KATHOLIEKE UNIVERSITEIT LEUVEN

Modeling and control of Multi-terminal VSC HVDC Systems

Jef Beerten

University of Leuven (KU Leuven), Belgium

VSC HVDC at KU Leuven

prof. Ronnie Belmans & prof. Dirk Van Hertem

- PhD projects
  - VSC HVDC in AC meshed grids (Stijn Cole, finished 2010)
  - Integration of Multi-terminal VSC HVDC (Jef Beerten)
  - Optimal investment strategies for offshore wind (Hakan Ergun)
  - …

- Projects (2006 – …)
  - Randstad HVDC (2006 – 2007)
  - BelGer – Nemo (2006 – 2007)
  - Imera power (2007 – 2009)

VSC HVDC at KU Leuven

- Member of CIGRE WG on HVDC (2006 – …)
  - B4.46 – Economic Aspects of VSC HVDC
  - B4.52 – DC Grids Feasibility Study
  - B4.58 –Load flow and Direct Voltage Control in a HVDC Grid
  - B4/B5.59 – Control and Protection of HVDC Grids
  - C4/B4/C1 - Influence of Embedded HVDC Transmission on System Security and AC Network Performance

- Master thesis (2008 - …)
  - Loss minimization (Gilles Daelemans*)
  - Economics of AC and DC wind farm connections (Bram Van Eeckhout*)
  - MTDC protection (Kenny De Kerf*)
  - Connecting Belgium and th UK (Frederik Leung Shun*)
  - VSC HVDC Connected variable speed operated wind farms (Pieter Hellings)
  - DC voltage control (Carlos Dierckxsens*)
  - HVDC connected large-scale solar plants (Philippe Hoylaerts*)
  - Multi-terminal HVDC and wind (Stijn Vandenbroucke*)

**: in cooperation with ABB Sweden*

VSC HVDC at KU Leuven Publications: Journal

- Beerten J., Cole S., Belmans R.: "Generalized Steady-State VSC MTDC Model for Sequential AC/DC Power Flow Algorithms.," IEEE Transactions on Power Systems, accepted for publication., 2012.
- Dierckxsens C, Srivastava K., Reza M., Cole S., Beerten J., Belmans R.: "A Distributed DC Voltage Control Method for VSC MTDC Systems," Journal: Electric Power Systems Research, vol. 82,, 2012; pp.54– 58.
- De Kerf K., Srivastava K., Reza M., Bekaert D., Cole S., Van Hertem D., Belmans R.: "Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems," IET GTD, April, 2011; pp. 496 - 503.
- Buijs P., Bekaert D., Cole S., Van Hertem D., Belmans R.: " Transmission investments in Europe: Going beyond standard solutions," Energy Policy: volume 39, issue 3, 2011; pp. 1794-1801.
- Van Hertem D., Ghandhari M.: "Multi-terminal VSC HVDC for the European supergrid: Obstacles," Renewable and Sustainable Energy Reviews, Volume 14, Issue 9, ISSN 1364-0321, 2011; pp. 3156-3163.
- Cole S., Beerten J., Belmans R.: "Generalized Dynamic VSC MTDC Model for Power System Stability Studies," IEEE Trans. on Power Systems, vol.25, no.3, August, 2010; pp. 1655-1662.
- Cole S., Belmans R.: " Transmission of bulk power. The History and Applications of Voltage-Source Converter High-Voltage Direct Current Systems. ," IEEE Industrial Electronics Magazine , September 2009, 2009; pp. 19-24.
- Van Eeckhout B., Van Hertem D., Reza M., Srivastava K., Belmans R.: "Economic comparison of VSC HVDC and HVAC as transmission system for a 300 MW offshore wind farm," ETEP, 2009

VSC HVDC at KU Leuven Publications: Conference I

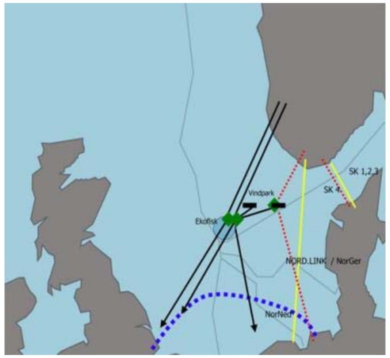
- Ergun H., Van Hertem D., Belmans R.: "Multi level optimization for offshore grid planning.," Cigrè International Symposium The Electric Power System of the future, Integrating supergrids and microgrids., Bologna-Italy, September 13-16, 2011.
- Beerten J., Van Hertem D., Belmans R.: "VSC MTDC Systems with a Distributed DC Voltage Control - A Power Flow Approach," Proc. IEEE PowerTech 2011, Trondheim, Norway, June 19-23, 2011
- Leung Shun E., Reza M., Srivastava K., Cole S., Van Hertem D., Belmans R.: "Influence of VSC HVDC on Transient Stability: Case study of the Belgian grid," , July 29, 2010
- Ergun H., Van Hertem D., Belmans R.: "CoST Of Wind - Appropriate Connection Selection Tool for Offshore Wind Farms," International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks or Offshore Wind Power Plants, Quebec, October 18-19, 2010
- Van Hertem D., Eriksson R., Söder L., Ghandhari M.: "Coordination of Multiple Power Flow Controlling Devices in Transmission Systems," IET ACDC edition:9, London, UK, October 20-21, 2010
- Westermann D., Van Hertem D., Küster A., Klöckl B., Atmuri R., Rauhala T.: "Voltage Source Converter (VSC) HVDC for Bulk Power Transmission – Technology and Planning Method," IET ACDC edition:9, London, UK, October 20-21, 2010
- Beerten J., Cole S., Belmans R.: "Implementation Aspects of a Sequential AC/DC Power Flow Computation Algorithm for Multi-terminal VSC HVDC Systems," Proc. IET ACDC2010, London, October 20-21, 2010

VSC HVDC at KU Leuven Publications: Conference II

- Beerten J., Cole S., Belmans R.: "A Sequential AC/DC Power Flow Algorithm for Networks Containing Multi-terminal VSC HVDC Systems.," IEEE PES GM'10.
- Daelemans G., Srivastava K., Reza M., Cole S., Belmans R.: "Minimization of steady state losses in meshed networks using VSC HVDC," IEEE PES GM'09.
- Buijs P., Cole S., Belmans R.: " TEN-E revisited: opportunities for HVDC technology," EEM'09, Leuven, Belgium, May 27-29, 2009; 6 pages.
- Cole S., Van Hertem D., Belmans R.: " VSC HVDC as an Alternative Grid Investment in Meshed Grids," ICIS, Rotterdam, The Netherlands, 10-12 November, 2008; 6 pages.
- Cole S., Belmans R.: " Modelling of VSC HVDC Using Coupled Current Injectors," IEEE PES GM'08
- Cole S., Van Hertem D., Pardon I., Belmans R.: " Randstad HVDC: A Case Study of VSC HVDC Bulk Power Transmission in a Meshed Grid," Security and Reliability of Electric PowerSystems, Cigré regional meeting, Tallinn, Estonia , June 18-20 , 2007; pp. 83-89.
- Cole S., Van Hertem D., Belmans H.: " Connecting Belgium and Germany using HVDC: A
- preliminary study," Power Tech 2007, 2007 IEEE Powertech, Lausanne, Switzerland, 1 - 5
- July 2007 , 2007; 5 pages.
- Van Hertem D., Verboomen J., Cole S., Kling W., Belmans R.: " Influence of phase shifting transformers and HVDC on power system losses," IEEE PES 2007.

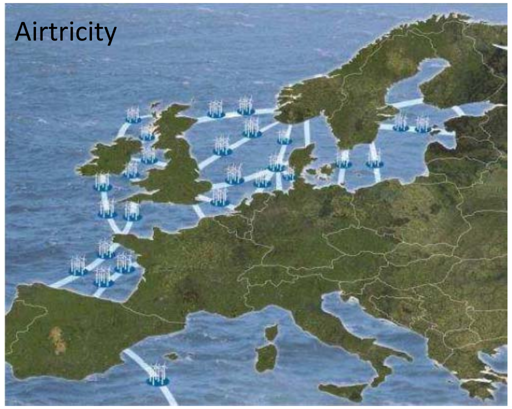
Offshore grids and supergrid …

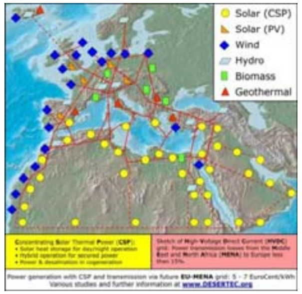
What will the future grids look like?



Offshore Grid Proposal by Statnett
(Source Statnett, 2008)

Vision of High Voltage
Super Grid
(Source: Dowling and





KEMA Ocean grids

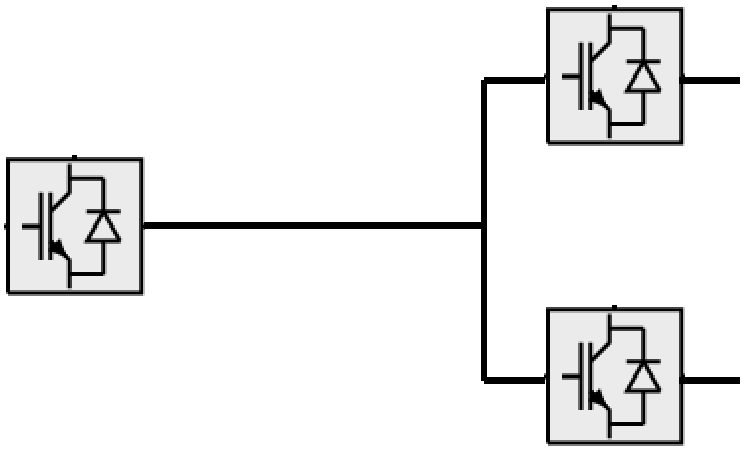
Offshore Grid examined in the
Greenpeace study
(Source: Woyte et al, 2008)

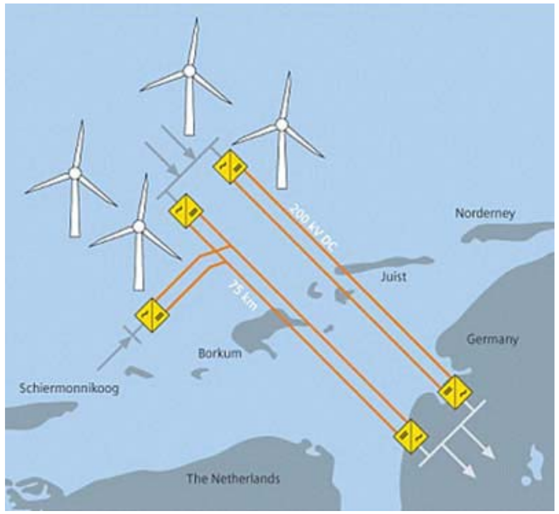
FIGURE [22]: Possible meshed HVDC (meshed 2) connection of offshore wind farms.
Dotted lines are HVDC interconnectors. NorNed2 and NorGer are replaced by a HVDC connections between Norwegian and German offshore wind farms.

Czisch – Supergrid
for renewab le
energies

Offshore grids and supergrid …
VSC HVDC technology

- VSC HVDC only developed for point-to-point, but…
- …looks very promising for future DC grids
  - Converter's DC side has constant voltage → converters can be easily connected to DC network.
- Extension to 'pseudo-multi-terminal' systems straightforward: e.g. star-connections





Offshore grids and supergrid …
DC voltage control

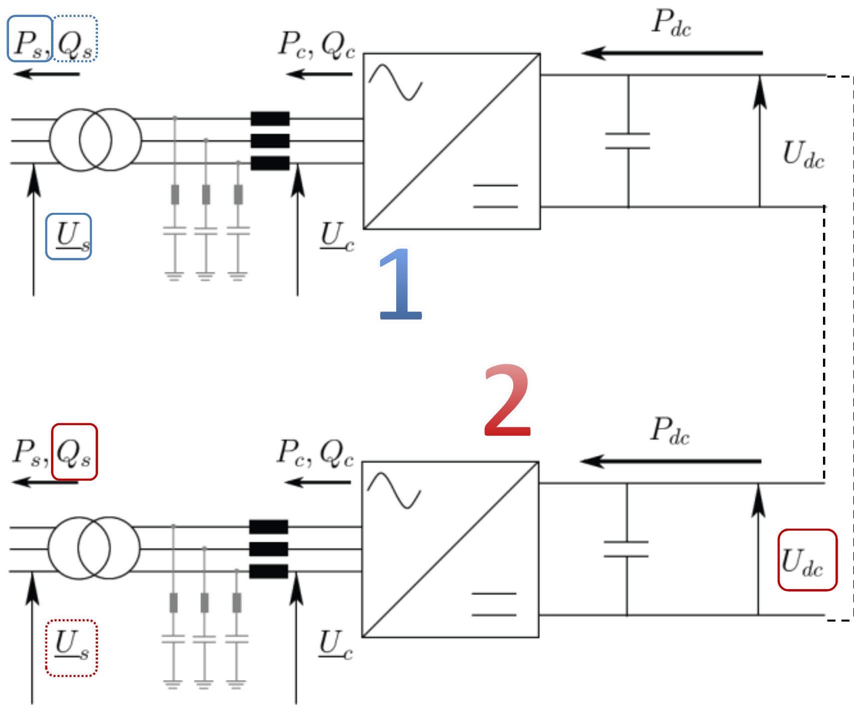
- DC Voltage ≈ AC frequency
  - Changes when ‘consumption’ ≠ ‘production’

- Can different converters contribute to the DC voltage control?

Converter control principles

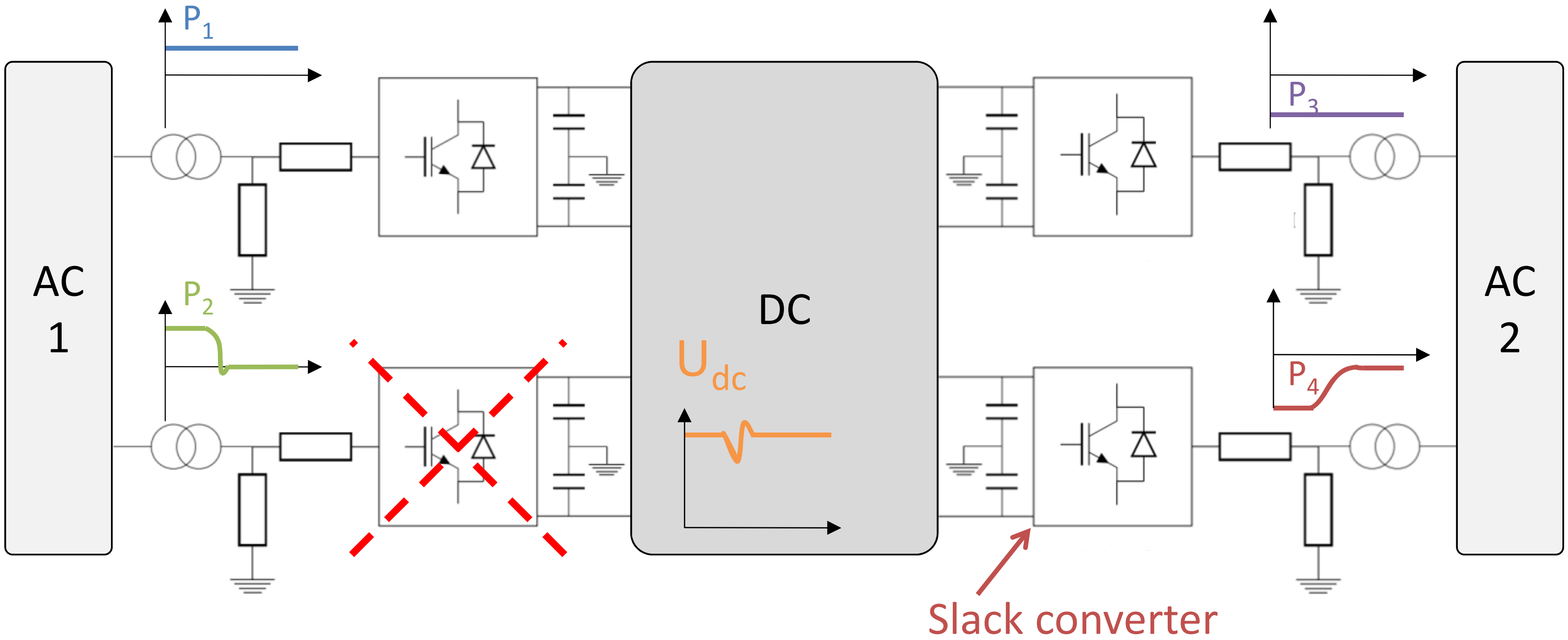
- **2-terminal scheme**
  - Active power control
    - converter 1
  - DC voltage control
    - converter 2
  - Reactive power control
    - converter 1 and/or 2
  - AC voltage control
    - converter 1 and/or 2

Example:



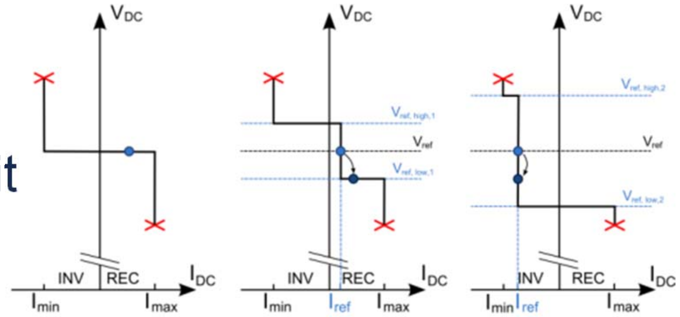
DC Voltage Control in DC Grid
Master-slave

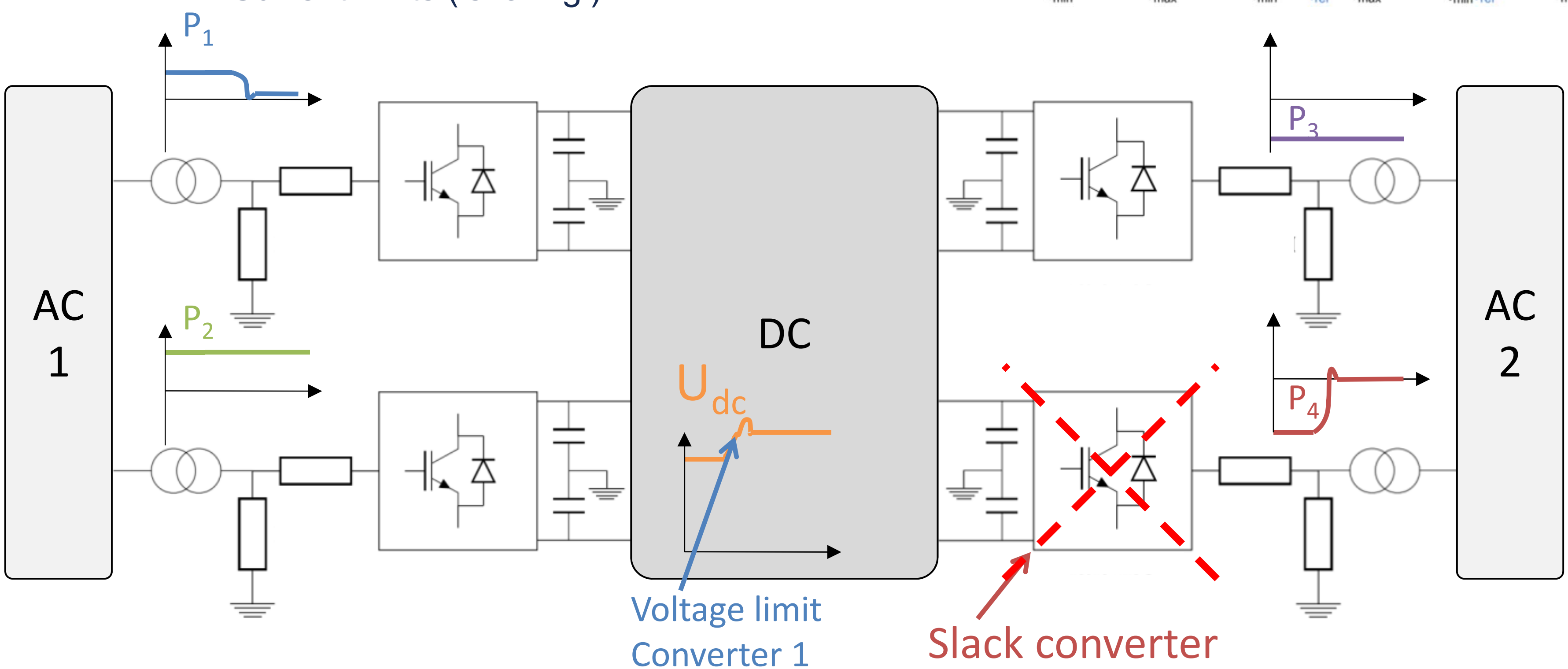
- 1 DC voltage controlling converter
  - Converter has to deal with all DC grid events
  - What if this converter fails?
  - Which TSO wants this 'DC slack bus'?



DC Voltage Control in DC Grid
Voltage Margin Method

- Improved master-slave approach
  - 1 DC voltage controlling converter at a time
- Converter takes over when margins/limits hit
  - Voltage limits (slack outage)
  - Current limits ('sharing')





DC Voltage Control in DC Grid
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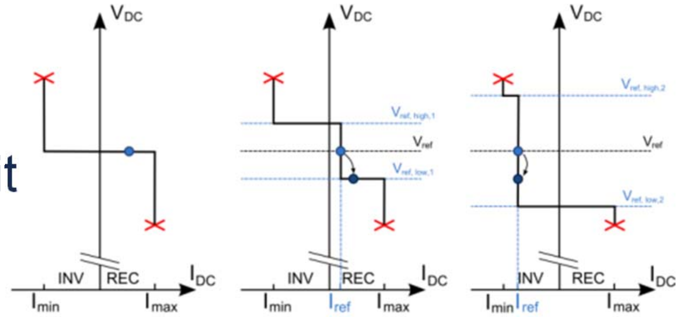
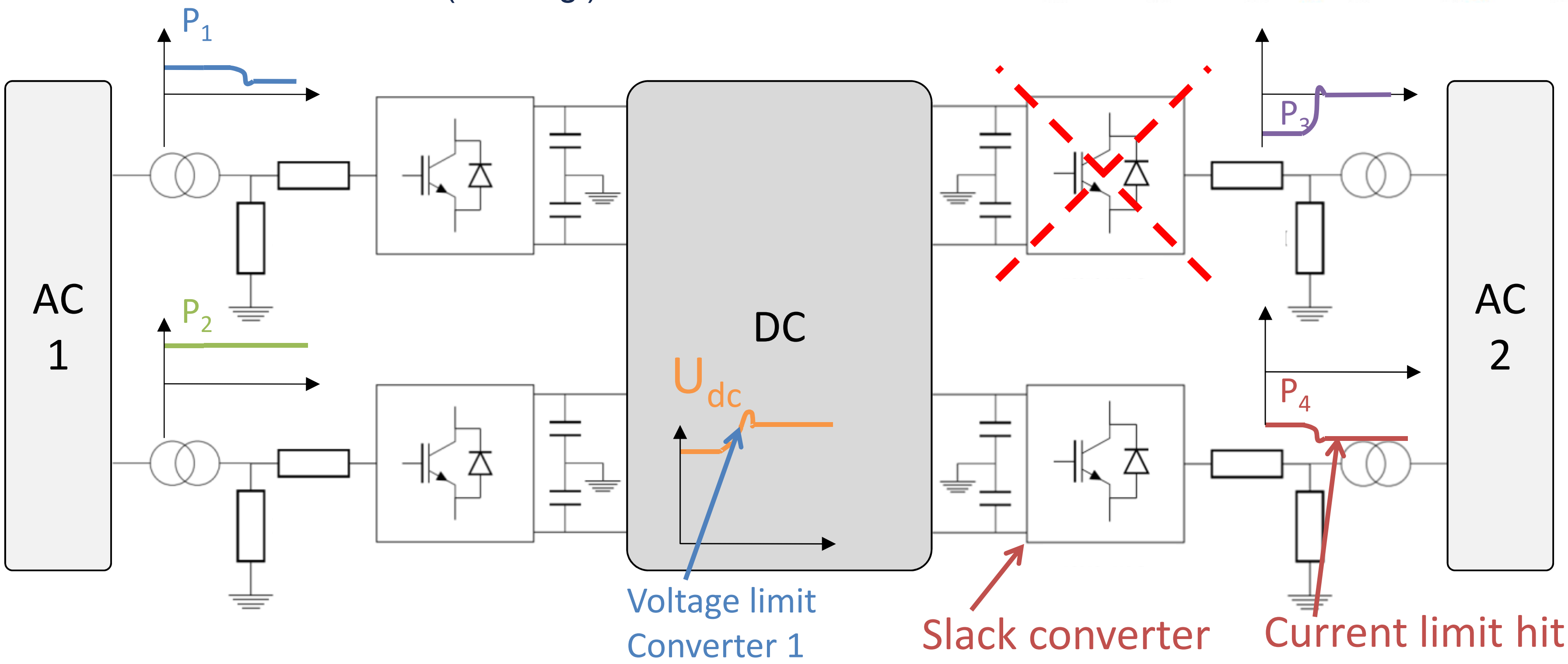
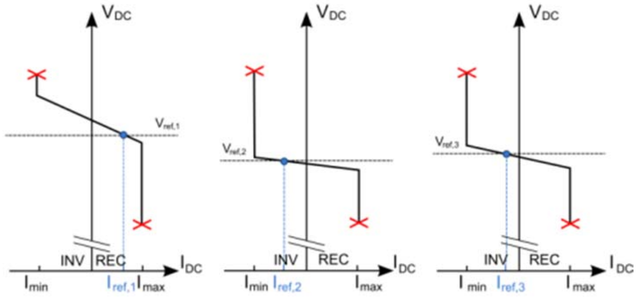
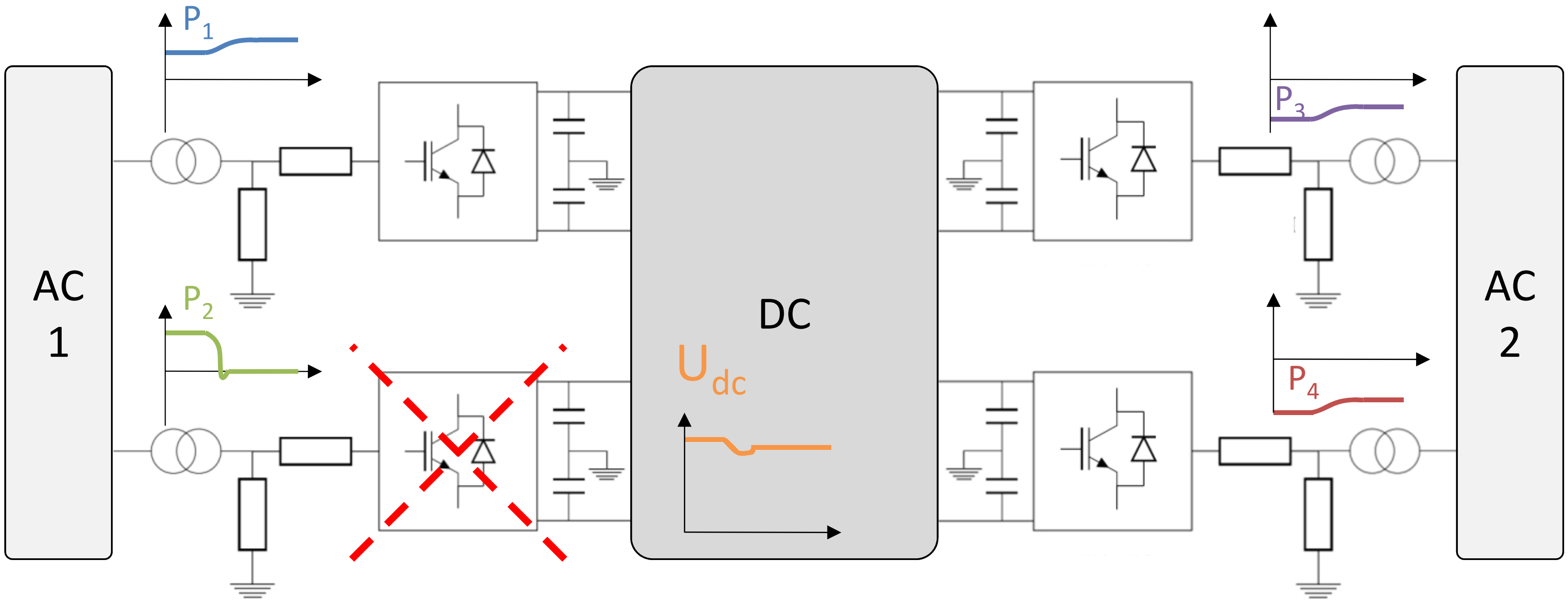




DC Voltage Control in DC Grid
Voltage droop

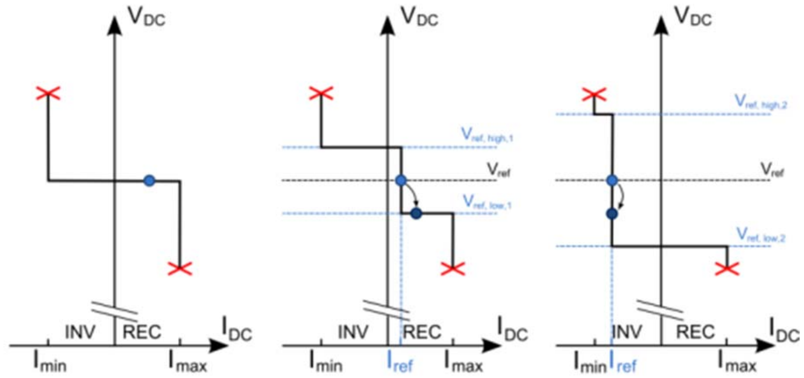
- Distributed DC voltage control
  - Often referred to as ‘distributed slack bus’
  - Based on DC voltage droop



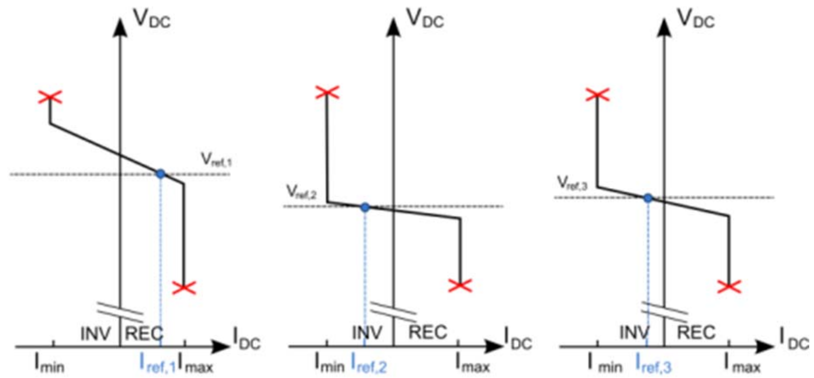


Power or DC voltage control? Control objectives

- P_{ac} constant
- P_{dc} constant
- U_{dc} constant



- U_{dc} distributed control
  - $U_{dc} - I_{dc}$ droop
  - $U_{dc} - P_{dc}$ droop
  - $U_{dc} - P_{ac}$ droop



- …

Modeling VSC HVDC Systems

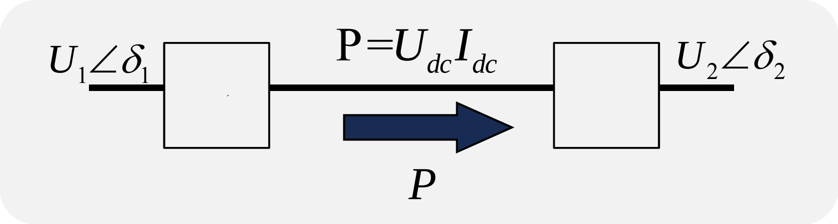
- Steady-state (power flow control)
  - Effect on AC and DC power flows
  - Overall grid state after disturbance
  - N-1 contingency analyses
  - DC voltage droop settings (primary control)
  - Starting point for restorative actions (secondary control)

- Dynamics
  - AC and/or DC system interactions (transient stability)
  - Fast converter dynamics + switching (EMTP)

Different time scales

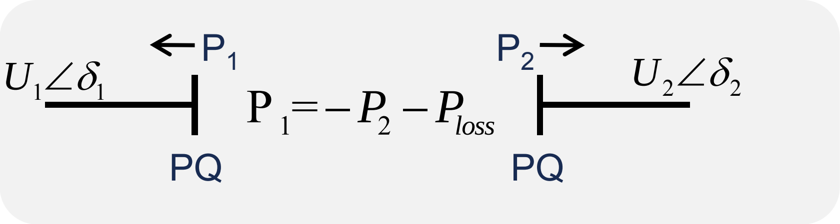
→ different programs and modeling requirements

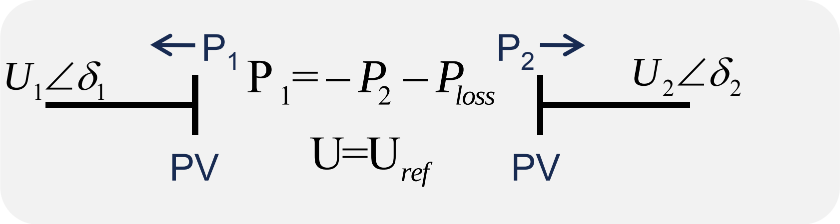
Power flow modeling



Simplified model

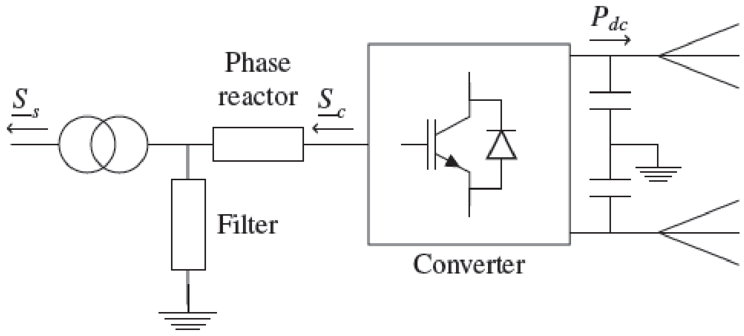
- represent converter as PQ or PV node
- one converter positive active power, second one negative active power



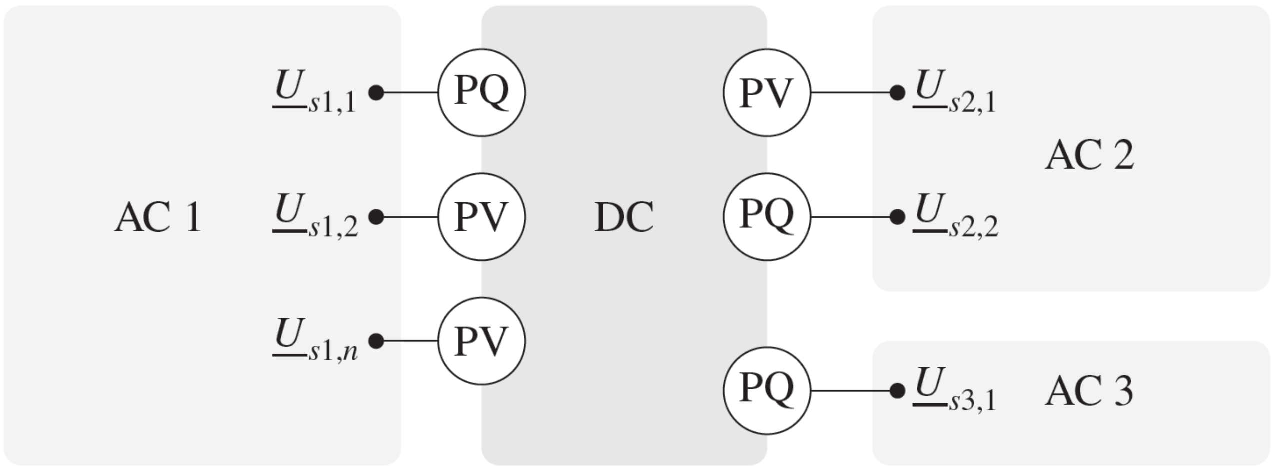


Power flow modeling

- **Combined/unified approach (AC+DC)**
  - Solution of AC and DC grid together
  - Extension of Jacobian matrix
  - → *Only one iterative problem*



- **Sequential approach (AC, DC)**
  1. Use DC grid variables as inputs to solve the AC equations
  2. Use AC grid variables as inputs to solve the DC equations
  - → *Easy extension of existing power flow programs*



AC/VSC MTDC power flow
DC grid power flow

- DC grid power flow equations:

$$P_{dc_i} = 2\,U_{dc_i} \sum_{\substack{j=1 \\ j\neq i}}^{n} Y_{dc_{ij}} \cdot (U_{dc_i} - U_{dc_j})$$

with power-voltage droop

$$P_{dc_i} = P_{dc,0_i} - \frac{1}{k_i}(U_{dc_i} - U_{dc,0_i})$$

$$I_{dc_i} = \sum_{\substack{j=1 \\ j\neq i}}^{n} Y_{dc_{ij}} \cdot (U_{dc_i} - U_{dc_j})$$

with current-voltage droop:

$$I_{dc_i} = I_{dc,0_i} - \frac{1}{k_i}(U_{dc_i} - U_{dc,0_i})$$

- Defining modified active power vector,

$$\boldsymbol{X_{dc}} = [\underbrace{P_{dc_1}}_{\text{slack}}, \underbrace{P_{dc_2} \ldots P_{dc_k}}_{P-\text{control}}, \underbrace{I_{dc,0_{k+1}} \ldots I_{dc,0_l}}_{U-I \text{ droop}}, \underbrace{P_{dc,0_{l+1}} \ldots P_{dc,0_m}}_{U-P \text{ droop}}, \underbrace{0 \ldots 0}_{\text{outage}}]^T$$

- the set of equations can be solved using a NR iteration.

$$\left(\boldsymbol{U_{dc}} \frac{\partial \boldsymbol{X_{dc}}}{\partial \boldsymbol{U_{dc}}}\right)^{(j)} \cdot \frac{\boldsymbol{\Delta U_{dc}}^{(j)}}{\boldsymbol{U_{dc}}} = \boldsymbol{\Delta X_{dc}}^{(j)} \qquad \Delta X_{dc_i}^{(j)} = \begin{cases} P_{dc_i}^{(k)} - P_{dc_i}(\boldsymbol{U_{dc}}^{(j)}) & \forall i:\ 2 < i \leq k \\ I_{dc,0_i} - I_{dc,0_i}(\boldsymbol{U_{dc}}^{(j)}) & \forall i:\ k \leq i \leq l \\ P_{dc,0_i} - P_{dc,0_i}(\boldsymbol{U_{dc}}^{(j)}) & \forall i:\ l \leq i \leq m \\ -P_{dc_i}(\boldsymbol{U_{dc}}^{(j)}) & \forall i:\ m < i \leq n \end{cases}$$

Modeling VSC HVDC Systems

- Steady-state (power flow control)
  - Effect on AC and DC power flows
  - Overall grid state after disturbance
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  - DC voltage droop settings (primary control)
  - Starting point for restorative actions (secondary control)

- Dynamics
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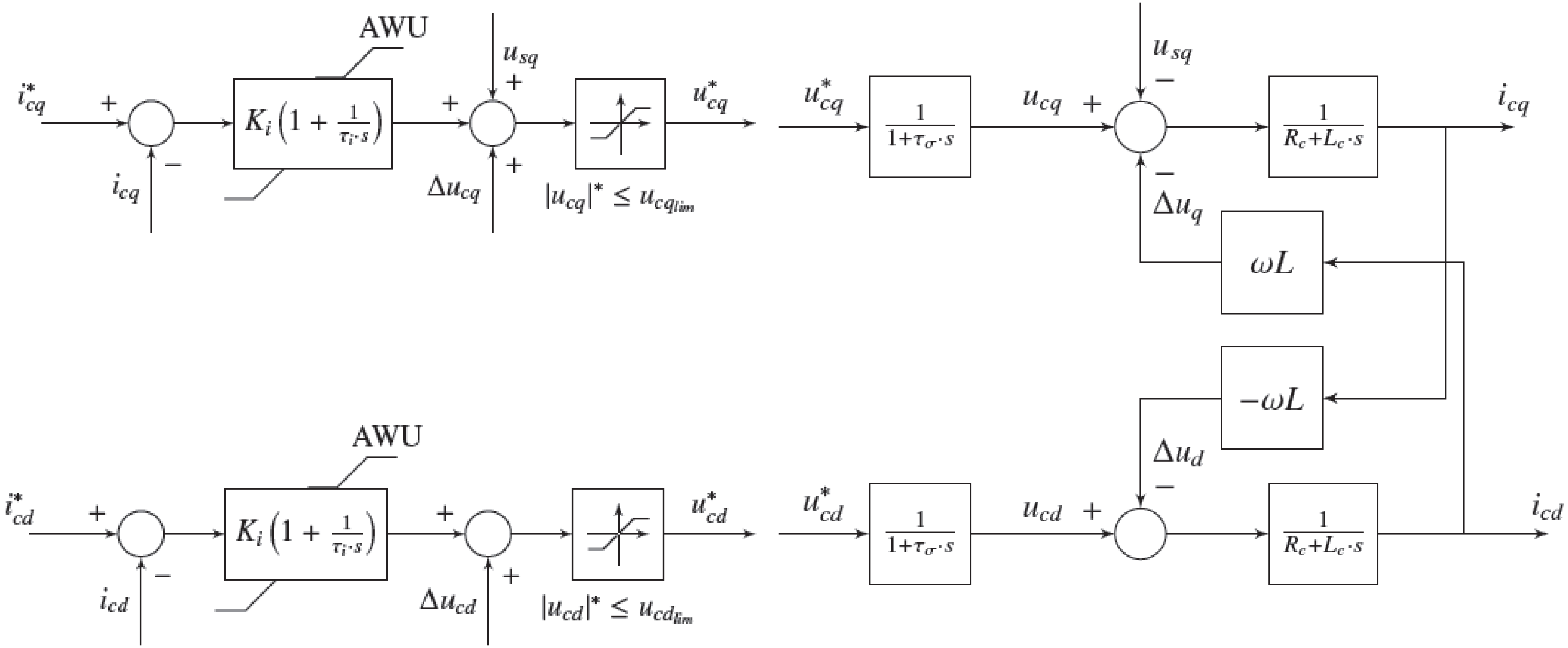
Different time scales

→ different programs and modeling requirements

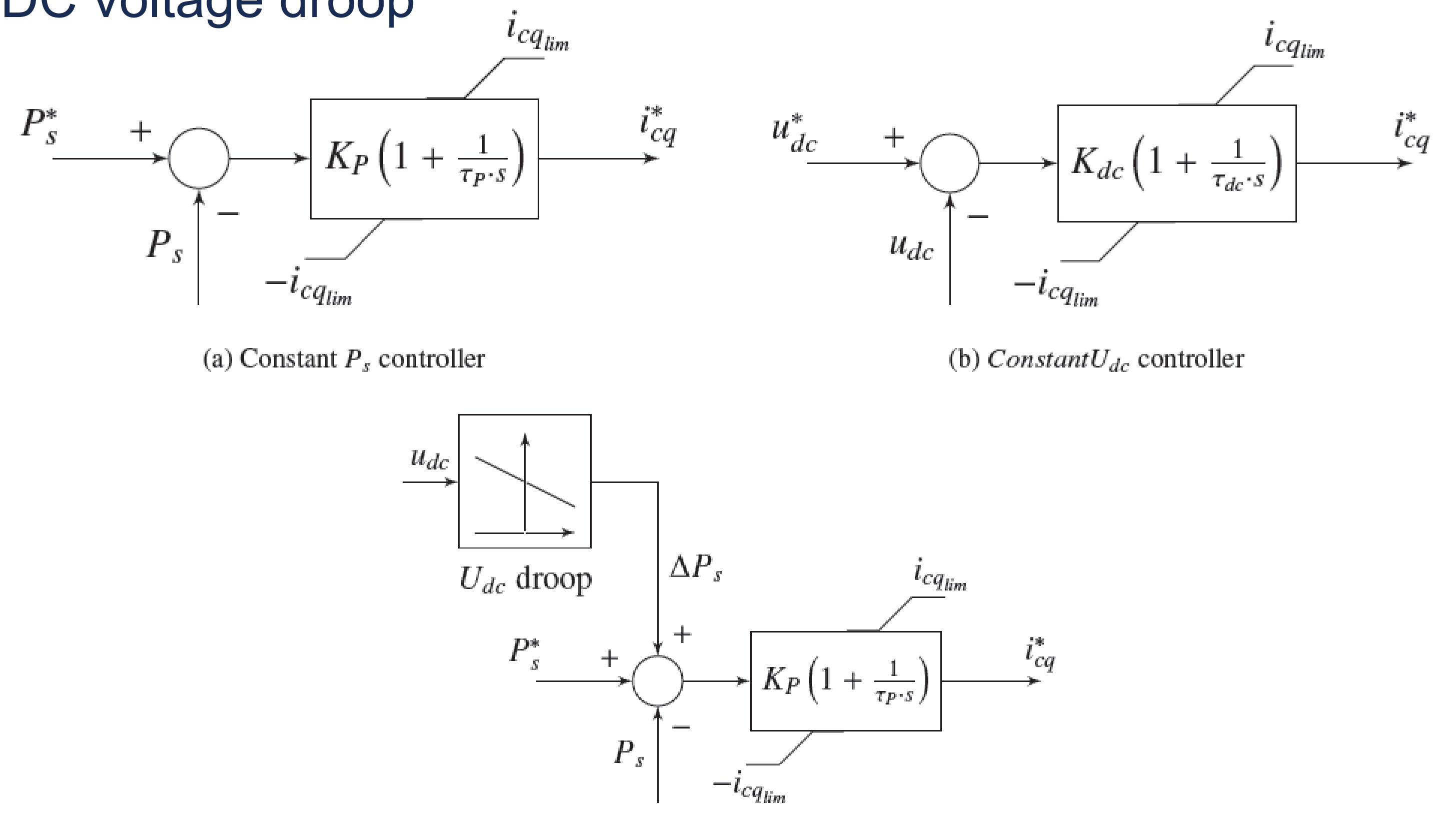
Transient stability modeling

- Converter dynamics
- Power electronics time delay
- Decoupled current control (limits and AWU)



Transient stability modeling

- Outer q control loop
  - Constant active power control
  - Constant DC voltage control
  - DC voltage droop



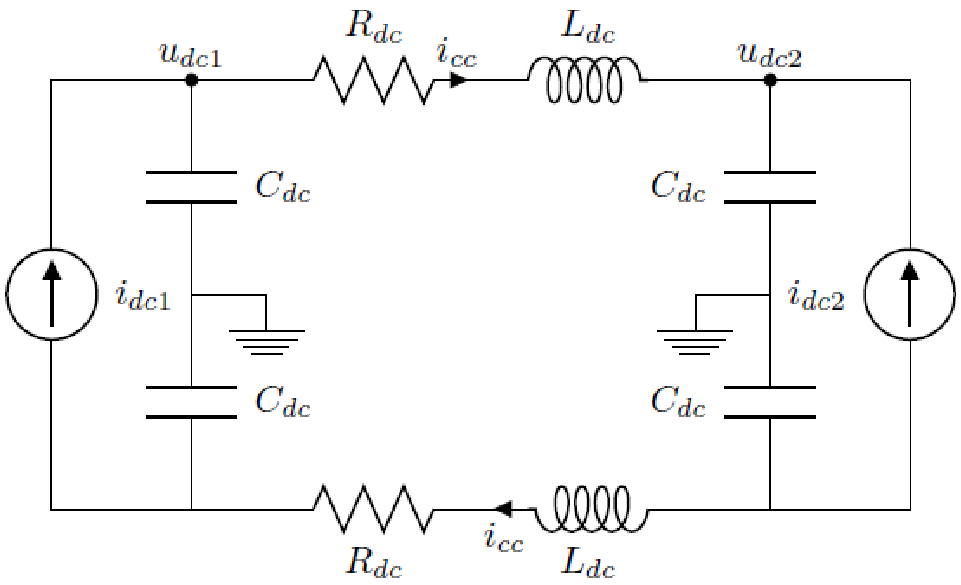
(a) Constant P_s controller

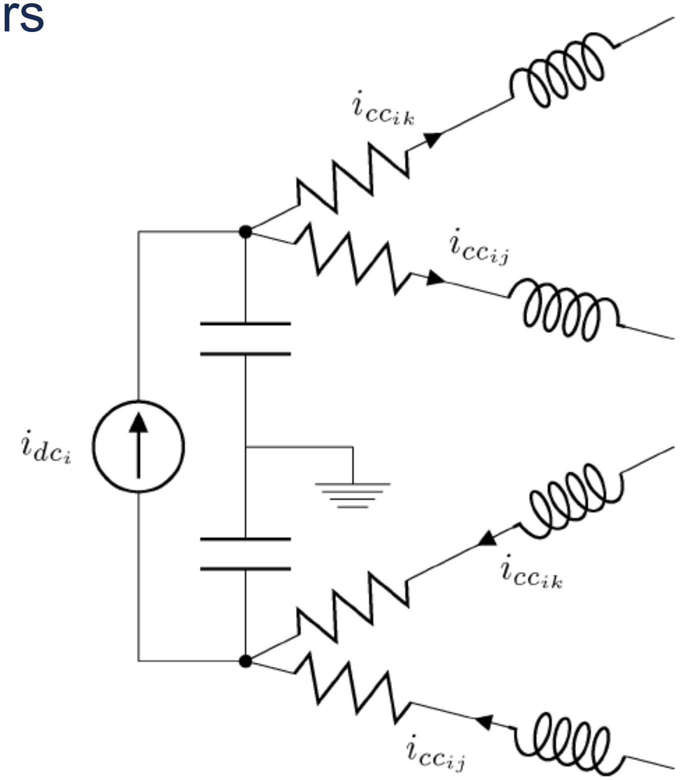
(b) $Constant U_{dc}$ controller

(c) U_{dc} droop controller

Transient stability modeling

- DC grid model
  - Pi equivalent with lumped parameters





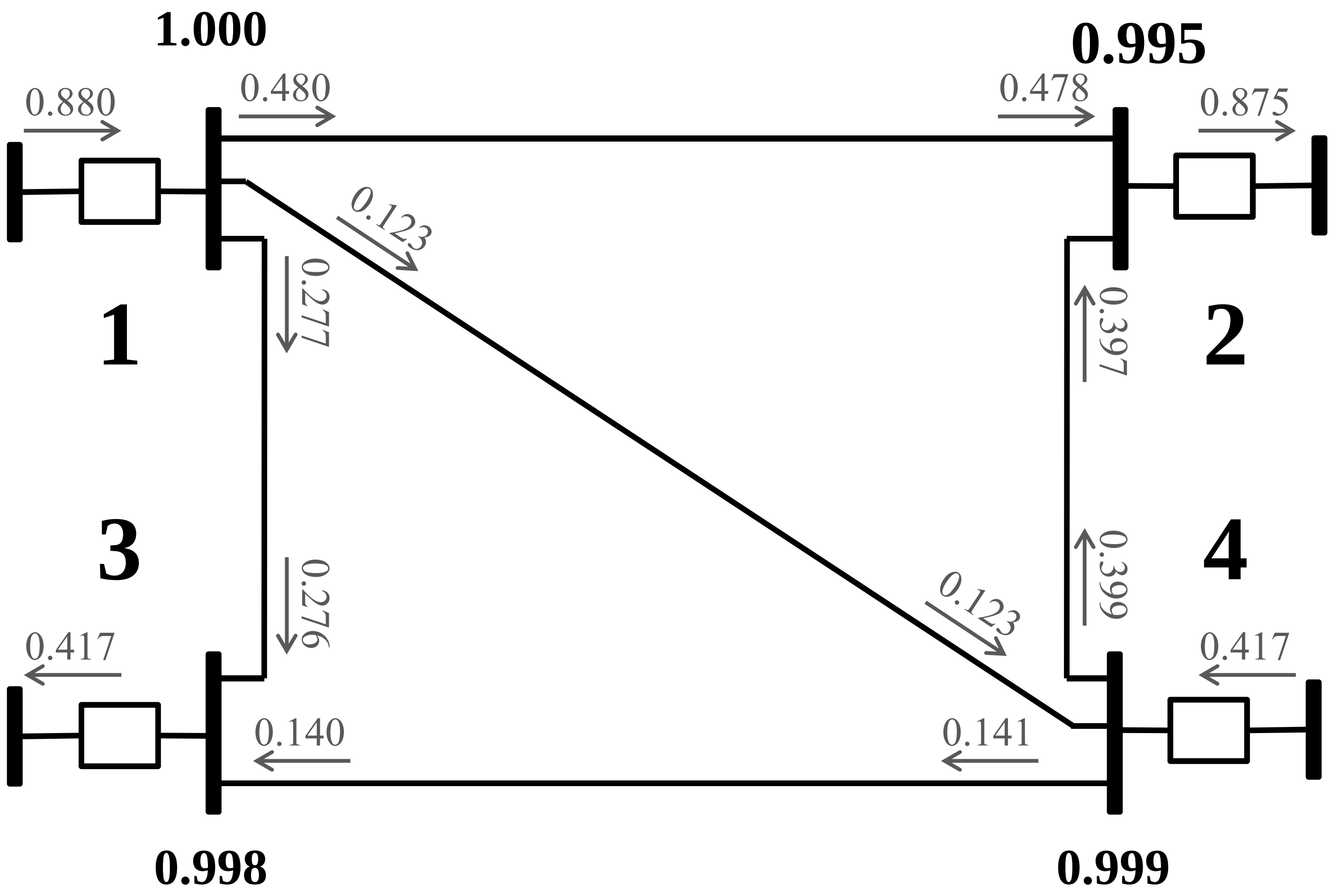
$$C_{dc}\frac{du_{dc_1}}{dt} = i_{dc_1} - i_{cc},$$

$$C_{dc}\frac{du_{dc_2}}{dt} = i_{dc_2} + i_{cc},$$

DC line dynamics: $L_{dc}\frac{di_{cc}}{dt} = u_{dc_1} - u_{dc_2} - R_{dc}i_{cc}.$

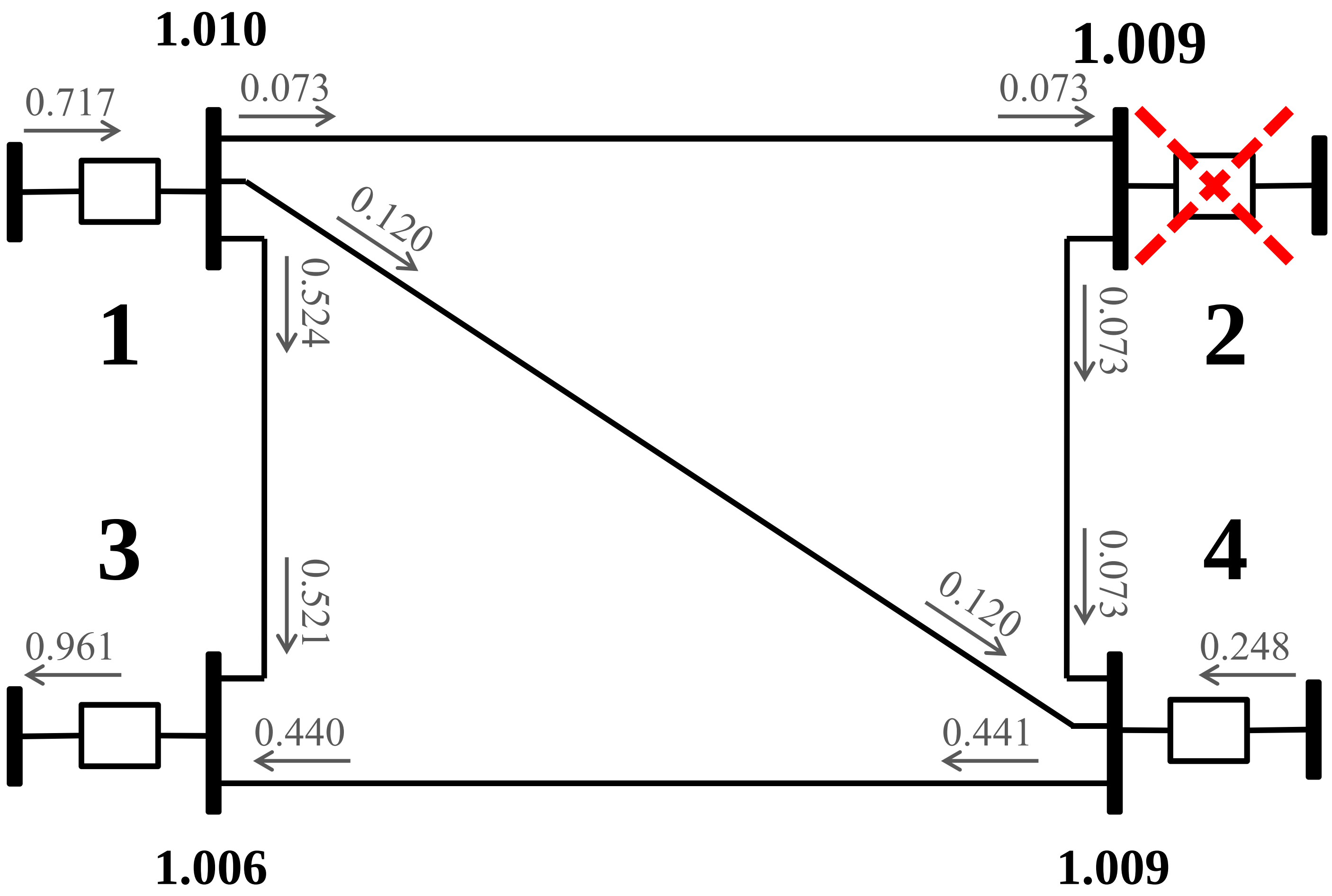
Linking steady-state and dynamics

- DC power flow before converter outage

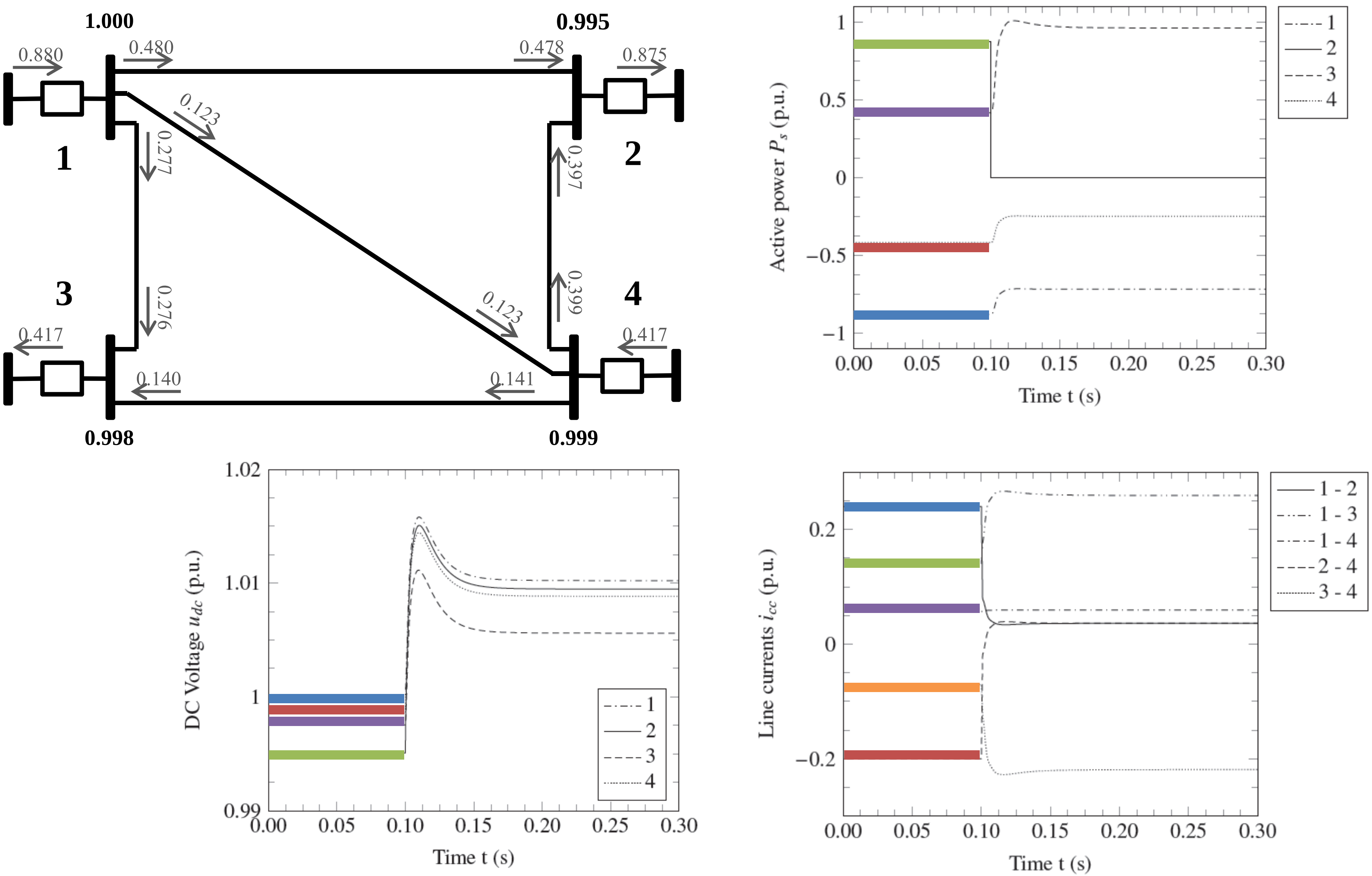


Linking steady-state and dynamics

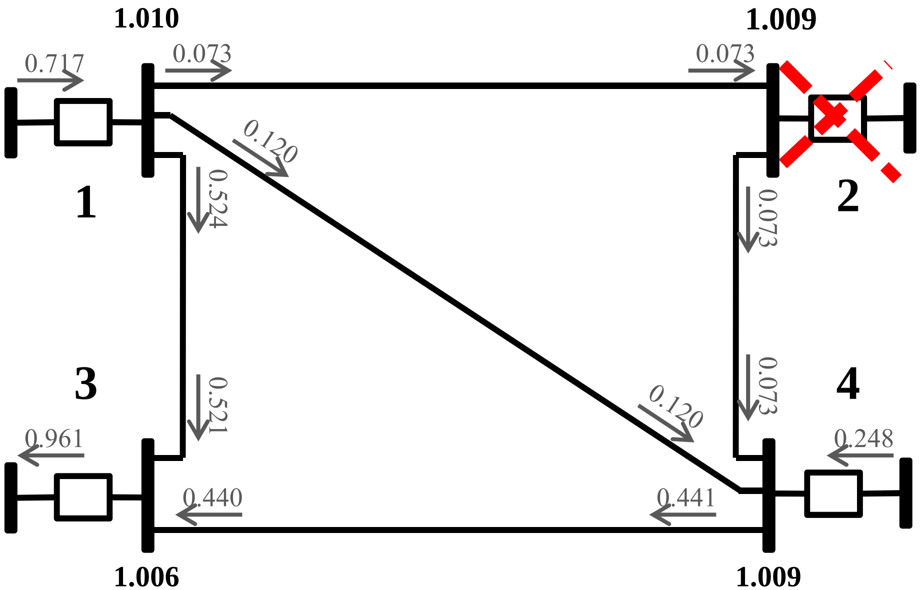
- DC power flow **after** converter outage

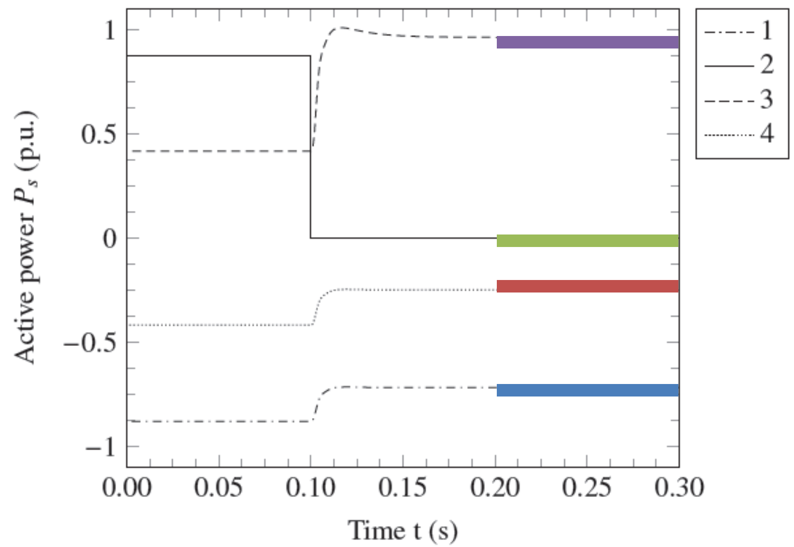


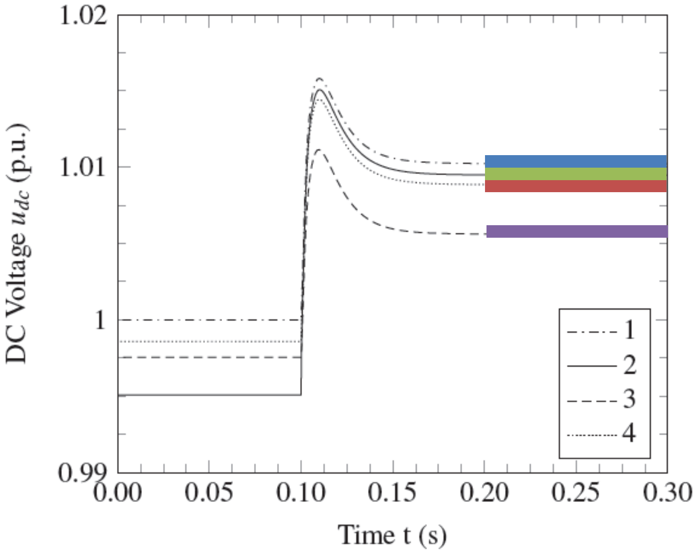
Linking steady-state and dynamics

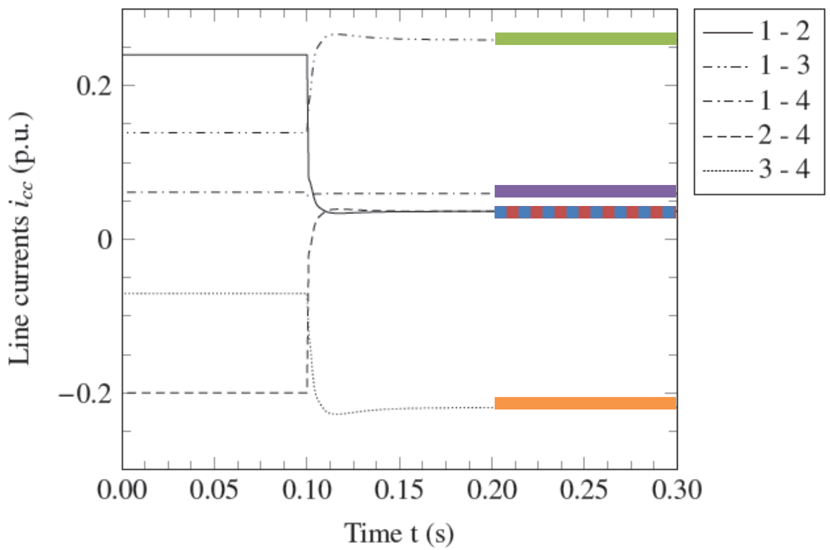


Linking steady-state and dynamics









Conclusions

- Steady-state and dynamic models serve different purposes
  - Power flow algorithms allow to study the post-disturbance effect of control strategies, droop values, limits, … on the steady-state powers and voltage.
  - Transient models allow to study the dynamic interactions between the converters and the dynamic effect of control schemes, droop values, limits, …

- When properly modeled, the results of the power flow analysis are in line with the steady-state post-disturbance dynamic results.