ProOfGrids

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Active Damping of DC Voltage Oscillations in Multi-Terminal HVDC Systems

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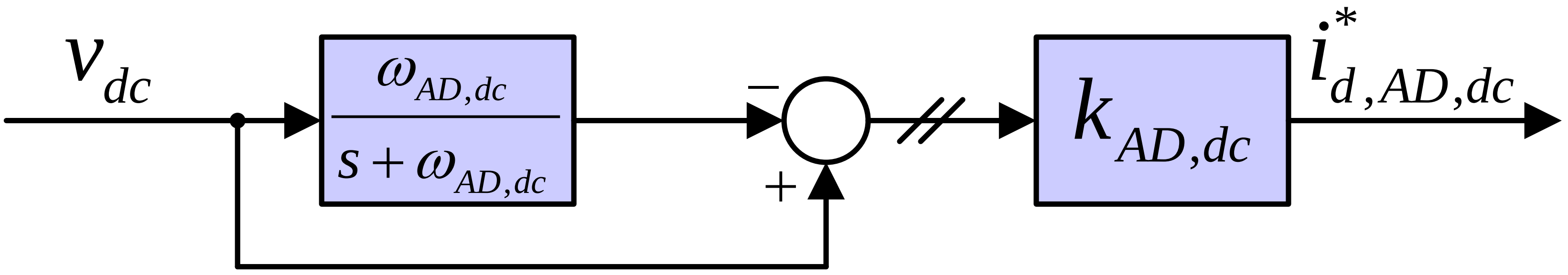
Introduction

- Cable connections in HVDC systems are characterized by substantial capacitance and inductance
- The dc side of an HVDC system can exhibit not well damped oscillatory behaviours as a reaction to changes of the system conditions
- Resistance is in general responsible for dampening of oscillations in physical circuits but this generates losses and conflicts with efficiency goals (Passive Damping)
- Damping of oscillations in power electronics can be also integrated in the control (Active Damping)

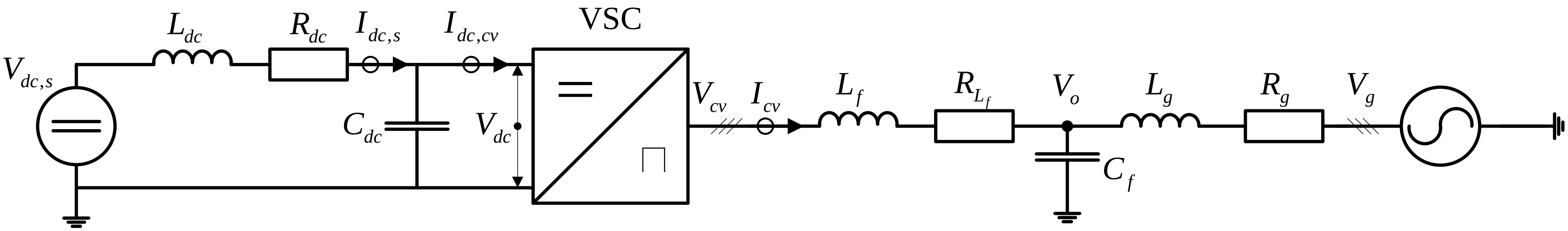
AC Active Damping

- Active damping is common in power electronics systems sensitive to oscillations
  - Grid connected converters with LCL filters
- The principle is to add to the output voltage a component in counterphase with the oscillations in order to force a damping (similar to noise cancelling headphones)
- Oscillations are isolated with high pass filtering

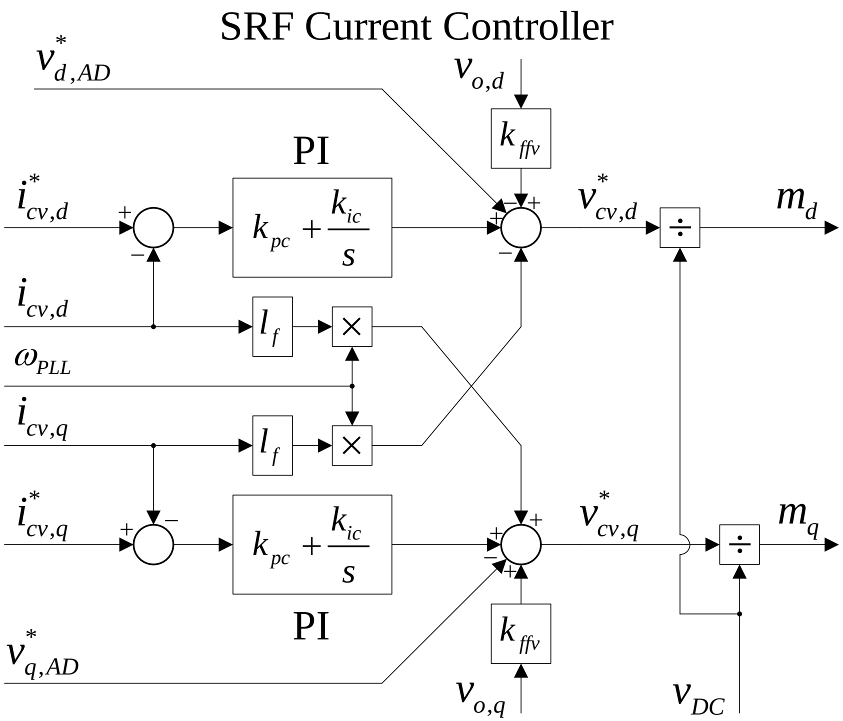


Reference model for HVDC terminal

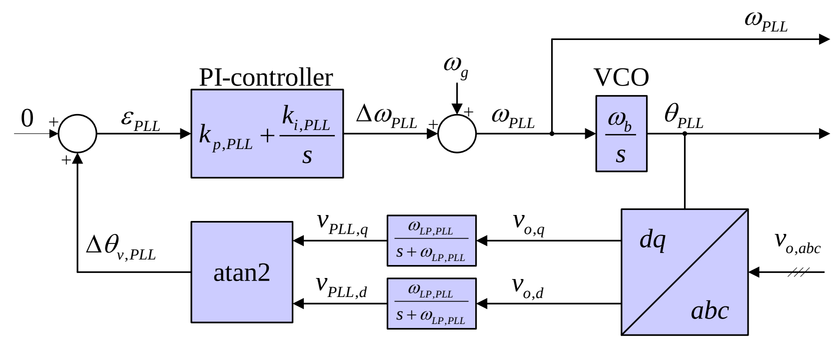
- Rated power: 1200MW
- Rated Voltage AC: 220 kV
- Line length: 200 km
- Line resistance: 0.011 Ω /km
- Line capacitance: 0.19 μF/km
- Line inductance: 2.6 mH/km
- Bus capacitance: 8.2 mF
- Worst case configuration



Overview Control Scheme



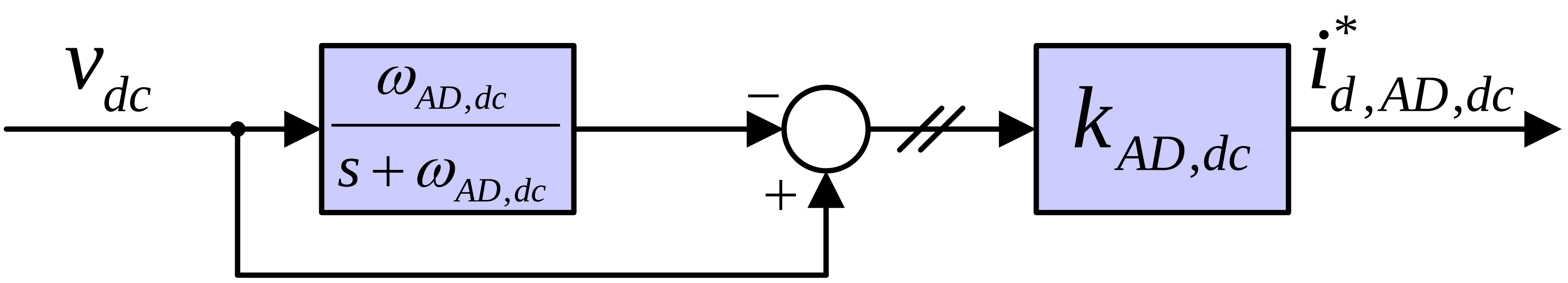
Current controller



PLL

DC Active Damping

- The concept and the implementation of the DC Active Damping is similar to the AC Active Damping
  - The oscillations in the dc voltage are isolated by high pass filtering the measured voltage on the dc bus
  - A counterphase component is added to the reference current for the current controller
  - The damping effect is lossless and can be tuned by the gain and the filtering frequency



Small signal modelling

- A small signal linearized system is derived in the dq frame (17 th order)

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\cdot\Delta\mathbf{x} + \mathbf{B}\cdot\Delta\mathbf{u}$$

$$\mathbf{x} = \begin{bmatrix} v_{o,d} & v_{o,q} & i_{l,d} & i_{l,q} & \gamma_d & \gamma_q & i_{o,d} & i_{o,q} & \varphi_d & \varphi_q \\ v_{PLL,d} & v_{PLL,q} & \varepsilon_{PLL} & \delta\theta_{PLL} & v_{dc} & i_{dc} & \rho \end{bmatrix}^T$$

$$\mathbf{u} = \begin{bmatrix} i_{l,q}^* & i_{l,d}^* & v_{dc,s} & \hat{v}_g & \omega_g \end{bmatrix}^T$$

Small signal modelling

$$
\mathbf{A}=\begin{bmatrix}
0 & \omega_b\omega_{g,0} & \frac{\omega_b}{c_f} & 0 & 0 & 0 & -\frac{\omega_b}{c_f} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\omega_b\omega_{g,0} & 0 & 0 & \frac{\omega_b}{c_f} & 0 & 0 & 0 & -\frac{\omega_b}{c_f} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\omega_b\frac{k_{ffv}-1-k_{AD}}{l_f} & 0 & -\omega_b\frac{k_{pc}+r_f}{l_f} & 0 & \omega_b\frac{k_{ic}}{l_f} & 0 & 0 & 0 & \omega_b\frac{k_{AD}}{l_f} & 0 & 0 & -\omega_b\frac{k_{p,PLL}i^*_{l,q,0}}{v_{o,d,0}} & -\omega_b k_{i,PLL}i^*_{l,q,0} & 0 & \omega_b\frac{k_{pc}k_{AD,dc}}{l_f} & 0 & -\omega_b\frac{k_{pc}k_{AD,dc}}{l_f} \\
0 & \omega_b\frac{k_{ffv}-1-k_{AD}}{l_f} & 0 & -\omega_b\frac{k_{pc}+r_f}{l_f} & 0 & \omega_b\frac{k_{ic}}{l_f} & 0 & 0 & 0 & \omega_b\frac{k_{AD}}{l_f} & 0 & \omega_b\frac{k_{p,PLL}i^*_{l,d,0}}{v_{o,d,0}} & \omega_b k_{i,PLL}i^*_{l,d,0} & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{AD,dc} & 0 & -k_{AD,dc} \\
0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{\omega_b}{l_g} & 0 & 0 & 0 & 0 & 0 & -\frac{\omega_b r_g}{l_g} & \omega_b\omega_{g,0} & 0 & 0 & 0 & 0 & 0 & k_{7,14} & 0 & 0 & 0 \\
0 & \frac{\omega_b}{l_g} & 0 & 0 & 0 & 0 & -\omega_b\omega_{g,0} & -\frac{\omega_b r_g}{l_g} & 0 & 0 & 0 & 0 & 0 & k_{8,14} & 0 & 0 & 0 \\
\omega_{AD} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\omega_{AD} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \omega_{AD} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\omega_{AD} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\omega_{LP,PLL} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\omega_{LP,PLL} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \omega_{LP,PLL} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\omega_{LP,PLL} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{v_{o.d.0}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\omega_b k_{p,PLL}}{v_{o.d.0}} & \omega_b k_{i,PLL} & 0 & 0 & 0 & 0 \\
\omega_b\frac{(k_{AD}-k_{ffv})i^*_{l,d,0}}{c_{dc}v_{dc,0}} & \omega_b\frac{(k_{AD}-k_{ffv})i^*_{l,q,0}}{c_{dc}v_{dc,0}} & k_{15,3} & k_{15,4} & -\omega_b\frac{k_{ic}i^*_{l,d,0}}{c_{dc}v_{dc,0}} & -\omega_b\frac{k_{ic}i^*_{l,q,0}}{c_{dc}v_{dc,0}} & 0 & 0 & -\omega_b\frac{k_{AD}i^*_{l,d,0}}{c_{dc}v_{dc,0}} & -\omega_b\frac{k_{AD}i^*_{l,q,0}}{c_{dc}v_{dc,0}} & 0 & 0 & 0 & 0 & k_{15,15} & \frac{\omega_b}{c_{dc}} & -\omega_b\frac{k_{pc}k_{AD,dc}i^*_{l,d,0}}{c_{dc}v_{dc,0}} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{\omega_b}{l_{dc}} & -\frac{\omega_b r_{dc}}{l_{dc}} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_{AD,dc} & 0 & -\omega_{AD,dc}
\end{bmatrix}
$$

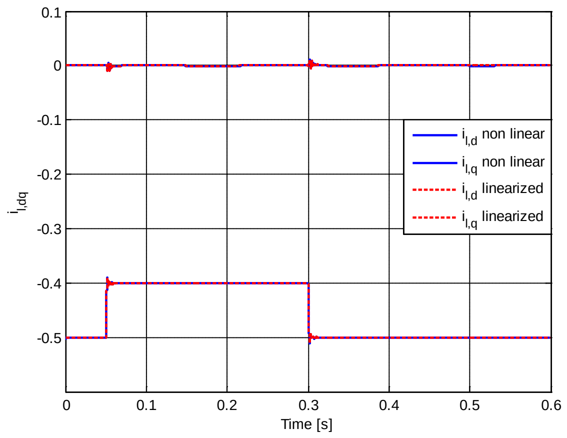
$$
\mathbf{B}=\begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\omega_b v_{o,d,0} \\
0 & \frac{\omega_b k_{pc}}{l_f} & 0 & 0 & 0 \\
\frac{\omega_b k_{pc}}{l_f} & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\frac{\omega_b\cos(\delta\theta_{PLL,0})}{l_g} & \omega_b i_{o,q,0} \\
0 & 0 & 0 & -\frac{\omega_b\sin(\delta\theta_{PLL,0})}{l_g} & -\omega_b i_{o,d,0} \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
-\frac{\omega_b k_{pc}i^*_{l,q,0}}{c_{dc}v_{dc,0}} & -\frac{\omega_b k_{pc}i^*_{l,d,0}}{c_{dc}v_{dc,0}} & 0 & 0 & 0 \\
0 & 0 & \frac{\omega_b}{l_{dc}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

A

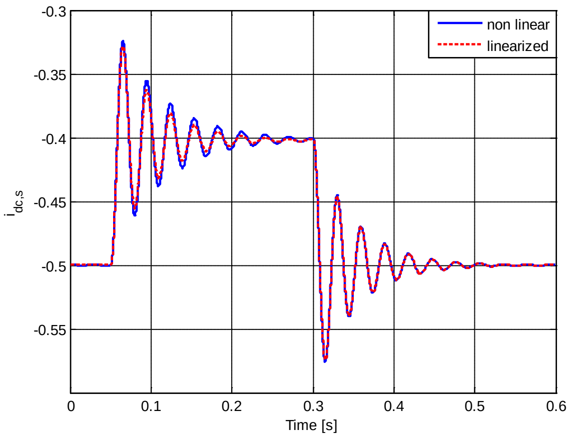
B

Example of oscillatory behaviour without active damping

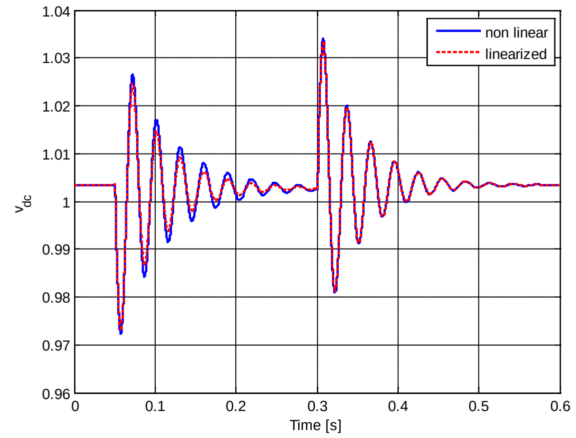
- Response to a step change in the id reference of 0.1 pu
- Very good match between the linearized and the non linear model



DQ CURRENT

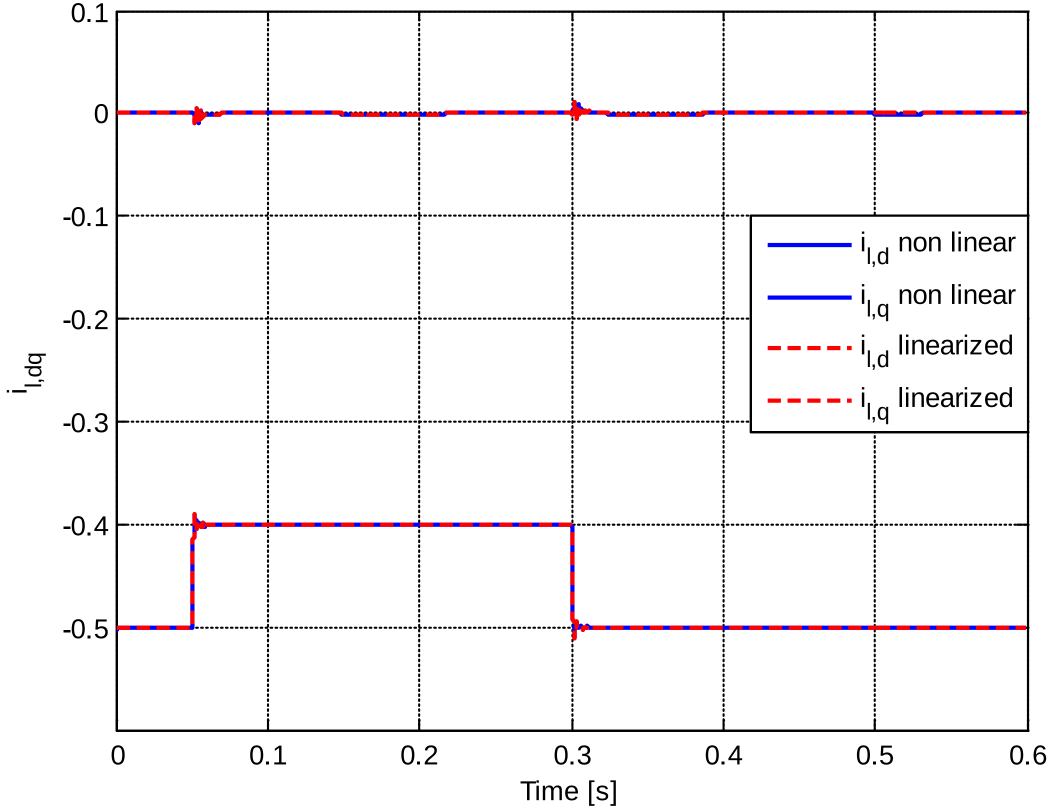


DC LINE CURRENT



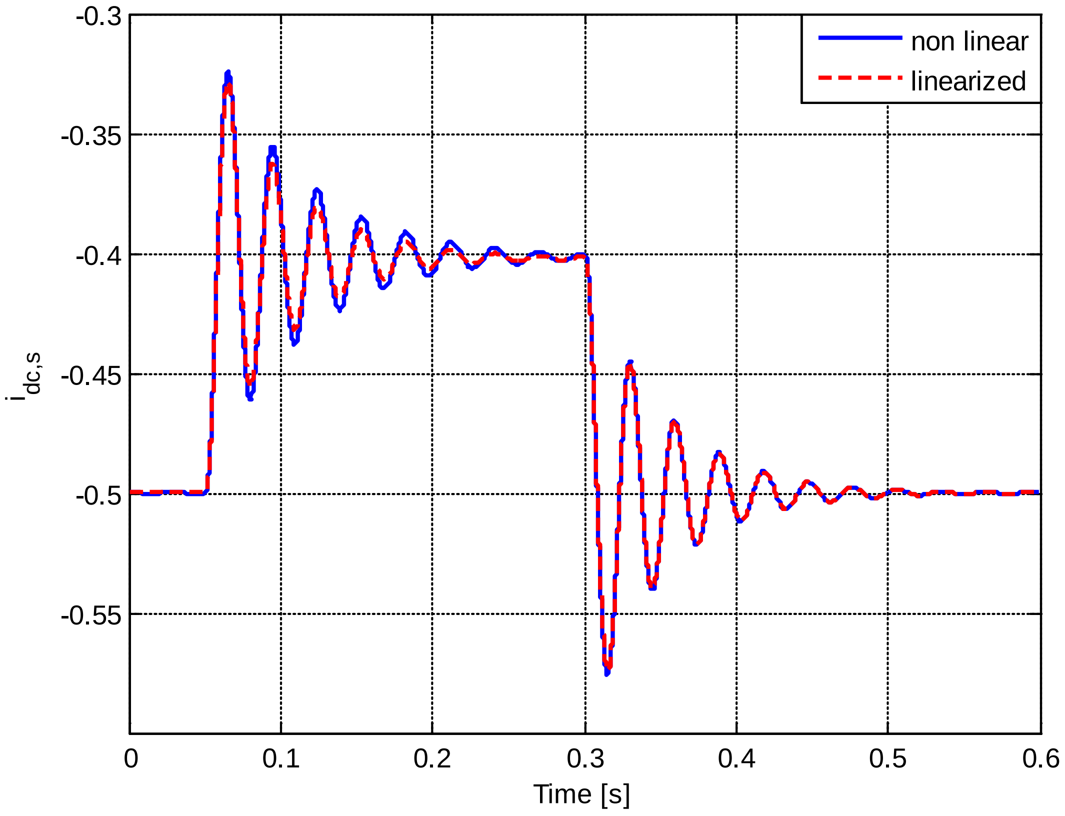
DC LINE VOLTAGE

DQ Current

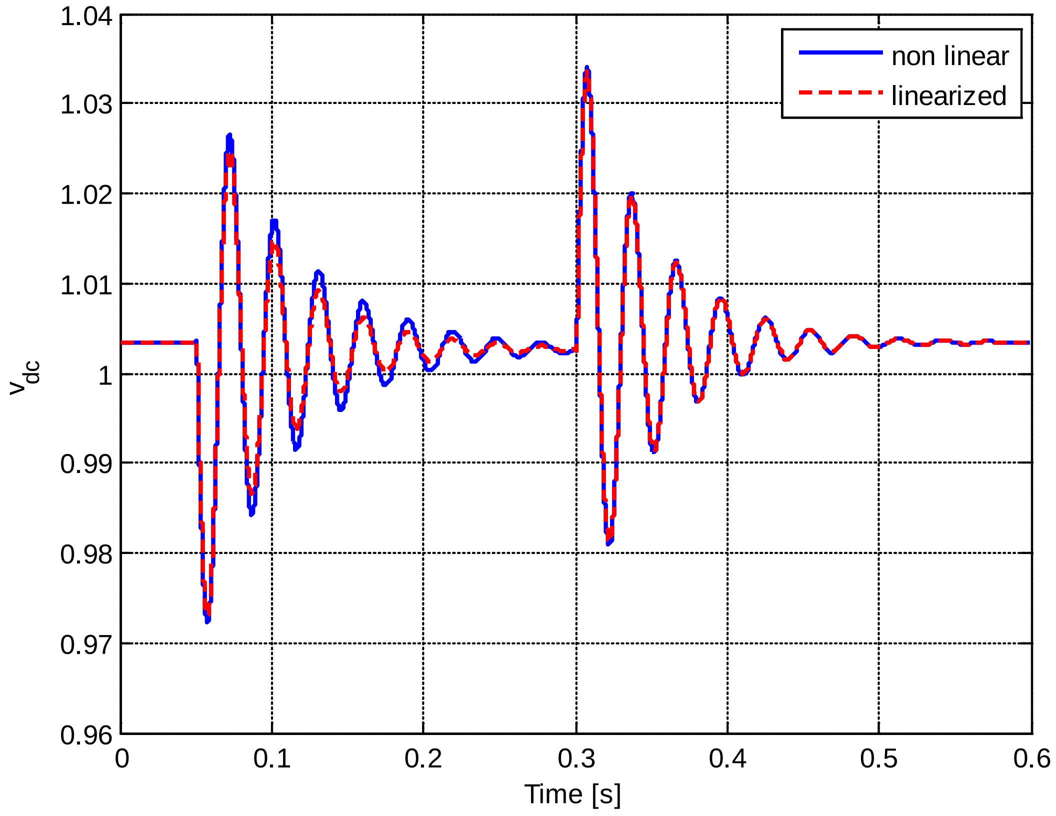


0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
Time [s]
i l,dq
i l,d non linear
i l,q non linear
i l,d linearized
i l,q linearized

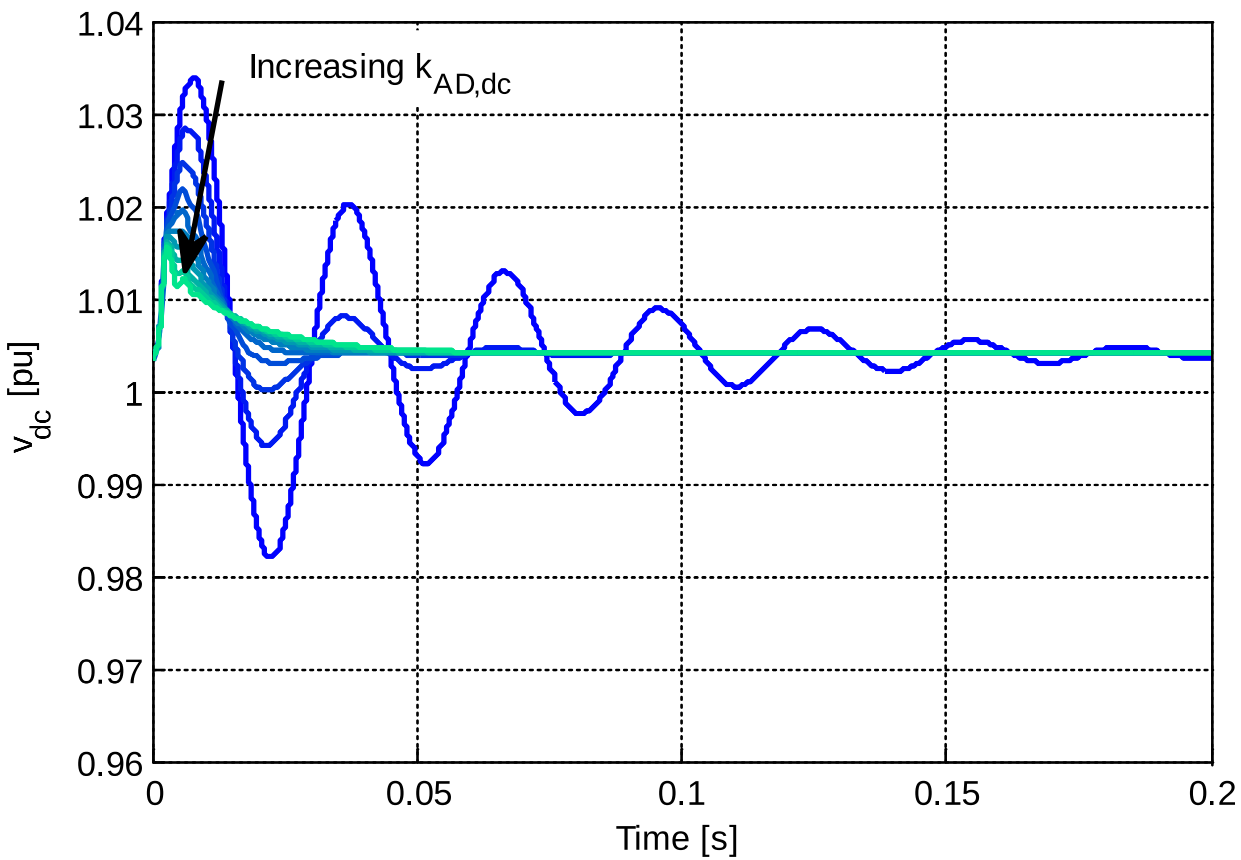
DC Line Current



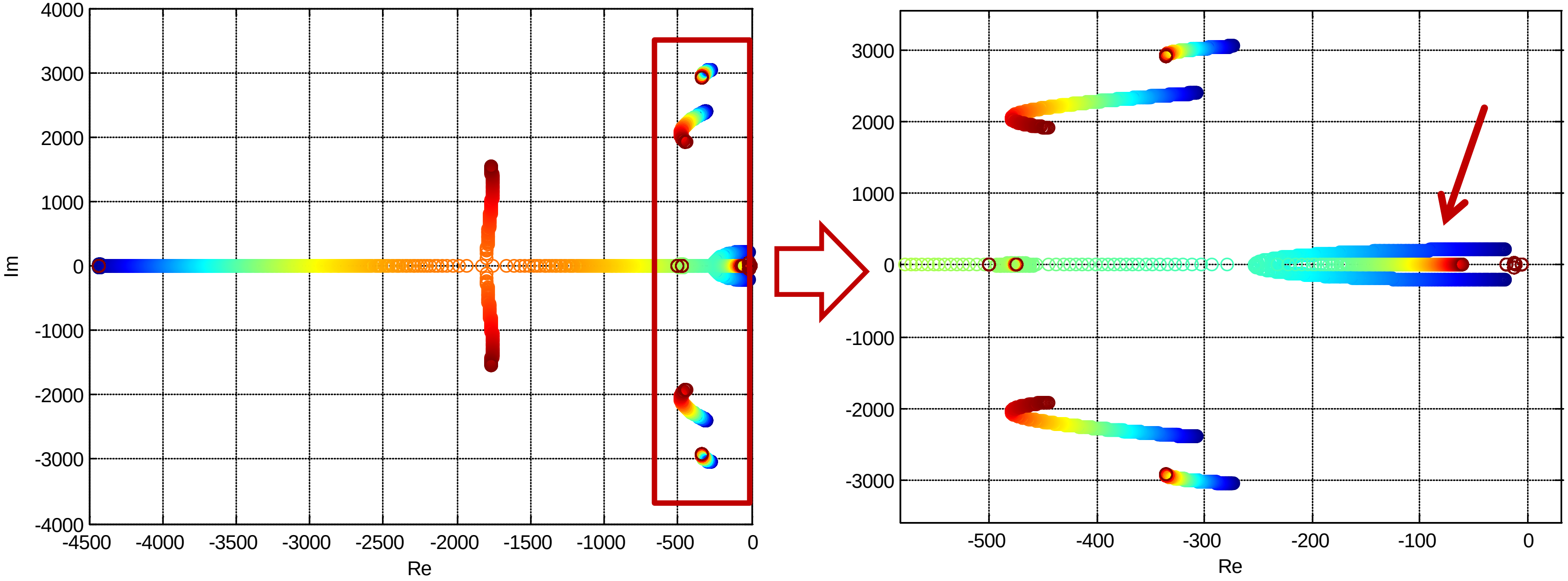
DC Line Voltage



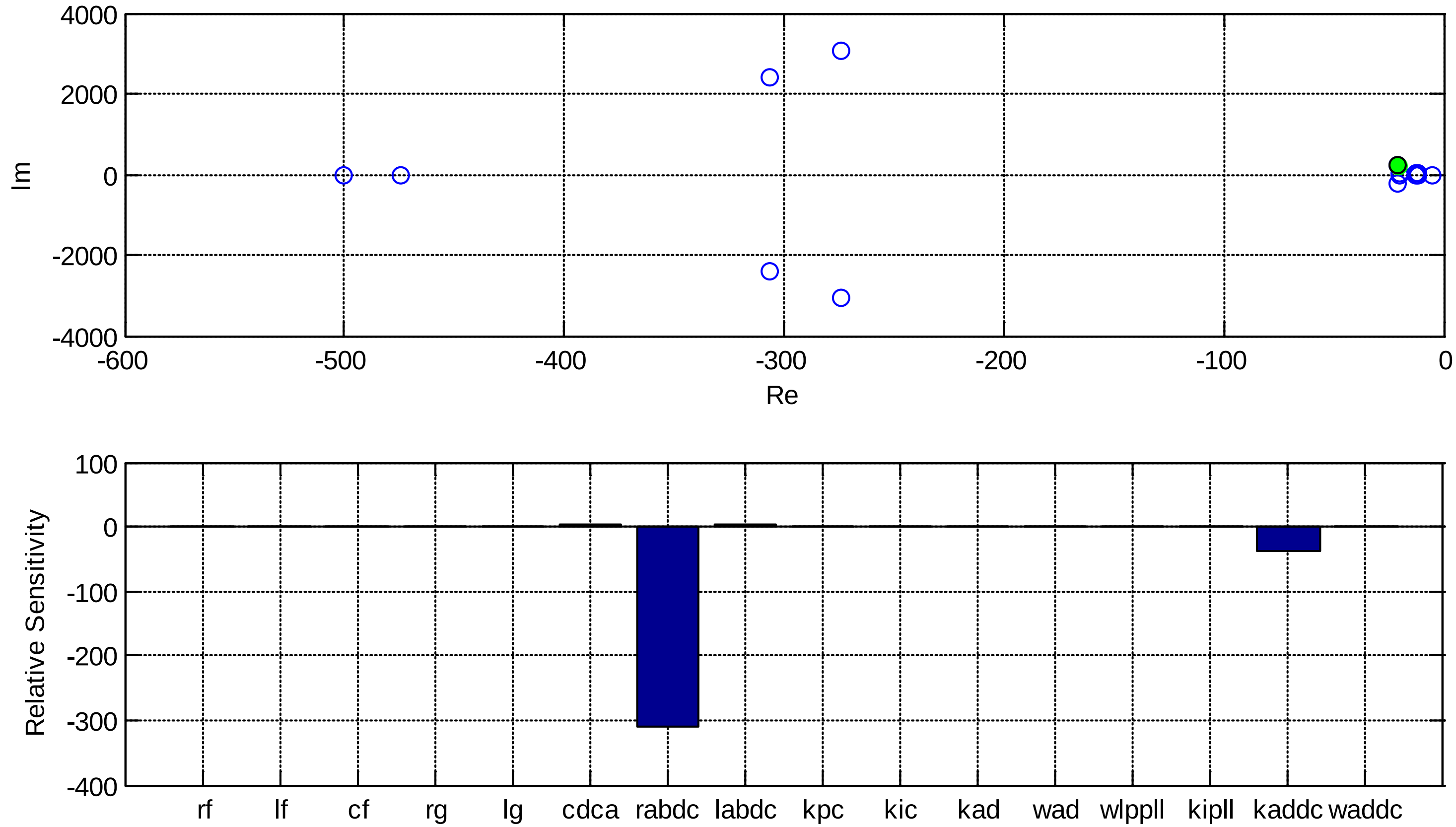
Effect of active damping on dc voltage oscillations



Root locus for Active Damping gain sweep



Pole parametric sensitivity



Example of behaviour with active damping

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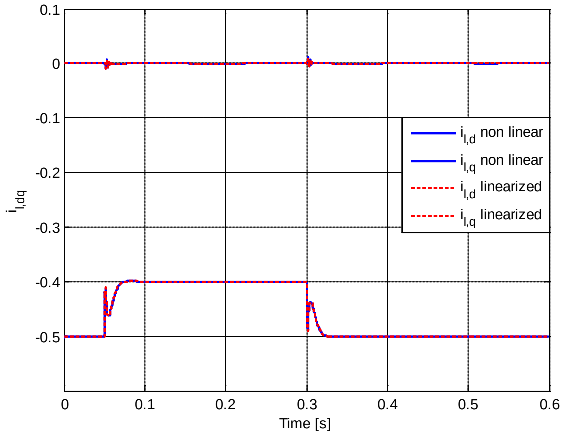
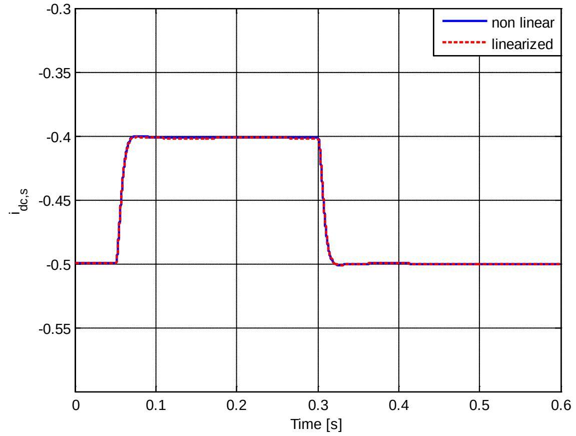
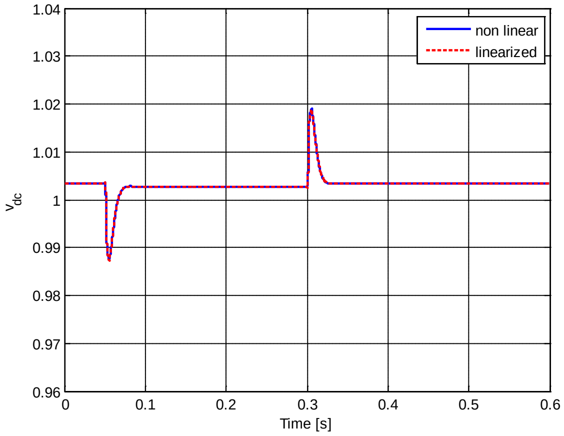


DQ CURRENT

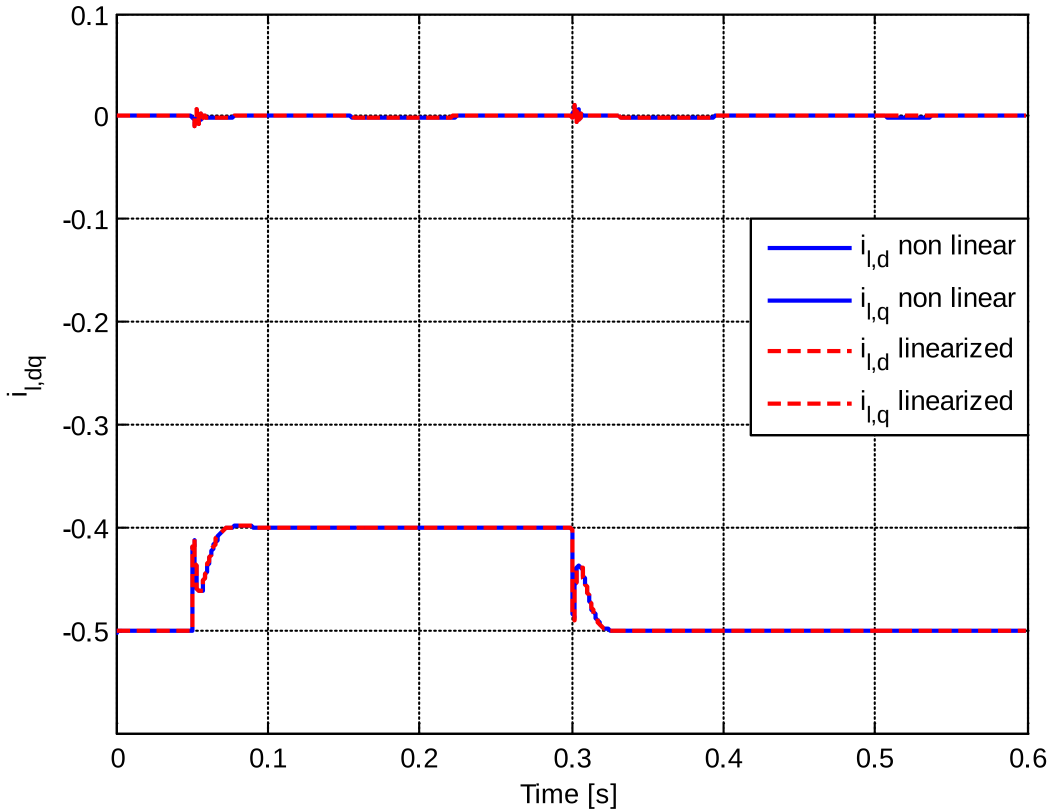


DC LINE CURRENT



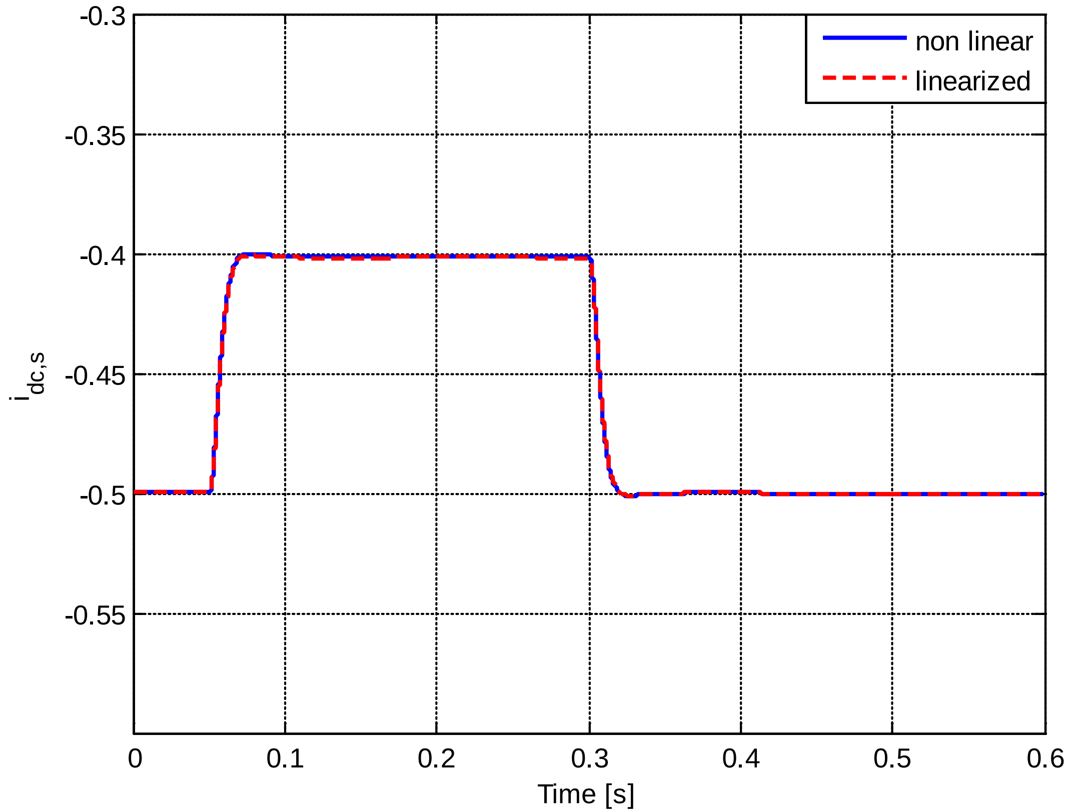
DC LINE VOLTAGE

DQ Current

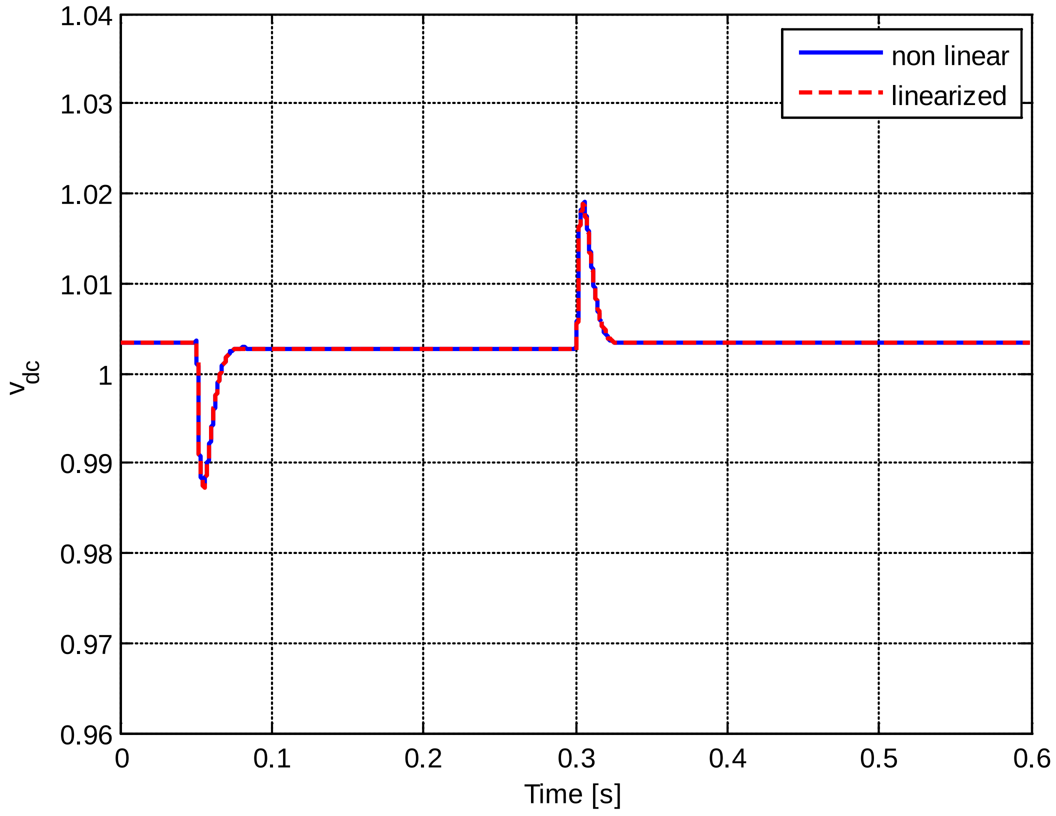


0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
$i_{l,dq}$
0
0.1
0.2
0.3
0.4
0.5
0.6
Time [s]
$i_{l,d}$ non linear
$i_{l,q}$ non linear
$i_{l,d}$ linearized
$i_{l,q}$ linearized

DC Line Current



DC Line Voltage



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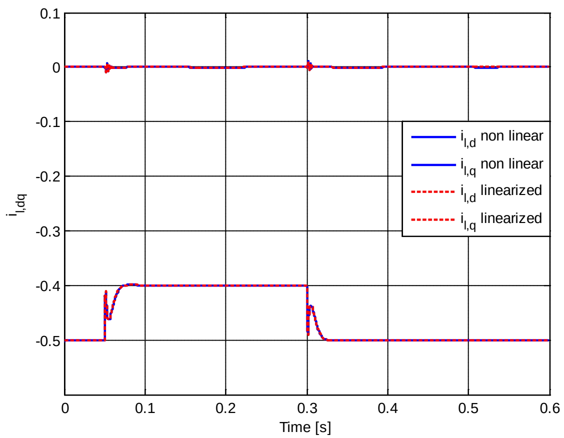
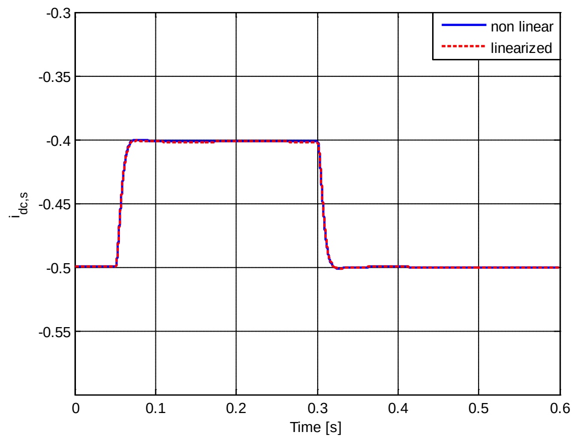
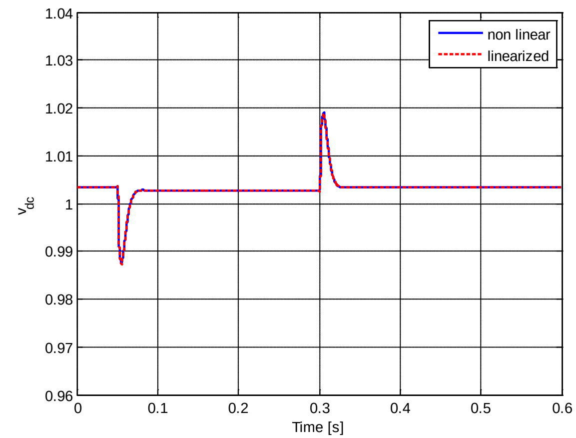


DQ CURRENT



DC LINE CURRENT



DC LINE VOLTAGE

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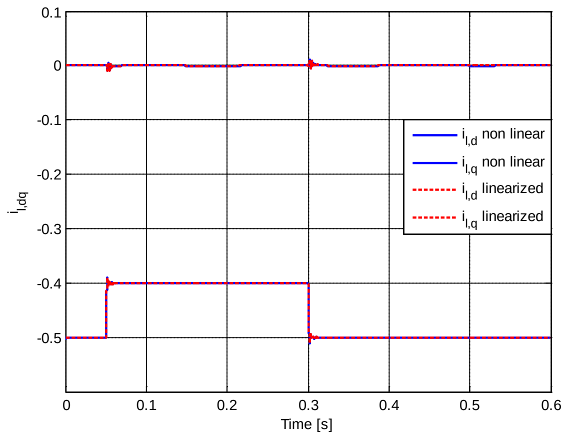
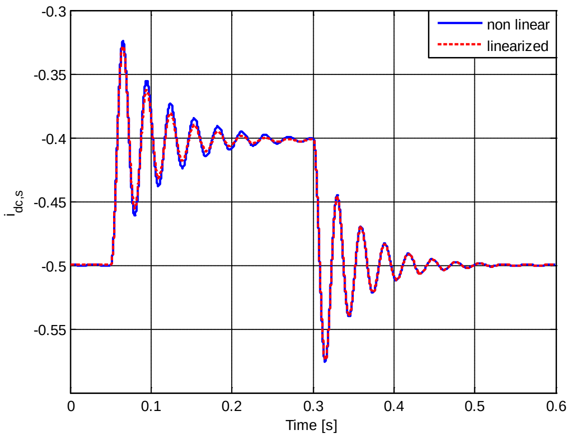
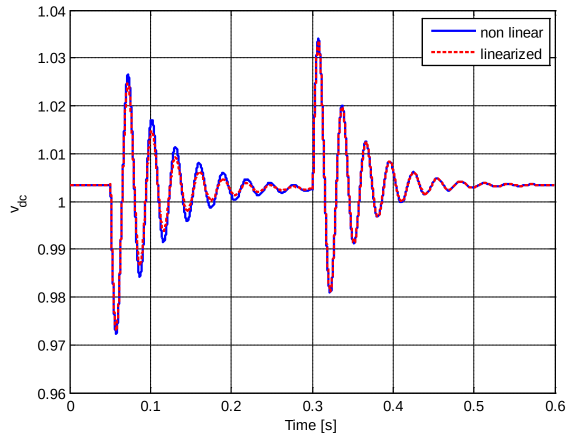


DQ CURRENT



DC LINE CURRENT



DC LINE VOLTAGE

Conclusions

- Changes in operating conditions can trigger oscillations on the dc side of HVDC systems due to the relatively large capacitance and inductance of the cable connections
- An active damping scheme has been proposed and its operation demonstrated on a sample case
- The active damping can effectively reduce the oscillatory behaviours.

Questions?

This activity is supported by the project:

Protection and Fault Handling in **Of**fshore HVDC **Grids**

contact: salvatore.darco@sintef.no

ProOfGrids Protection and Fault Handling in Offshore HVDC Grids

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