Open workshop on virtual inertia from HVDC converters in future power systems
28th April 2022

Representation of virtual inertia from HVDC converters and impact of placement

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Research project "HVDC inertia provision"

Outline

1) Implementation of control strategies for providing virtual inertia
   - Models developed for power system studies
   - Example of simulation results
   - Nordic 44-bus
2) Impact of placement of virtual inertia units
   - Problem description and use of centre of inertia concept for placement
   - Frequency deviation index
   - Case study: Nordic 44-bus
3) Concluding remarks

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1) Implementation of control strategies for providing virtual inertia

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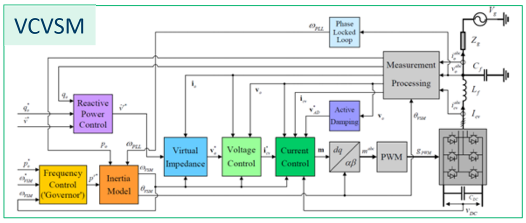
[1] Suul, J.A. and D'Arco, S., Comparative Analysis of Small-Signal Dynamics in Virtual Synchronous Machines and Frequency-Derivative-Based Inertia Emulation, IEEE 18th Inter. Power Electronics and Motion Control Conference (PEMC), 2018.

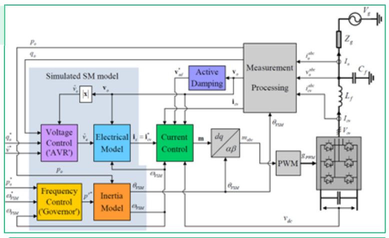
Models developed for power system studies

- Overall aim of control strategies for providing virtual inertia: to emulate the electromechanical characteristics of synchronous generators.
- Virtual Synchronous Machine (VSM)-based control: Internal simulation of virtual swing equation [1]
  - Voltage Controlled (VC) VSM
  - Current Controlled (CC) VSM
- Frequency derivative-based Inertia Emulation (IE): Equivalent inertial response of a SM calculated from the derivative of the grid frequency [1].
- Implementation in DigSILENT PowerFactory.

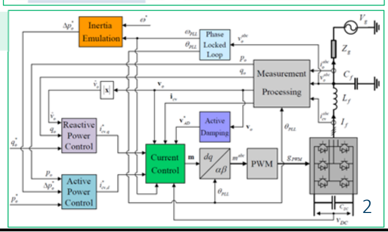
VCVSM



CCVSM



IE df/dt



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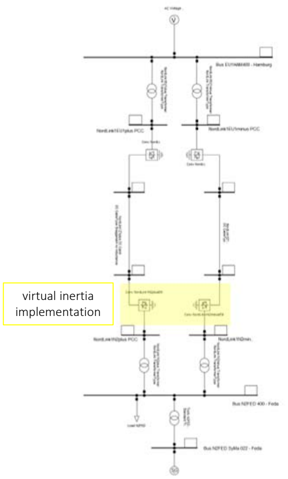
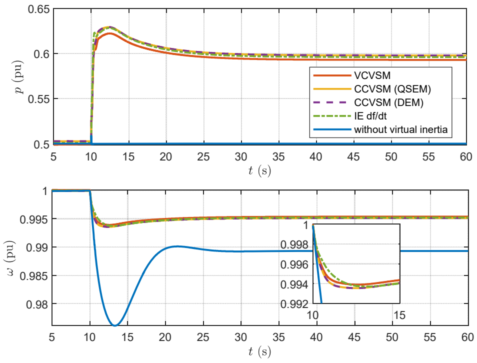
[2] Palombi, F., Piegari, L., D'Arco, S., Endegnanew, A.G., and J. A. Suul, Impact on power system frequency dynamics from an HVDC transmission system with converter stations controlled as virtual synchronous machines, Proc. of IEEE PowerTech Conf., 2019.

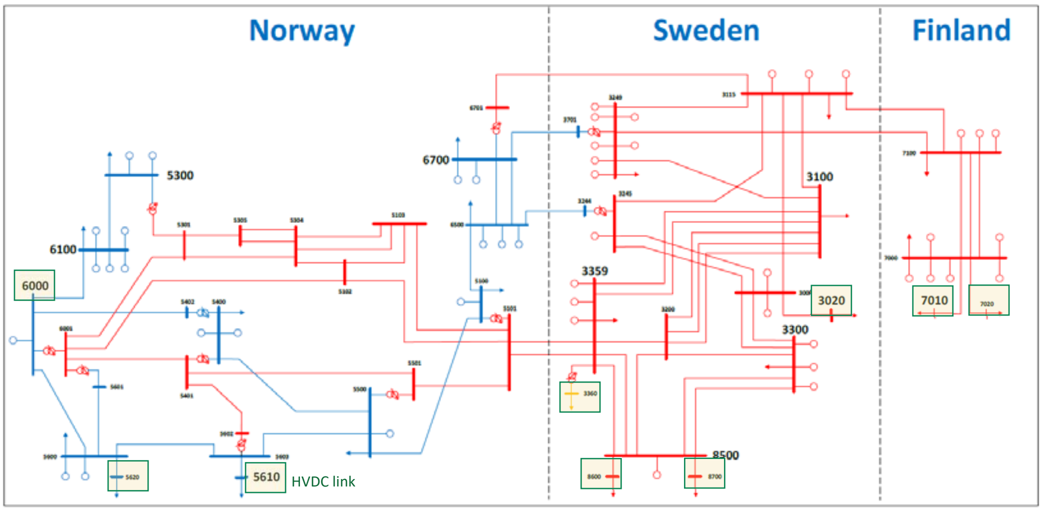
Example of simulation studies



- Figure (left): Single-line diagram of an HVDC transmission system with converter stations in PowerFactory. Initial model with the VCVSM as developed in [2].
- Point to point HVDC interconnector with an ideal AC voltage source (Europe side) and an equivalent AC grid (Norway side).
- HVDC interconnection based on characteristics of the interconnector between Norway and Germany (Nordlink).
- One side is controlled for virtual inertia provision.
- Figure (right): results from 10% load step at 10 seconds for different control strategies.



Nordic 44-bus model



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2) Impact of placement of virtual inertia units

[3] Ulbig, A., Borsche, T.S., Andersson, G., Impact of Low Rotational Inertia on Power System Stability and Operation, Proc. of the 19th IFAC World Congress 2014. [4] Borsche, T.S., Liu, T., Hill, D.J., Effects of Rotational Inertia on Power System Damping and Frequency Transients, Proc. of the 54th IEEE Conf. on Decision and Control, 2015. [5] Poolla, B.K., Bolognani, S., Dörfler, F., Optimal Placement of Virtual Inertia in Power Grids, IEEE Trans. on Automatic Control 62(12), 2017. [6] Poolla, B.K., Groß, D., and Dörfler, F., Placement and Implementation of Grid-Forming and Grid-Following Virtual Inertia and Fast Frequency Response, in IEEE Trans. on Power Systems 34(4), 2019.

Problem description

- Detrimental effects of reduced system inertia are worsened by spatially heterogeneous inertia profiles [3].
- Not only the total amount of system inertia is directly connected to the frequency stability and robustness of the grid, but also its specific location, especially in low inertia systems.
- Considering the possibility of adding synthetic inertia in the grid, and therefore, defining its location, many works, e.g. [4-6], have focused on the fundamental problem of “where to optimally place synthetic inertia in the grid".
  - Different metrics based on frequency transient behaviour after a disturbance.

[7] Pulgar-Painemal, H., Wang, Y., and Silva-Saravia, H., On inertia distribution, inter-area oscillations and location of electronically-interfaced resources, IEEE Trans. on Power System 33(1), 2018.

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Use of centre of inertia concept for placement

- The highest impact of devices with inertia emulation functionality on inter-area oscillations is obtained when
  - they are placed electrically the farthest away from the Center of Inertia (COI) [7],
  - COI frequency:

$$f_{COI} = \frac{\sum_{i=1}^{n} H_i f_i}{\sum_{i=1}^{n} H_i} \qquad (1)$$

- On this basis, the problem is to estimate the electrical distance of all buses from the COI, after a power disturbance.
- A proper metric to estimate this distance can be used to identify where to place the virtual inertia units.

(H_i: inertia constant of generator i, f_i: generator frequency)

[8] Garcia-Rosa, P.B., D'Arco, S., and Suul, J.A., Placement of virtual inertia from HVDC terminals based on a frequency deviation index, Proc. of IEEE PowerTech Conf., 2021.

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Frequency Deviation Index (FDI)

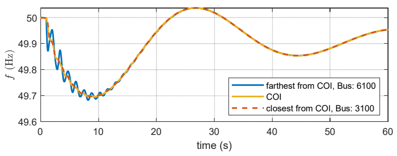
- To estimate the distance, an index (FDI) is proposed [8]. FDI estimates the maximum distance in Hz from each bus to the COI: ℓ_∞-norm of a vector of distances

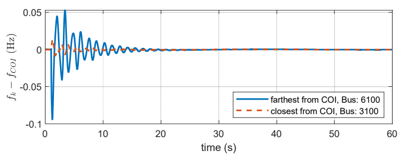
$$F_d \coloneqq \|d_k\|_\infty = \max_i |d_{k,i}| \qquad (2)$$

- Vector of distances for a bus k:

$$d_k = \left[\, f_{k,1} - f_{COI,1}, f_{k,2} - f_{COI,2}, \cdots, f_{k,n} - f_{COI,n} \,\right]^T \qquad (3)$$

- Example (from simulation results):





(n: total number of samples corresponding to a time interval t_m within a power disturbance, f_k: bus frequency, f_{COI}: COI frequency)

[8] Garcia-Rosa, P.B., D'Arco, S., and Suul, J.A., Placement of virtual inertia from HVDC terminals based on a frequency deviation index, Proc. of IEEE PowerTech Conf., 2021.

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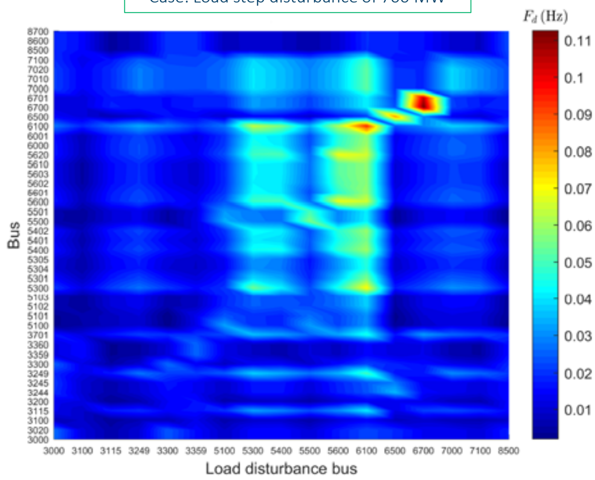
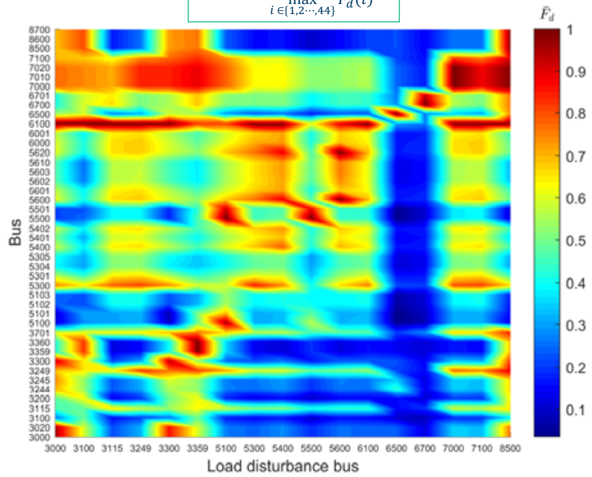
Case study: FDI on the Nordic 44-bus model

Case: Load step disturbance of 700 MW

$$\bar{F}_d(i) = \frac{F_d(i)}{\max_{i \in \{1,2\cdots,44\}} F_d(i)}$$





Normalization with respect to the highest F_d obtained for all 44 buses after a load disturbance

[8] Garcia-Rosa, P.B., D'Arco, S., and Suul, J.A., Placement of virtual inertia from HVDC terminals based on a frequency deviation index, Proc. of IEEE PowerTech Conf., 2021.

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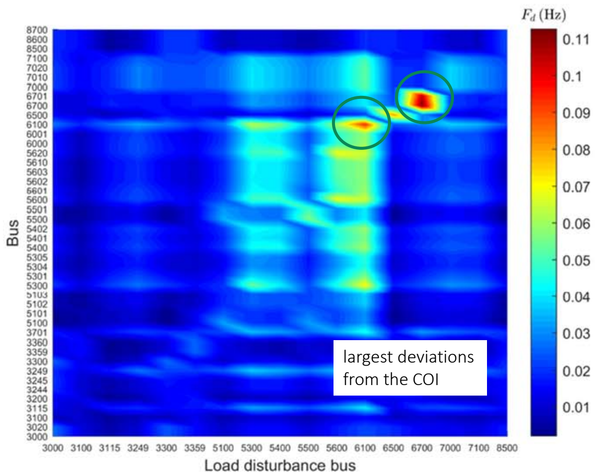
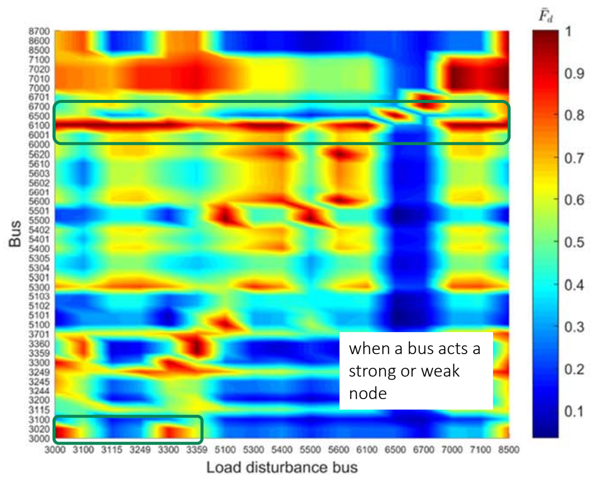
Case study: FDI on the Nordic 44-bus model

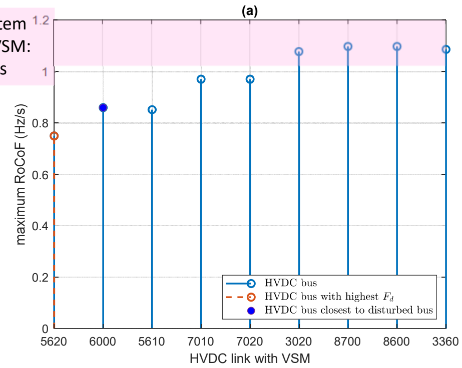




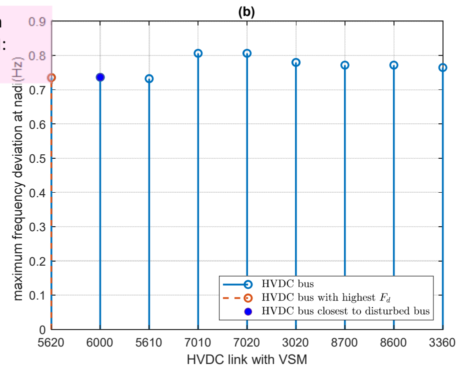
Case study: Placement of virtual inertia provided by HVDC converters on the N44

- Case: Load step disturbance of 2200 MW at bus 6100.
- VCVSM placed at each one of the HVDC buses (not at the same time).

Initial system without VSM: 1.014 Hz/s



Initial system without VSM: 0.958 Hz

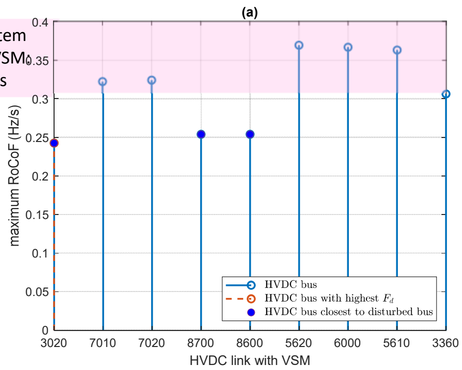


- When VCVSM is placed at HVDC bus with highest FDI, RoCoF and nadir shows better improvement.
- Some placements result in RoCoF worse than in the initial system.

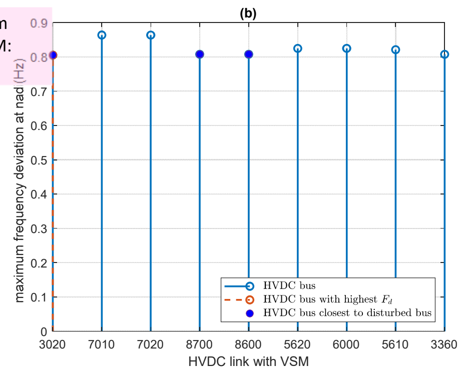
Case study: Placement of virtual inertia provided by HVDC converters on the N44

- Case: Load step disturbance of 2200 MW at bus 3300.
- VCVSM placed at each one of the HVDC buses (not at the same time).

Initial system without VSM: 0.312 Hz/s



Initial system without VSM: 1.020 Hz



- When VCVSM is placed at HVDC bus with highest FDI, RoCoF and nadir shows better improvement.
- Some placements result in RoCoF worse than in the initial system.

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3) Concluding remarks

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Conclusions: Impact of placement on RoCoF and frequency nadir

- While the implementation of VCVSM improves the frequency nadir regardless of where it is placed, this is not always the case for the RoCoF:
  - Some allocations result in higher RoCoF than in the initial system.
  - However, placing at an HVDC bus with the highest FDI results in lower RoCoF.
- The impact of placing the virtual inertia at different locations in the grid is not as significant for the frequency nadir as it is for the RoCoF:
  - An average improvement of about 29% was obtained for the RoCoF when the maximum observed values from different VCVSM placements are compared,
  - in contrast to an average improvement of about 6% when the frequency deviations at nadir are compared.

Conclusions: FDI

- An FDI map shows the impact of disturbances located at different buses and can be useful for indicating the magnitude of local transients (compared to the COI frequency).
- A map with the normalized indexes can indicate in which cases a bus will be electrically far or close from the COI.
  - This outlines that a bus is often far from the COI when there is a disturbance at the bus itself or around its neighborhood.
  - However, this is not the only case. For instance, numerical simulations with the N44 model showed that bus 6100 in Norway is the farthest from the COI for most of the load disturbances, regardless of the disturbance location.
  - Initial assessment indicates that placing virtual inertia at an HVDC bus with the highest FDI is a good option to improve both nadir and RoCoF.

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