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Welcome to the webinar in collaboration between
CIGRE U.S. NGN & CIGRE Denmark NGN on

Power System Stability: Challenges & Analyses

In today's webinar, **Julia Matevosyan** will discuss measures like electromagnetic transient studies and model validation and verification processes, when and why these innovative and dynamic measures were introduced, and related initiatives underway at the Electric Reliability Council of Texas (ERCOT). This webinar will also include **Heng Wu** focusing on fundamental basis of impedance-based stability criterion, an introduction of the impedance measurement toolbox, and case studies to demonstrate how the impedance measurement toolbox can predict the stability of power-electronics' converter-dominated power system in practice.

Thursday, September 2, 2021
12 noon U.S. Eastern Time | 6 pm Denmark time

CIGRE U.S. Next Gen Network

- Top 5 finalists of the 2021 NGN Paper Competition doing an exciting round of presentations at this year's Grid of the Future Symposium.

2021
Grid of the Future
OCTOBER 17-20, 2021 || PROVIDENCE, RI

- **Global Youth Engineering Climate Conference** on Sep 7-8, bringing together principal partners and a wide variety of global organizations, societies and networks to create an exciting and dynamic virtual global program, including:
  - Conference and main plenary including Q&A, featuring a range of panelists.
  - Virtual exhibition comprising a variety of stands featuring films.
  - Four interactive workstreams, themed on issues for green energy transition.
  - Virtual networking, including space to help audience build new contacts and become part of a sustainable community with a common aim.
  - Virtual green jobs board, advertising globally available "green" vacancies in engineering and related technical fields, posted by supporting partners at the event.
  - To maximize opportunities to join this event globally.

Global Youth
Engineering
Climate
Conference
2021

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2021 Grid of the Future

2021
Grid of the Future
OCTOBER 17–20, 2021 || PROVIDENCE, RI

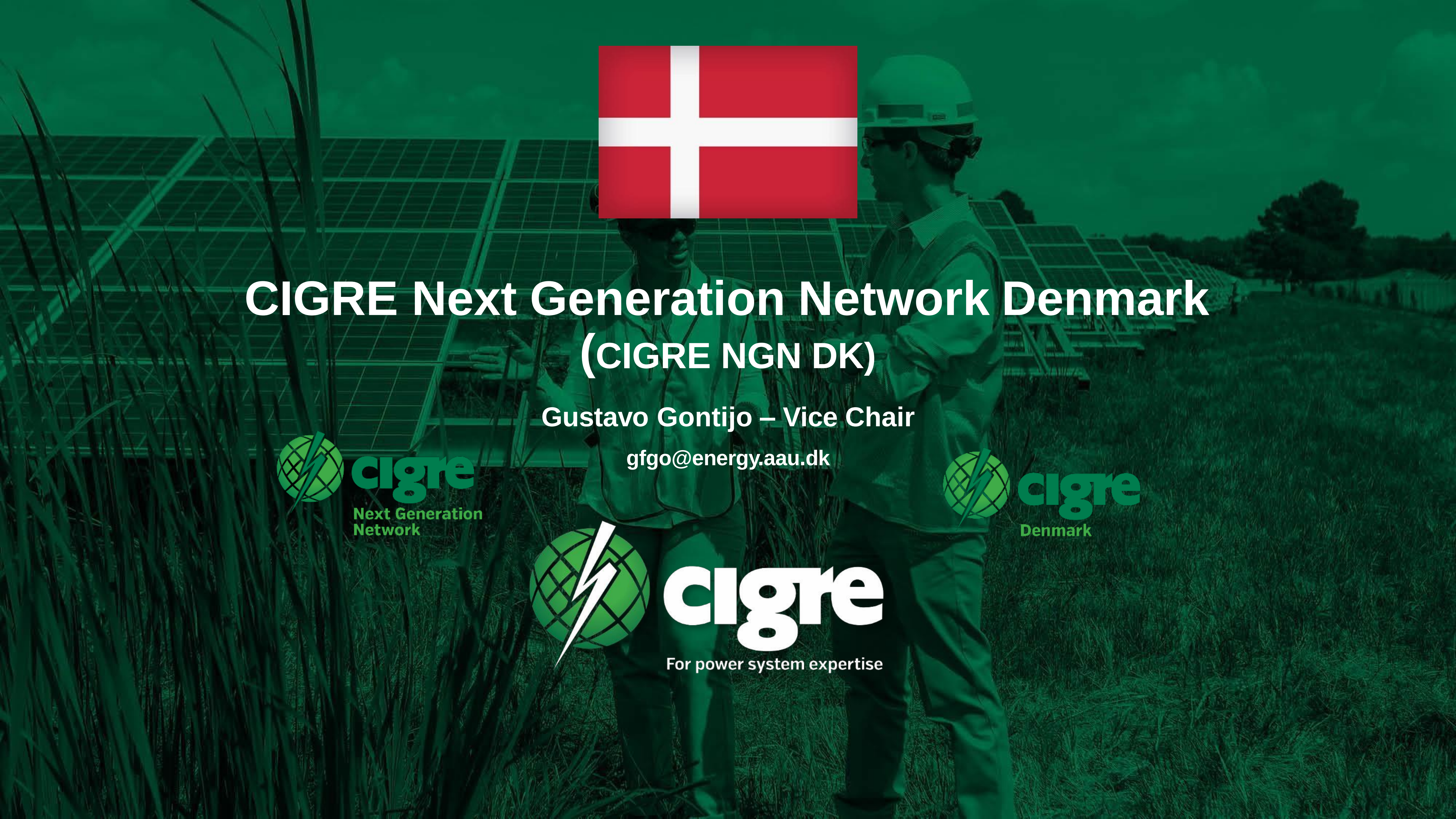
- A hybrid event
- Technology for the 21st century electric utility
- Grid of the Future 2021 will feature plenary sessions, technical paper sessions, and tutorials by international experts; contributions from Next Generation Network (NGN) young engineers are encouraged

- **NGN Tutorial and visit to National Grid owned solar farm**
  Sunday, October 17, 1 pm to 4:45 pm
- Learn how National Grid is experimenting with Advanced Inverters, Dynamic VAR, Energy Storage and SCADA Controls to enable a clean energy grid; opportunity to visit one of the most advanced PV and Energy Storage sites in the country

- **IEC 61850 Tutorial & tour of Digital Substation Lab**
  Wednesday, October 20, 8 am to 12 noon

- **National Grid spot Robot Tutorial with HVDC use-case, demo & substation tour**
  Wednesday, October 20, 8 am to 12 noon

nationalgrid



CIGRE Next Generation Network Denmark

(CIGRE NGN DK)

Gustavo Gontijo – Vice Chair

gfgo@energy.aau.dk

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What is CIGRE NGN DK?

CIGRE Next Generation Network (NGN) Denmark is the affiliation of CIGRE Denmark for **young members** (students/less than 10 years in the industry).

CIGRE Denmark is the Danish chapter of a large knowledge sharing organization for large electric power systems, that publishes articles, hosts Working Groups (WGs), conferences and symposia.

The steering committee of CIGRE NGN wants to **create and host events where young engineers can learn and network**. We are arranging a series of technical webinars and (when possible) physical events.

Website: https://cigre.dk/new-generation-network.html

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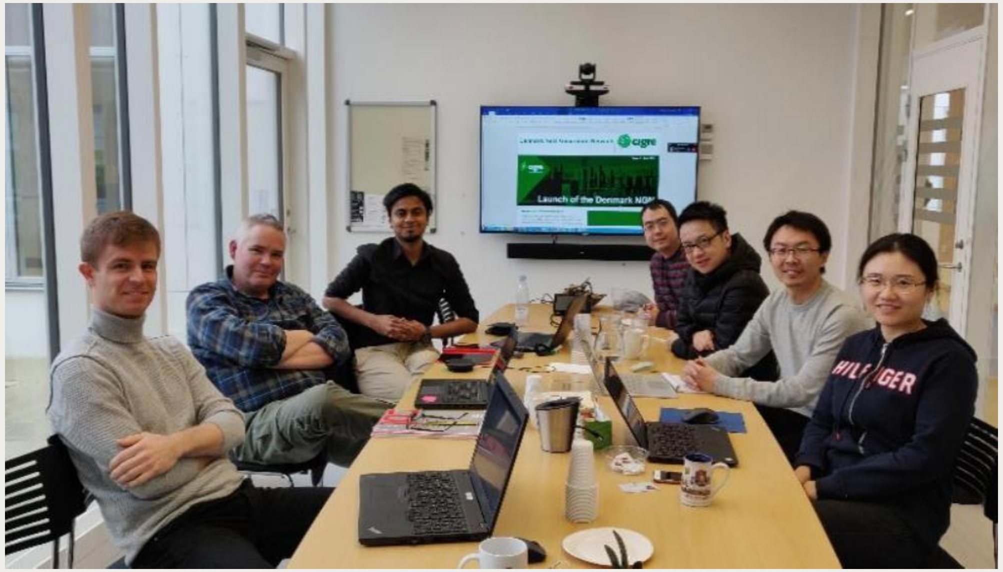
CIGRE NGN DK Facts

- Kick-off in March 2019
- Currently over 80 members
- Inspirations from CIGRE Paris Session 2018
- Experience of peers from the UK, the Netherlands and Germany
- Interest of Danish National Committee (NC)



CIGRE Denmark National Committee

- Claus Leth Bak, Chair - **Aalborg University (AAU)**
- Jørgen S. Christensen - **Dansk Energi**
- Troels Stybe Sørensen - **Ørsted**
- Joachim Holbøll - **Technical University of Denmark (DTU)**
- Philip Carne Kjær - **Vestas**
- Peter Weinreich-Jensen – **Siemens**

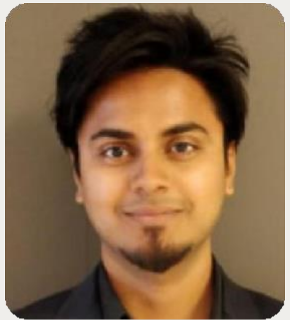
→ Secretary: Anette Lundsgaard Larsen - **AAU**

Steering Committee: The Team

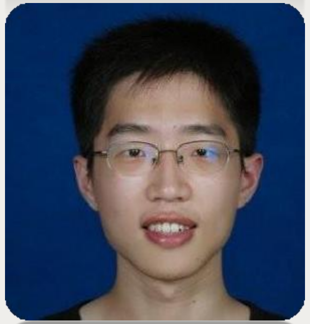
Daniela Pagnani

Eli Maria Stenseth

Lennart Petersen



Syed Hamza Kazmi



Heng Wu

Gustavo Figueiredo Gontijo

cigré DK NGN

BREAKING NEW GROUND
AALBORG UNIVERSITY

Vestas

ENERGINET

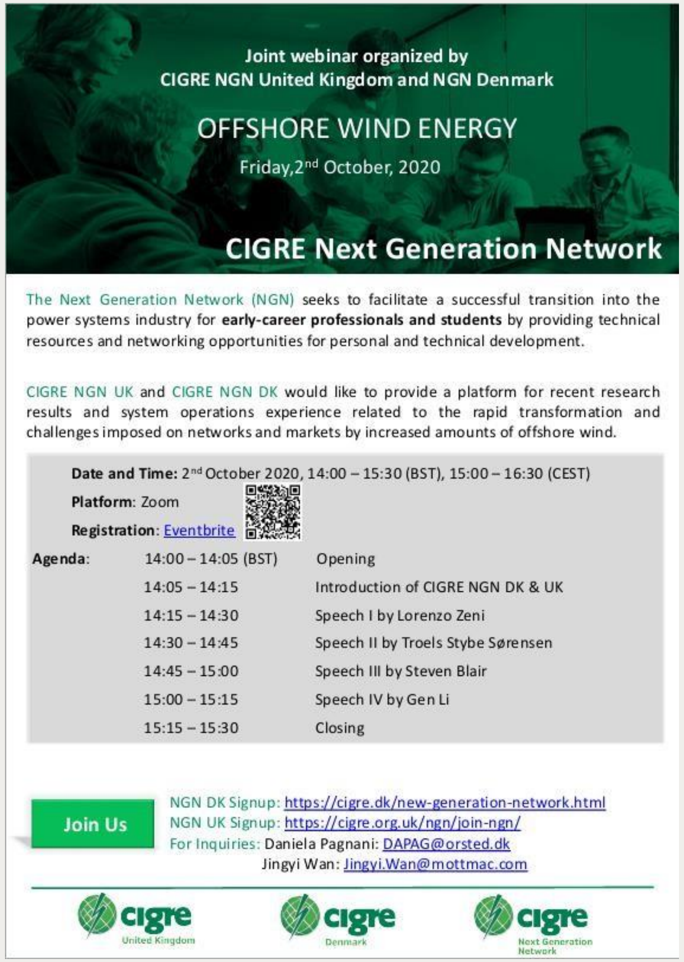
Ørsted

DTU
Technical University
of Denmark

NGN Events

Events organized in **2020**:

- Webinar ”**Offshore Wind Energy**”, in collaboration with NGN UK. Led by our SC members in Ørsted and AAU.
- Webinar ”**Offshore Energy Hubs**”, in collaboration to NGN NL. Led by our SC members in Energinet and Ørsted.



Joint webinar organized by
CIGRE NGN United Kingdom and NGN Denmark

OFFSHORE WIND ENERGY

Friday,2nd October, 2020

CIGRE Next Generation Network

The Next Generation Network (NGN) seeks to facilitate a successful transition into the power systems industry for **early-career professionals and students** by providing technical resources and networking opportunities for personal and technical development.

CIGRE NGN UK and CIGRE NGN DK would like to provide a platform for recent research results and system operations experience related to the rapid transformation and challenges imposed on networks and markets by increased amounts of offshore wind.

Date and Time: 2nd October 2020, 14:00 – 15:30 (BST), 15:00 – 16:30 (CEST)
Platform: Zoom
Registration: Eventbrite

Agenda:		
	14:00 – 14:05 (BST)	Opening
	14:05 – 14:15	Introduction of CIGRE NGN DK & UK
	14:15 – 14:30	Speech I by Lorenzo Zeni
	14:30 – 14:45	Speech II by Troels Stybe Sørensen
	14:45 – 15:00	Speech III by Steven Blair
	15:00 – 15:15	Speech IV by Gen Li
	15:15 – 15:30	Closing

Join Us

NGN DK Signup: https://cigre.dk/new-generation-network.html
NGN UK Signup: https://cigre.org.uk/ngn/join-ngn/
For Inquiries: Daniela Pagnani: DAPAG@orsted.dk
Jingyi Wan: Jingyi.Wan@mottmac.com

cigre United Kingdom
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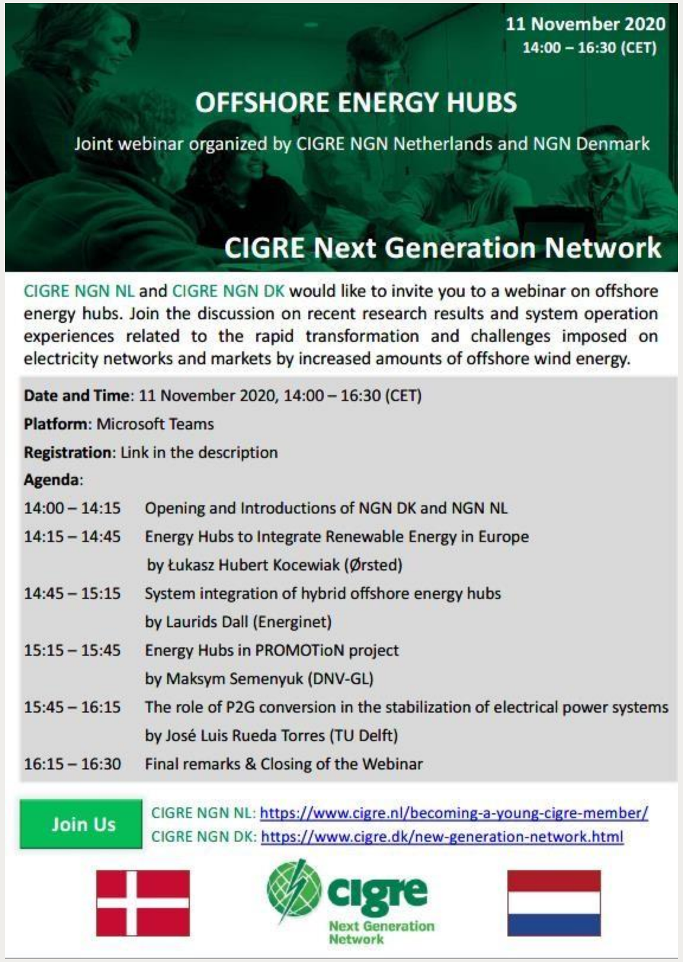

11 November 2020
14:00 – 16:30 (CET)

OFFSHORE ENERGY HUBS

Joint webinar organized by CIGRE NGN Netherlands and NGN Denmark

CIGRE Next Generation Network

CIGRE NGN NL and CIGRE NGN DK would like to invite you to a webinar on offshore energy hubs. Join the discussion on recent research results and system operation experiences related to the rapid transformation and challenges imposed on electricity networks and markets by increased amounts of offshore wind energy.

Date and Time: 11 November 2020, 14:00 – 16:30 (CET)
Platform: Microsoft Teams
Registration: Link in the description
Agenda:

14:00 – 14:15	Opening and Introductions of NGN DK and NGN NL
14:15 – 14:45	Energy Hubs to Integrate Renewable Energy in Europe by Łukasz Hubert Kocewiak (Ørsted)
14:45 – 15:15	System integration of hybrid offshore energy hubs by Laurids Dall (Energinet)
15:15 – 15:45	Energy Hubs in PROMOTioN project by Maksym Semenyuk (DNV-GL)
15:45 – 16:15	The role of P2G conversion in the stabilization of electrical power systems by José Luis Rueda Torres (TU Delft)
16:15 – 16:30	Final remarks & Closing of the Webinar

Join Us

CIGRE NGN NL: https://www.cigre.nl/becoming-a-young-cigre-member/
CIGRE NGN DK: https://www.cigre.dk/new-generation-network.html

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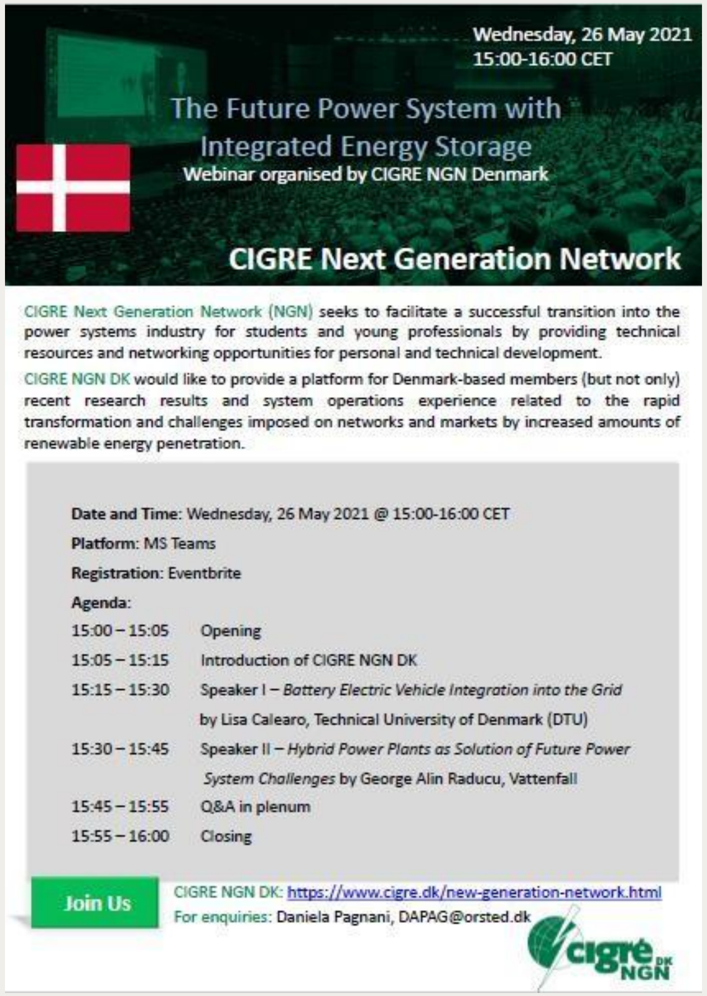
NGN Events

Events organized in **2021**:

- Webinar “**The Future Power System with Integrated Energy Storage**”, Led by our SC members in Ørsted, Energinet and AAU.

DTU Danmarks Tekniske Universitet

VATTENFALL



Wednesday, 26 May 2021
15:00-16:00 CET

The Future Power System with Integrated Energy Storage

Webinar organised by CIGRE NGN Denmark

CIGRE Next Generation Network

CIGRE Next Generation Network (NGN) seeks to facilitate a successful transition into the power systems industry for students and young professionals by providing technical resources and networking opportunities for personal and technical development.

CIGRE NGN DK would like to provide a platform for Denmark-based members (but not only) recent research results and system operations experience related to the rapid transformation and challenges imposed on networks and markets by increased amounts of renewable energy penetration.

Date and Time: Wednesday, 26 May 2021 @ 15:00-16:00 CET

Platform: MS Teams

Registration: Eventbrite

Agenda:

15:00 – 15:05	Opening
15:05 – 15:15	Introduction of CIGRE NGN DK
15:15 – 15:30	Speaker I – *Battery Electric Vehicle Integration into the Grid* by Lisa Calearo, Technical University of Denmark (DTU)
15:30 – 15:45	Speaker II – *Hybrid Power Plants as Solution of Future Power System Challenges* by George Alin Raducu, Vattenfall
15:45 – 15:55	Q&A in plenum
15:55 – 16:00	Closing

Join Us

CIGRE NGN DK: https://www.cigre.dk/new-generation-network.html

For enquiries: Daniela Pagnani, DAPAG@orsted.dk

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Technical Visits in the Pipeline - Avedøre Power Station and Wind Farm Visit

- Event at Ørsted's Avedøre power station (close to Copenhagen)
- Visit Avedøre offshore wind farm and combined heat and power station
- Technical tour to the power station

Ørsted

Source: https://ramboll.com/projects/re/avedore_power_station .

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Technical Visits in the Pipeline - Vester Hassing HVDC Substation Visit

- Event at the Vester Hassing substation in North Jutland
- Event in collaboration with Energinet and AAU
- Konti–Skan HVDC connection with Sweden

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Source: https://en.wikipedia.org/wiki/Konti%E2%80%93Skan#/media/File:KontiSkan_Vester_Hassing_converter_station_2011.jpg

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Technical Visits in the Pipeline - COBRAcable HVDC Visit

- Event led by Energinet
- Visit to Energinet headquarters in Fredericia and Endrup substation
- HVDC connection to the Netherlands

Source: http://www.cobracable.eu/ .

Technical Visits in the Pipeline - Vestas Nacelle Production

- Event led by Vestas
- Technical talks/tutorials
- Technical tour to the factory to see how the power equipment are manufactured

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Joining CIGRE NGN DK

- Become a CIGRE member (**free** for students or through affiliation with companies and universities with Collective membership)
- Registration form for CIGRE NGN DK (**free** as well) at: https://cigre.dk/new-generation-network.html

Young Cigré Denmark
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Today’s speakers

Julia Matevosyan

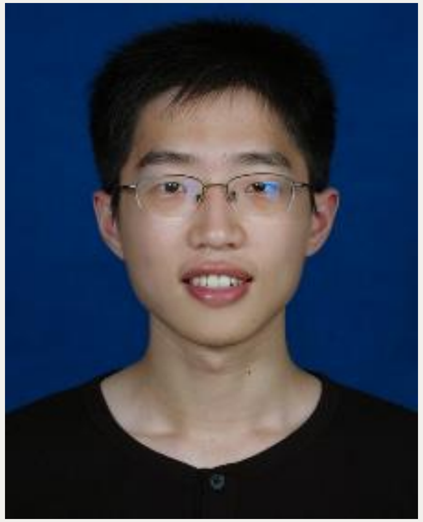
Lead Planning Engineer at ERCOT

Julia Matevosyan is Lead Planning Engineer at the Electric Reliability Council of Texas (ERCOT), Resource Adequacy Group, primarily working on adequacy of system inertial response, system flexibility, frequency control and performance issues related to high penetration levels of inverter-based generation. Her other interests are integration of storage and distributed generation. Julia is a member of CIGRE Working Group C2/C4.41 “Impact of High Penetration of Inverter-based Generation on System Inertia of Networks” and serves on a number of the technical advisory committees for projects related to high penetration of inverter-based generation carried out by NREL, EPRI, NERC and others. Julia received her BSc from Riga Technical University in Latvia, and her MSc and PhD from the Royal Institute of Technology (KTH) in Sweden.

Heng Wu

Postdoctoral Researcher at Aalborg University

Heng Wu received B.S. and M.S. degrees in electrical engineering from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2012 and 2015, respectively, and the Ph.D. degree in electrical engineering from Aalborg University, Aalborg, Denmark, in 2020. He is currently a postdoctoral researcher with the Department of Energy Technology, Aalborg University. He has worked with NR Electric Co., Ltd in Nanjing, China, Ørsted Wind Power in Denmark, and with Bundeswehr University Munich in Germany. He is the co-chair of IEEE Taskforce on Frequency-domain Modeling and Dynamic Analysis of HVDC and FACTS, a member of CIGRE working group B4.85, and a Steering Committee Member of CIGRE NGN Denmark. He received the 2019 Outstanding Reviewer Award by the IEEE Transactions on Power Electronics.



Power System Stability with High Renewable Penetration

Julia Matevosyan
System Planning

CIGRE NGN Webinar: Power System Stability – Challenges and Analyses

September 2, 2021

Outline

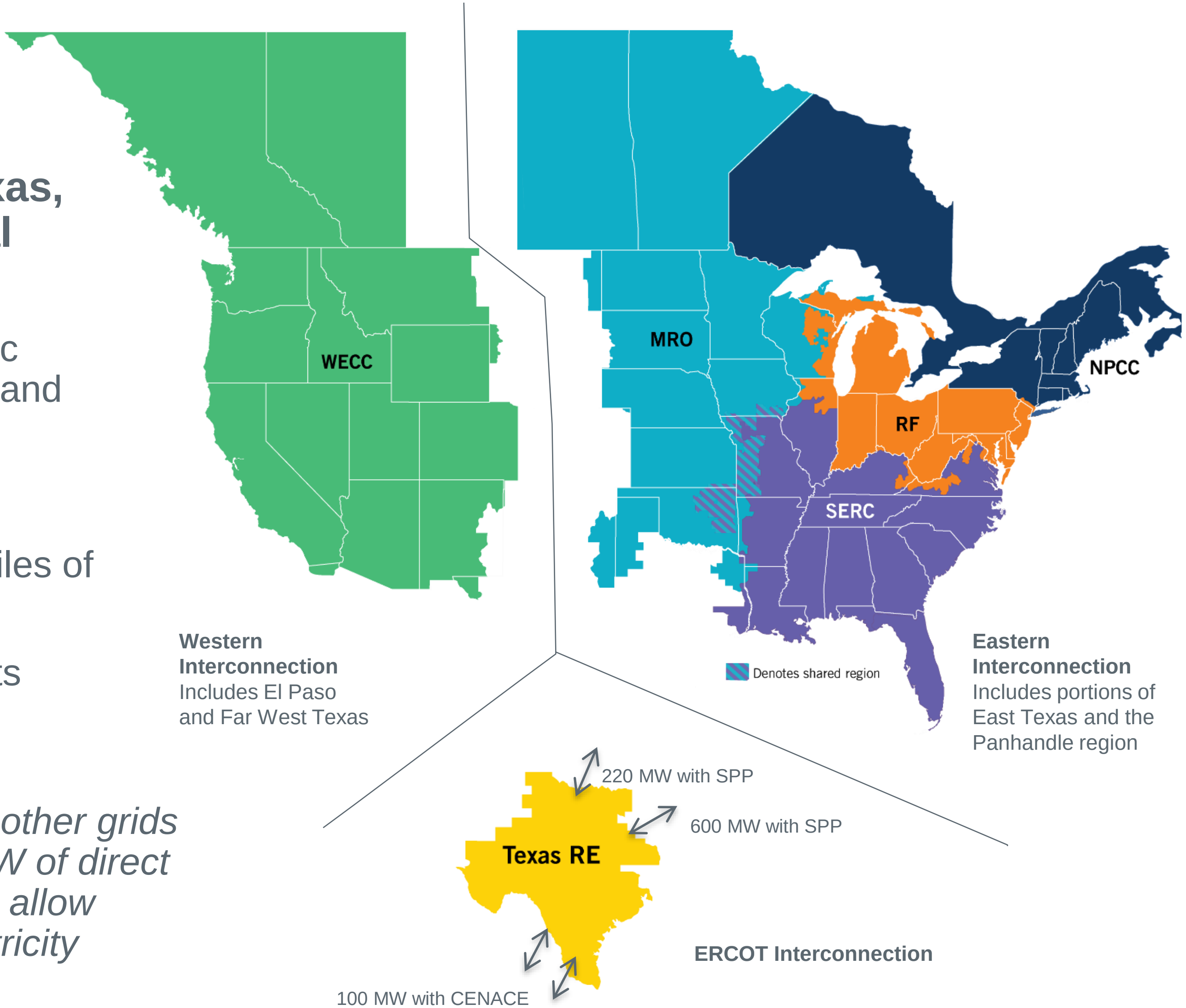
- ERCOT background
- Inverter-Based Resources (IBRs) in ERCOT
- System Strength
- IBR Interconnection
- Models and simulation tools
- Inertia and Frequency Containment
- Summary

The ERCOT Region

The interconnected electrical system serving most of Texas, with limited external connections

- 90% of Texas electric load; 75% of Texas land
- 74,820 MW peak, Aug. 12, 2019
- More than 46,500 miles of transmission lines
- 710+ generation units (excluding PUNs)

ERCOT connections to other grids are limited to ~1,220 MW of direct current (DC) ties, which allow control overflow of electricity



Western Interconnection
Includes El Paso
and Far West Texas

Eastern Interconnection
Includes portions of
East Texas and the
Panhandle region

ERCOT Interconnection

220 MW with SPP

600 MW with SPP

100 MW with CENACE
at Laredo

300 MW with CENACE at McAllen

ERCOT, Inc.

Who we are

The Electric Reliability Council of Texas, or ERCOT, is a nonprofit organization that operates an energy-only wholesale electricity market for 90 percent of the state of Texas, operating 24/7/365 days a year, with a business model that allows market participants to buy and sell power in a voluntary Day-Ahead Market or during real-time operations.

ERCOT is not a market participant and does not own generation or transmission/ distribution wires. Similar to an air traffic controller, it doesn't own the airplanes or runways, but it steps back and make sure everything is flowing properly and efficiently.

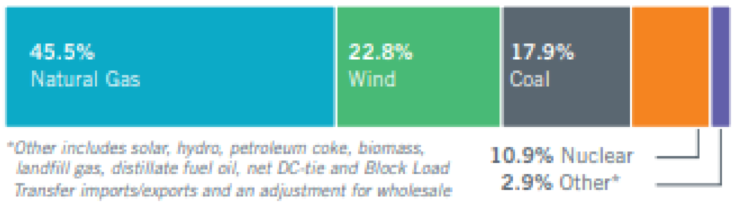
The Texas Legislature restructured the Texas electric market in 1999 and assigned ERCOT four primary responsibilities:

- **System reliability**
- **Competitive wholesale market**
- **Open access to transmission**
- **Competitive retail market**

ERCOT Facts

More than
26 million
customers in the
ERCOT region

- 1,800+ active market participants that generate, move, buy, sell or use wholesale electricity
- 86,000+ megawatts (MW) of expected capacity for summer 2021 peak demand



2020 Energy Use

*Other includes solar, hydro, petroleum coke, biomass, landfill gas, distillate fuel oil, net DC-tie and Block Load Transfer imports/exports and an adjustment for wholesale storage load

382 billion kilowatt-hours of energy were used in 2020, a 0.6 percent decrease compared to 2019.

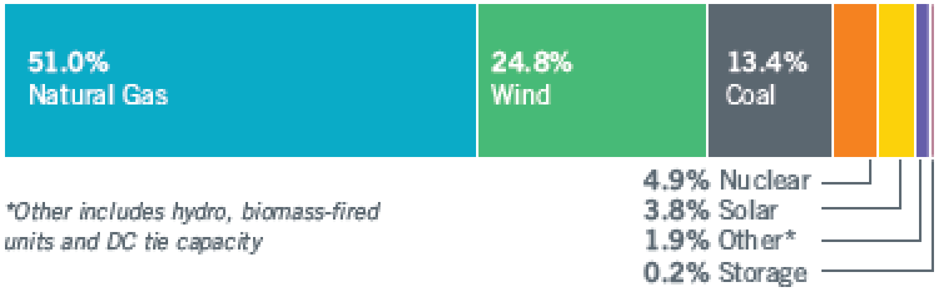
74,820 MW
Record peak demand
(Aug. 12, 2019)

71,930 MW
Weekend peak demand record
(Aug. 11, 2019)

1 MW of electricity can power about 200 Texas homes during periods of peak demand.

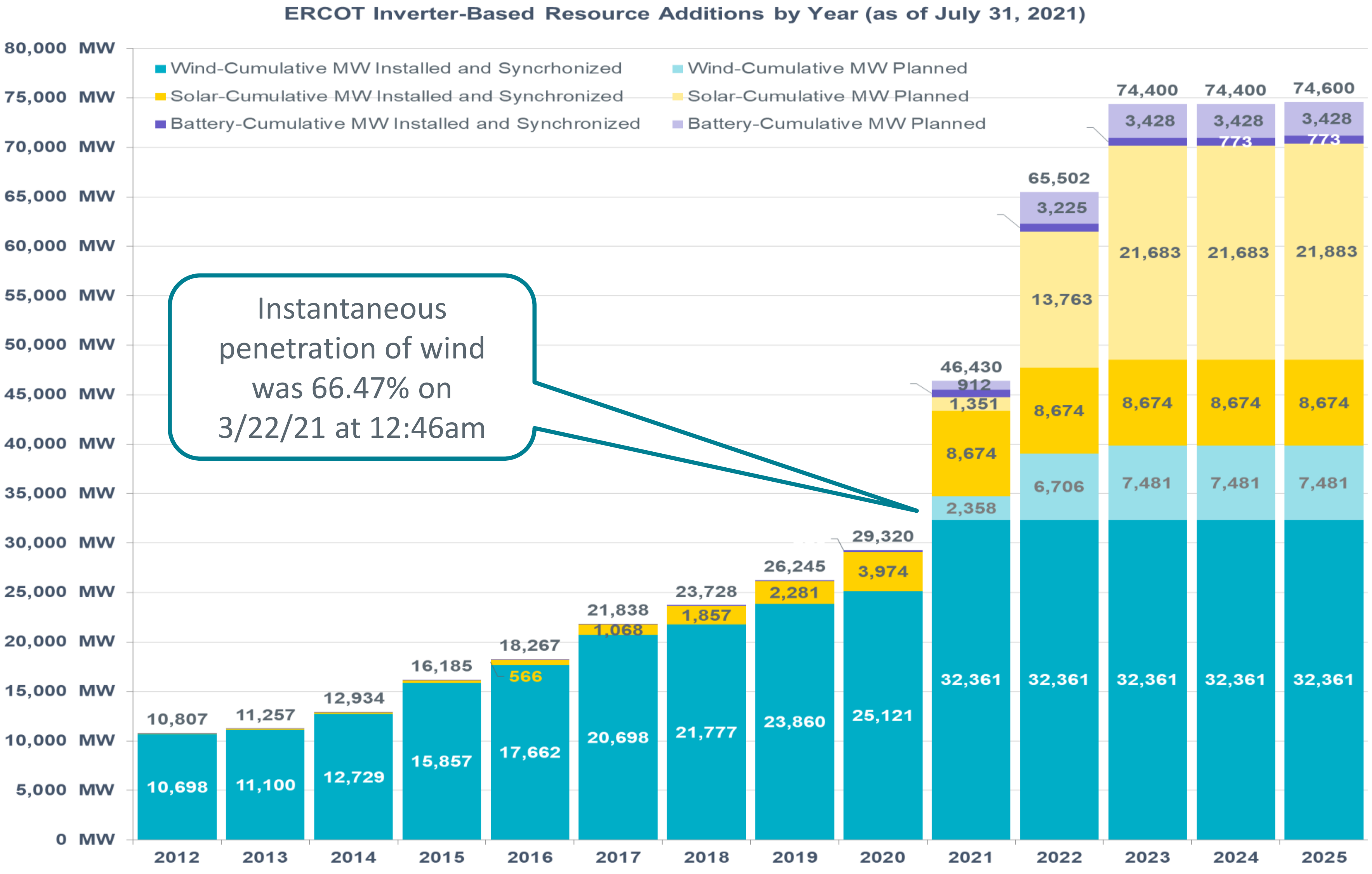
- 710+ generating units, excluding PUNs
- Transmission projects endorsed in 2020 total $1,071 million
- 46,500+ miles of high-voltage transmission

2021 Generating Capacity *Reflects operational installed capacity based on the December 2020 CDR report*



*Other includes hydro, biomass-fired units and DC tie capacity

Inverter-Based Resource Capacity – July 2021



Instantaneous penetration of wind was 66.47% on 3/22/21 at 12:46am

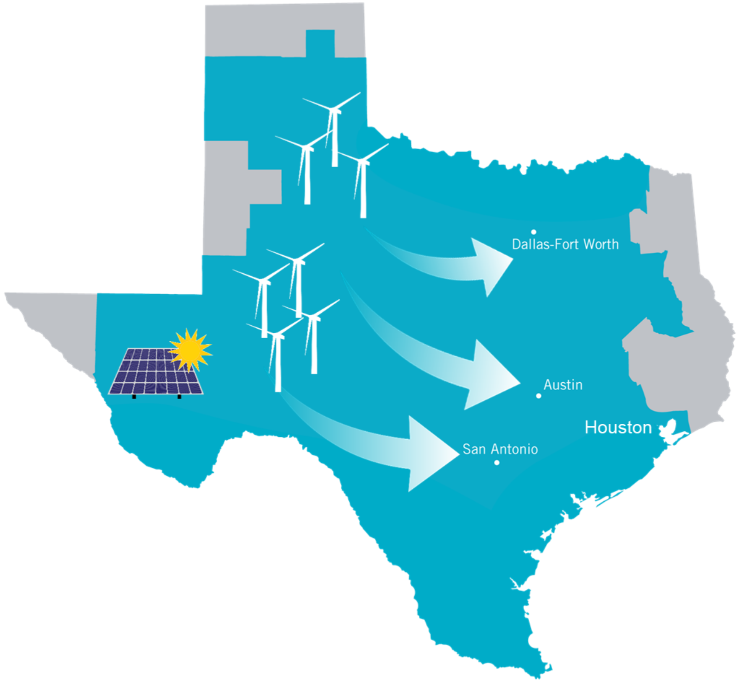
Cumulative MW Planned include projects with signed interconnection agreeements

Inverter-Based Resources in ERCOT

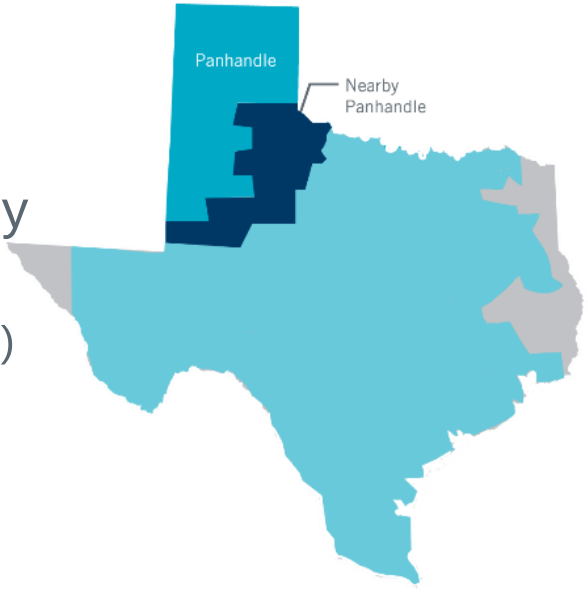
- > 46 GW IBRs are expected to be connected to the ERCOT transmission grid by the end of 2021.
- Most wind and solar generation are in West Texas:
  - Long distance transfer to load centers
  - Limited/no online synchronous generators in West Texas during high IBR output periods

2021	2023
• >35 GW Wind • >10 GW Solar • >1.9 GW Battery	• >39 GW Wind • >30 GW Solar • >4.2 GW Battery

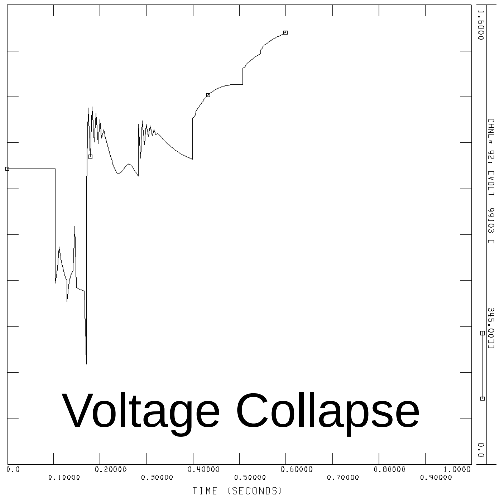
*As of July, 2021



ERCOT Panhandle



- > 10 GW IBRs connect to Panhandle and nearby Panhandle
  - IBRs are located at remote areas (high IBR penetration)
  - Limited/no online synchronous generators (low short circuit)
  - Long distance large power transfer (high impedance)
- Indicators of weak grid
  - High frequency oscillation or numerical instability in PSS/e
  - High voltage overshoot or even high voltage collapse
  - Low WSCR (weighted short circuit ratio)
- Improvement Options
  - Two synchronous condensers were added to Panhandle: stability associated with condensers needs to be checked
  - Reduce impedance: adding new circuits
  - Control tuning and coordination



Voltage Collapse

What is System Strength?

- The ability of power system equipment to operate in a stable manner and for the system to recover from major disturbances, is influenced by the electrical ‘strength’ of the system at the point where equipment connects.
- ‘Stronger’ systems are more tolerant to variations and perturbations occurring within connected plant and recover more easily from major disturbances such as faults and the sudden loss of equipment.

Source: Babak Badrzadeh et.al., “System strength”, CIGRE Science and Engineering, February 2021

System Strength

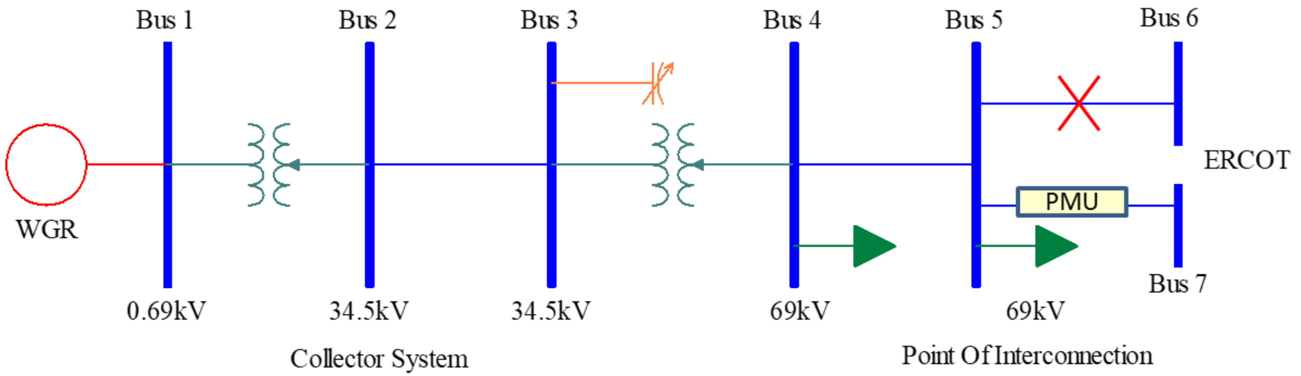
- There is a limit of how many conventional (grid following) Inverter Based Resources (IBRs) can be accommodated (due to system strength and inertia issues).

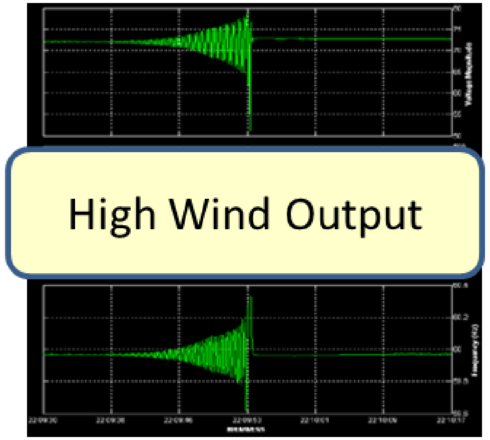
- System operators may limit the output of IBRs and supply the remaining load with synchronous generators to ensure sufficient system strength and/or inertia (e.g., Australia, Ireland, Texas).

  - Such operational constraints in the long run may impact further development of IBRs.

- Alternatively, synchronous condensers are installed to provide grid support, but the associated constraints (e.g.. stability) must be assessed.

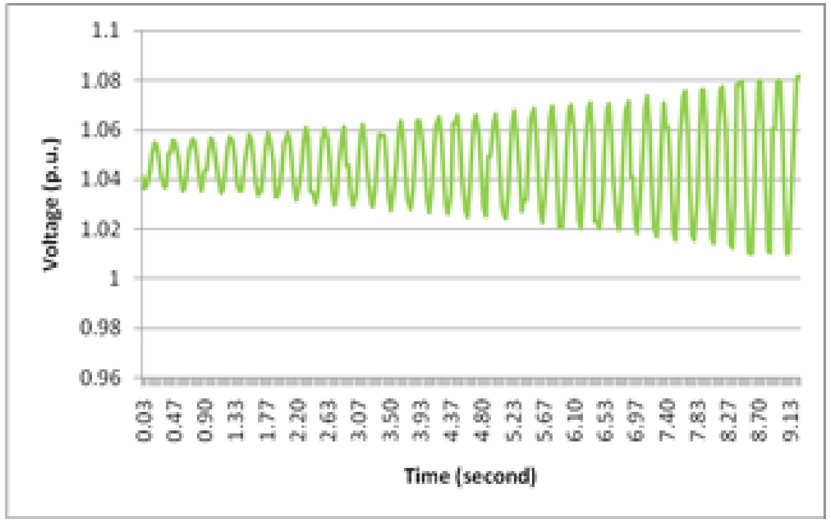
Weak Grid: Operations Example




High Wind Output

PMU Records

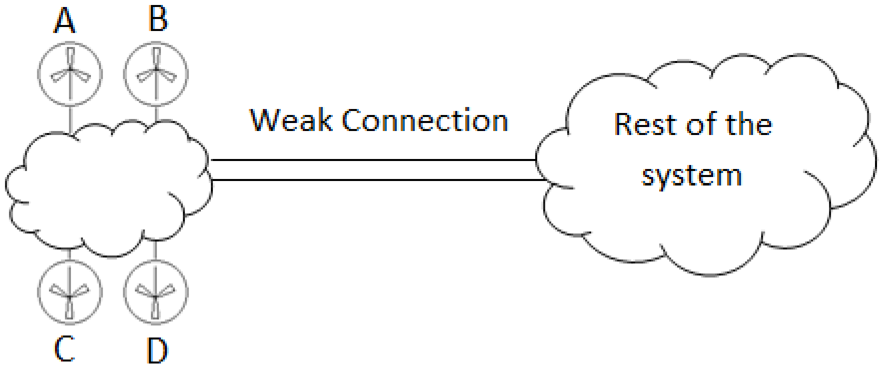
- Lessons Learned:
  - Model and tool adequacy
  - Impact on IBR control
  - Mitigation options:
    - IBR dispatch
    - IBR control tuning
    - System strength enhancement



Weighted Short Circuit Ratio (WSCR)

- 2014 Panhandle study recognized limitations of a single plant Short Circuit Ratio for characterizing system strength:
  - Ignores the interactions between neighboring IBRs in a region
  - May give an overly-optimistic estimation of system strength
- ERCOT proposed the concept of WSCR:
  - Recognizes interactions between neighboring IBRs
  - Assumes all interacting IBRs are connected at the same bus (!)
    - $WSCR = \frac{\sum_i^N S_{SCMVA i} * P_i}{(\sum_i^N P_i)^2}$
- WSCR=1.5 was proposed as the minimum pre-contingency system strength for Panhandle (based on PSS/E study results).

Example of WSCR Calculation



Wind Plant	Wind Power Production (MW)	Short Circuit Capacity (S_{SC_MVA})	Single Plant SCR
A	1,200	6,500	5.42
B	1,000	8,000	8.00
C	800	8,500	10.63
D	2,000	7,000	3.5

$$WSCR = \frac{1200 * 6500 + 1000 * 8000 + 800 * 8500 + 2000 * 7000}{(1200 + 1000 + 800 + 2000)^2} = 1.46$$

Determination of WSCR

ERCOT re-evaluated Panhandle area in both phasor-domain stability studies and detailed Electromagnetic Transient Studies (EMT) in 2016, 2018 and 2019:

- WSCR of 1.5 for Panhandle region was found appropriate.
- WSCR concept was found applicable in the absence of local load and synchronous generation, as well as electrically close IBRs remotely connected to the main grid.
- The application of WSCR and its threshold are highly system-dependent and should be verified and regularly reviewed through detailed studies (e.g. EMT) as the system evolves.

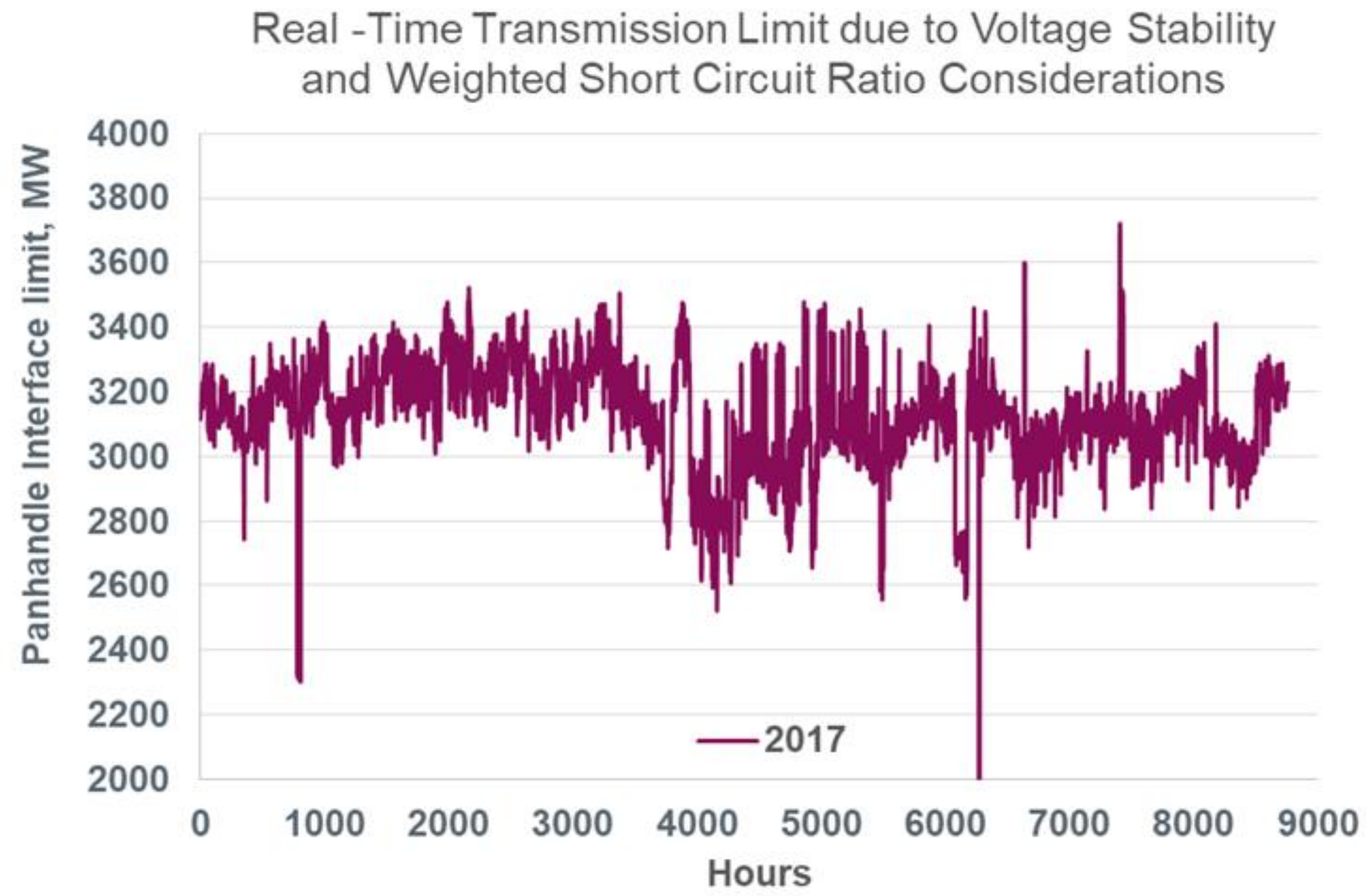
Evaluation of Panhandle Export Limit in Real-Time

- For the past 6 years, WSCR≥1.5 was maintained in Panhandle by curtailing wind generation, if WSCR was the most limiting constraint.

- WSCR calculation is built into real-time VSAT*, from which Panhandle export limit is determined every 10 minutes:
  - $WSCR = \frac{\sum_i^N S_{SCMVAi} * P_i}{\left(\sum_i^N P_i\right)^2}$
  - $\sum_i^N P_i$ is total Panhandle generation at the time of evaluation
  - If WSCR <1.5, scale down all P_i proportionally so that WSCR = 1.5 under pre-contingency condition
  - New $\sum_i^N P_i$ determines Panhandle export limit based on WSCR

*VSAT – Voltage Stability Assessment Tool by Powertech Labs

Real-Time Panhandle Export Limit

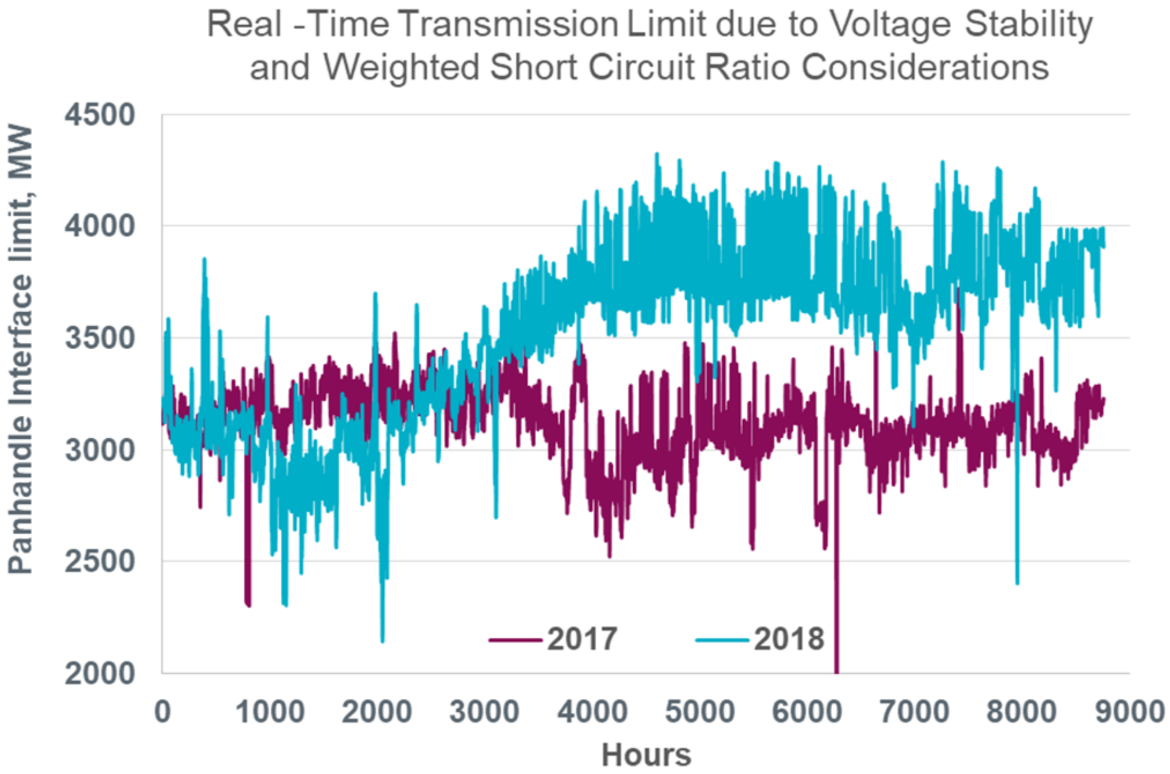


Synchronous Condenser (SynCon) Characteristics

- Two Synchronous Condensers were installed in Panhandle in 2018, each with the following specifications:
  - ~175/-125 MVAR, for +/- 10% voltage variation range
  - ~1600 Amps short circuit capability on the high-voltage side
- Placed in locations that increase WSCR but also improve voltage support and transient response.
- High availability design is required since SynCons’ outage directly translates into reduction of the maximum power export.
  - Redundancy in cooling system aux supply, control and protection systems
  - The wide range of the machine operating voltage
  - Brushless excitation system to reduce maintenance time

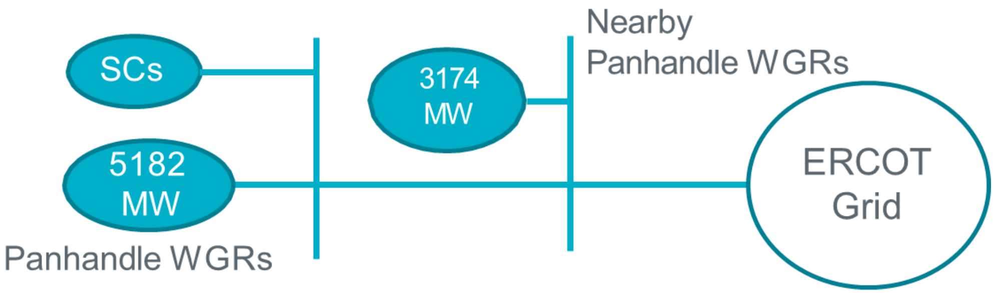
Impact of SynCons on Panhandle Export Limit

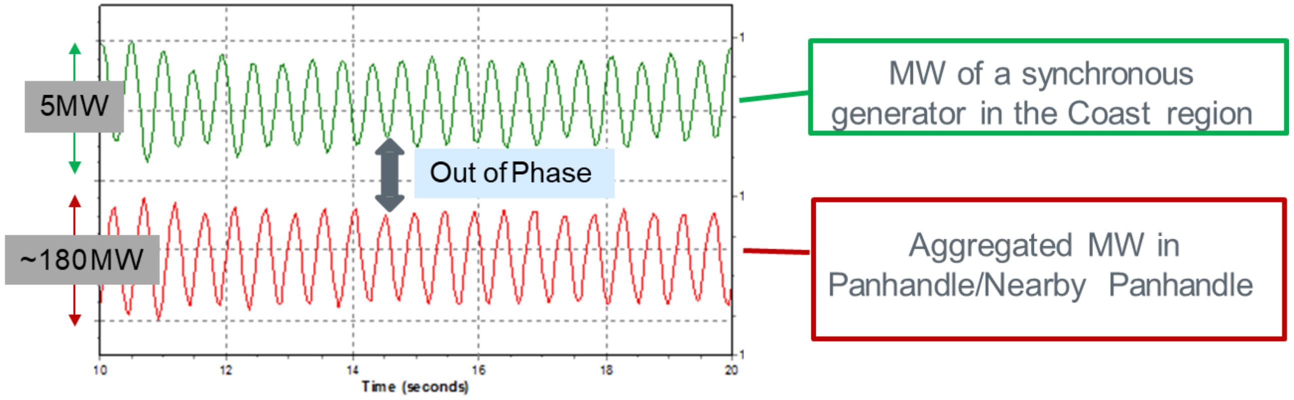
- SynCons have enabled increase in Panhandle export limit by ~470 MW.
- The benefit may diminish with additional IBRs and topology changes.



Intra-Area Oscillations Observed with SynCons

- 2019 Panhandle dynamic studies identified oscillatory behavior (~1.8 Hz) between SynCons and rest of ERCOT’s synchronous generators.

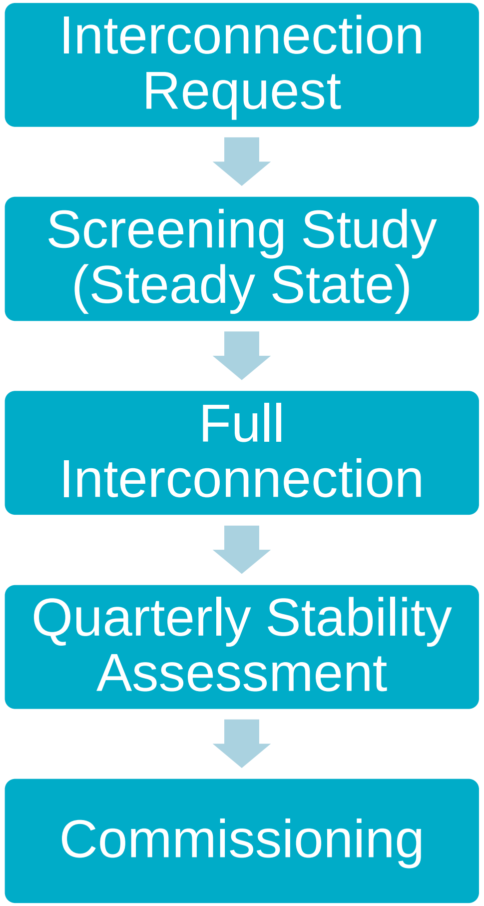




MW of a synchronous generator in the Coast region

Aggregated MW in Panhandle/Nearby Panhandle

General Resource Interconnection Process



Interconnection Request

Screening Study (Steady State)

Full Interconnection

Quarterly Stability Assessment

Commissioning

- Full Interconnection
  - Steady State, Dynamic, Short Circuit, and Facility Studies
  - Subsynchronous Resonance (if applicable)
  - Reactive Study
- Quarter Stability Assessment
  - Include existing resources and resources with planned initial Synchronization dates ~3-6 months in the future
- Include high renewable scenarios with the consideration of limited nearby synchronous generators and/or transmission outages

A typical timeline for IBR Interconnection: ~24 Months

Dynamic Model Requirements

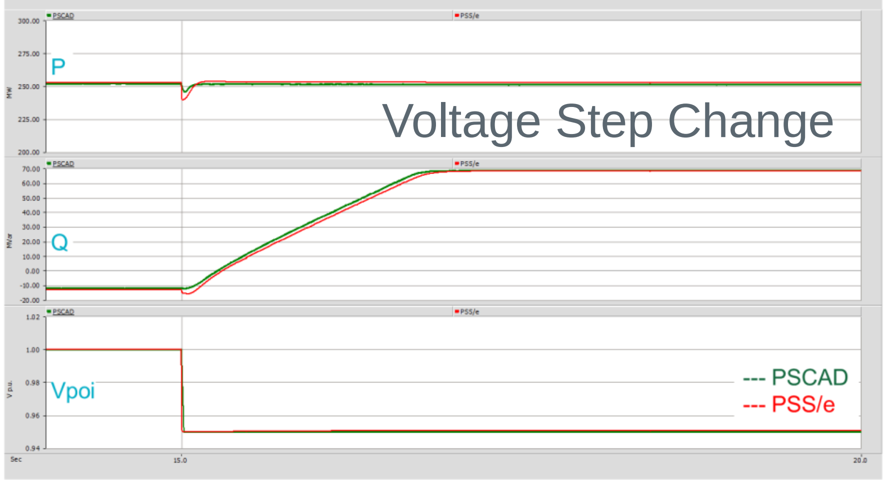
- IBRs are required to provide both dynamic (PSS/e and TSAT, User Defined or Generic) and EMT (PSCAD) models.
- Resource Entities and Interconnection Entities are responsible for providing models and associated test results and document.

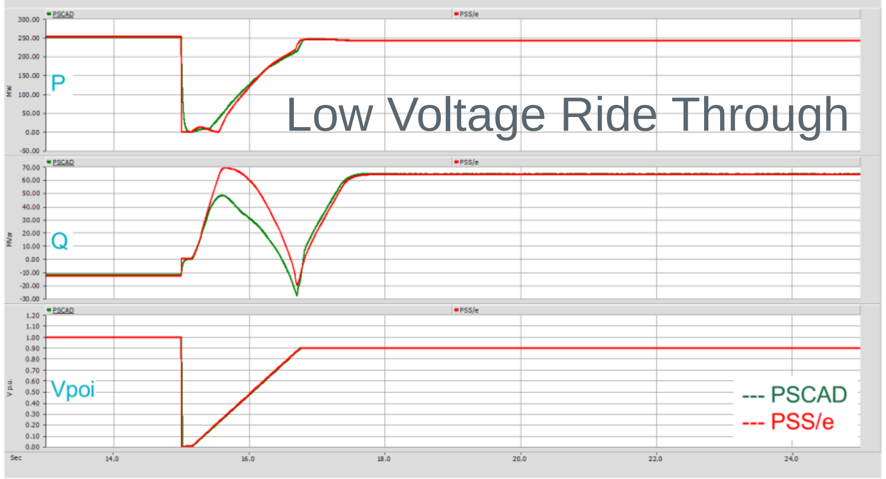
Model Quality Tests (PSS/E and PSCAD)	• Flat Start, Voltage Test (small and large disturbance), Frequency Test (e.g., +/-0.3 Hz), **System Strength Tests** • Phase-angle Jump (PSCAD only)
Unit Model Validation (PSCAD)	• Voltage Test (small and large disturbance), System Strength, Phase-angle Jump, and Subsynchronous Test
Model Verification	• Provide evidence that tunable model parameters match what is implemented in the field. For example: screenshots, nameplate photographs, signed manufacturer commissioning reports, etc.

Few Modeling Notes

- Caution about generic models
  - Existing generic models may not work properly in weak grids
  - Equipment manufactures should be consulted for parameterization of generic models
- Use of dynamic model template
  - Excel spreadsheet
  - Facilitate consistent model submittal format
- Develop and share tools to help the model quality tests
  - For PSS/E models: Complete
  - For PSCAD models: 3Q, 2021

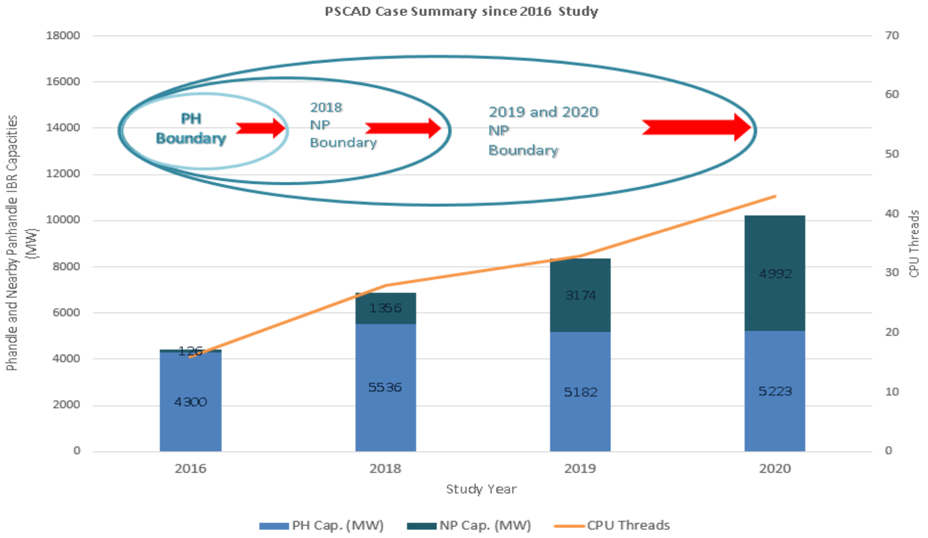
Example: Model Quality Tests

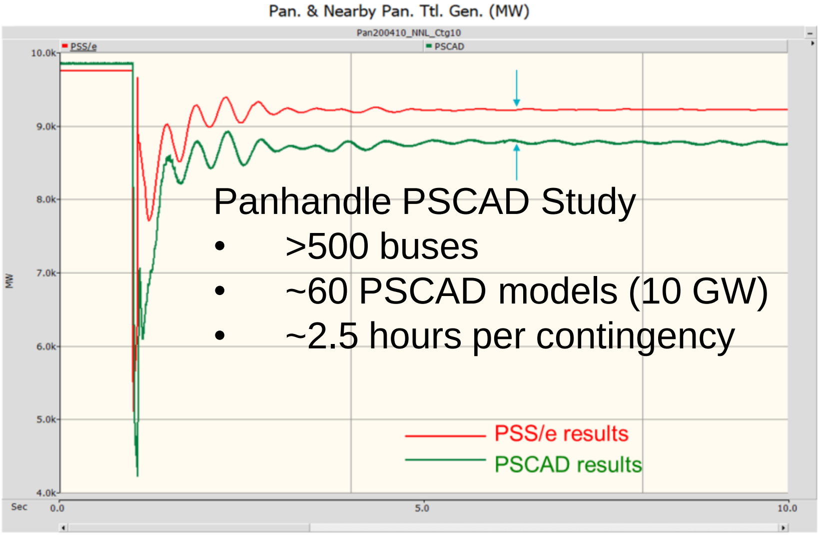




EMT (PSCAD) Study

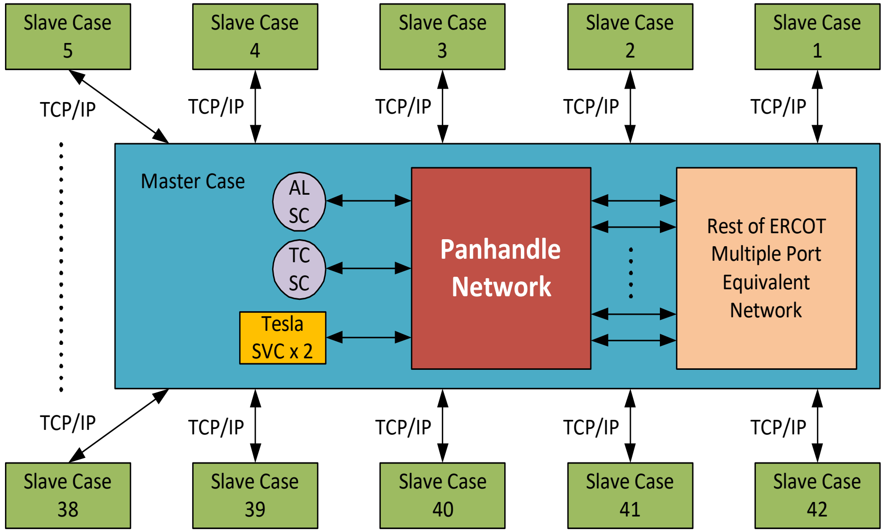
- Require regular PSCAD studies
  - To assess the instability that may not be identified in PSS/E.
  - To confirm the adequacy of dynamic models and simulation tools.
  - To identify the adequacy and threshold of WSCR application.


PSCAD Case Summary since 2016 Study


Pan. & Nearby Pan. Ttl. Gen. (MW)

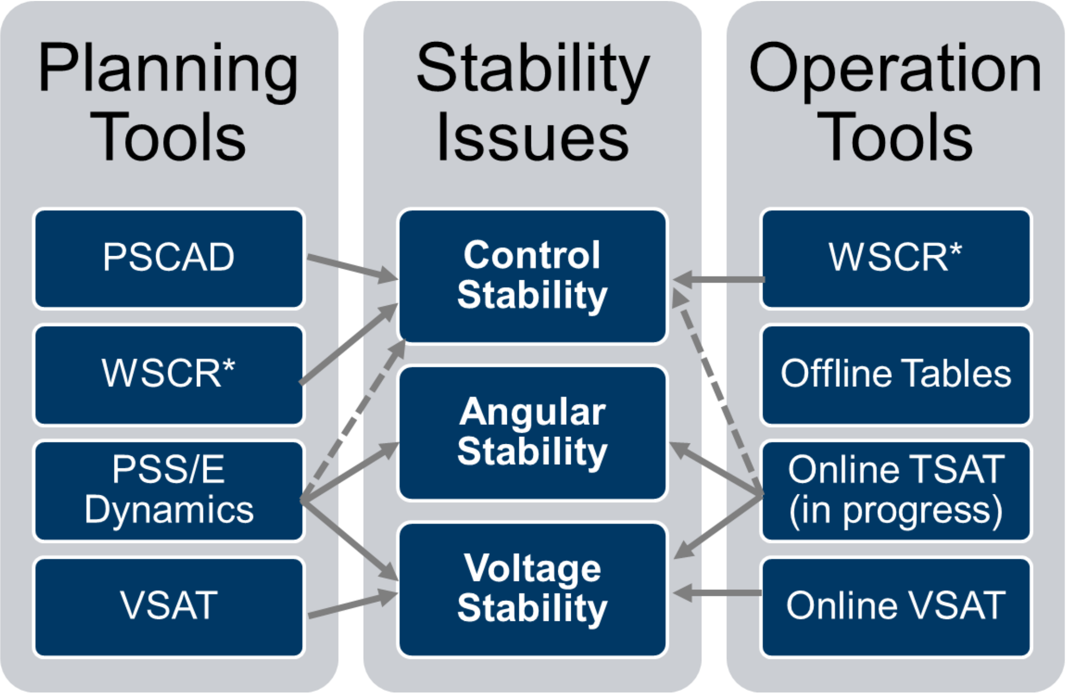
Panhandle PSCAD Study

- >500 buses
- ~60 PSCAD models (10 GW)
- ~2.5 hours per contingency



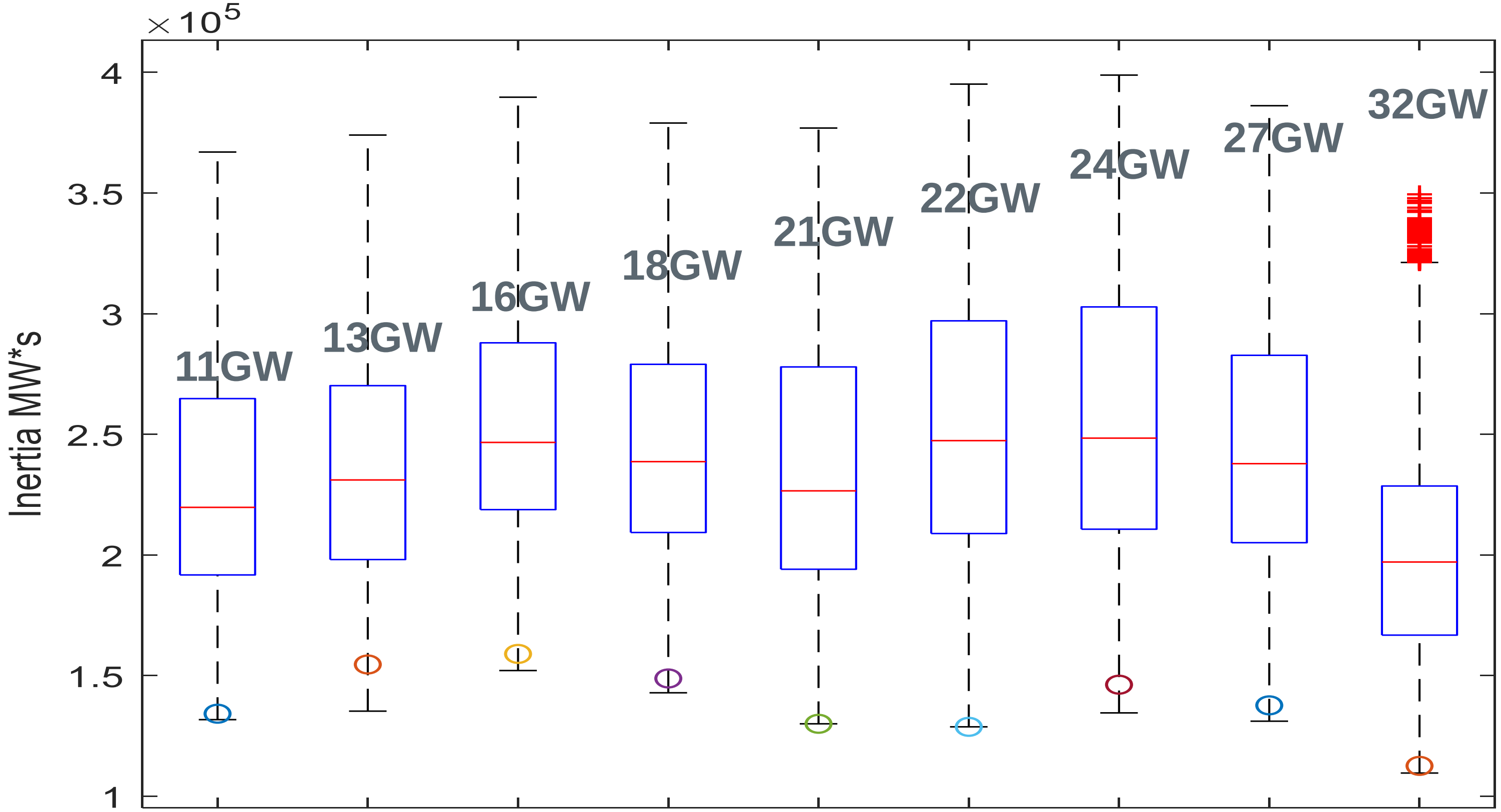
Stability Assessment and Tools

- With more IBRs
  - Increasing stability challenges
  - Require PSCAD studies: complex and time consuming
- Needs and improvements
  - Model accuracy and usability
  - Tool and simulation efficiency
  - Better communication and coordination



* WSCR (weighted short circuit ratio) is used to identify the system strength of an area with multiple IBRs. Detailed PSCAD studies are required to validate the adequacy of WSCR application and its threshold for weak grid identification.

ERCOT Inertia 2013-2021(Jan-Jul)



Date and Time	**2013** 3/10 3:00 AM	**2014** 3/30 3:00 AM	**2015** 11/25 2:00 AM	**2016** 4/10 2:00 AM	**2017** 10/27 4:00 AM	**2018** 11/03 3:30 AM	**2019** 3/27 1:00 AM	**2020** 05/01 2:00 AM	2021 03/22 00:00 AM
Min synch. Inertia (GW*s)	132	135	152	143	130	128.8	134.5	131.1	109
System load at minimum synch. Inertia (MW)	24,726	24,540	27,190	27,831	28,425	28,397	29,883	30,679	32,599
Non-synch. Gen. in % of System Load	31	34	42	47	54	53	50	57	65

Inertia and Frequency Containment

- Defined critical inertia level as minimum level of system inertia that will ensure frequency containment reserve has sufficient time to respond before frequency reaches 59.3 Hz (UFLS threshold).
- Monitoring of inertia in real-time and forecasting several hours ahead.
- If inertia is getting close to critical level, operator will start additional synchronous generation to bring inertia back up.
- Above critical inertia, based on expected inertia conditions, needed amounts of frequency containment reserves are procured.
- Faster frequency response is more effective than traditional governor response in low inertia conditions.
- Fast Frequency Response has been introduced to ensure faster and earlier response. This allows reduction of critical inertia level and reduces overall amount of frequency containment reserves.

Summary: ERCOT Practices and Experience

- Increasing stability and system strength challenges with more IBRs connected to the grid
  - Complex, time consuming, model and tool adequacy
  - Additional stability challenges (control instability, overvoltage/high voltage collapse)
  - May require tight voltage control (may no longer be a local issue)
  - Identification and management of stability constraints in planning and operations
  - Early communication and coordination is always better
  - Continue to explore ways to reliably operate under weak grid conditions or improve the system strength

- Diminishing inertia and faster rate of change of frequency with more IBRs
  - Can be addressed through inertia floor and adequate amounts of reserves
  - Faster Frequency Response helps to reduce critical inertia and amounts of reserves needed.

Appendix: References

- http://www.ercot.com/content/wcm/lists/168284/ERCOT_Model_Quality_Guideline.zip
- http://www.ercot.com/content/wcm/key_documents_lists/89026/2020_PanhandleStudy_public_final__004_.pdf
- http://www.ercot.com/content/wcm/key_documents_lists/89026/The_Use_of_GTCs_in_ERCOT_July_2020.pdf
- http://www.ercot.com/content/wcm/lists/144927/Panhandle_and_South_Texas_Stability_and_System_Strength_Assessment_March....pdf
- http://www.ercot.com/content/wcm/lists/144927/Dynamic_Stability_Assessment_of_High_Penetration_of_Renewable_Generation_in_the_ERCOT_Grid.pdf
- http://www.ercot.com/content/wcm/lists/144927/Inertia_Basic_Concepts_Impacts_On_ERCOT_v0.pdf#:~:text=This%20white%20paper%20describes%20ERCOT%20staff%E2%80%99s%20initiatives%20to,the%20future.%20The%20paper%20is%20structured%20as%20follows%3A
- http://www.ercot.com/content/wcm/key_documents_lists/108744/05._RRS_Study_2017_Methodology_11022017.docx
- https://www.youtube.com/watch?v=029gAj7xr30 (ESIG webinar on evolution of ERCOT's frequency control)

Automated Impedance Measurement Toolbox for Power System Stability Analysis

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Heng Wu
hew@energy.aau.dk

AALBORG UNIVERSITY
DENMARK

Outline

- ❑ Background and Challenge
- ❑ Theoretical Basis for the Impedance-based Stability Analysis
- ❑ Introduction of Impedance Measurement Toolbox
- ❑ Case Studies

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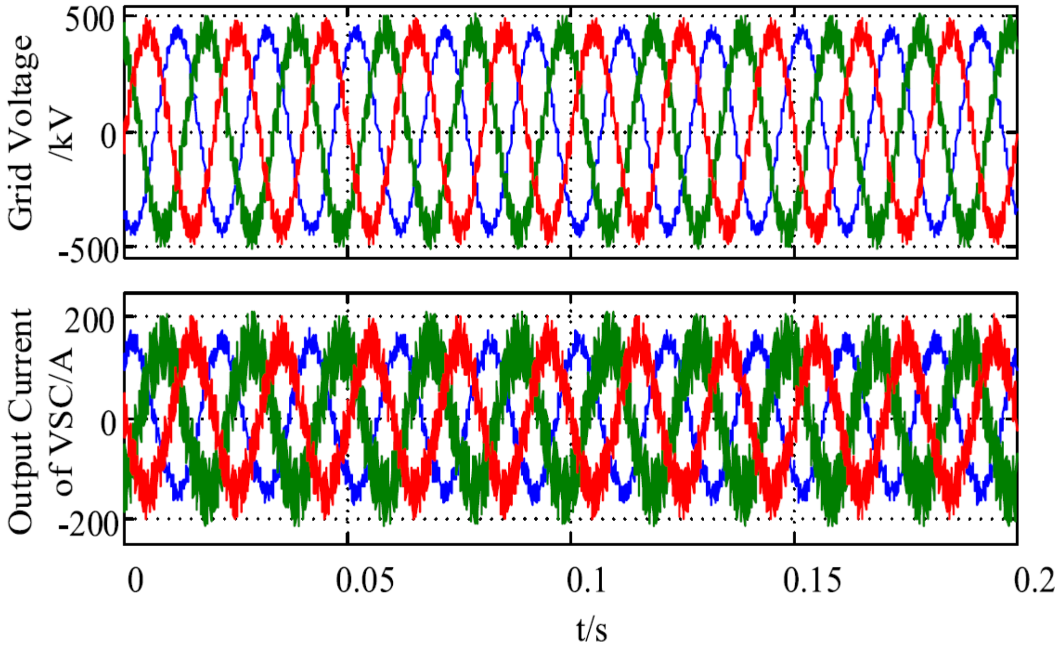
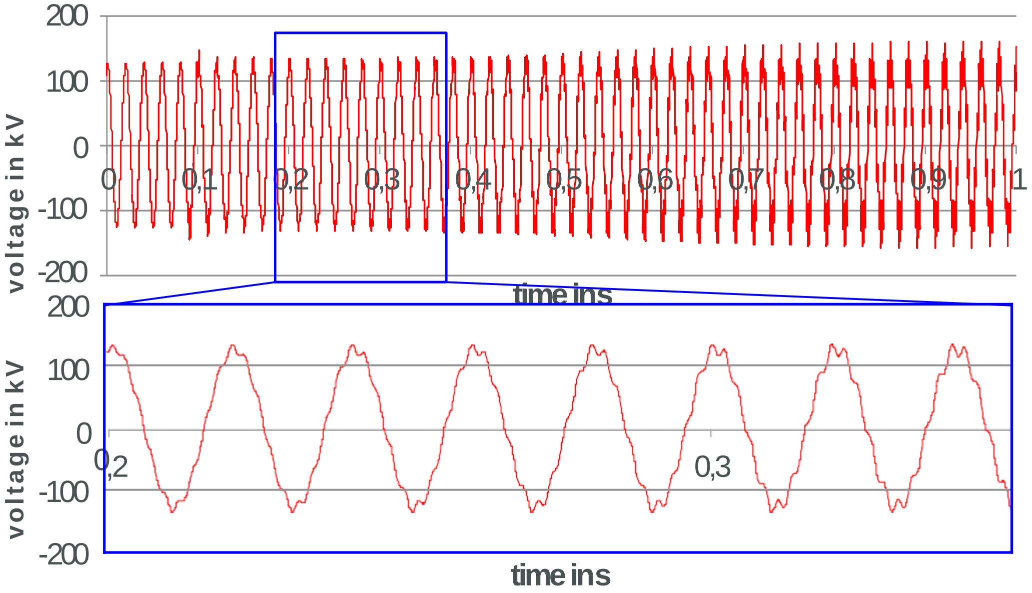
Challenge

Power system oscillation due to the interactions between power converters and grid are increasingly reported



MMC-HVDC in AC Grid, Luxi, Yunnan, China[1]

- 1270 Hz resonance



MMC-HVDC in Offshore Wind Farm, Germany[2]

- 451 Hz resonance

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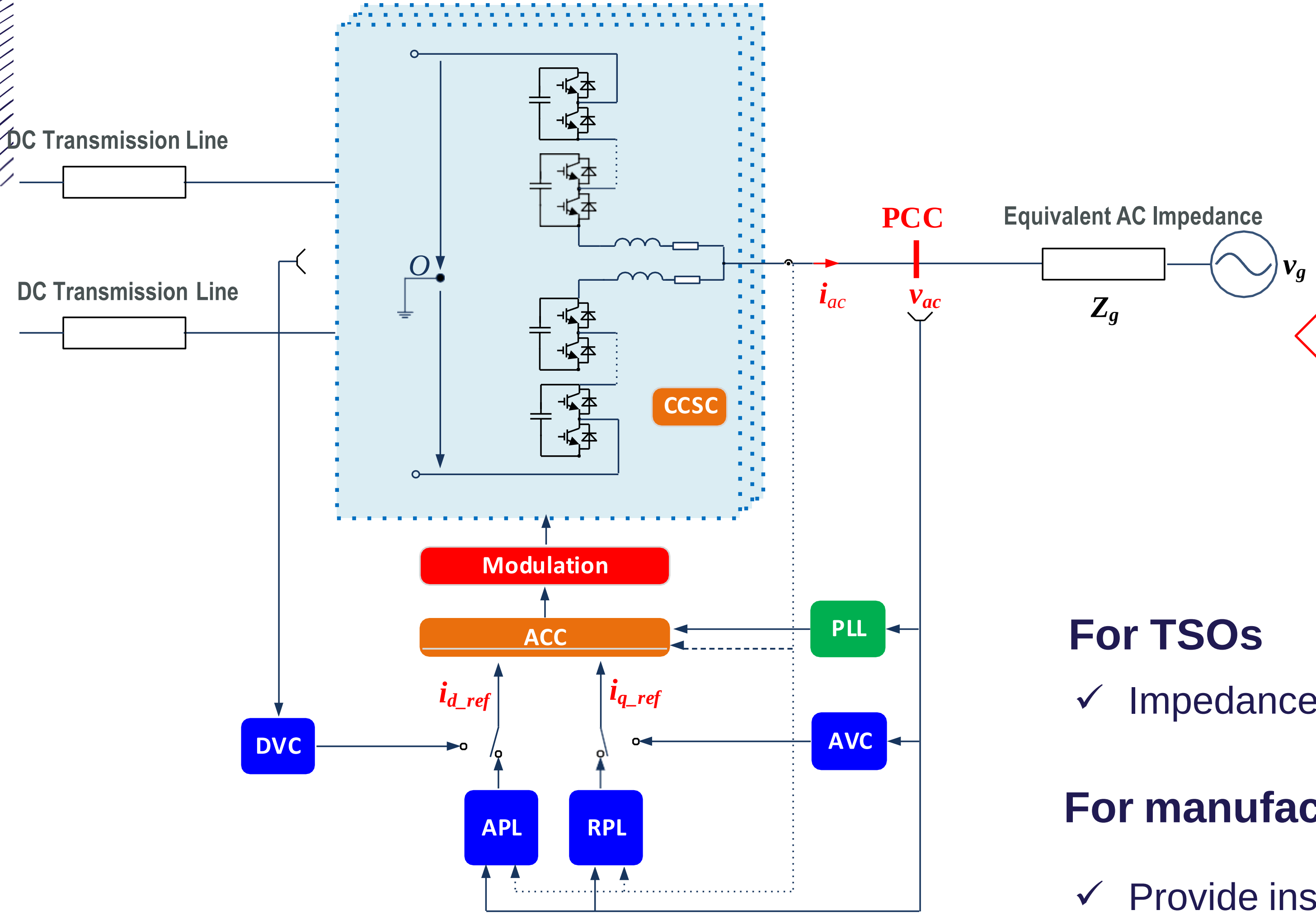
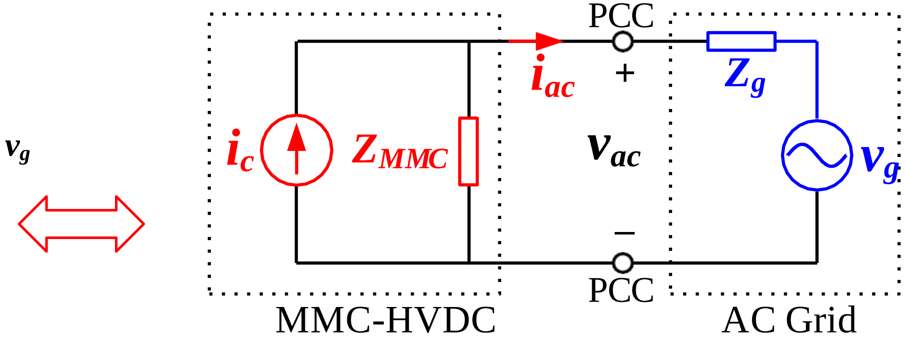
1 C. Zou, H. Rao, S. Xu, et al., ”Analysis of resonance between a VSC-HVDC converter and the ac grid,” *IEEE Trans. Power Electron.*, vol. 33, no. 12, pp. 10157–10168, 2018.

2 C. Buchhagen, M. Greve, A. Menze, and J. Jung, “Harmonic stability-practical experience of a TSO,” *Proc. 15th Wind Integration Workshop*, pp. 1–6, 2016.

Motivation of impedance-based stability analysis



System diagram of an MMC-HVDC station



Equivalent circuit of MMC-HVDC and AC Grid

For TSOs

- ✓ Impedance can be directly measured from the black-box model

For manufacturers

- ✓ Provide insight for stabilization based on impedance shaping

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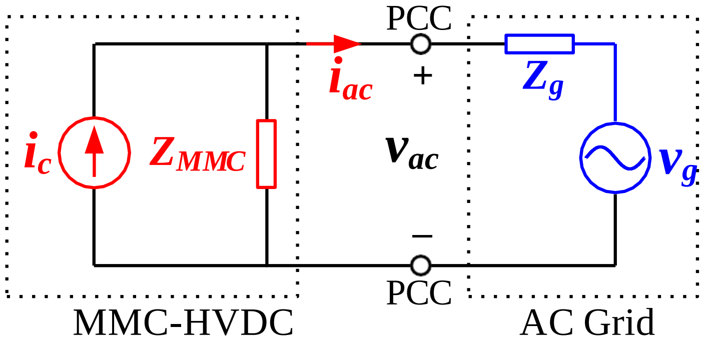
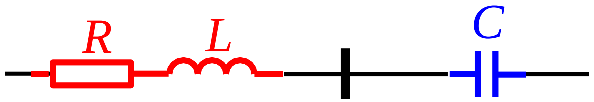
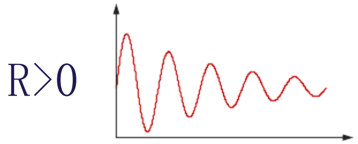
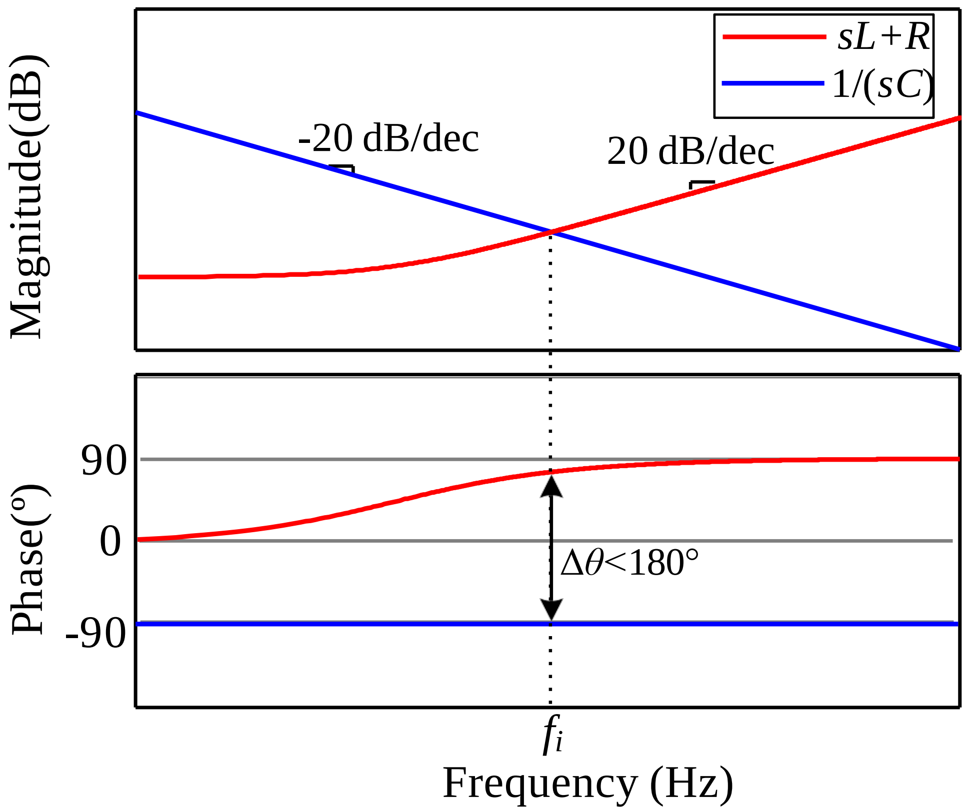
Impedance-Based Analysis—Concept



Equivalent circuit of MMC-HVDC and AC Grid







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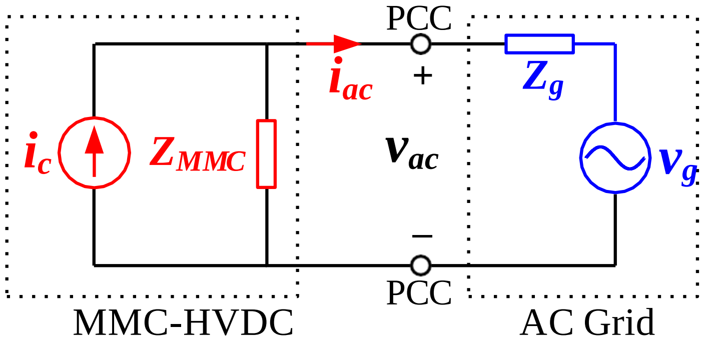
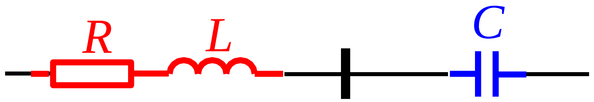
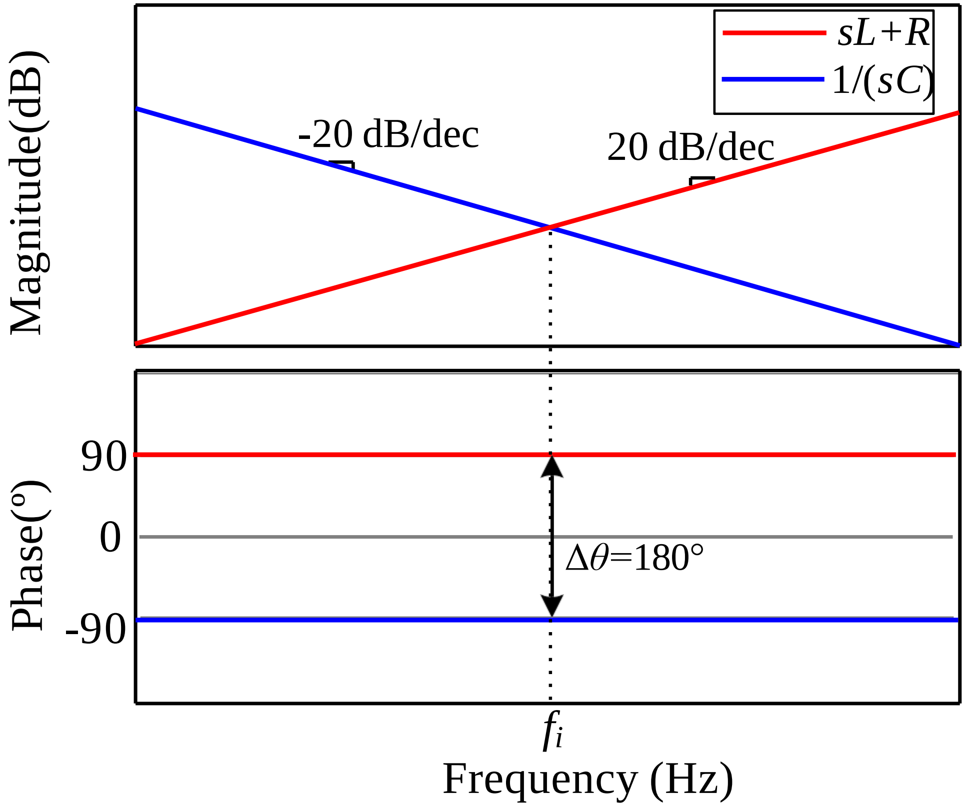
Impedance-Based Analysis—Concept

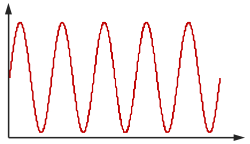


Equivalent circuit of MMC-HVDC and AC Grid

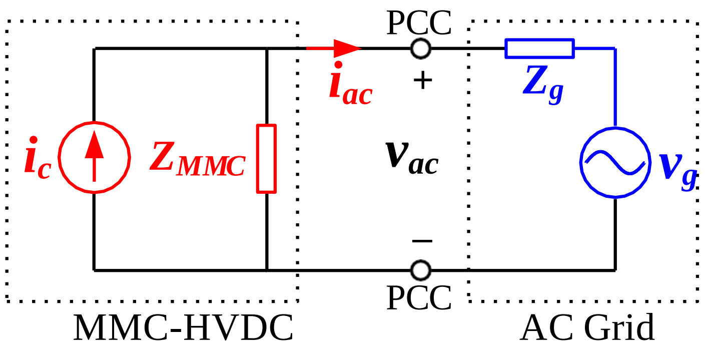




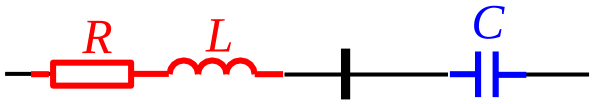
R=0

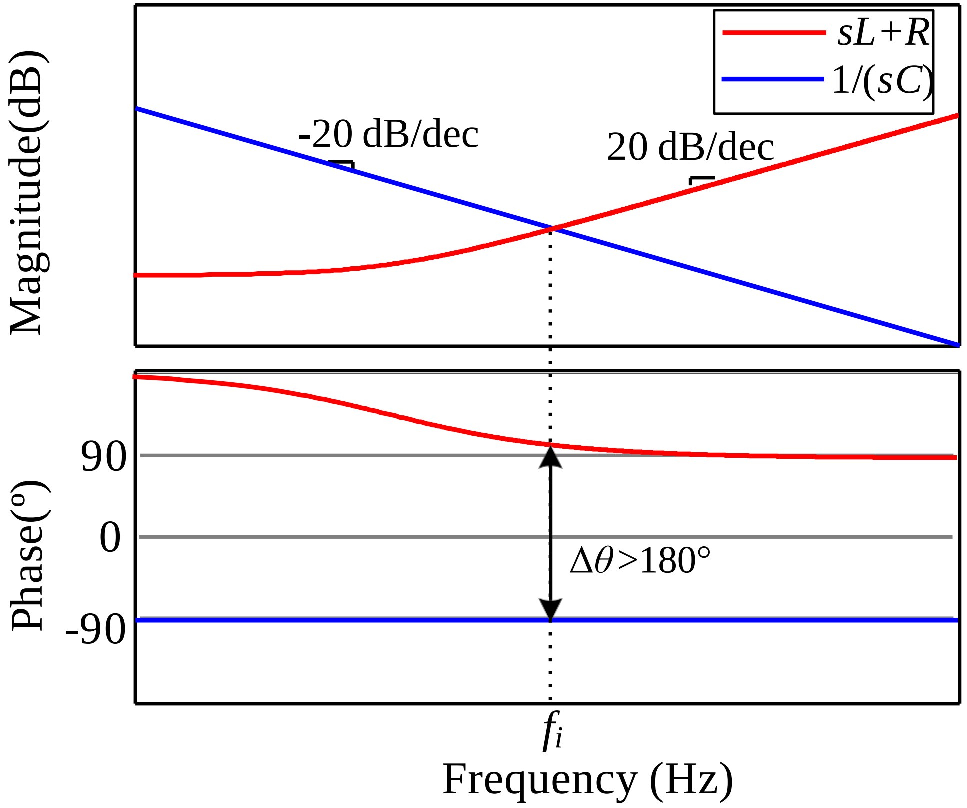


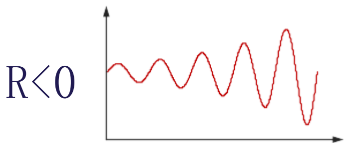
Impedance-Based Analysis—Concept



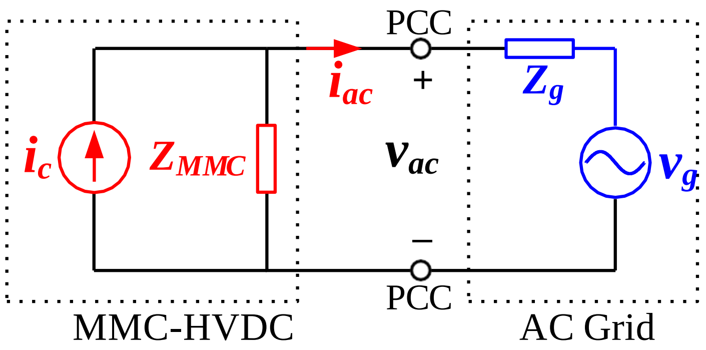
Equivalent circuit of MMC-HVDC and AC Grid



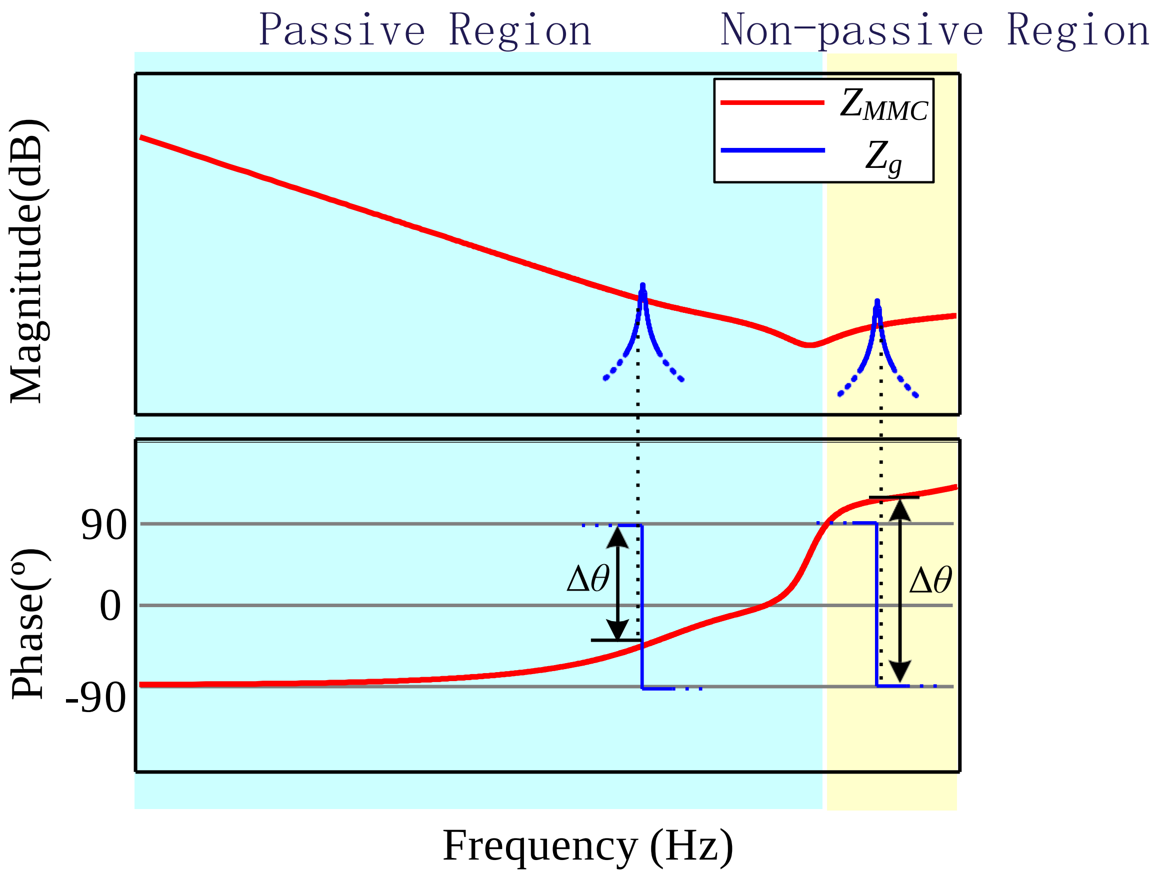




Impedance-Based Analysis—Concept



Equivalent circuit of MMC-HVDC and AC Grid



Re{Z_{MMC}}>=0 ➔ -90°≤∠Z_{MMC}≤ 90° ⇔ Passive

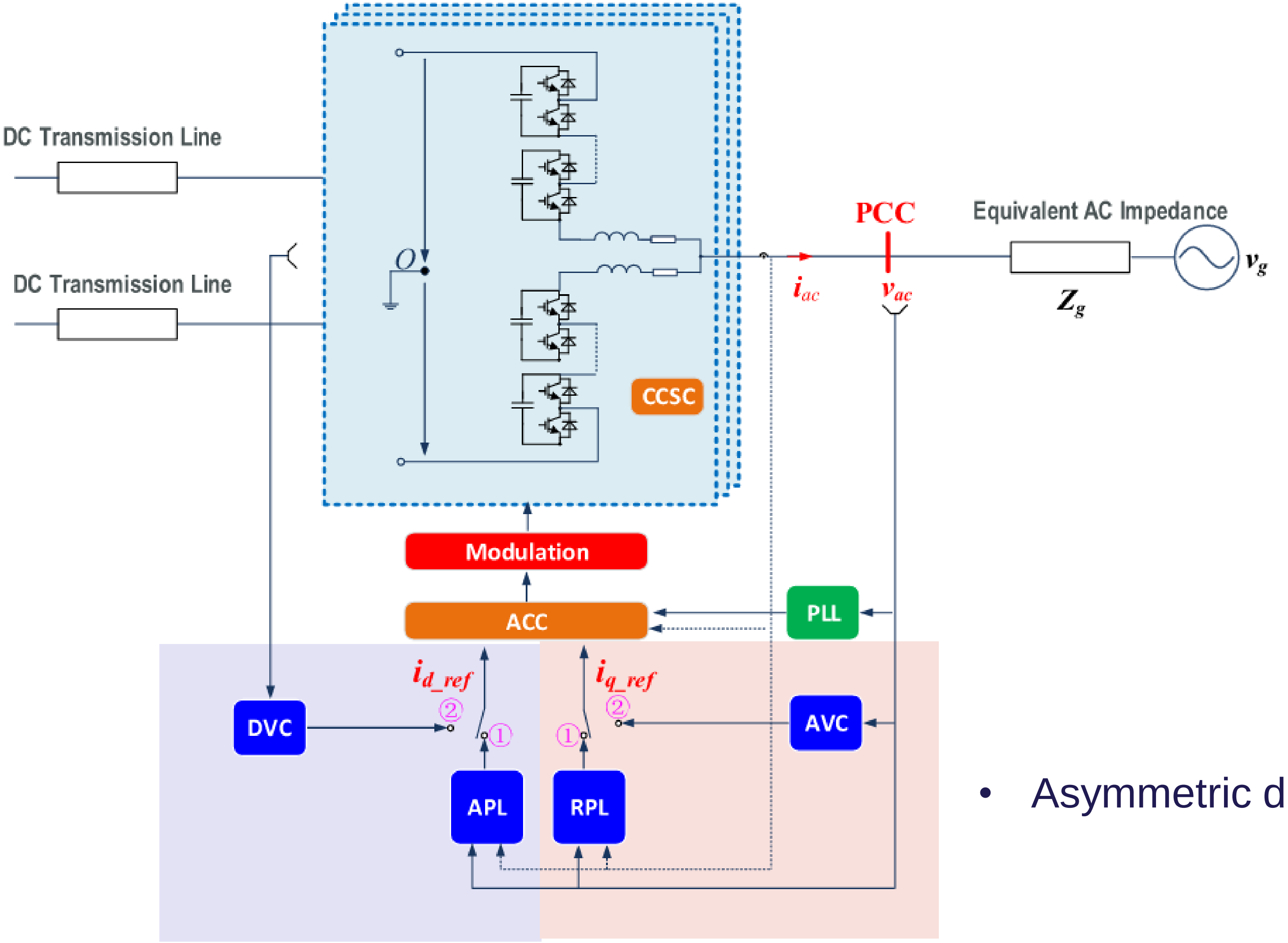
Re{Z_{MMC}}<0 ➔ ∠Z_{MMC} > 90°
or ∠Z_{MMC} < -90° ⇔ Non-passive

Good Physical Insight

- Identify the harmonic instability risk just by **taking a glance** at the converter impedance Z_{MMC}
- Define the **converter impedance specifications** to manufactures to avoid the risk of the instability

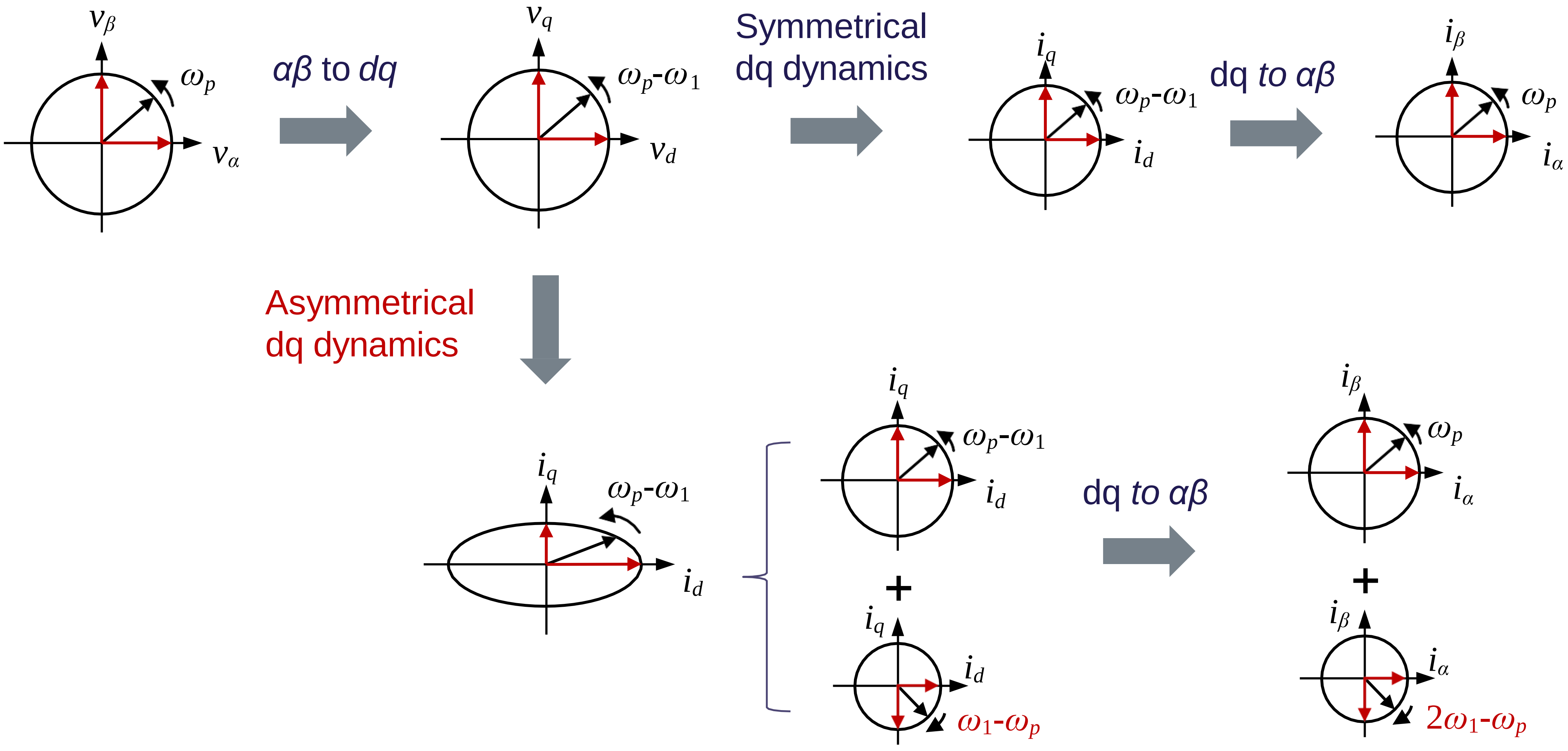
Impedance representation

SISO or MIMO



- Asymmetric dq control dynamics

Graphical illustration of frequency coupling dynamics



αβ to *dq*

Symmetrical dq dynamics

dq *to αβ*

Asymmetrical dq dynamics

dq *to αβ*

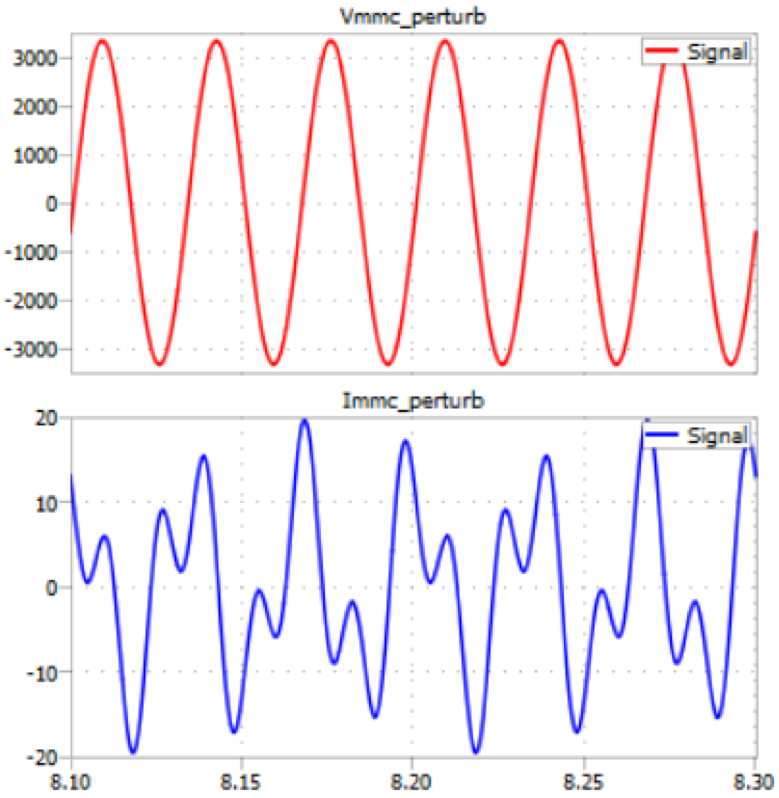
- Coupling between ω_p and $2\omega_1$-ω_p

Simulation results

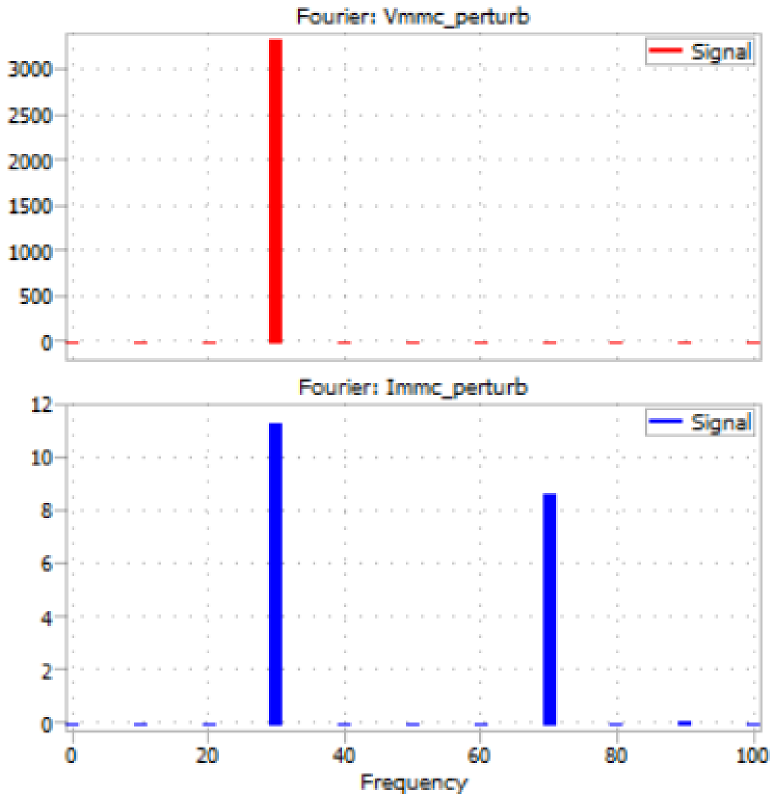
$$\begin{bmatrix} i_{\alpha\beta}(\omega_p) \\ i_{\alpha\beta}(2\omega_1-\omega_p)\end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22}\end{bmatrix}\begin{bmatrix} v_{\alpha\beta}(\omega_p) \\ v_{\alpha\beta}(2\omega_1-\omega_p)\end{bmatrix} \Leftrightarrow \begin{bmatrix} i_d(\omega_p)\\ i_q(\omega_p)\end{bmatrix} = \begin{bmatrix} Y_{dd} & Y_{dq}\\ Y_{qd} & Y_{qq}\end{bmatrix}\begin{bmatrix} v_d(\omega_p) \\ v_q(\omega_p)\end{bmatrix}$$

- Equivalent in dq/αβ frame
- MIMO representation

Inject 30Hz voltage perturbation



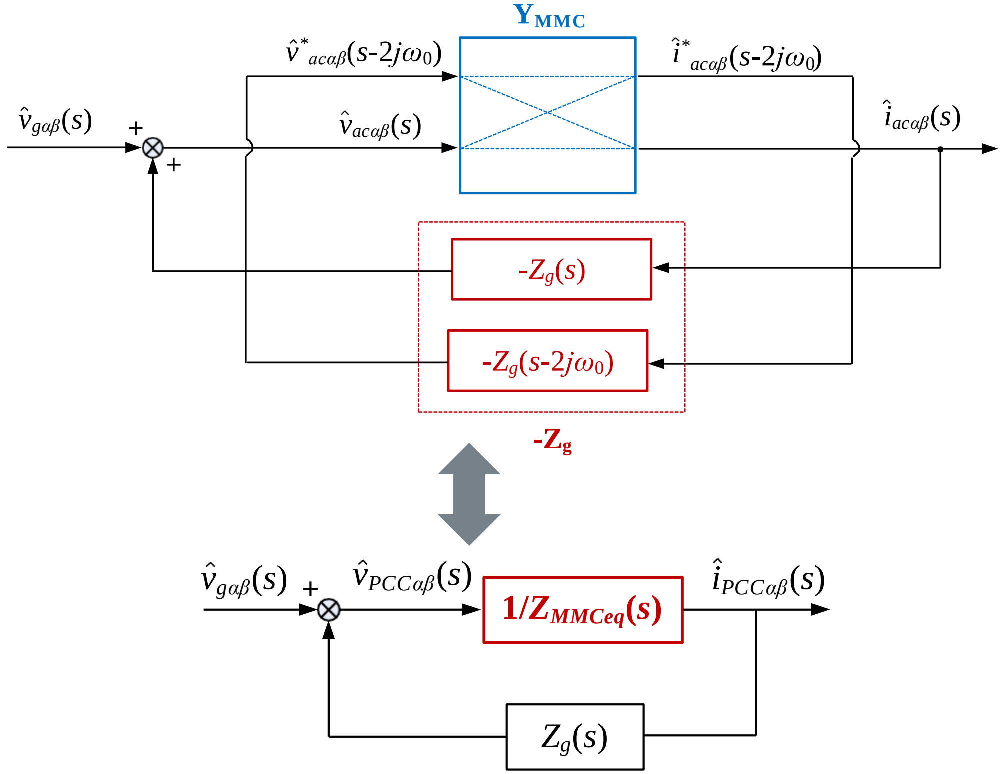
FFT results



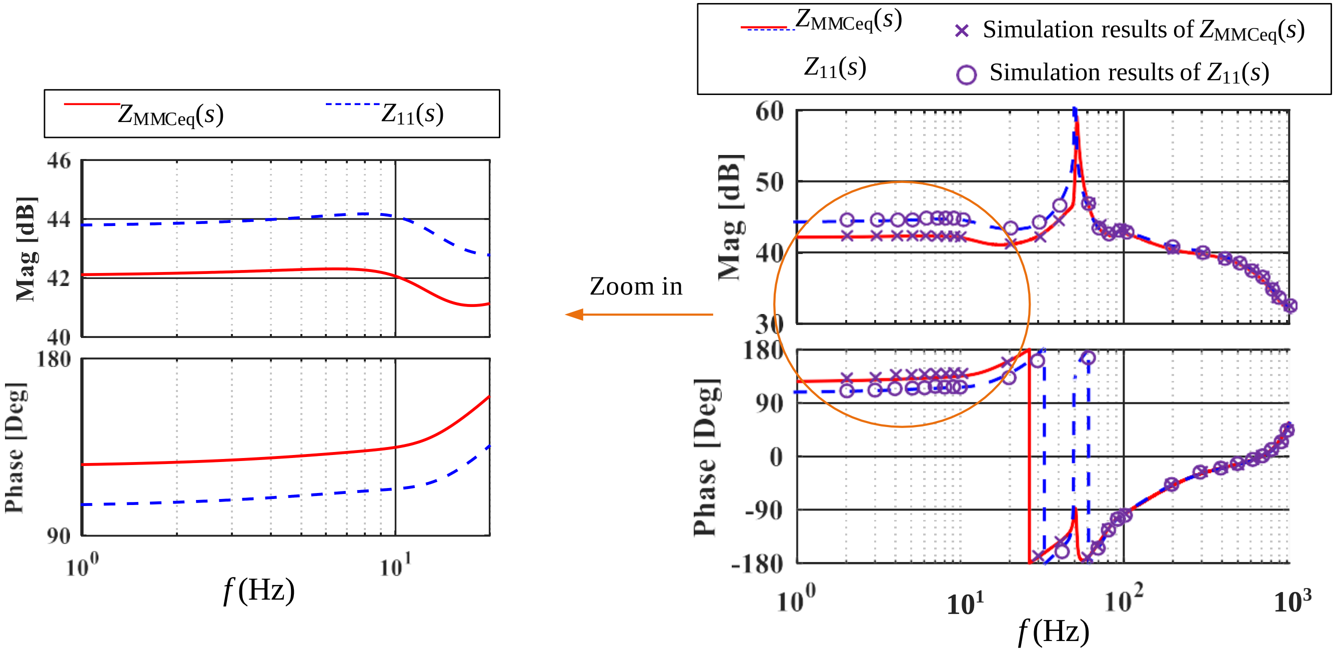
X. Wang, L. Harnefors, and F. Blaabjerg, "Unified impedance model of grid connected voltage-source converters," *IEEE Trans. Power Electron.*, vol. 33, no. 2, pp. 1775-1787, Feb. 2018.

Stability criterion

$$\begin{bmatrix} i_{\alpha\beta}(\omega_p) \\ i^*_{\alpha\beta}(\omega_p-2\omega_0) \end{bmatrix} = \underbrace{\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}}_{\mathbf{Y_{MMC}}} \begin{bmatrix} v_{\alpha\beta}(\omega_p) \\ v^*_{\alpha\beta}(\omega_p-2\omega_0) \end{bmatrix}$$



SISO impedance ratio Z_g/Z_{MMCeq} can be used for stability assessmentc



- The frequency coupling terms have significant impact on Z_{MMCeq} within 100 Hz
- The frequency coupling terms have no obvious impact on Z_{MMCeq} beyond 300 Hz and can be neglected

H. Wu and X. Wang, “Dynamic impact of zero-sequence circulating current on modular multilevel converters: complex valued AC impedance modeling and analysis,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1947-1963, June 2020.

Conclusion

- The accurate impedance/admittance representation of the converter would have a matrix form (no matter in dq/αβ frame)

- The frequency coupling terms are normally resutled from asymmetrtical dq control dynamics of outer control loops. In the high frequency range that is far beyond the bandwidth of outer loops, the frequency coupling terms can be neglected without jeopardizing the accuracy of statbility assessment

- Insight for impedance measurement

  Define a boundary frequency f_{bound}. Perform the MIMO measurement when $f_{start} \leq f \leq f_{bound}$, and switches to the SISO measurement when $f_{bound} < f \leq f_{end}$.

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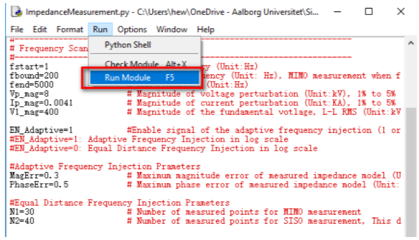
Development of the toolbox

2019

Start software development in corporation with German TSO TenneT

ImpedanceMeasurement

MathWorks



```
#-------------------------------------------------------------------------
# Frequency Scan
#-------------------------------------------------------------------------
fstart=1                                         y (Unit:Hz)
fbound=200                                  ency (Unit: Hz), MIMO measurement when f
fend=5000                                        (Unit:Hz)
Vp_mag=8                    # Magnitude of voltage perturbation (Unit:kV), 1% to 5%
Ip_mag=0.0041               # Magnitude of current perturbation (Unit:KA), 1% to 5%
V1_mag=400                  # Magnitude of the fundamental votlage, L-L RMS (Unit:kV

EN_Adaptive=1               #Enable signal of the adaptive frequency injection (1 or
#EN_Adaptive=1: Adaptive Frequency Injection in log scale
#EN_Adaptive=0: Equal Distance Frequency Injection in log scale

#Adaptive Frequency Injection Prameters
MagErr=0.3                  # Maximun magnitude error of measured impedance model (U
PhaseErr=0.5                # Maximun phase error of measured impedance model (Unit:

#Equal Distance Frequency Injection Prameters
N1=30                       # Number of measured points for MIMO measurement
N2=40                       # Number of measured points for SISO measurement, This d
```

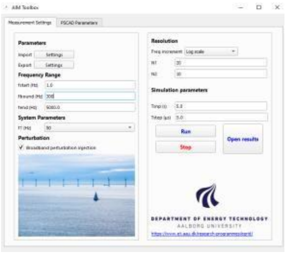
- ✓ Beta version of the software is developed
- ✓ Automatic impedance matrix measurement
- ✓ Tested by TenneT in the real HVDC project

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

2021. 01-2021.07

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

Imp_Toolbox



- ✓ Get rid of matlab
- ✓ Convert python scripts to exe Graphical user interface development
- ✓ Licesne system developement
- ✓ More funcitonalities
- ✓ Software robustness test in different comupter sytem environment
- ✓ **1st commercial version**

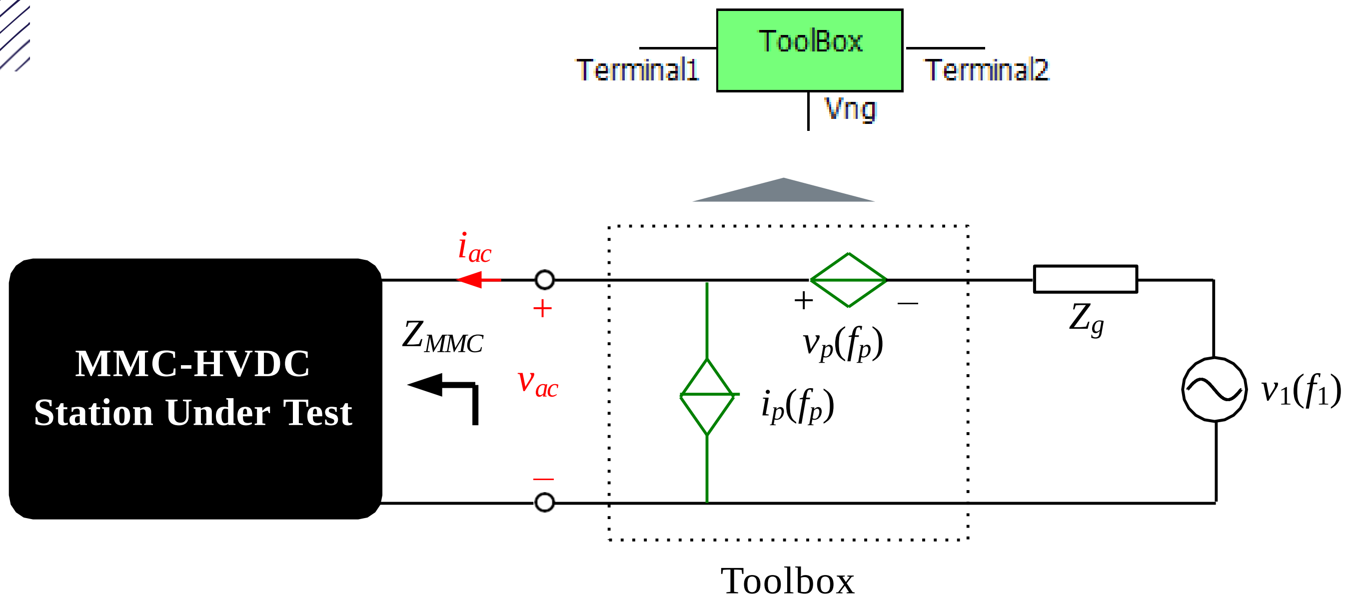
2021.07-2022.07

- Innoexplorer is granted
- Version 2 is excepted

Innovation Fund Denmark

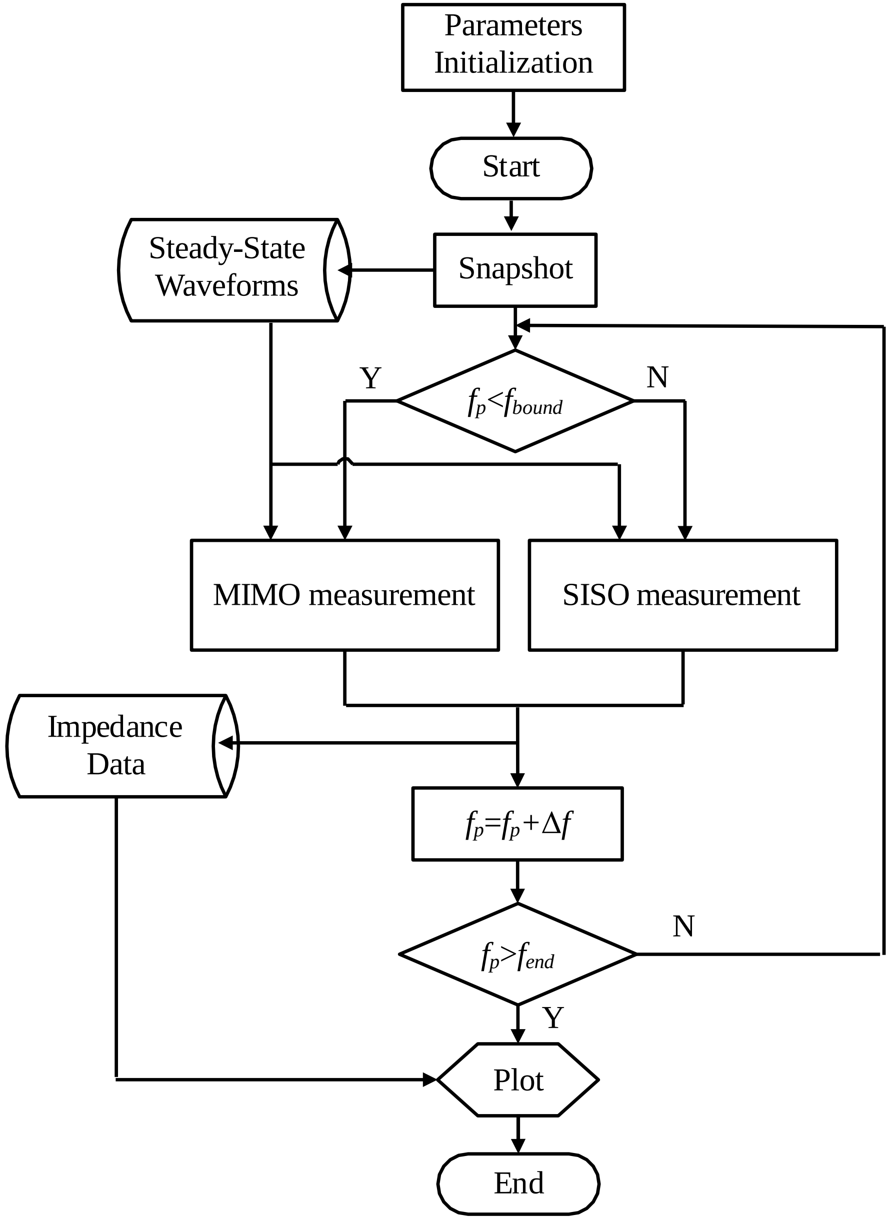
- ✓ Using AI to make the toolbox more intelligant

Circuit diagram of the toolbox



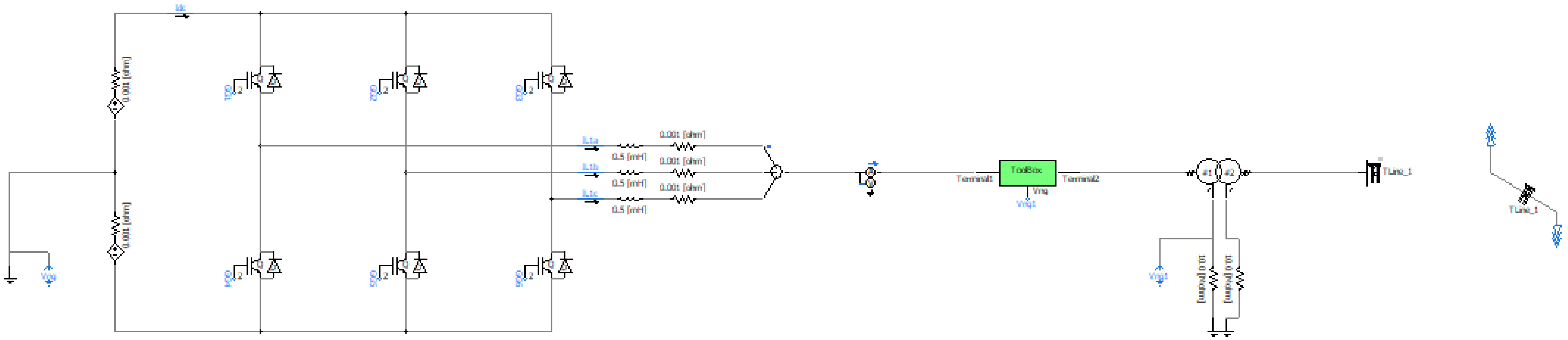
Basic impedance measurement scheme

The impedance/admittance matrix seen from Terminal 1 and Terminal 2 can be measured at the same time

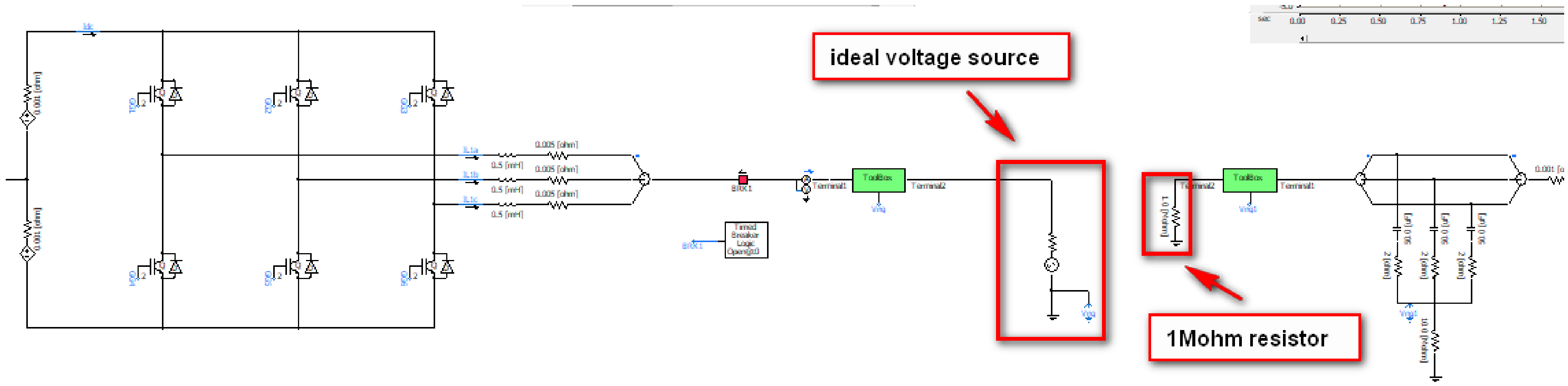


Circuit diagram of the toolbox

Impedance measurement for a stable system



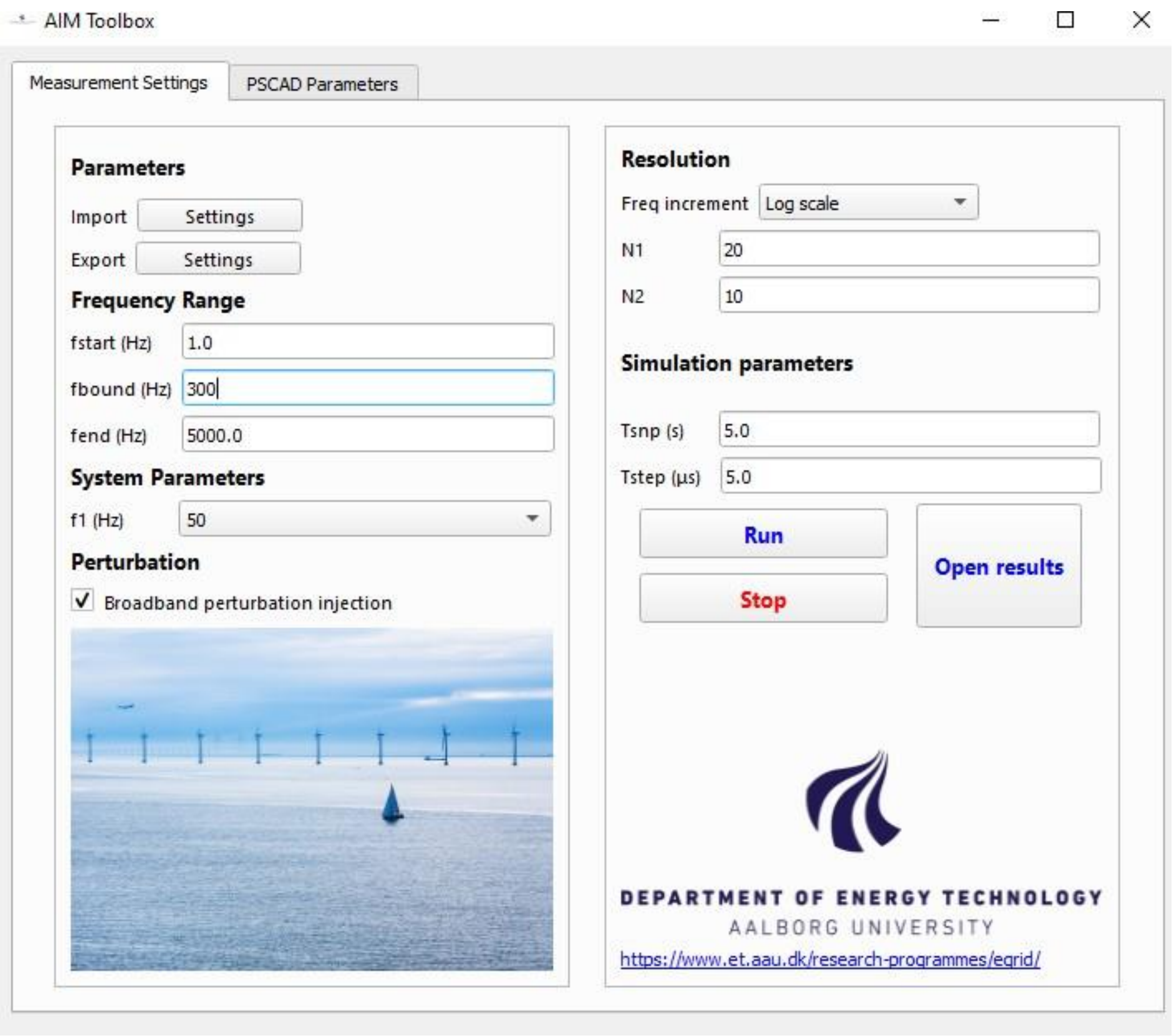
Impedance measurement for a stable/unstable system (**recommended**)



ideal voltage source

1Mohm resistor

GUI of the Toolbox



Parameters

Frequency Range

fstart (Hz) 1.0

fbound (Hz) 300

fend (Hz) 5000.0

System Parameters

f1 (Hz) 50

Perturbation

☑ Broadband perturbation injection

Resolution

Freq increment Log scale

N1 20

N2 10

Simulation parameters

Tsnp (s) 5.0

Tstep (µs) 5.0

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 αβ frame**
- **Has already be used by TenneT in the real MMC-HVDC projects and the measurement results show high accuracy**

Measurement results

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

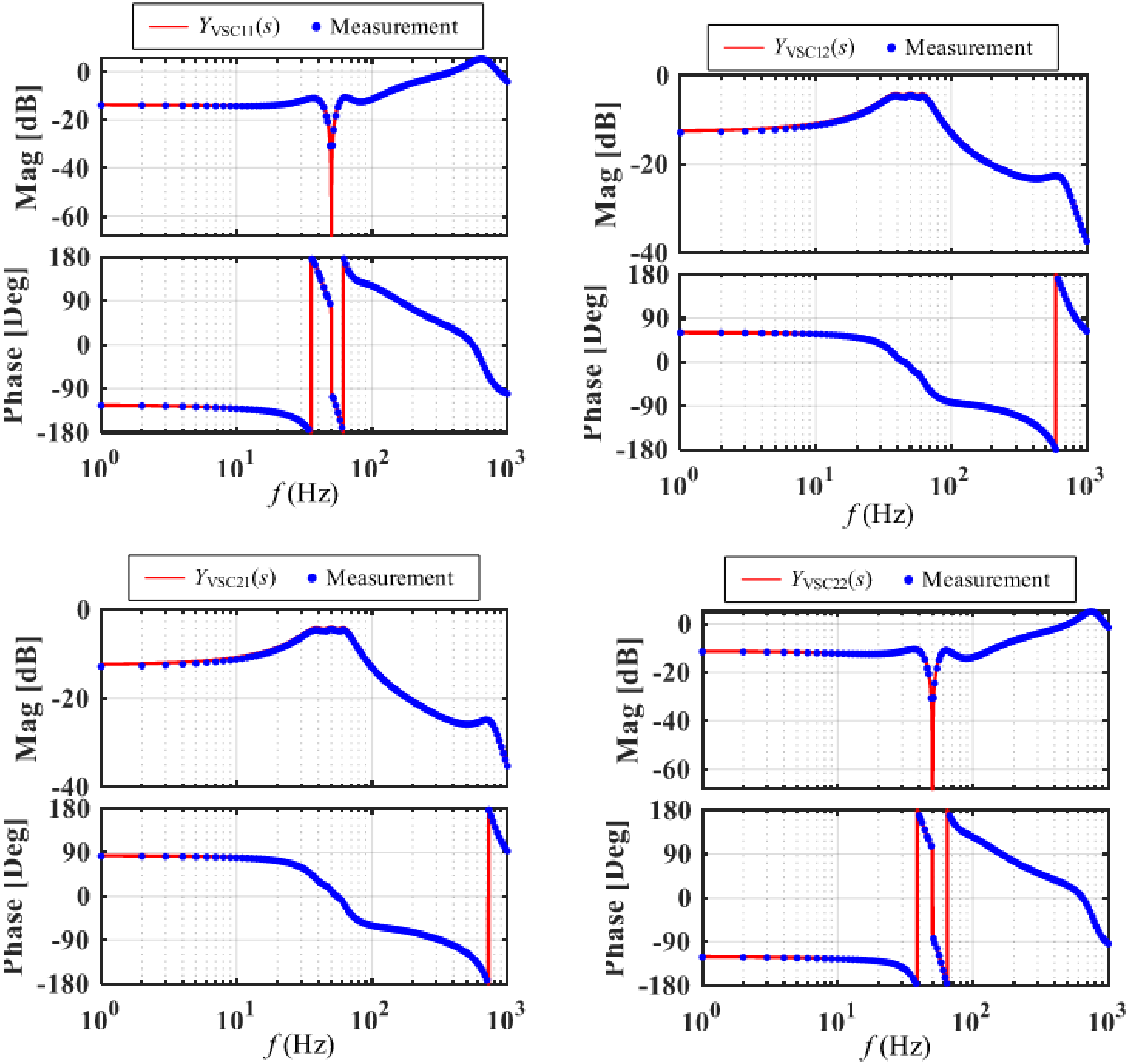
T1_admittance_dq_MIMO1	✓	6/2/2021 1:00 PM	Text Document	2 KB
T1_admittance_stationary_MIMO1	✓	6/2/2021 3:12 PM	Text Document	4 KB
T1_admittance_stationary_SISO1	✓	6/2/2021 2:27 PM	Text Document	1 KB
T1_impedance_dq_MIMO1	✓	6/2/2021 1:00 PM	Text Document	2 KB
T1_impedance_stationary_MIMO1	✓	6/2/2021 3:12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

Cross-validation

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

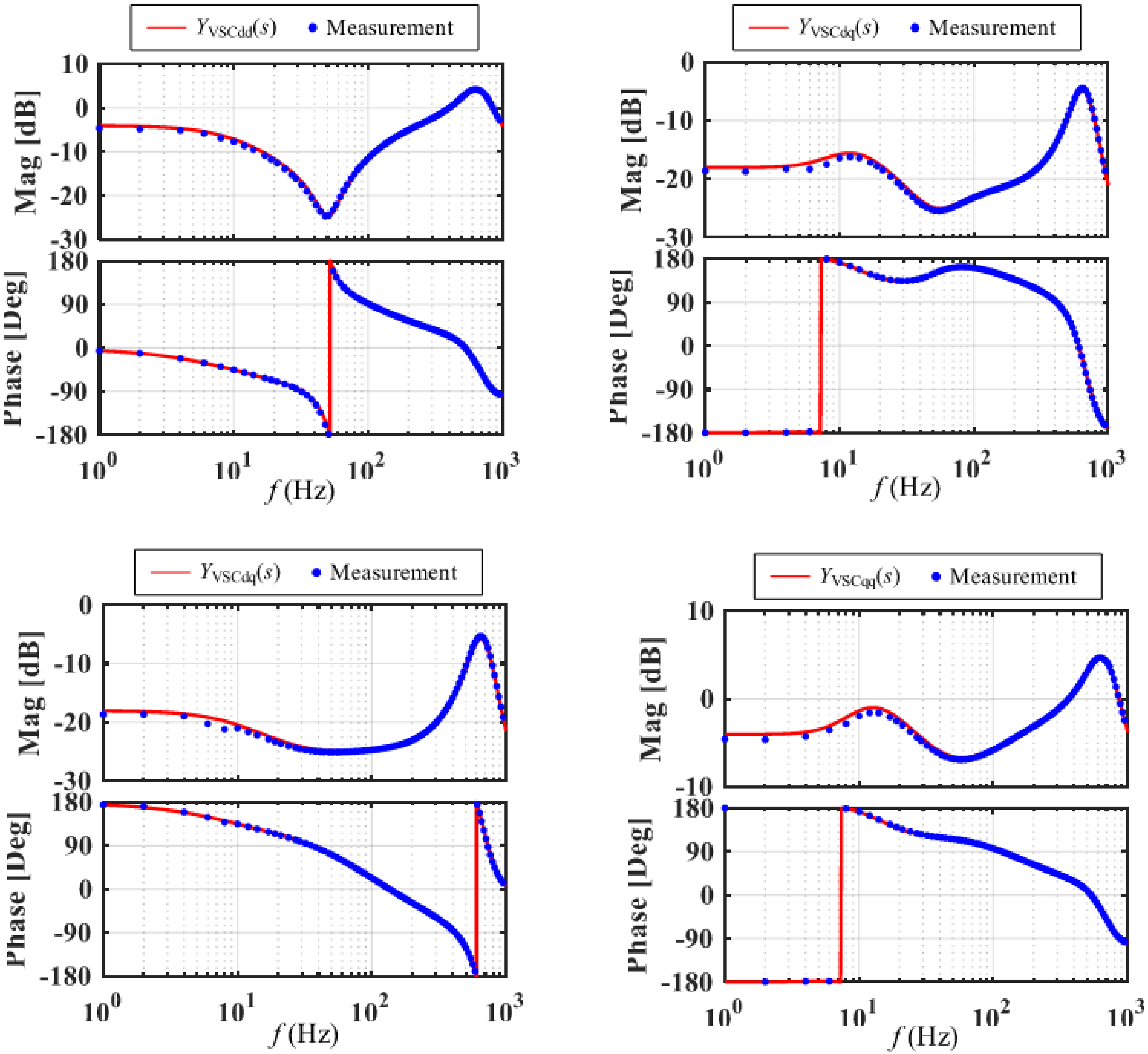
Admittance matrix in αβ frame



Cross-validation

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

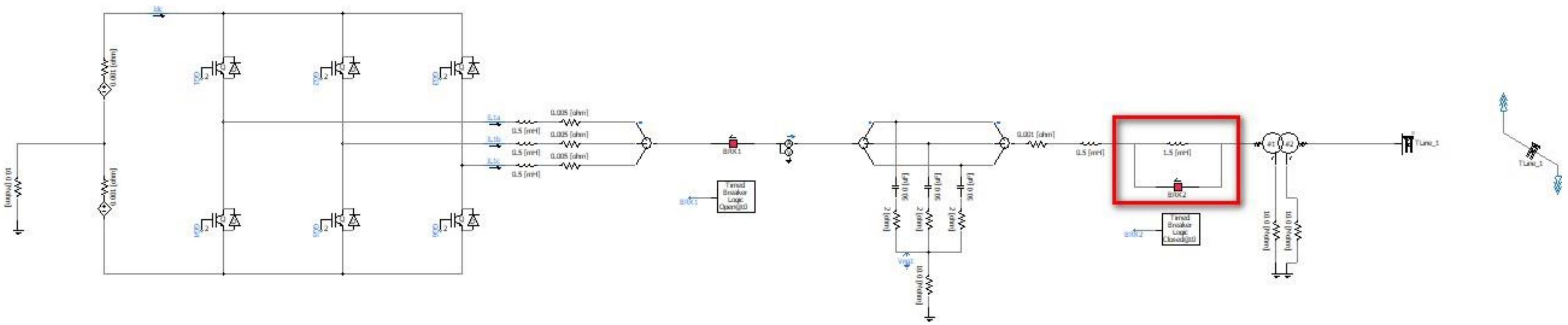
Admittance matrix in dq frame

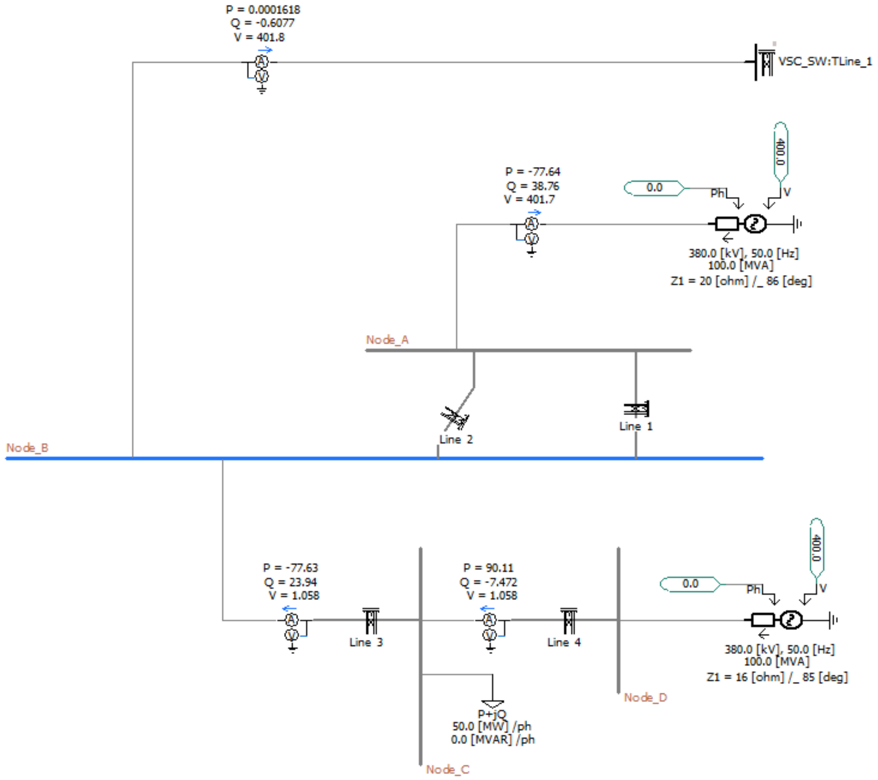


Outline

- ❑ Background and Challenge
- ❑ Theoretical Basis for the Impedance-based Stability Analysis
- ❑ Introduction of Impedance Measurement Toolbox
- ❑ **Case Studies**

Case studies: passive network configuration

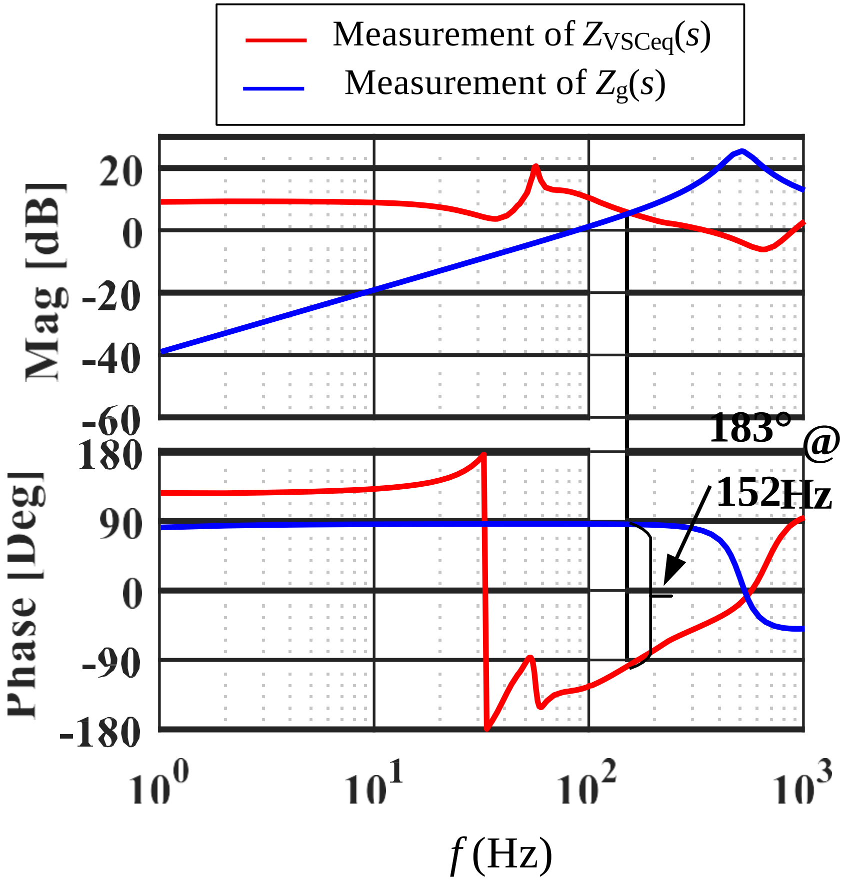


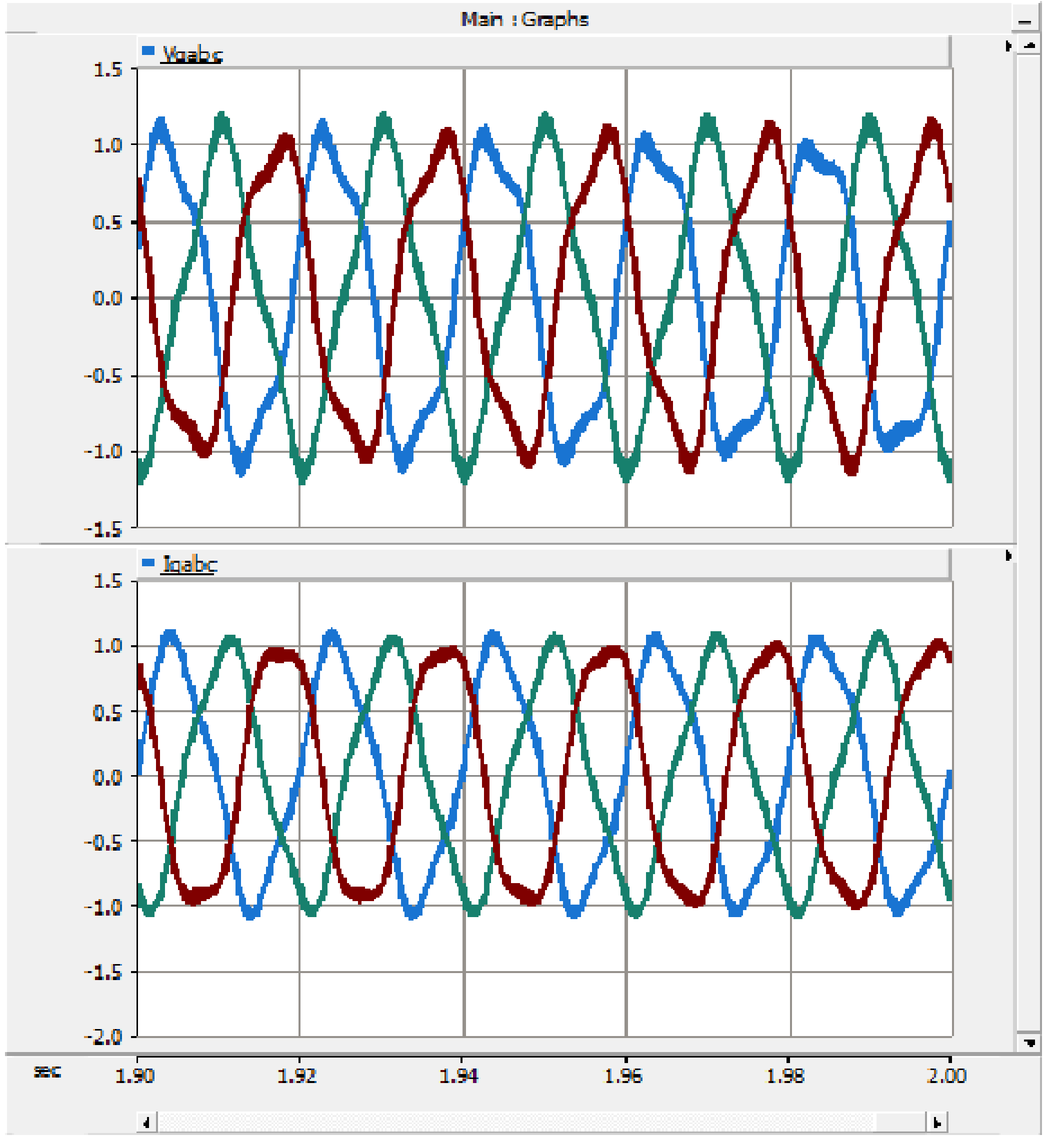


- BRK opens, weak grid
- BRK closes, strong grid

Weak Grid

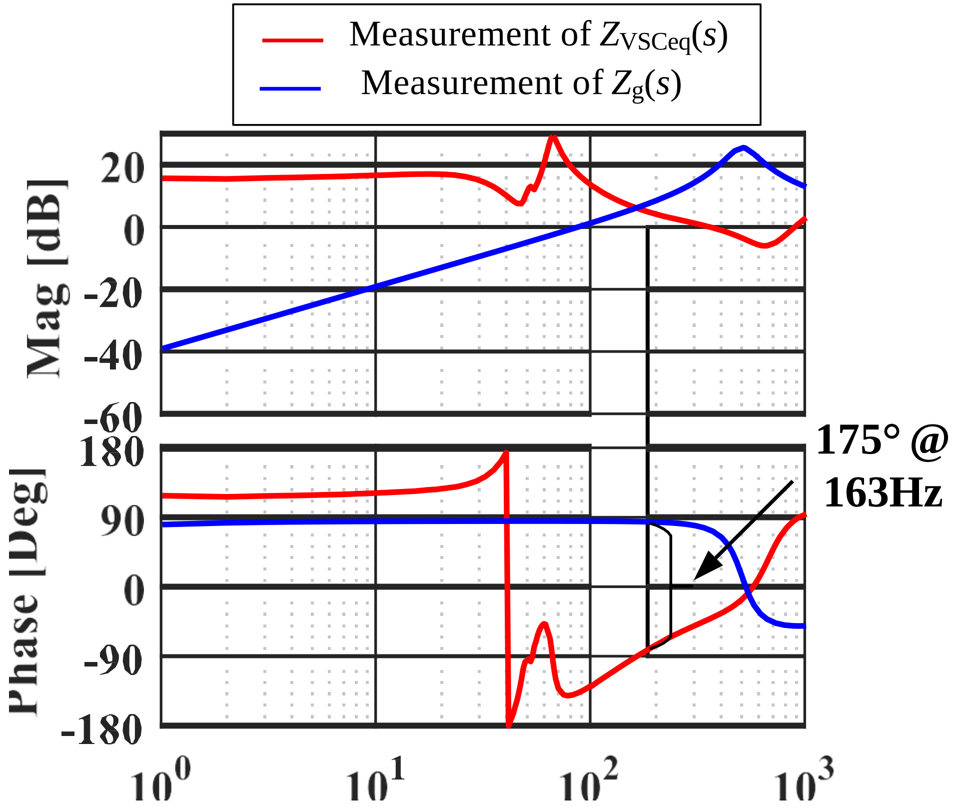
f_{PLL}=25Hz, unstable

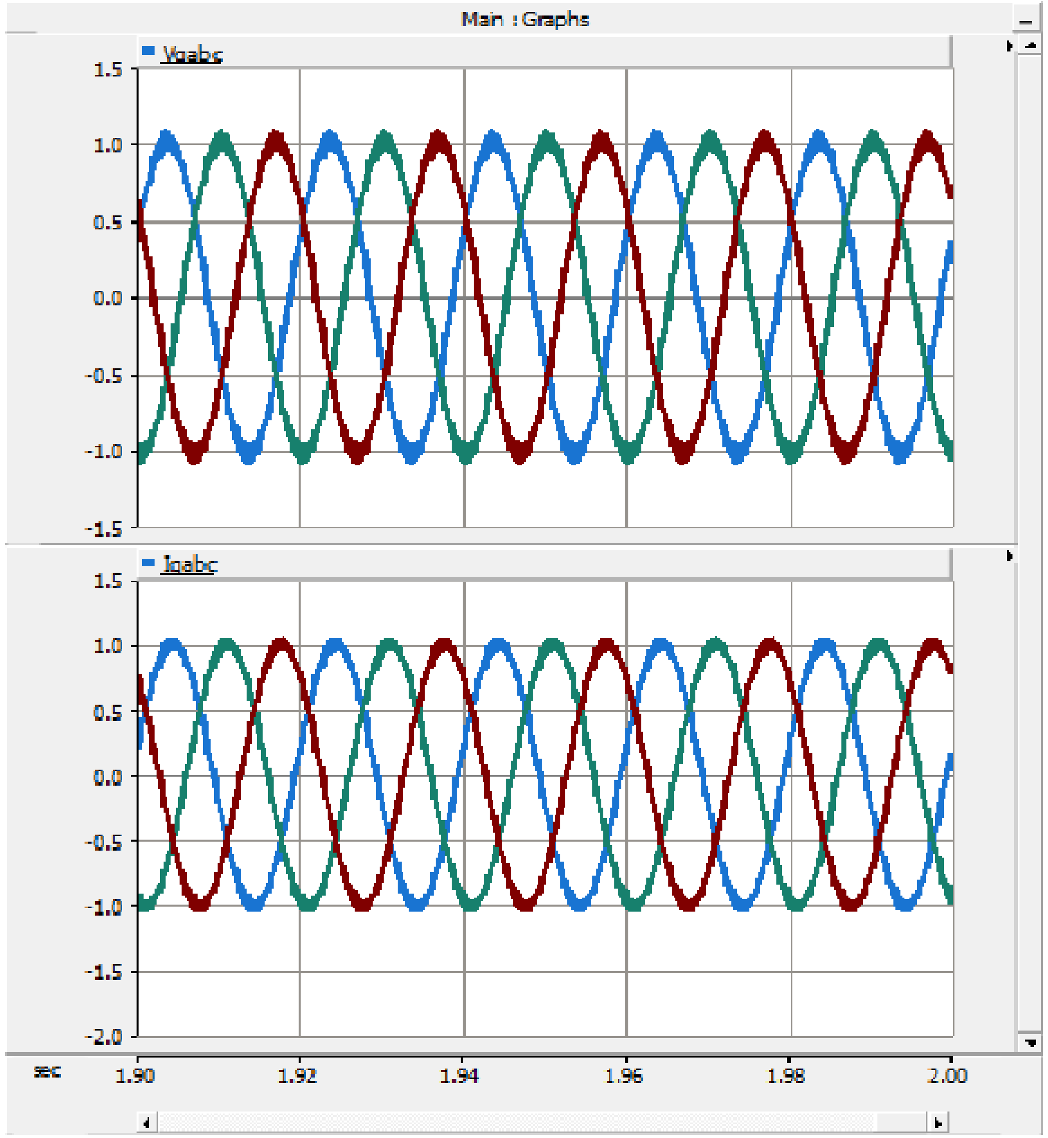




Weak Grid

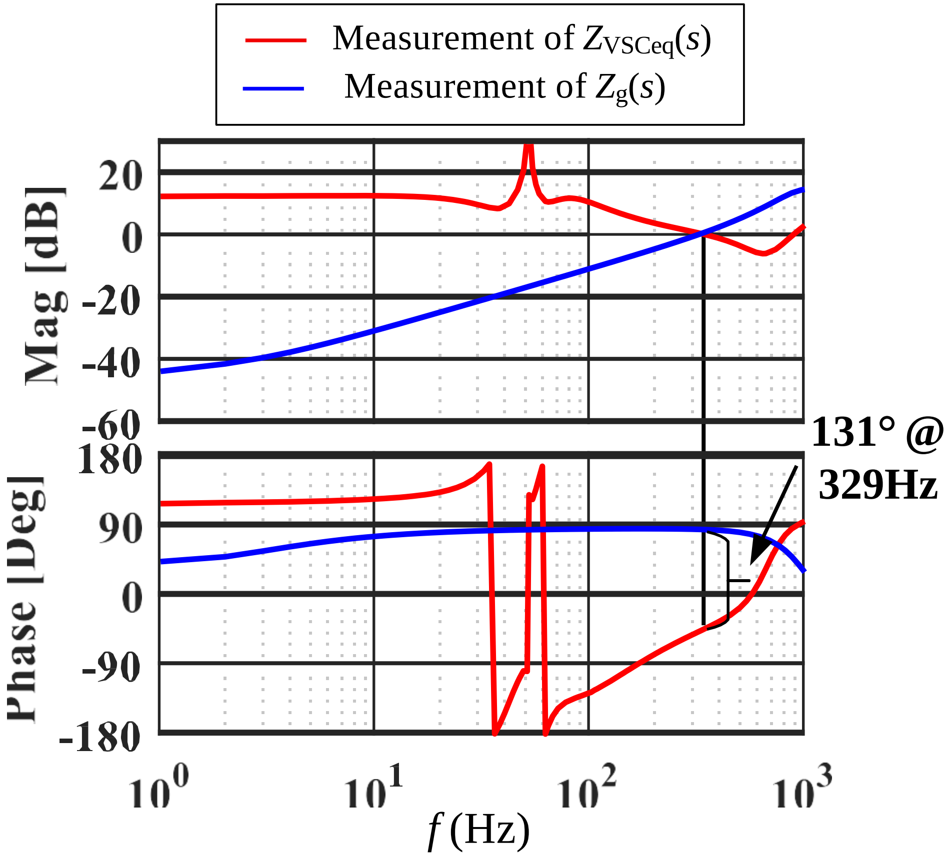
f_{PLL}=5Hz, stable

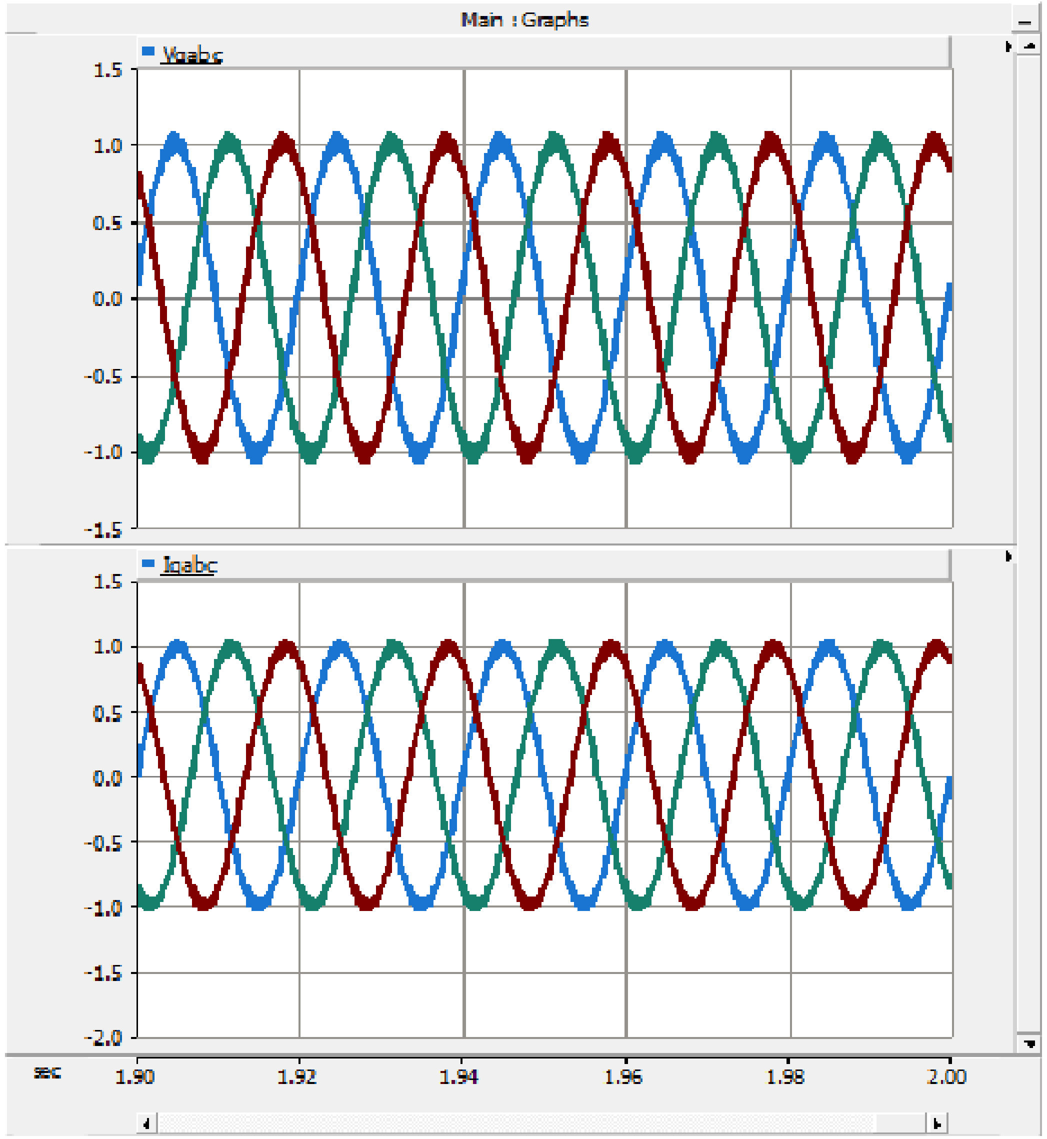




Stiff Grid

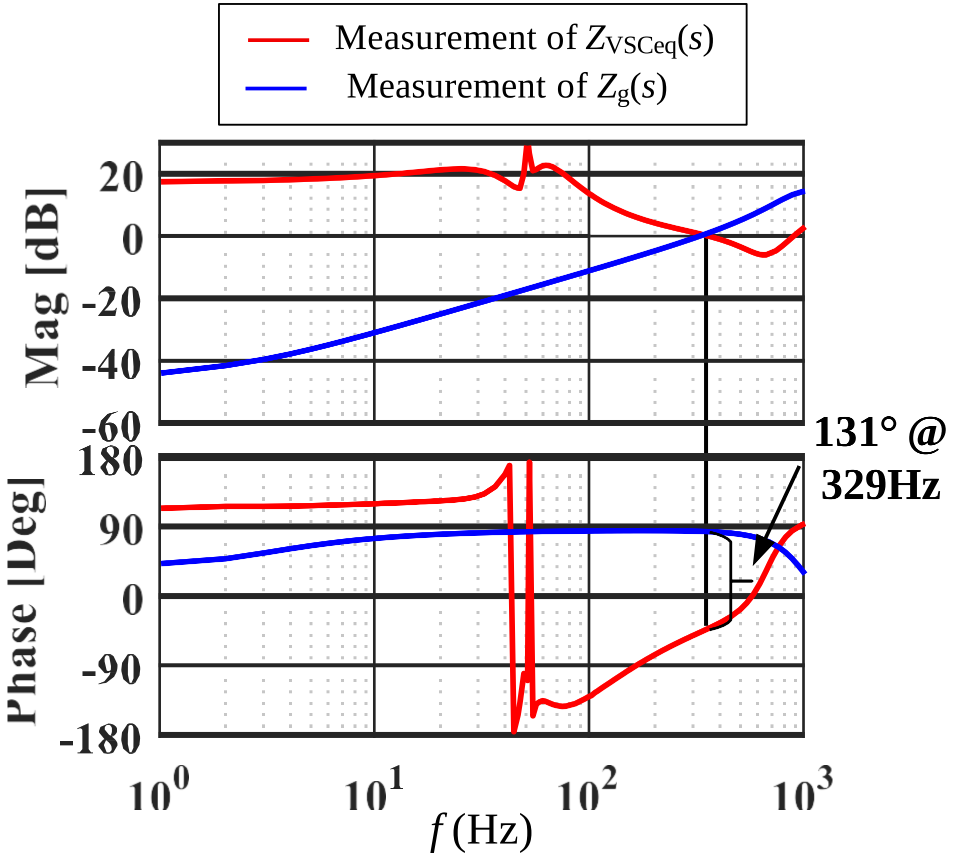
f_{PLL}=25Hz, stable

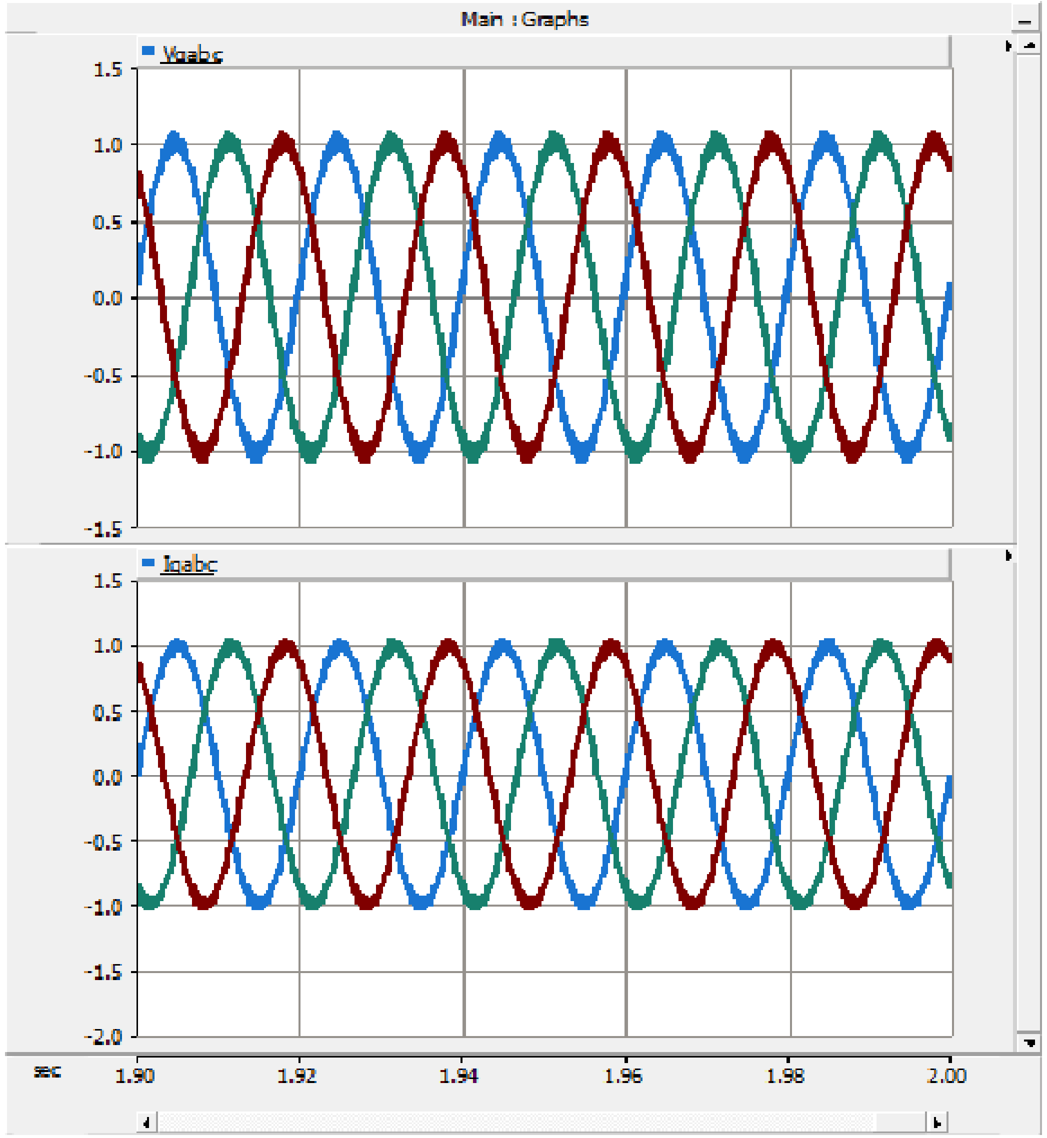




Stiff Grid

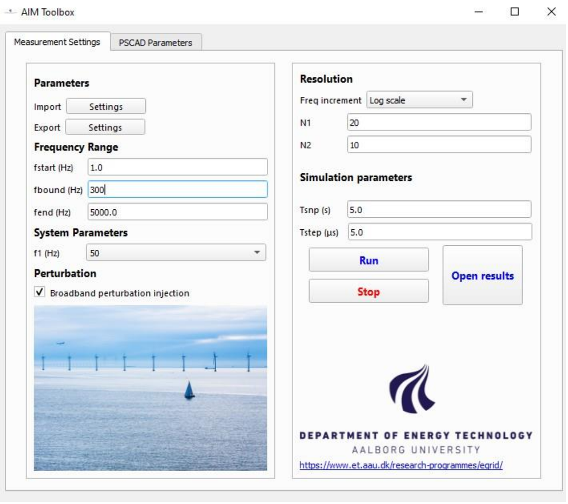
f_{PLL}=5Hz, stable





What we offer

Impedance measurement toolbox



Parameters

Import

Export

Frequency Range

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fend (Hz): 5000.0

System Parameters

f1 (Hz): 50

Perturbation

☑ Broadband perturbation injection

Resolution

Freq increment: Log scale

N1: 20

N2: 10

Simulation parameters

Tsnp (s): 5.0

Tstep (µs): 5.0

User's manual

For further information, please contact:

hew@energy.aau.dk

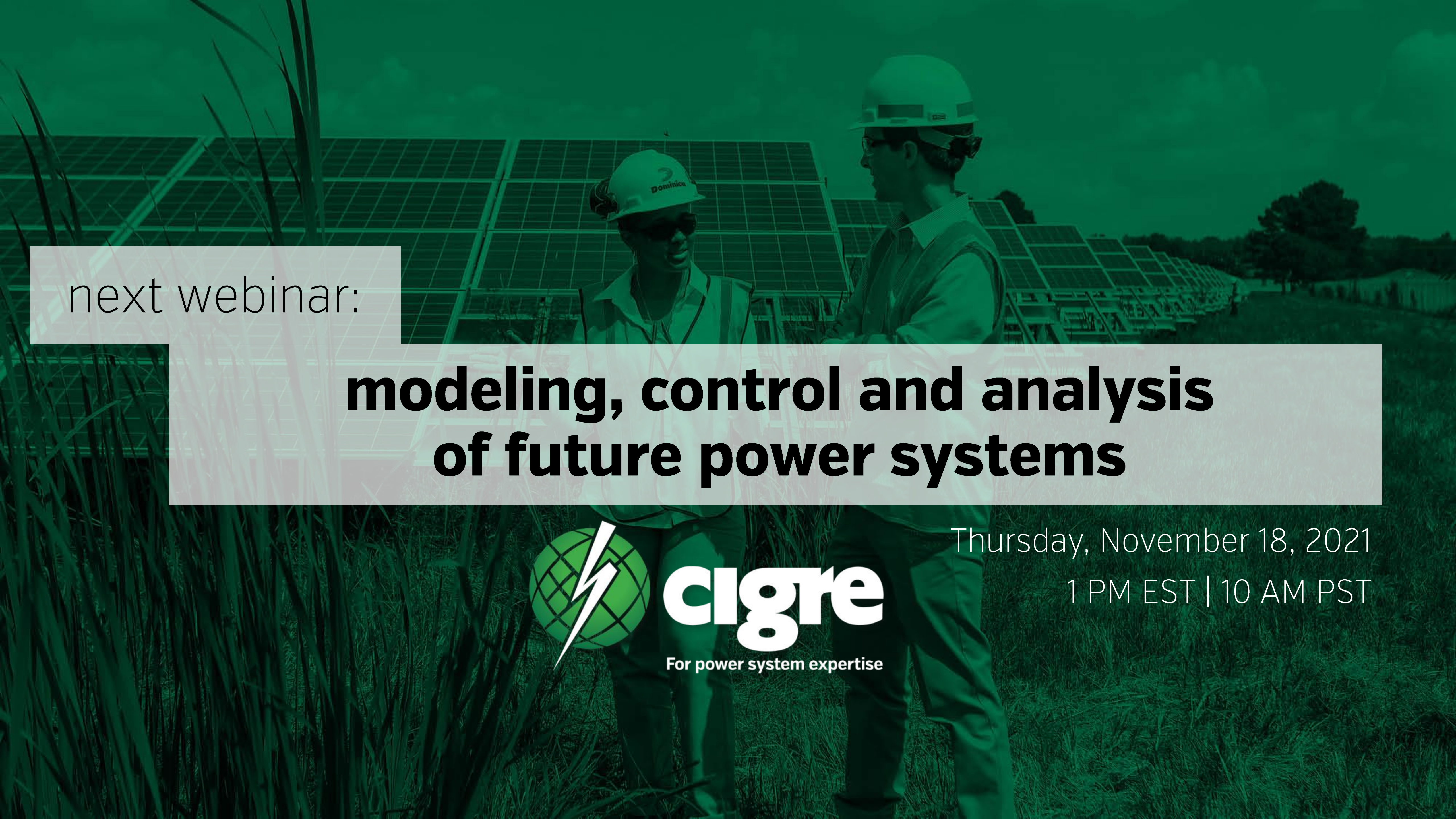
Cross-validation

Generic EMT model of two-level voltage source converter

Theoretical calculated impedance of two-level voltage source converter

Any Questions?

AALBORG UNIVERSITY
DENMARK



next webinar:

modeling, control and analysis of future power systems

Thursday, November 18, 2021

1 PM EST | 10 AM PST

cigre

For power system expertise