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Small Signal Modelling and Eigenvalue Analysis of Multiterminal HVDC Grids

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Eigenvalue based small signal analysis

- Power system stability is commonly assessed by eigenvalue analysis
  - Enables analysis and mitigation of oscillatory behaviour or instability due to system configuration, system parameters and controller settings

- VSC HVDC systems has different dynamics compared to traditional generators
  - Models of MMC HVDC terminals are currently under development

- State-space models for HVDC systems can be used for multiple purposes
  - Analysis, identification and mitigation of oscillations and small-signal instability mechanisms in HVDC transmission schemes
  - Analysis of controller tuning and interaction between control loops in HVDC terminals
  - Integration in larger power system models for assessment of how HVDC transmission will influence overall small signal stability and oscillation modes

ProOfGrids

Protection and Fault Handling in Offshore HVDC grids

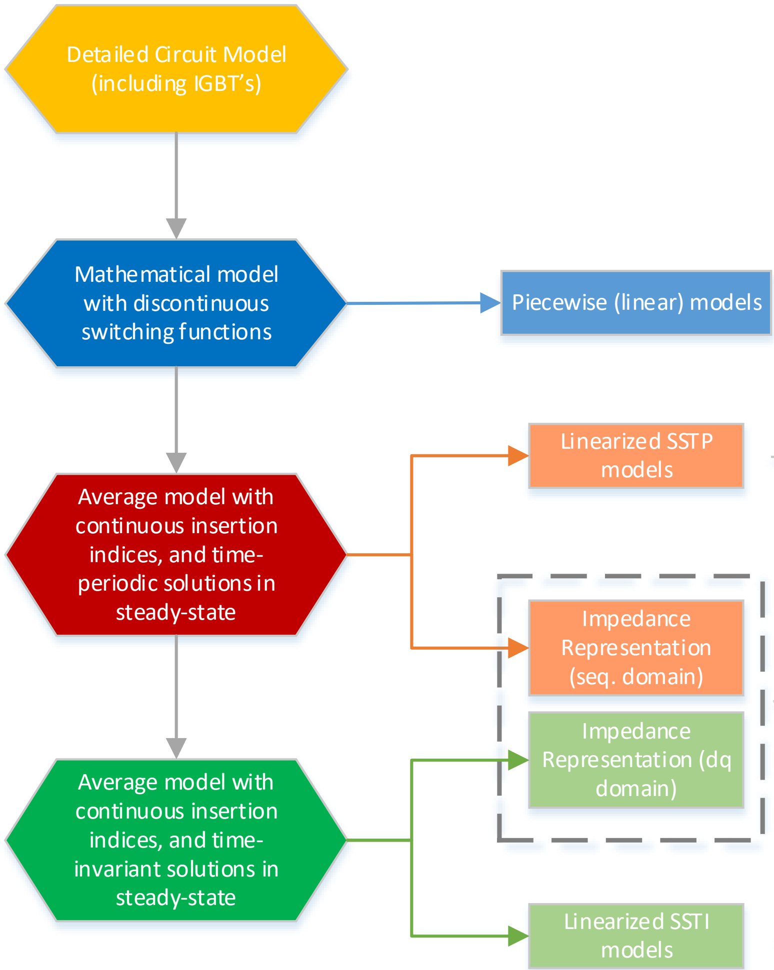
Objectives: Establish tools and guidelines to support the design of multi-terminal offshore HVDC grids in order to maximize system availability. Focus will be on limiting the effects of failures and the risks associated to unexpected interactions between components.

- Develop **models of offshore grid components** (cables, transformers, AC and DC breakers, HVDC converters) for electromagnetic transient studies.
- Define guidelines to reduce the risks of **unexpected interactions** between components during normal and fault conditions.
- Define strategies for **protection and fault handling** to improve the availability of the grid in case of failures.
- **Demonstrate** the effectiveness of these tools with numerical simulations (PSCAD, EMTP), real time simulations (RTDS, Opal-RT) and experimental setups.
- Expand the **knowledge** base on offshore grids by completion of two PhD degrees / PostDoc at NTNU and one in RWTH.

ProOfGrids Protection and Fault Handling in Offshore HVDC Grids

NTNU Norwegian University of Science and Technology · The Research Council of Norway · Statnett · nationalgrid · SIEMENS · RWTH AACHEN UNIVERSITY · Statoil · Statkraft · EDF · NVE

Overview of models and methods for stability analysis



- Computationally intensive, time-consuming EMT simulation studies for large signal stability.

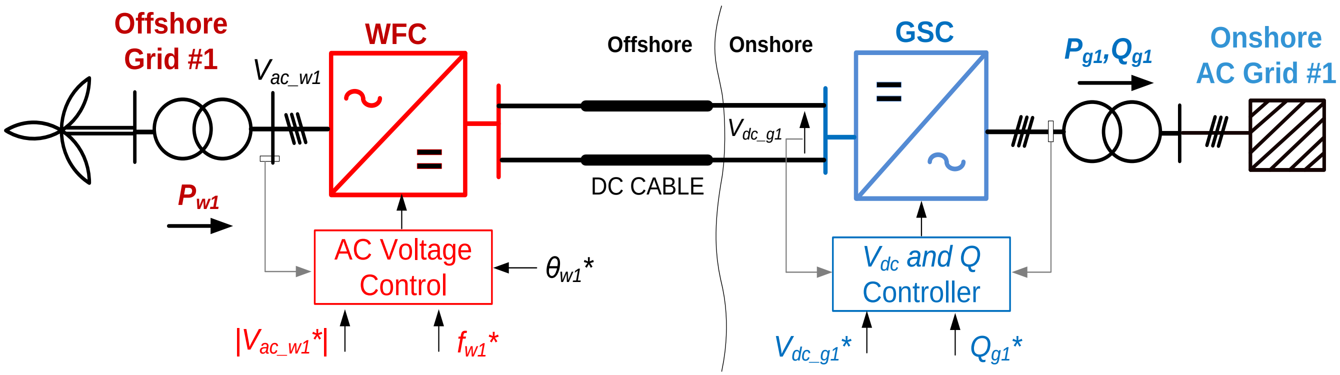
Lyapunov methods for piecewise linear models:
- Common quadratic Lyapunov function,
- Switched quadratic Lyapunov function
- Multiple Lyapunov functions

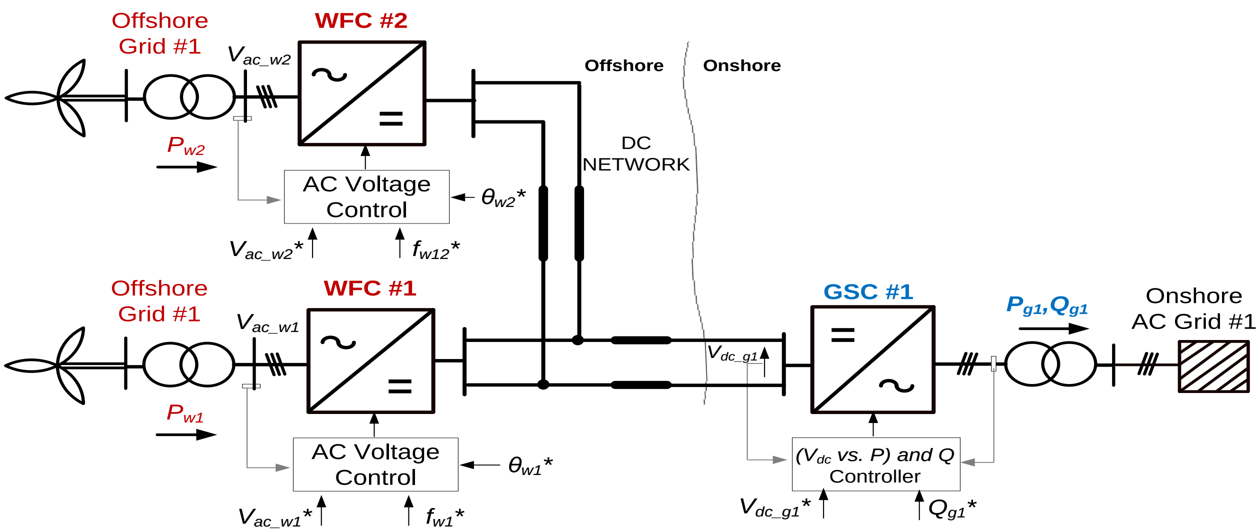
Small-signal stability assessment via time-periodic theory:
- Poincaré multipliers

- Search for a Lyapunov function to prove large-signal stability.
- Estimate of regions of attraction as a measure of the system large-signal stability robustness.

Small-signal stability assessment via by means of Nyquist criteria.

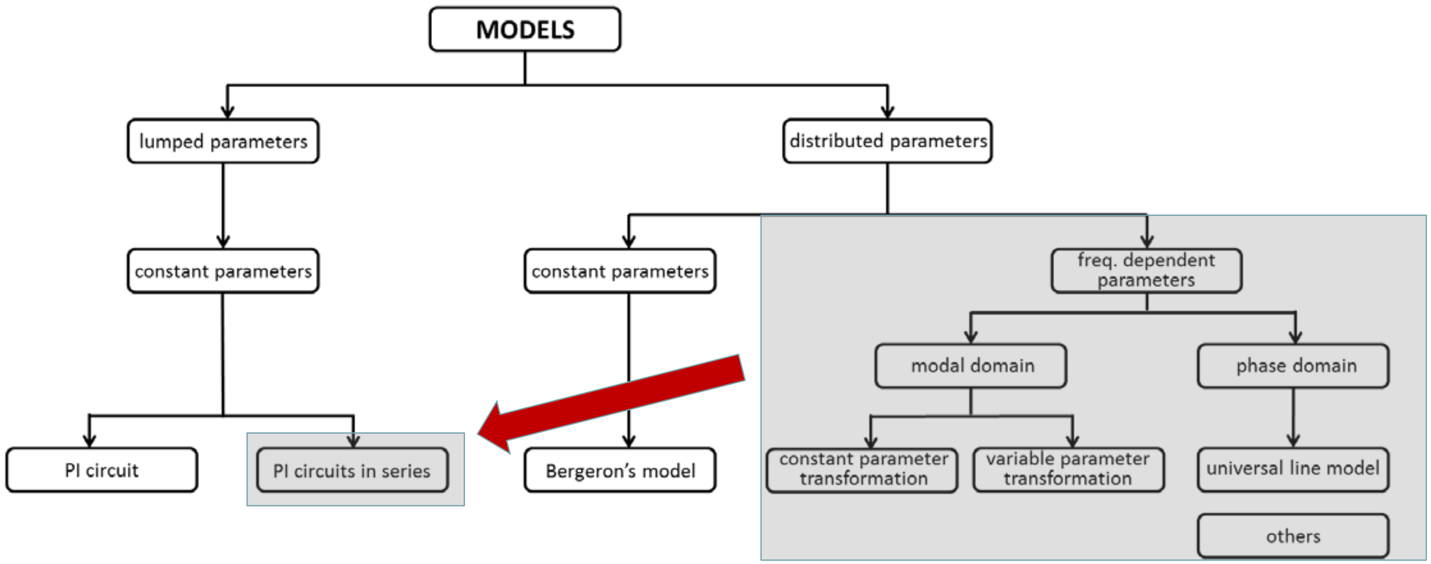
Small-signal stability assessment via traditional eigenvalue-based methods
- Eigenvalue plots
- Parametric sensitivity
- Participation factor analysis


Offshore
Grid #1
WFC
V_{ac_w1}
P_{w1}
Offshore
Onshore
DC CABLE
V_{dc_g1}
GSC
P_{g1}, Q_{g1}
Onshore
AC Grid #1
AC Voltage
Control
θ_{w1}*
$|V_{ac\_w1}$*$|$
f_{w1}*
V_{dc} and Q
Controller
V_{dc_g1}*
Q_{g1}*

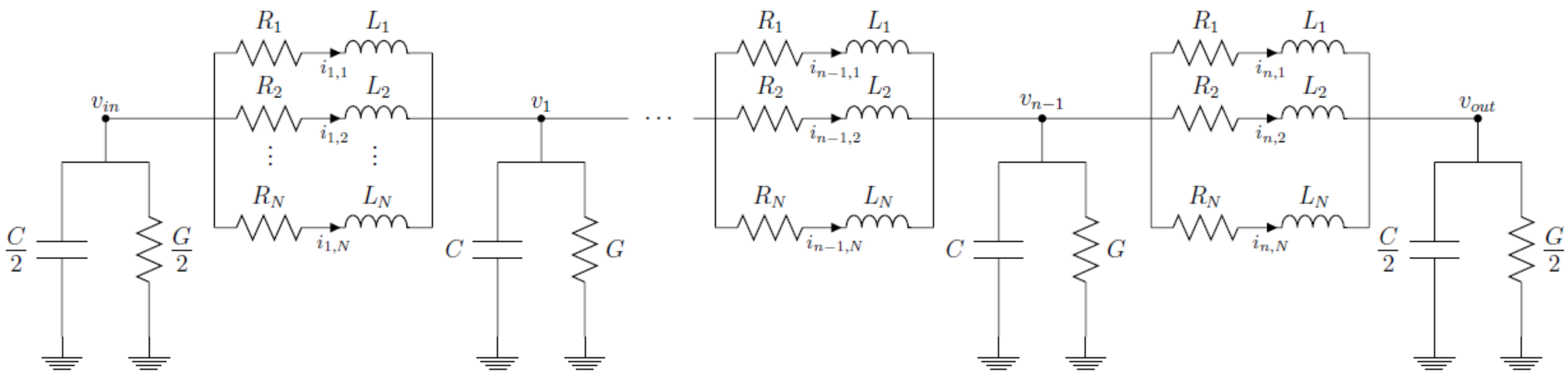

Offshore
Grid #1
WFC #2
V_{ac_w2}
P_{w2}
AC Voltage
Control
θ_{w2}*
V_{ac_w2}*
f_{w12}*
Offshore
Onshore
DC
NETWORK
Offshore
Grid #1
WFC #1
V_{ac_w1}
P_{w1}
AC Voltage
Control
θ_{w1}*
V_{ac_w1}*
f_{w1}*
GSC #1
V_{dc_g1}
P_{g1}, Q_{g1}
Onshore
AC Grid #1
(V_{dc} vs. P) and Q
Controller
V_{dc_g1}*
Q_{g1}*

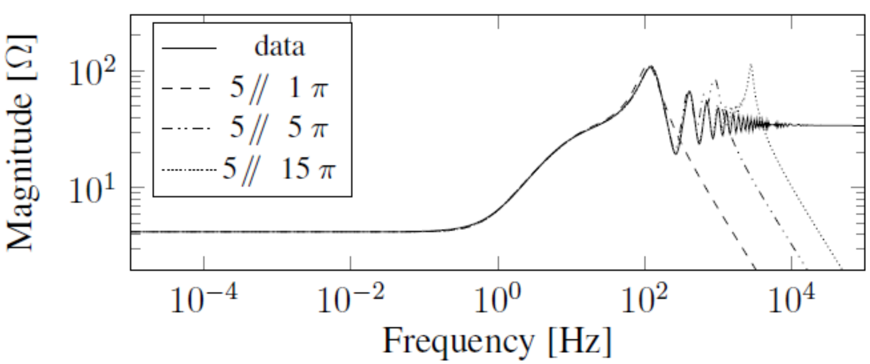
Frequency-Dependent State-Space modelling of HVDC cables

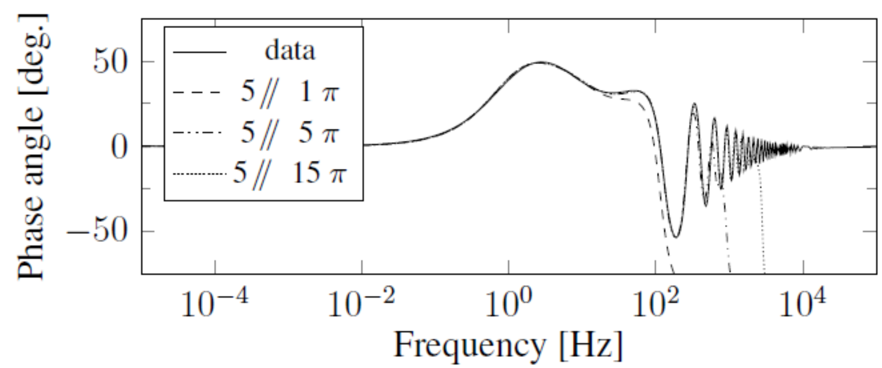
- The modelling approach is based on a lumped circuit and constant parameters
  - Parallel branches allow for capturing the frequency dependent behavior of the cable
  - Compatible with a state space representation in the same way as classical models with simple π sections
  - Model order depends on the number of parallel branches and the number of π sections



State-space frequency-dependent π section modelling







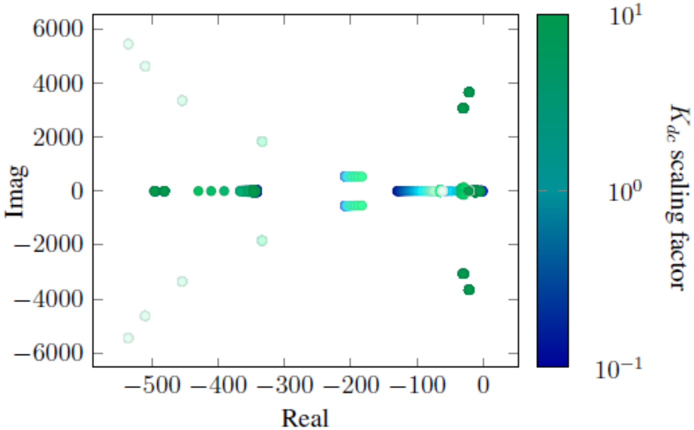
Behavior in a point to point HVDC transmission scheme

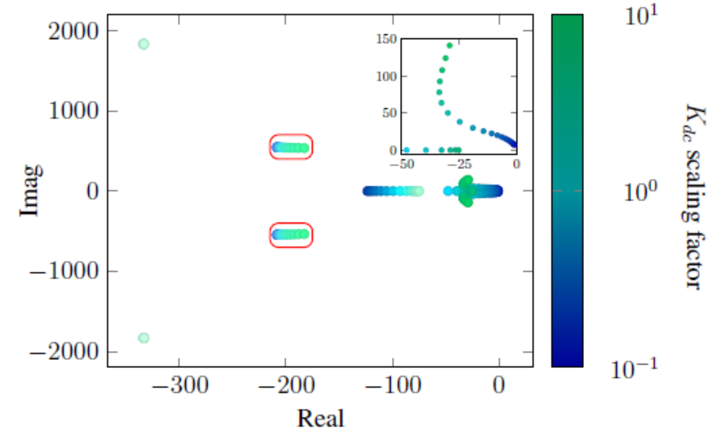
Eigenvalue trajectory for a sweep of dc voltage controller gain

All modes

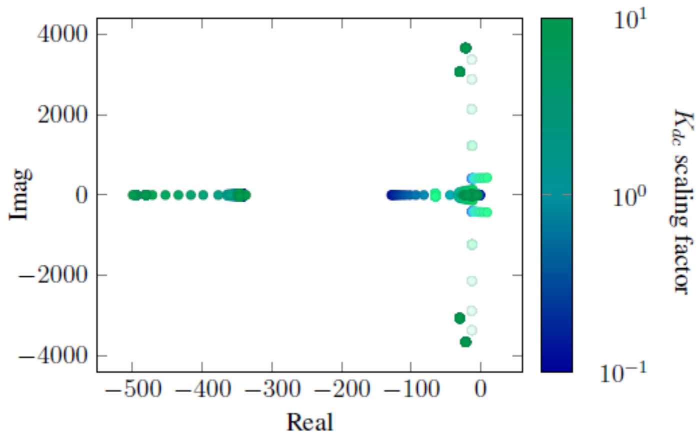
Interaction modes

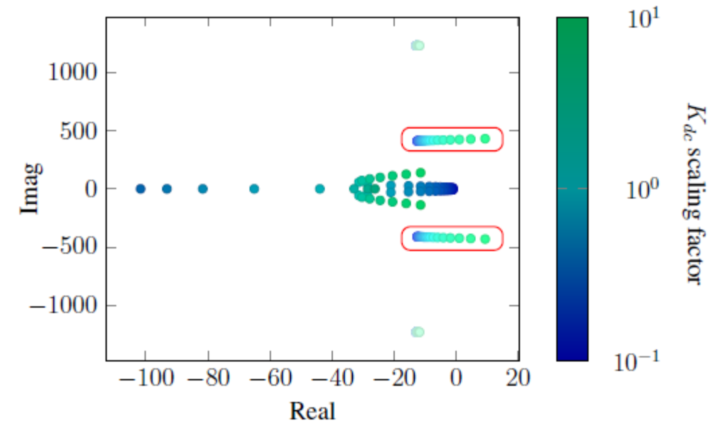
5 π sections
5 parallel branches





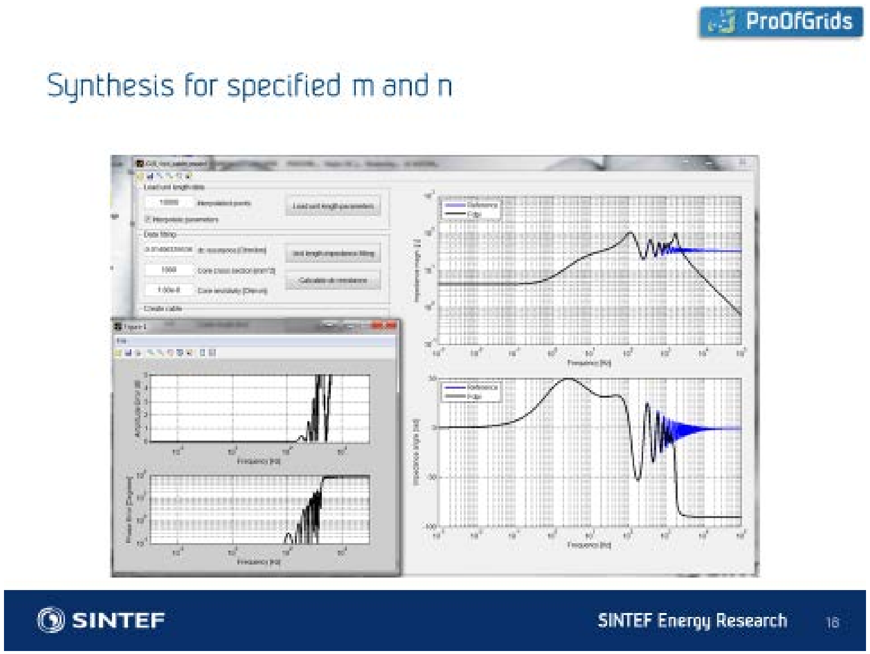
5 π sections
classical





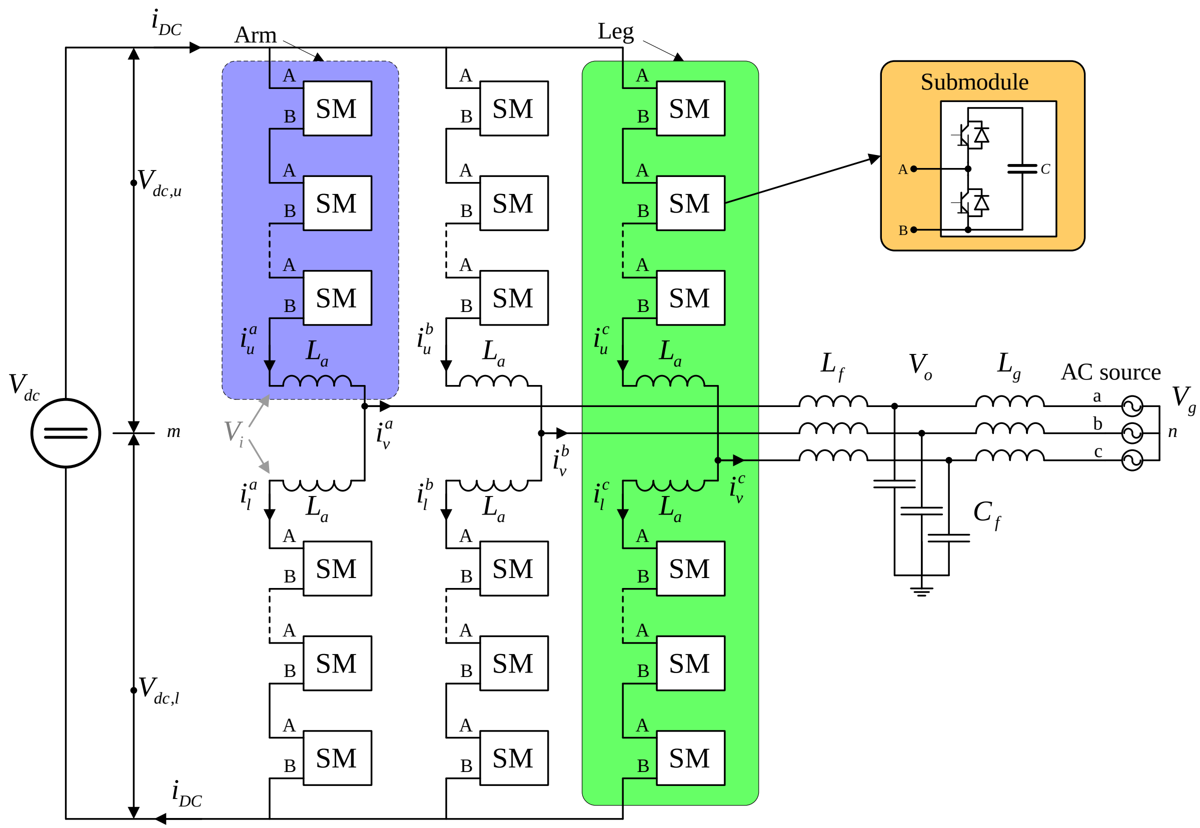
Main conclusions related to cable modelling

- ULM is established for EMT simulations
- Traditional π-section models of HVDC cables are not suitable for dynamic simulation or stability-assessment of HVDC systems
    - Single inductive branches imply significant under-representation of the damping in the system
- Frequency-dependent (FD) π-model for small-signal stability analysis
    - For simplified models, representation of cables by equivalent resistance and capacitance can be sufficient
- Developed Matlab-code and software tool for generating FD-π models



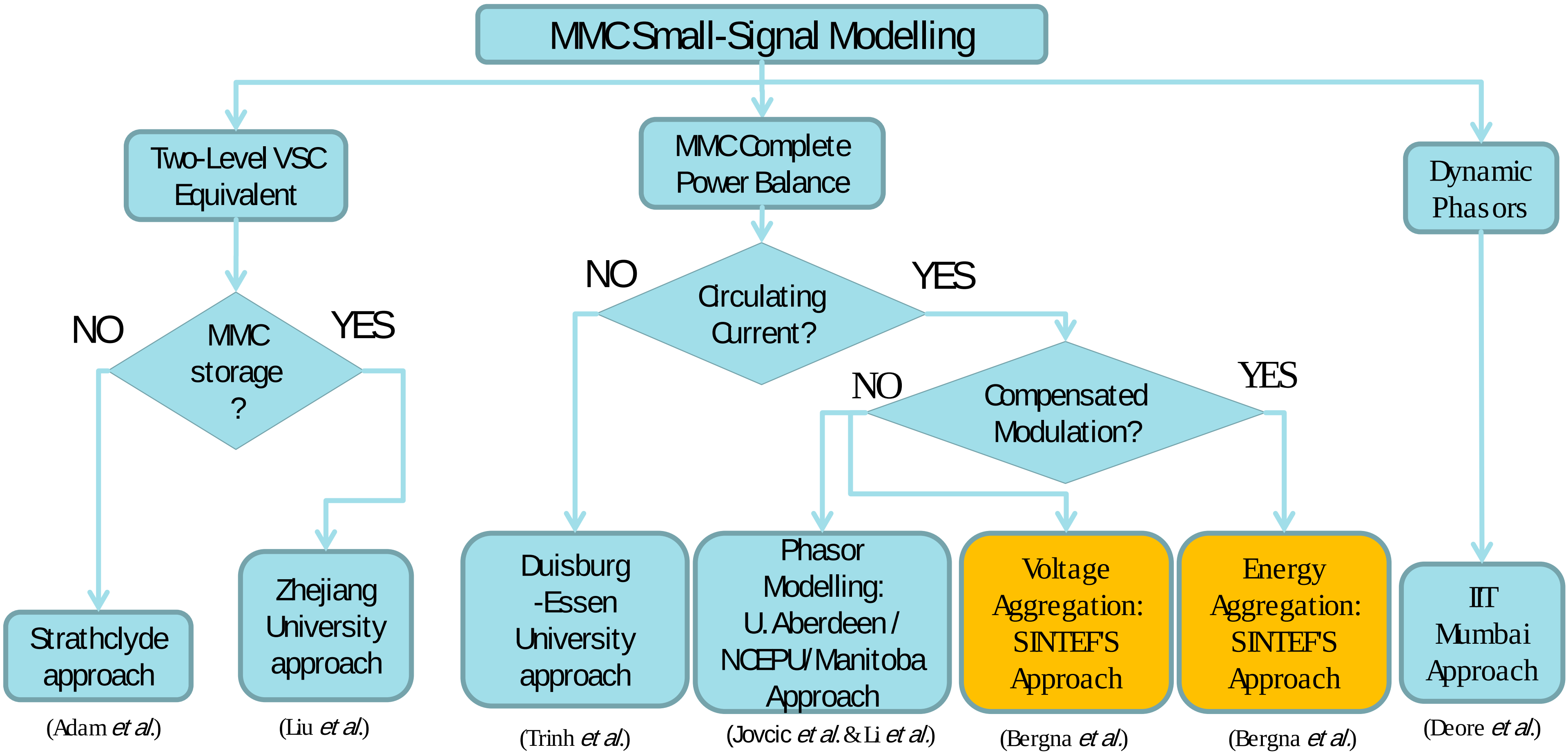
3-phase MMC: Basic Topology

- Advantages
  - Modularity
  - Scalability
  - Redundancy
  - Low losses
  - DC-capacitor is not required
- Disadvantages
  - High number of switches
  - Large total capacitance
  - Complexity
  - **Sub-module Capacitors will have steady-state voltage oscillations and internal currents can have corresponding frequency components**



→ **Main challenge for small-signal modelling**

Classification of MMC Modelling for eigenvalue analysis



Compensated vs. Uncompensated Modulation

Compensated Modulation

Insertion Indexes

$$n_{uk} = \frac{-e_{vk}^* + u_{ck}^*}{u_{cu}^\Sigma}$$

$$n_{lk} = \frac{e_{vk}^* + u_{ck}^*}{u_{cl}^\Sigma}$$

Voltage reference signals are divided by the actual arm voltage

$$u_{ck} \approx u_{ck}^*$$

$$e_{vk} \approx e_{vk}^*$$

MMC output voltage component will be approximately equal to the reference

Appropriate for energy-based modelling

Uncompensated Modulation

Insertion Indexes

$$n_{uk} \approx \frac{-e_{vk}^* + u_{ck}^*}{V_{dc}}$$

$$n_{lk} \approx \frac{e_{vk}^* + u_{ck}^*}{V_{dc}}$$

Voltage references are divided by a constant value

$$\begin{bmatrix} u_{ck} \\ e_{vk} \end{bmatrix} = \frac{1}{2V_{dc}} \begin{bmatrix} \left(\sqrt{w_{\Sigma k} + w_{\Delta k}} + \sqrt{w_{\Sigma k} - w_{\Delta k}}\right) & -\left(\sqrt{w_{\Sigma k} + w_{\Delta k}} - \sqrt{w_{\Sigma k} - w_{\Delta k}}\right) \\ -\left(\sqrt{w_{\Sigma k} + w_{\Delta k}} - \sqrt{w_{\Sigma k} - w_{\Delta k}}\right) & \left(\sqrt{w_{\Sigma k} + w_{\Delta k}} + \sqrt{w_{\Sigma k} - w_{\Delta k}}\right) \end{bmatrix} \begin{bmatrix} u_{ck}^* \\ e_{vk}^* \end{bmatrix}$$

The control output is modified by the energy information in each arm/phase

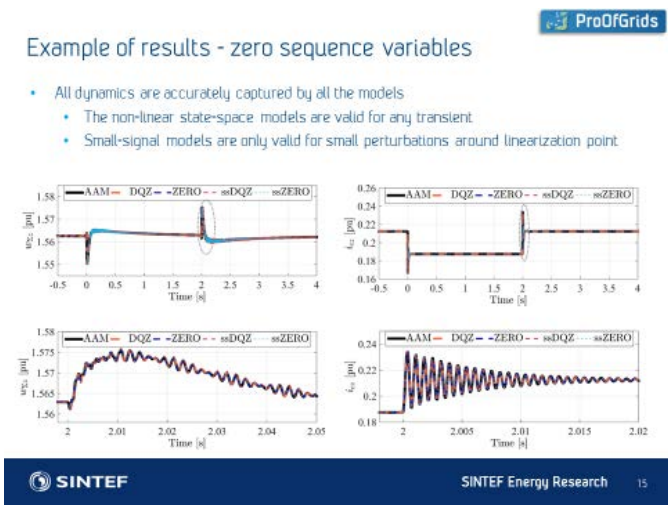
Non-linear relationship between reference and "real" driving voltages

Energy-based modelling is not suitable for this case

Main conclusions related to MMC modelling

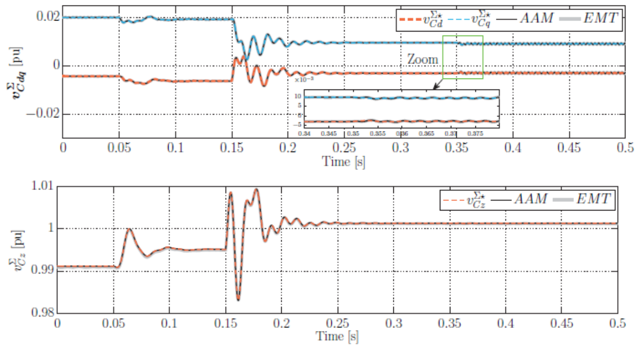
- The internal energy storage dynamics of MMCs must be represented for obtaining accurate models
  - Established models of 2-Level VSCs should not be used for studying fast dynamics in HVDC systems
  - Models assuming ideal power balance between AC- and DC-sides can only be used for studying phenomena at very low frequency

Energy-based model



- Two cases of MMC modelling
  - Compensated modulation with Energy-based modelling
  - Un-compensated modulation with Voltage-based modelling

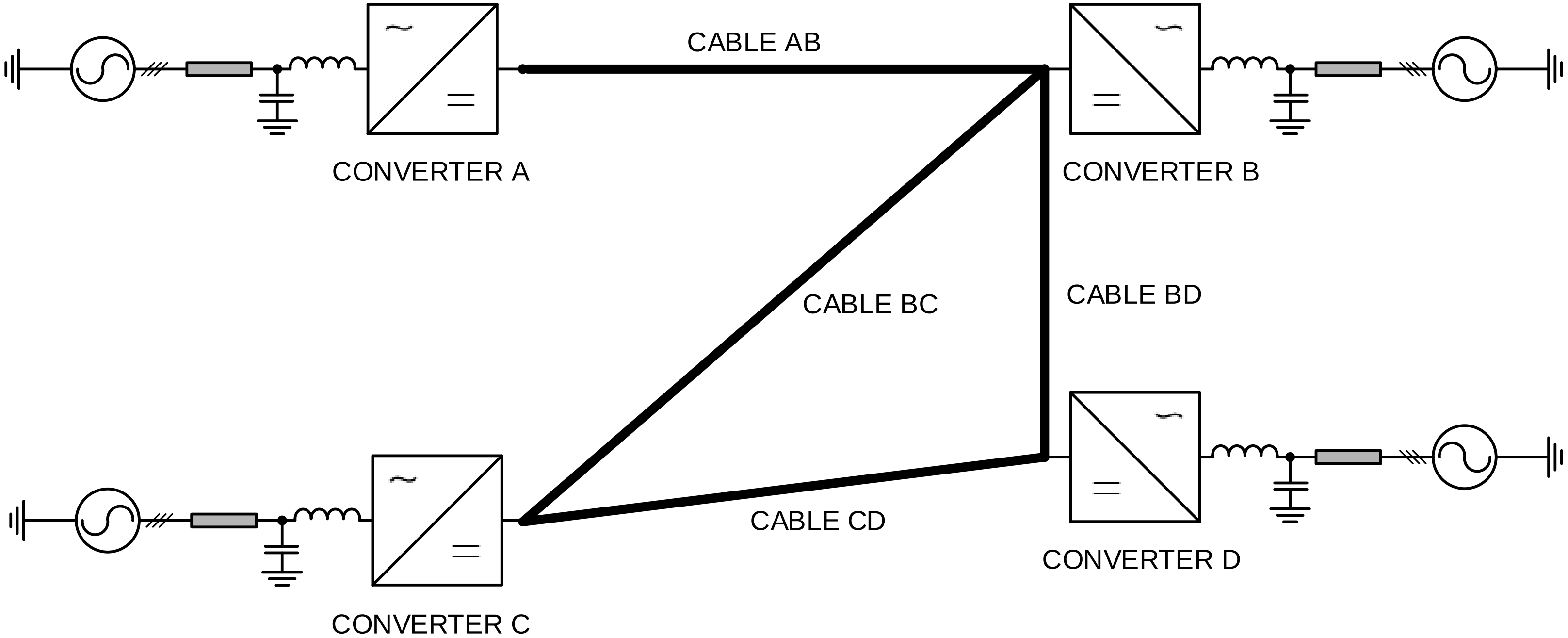
Voltage-based model



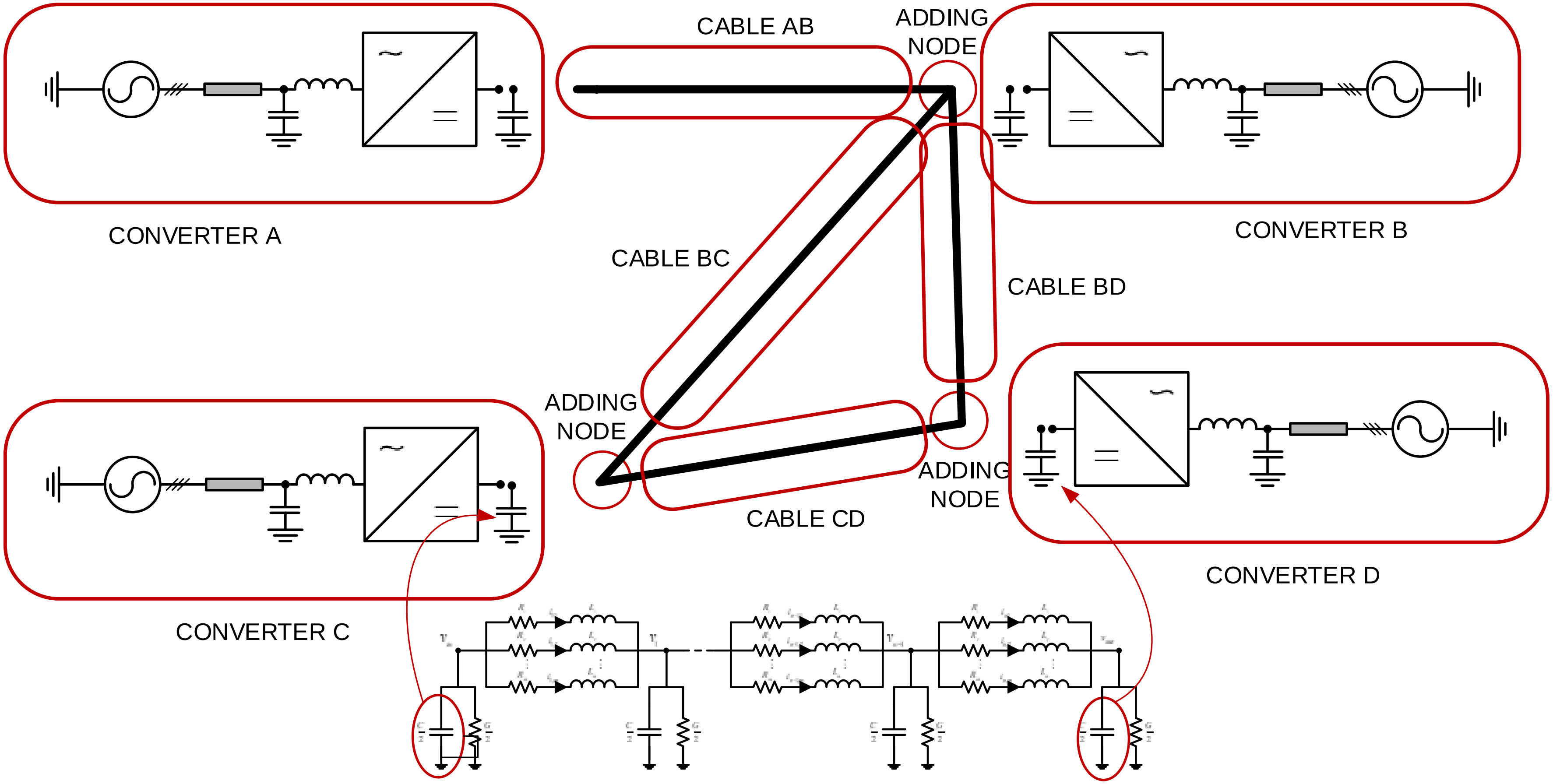
Generation of a small signal model for MT HVDC

- A modular approach was developed to generate the small signal model of MT HVDC transmission system
  - Decompose the HVDC MT into predefined modular blocks (cable, converters)
  - Modules can be customized by modifying the parameters but not the structure of the subsystem
  - Several blocks are developed for the converters reflecting the topology and the control
  - Steady state conditions (linearization points) for each block were precalculated as a function of the input
  - Steady state conditions for the entire system were obtained by implementing a dc loadflow

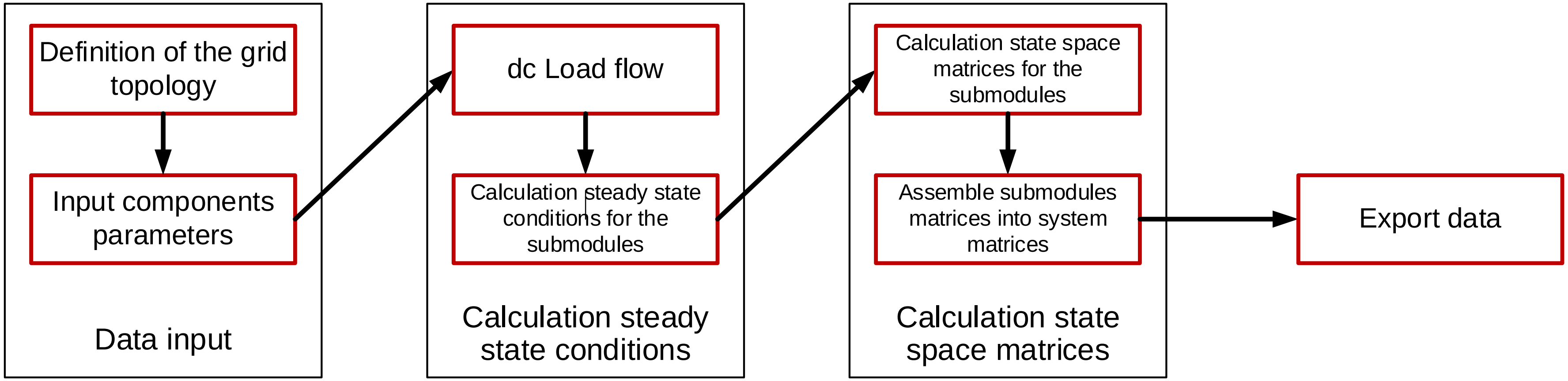
Definition of subsystem interfaces

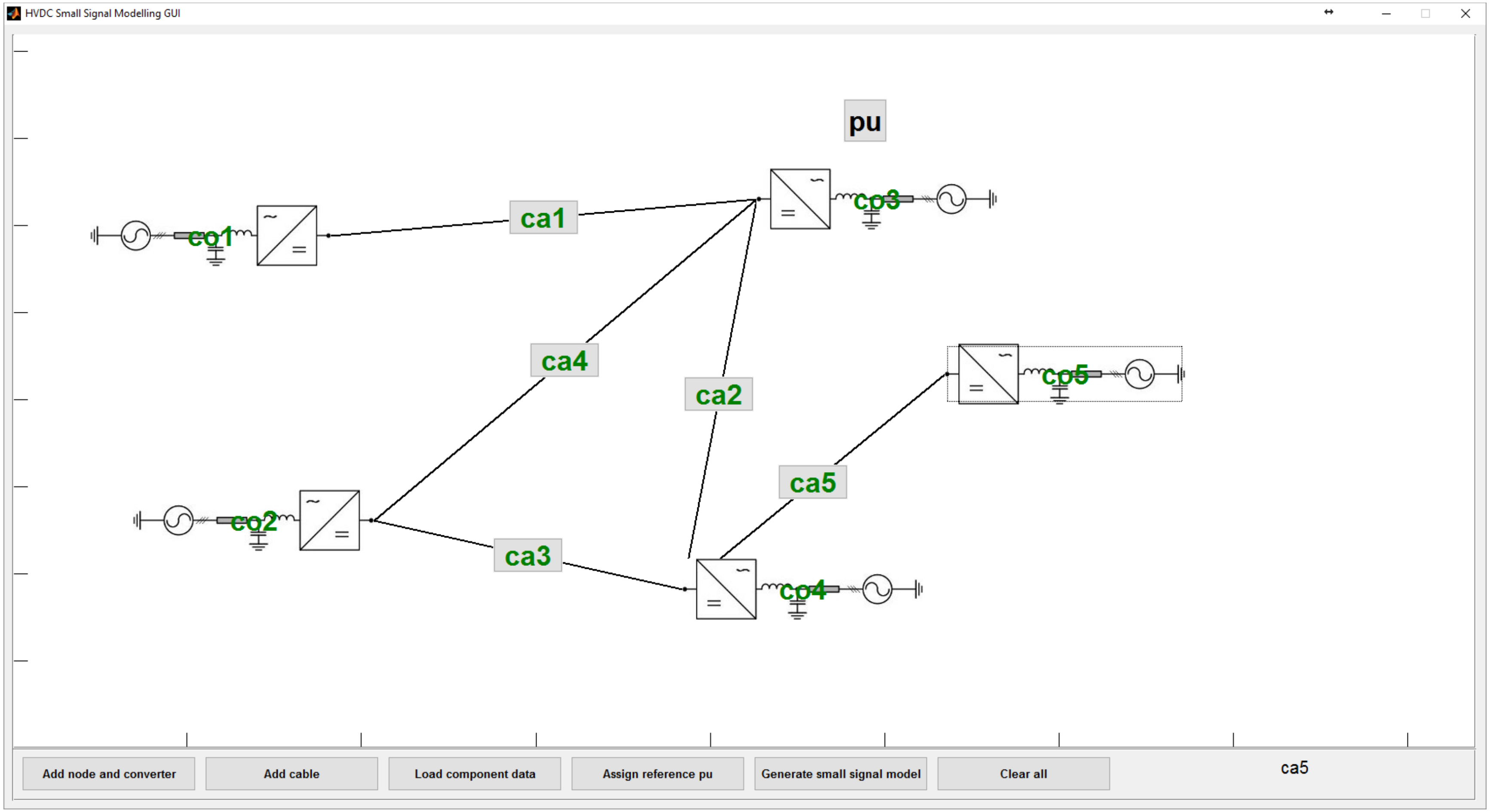


Definition of subsystem interfaces



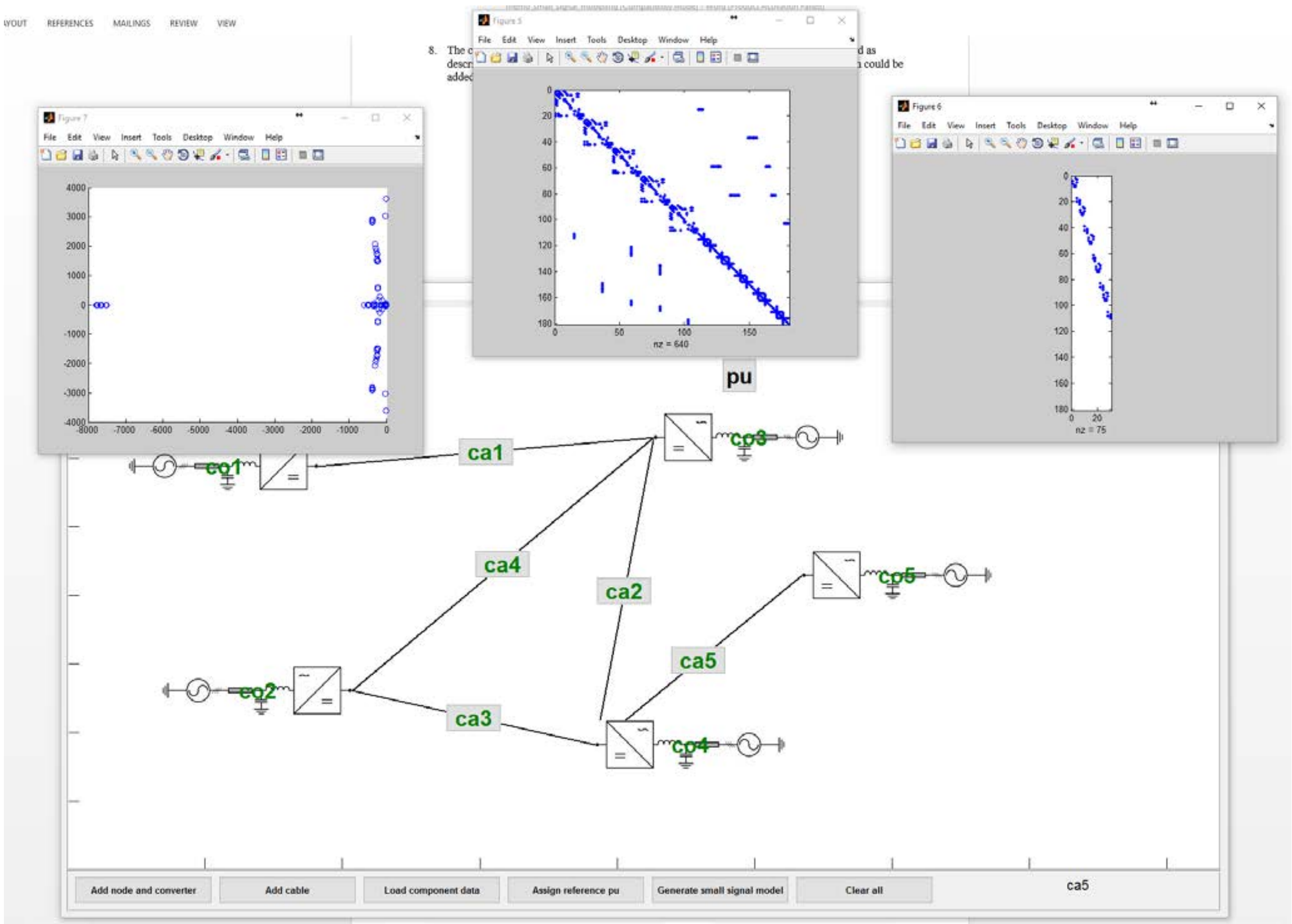
Workflow for generating the small signal model



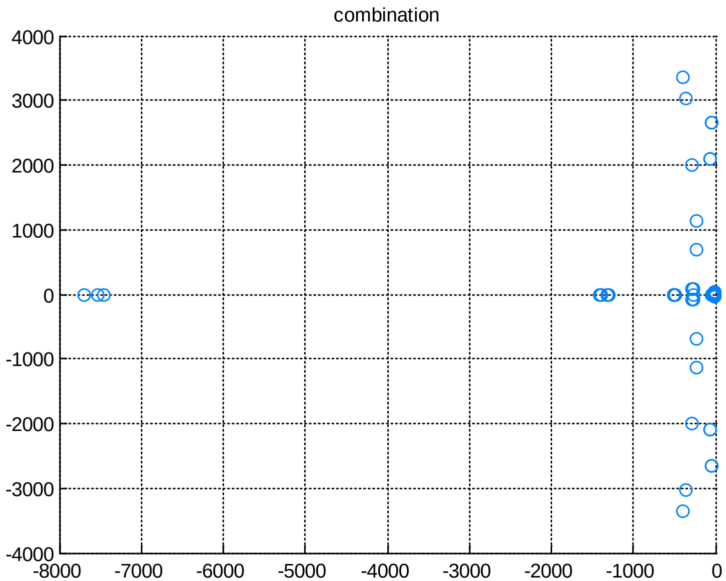


HVDC Small Signal Modelling GUI
pu
ca1
ca2
ca3
ca4
ca5
co1
co2
co3
co4
co5
Add node and converter
Add cable
Load component data
Assign reference pu
Generate small signal model
Clear all
ca5

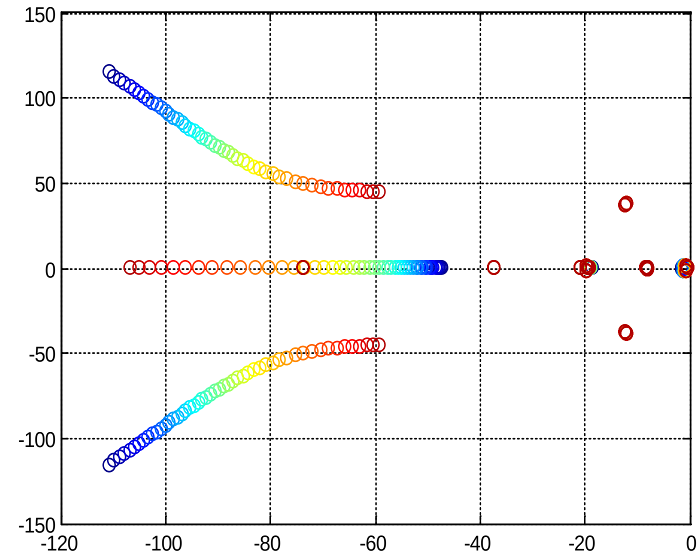
Screenshot of the GUI after generating the small signal model



MMC-based point-to-point transmission scheme



Eigenvalues of MMC HVDC point-to-point scheme



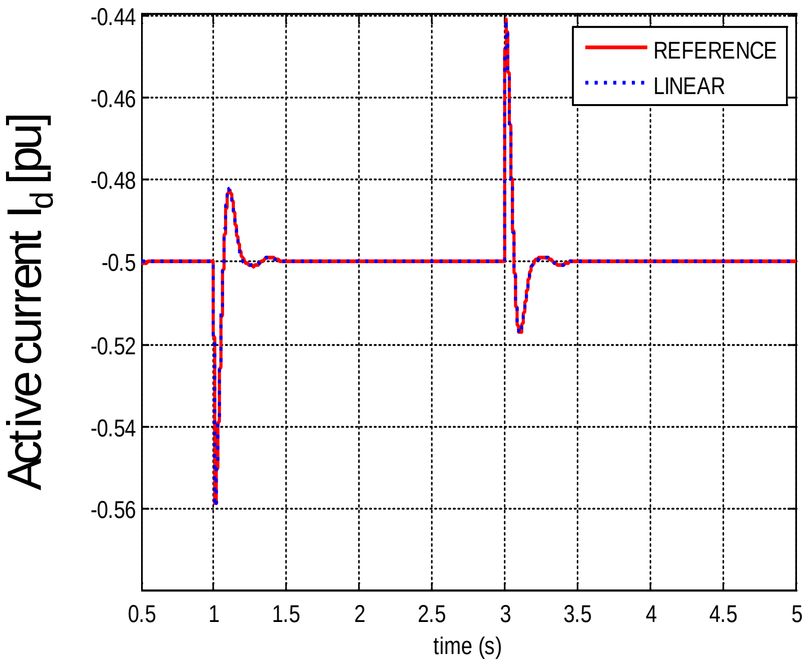
Trajectory of critical eigenvalue with power reference is varied from -1.0 to 1.0 pu

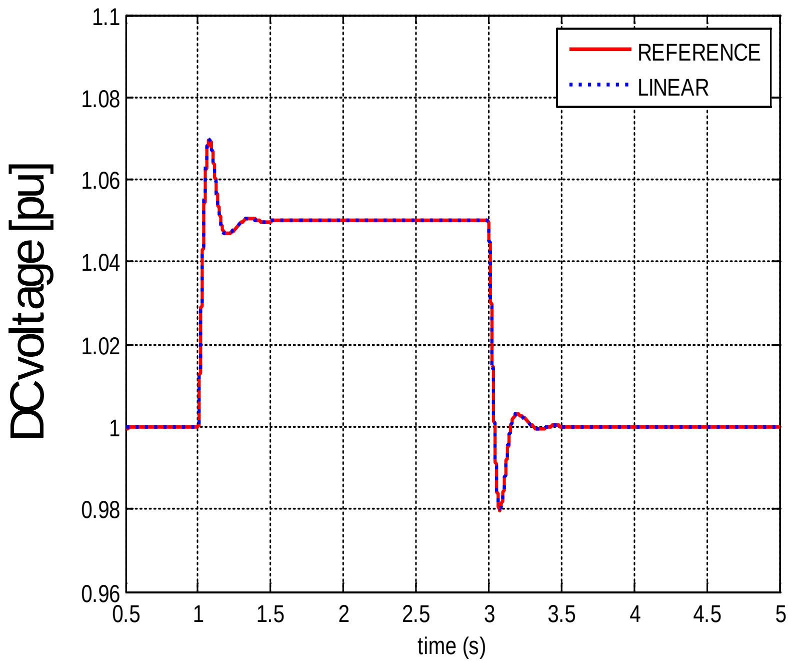
- Modes associated with the cable are quite quickly damped
- One oscillatory mode and one real pole are slightly dependent on operating conditions
  System is stable and well-damped in the full range of expected operating conditions

Time-domain verification of point-to-point MMC scheme

- Variables of small-signal model can accurately represent the nonlinear system model for variables at both terminals

DC voltage controlled terminal



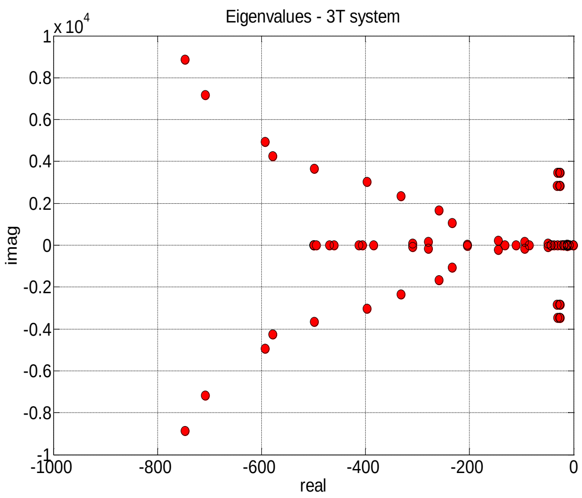


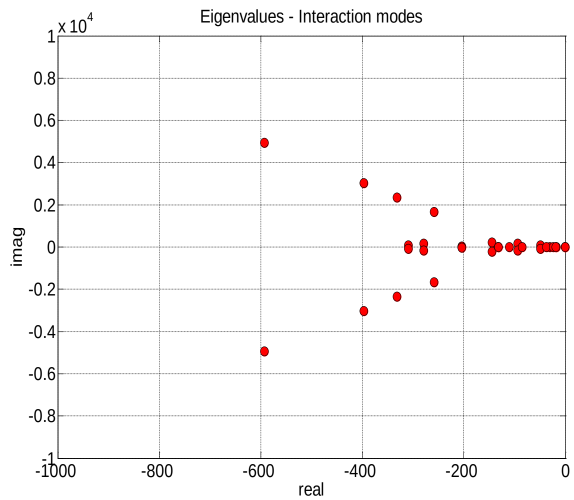
Aggregated participation factor analysis

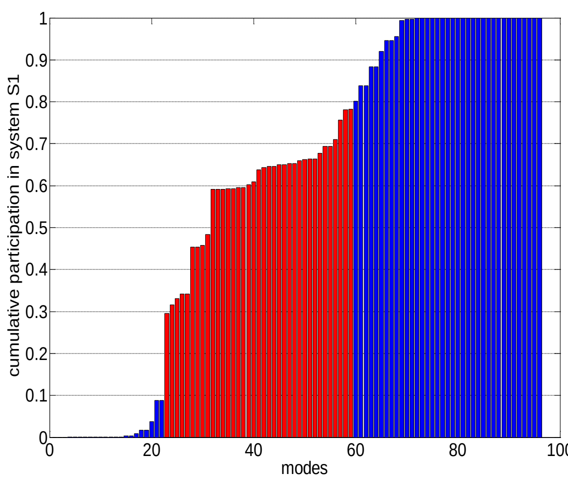
- Approach proposed for identifying interactions in an interconnected system
  - An interaction mode is defined as an eigenvalue having participation ρ higher than a threshold χ from both parts of the interconnected system
- Interaction modes identified as shown below for $\chi = 0.20$
- Close correspondence can be identified between identified interaction modes and eigenvalues that are significantly influenced by the interconnection

$$\eta_{\alpha,i} = \frac{\left\| \mathbf{p}_{\alpha,i} \right\|}{\left\| \mathbf{p}_i \right\|}$$

$$\rho_{\alpha,i} = \frac{\eta_{\alpha,i}}{\sum_{\gamma \in S} \eta_{\gamma,i}}$$

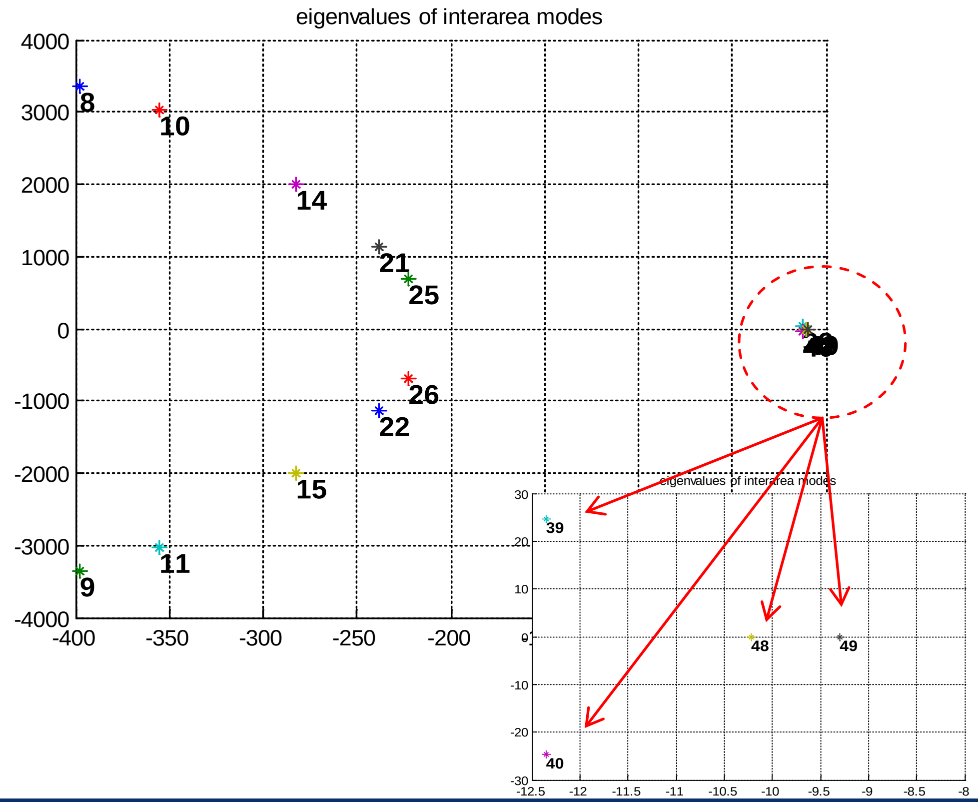






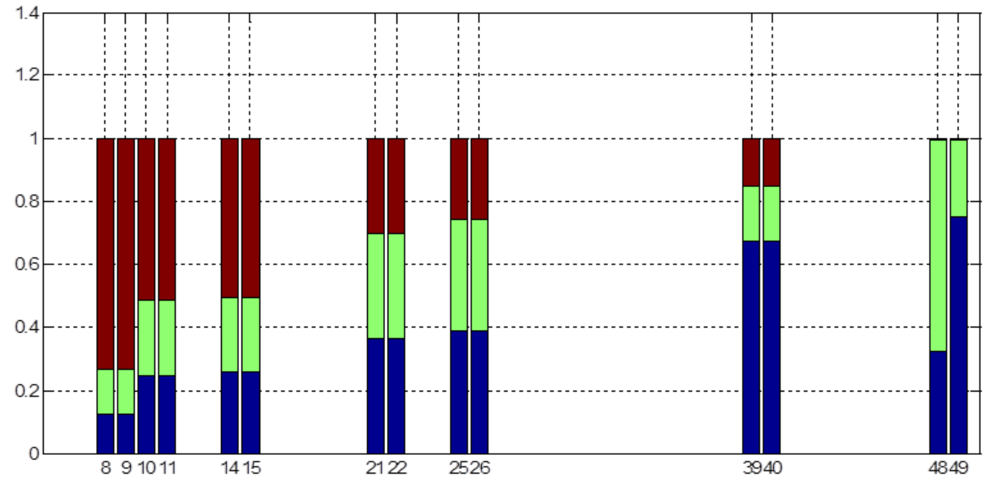
Interaction modes – MMC HVDC point-to-point scheme

- More interaction modes compared to case with 2L VSCs
    - In total 14 eigenvalues - 12 oscillatory modes (6 pairs) and two real poles.
- A first group is defined as those well damped oscillatory modes (real part smaller than -200).
- A second group of interaction modes is found much closer to the imaginary axis
    - Oscillatory mode (39-40)
    - Two real eigenvalues (48 and 49)



Interaction modes – Aggregated participation factor analysis

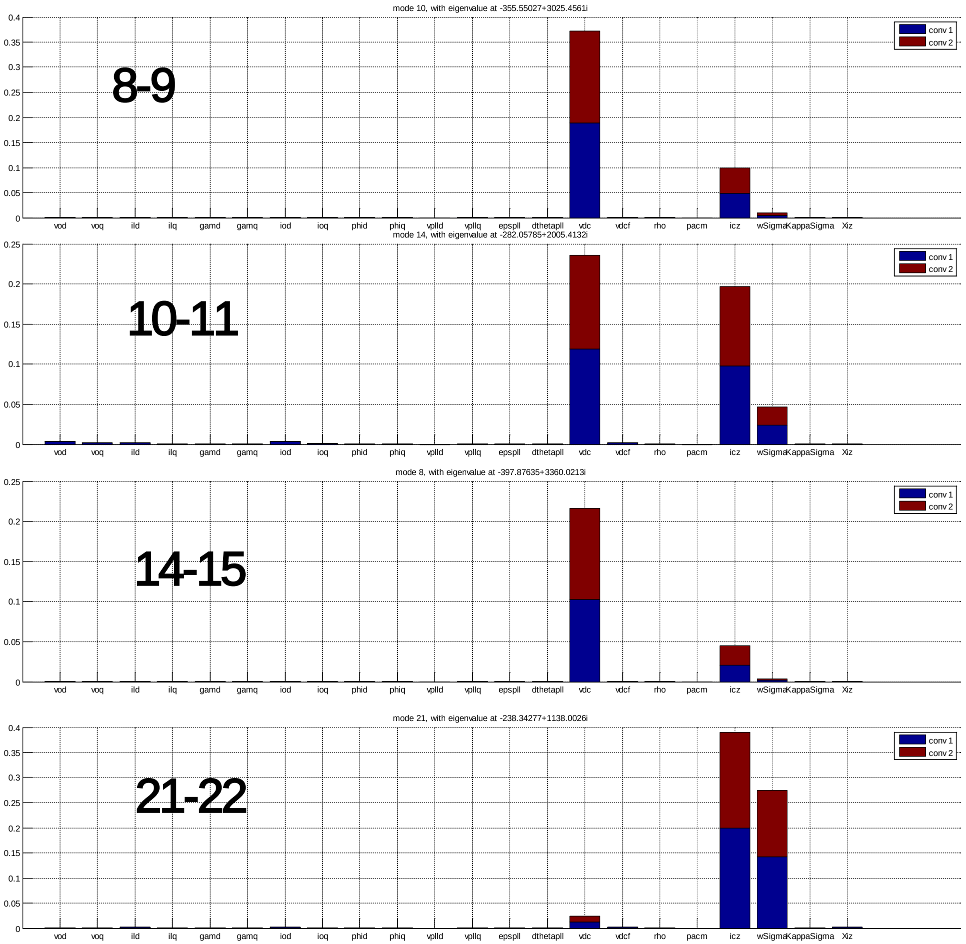
- For fast interaction modes:
  - Balanced participation from the two converter stations
  - High participation from the cable in the fastest modes
- Slow interaction modes
  - Dominant participation from the DC-voltage controlled terminal in oscillatory modes
  - Low participation from the cable, especially for the two real poles
- Depending on the eigenvalue, one station will have a higher participation



Aggregated participation factor analysis of interarea modes of the MMC-HVDC point-to-point scheme
– **blue**: DC Voltage controlling station
– **green**: power controlling station
– **brown**: dc cable

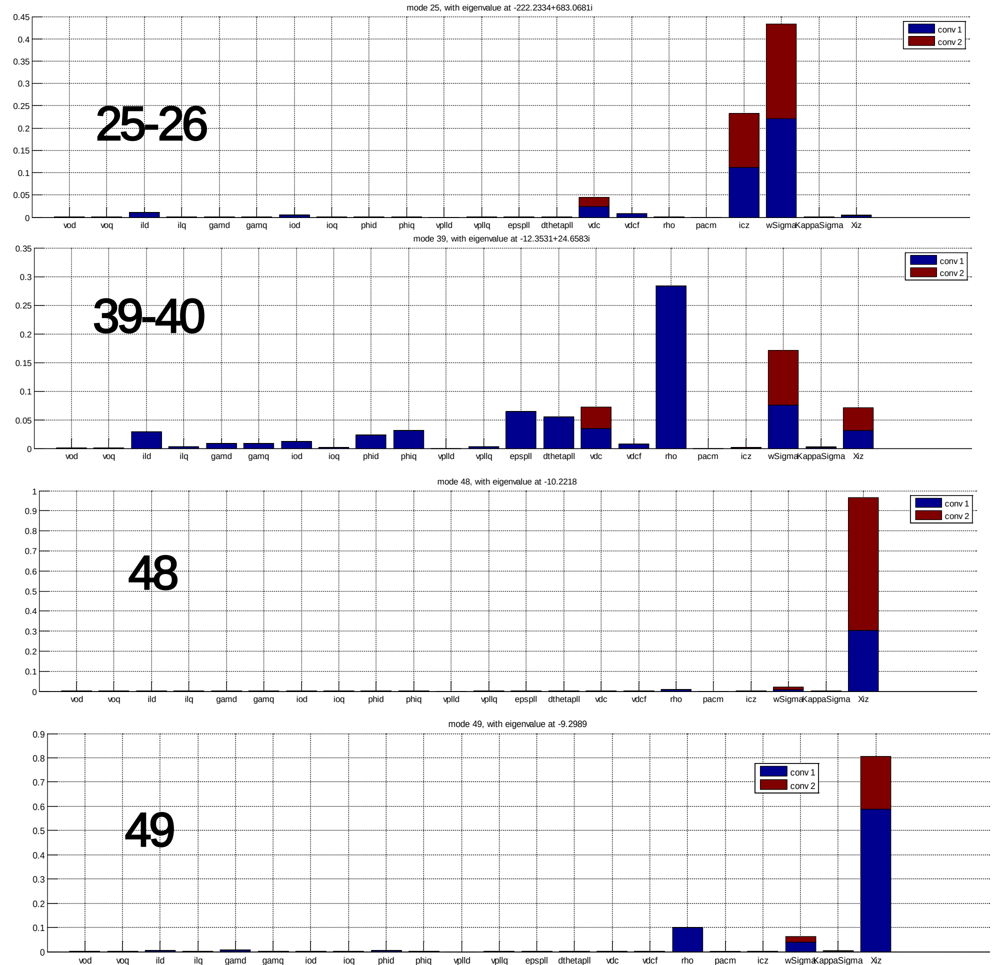
Participation Factor Analysis of Interaction Modes

- The fast oscillatory modes (8-9, 10-11, and 14-15)
  - Related to dc voltages at both cable ends
  - Associated with cable dynamics
- Modes 21-22 and 25-26
  - "DC-side" interactions
  - Almost no participation from the AC-sides
  - Associated with the MMC energy-sum w_{Σ} and the circulating current $i_{c,z}$.



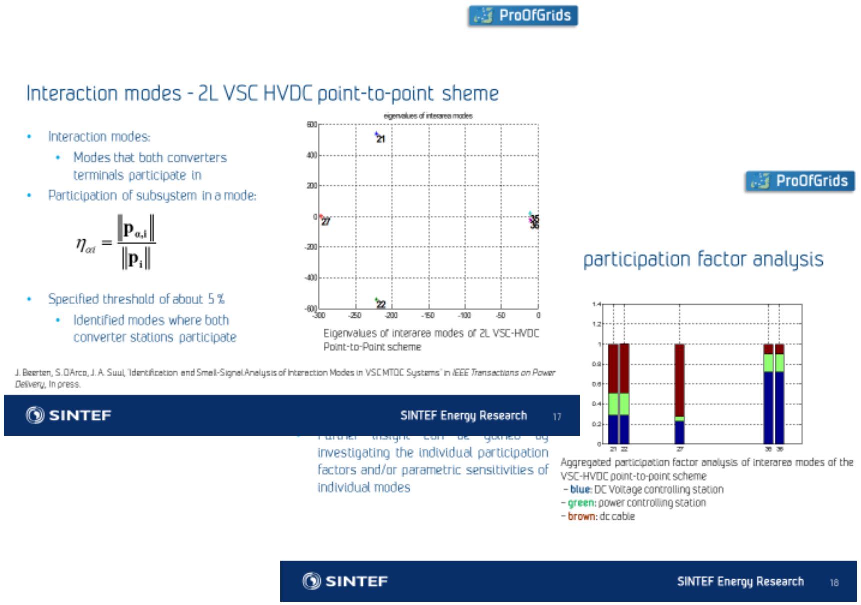
Participation Factor Analysis of Interaction Modes

- Oscillatory mode given by eigenvalues 39-40
  - Interaction modes associated with the power flow control in the system
  - Associated with the integrator state of the DC voltage controller, ρ
- Real poles 48 and 49
  - Associated with integrator states of the PI controllers for the circulating current, ξ_z
  - The interaction of both stations in these eigenvalues is mainly due to the power transfer through the circulating current.
  - Small participation of the cable since the dynamics are slow and the equivalent parameters of the arm inductors dominate over the equivalent DC parameters of the cable

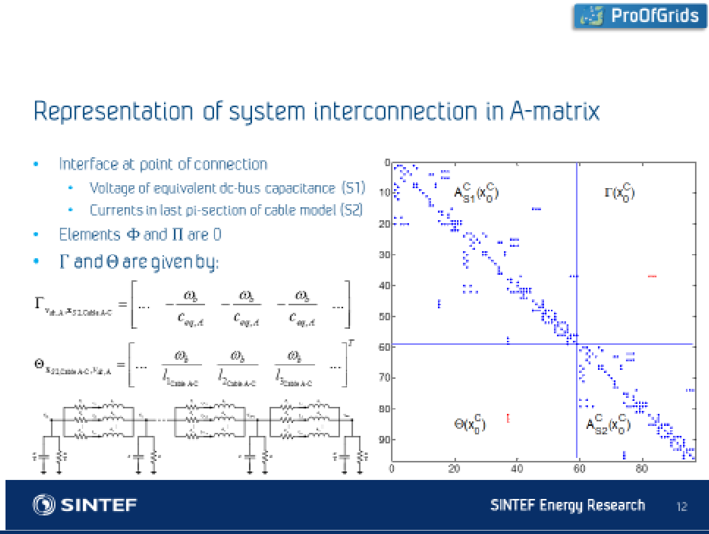


Main conclusions related to interaction analysis

- Small-signal eigenvalue analysis can be utilized to reveal the properties of modes and interactions in the system
  - Participation and sensitivity of all oscillations and small-signal stability problems can be analyzed
  - Suitable for system design, controller tuning and screening studies based on open models



- Aggregated participation factor analysis can reveal interaction between different elements or sub-systems



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