Stability Assessment and Mitigation of Converter Interactions (Phase 2)

17th June 2021 | Webcast

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&
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University of Strathclyde

We are expecting a large number of participants to join, so the session will start a couple of minutes late.

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Welcome to the HVDC Stability Assessment Tools Webcast

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Due to large audience, please turn off video & put microphone on mute

Questions for speaker/panel will be managed using Slido. Please direct interactive discussions to MS Teams chat.

This webinar may be recorded. Link to slides will be shared after the webcast.

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Considering a lot of participants are expected, all questions or comments may not be addressed during the webcast. A briefing note with summary of questions, answers and technical discussions will be published and circulated to all participants after the webinar.

Expected audience by industry sector

Agenda

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Time	Description
12.30 - 12:40	Welcome and Context Setting
12.40 - 13:20	Small Signal Impedance Modelling of LCC HVDC System – methods, tools & results.
13:20 – 13:30	Overview of the Small Signal Stability Assessment Process Journey
13:30 – 13:45	Panel Session - Colin Foote, SP Energy Networks - David Gregory, National Grid ESO
13:45 – 14:00	Q&As

Q & As

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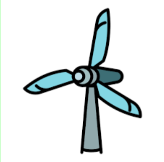
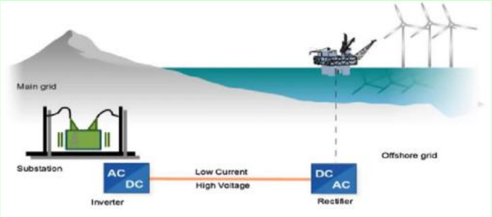
Drivers for HVDC development in GB

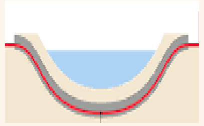
To meet our net-zero targets by 2050, GB needs:



Offshore Wind Connections

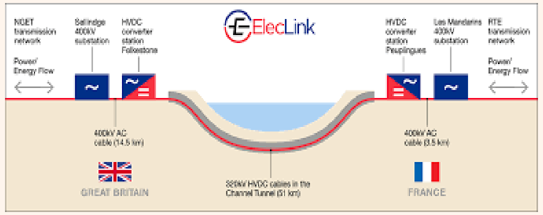
83-88GW offshore wind (with only 10GW connected so far)





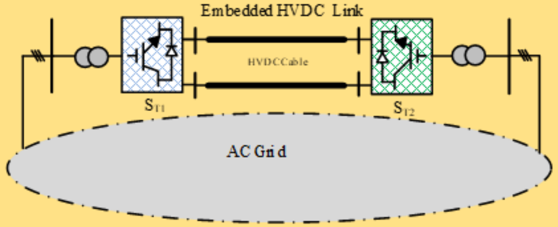
Interconnectors (between networks)

Up to 27GW of HVDC interconnectors (up from 6GW today)

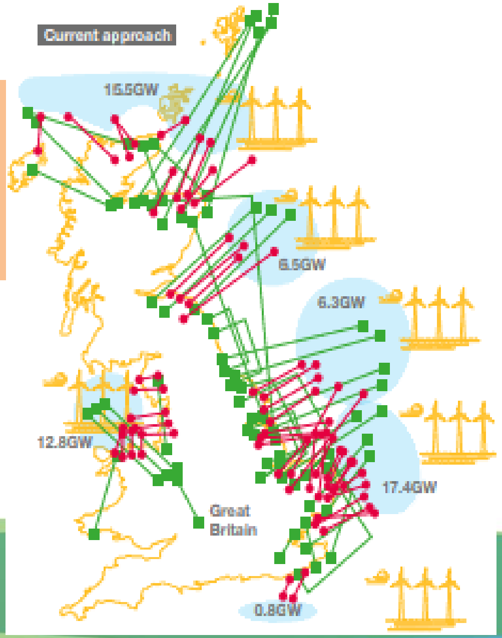


Embedded Links (& Island Connections)

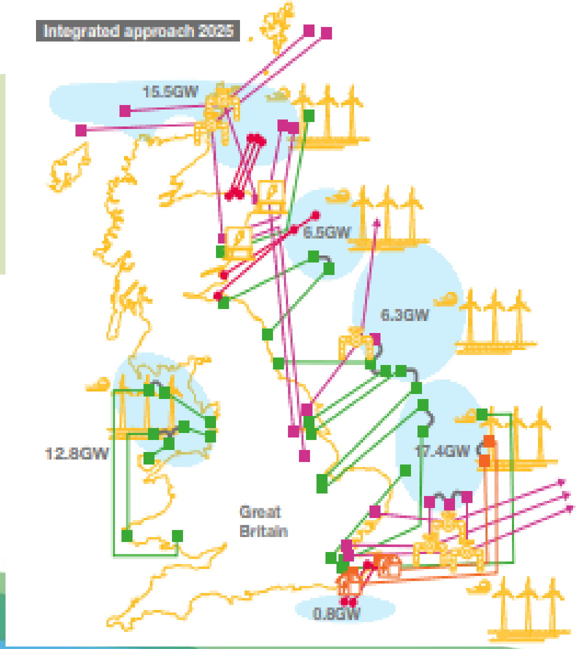
Additional Embedded Links & Island (up from 3.4GW so far)



Connecting Offshore Wind
Current Approach



Connecting Offshore Wind
Integrated Approach



HVDC Innovation Programme

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Completed Innovation Projects

- Design of DC/DC Converter *(NIA Funded)* — University of Aberdeen
- Developing Open-Source Converter Models — University of Strathclyde
- Stability assessment for co-located converters — Manchester 1824, The University of Manchester
- Improving Grid Code For HVDC — Cardiff University, Prifysgol Caerdydd
- Coordination of AC network protection during energization — EPRI Electric Power Research Institute
- Stability assessment and mitigation converter interactions — University of Strathclyde

2020-21 Innovation Projects

- Protection Performance Overview and Validation in Low Strength Areas — Manitoba Hydro International
- Evaluation of HVDC with Synchronous Condenser impact on AC Protection — University of Strathclyde
- Adaptive Damping of Power Oscillations using HVDC — EPRI Electric Power Research Institute
- COMPOSITE Testing of HVDC-connected Offshore Wind Farms — RTE international
- Stability Assessment and Mitigation of Converter Interactions (Phase 2) — University of Strathclyde

2021+ Innovation Projects

- De-Risking Strategic Offshore Assets *(Partnership funded)* — Imperial College London
- Protection Solutions for Lower Fault Current Level AC Networks *(NIA funded)* — University of Strathclyde
- RTDS Model Development Project — transgrid SOLUTIONS
- HVDC R&D Strategy *(commissioned by BEIS)* — Department for Business, Energy & Industrial Strategy

Potential SIF/NIA/EU Projects

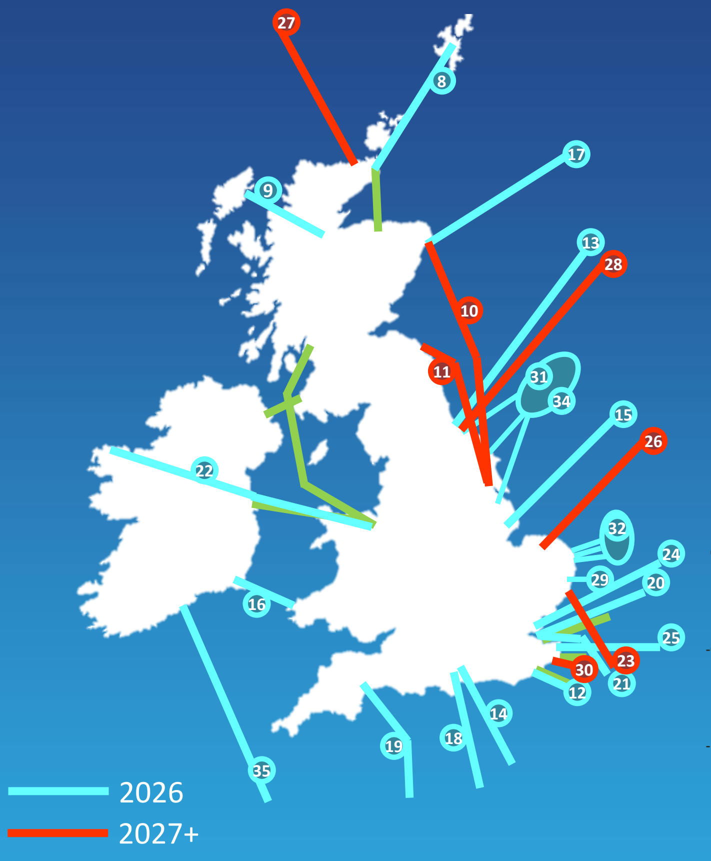
- Horizon Europe call on multi-vendor HVDC
- SIF call on whole system solutions for de-risking Integrated AC/DC Networks

Horizon 2020 Research Programme

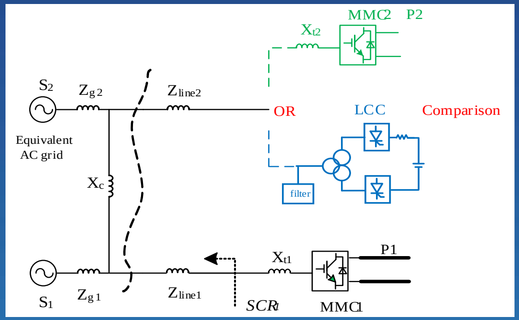
- PROMOTioN: Protection system demonstration *(WP9 Lead)* — PROMOTioN, Progress on Meshed HVDC Offshore Transmission Networks

Key Drivers for Small Signal Stability Assessment

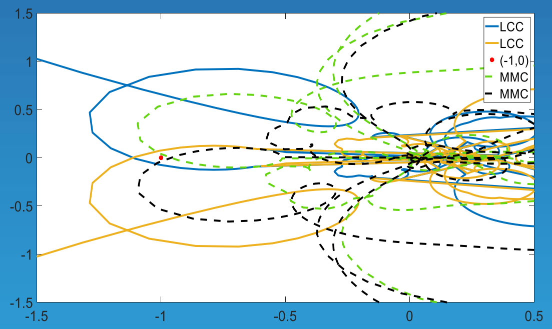
Development of HVDC Connections in GB



Source: National Grid Interconnector Register 01 08 2019



Nyquist curve with different Converters

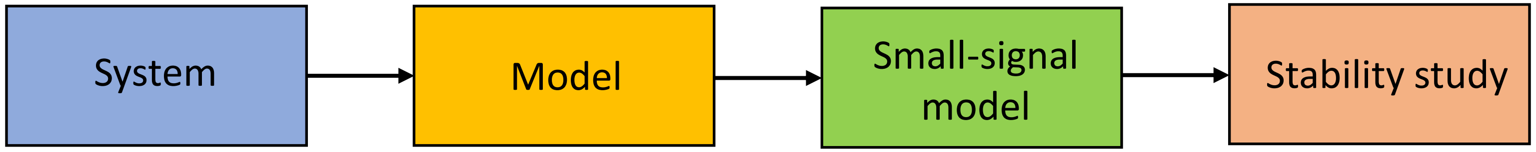


- Rapid growth in converter-interfaced sources is significantly changing the characteristics of the GB grid.
- Increasing risk of interactions among HVDC converters & actively controlled devices such as wind farms, conventional power stations & FACTS devices.
- The control dynamics of converters located in close proximity can lead to oscillations across a wide frequency range.
- Accurate assessment of potential system interactions is critical for ensuring stable operation of future and evolving GB network.

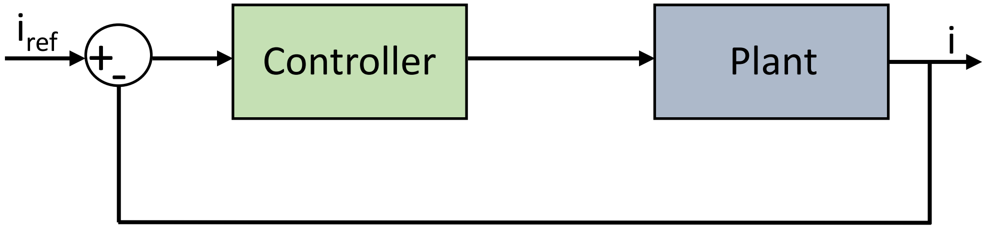
Contents

1. Brief review of previous work on MMC modelling and system stability
2. LCC HVDC system impedance model development
3. Stability of system with LCC and MMC converters

Study of System stability



- Develop system model – usually non-linear (understand the system/plant)
- Develop a small-signal model of the system in the frequency domain (model linearlisation)
- Apply classic feedback control theory to study the system stability



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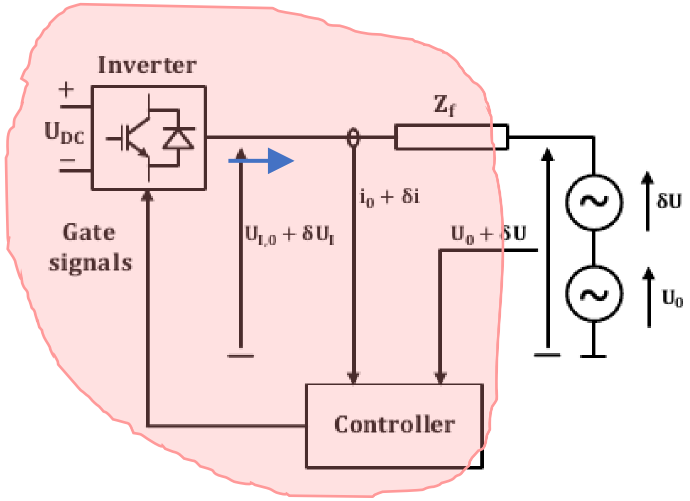
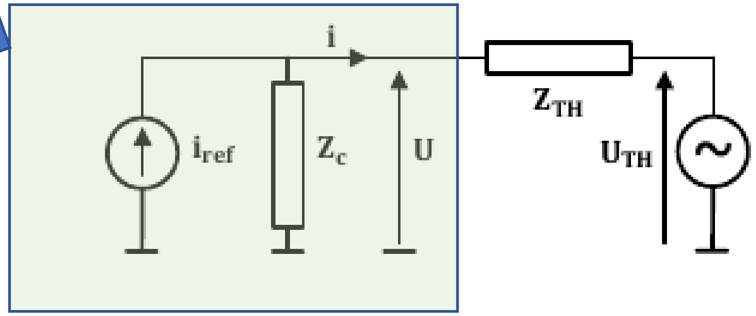
Impedance based stability analysis



$$Y_C(s) = -\frac{\delta i(s)}{\delta U(s)}$$



- The converter can be described in terms of its impedance / admittance- if its structure, control philosophy & tuning are included.
  - ❖ In a vendor model these are hidden to preserve IP, as such its critical to inform vendors clearly what exactly is required.
- By presenting this impedance model detailed device control parameters are no longer required to assess risk.
  - ❖ It only requires information on the equivalent impedance of the grid.
  - ❖ Multiple converters can be studied together – to simply include additional impedances.

Small Signal MMC / AC Network Model for Stability Analysis

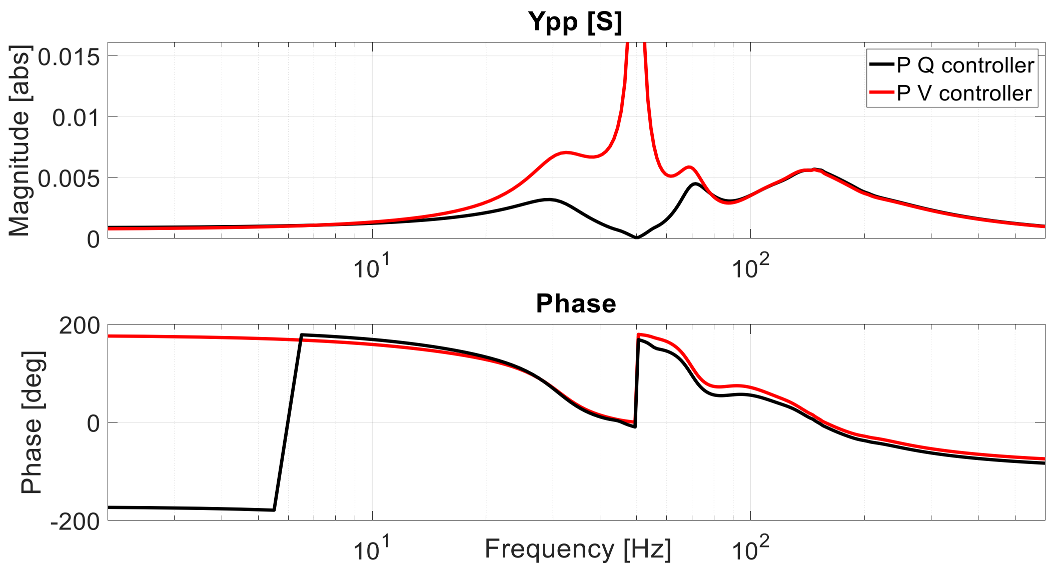
- Develop suitable small signal models for assessing network stability considering large converter penetration.
- Develop frequency domain models of HVDC converters and representative network considering future HVDC deployment in the GB network for stability analysis.
- Time-domain PSCAD and RTDS simulations are used to validate the theoretical analysis and assessment.
- Recommendations for specifications of converter models are proposed.

MMC Impedance Modelling

❑ Control Mode and Set-Point Impact

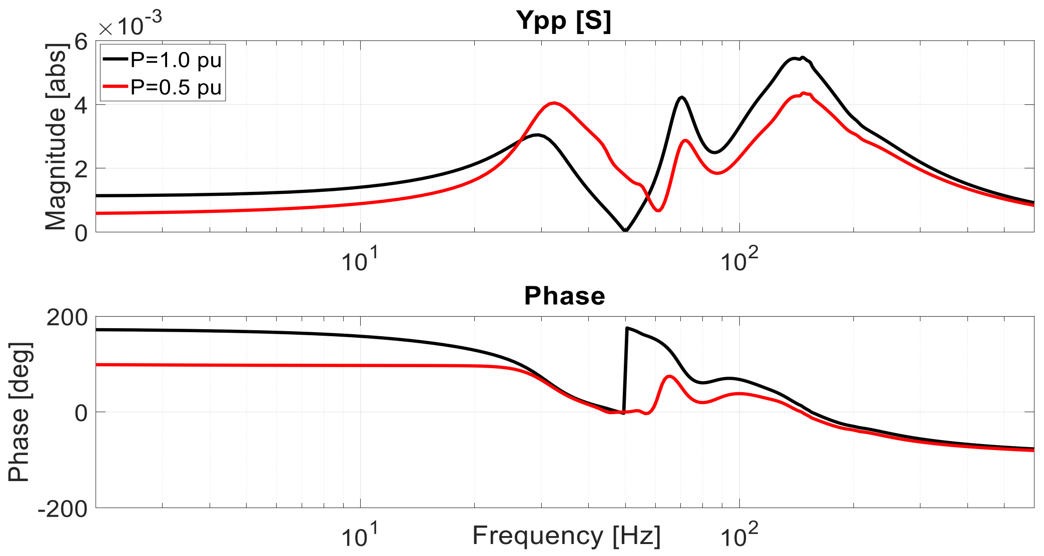
- Control: **P-Q** v.s. **P-Vac**

(P*=1pu, Q*=0.08pu, V_{ac}=1.0)



- P*: **1pu** v.s. **0.5pu**

(P-Q control, Q*=0.12pu, V_{ac}≈1.0 pu)



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MMC Impedance Modelling Summary (1)

- The frequency dependant impedance of the convertor is dependent on:
    - Control parameters and mode, (e.g. power control, AC voltage control, DC voltage control);
    - Operating point;
    - PLL tuning;
- The above parameters can be modified both in a projects’ detailed design phase and ahead of, and during, commissioning of a project.
- When specifying converter impedance, it is thus important to cater for possible wide operating points and retuning of control parameters up to commissioning, and in ongoing operation.

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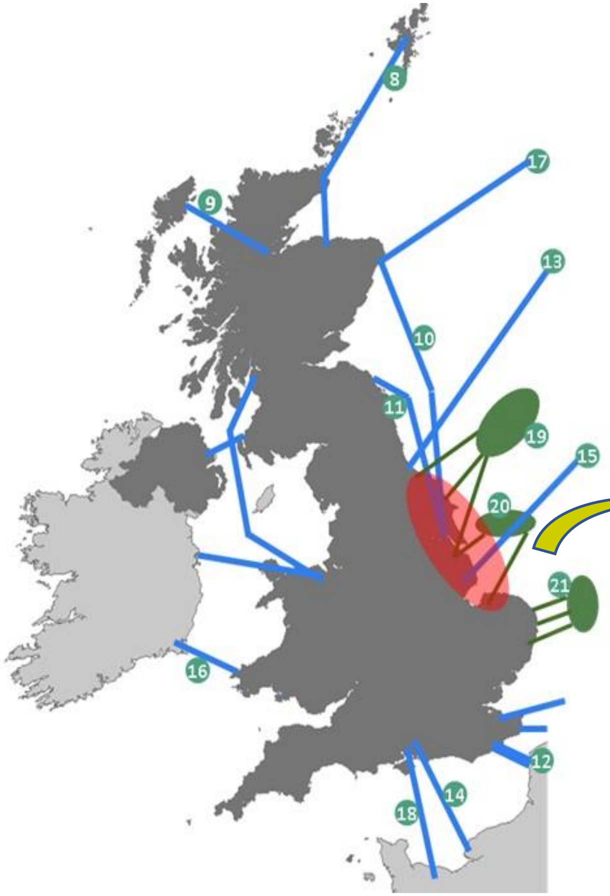
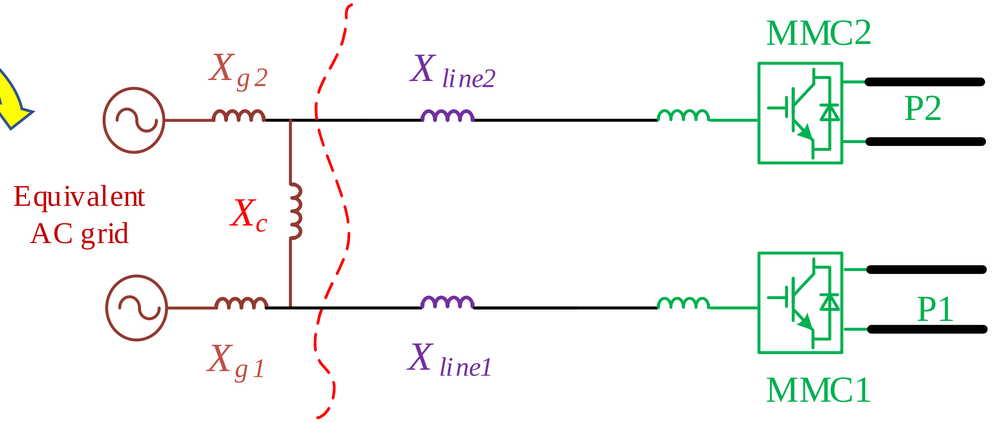
Stability Assessment of Multiple (2) Converters



- X_{g1}: define the network condition of one region
- X_{g2}: define the network condition of the other regions
- X_c: defines the coupling between MMC1 and MMC2
- X_{line1} and X_{line2} considered as the lines between converters and main connection points
- *By varying* X_{g1}, X_{g2}, and X_c , different network conditions and couplings can be considered



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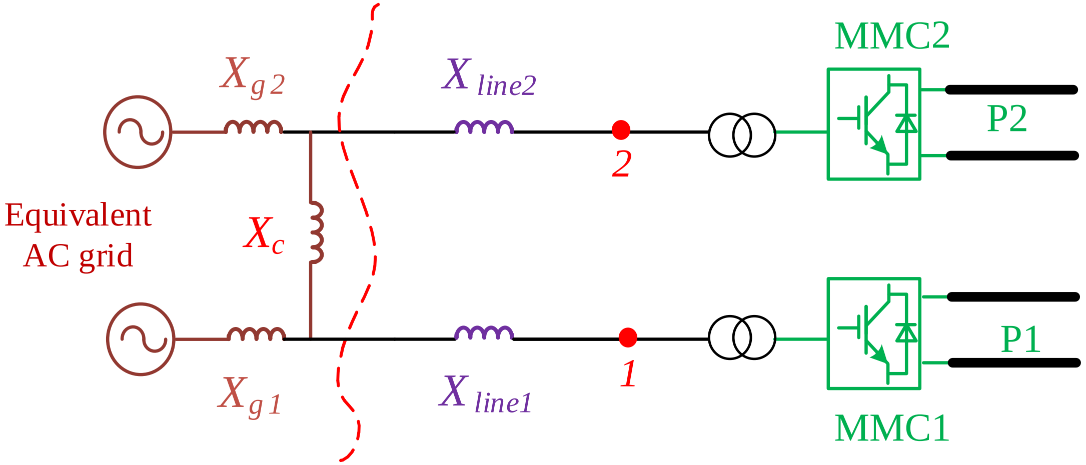
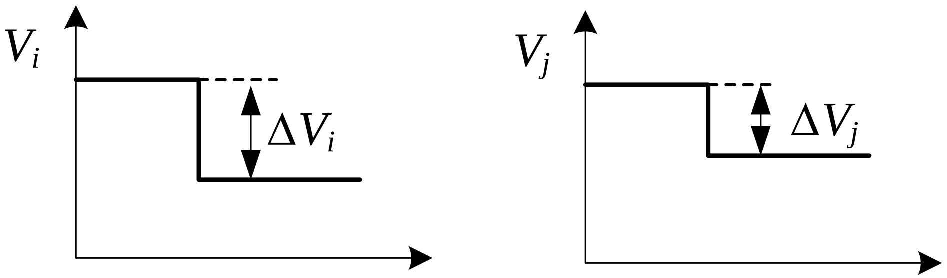
Stability Assessment of Multiple Converters

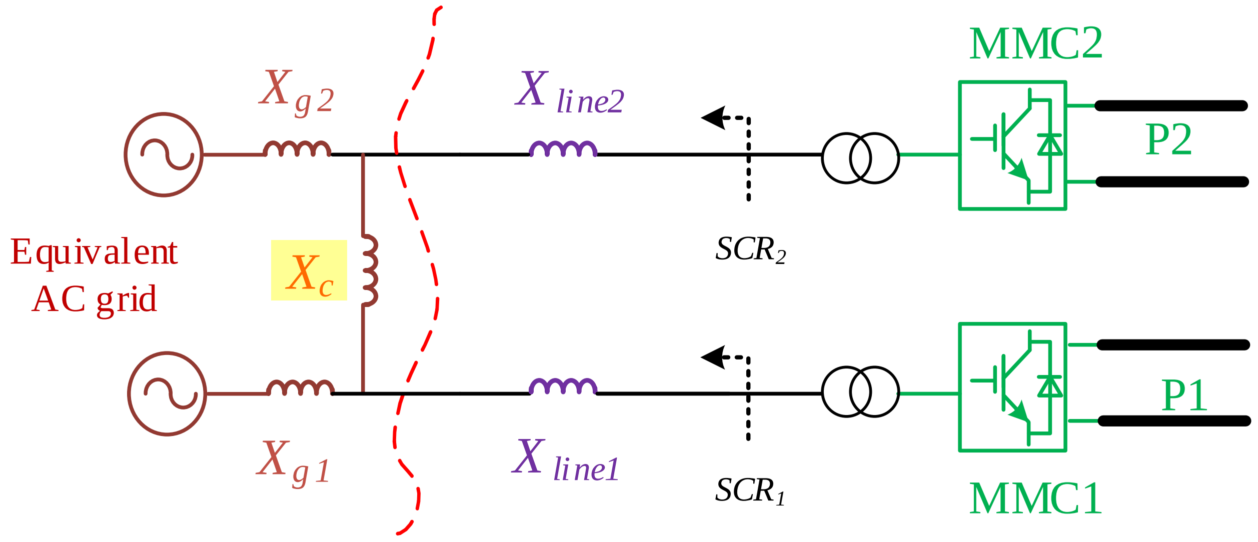


- To measure the interactions among multiple HVDC converters, the multi-infeed impact factor (MIIF), proposed by CIGRE WG B4 Working Group is used to categorize the network and identify the most important interactions to focus on.



$$MIIF_{j,i} = \frac{\Delta V_i}{\Delta V_j}$$

Stability Assessment of Multiple Converters



Case 1: weak coupling (large Xc)

- SCR_1= 2.59, SCR_2=2.59, $MIIF_{2,1}$=0.26, $MIIF_{1,2}$=0.26

Case 2: strong coupling (small Xc)

- SCR_1= 2.74, SCR_2=2.64, $MIIF_{2,1}$=0.81, $MIIF_{1,2}$=0.78

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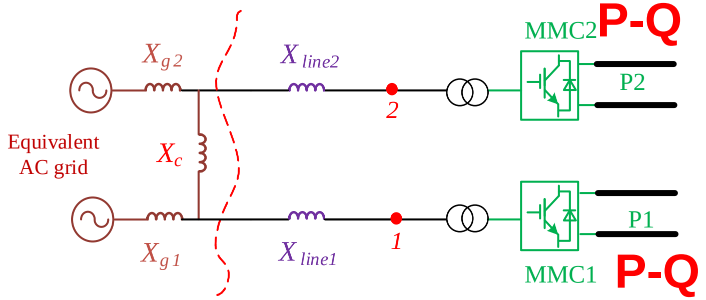
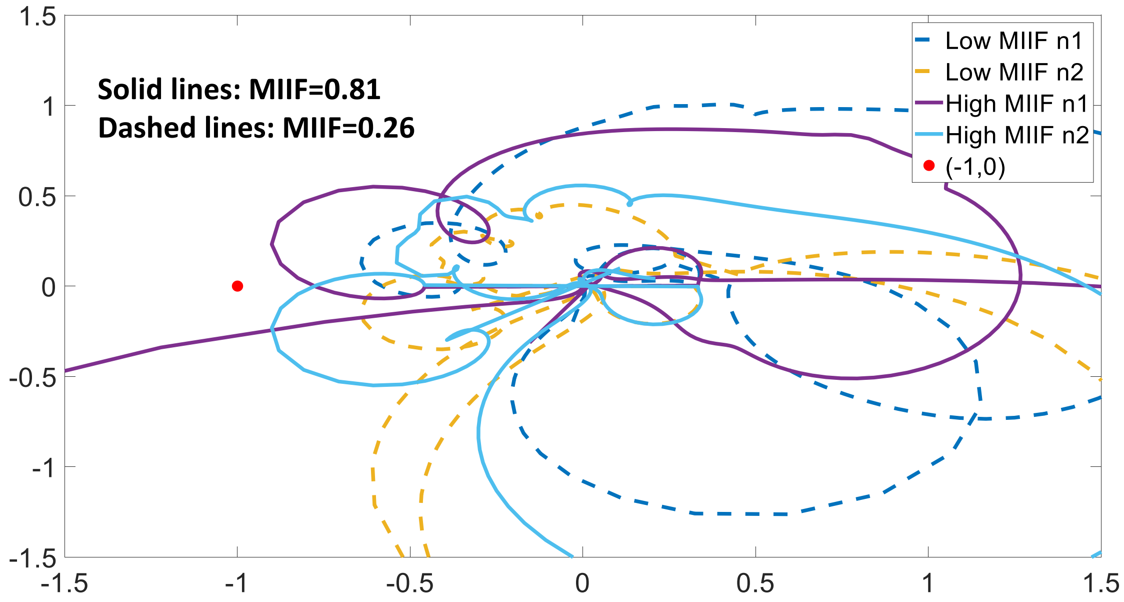
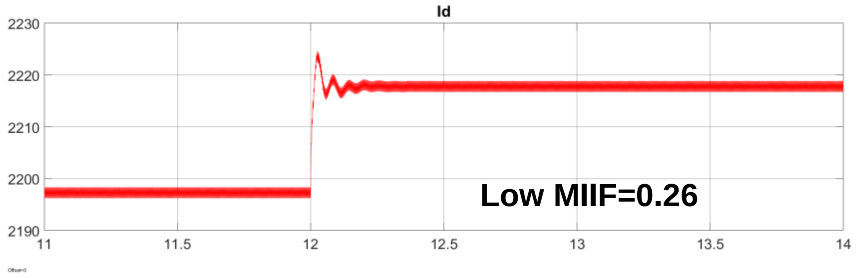
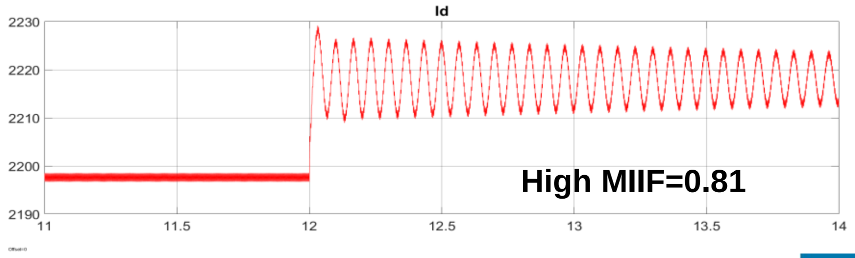
Stability of 2 Converters (Results for P-Q Control)



MMC1 with P-Q control, MMC2 with P-Q control







- Both systems are stable
- For low MIIF (case 1), the system has higher stability margin.
- For high MIIF (case 2), the system has lower stability margin.

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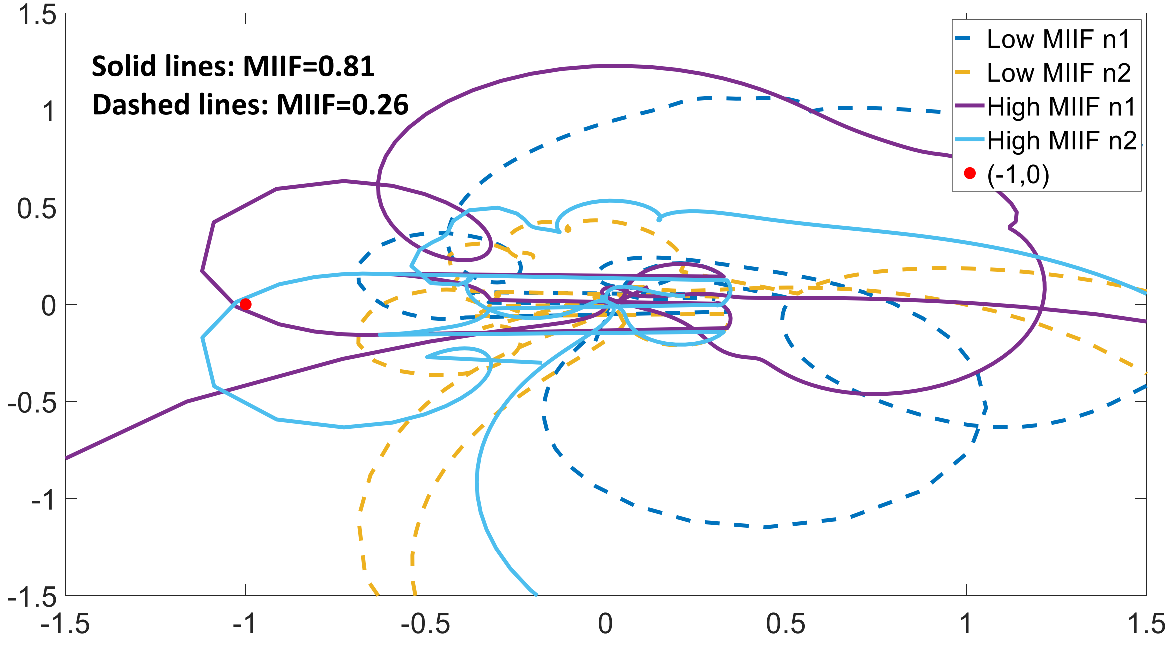
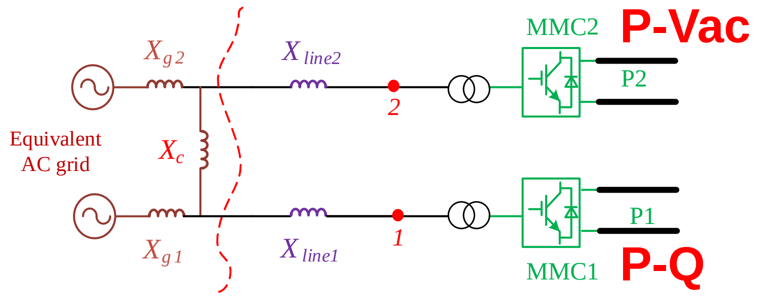
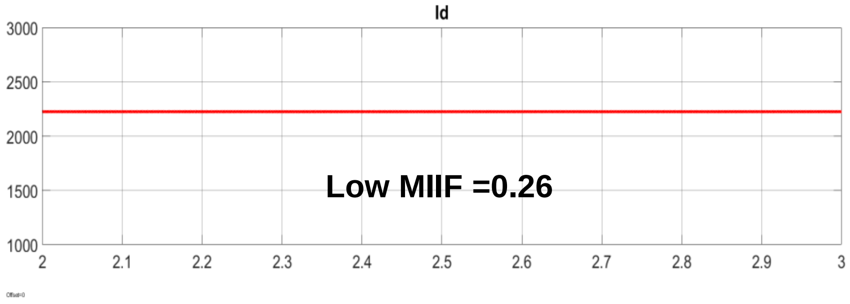
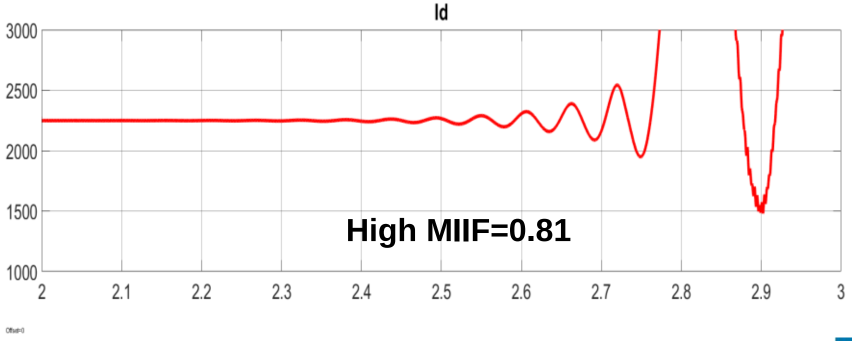
Stability of 2 Converters (with P-Q and P-Vac mode)

MMC1 with P-Q control and MMC2 with P-Vac control









- For low MIIF (case 1) , the system has sufficient stability margins.
- For high MIIF (case 2), the system becomes unstable.

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Converter Interaction Analysis – Summary (2)

- Preliminary study indicates that multiple converters in close electrical proximity (in frequency domain) can significantly affect system stability.
- Different converter operation modes, control structure, and tuning can lead to varied system damping and stability.
- Thus, network connection conditions and converter couplings need to be carefully examined to ensure system stability.

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Key Outputs of Phase 1 project can be found at: https://www.hvdccentre.com/hvdc-stability-assessment/

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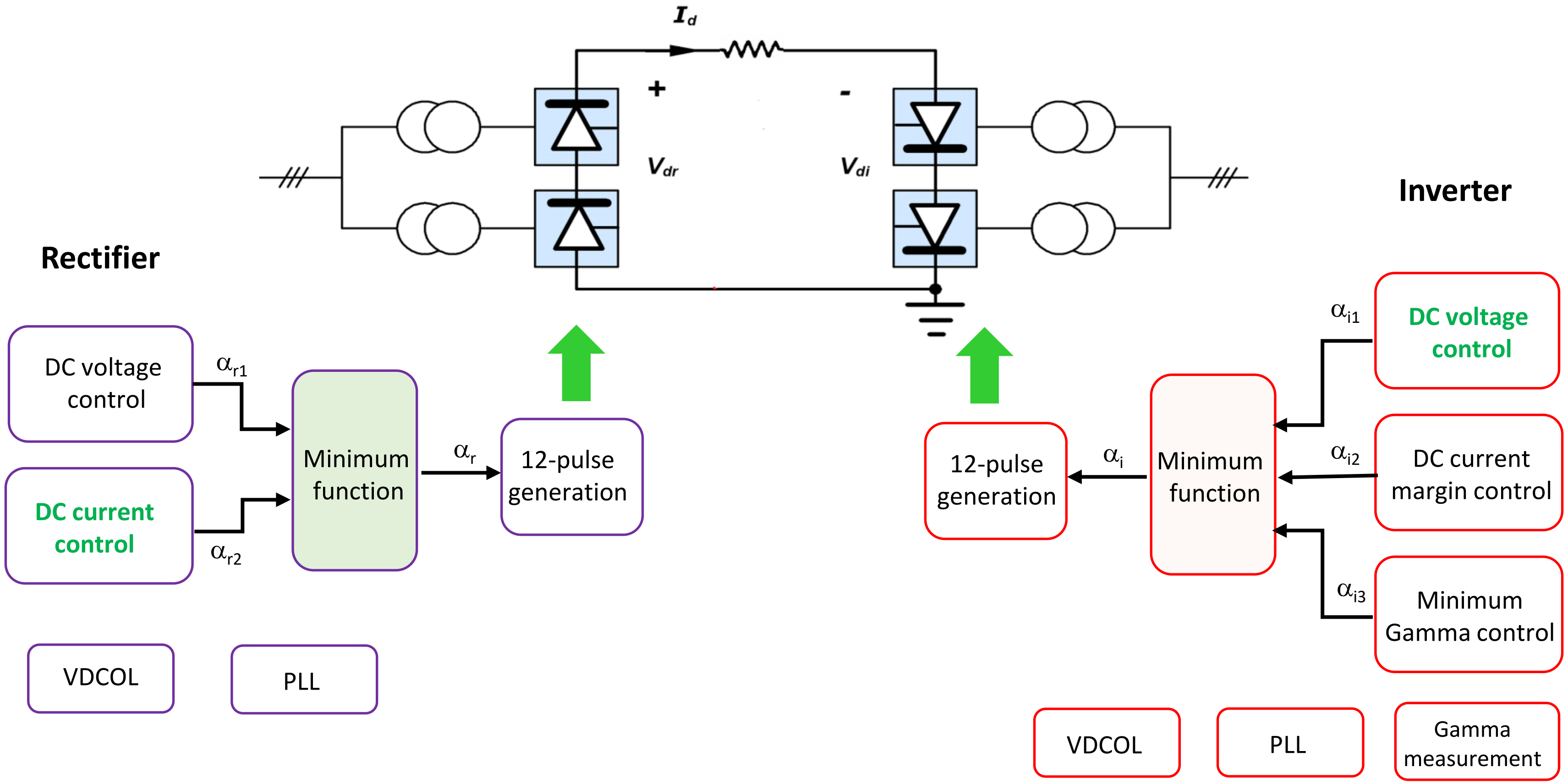
1. Brief review of previous work on MMC modelling and system stability
2. LCC HVDC system impedance model development
3. Stability of system with LCC and MMC converters

Overview of LCC HVDC Control

- **Main LCC HVDC control requirements:**
  - DC voltage, DC current
  - Minimum rectifier delay angle, minimum inverter extinction (Gamma) angle
- **Inverter usually controls the DC voltage and rectifier controls the DC current.**



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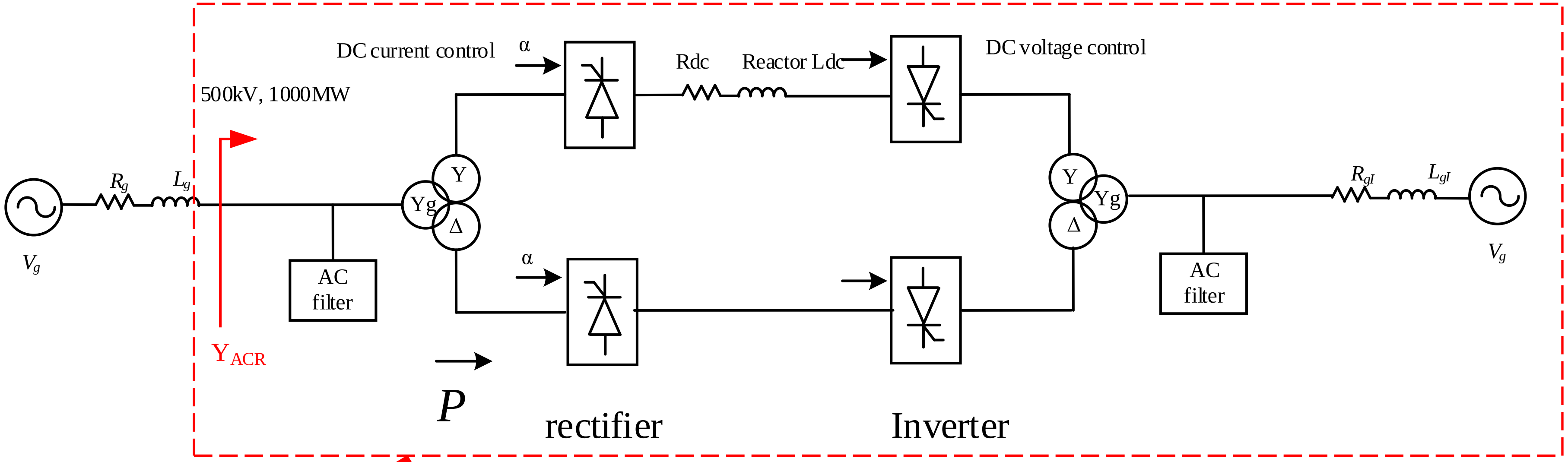
LCC HVDC System Impedance Modelling

- **Objectives:** to develop small signal LCC converter model so systems with LCC / MMC / WF can be analysed together.



$$\begin{bmatrix} Vi_{gP}(s) \\ Vi_{gN}(s-j2\omega_0) \end{bmatrix} = \begin{bmatrix} Y_{PP}(s) & Y_{PN}(s) \\ Y_{NP}(s-j2\omega_0) & Y_{NN}(s-j2\omega_0) \end{bmatrix} \begin{bmatrix} Vv_{pP}(s) \\ Vv_{pN}(s-j2\omega_0) \end{bmatrix}$$

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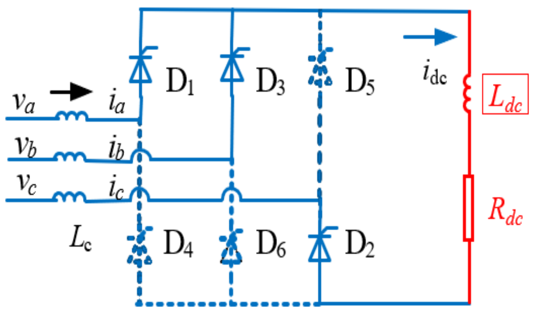
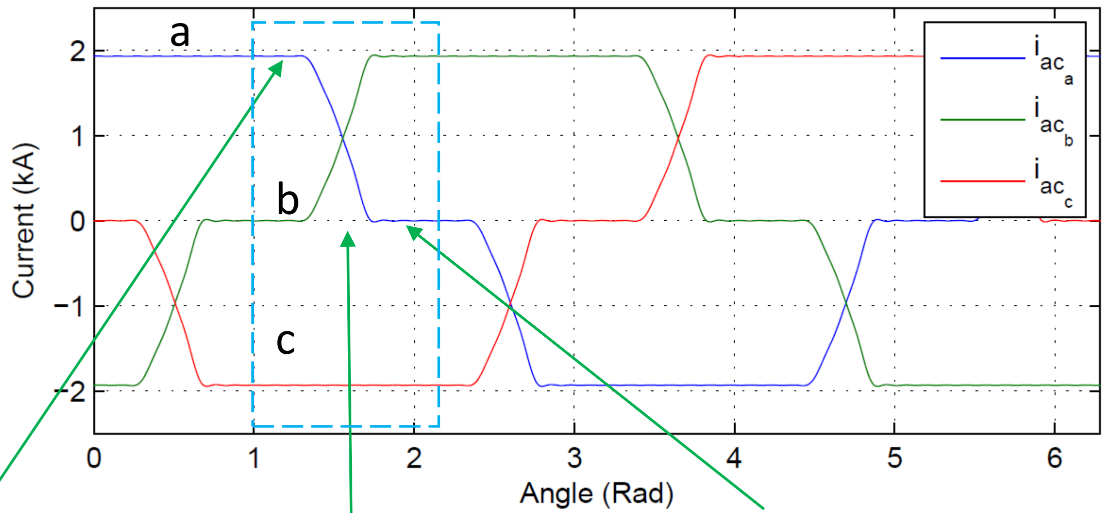
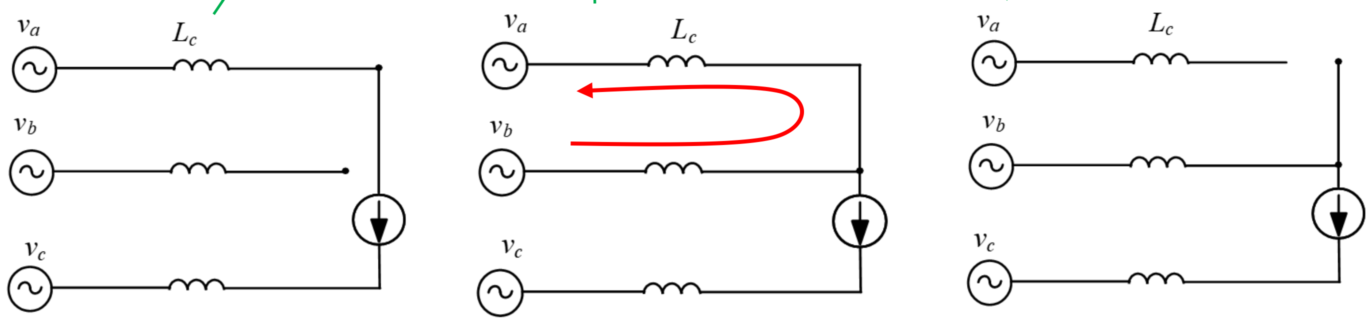
LCC HVDC System Impedance Modelling

Current waveform







The direct conduction period

The commutation period

The non-conduction period

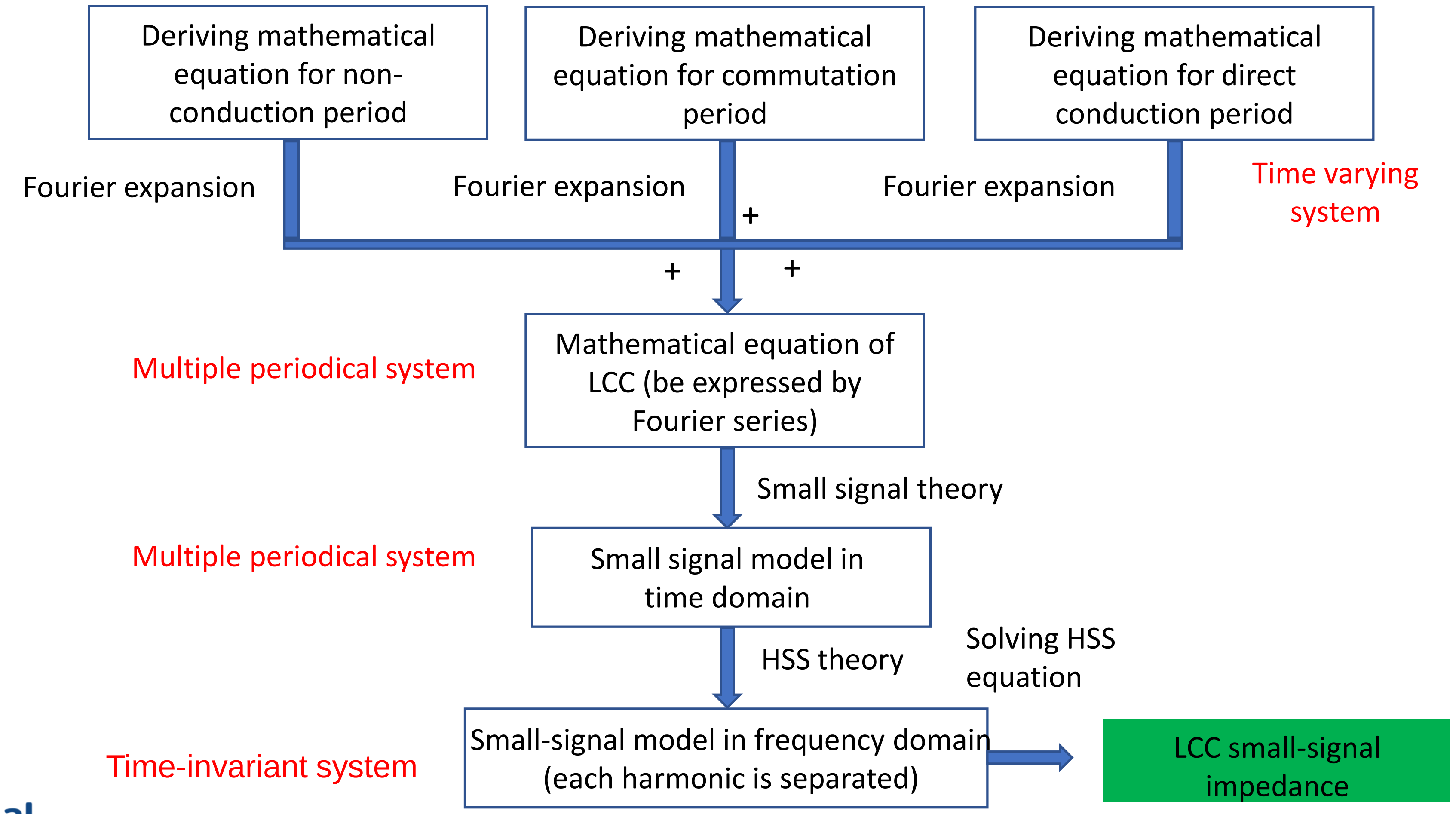
- The system is a nonlinear time-varying system, and the waveforms are piecewise functions of time.

LCC Converter Modelling Challenges

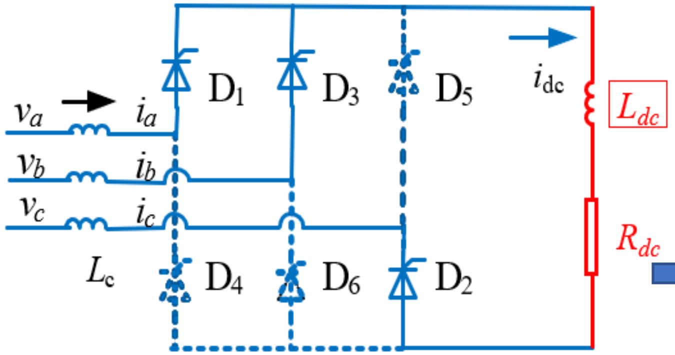
- The voltage and current are time-varying and are piecewise functions, which make the transformation from nonlinear time-varying system to linear time-invariant system extremely challenging.
- Due to the significant 11th and 13th harmonic current inside the LCC converter, there potentially exist harmonic interactions at relatively high frequency.
- LCC converters have many different operation modes, e.g., constant voltage control, constant current control, minimum gamma control etc, and which may be frequently switched with the change of network and operation conditions.
- The impedance characteristics associated with each operation mode may vary significantly, so it is important to capture the most “critical” mode when analysing system stability in order to avoid the need for excessive studies.

LCC HVDC System Impedance Modelling

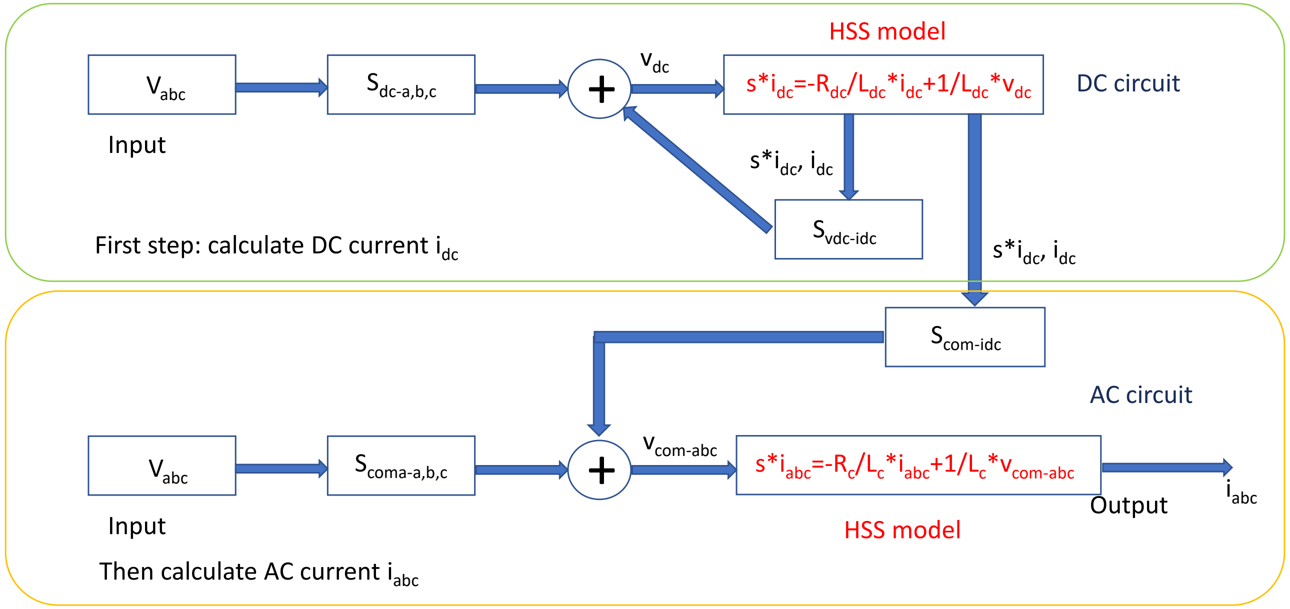
Flow chat of the modelling approach



Steady-state Model



Mathematical model



The input is the three-phase AC voltage v_{abc} and the output is the three-phase current i_{abc}.

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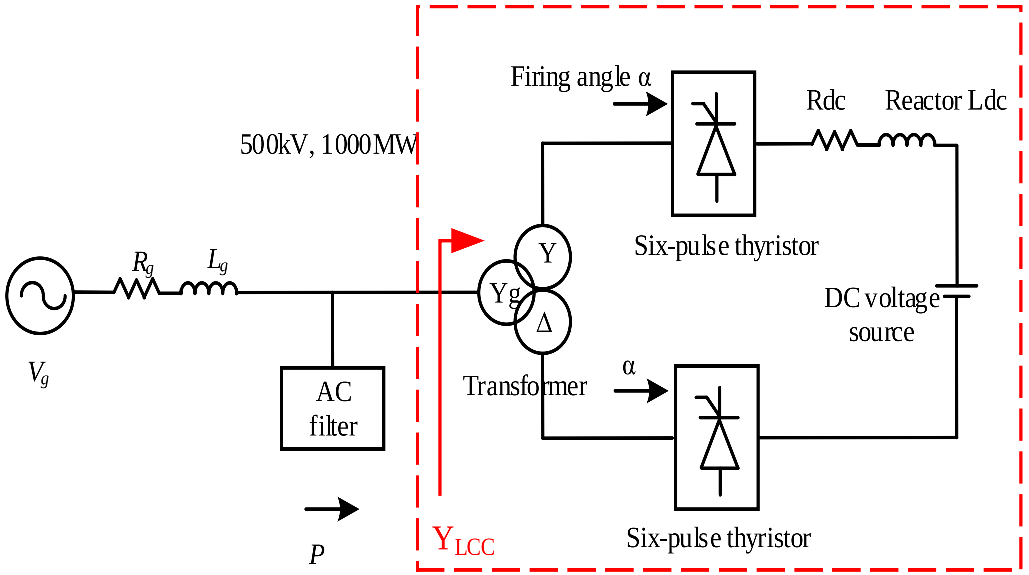
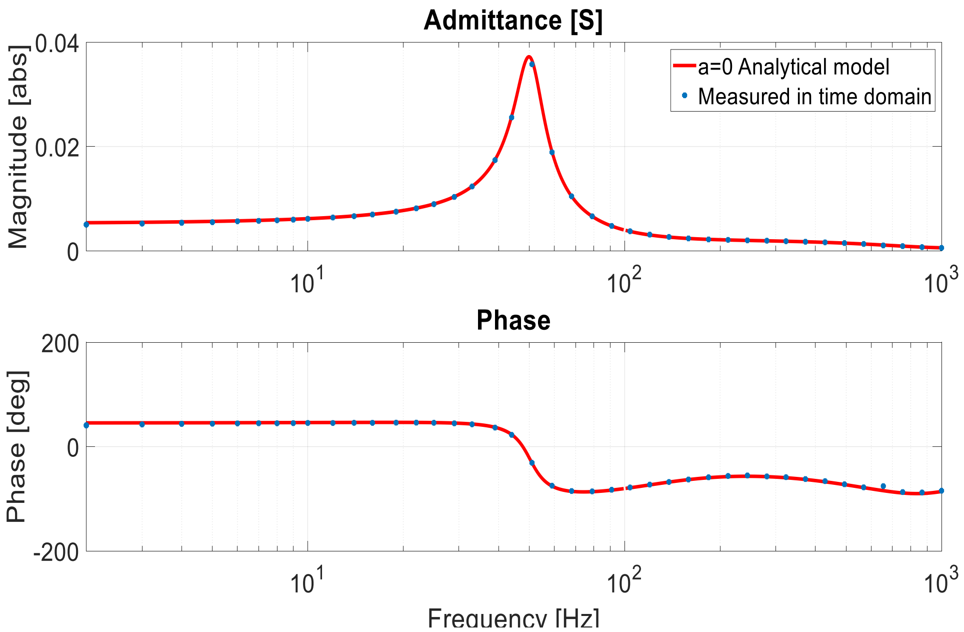
Admittance of a 12-pulse LCC Rectifier (Open-loop)



Twelve-pulse thyristor rectifier



The admittances from the analytical model and time-domain simulation model at α=0

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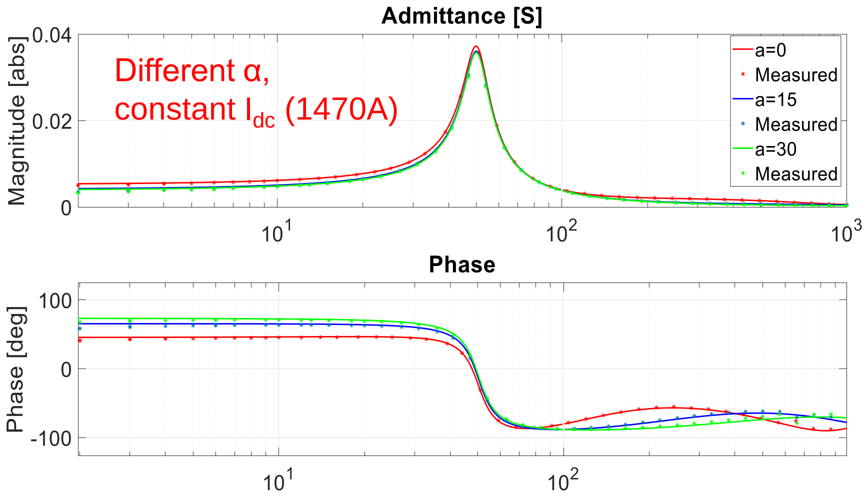
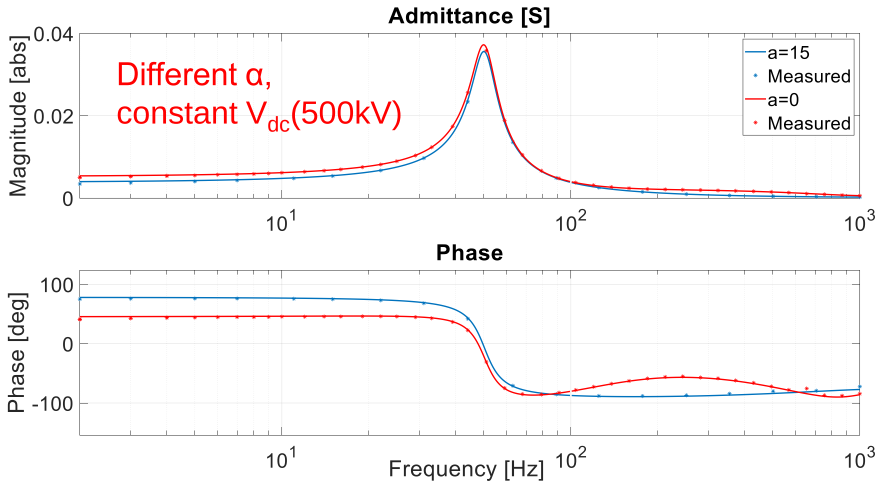
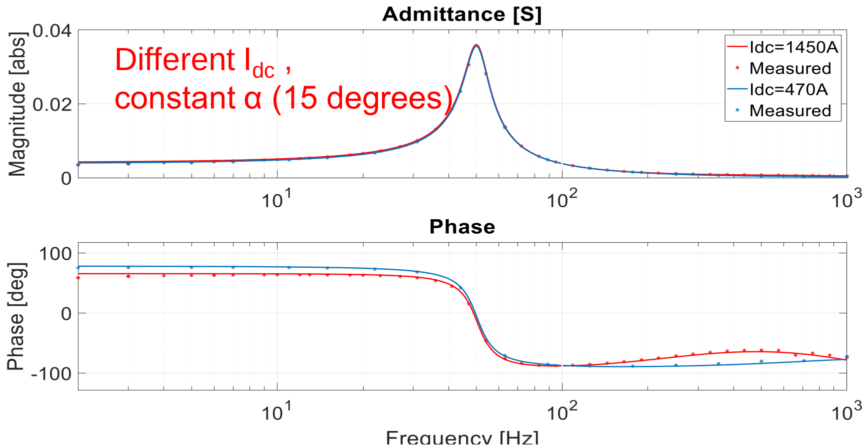
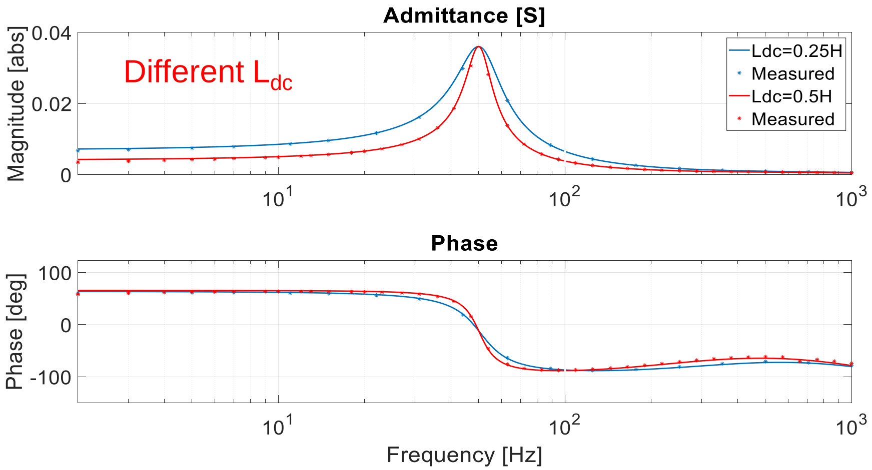
Open-loop Admittance with Different Operating Points









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- The operating point such as power and firing angle, affects the impedance, but the impact is not significant.

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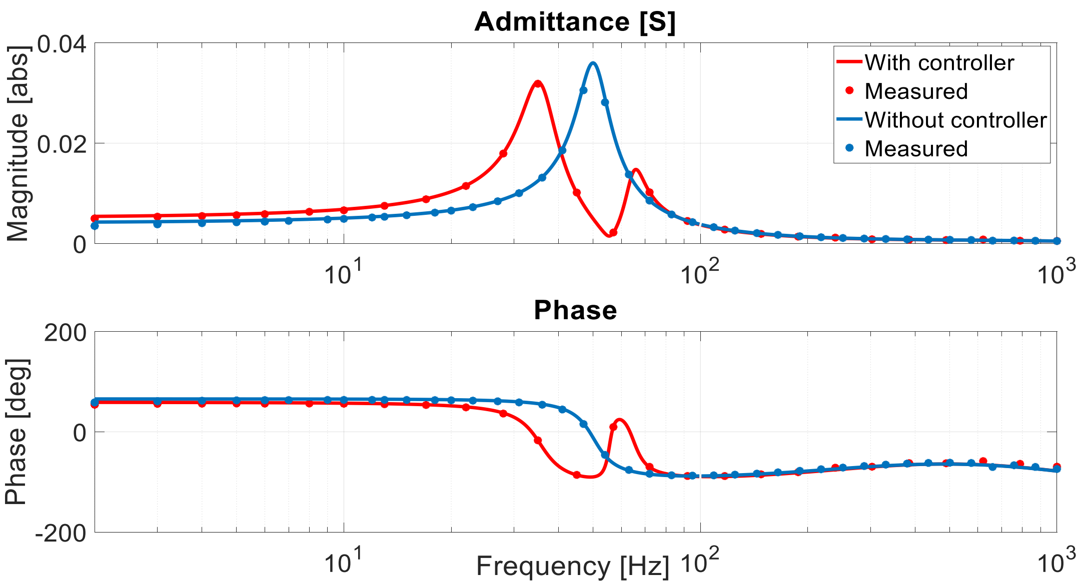
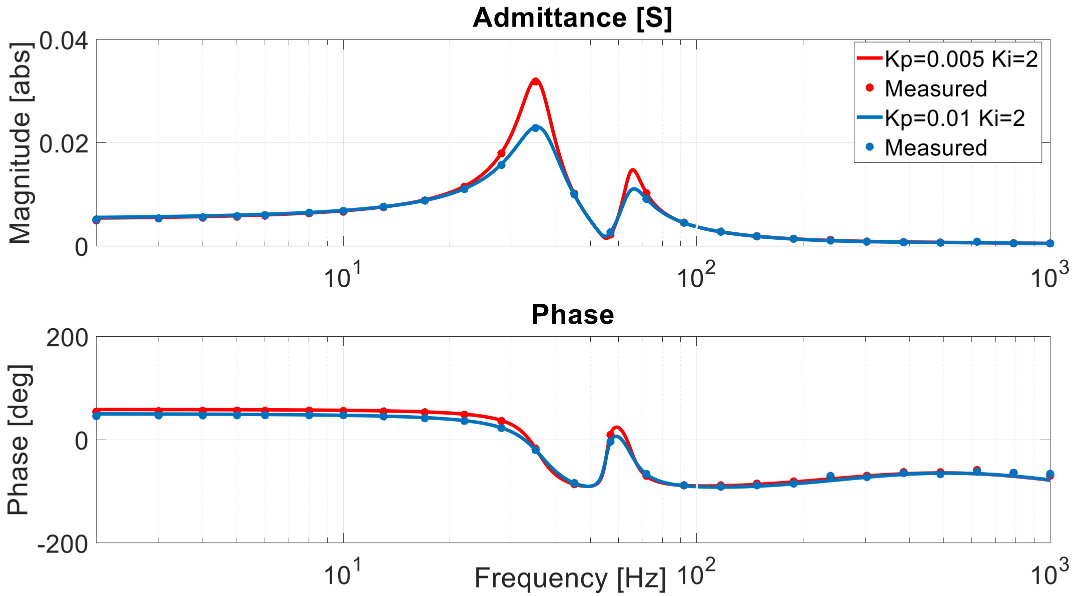
Admittance with DC current controller



With DC controller and open loop



Different K_p

- The frequency of the impedance peaks with the DC current controller is shifted from 50Hz to around 35Hz and 70 Hz. At high frequencies, the admittances are largely identical.
- With different Kp values, the main difference in the admittances are around the peak in the range of 20Hz to 70Hz, while larger K_p leads to smaller admittance.

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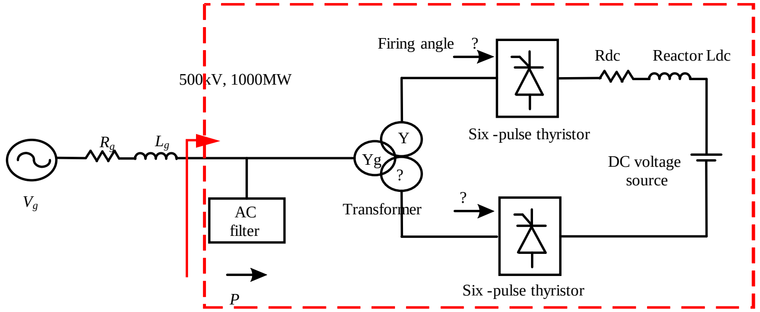
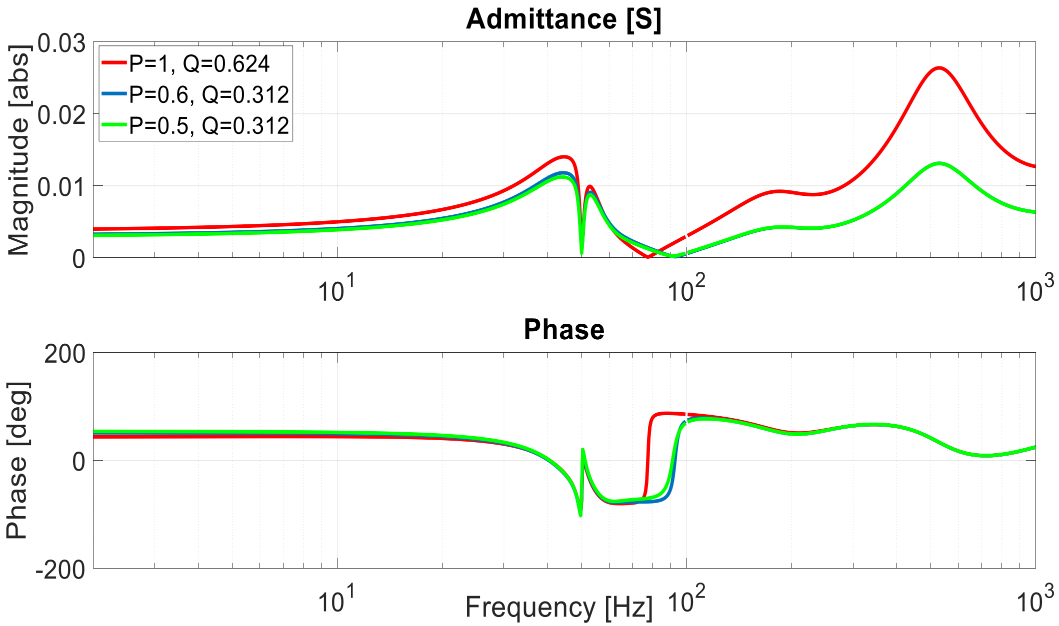
Admittance with Different Power and AC Filters





- With 1GW active power, a total of 624 MVar of AC filters are connected; while for 0.5 GW and 0.6 GW active power, the connect AC filters are 312 MVar.
- The admittance above 100 Hz is dominated by the AC filters, with the active power flow in the system has small influence on the admittance at the low frequency range.

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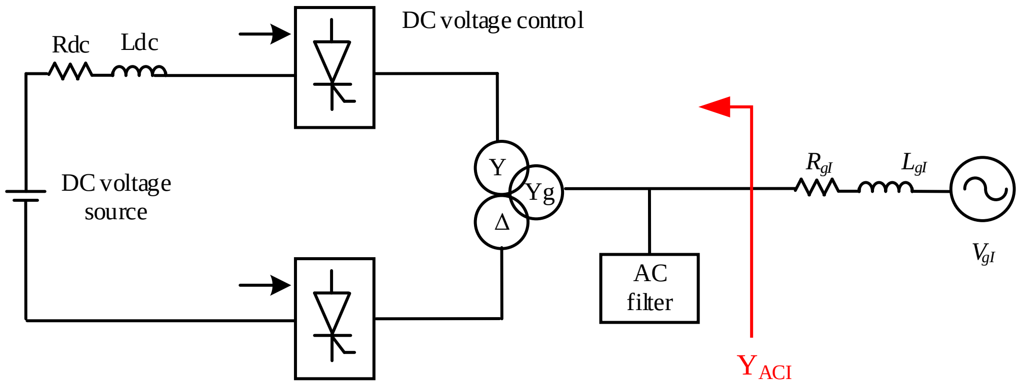
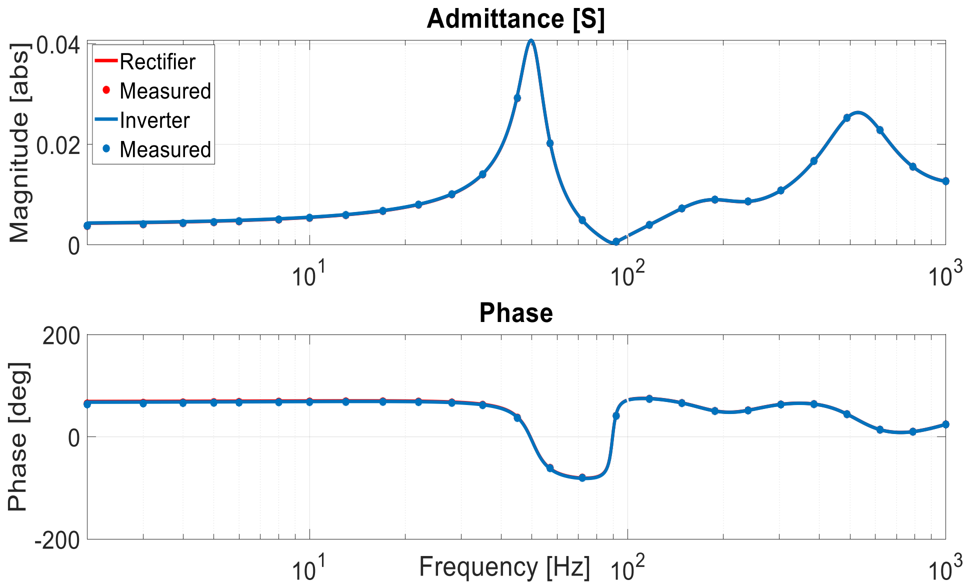
LCC Admittance in Inverter Mode

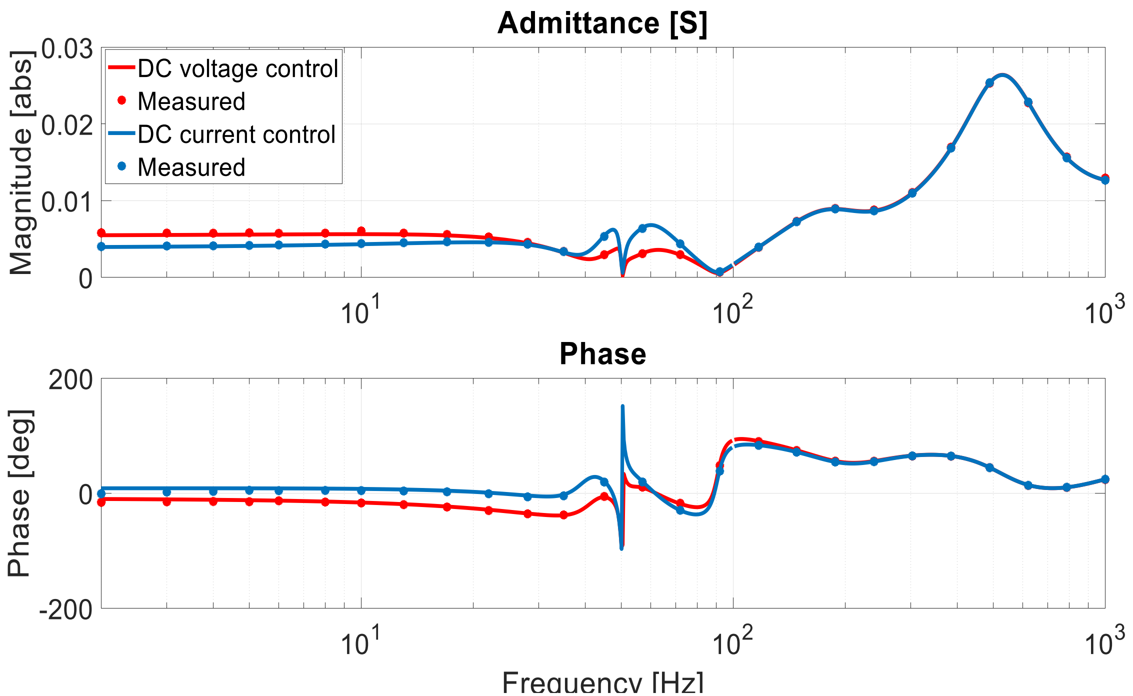


Twelve-pulse thyristor inverter



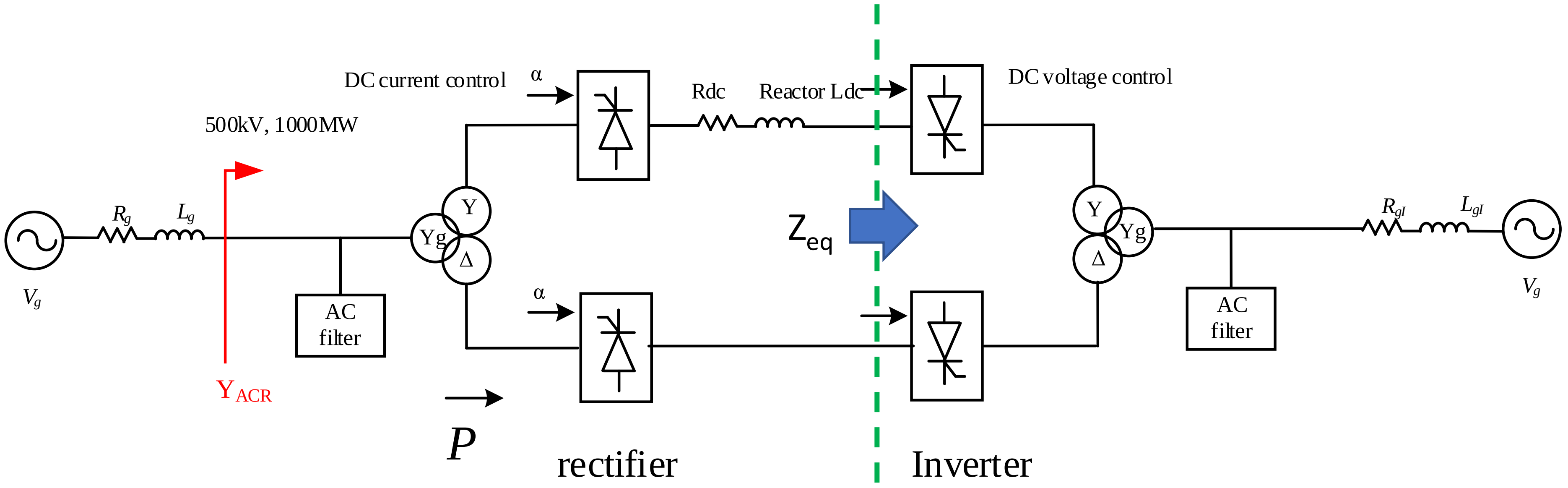
- The two systems have the same DC and AC circuits while the firing angles are adjusted so they produce the same active power of 1 GW.
- The open-loop admittances overlap indicating that LCC admittances are largely unaffected by operating as either an inverter or a rectifier.

Inverter Admittance with Different Control Modes



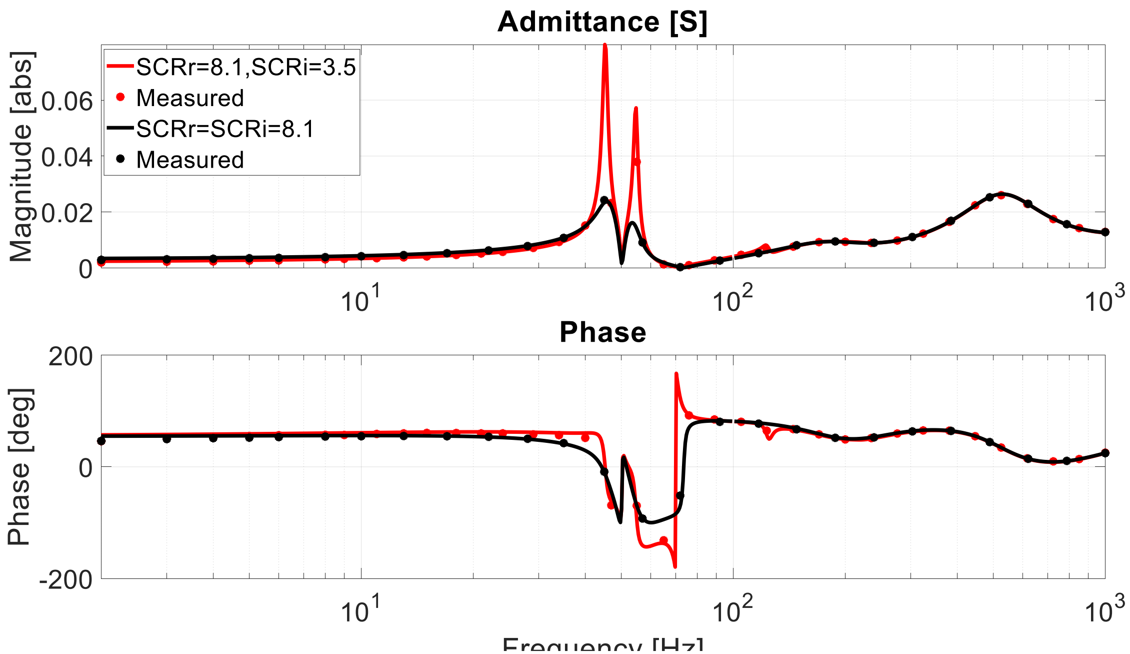
- The inverter admittances show some differences at low frequencies, but remain largely the same at high frequencies due to the AC filters.

Admittance of LCC HVDC System (Rectifier)



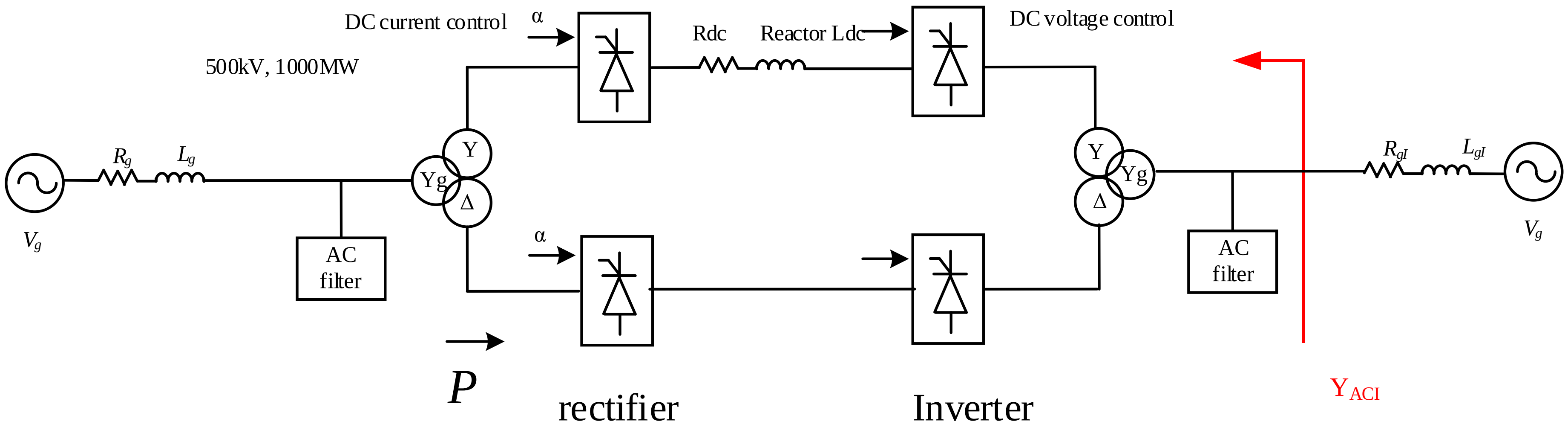
- LCC impedance at one terminal is determined by both the AC and DC dynamics.
- The DC equivalent impedance Z_{eq} of the inverter is seen by the rectifier and thus will affect the AC admittance at rectifier terminal.
- The inverter network and controller adopted impact on the DC equivalent impedance Z_{eq}.
- The rectifier AC impedance is affected by the inverter.

Rectifier Admittance with Different Inverter Grid Strength

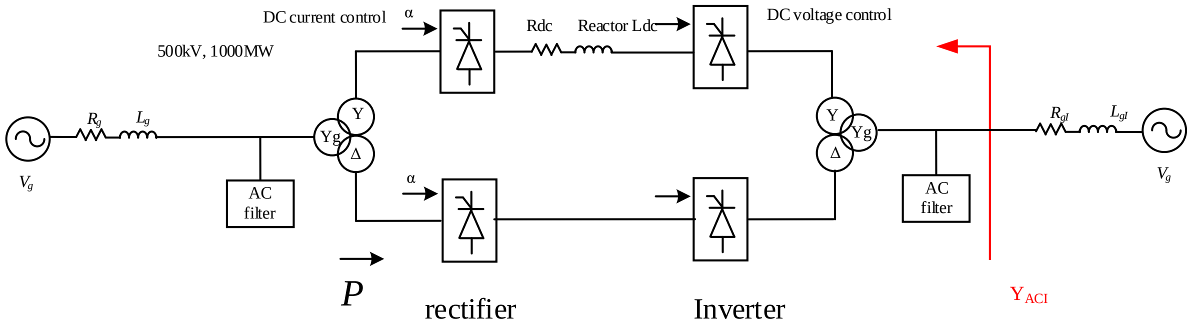


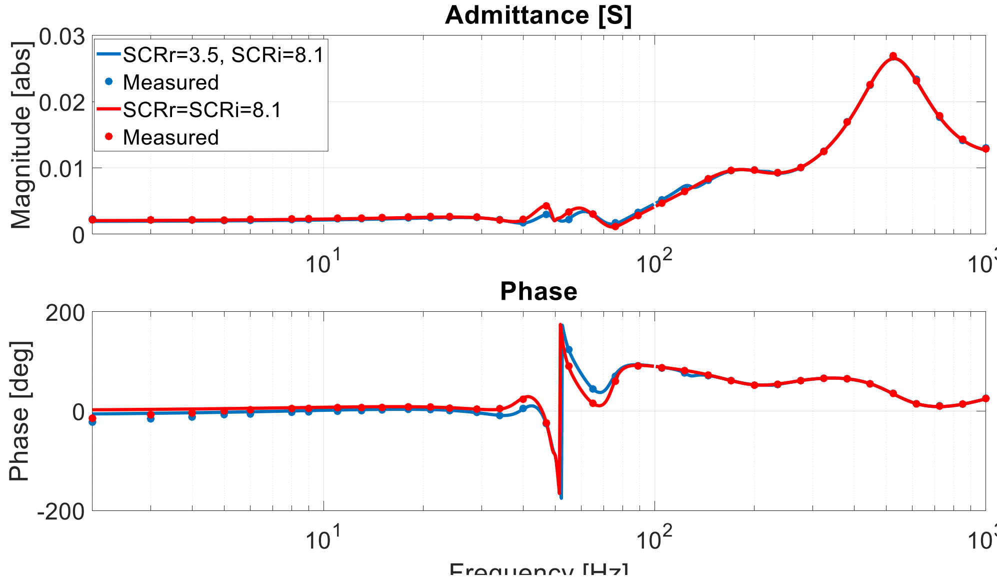
- Changing the network strength at the inverter side (SCRi=8.1 and 3.5), the AC impedance at the rectifier terminal is affected around the resonant peaks.

Admittance of LCC HVDC transmission system (inverter)



Inverter Admittance with Different Rectifier Grid Strength





- The AC admittance at inverter side sees smaller influence by the network strength at rectifier side (than the previous results of the rectifier impedance).

LCC Impedance Summary (3)

- The admittance of an LCC system can be represented in a similar way to VSCs. Thus, networks with different converter technologies can be assessed by considering the impedance of each converter and AC network.
- The operating point such as power and firing angle, affects the impedance, though less significant than those observed in other VSCs/MMCs.
- The control mode (e.g., DC current control, DC voltage control) impact on the converter admittance, while the controller parameters only have small impact on the converter admittance.
- The overall impedance of an LCC HVDC converter terminal at frequencies above 100 Hz is largely determined by the connected AC filters.
- For an LCC HVDC system, the AC impedance at one terminal is affected the AC network condition (network strength and AC filters) of the other terminal.
- Due to change of network condition during operation (e.g., post-fault), it is important that the most critical point of operation is considered.

1. Brief review of previous work on MMC modelling and system stability
2. LCC HVDC system impedance model development
3. Stability of system with LCC and MMC converters

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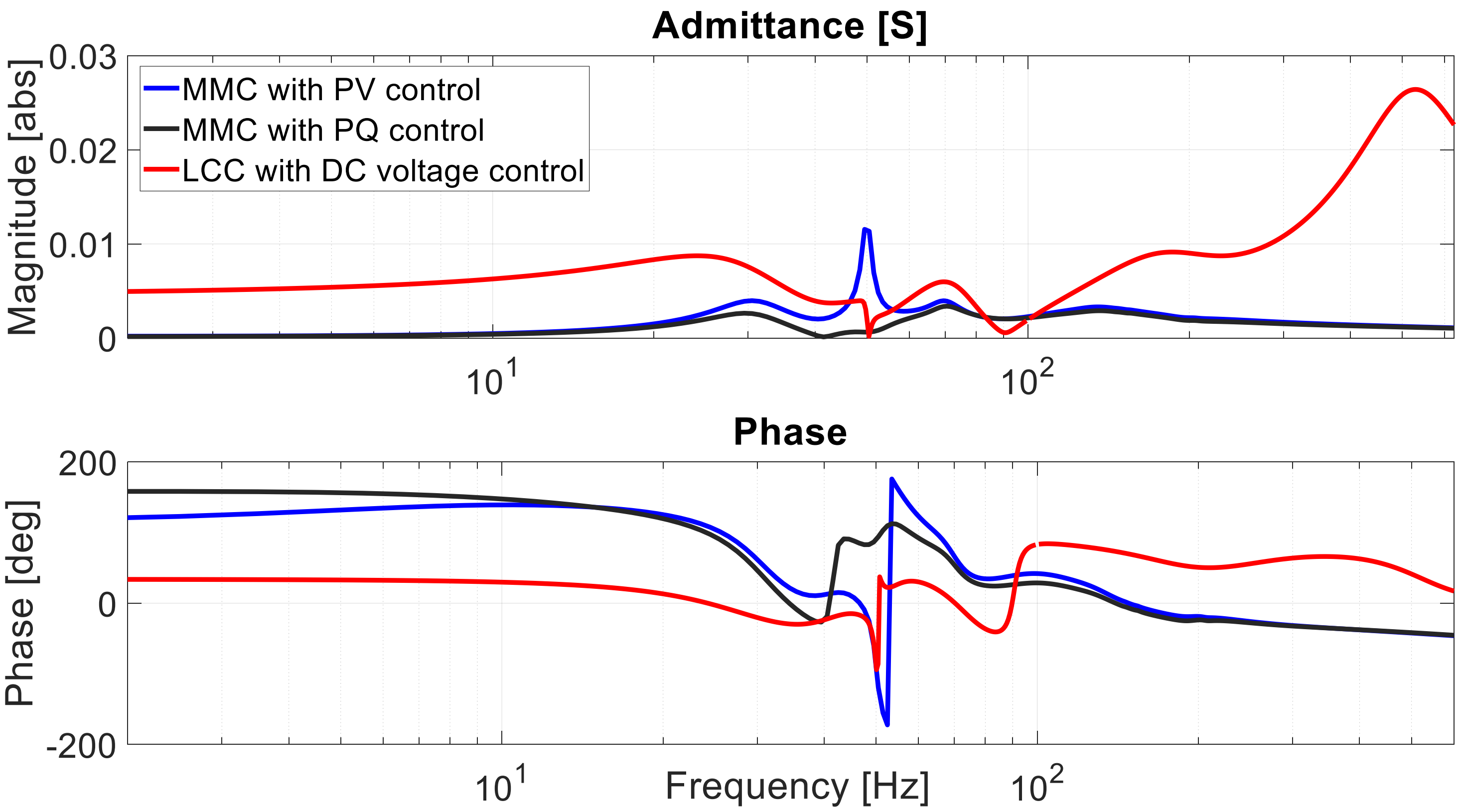
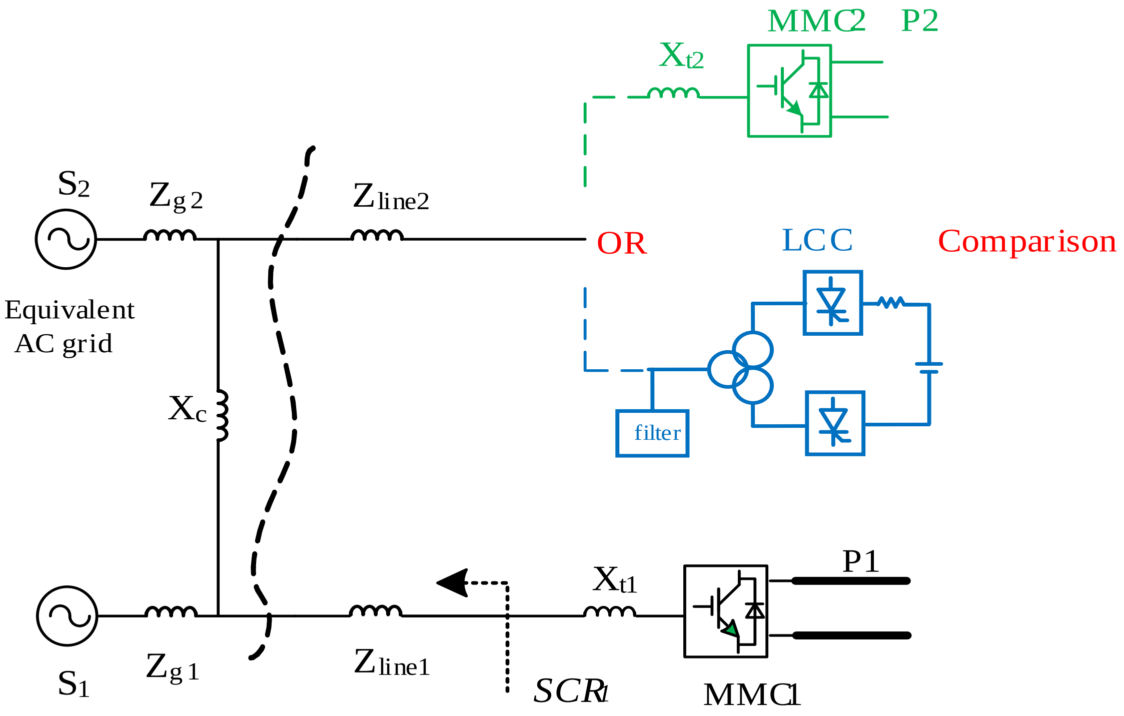
MMC and LCC Admittance Comparison



Stability of Network with Multiple (2) Converters



- All converters operate in inverter mode (feeding active power to the AC network)
- SCR_1=2.74 (weak grid), $MIIF_{1,2}$=0.78 (strong coupling), $P_1=P_2$=1GW (1p.u.)
- MMC1 and MMC2 adopt PQ control, LCC adopts DC voltage control.

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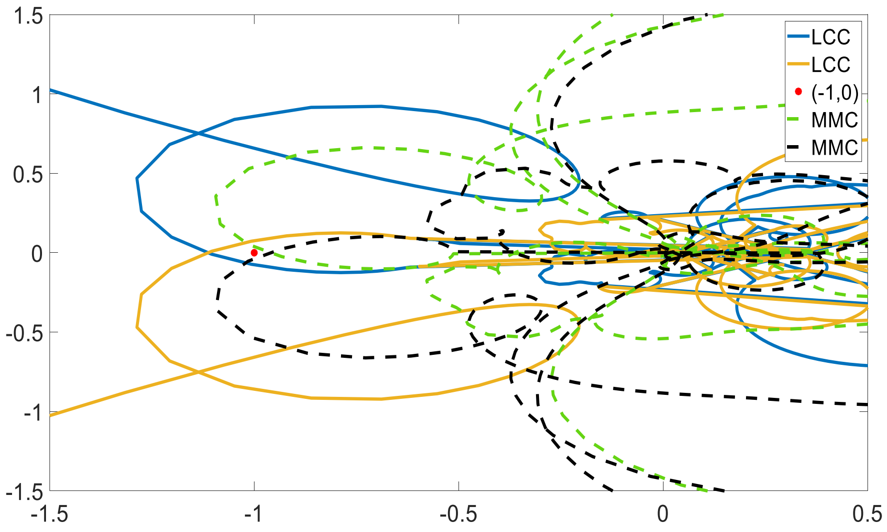
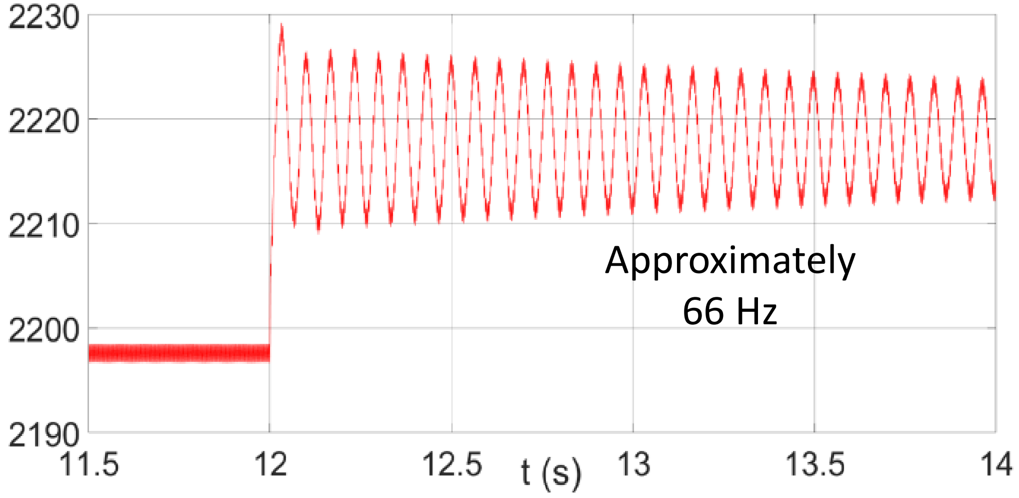
Stability of Network with Multiple (2) Converters

Nyquist curve with different Converters



Time-domain simulation with two MMCs



- When one LCC and one MMC are connected, the Nyquist curve encircles (-1,0) indicating unstable system; while for 2 MMCs the Nyquist curves do not encircle (-1,0) but are very close to the point indicating (weak) stable system.
- In time-domain simulation, the system with LCC is unstable (not shown), and is stable (weak) with 2 MMCs.

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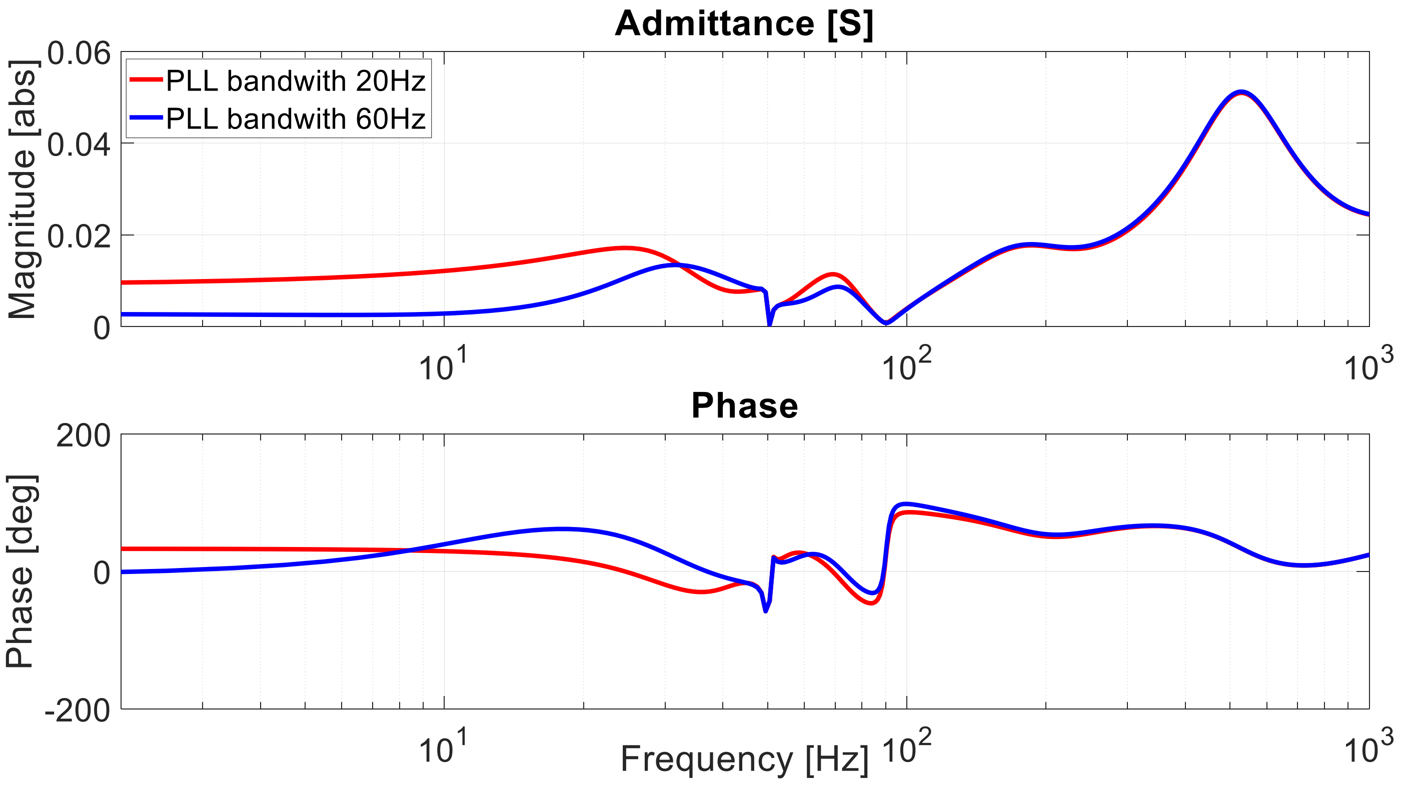
LCC with Different PLL Bandwidths



- PLL bandwidth impacts on the admittance, which could affects the system stability.

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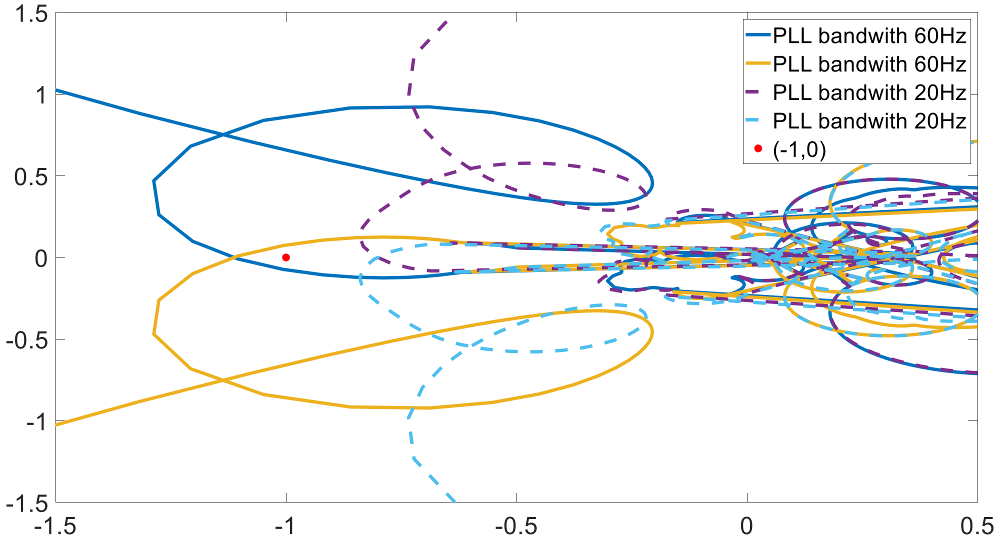
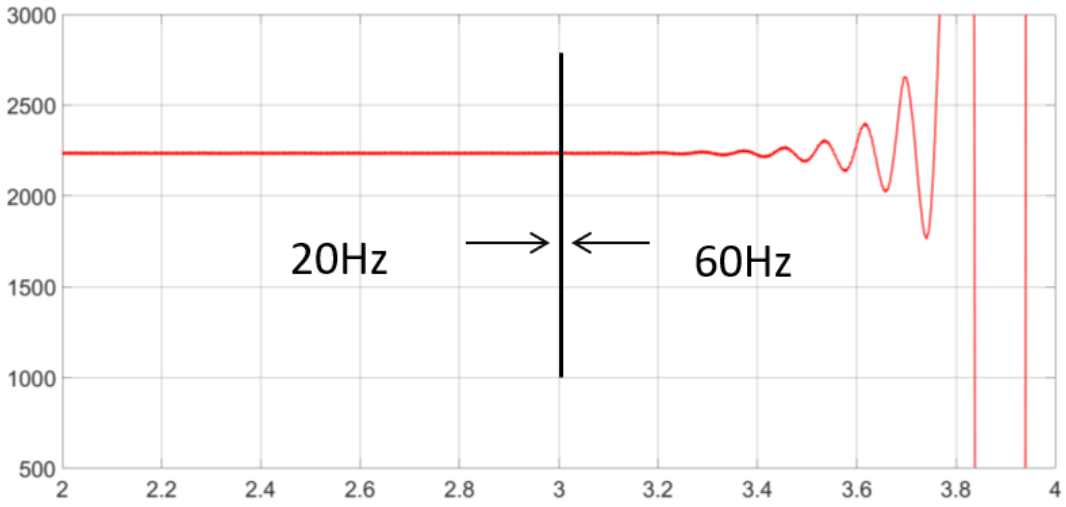
Stability with Different PLL Bandwidths





- In previous study, the PLL bandwidth in the LCC was 60Hz.
- From the Nyquist curve, if reduce the bandwidth to 20Hz, the system becomes stable.
- Time domain simulation validates the assessment.
- In practical systems, to ensure satisfactory transient response, adequate PLL (or equivalent) bandwidth would be required.

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Main Observation on System Stability: Key Findings

- Similar to MMC, LCC system can affect network stability which is influenced by network condition, control parameter, and operation mode.
- When comparing LCC with MMC in terms of stability, studies indicate that it is difficult to draw any general conclusion.
- Again, network connection conditions and converter couplings need to be carefully examined to ensure system stability.
- Multiple converters and systems, including wind farms need to be fully considered when assessing system stability.

Q & As

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The small signal process Journey

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Earlier work

We're here on the journey!

Small signal description of "typical" converters

- MMC, DFIG, LCC etc. across range of technologies
- PLL types, typical control strategies in response to system strength

How do I understand the potential for instability?

Project Specific small signal definition of key connections

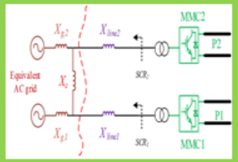
- Across operating points.
- Encompassing all relevant factors to small signal response

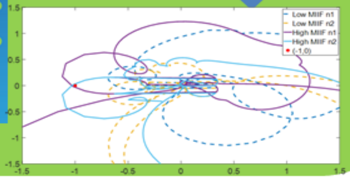
How do I identify the potential drivers of instability?

Focussed EMT Simulation

Focused RTDS-HiL tests & validation

Informed control mitigation





Identify regional modes of interaction risk

- Frequency ranges
- Define margins

Where are these instabilities- how do they occur?

What do I want to do about it?

Link risk to regional system strength Measures

- Define regionality by interactions
- Benchmark against MIIF, WSCR, ESCR etc.

Inform Operation, Development and Planning

Inform acceptable network topologies/ outage states

Inform frequencies of acceptable future convertor small signal sensitivity in a region

Inform the benefit and nature of further study to mitigate risk conditions/ designs

Inform the benefit and nature of further study to mitigate risk conditions/ designs

Scope of ETP project

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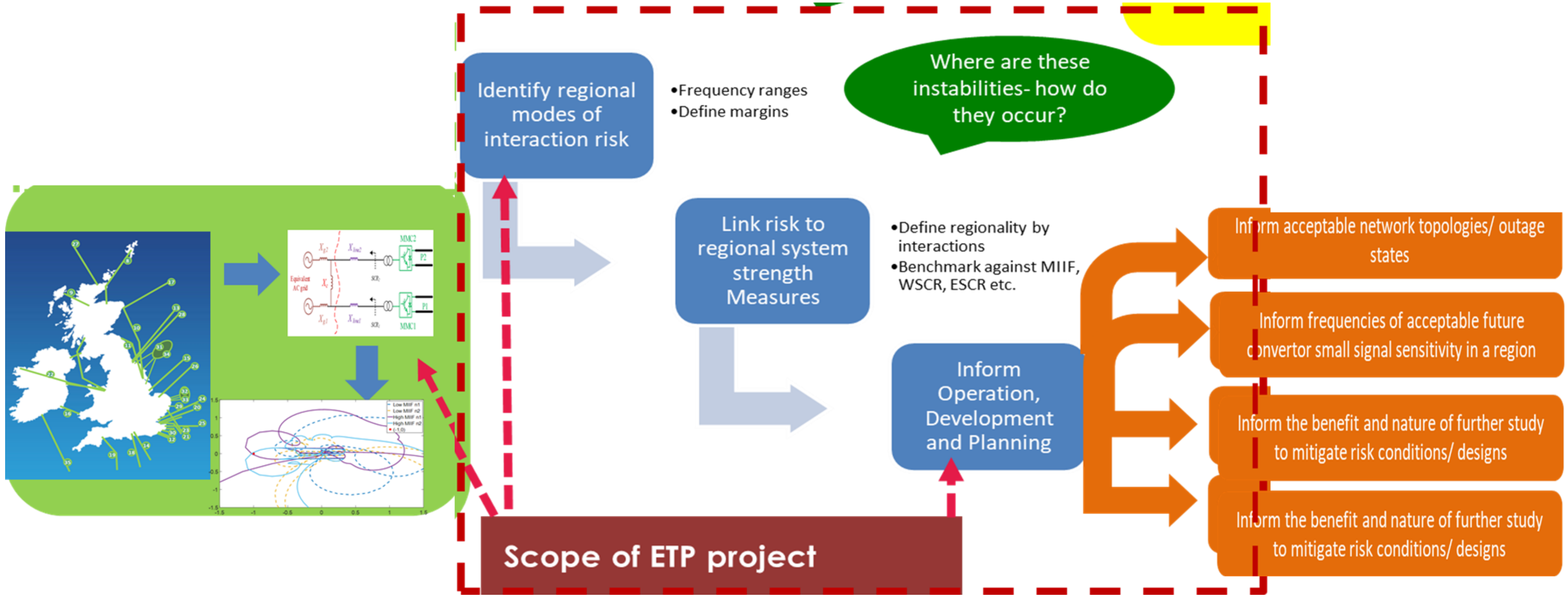
Future work - what is the Proposed ETP project?

- Energy Technology Partnership proposal
- Focussed on scaling existing work & tools to the complexities of the GB network, and its range of operation
- Submitted for doctoral funding in collaboration with the Centre - delivering over 3.5 years
- Centre & Academically hosted – will report at key milestones in project (**subject to approval**).



What we have delivered to date, and what this gives us

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Results (we have…)	Benefit (we can achieve…)
Demonstrated the characteristics of accurate small signal models, across all relevant technologies.	A consistent method to derive Z plots, and to scan for interactions.
Highlighted what operating states the models depend upon	Clear identification of required network state and relevance of different control modes of operation.
Demonstrated the relevance of the Harmonic MIIF method to the small signal analysis approach	An improved method for screening interactions between devices regardless of different devices
The tools we need now	Using the tools to address real network challenges

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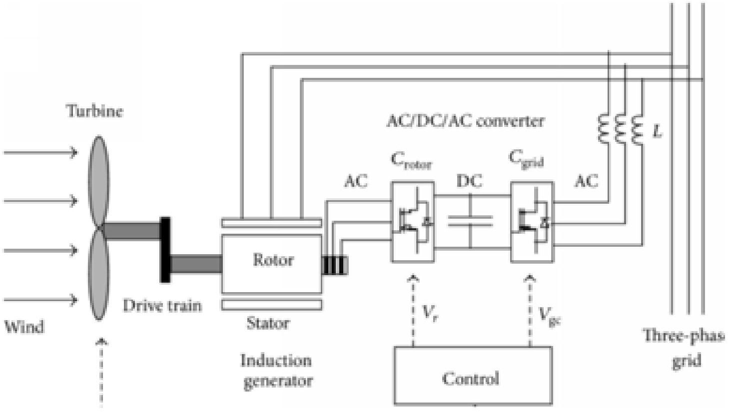
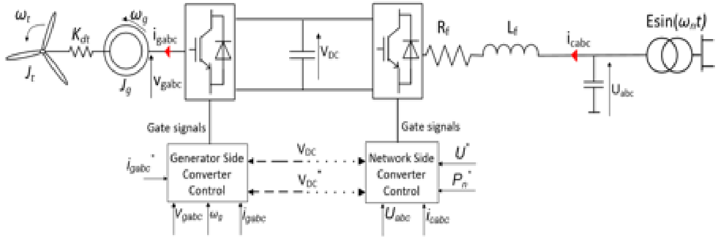
More to come in published Reports (Type 3 &4 WTG)

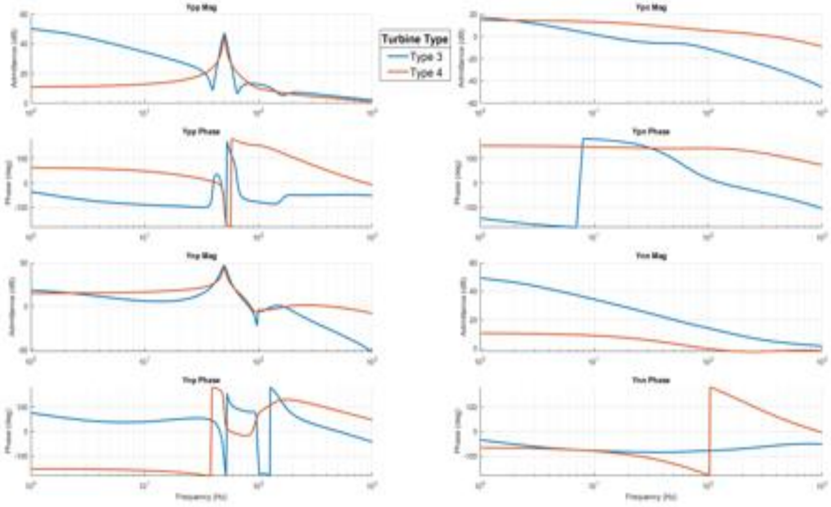
Type 3 Turbine



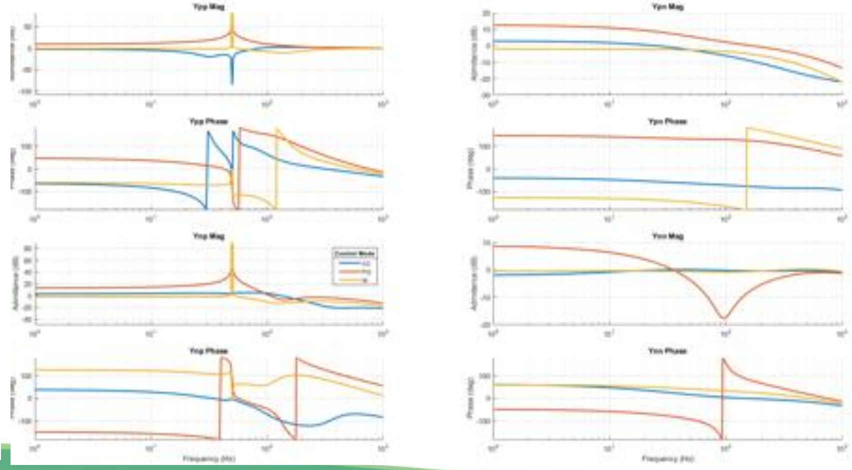
Type 4 Turbine



PQ Control Mode

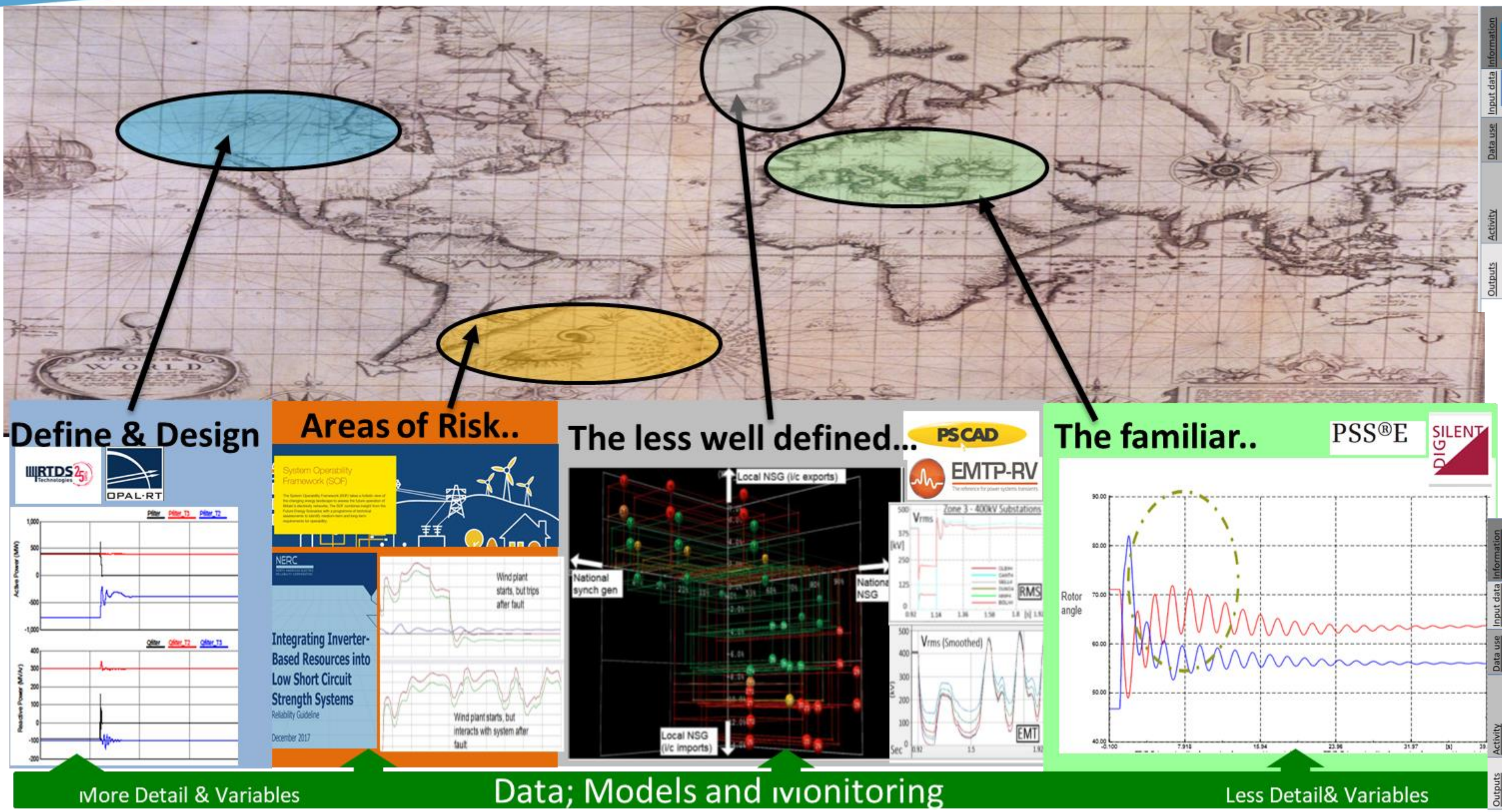


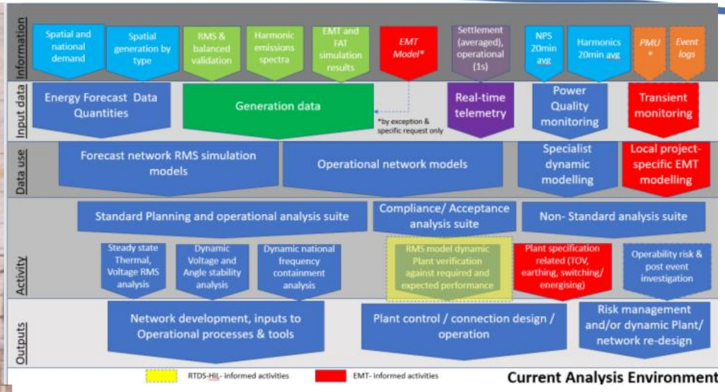
Type 4 Control Modes



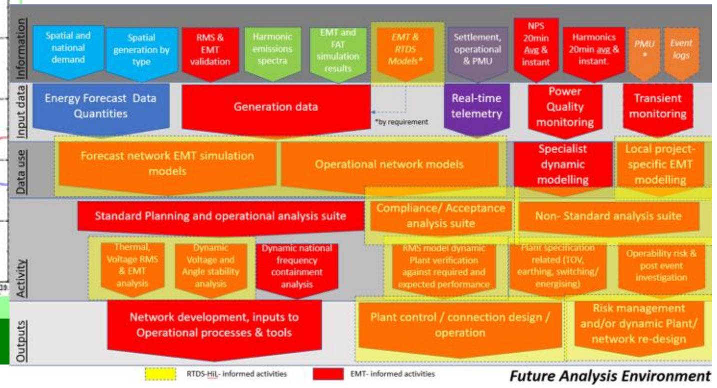
- PQ mode operation shows greatest variation across frequency domain
- Operating point sensitive (results left shows c.70% power, full lead operation)
- Type 4 > than Type 3 in variation
- Type 4 has greater range of control mode variation
- Type 4 have higher impedance variation
- Early results- supports same approach identifying interaction then supported in EMT simulation

Why this Journey is needed..





Direction of Change..



The Transition to Net Zero= a Control Dominated GB grid= need to screen and focus on key Interaction risks

This is an Internationally relevant analysis area:

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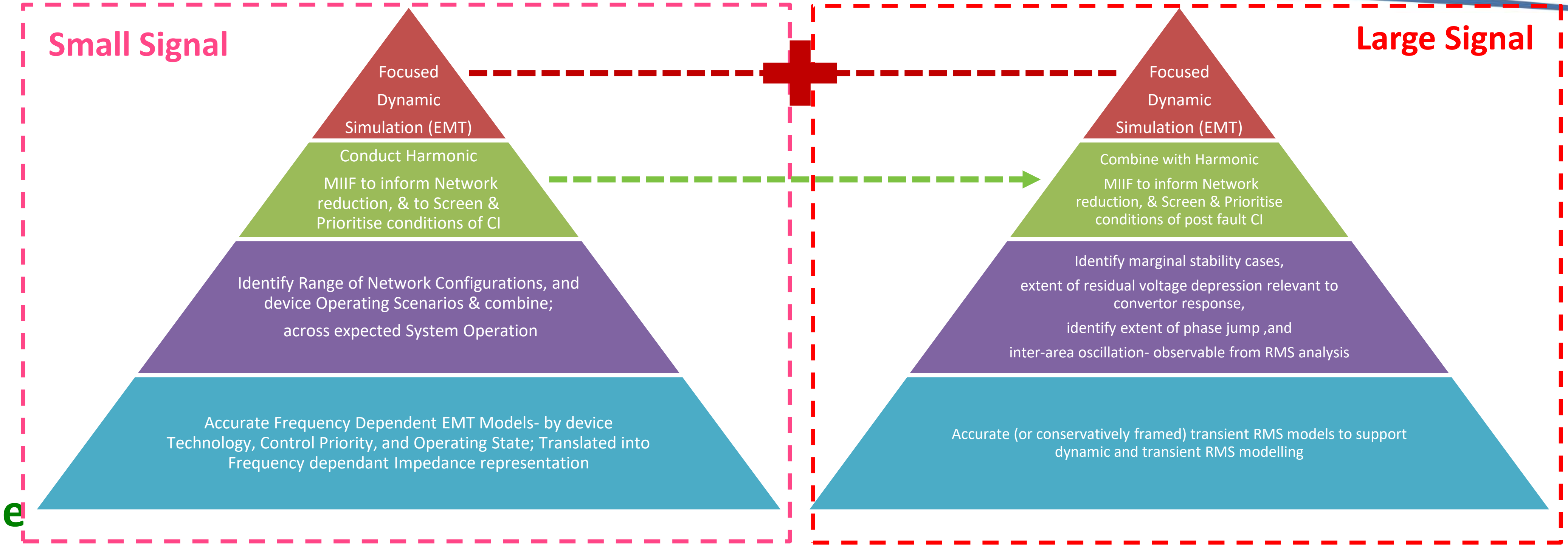
- Cigre B4.81
- NERC
- NREL
- ESIG
- AEMO
- Elia
- ENTSO-e
- GB Grid Code



Small signal techniques are well established, but applying these *at scale across diverse operating states of network and convertor: efficiently and accurately* is not.

We need standardised processes and approaches for doing this, and for combining with other CI analysis- Small Signal alone does not cover all Control Interaction risk (but is a good start!).

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Panel Discussion / Q&A's

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- ❑ **Panellists:**
  - Colin Foote, Scottish Power Energy Networks
  - David Gregory, National Grid ESO
- ❑ **Speakers:**
  - Prof. Lie Xu – University of Strathclyde
  - Oluwole Daniel Adeuyi – The National HVDC Centre
  - Benjamin Marshall – The National HVDC Centre
- ❑ **Moderator:**
  - Habibur Rahman – The National HVDC Centre

Q & As

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Thanks for listening.

Any questions, please?

- For further information, please visit www.hvdccentre.com ; OR email: info@hvdccentre.com

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