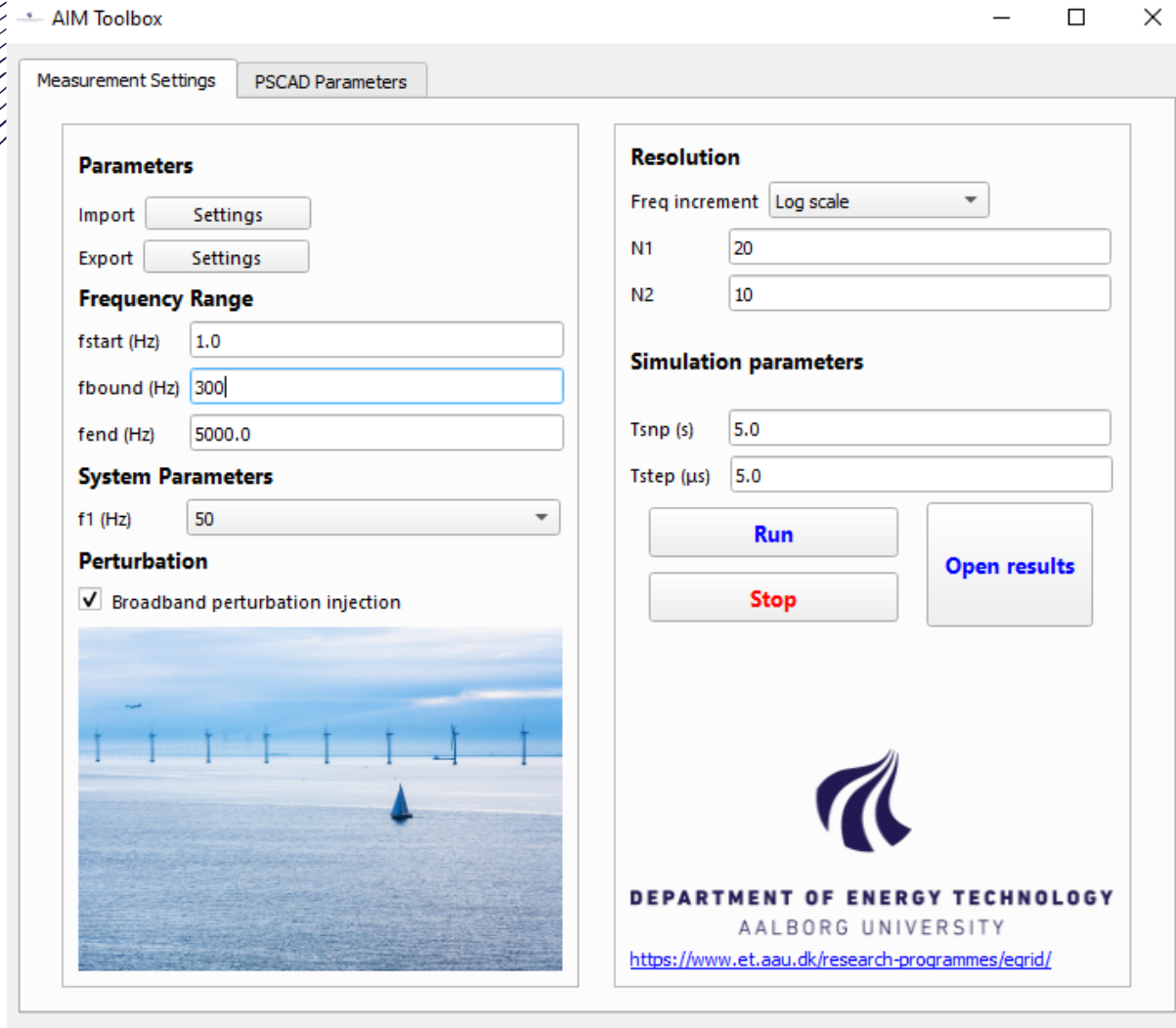
- ✗ Matlab needed for data processing
- ✗ Open source python and matlab scripts, no graphical user interface
- ✗ No license system

- ✓ Get rid of matlab
- ✓ Convert python scripts to exe
- ✓ Graphical user interface development
- ✓ License system development
- ✓ More functionalities
- ✓ Software robustness test in different computer system environment
- ✓ 1st commercial version

- ✓ Using AI to make the toolbox more intelligent

GUI of the toolbox

10

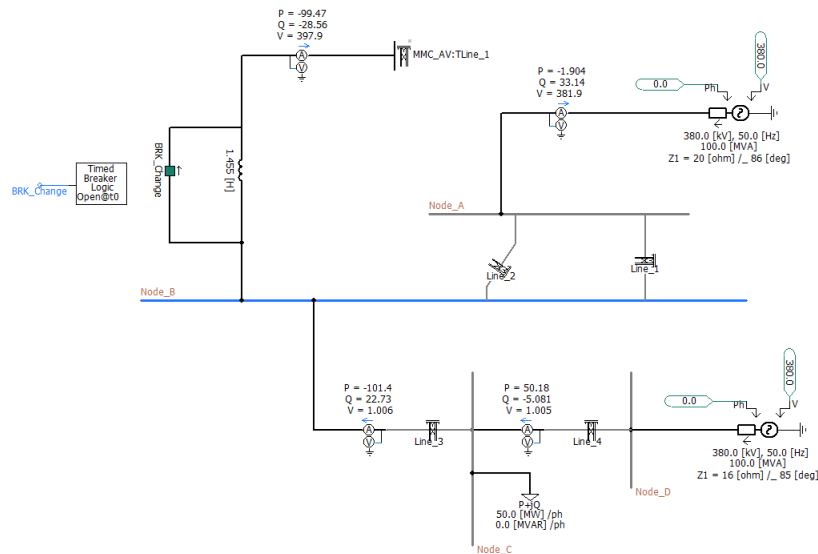
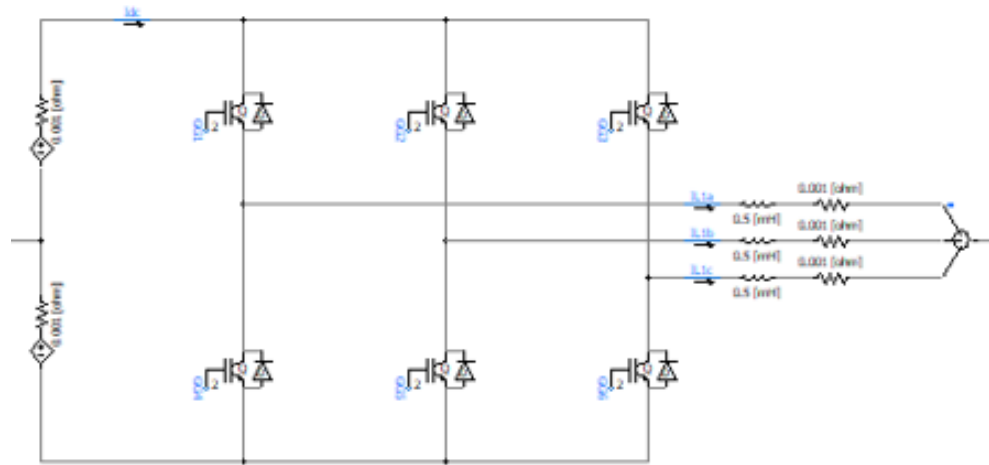
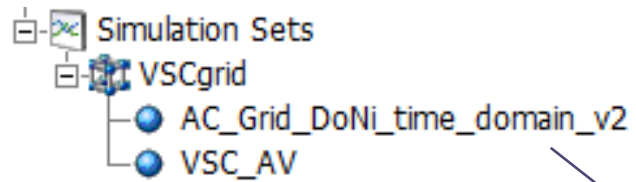


Features

- Fully compatible with PSCAD simulation environment
- Fully automated, one click and the results are automatically generated
- Able to measure all elements in the impedance (admittance) matrix in both dq and $\alpha\beta$ frame
- Has already be used by TenneT in the real MMC-HVDC projects and the measurement results show high accuracy

Features

- Compatible if parallel simulation is used in PSCAD



Number of projects	2
Project Name	
1	VSC_AV
2	AC_Grid_DoNi_time_domain_v2
Simulation_set	VSCgrid

Features

- Impedance measurement of multiple converters within one simulation

The diagram illustrates a power system configuration for impedance measurement. It features two Offshore wind power plants connected to two MMC Stations (MMC Station 1 and MMC Station 2) via PCC1 and PCC2. Each MMC station is associated with a specific Toolbox (Toolbox 1 and Toolbox 2). Red arrows indicate the flow of information from the toolboxes in the schematic to the software interface.

The software interface shows a context menu for a 'Terminal1' component, with the 'Attributes...' option highlighted. The 'Attributes' window displays the following information:

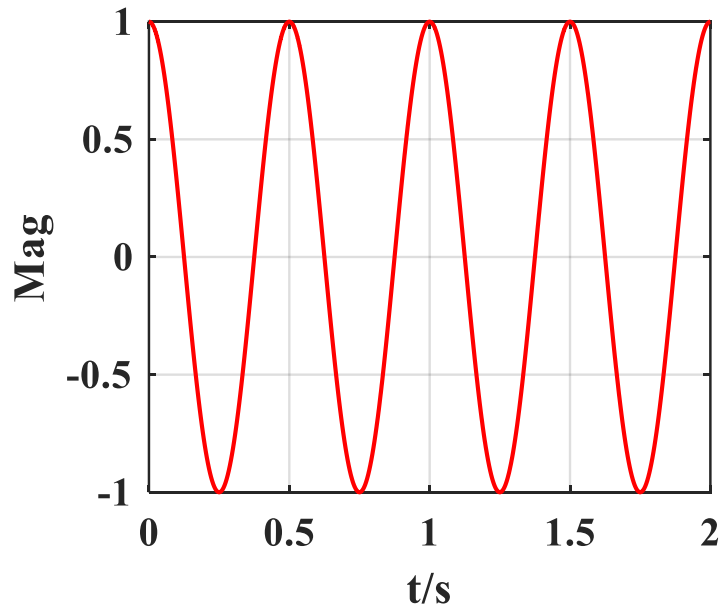
General	
Class	UserCmp
Id	1613473414
Name	fscan_tools:toolbox
Definition	fscan_tools:toolbox
Build Label	
Schematic	
x (position)	3690
y (position)	684

The 'Toolbox ID' is highlighted in red in the attributes window. Below this, the 'Toolbox settings' section includes a text input field for 'Number of toolboxes' set to 2, and a table with the following data:

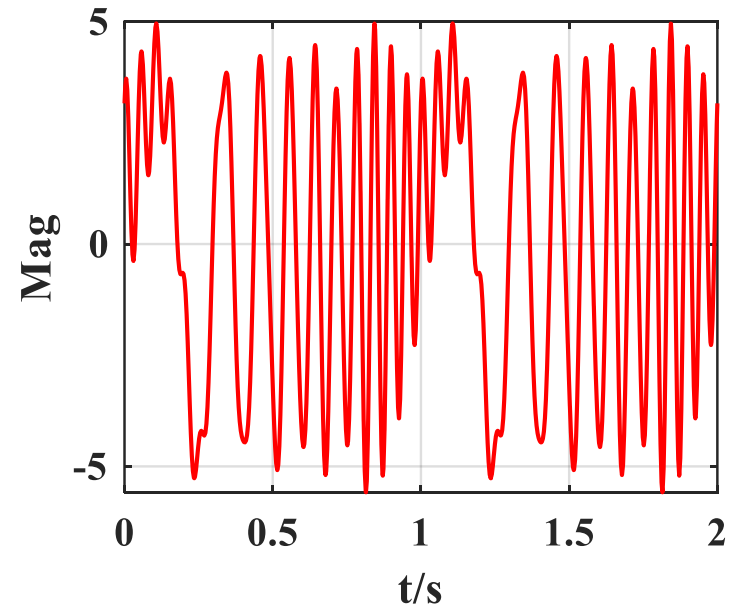
Toolbox ID	Vp_mag (kV)	Ip_mag (kA)	Project number
1	1613473414	0.003	0
2	1015356345	0	0.002

Features

- Broadband perturbation injection to speed up the simulation



Single frequency perturbation injection



Broadband perturbation injection

Perturbation

Broadband perturbation injection

Measurement results

Format of generated files

T1_admittance_dq_MIMO1	✓	6/2/2021 1:00 PM	Text Document	2 KB
T1_admittance_stationary_MIMO1	✓	6/2/2021 3:12 PM	Text Document	4 KB
T1_admittance_stationary_SISO1	✓	6/2/2021 2:27 PM	Text Document	1 KB
T1_impedance_dq_MIMO1	✓	6/2/2021 1:00 PM	Text Document	2 KB
T1_impedance_stationary_MIMO1	✓	6/2/2021 3:12 PM	Text Document	4 KB
T1_impedance_stationary_SISO1	✓	6/2/2021 2:27 PM	Text Document	1 KB

MIMO measurement results, impedance/admittance matrix in dq/αβ frame

T1_admittance_dq_MIMO1	✓	6/2/2021 1:00 PM	Text Document	2 KB
T1_admittance_stationary_MIMO1	✓	6/2/2021 3:12 PM	Text Document	4 KB
T1_admittance_stationary_SISO1	✓	6/2/2021 2:27 PM	Text Document	1 KB
T1_impedance_dq_MIMO1	✓	6/2/2021 1:00 PM	Text Document	2 KB
T1_impedance_stationary_MIMO1	✓	6/2/2021 3:12 PM	Text Document	4 KB
T1_impedance_stationary_SISO1	✓	6/2/2021 2:27 PM	Text Document	1 KB

SISO measurement results, impedance/admittance in αβ frame

Cross-validation

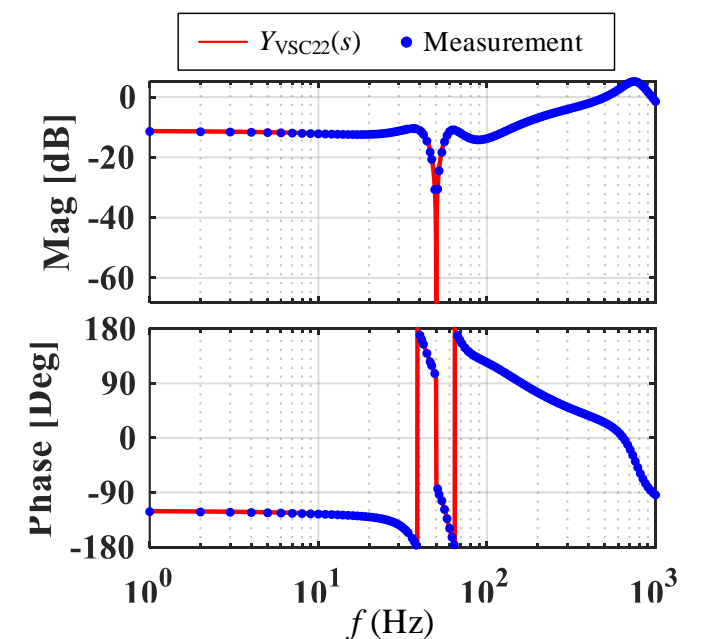
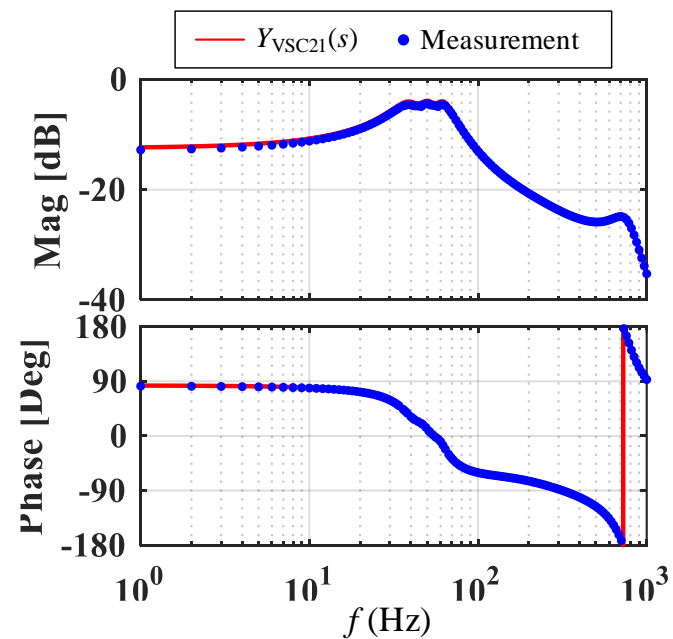
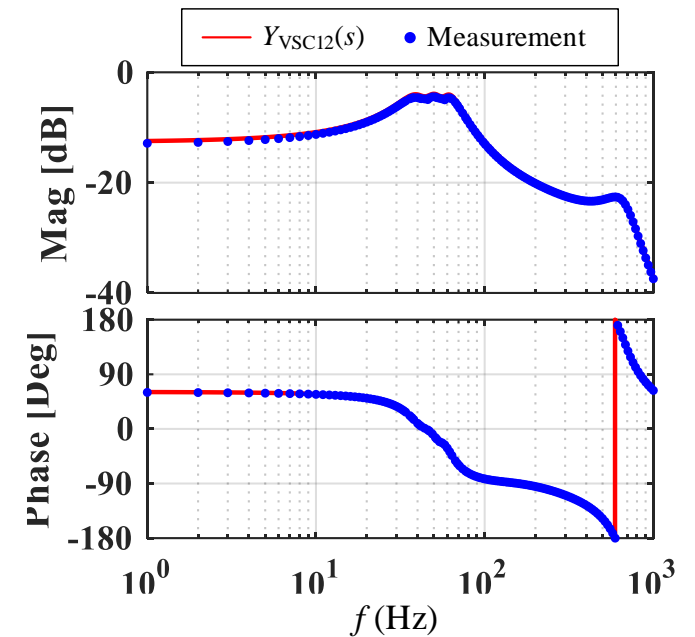
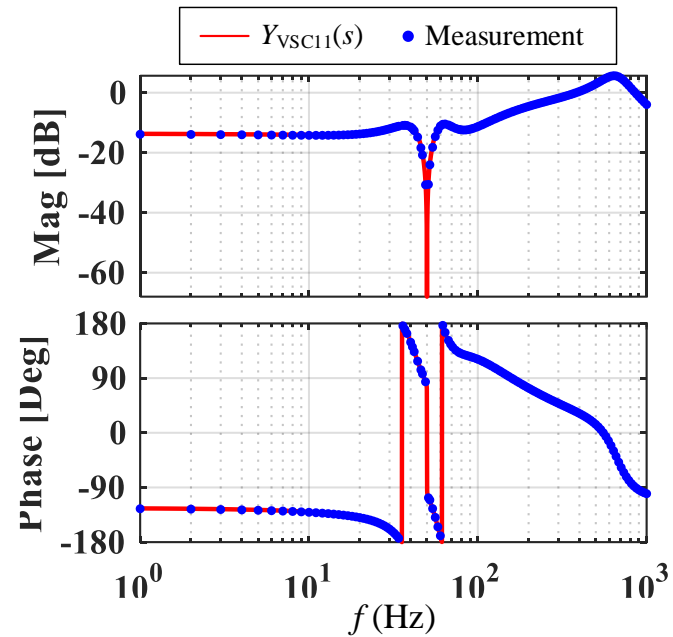
AC impedance matrix

Mag error < 1dB
Phase error < 1°

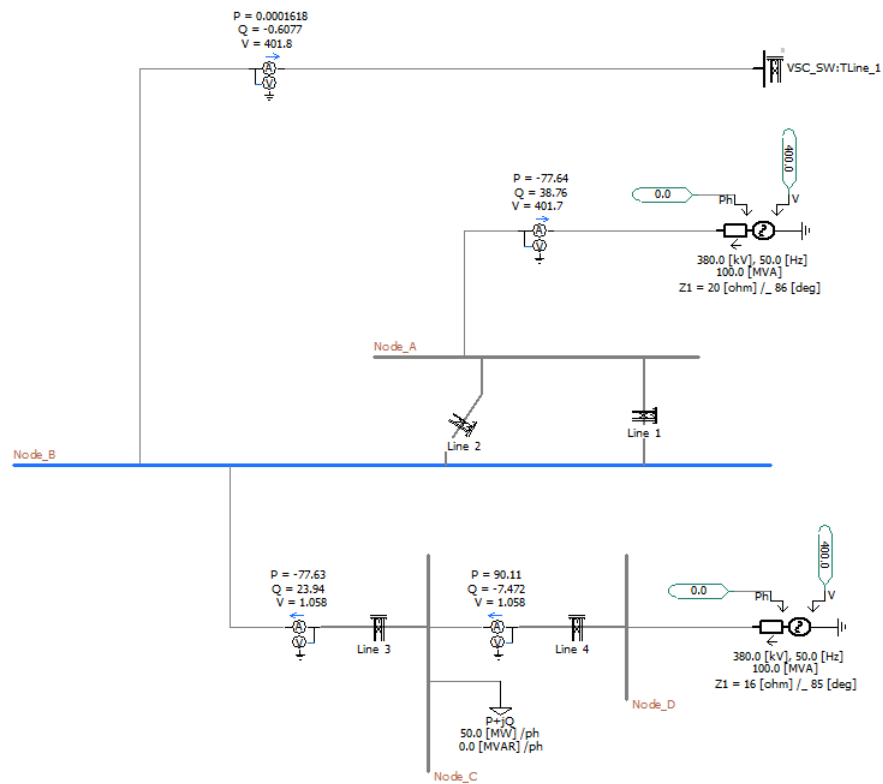
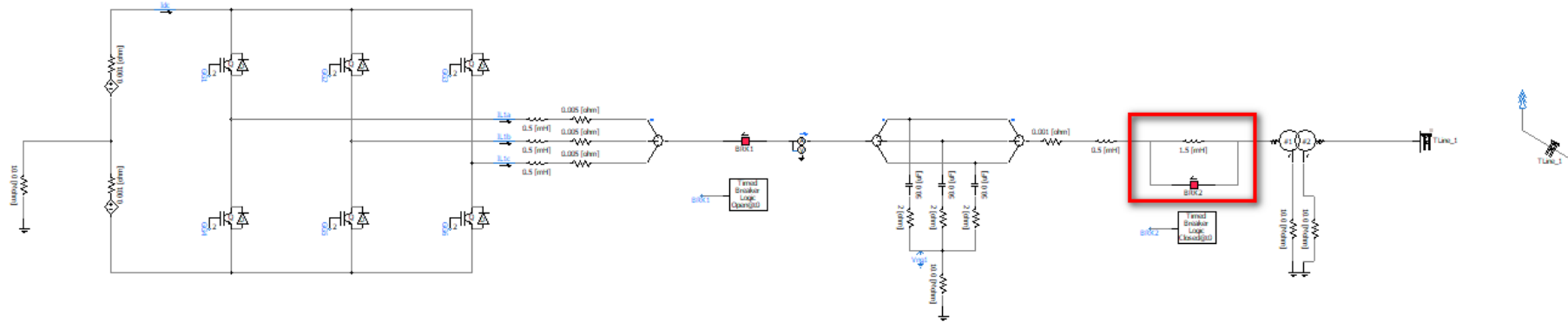
$$\begin{bmatrix} i_{\alpha\beta}(\omega_p) \\ i_{\alpha\beta}(2\omega_1 - \omega_p) \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} v_{\alpha\beta}(\omega_p) \\ v_{\alpha\beta}(2\omega_1 - \omega_p) \end{bmatrix}$$

Admittance matrix in $\alpha\beta$ frame

H. Wu, X. Wang, Y. Liao, M. Ndreko, R. Dimitrovski and W. Winter, "Development of an AC/DC impedance matrix measurement Toolbox for MTDC System", in 20th Proc. Wind Integr. Workshop, 2021.



Case studies with AIM toolbox

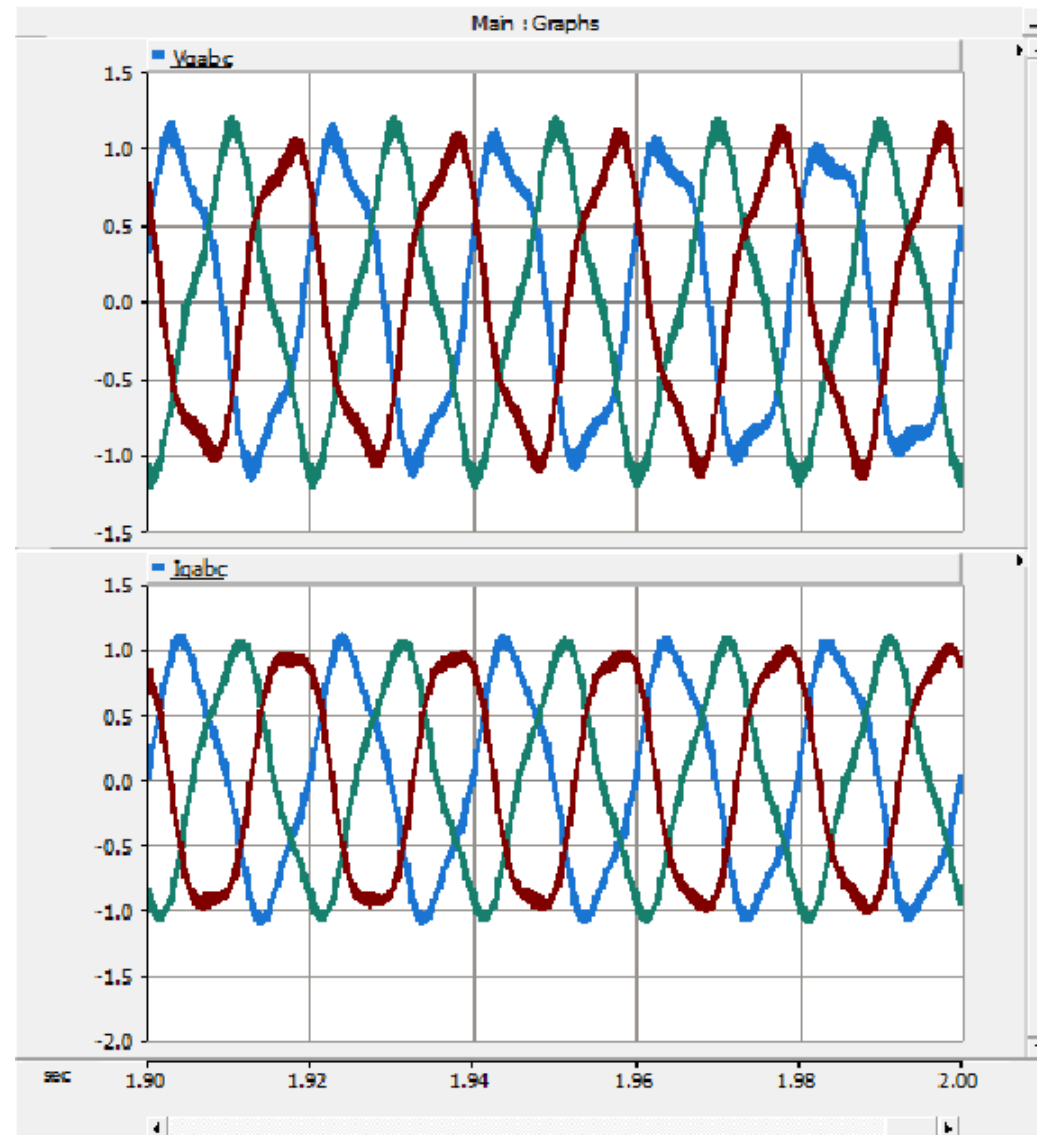
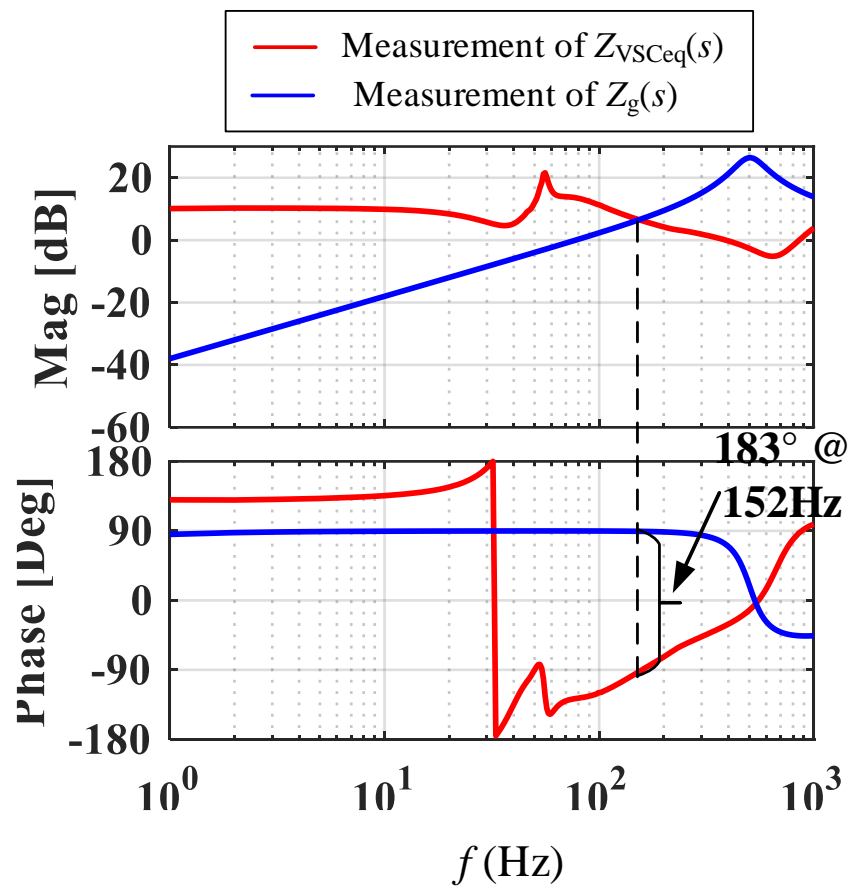


- BRK opens, weak grid
- BRK closes, strong grid

Weak Grid

$f_{PLL}=25\text{Hz}$, unstable

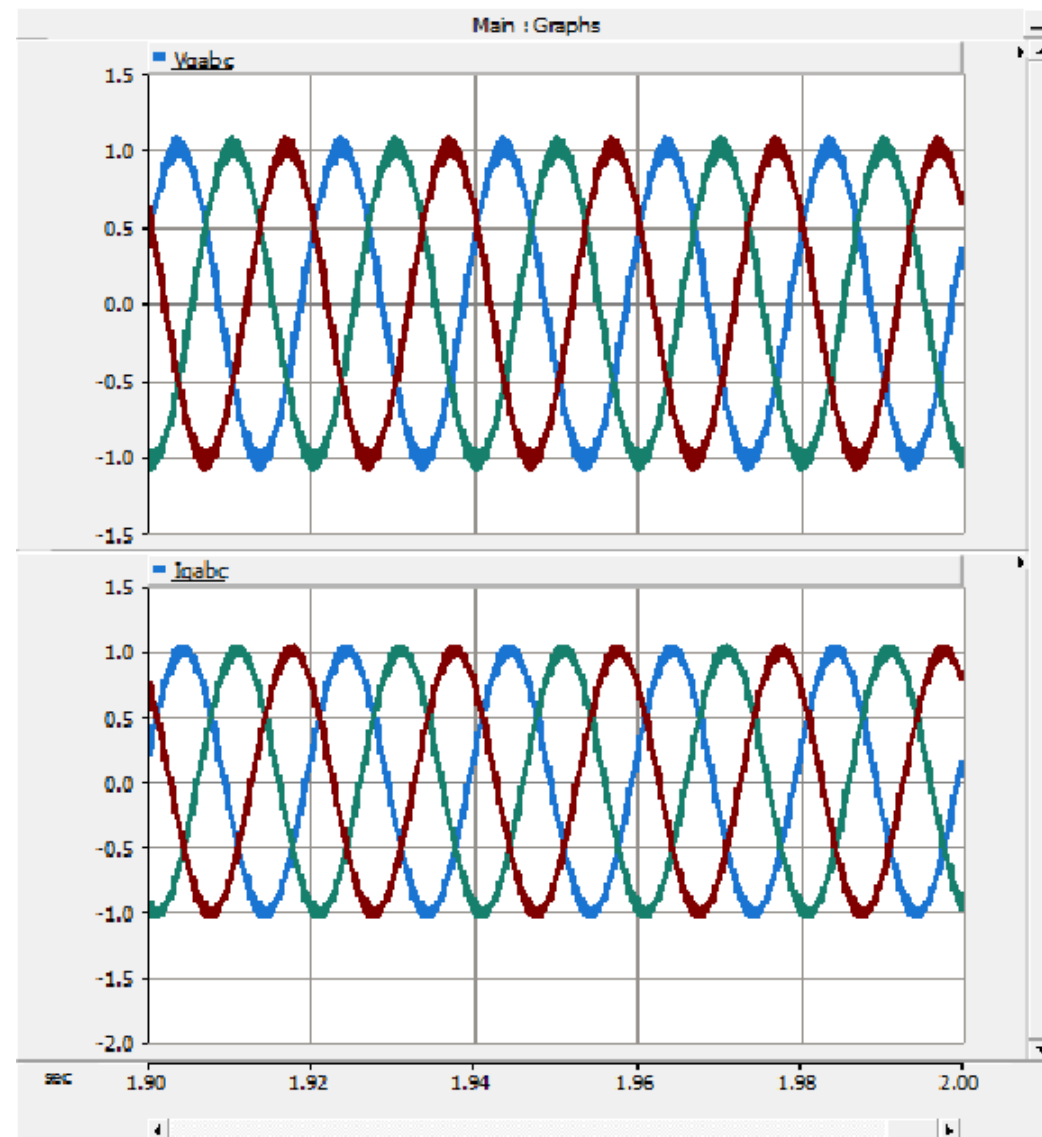
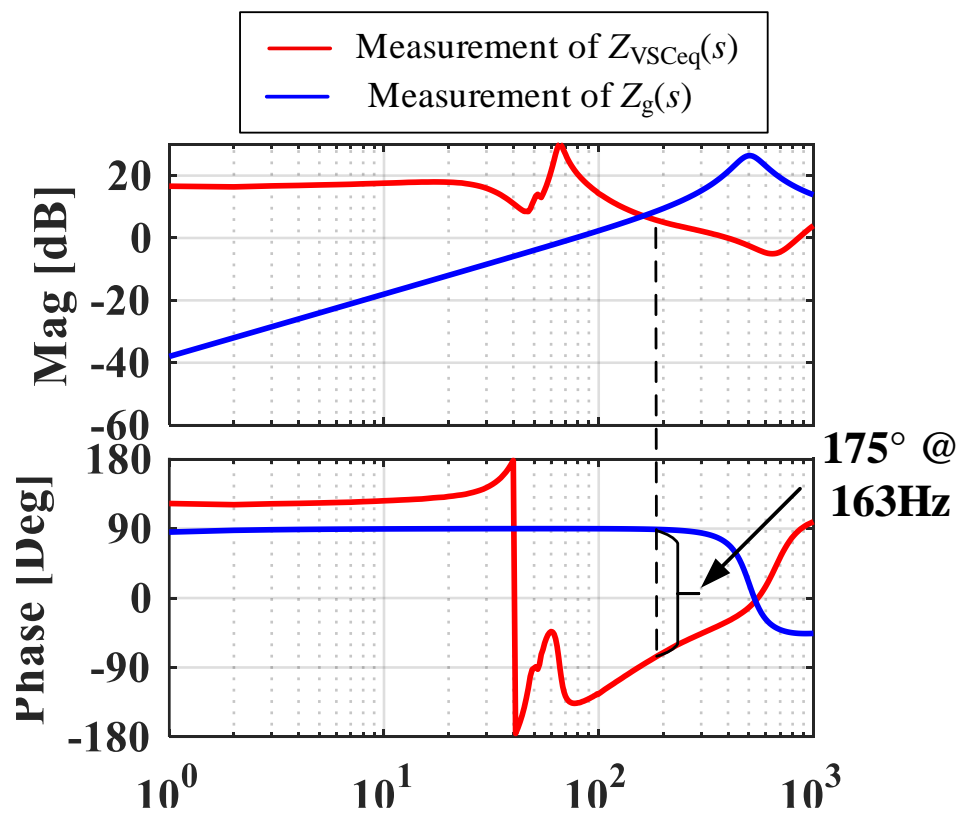
Accurate stability prediction based on the impedance measurement data



Weak Grid

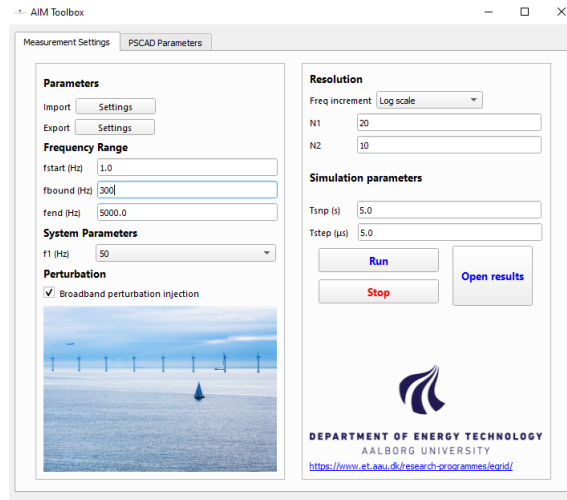
$f_{PLL}=5\text{Hz}$, stable

Accurate stability prediction based on the impedance measurement data

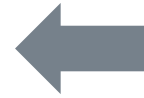


Commercialized software toolbox for power system stability analysis

Impedance measurement toolbox



User's manual



Cross-validation



Generic EMT model of two-level voltage source converter



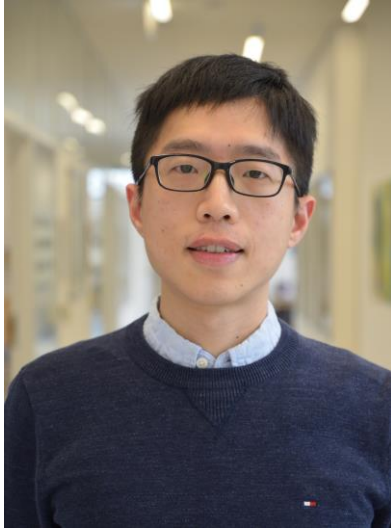
Theoretical calculated impedance of two-level voltage source converter

For more information

<https://www.energy.aau.dk/research-groups/egrid/Research/AIM-Toolbox>

<https://www.en.patent.aau.dk/technologies/impedance-measurement/>

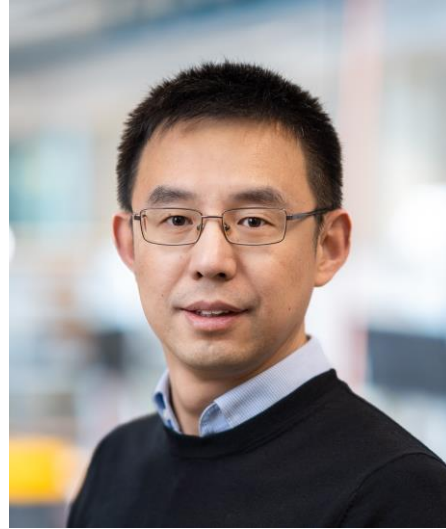
Spin-out on the way....



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