Control of HVDC Transmission Systems: *1-2-Many Coordinated HVDC Links*

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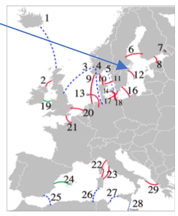
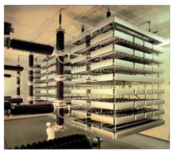
High Voltage Direct Current (HVDC) Transmission

- World's first commercial HVDC link in 1954
- Traditional HVDC tradeoffs
  - \+ Lower resistive losses for long transmissions
  - \+ Separating asynchronous AC systems
  - – Expensive converters
- Emerging use of HVDC
  - Inter-area oscillation damping
  - Sharing frequency control reserves
  - Integration of renewables (offshore grids)



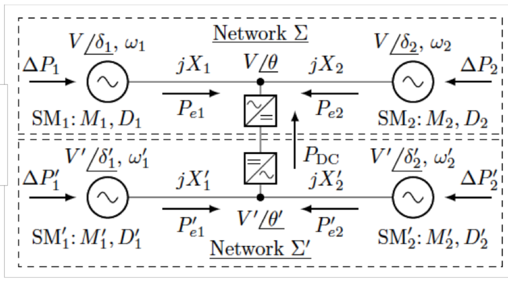


- **J. Björk**, K. H. Johansson, and L. Harnefors, Fundamental performance limitations utilizing HVDC to damp interarea modes. IEEE Transactions on Power Systems, 2019
- **J. Björk**, K. H. Johansson, L. Harnefors, and R. Eriksson, Analysis of coordinated HVDC control for power oscillation damping, IEEE Workshop on the Electronic Power Grid, 2018
- **M. Andreasson**, R. Wiget, D. V. Dimarogonas, K. H. Johansson, and G. Andersson, Distributed frequency control through MTDC transmission systems. IEEE Transactions on Power Systems, 2017

Power Oscillation Damping using HVDC

AC networks represented by two two-machine models:

$$\dot{\delta}_i = \omega_i$$
$$M_i\dot{\omega}_i = \Delta P_i - \overbrace{\frac{V^2}{X_i}\sin(\delta_i - \theta)}^{P_{ei}} - D_i\omega_i$$



Interconnected by HVDC link

$$P_{\mathrm{DC}} + \sum_{i=1}^{2} \frac{V^2}{X_i}\sin(\delta_i - \theta) = 0$$

Linearization gives overall dynamics

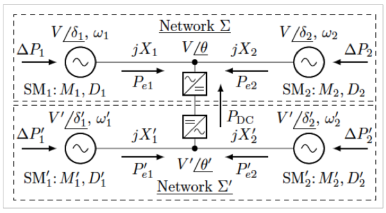
$$\dot{\boldsymbol{z}} \triangleq \begin{bmatrix} \dot{z} \\ \dot{z}' \end{bmatrix} = \begin{bmatrix} A_z & 0 \\ 0 & A'_z \end{bmatrix} \begin{bmatrix} z \\ z' \end{bmatrix} + \begin{bmatrix} B_z \\ B'_z \end{bmatrix} \boldsymbol{u} \triangleq \boldsymbol{A}_z \boldsymbol{z} + \boldsymbol{B}_z \boldsymbol{u}$$

with states corresponding to relative angles and frequencies, and control $u = P_{\mathrm{DC}}$.

Harnefors et al., 2017; Björk et al., 2018

Fundamental Limitations in Single-line HVDC Power Oscillation Damping

Proximity in frequencies f_0 and f_0' of poorly damped oscillatory modes in the AC networks limits the achievable power oscillation damping



Follows from a controllability analysis with Gramian

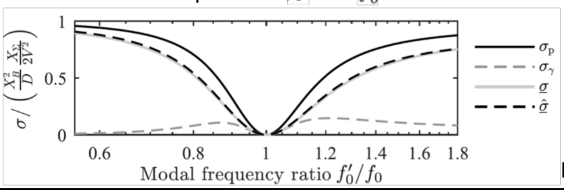
$$\boldsymbol{W}_C = \int_0^T e^{\boldsymbol{A}_z t} \boldsymbol{B}_z \boldsymbol{B}_z^T e^{\boldsymbol{A}_z^T t} dt.$$

representing the control effort required to transfer an initially disturbed system state to the origin

$$\|\boldsymbol{u}\|_2^2 = z_0^T \boldsymbol{W}_C^{-1} z_0$$

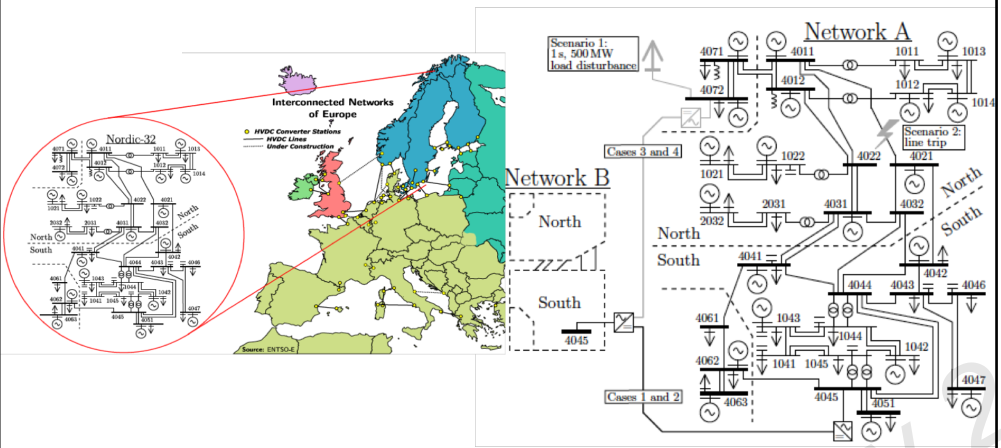
Controllability lost when the modal frequencies f_0 and f_0' are close.

Normalized $\sigma(W_C)$:



Björk et al., 2019

Numerical Study on Two Interconnected Nordic 32-bus Models



Björk et al., 2019

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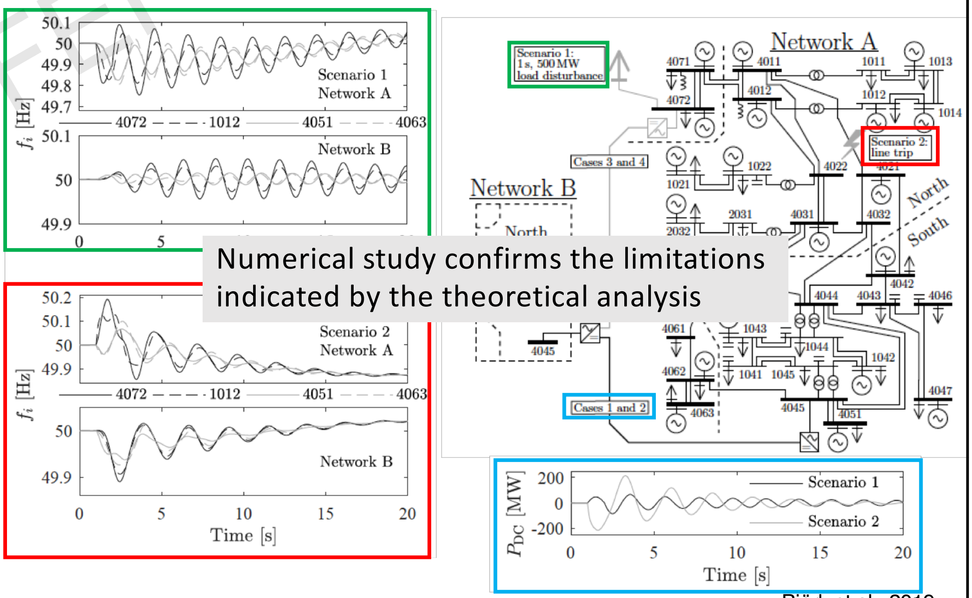
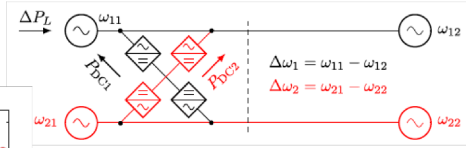


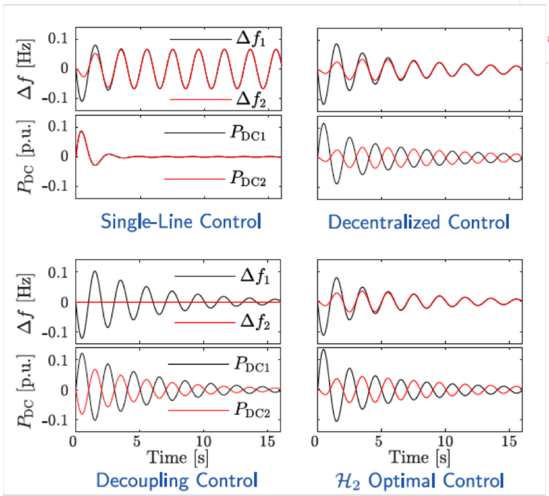
Numerical study confirms the limitations indicated by the theoretical analysis

Björk et al., 2019

Two Coordinated HVDC Lines

Two coordinated HVDC lines do not have the same limitations as single lines

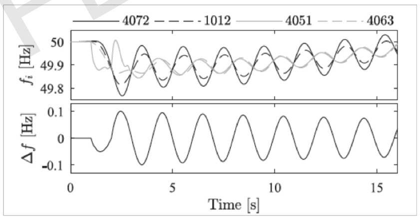




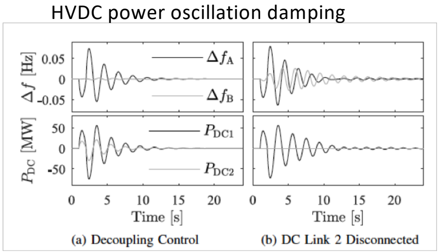
Björk et al., 2018

Interconnected Nordic 32-bus Models Revisited

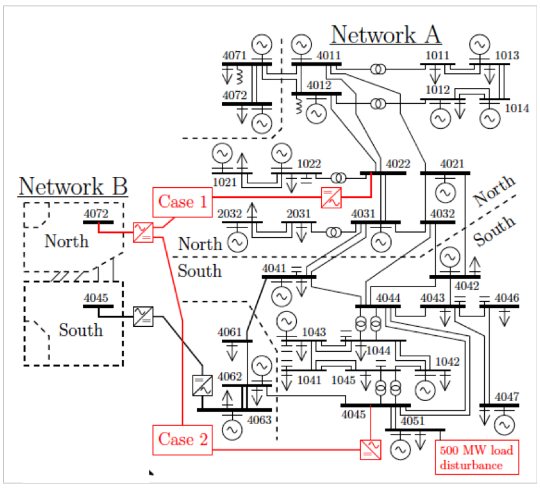
Disturbance response without HVDC power oscillation damping



Disturbance and fault responses with HVDC power oscillation damping

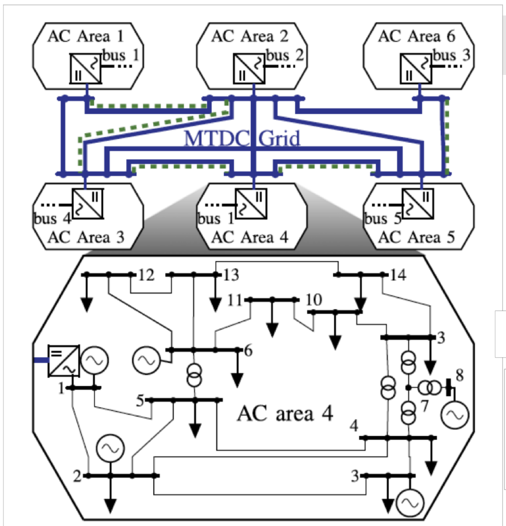


Inter-area oscillatory mode frequencies f_0=0.5 and f'_0=0.6 Hz for Networks A and B



Björk et al., 2018

Distributed Frequency Control Through **Multi-Terminal HVDC** Transmission Systems



IEEE 14 bus AC grid

Andreasson et al., 2017

How to share frequency control reserves between AC areas through a multi-terminal HVDC grid?

Converter dynamics

$$C_i \dot{V}_i = -\sum_{j \in \mathcal{N}_i} \frac{1}{R_{ij}} (V_i - V_j) + I_i^{\text{inj}},$$

AC system dynamics (single generator)

$$m_i \dot{\omega}_i = P_i^{\text{gen}} + P_i^m - P_i^{\text{inj}}$$

Objectives

$$\lim_{t \to \infty} \omega_i(t) - \omega^{\text{ref}} = 0 \quad i = 1, \dots, n,$$

$$\lim_{t \to \infty} P_i^{\text{gen}} = P_i^{\text{gen}^*}, \forall i = 1, \dots, n, \text{ where}$$

$$[P_1^{\text{gen}^*}, \dots, P_n^{\text{gen}^*}] = \operatorname*{argmin}_{P_1, \dots, P_n} \frac{1}{2} \sum_{i=1}^{n} f_i^P \left(P_i^{\text{gen}}\right)^2$$

$$\lim_{t \to \infty} V_i = \breve{V}_i^*$$

$$[V_1^*, \dots, V_n^*] = \operatorname*{argmin}_{V_1, \dots, V_n} \frac{1}{2} \sum_{i=1}^{n} f_i^V (V_i - V_i^{\text{ref}})^2$$

Stability of Distributed Frequency Control

Distributed generation controller of the AC systems

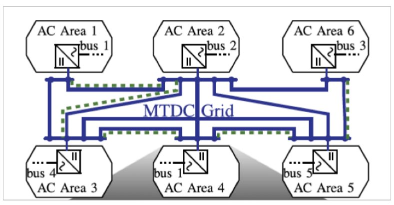
$$P_i^{\text{gen}} = -K_i^{\text{droop}} (\omega_i - \omega^{\text{ref}}) - \frac{K_i^V}{K_i^\omega} K_i^{\text{droop,I}} \eta_i$$

$$\dot{\eta}_i = K_i^{\text{droop,I}} (\omega_i - \omega^{\text{ref}}) - \sum_{j \in \mathcal{N}_i} c_{ij}^\eta (\eta_i - \eta_j),$$

Converter controller for the HVDC lines

$$P_i^{\text{inj}} = K_i^\omega (\omega_i - \omega^{\text{ref}}) + K_i^V (V_i^{\text{ref}} - V_i) + \sum_{j \in \mathcal{N}_i} c_{ij}^\phi (\phi_i - \phi_j)$$

$$\dot{\phi}_i = \frac{K_i^\omega}{K_i^V} \omega_i - \gamma \phi_i,$$



Theorem

Suppose the Laplacian matrices of the HVDC grid and its communication graph fulfills

$$\mathcal{L}_\phi = k_\phi \mathcal{L}_R.$$

and the converter control gain satisfies

$$\gamma > k_\phi / (4V^{\text{nom}}).$$

Then, the closed-loop dynamics

$$\dot{\hat{\omega}} = M\Big(-(K^{\text{droop}} + K^\omega)\hat{\omega} + K^V \hat{V} - K^V (K^\omega)^{-1} K^{\text{droop,I}} \eta - \mathcal{L}_\phi S \phi'' + P^m \Big)$$

$$\dot{\hat{V}} = \frac{1}{V^{\text{nom}}} E K^\omega \hat{\omega} - E \left(\mathcal{L}_R + \frac{K^V}{V^{\text{nom}}} \right) \hat{V} + \frac{1}{V^{\text{nom}}} E \mathcal{L}_\phi S \phi''$$

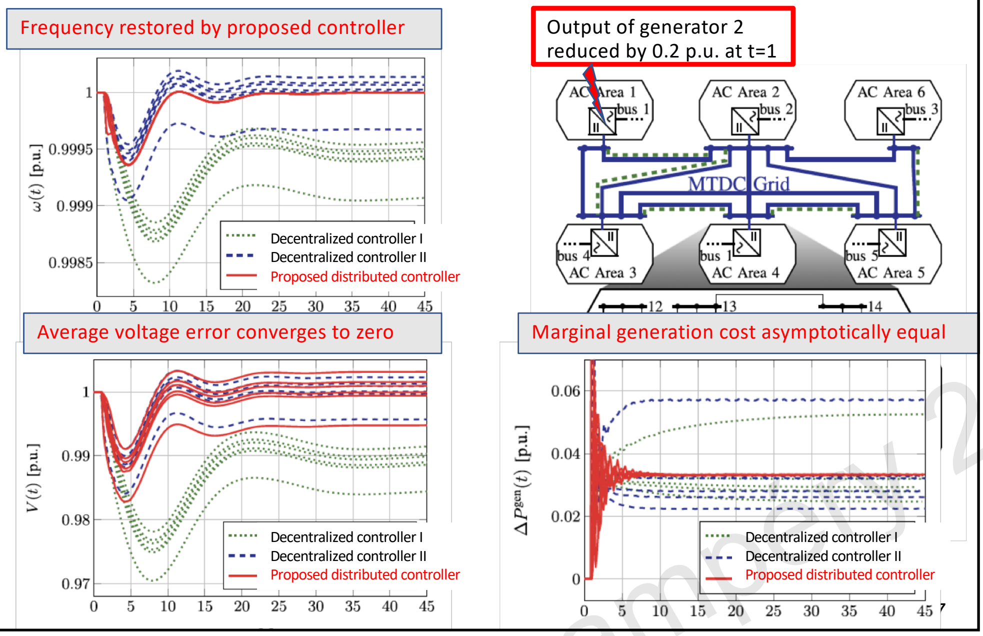
$$\dot{\eta} = K^{\text{droop,I}} \hat{\omega} - \mathcal{L}_\eta \eta$$

$$\dot{\phi}'' = S^T (K^V)^{-1} K^\omega \hat{\omega} - \gamma \phi''.$$

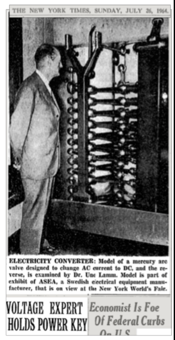
is globabally asymptotically stable. The objectives are fullfilled for classes of control parameters.

Andreasson et al., 2017

Simulation Evaluation of Proposed Controller



Conclusions



- HVDC can be used to damp inter-area oscillations
- Damping by single HVDC line poses some limitations
- Can be overcome by coordinating multiple HVDC lines
- Multi-terminal HVDC for frequency reserve control

Future work

- Detailed converter models in numerical studies
- Resilient coordinated HVDC control
- Realistic test scenarios in the Nordic grid

https://people.kth.se/~kallej