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Risk of dc-side instabilities in VSC-based HVDC systems

Gustavo Pinares

Massimo Bongiorno

Chalmers University of Technology

Outline of the presentation

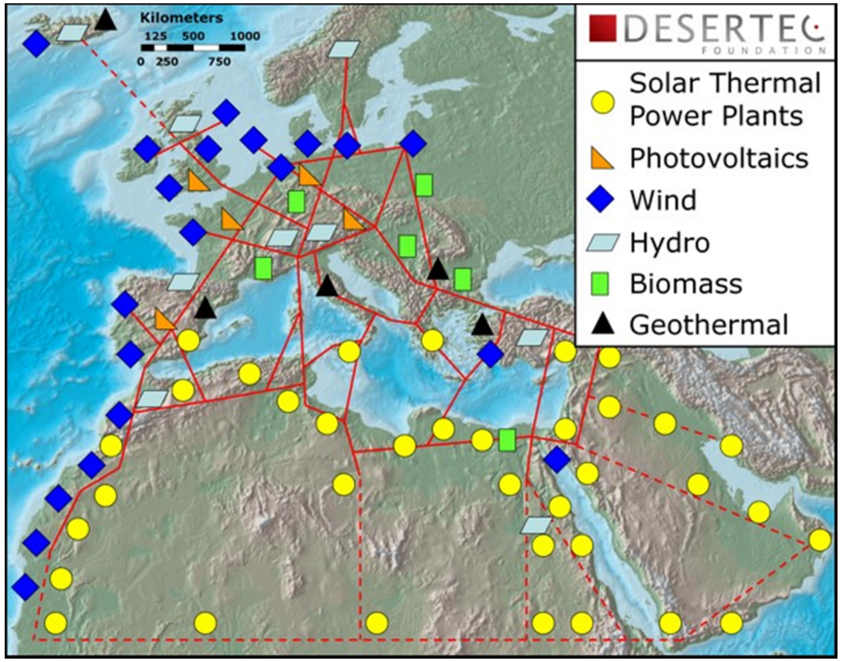
1. Background and motivation
2. VSC-HVDC modelling for eigenvalue analysis
3. Frequency domain modelling
4. Conclusions

Why HVDC systems and VSC?

Gotland, 1954
(figure from ABB)

<ins>Main advantage</ins>

Suitable for the transmission of high amounts of power over long distances.



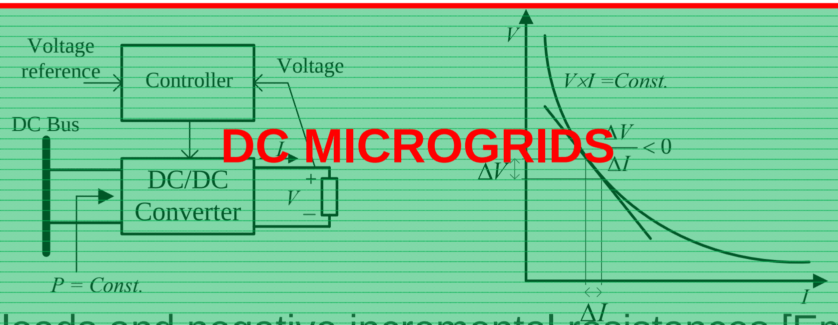
Challenges

Problems when VSCs are interconnected through cables?

Focused on the dc network dynamics

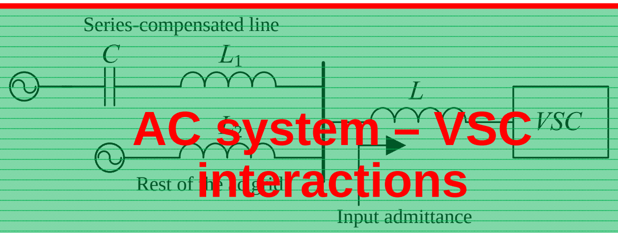
Dynamic issues in dc networks?

DC MICROGRIDS



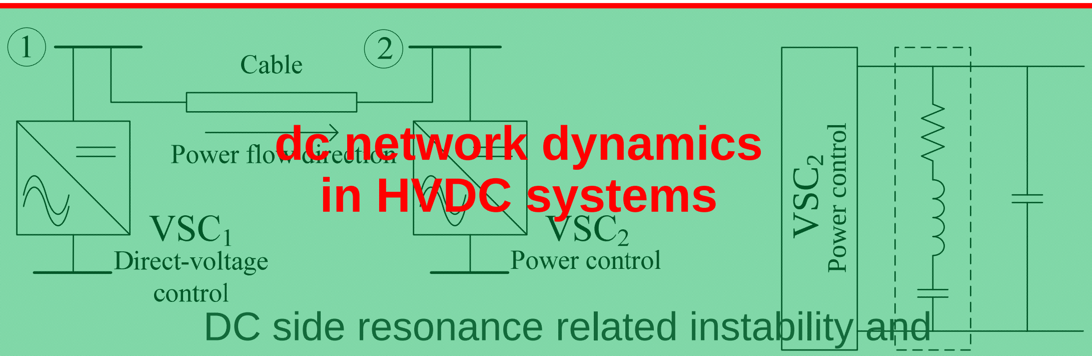
Constant power loads and negative incremental resistances [Emadi et al, 2006]

AC system – VSC interactions



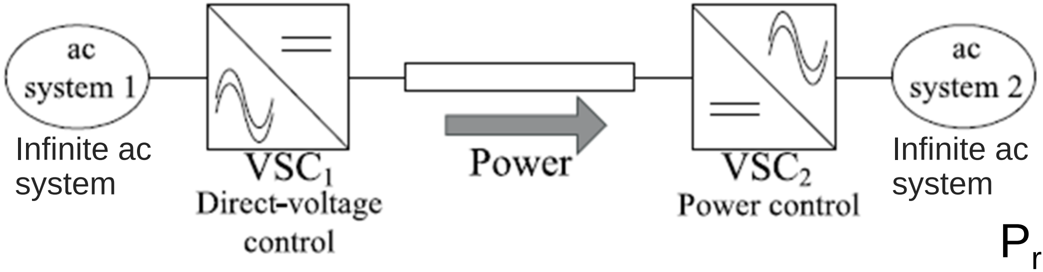
The input admittance concept [Harnefors et al, 2007]

dc network dynamics in HVDC systems



DC side resonance related instability and mitigation proposal [Tang, 2003]

Simulations in a point to point HVDC



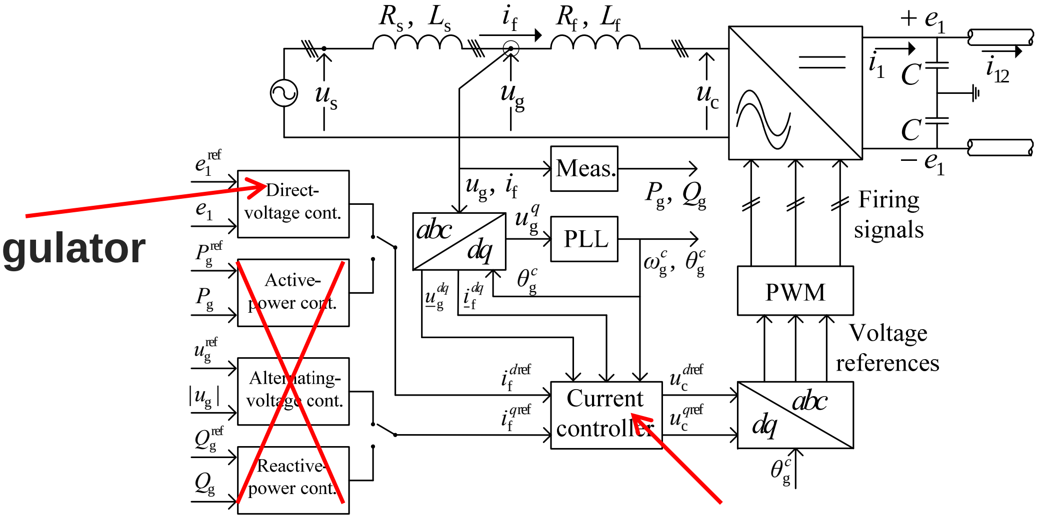
Infinite ac system

Infinite ac system

V_{ac}=300 kV

V_{dc}= ±300 kV

P_{rated} = 600 MW



PI regulator

PI regulator

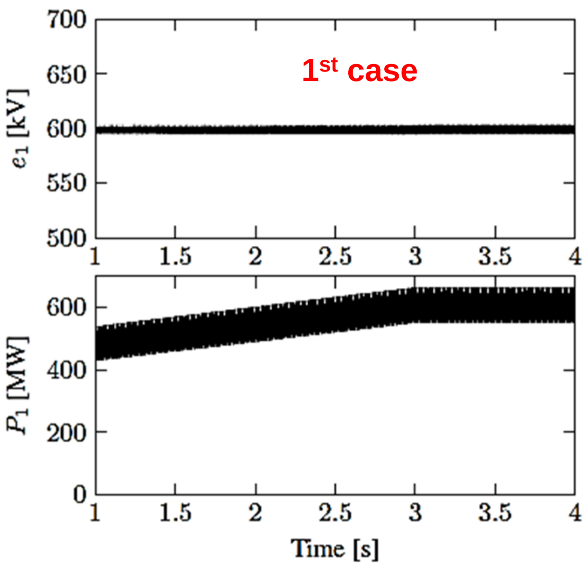
Simulated cases

Ramp up of the power transfer from 0 to 600 MW in both directions for:

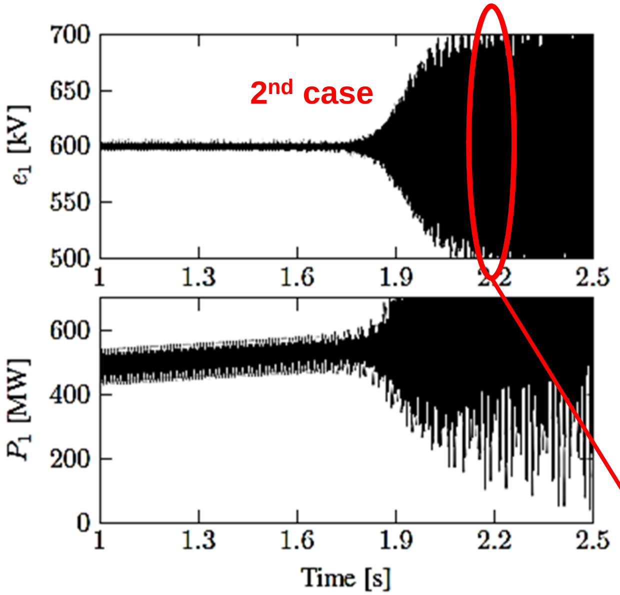
- High and low DVC gains and,
- 50 and 100 km cable length

Simulations in a point to point HVDC

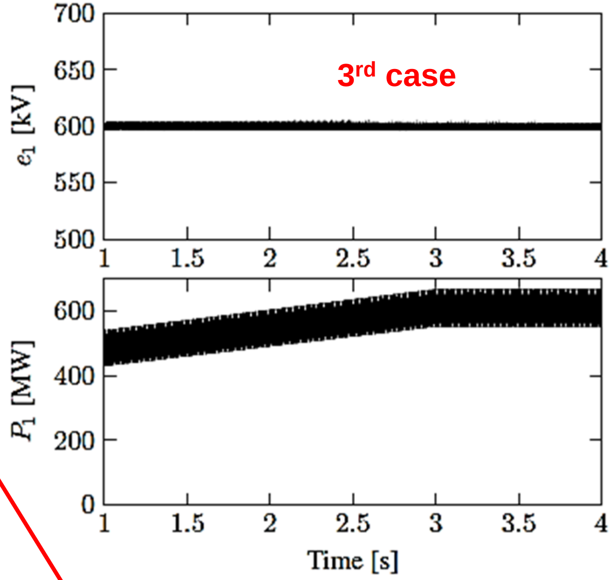
No problem for power increase from VSC$_2$ to VSC$_1$!



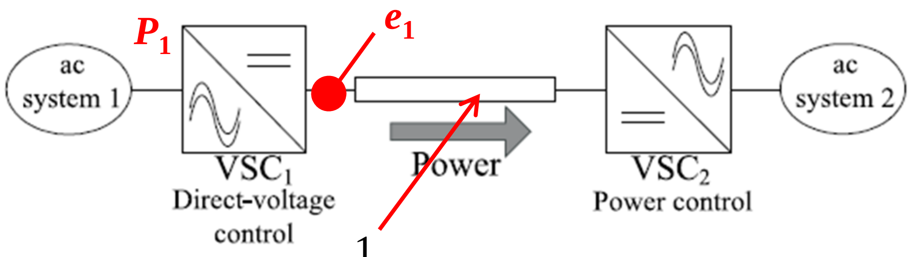
Low DVC gains, 50 km cable



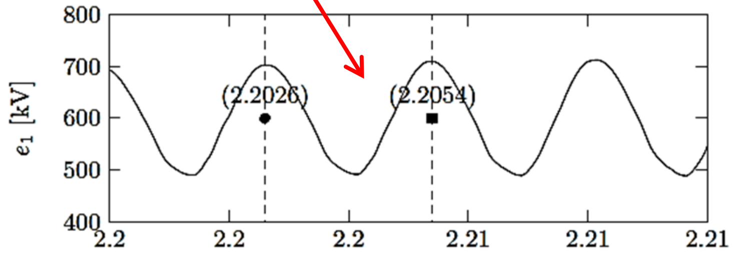
High DVC gains, 50 km cable



High DVC gains, 100 km cable



$$f_{\text{cable-res}} = \frac{1}{2\pi\sqrt{L_{\text{cable}}\left(\frac{C_{\text{cable}} + C_{\text{VSC}}}{2}\right)}} = 350.7\ \text{Hz}$$



Calculated resonance frequency = 357 Hz

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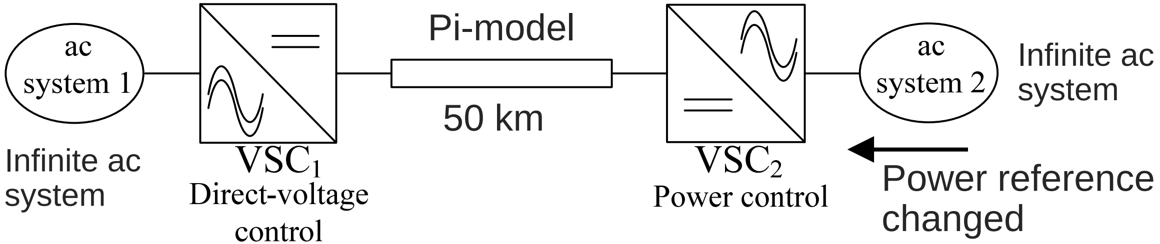
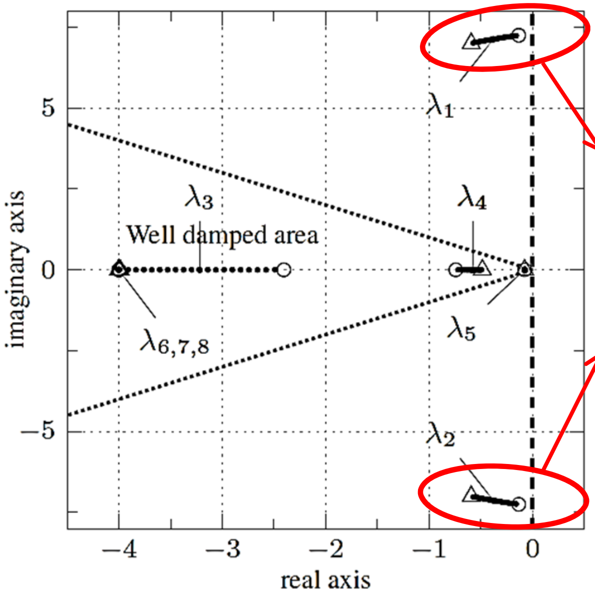
Eigenvalue calculations – impact of power flow and DVC gains



Power reference changed (positive)

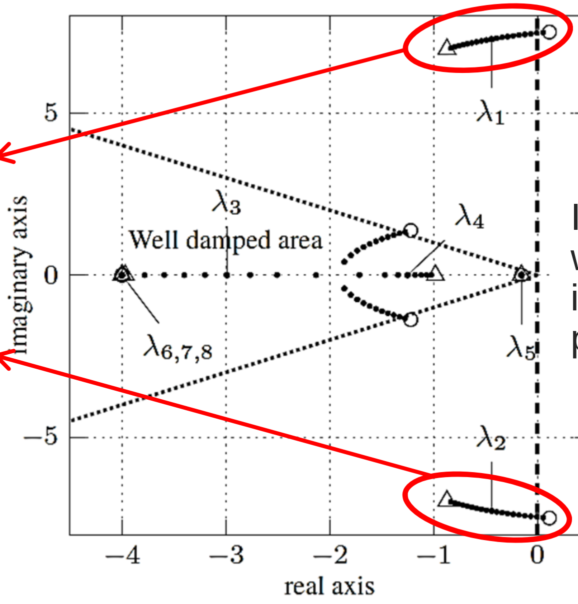
Power reference changed at VSC_2 from +1 to –1 pu



Low DVC gains

im. part of around 7 pu, i.e. 350 Hz

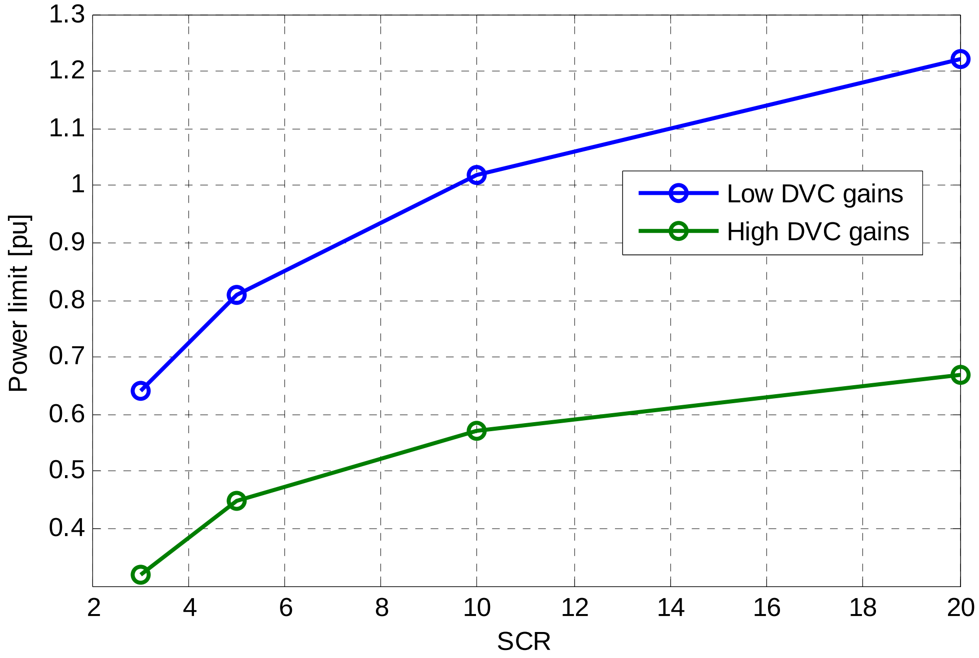
Resonance related poles!



High DVC gains

Instability occurs when the power is below –0.81 pu

Power limit vs ac system strength



SCR of the ac system to which the VSC that controls the direct voltage is connected.

For the same 50 km cable, power limit increases:

- As the Short Circuit Ratio (SCR) increases.
- As with low direct-voltage controller gains.

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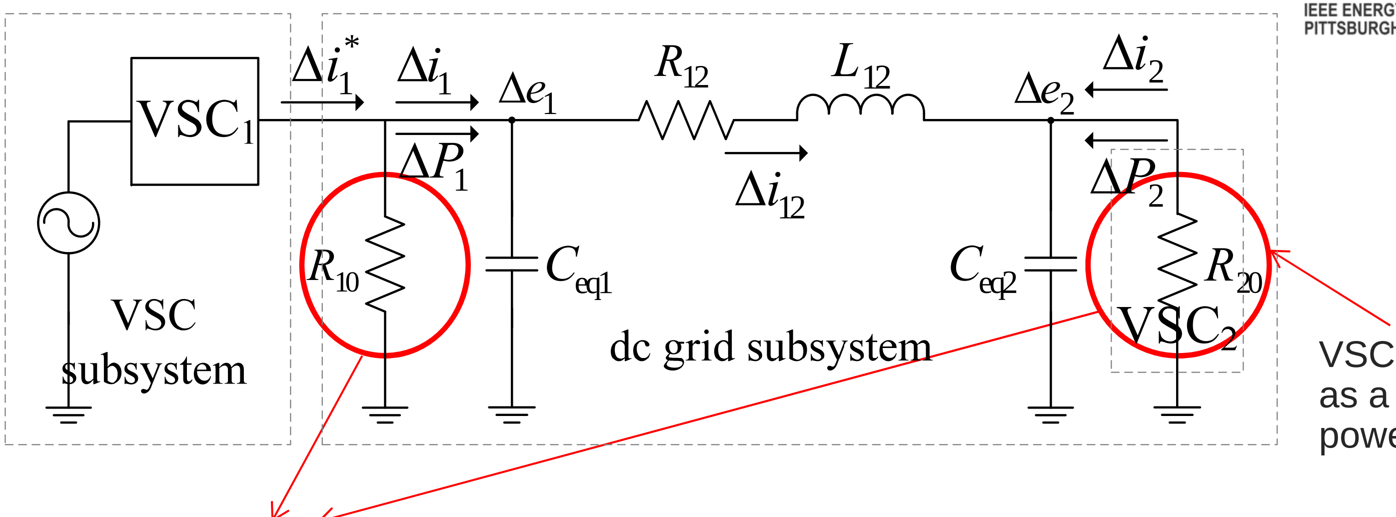
Small signal model



VSC$_2$ modelled as a constant power device

What are these resistances?

$$i_i = \frac{P_i}{e_i}$$

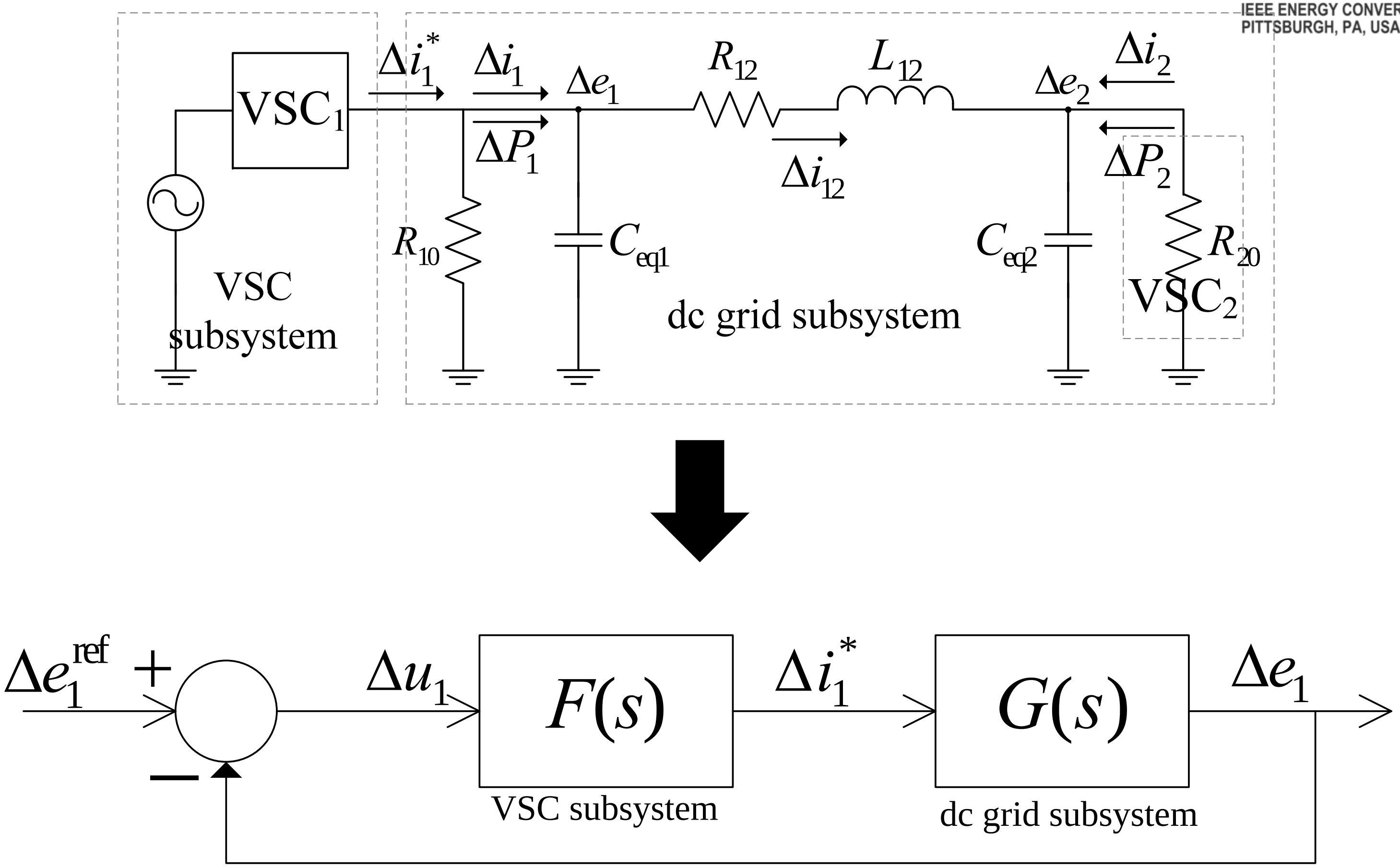
$$\Delta i_i = \underbrace{-\frac{P_{i0}}{e_{i0}^2}}_{\frac{1}{R_{i0}}}\Delta e_i + \underbrace{\frac{1}{e_{i0}}\Delta P_i}_{\Delta i_i^*}$$

where:

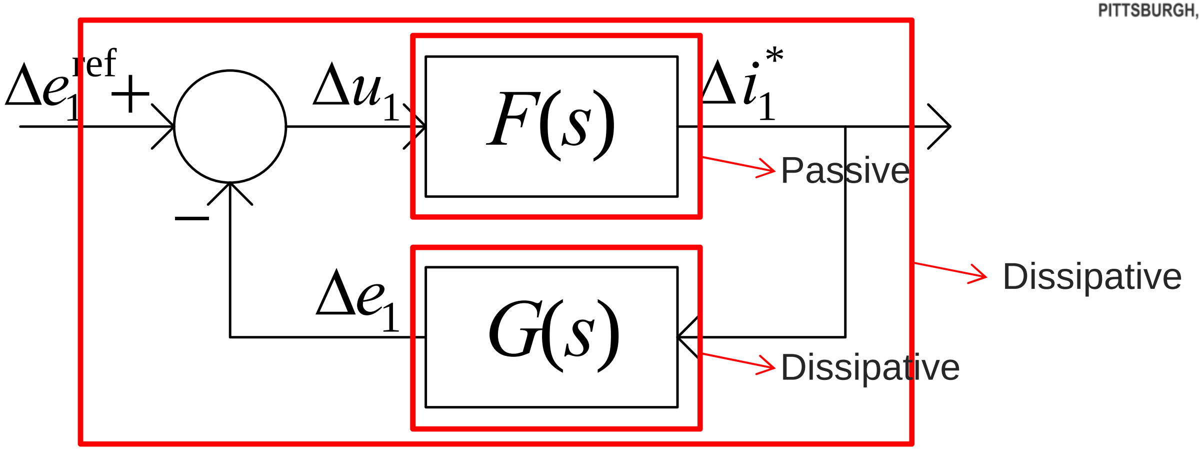
$$R_{10} = \frac{e_{10}^2}{P_{10}} \text{ and } R_{20} = \frac{e_{20}^2}{P_{20}}$$

$\Delta P_2 = 0$ VSC$_2$ is a constant power device

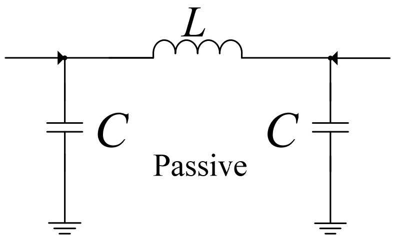
VSC-HVDC as a SISO feedback system

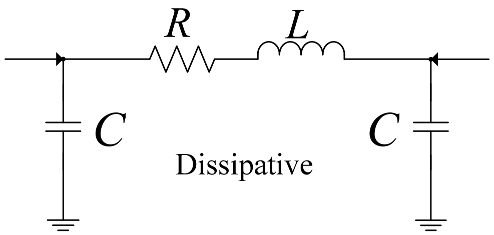


Passivity on feedback systems



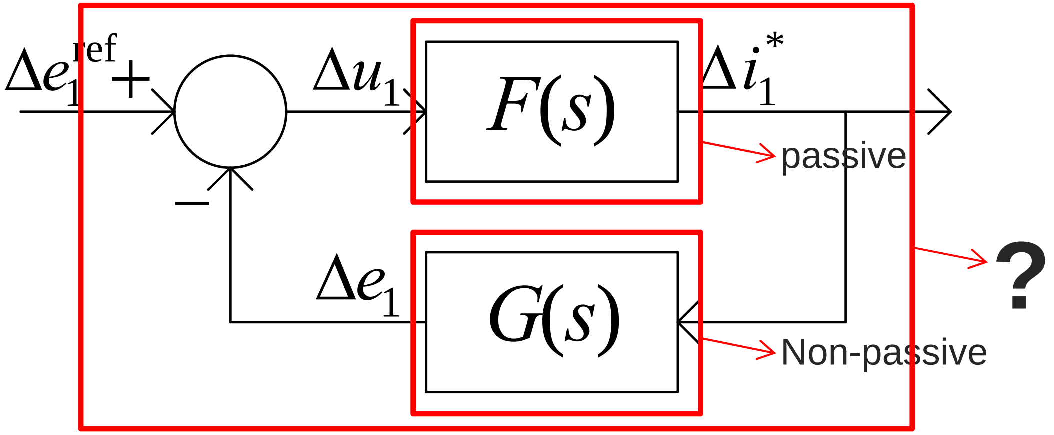
- If a system does not store more energy than what it is supplied, the system is passive. If a system dissipates energy, the system is dissipative. Examples:





- If $\mathrm{abs}(\mathrm{angle}[F(\mathrm{j}\omega)]) \leq 90^\circ$ and $F(\mathrm{s})$ is stable, then, the system is passive

Passivity on feedback systems



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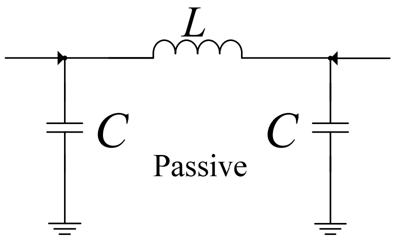
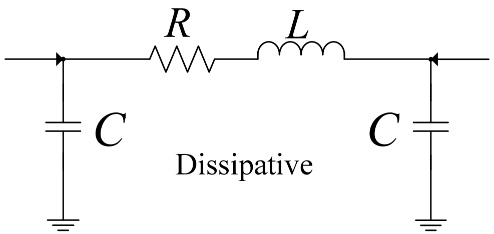
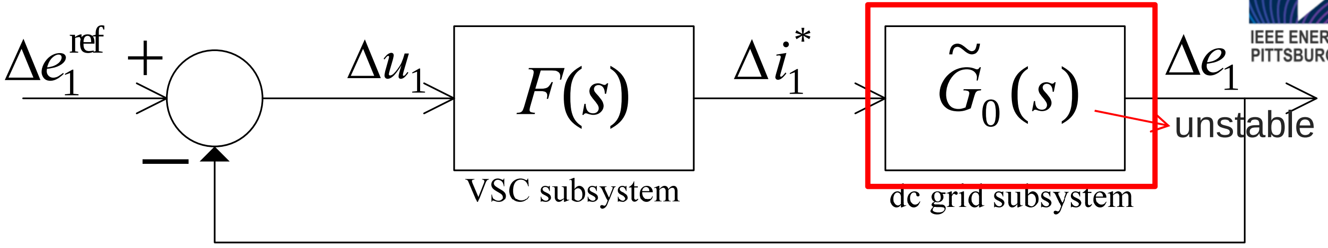


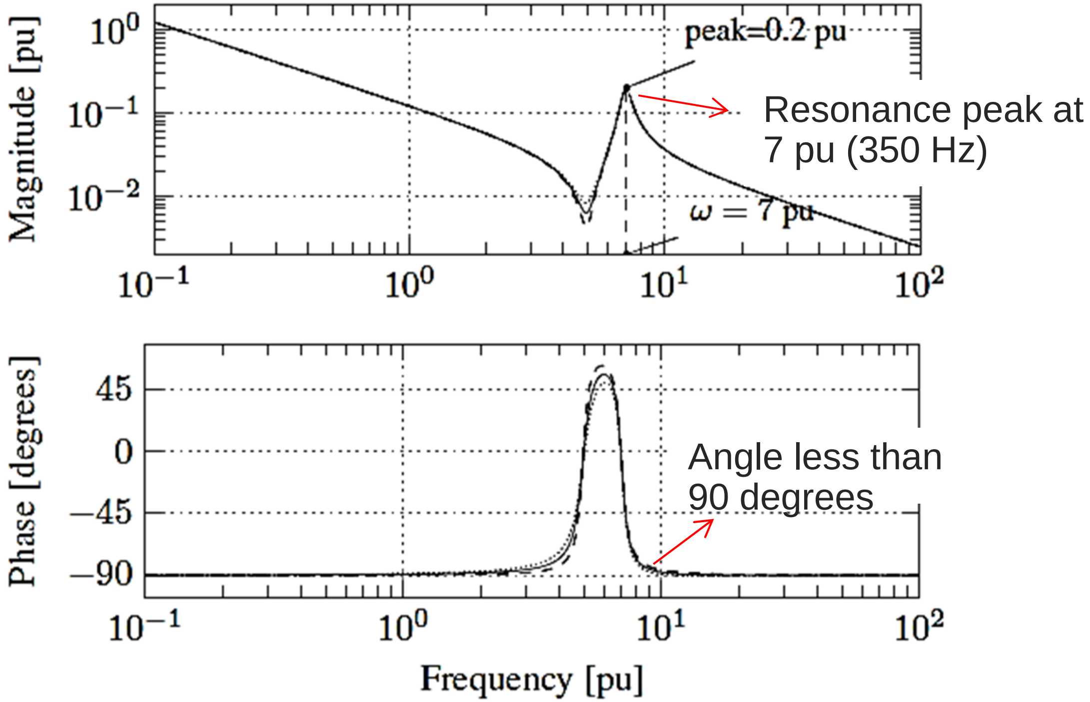


- If $\mathrm{abs}(\mathrm{angle}[F(j\omega)]) \le 90^\circ$ and $F(s)$ is stable, then, the system is passive

Frequency response of the dc grid subsystem



unstable

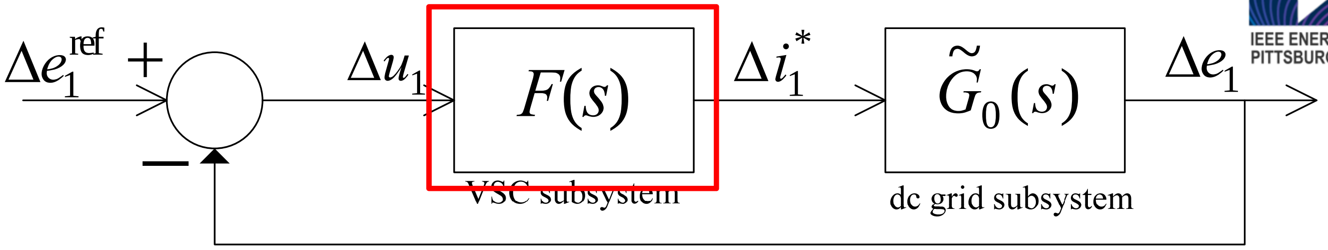


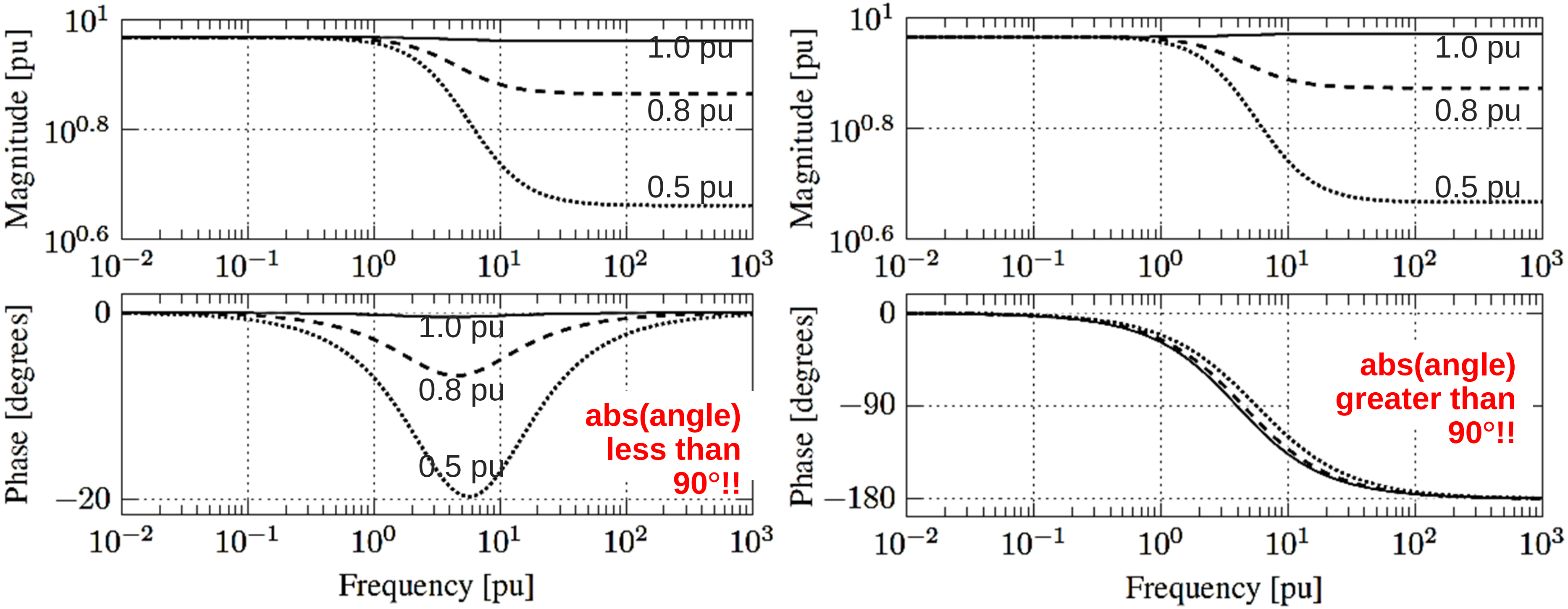
Resonance peak at 7 pu (350 Hz)

Angle less than 90 degrees

The approximated dc grid subsystem is passive!

Frequency response of the VSC subsystem

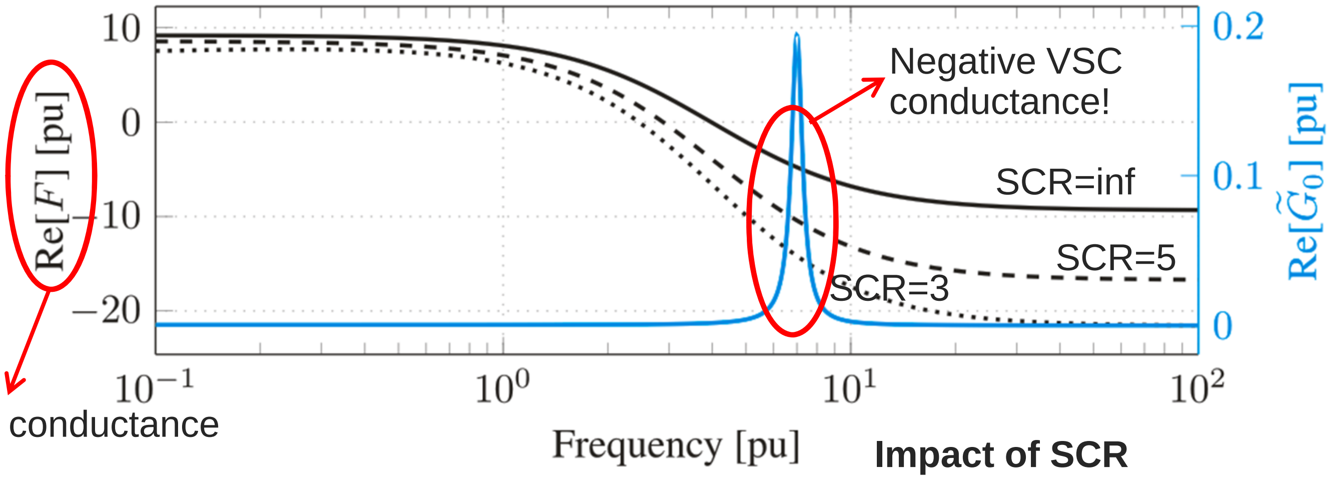




abs(angle) less than 90°!!

abs(angle) greater than 90°!!

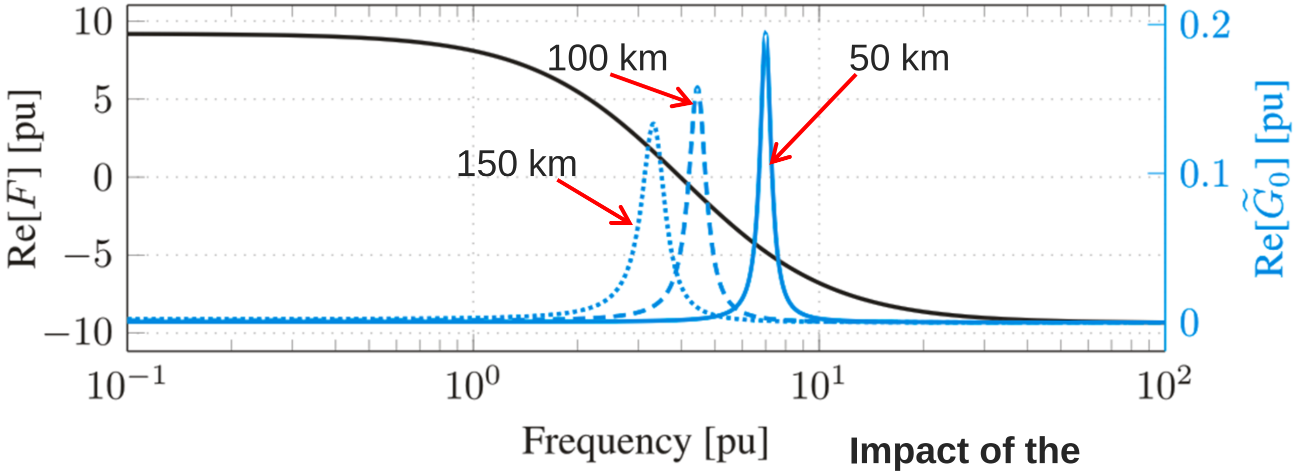
VSC subsystem freq. response seen as an admittance



Negative VSC conductance!

VSC conductance

Impact of SCR



Impact of the cable length

Conclusions

DC network instability can occur and it is related to:

- The physical characteristics of the dc grid.
- The operating point.
- The controller structure.
- The strength of the ac system.

Frequency domain analysis shows that:

- The origin of the instability is the VSC subsystem which turns non passive in certain conditions.
- Instability may occur if the dc side resonance coincides with a negative VSC conductance.

Thanks for your attention!

Important equations

VSC subsystem transfer function:

$$F(s) = \frac{\Delta i_{\mathrm{dc1}}^{*}}{\Delta u_1} = -\frac{\alpha_1 i_{\mathrm{f10}}^{d} L_{\mathrm{f1}} k_{\mathrm{pe1}}}{e_{10}} \left(\frac{s + z_1^d}{s + \alpha_1} \right) \qquad z_1^d = 2\frac{R_{\mathrm{t1}}}{L_{\mathrm{t1}}} - \frac{u_{\mathrm{s10}}^{d}}{i_{\mathrm{f10}}^{d} L_{\mathrm{t1}}}$$

DC grid subsystem transfer function:

$$G(s) = \frac{C_{\mathrm{eq}}^{-1} n(s)}{(s + \omega_{c1} + \omega_{\mathrm{c2}})(d(s) + \omega_{\mathrm{c1}}\omega_{\mathrm{c2}}) + \delta}$$

$$n(s) = s^2 + (\omega_{\mathrm{rl}} + \omega_{\mathrm{c2}})s + \omega_{\mathrm{lc}}^2 + \omega_{\mathrm{rl}}\omega_{\mathrm{c2}}$$

$$d(s) = s^2 + \omega_{\mathrm{rl}} s + 2\omega_{\mathrm{lc}}^2$$

Simplified dc grid subsystem transfer function:

$$\widetilde{G}_0(s) = \frac{C_{\mathrm{eq}}^{-1} n(s)}{s \times d(s)}$$

Publications

I. G. Pinares, T. A. Le, L. Bertling-Tjernberg, C. Breitholtz, A. Edris, "On the analysis of the dc dynamics of multi-terminal VSC-HVDC systems using small signal modeling," *IEEE Power Tech conference*, Grenoble, France, 16-20, June, 2013.

II. G. Pinares, T. A. Le, L. Bertling-Tjernberg, C. Breitholtz, "Analysis of the dc Dynamics of VSC-HVDC Systems Using a Frequency Domain Approach," presented at IEEE Asia Pacific Power Energy Engineering Conference, Hong Kong, China, 8-11, December, 2013.

III. G. Pinares, "Analysis of the dc Dynamics of VSC-HVDC Systems Connected to Weak AC Grids Using a Frequency Domain Approach," submitted to the Power Systems Computation Conference PSCC, Wroclaw, Poland, 18-22, August, 2014.