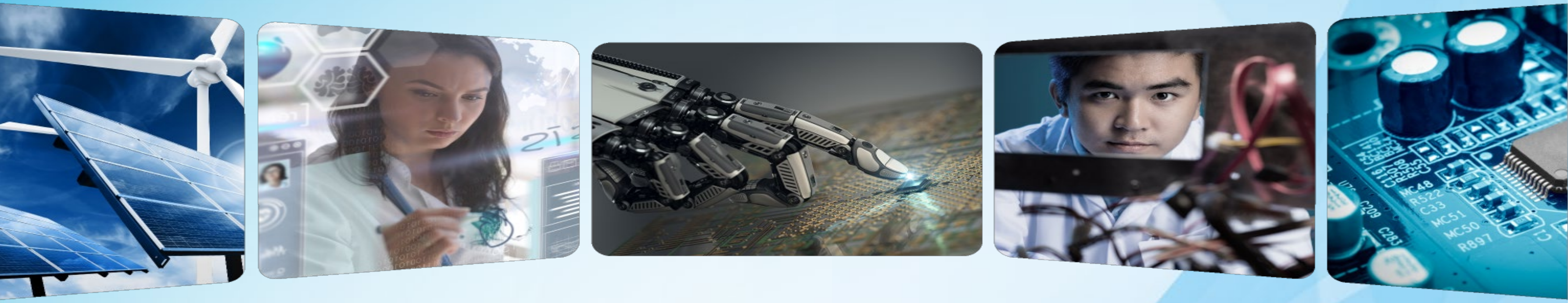

Impedance based analysis of interconnected power electronics system: Impedance operator and partition points

Chen Zhang, Marta Molinas, Atle Rygg, Xu Cai

Overview

- ❑ Background and motivation
- ❑ Impedance Operator and associated properties
- ❑ Impacts and sensitivity analysis of partition points
- ❑ Conclusions

Background

- Dynamic models of converters can be supplied as black boxes (terminal equivalents)

- Research has developed analytical impedance models of typical converter topologies (white boxes)

Open and important question: How to piece together individual submodels to perform network-level analysis?

How to form an Impedance-Network with individual building blocks?

- **Problem**: Each model is referred to its own (*local*) reference frame. Network analysis must be referred to a *global* reference frame

- **Solution**: Shift «local» models into the global reference frame by the **Impedance Operator (IO)** and use basic circuit laws for analysis

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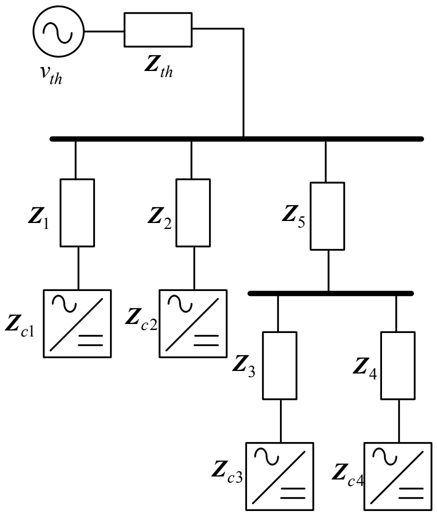
IO: Rotation from local to global frame

$$\mathbf{Z}_{dq}^{global} = \mathbf{T}_{rot}\mathbf{Z}_{dq}^{local}\mathbf{T}_{rot}^{-1}$$

$$\mathbf{T}_{rot} = \begin{bmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{bmatrix}$$



θ_i is the steady-state (fundamental) angle difference between local terminal voltage and the global voltage reference

IO and Properties for AC Coupled Systems

$$MSD: \mathbf{Z}_{\text{pn\_i}}^{\text{global}}(s) = \boxed{\begin{bmatrix} e^{\mathrm{j}\theta_i} & 0 \\ 0 & e^{-\mathrm{j}\theta_i} \end{bmatrix}} \mathbf{Z}_{\text{pn\_i}}^{\text{local}}(s) \boxed{\begin{bmatrix} e^{-\mathrm{j}\theta_i} & 0 \\ 0 & e^{\mathrm{j}\theta_i} \end{bmatrix}}$$

$\mathbf{T}_{\text{rot}}(\theta_i)$ $\qquad$ $\boldsymbol{T}_{\text{rot}}(-\theta_i)$

AC IO:

Impedance operator **for AC coupled VSCs in MSD :** $\mathbf{T}_{\text{rot}}(\theta_i)$ **,** θ_i **is the relative angle of *i* th VSC local frame to the global frame.**

Properties:

P.1 The **passive impedances** (strictly speaking, the *dq* symmetric* impedances) are **invariant in terms of IO**;

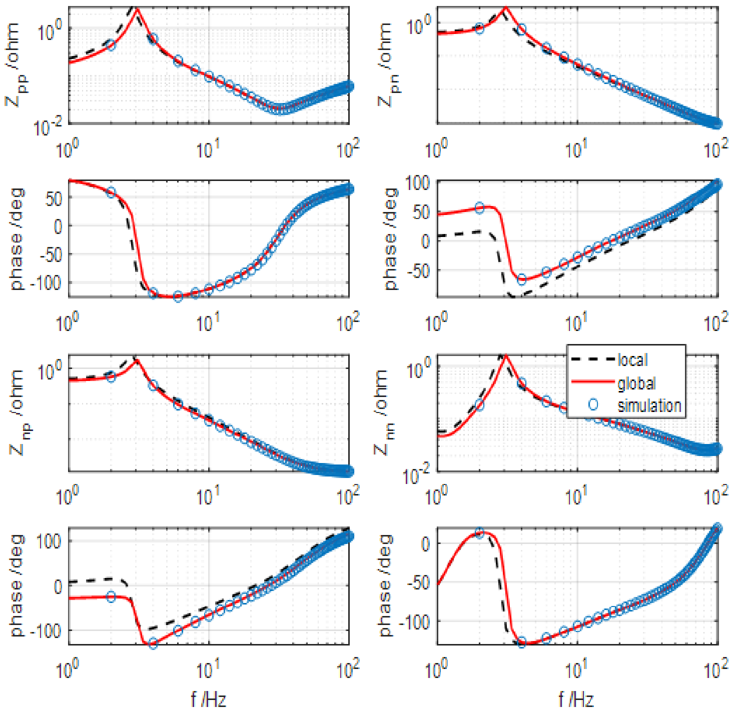
P.2 The IO only **affect the off-diagonals** of the active impedances (strictly speaking, the *dq* asymmetric impedances) by shifting their phases;

P.3 The **eigen-loci** of the active/passive impedances are **not affected** by the IO, i.e. property of impedances are not changed by IO.

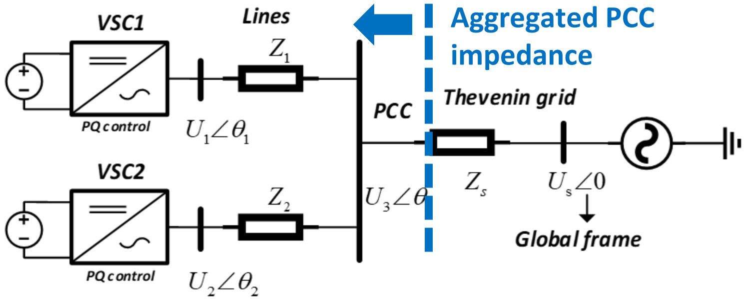
*L. Harnefors, "Modeling of Three-Phase Dynamic Systems Using Complex Transfer Functions and Transfer Matrices," IEEE Trans. Ind. Electron, vol. 54, no. 4, pp. 2239–2248, 2007.

Impact of AC IO on Impedance Characteristics

Aggregated Impedance seen from PCC



Pvsc1 = 1.0 p.u.; P vsc2 = -0.5p.u., PLL = 20 Hz, CC = 300 Hz, PQ = 20 Hz, Zs = 0.25 j p.u., Z1 = Z2 = 0.1j p.u.



Aggregated PCC impedance

Global PCC impedance (red line):

$$\mathbf{Z}_{\text{pn\_pcc}}^{\text{global}} = \left(\mathbf{Z}_1 + \mathbf{Z}_{\text{pn\_vsc1}}^{\text{global}}\right) \| \left(\mathbf{Z}_2 + \mathbf{Z}_{\text{pn\_vsc2}}^{\text{global}}\right)$$

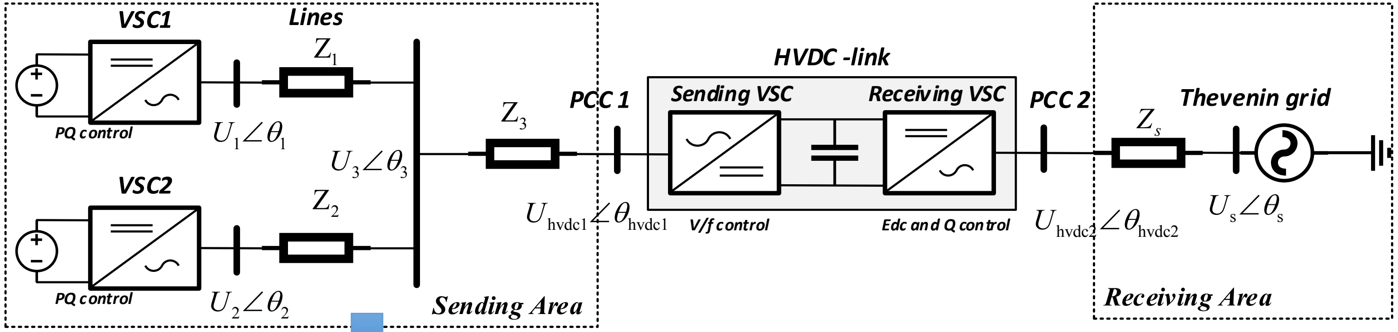
Local PCC impedance (dotted black line):

$$\mathbf{Z}_{\text{pn\_pcc}}^{\text{local}} = \left(\mathbf{Z}_1 + \mathbf{Z}_{\text{pn\_vsc1}}^{\text{local}}\right) \| \left(\mathbf{Z}_2 + \mathbf{Z}_{\text{pn\_vsc2}}^{\text{local}}\right)$$

- ✓ Though the IO only affects each impedance’s off-diagonals in accordance with **P.2**, *the effects propagate if* ***circuit operations*** *are applied* (e.g. series and parallel).
- ✓ Therefore, *its effects on stability should not be overlooked*

Impedance operator for AC/DC coupled systems

An AC/DC coupled benchmark system:



A unified reference system is defined according to a common reference frame as: $\angle\theta=0$

Each of the HVDC terminals can be represented as, ***three-port modules****:

$$\begin{bmatrix} I^{\text{local}}_{\text{p\_hvdc1}}(s) \\ I^{\text{local}}_{\text{n\_hvdc1}}(s) \\ I_{\text{dc\_hvdc1}}(s) \end{bmatrix} = \begin{bmatrix} \mathbf{Y}^{\text{local}}_{\text{pn\_hvdc1}}(s) & \mathbf{a}_{2\times1}(s) \\ \mathbf{b}_{1\times2}(s) & Y_{\text{dc\_hvdc1}}(s) \end{bmatrix}_{3\times3} \begin{bmatrix} U^{\text{local}}_{\text{p\_hvdc1}}(s) \\ U^{\text{local}}_{\text{n\_hvdc1}}(s) \\ U_{\text{dc\_hvdc1}}(s) \end{bmatrix} = \boxed{\mathbf{Y}^{\text{local}}_{\text{hvdc1}}} \begin{bmatrix} U^{\text{local}}_{\text{p\_hvdc1}}(s) \\ U^{\text{local}}_{\text{n\_hvdc1}}(s) \\ U_{\text{dc\_hvdc1}}(s) \end{bmatrix}$$

*C. Zhang, X. Cai, M. Molinas and A. Rygg, "On the Impedance Modeling and Equivalence of AC/DC Side Stability Analysis of a Grid-tied Type-IV Wind Turbine System," in IEEE Transactions on Energy Conversion.

IO and Properties for AC/DC Coupled Systems

$$\left[\mathbf{Y}_{\text{hvdc}}^{\text{global}}\right]_{3\times 3} = \boxed{\begin{bmatrix} \mathbf{T}_{\text{rot}}\left(-\theta_{\text{hvdc1}}\right) & \mathbf{0}_{2\times 1} \\ \mathbf{0}_{1\times 2} & 1 \end{bmatrix}} \left[\mathbf{Y}_{\text{hvdc}}^{\text{local}}\right]_{3\times 3} \boxed{\begin{bmatrix} \mathbf{T}_{\text{rot}}\left(\theta_{\text{hvdc1}}\right) & \mathbf{0}_{2\times 1} \\ \mathbf{0}_{1\times 2} & 1 \end{bmatrix}}$$

$\mathbf{T}_{\text{rot\_hvdc}}\left(-\theta_{\text{hvdc1}}\right)$ $\mathbf{T}_{\text{rot\_hvdc}}\left(\theta_{\text{hvdc1}}\right)$

AC/DC IO:

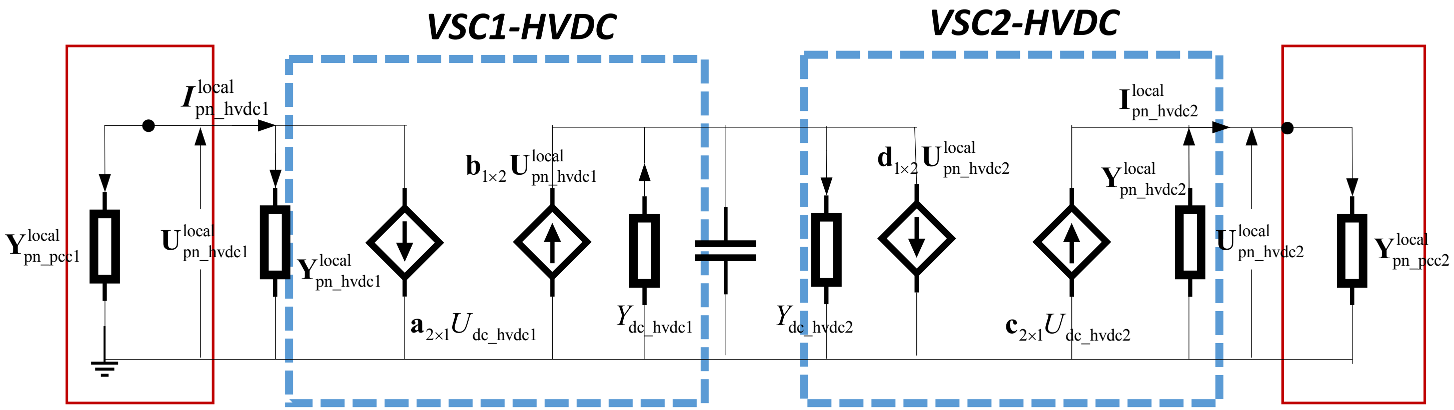
Impedance operator **for AC/DC coupled VSCs in MSD :** $\mathbf{T}_{\text{rot\_hvdc}}\left(\theta_{\text{hvdc1}}\right)$, θ_{hvdc1} **is the relative angle of the HVDC local frame to the global frame.**

DC side impedance: $$I_{\text{dc\_hvdc1}} = \left[\mathbf{b}_{1\times 2}\left(\mathbf{Y}_{\text{pn\_pcc1}}^{\text{local}} - \mathbf{Y}_{\text{pn\_hvdc1}}^{\text{local}}\right)^{-1}\mathbf{a}_{2\times 1} + Y_{\text{dc\_hvdc1}}\right] \cdot U_{\text{dc\_hvdc1}}$$

Properties:

P.1 When evaluating at the dc side of the HVDC, all the ac impedances of two sides (e.g. sending and receiving area), should be transformed to the individual reference provided by each HVDC terminal, corresponding ***AC IO*** is (e.g. the sending area): $\mathbf{T}_{\text{rot}}\left(\theta_i - \theta_{\text{hvdc1}}\right)$, θ_i is the *i* th VSC load angle relative to the common reference frame.

Circuit representation of AC/DC coupled system



Sending area: AC impedances are operated by the **AC IO**:

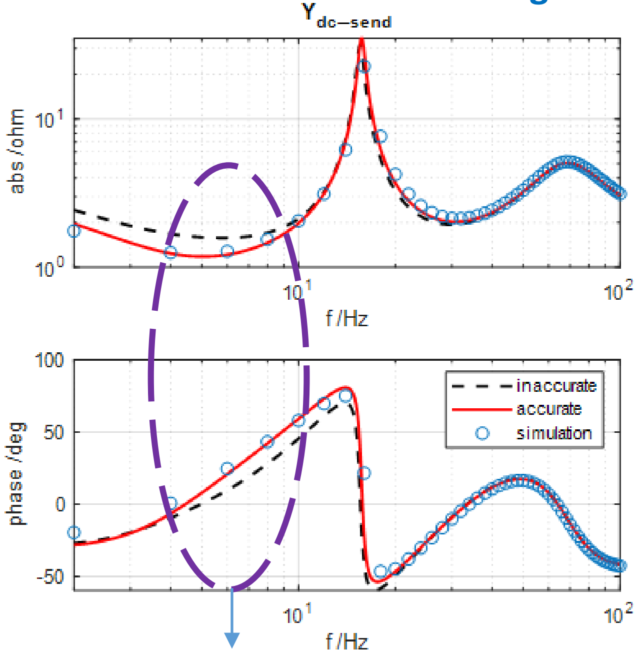
$$\mathbf{T}_{rot}\left(\theta_i - \theta_{hvdc1}\right)$$

Receiving area ：AC impedances in the are operated by the **AC IO**:

$$\mathbf{T}_{rot}\left(\theta_j - \theta_{hvdc2}\right)$$

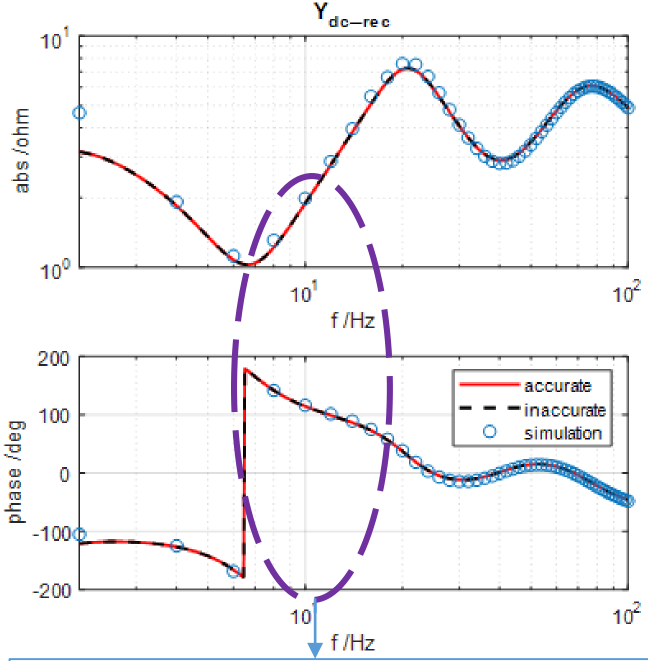
Impact of AC/DC IO on Impedance Characteristics

DC side admittance of sending area



- Evident discrepancies at low frequency range if the correct IO is not applied.

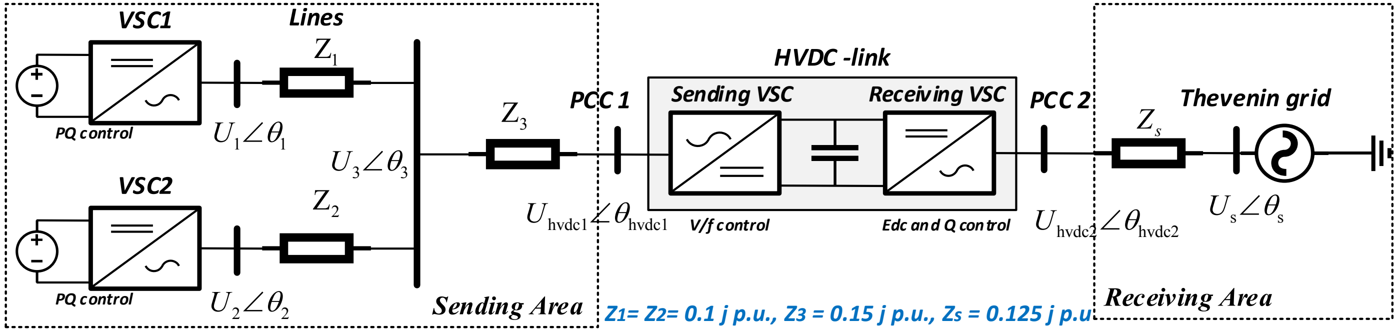
DC side admittance of receiving area



- The receiving area does not get affected by the IO because there are no active AC impedances (e.g. VSC) in this area.

Impact of IO on Stability Assessment

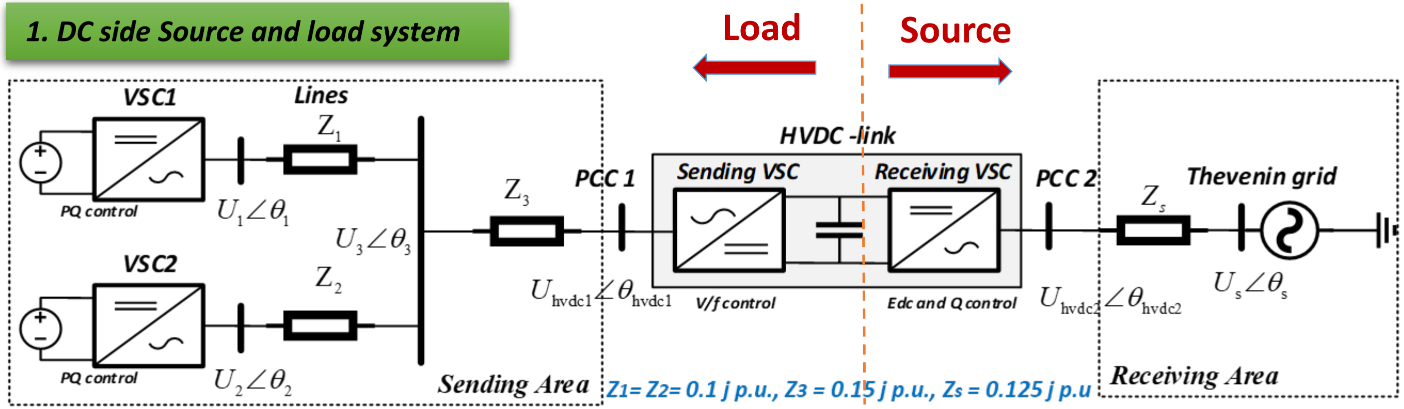
Study System :



Controllers	VSC1	VSC2	HVDC_sending	HVDC_receiving
Current controller	300Hz	300Hz	300Hz	300Hz
PLL	10Hz	10Hz	None	20Hz
Outer loop	10 Hz (PQ)	10 Hz (PQ)	AC voltage *kp* = 1 *ki* = 2;	10 Hz: Q 40 Hz: DC voltage
Active power	1.0 p.u.	1.0 p.u.		

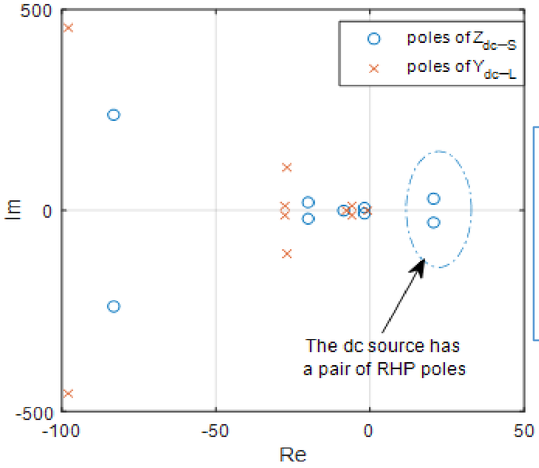
Nyquist-based stability analysis— *open loop poles check*

1. DC side Source and load system



2. Open-loop poles check

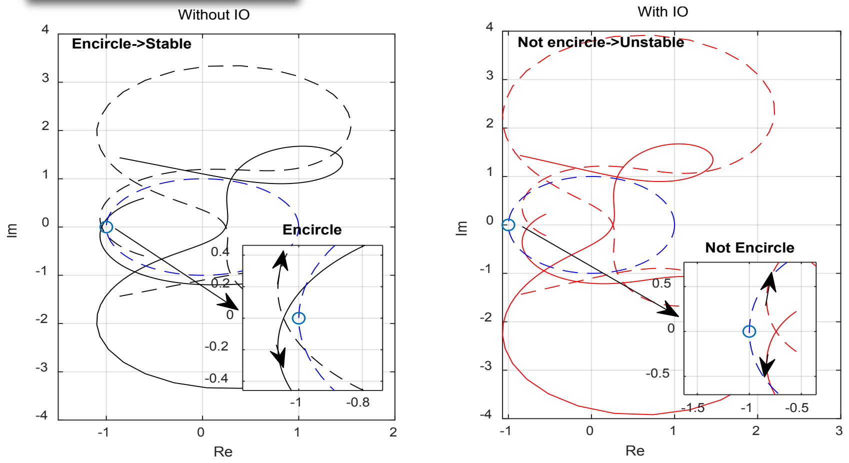
- The source has **<u>a pair of RHP</u>** poles;
- The load does not have any RHP poles;

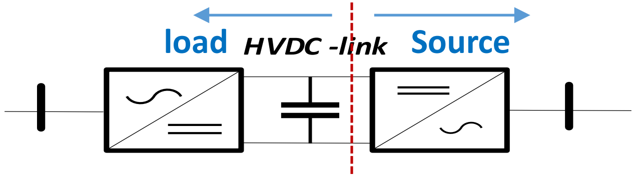


✓ *Due to the presence of RHP open-loop poles, a clockwise encirclement indicates a stable system*

Nyquist-based stability analysis— *Nyquist plots and simulation*

3. Nyquist plots

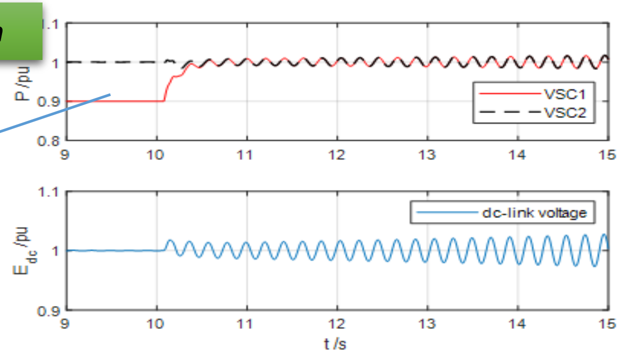




- ***Without*** the IO, predicts a ***stable*** system
- ***With*** the IO, predicts an ***unstable*** system

4. Time domain verification

- A small perturbation on the active power of VSC 1 is applied



✓ ***The system is indeed unstable***

✓ ***With the IO, draws the correct stability conclusion.***

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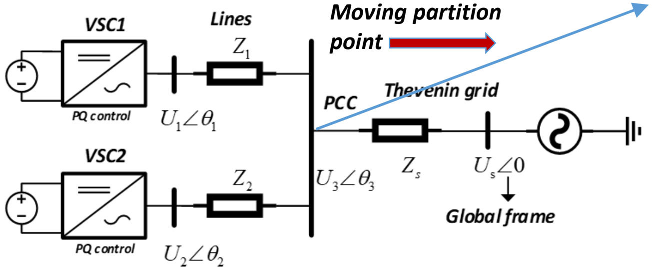
Impact of partition points on open-loop poles

Study system



Partition point moves from PCC towards the grid, emulated by the factor k_{part} .

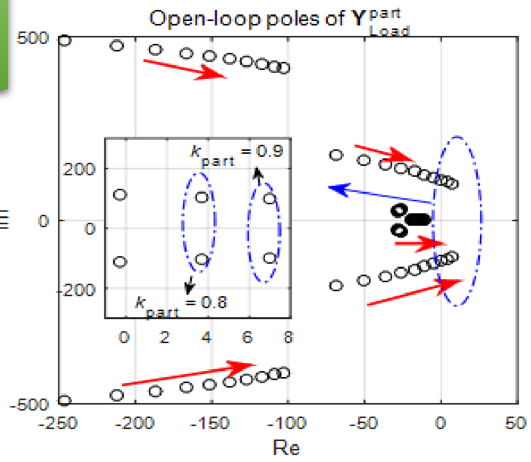
Equivalent source and load sub-systems as:

$$\boldsymbol{Z}_{\text{Source}}^{\text{part}}(s) = \left(1 - k_{\text{part}}\right)\boldsymbol{Z}_{\text{Source}}(s)$$

$$\boldsymbol{Y}_{\text{Load}}^{\text{part}}(s) = \left[\boldsymbol{Y}_{\text{Load}}^{-1}(s) + k_{\text{part}}\boldsymbol{Z}_{\text{Source}}(s)\right]^{-1}$$

Open-loop poles of the load with moving partition points

- As the partition points moves from PCC towards the grid, i.e. away from VSC terminal: ***poles of the load cannot be guaranteed in the LHP.***

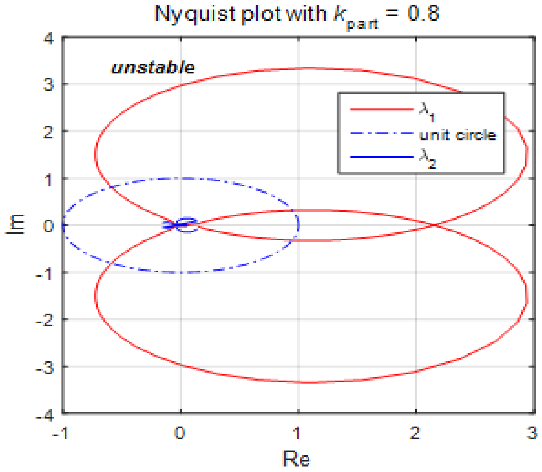


- Around $k_{part} = 0.8$, a pair of RHP poles appears.

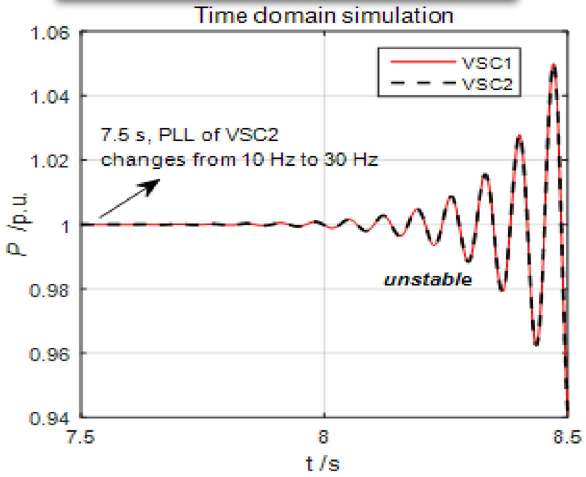
✓ ***A clockwise encirclement indicates a stable system.***

Nyquist-based analysis and simulation

Nyquist plots with k_{part} = 0.8



Time domain simulation



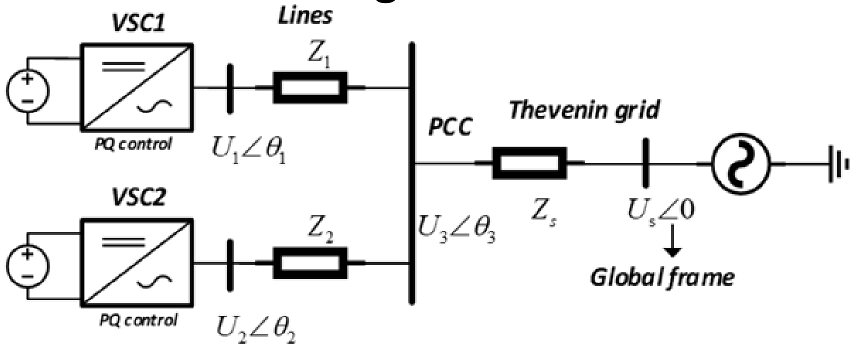
Parameters: for both VSC 1 and VSC2: PQ = 20 Hz, PLL = 30 Hz, CC = 300 Hz, P = 1.0 p.u., Z1 = Z2 = 0.1 j p.u., Zs = 0.1333 p.u.

- *Since there are no encirclements of the critical point, the system is an* ***unstable*** *one.*
- *Simulation also indicates an unstable system.*

✓ ***Open loop poles cannot be guaranteed in the LHP due to the interconnection. Therefore, as the partition point moves away from VSC terminal, open loop poles should always be checked.***

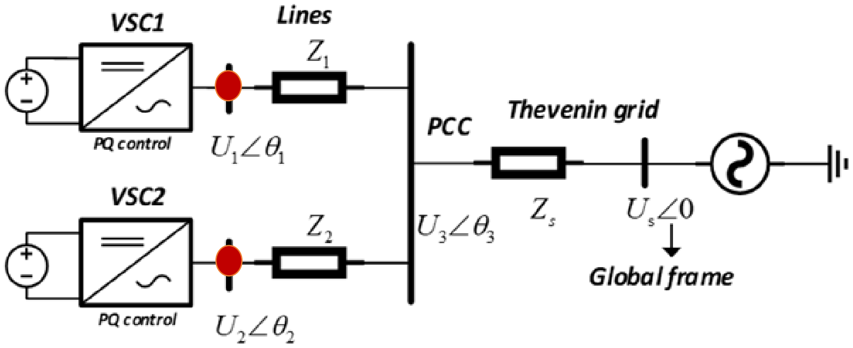
Sensitivity analysis of partition points—The relative stability margin

- Motivation
  - Previous Nyquist-based analysis can draw the overall stability conclusion accurately, but it cannot tell which part of the system is most vulnerable in terms of small signal perturbations. i.e. relative stability margin.
  - e.g. which VSC in the figure is less stable.



Sensitivity analysis of partition points —Identification of system’s weak point

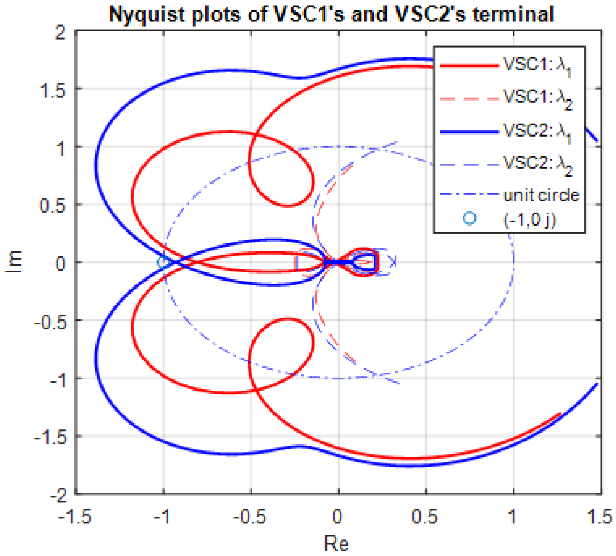
- A possible way
  - Evaluating and comparing the stability margin at interested points, can be a counterpart to the sensitivity analysis of eigenvalues of state-space models.
  - e.g. evaluating the margin at U1 and U2…



VSC1: CC = 300 Hz, PLL = 10 Hz, PQ = 10 Hz, P = 1.0 p.u.
VSC2: CC = 240 Hz, PLL = 25 Hz, PQ = 10 Hz, P = 1.0 p.u.
Lines: Z1 = Z2 = 0.1 j p.u., Zs = 0.125 p.u

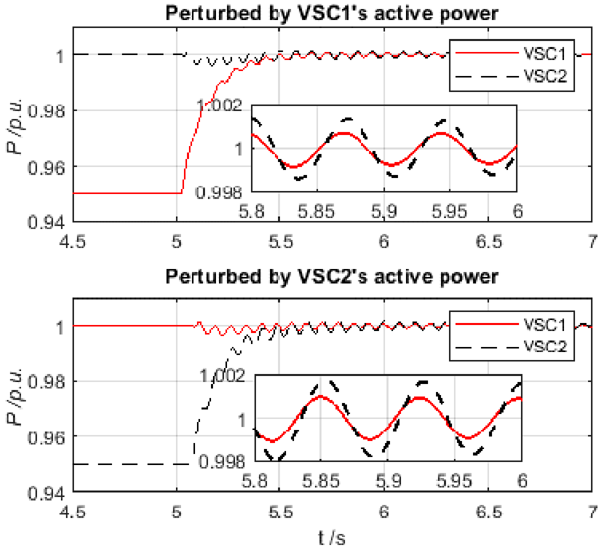
Preliminary results

Nyquist plots evaluated at VSC1 and VSC2 terminal



- *VSC2 exhibits* ***less margin*** *than VSC 1*

Time domain simulation



- *Time domain responses of VSC2 indeed exhibits* ***less damping*** *than VSC 1, regardless of the location of perturbations*

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Conclusions

- ❑ Impedance operator and associated properties for AC and AC/DC coupled systems;
- ❑ Impedance operator is verified through frequency responses, and its impacts on stability are emphasized;
- ❑ Sensitivity analysis of partition points through Nyquist-based analysis is explored:
  - ❑Impact of partition points on open-loop poles
  - ❑The capability of partition points and margin information of Nyquist plots for identifying the system's weak points.

For more details on this work click below:

https://www.researchgate.net/publication/328997531_Impedance_Network_of_Interconnected_Power_Electronics_Systems_Impedance_Operator_and_Stability_Criterion