
EERA DeepWind'2015
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Photo: Siemens

EERA DeepWind'2015 – Session B1: Grid Connection

Multi-Terminal HVDC Modeling in Power Flow Analysis Considering Converter Station Topologies and Losses

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- VSC-HVDC Technology Integration
  - Embedded Point-to-Point Connections
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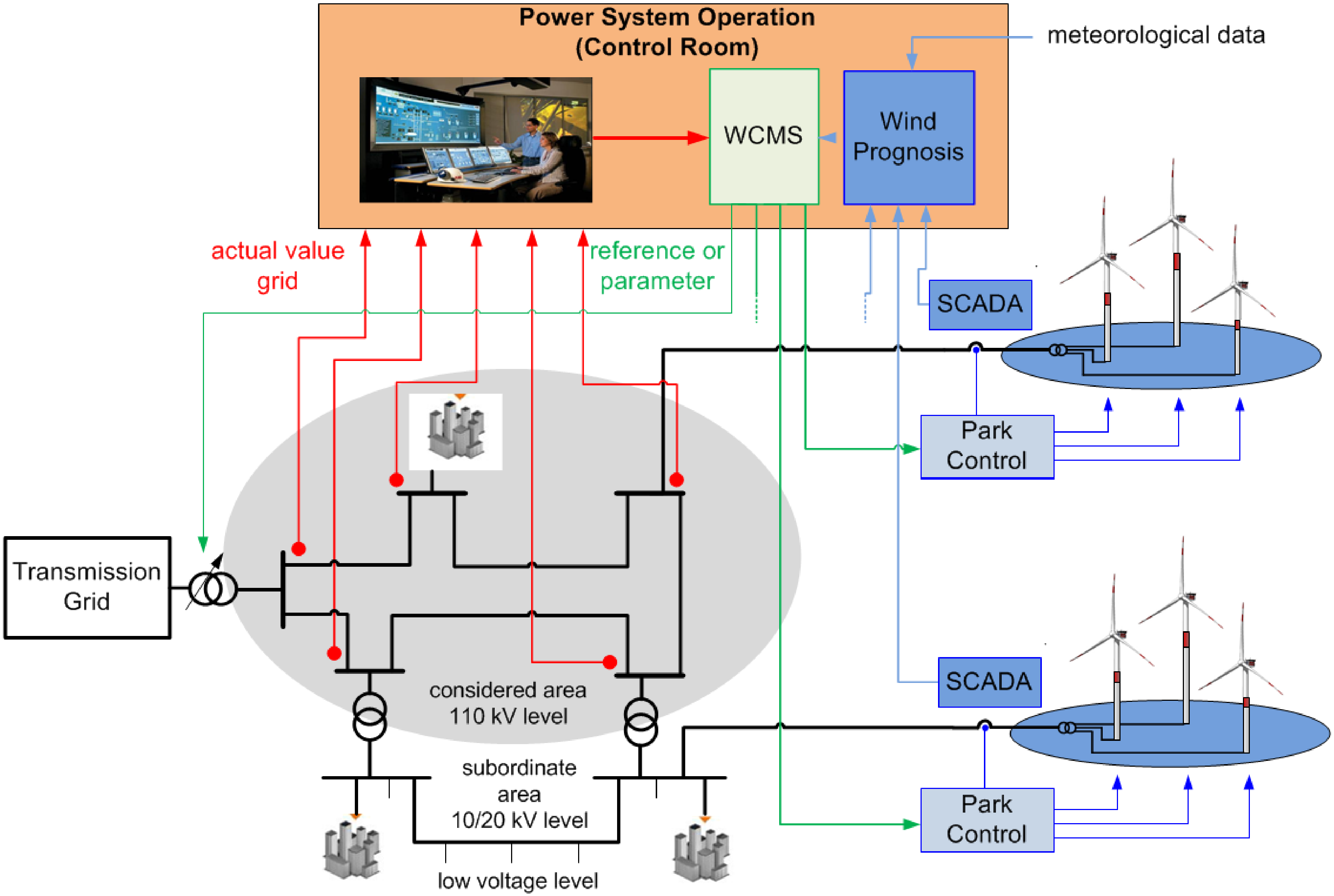
  - Loss Taxonomy
  - Converter Station Setup
  - Loss Models Based on Semi-Conductor Characteristic
  - HVDC Converter Topologies
  - Interconnection with the Power Flow Algorithm
- Study Case: CIGRE B4 DC Test System
- Next Steps

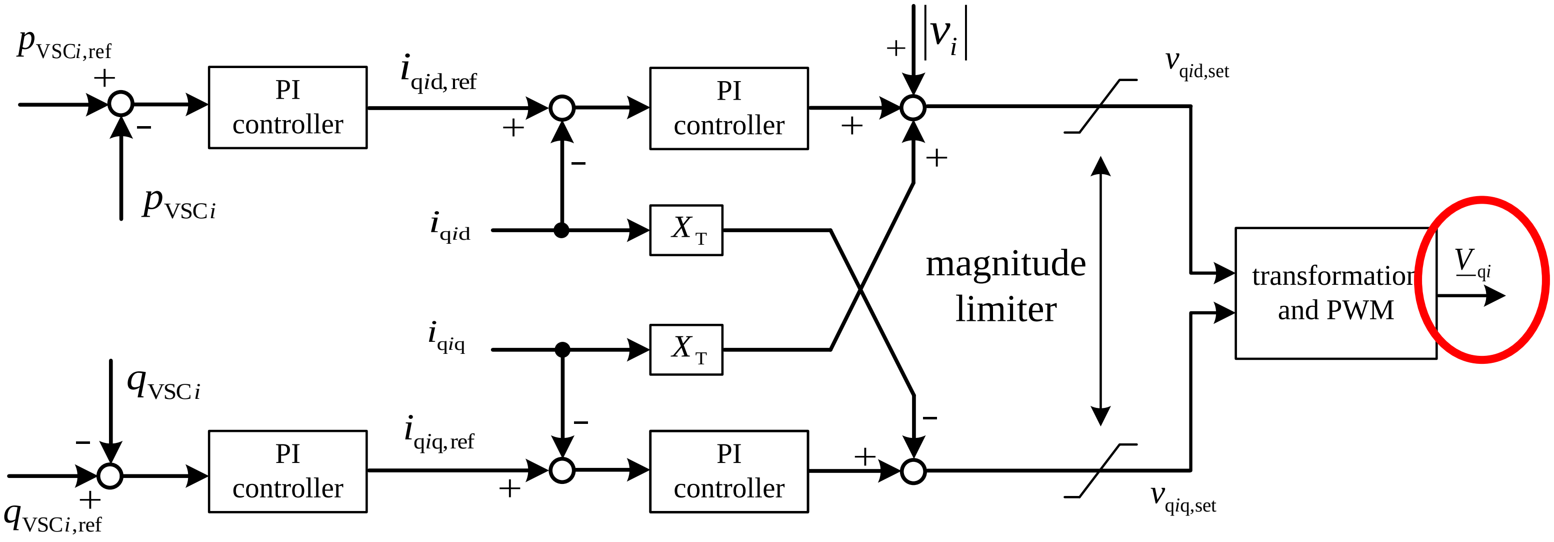
Wind Cluster Management System

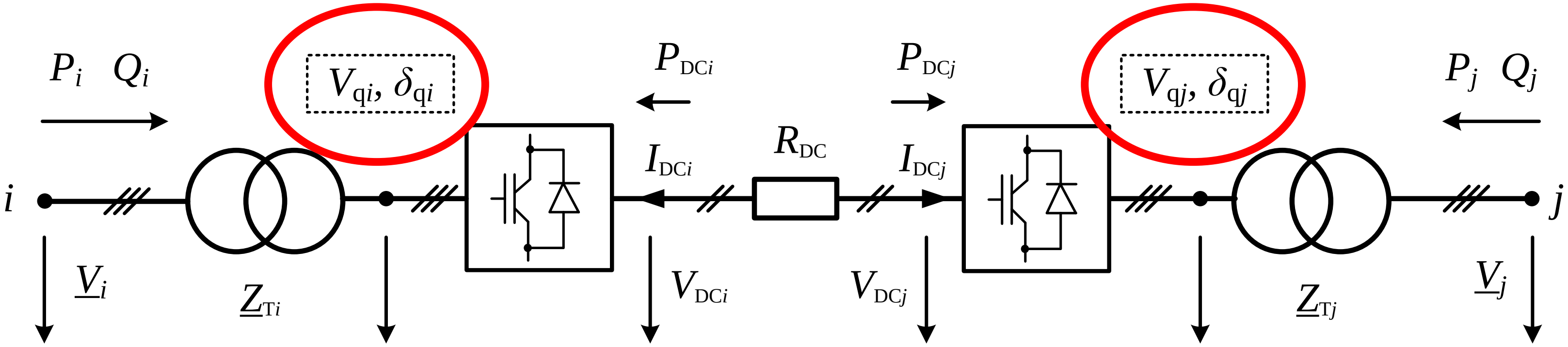


HVDC Technology Integration

- Major impact is evoked by representing and respecting HVDC technology during the calculation process
- VSC-HVDC systems are the preferred technology for offshore grids
  - Voltage control
  - Islanding operation
- CSC-HVDC systems manageable if the grid is strong enough
  - e.g. meshed connection to onshore nodes
- Critical size in terms of power → switching losses VSC still higher than CSC
- Both technologies considered and implemented

Embedded Point-to-Point Connections I





Embedded Point-to-Point Connections II

$$\begin{pmatrix} \Delta\vec{V}_{\mathrm{AC}} \\ \Delta\vec{\delta}_{\mathrm{AC}} \\ \boxed{\begin{matrix} \Delta\vec{V}_{\mathrm{q}} \\ \Delta\vec{\delta}_{\mathrm{q}} \end{matrix}} \end{pmatrix} = \begin{bmatrix} \mathbf{J}_{\mathrm{AC}} + \boxed{\mathbf{J}_{\mathrm{UL}}} & \boxed{\mathbf{J}_{\mathrm{UR}}} \\ \boxed{\mathbf{J}_{\mathrm{LL}}} & \boxed{\mathbf{J}_{\mathrm{LR}}} \end{bmatrix}^{-1} \cdot \begin{pmatrix} -\Delta\vec{P}_{\mathrm{AC}} \\ -\Delta\vec{Q}_{\mathrm{AC}} \\ \boxed{-\Delta\vec{f}_{\mathrm{VSC}}} \end{pmatrix}$$

- Additional state-variables (source nodes)
- Additional vector of state-variables
- Additional mismatches representing control goals
- Expansion of Jacobian matrix

Multi-Terminal HVDC with Droop-Control

- Unified, parallel or integrated approach:

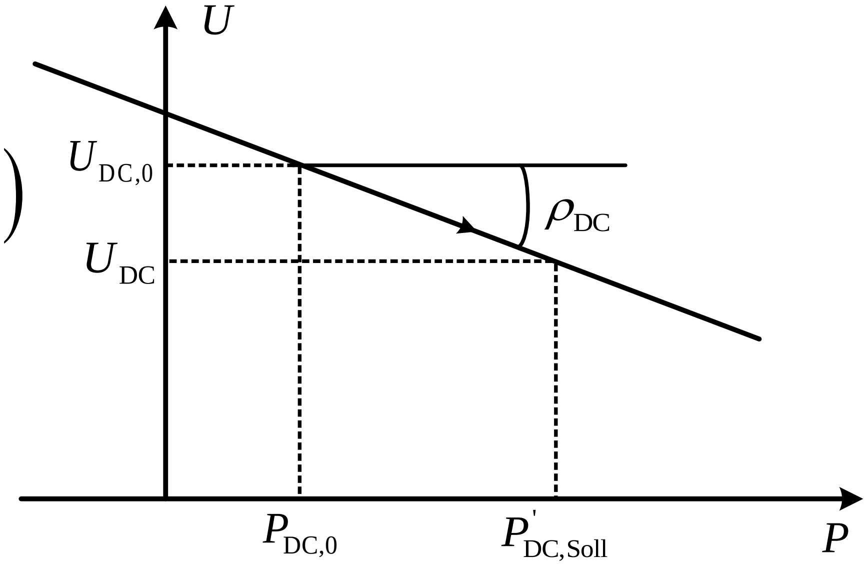
$$\begin{pmatrix}\Delta\boldsymbol{x}_{\mathrm{AC}}\\ \Delta\boldsymbol{x}_{\mathrm{q}}\\ \Delta\boldsymbol{x}_{\mathrm{DC}}\end{pmatrix} = \begin{bmatrix} \boldsymbol{J}_{\mathrm{AC}}+\boldsymbol{J}_{\mathrm{UL}} & \boldsymbol{J}_{\mathrm{UR}} & \\ \boldsymbol{J}_{\mathrm{LL}} & \boldsymbol{J}_{\mathrm{LR}} & \\ & & \boldsymbol{J}_{\mathrm{DC}}\end{bmatrix}^{-1} \cdot \begin{pmatrix}-\Delta\boldsymbol{y}_{\mathrm{AC}}\\ -\Delta\boldsymbol{f}_{\mathrm{VSC}}\\ -\Delta\boldsymbol{y}_{\mathrm{DC}}\end{pmatrix}$$

- New mismatch for active power

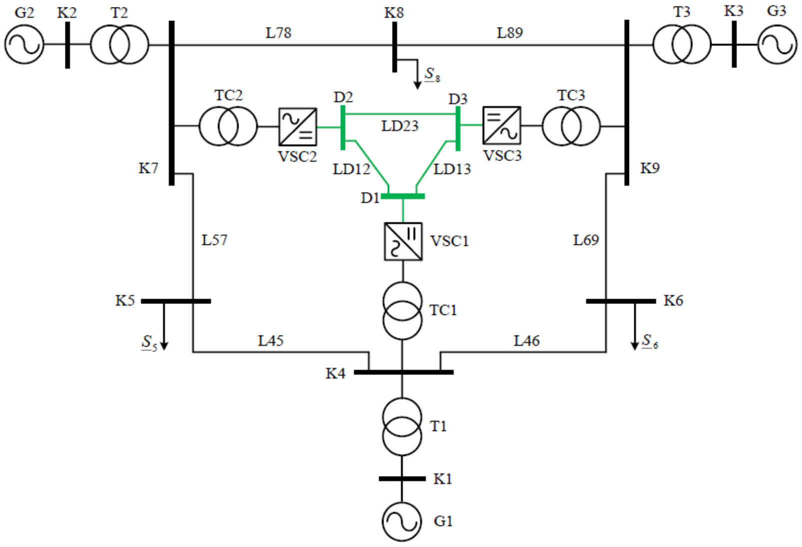
$$P'_{\mathrm{DC,Soll}} = P_{\mathrm{DC,0}} + \frac{1}{\rho_{\mathrm{DC}}}\left(U_{\mathrm{DC}} - U_{\mathrm{DC,0}}\right)$$

- New element of Jacobian:

$$\frac{\partial \Delta P'_{\mathrm{DC}}}{\partial \Delta u_{\mathrm{DC}}} = \frac{\partial \Delta P_{\mathrm{DC}}}{\partial \Delta u_{\mathrm{DC}}} - \frac{1}{\rho_{\mathrm{DC}}} U_{\mathrm{DC}}$$

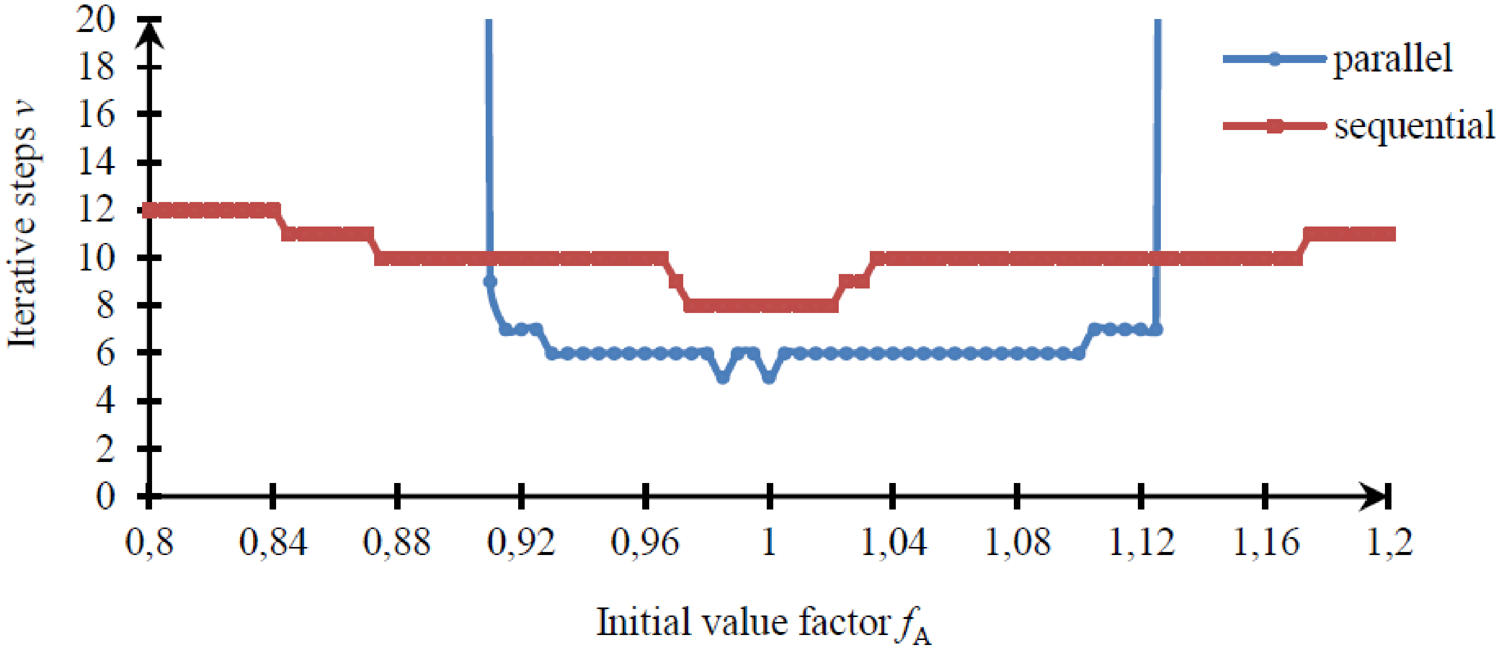


Comparison of Algorithms

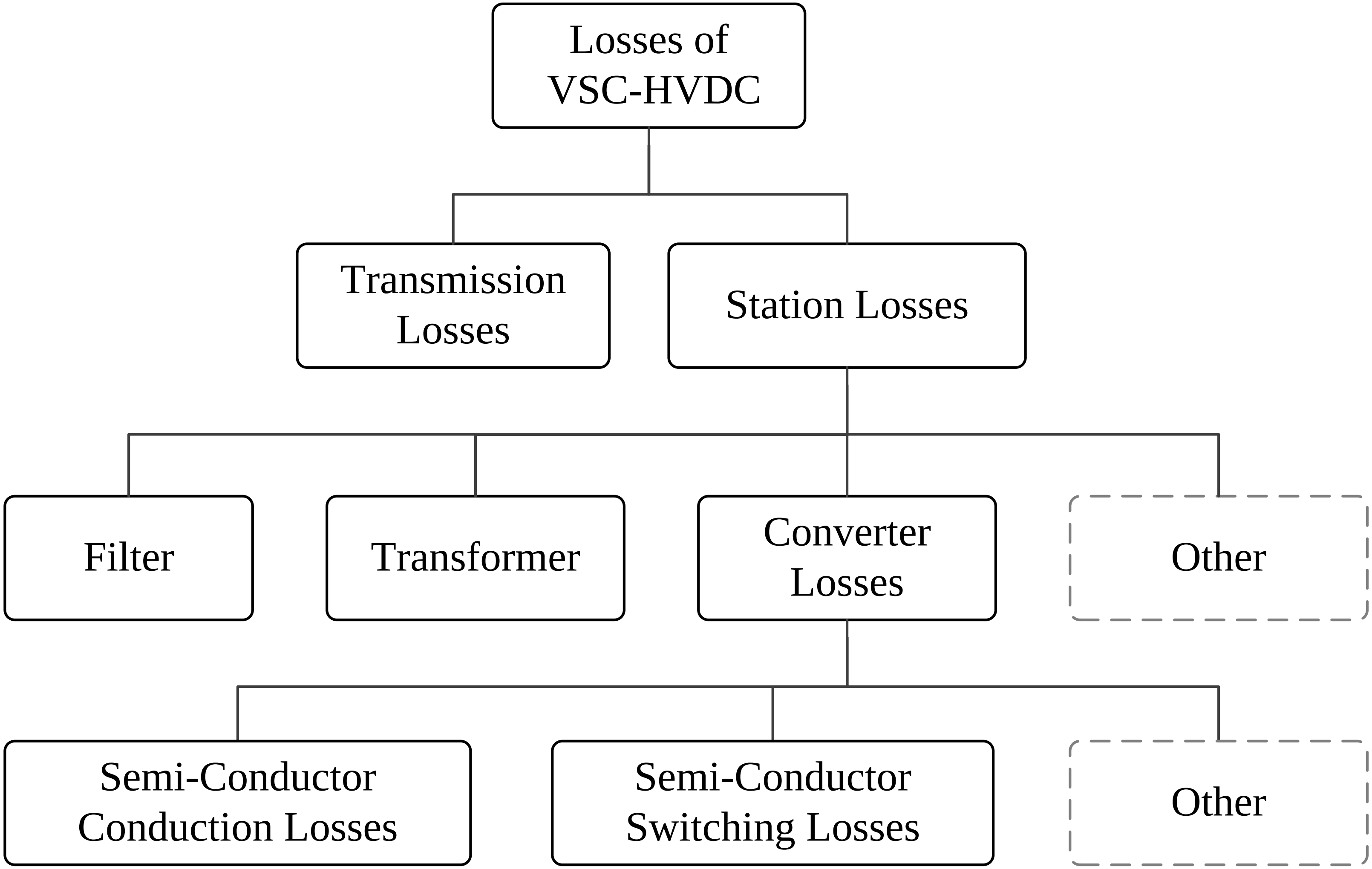


- Sequentiel approach:

$$\Delta \boldsymbol{x}_{\mathrm{DC}} = -\boldsymbol{J}_{\mathrm{DC}}^{-1}\Delta \boldsymbol{y}_{\mathrm{DC}}$$



Loss Taxonomy of HVDC Systems



Losses of VSC-HVDC

Transmission Losses

Station Losses

Filter

Transformer

Converter Losses

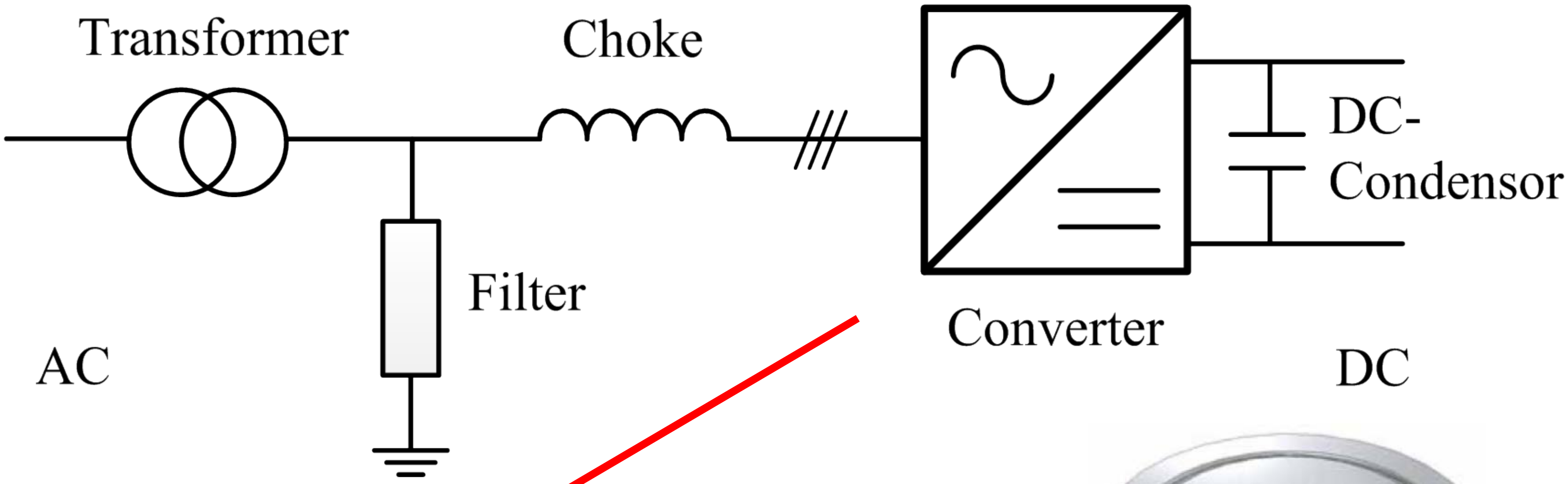
Other

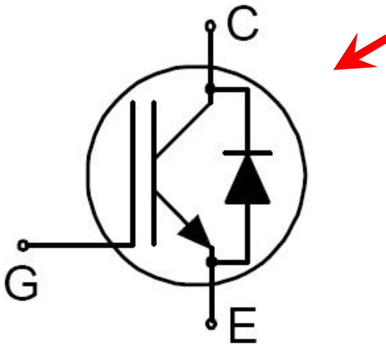
Semi-Conductor Conduction Losses

Semi-Conductor Switching Losses

Other

Converter Station Setup

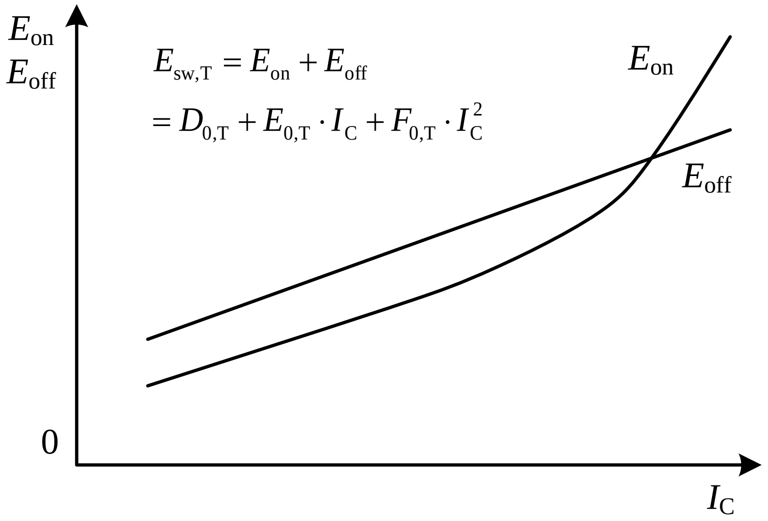




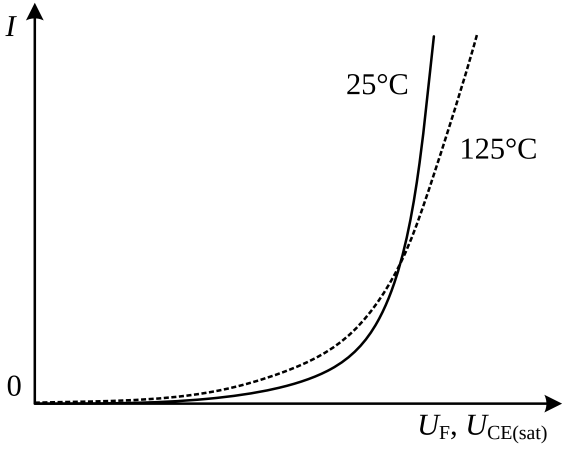
Semi-Conductor Characteristics

- Switching losses:
    - Number of IGBT
    - Switching frequeny
    - Device current
    - Supply voltage
- Conduction losses:
    - Linear approx.
    - Quadratic possbile

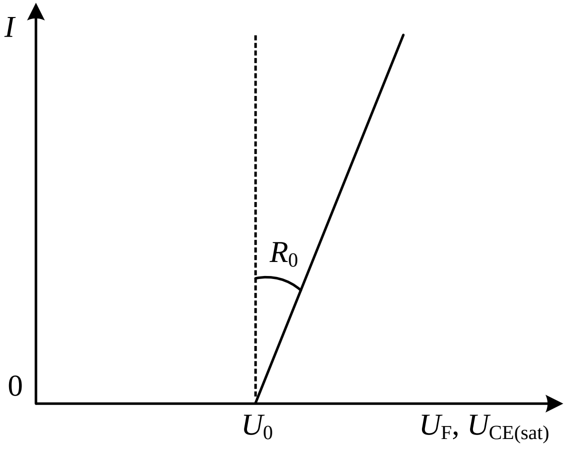
$$P_{\mathrm{cond}} = U_0 \cdot I_{\mathrm{am}} + R_0 \cdot I_{\mathrm{qm}}^2$$



$$E_{\mathrm{sw,T}} = E_{\mathrm{on}} + E_{\mathrm{off}} = D_{0,\mathrm{T}} + E_{0,\mathrm{T}} \cdot I_{\mathrm{C}} + F_{0,\mathrm{T}} \cdot I_{\mathrm{C}}^2$$

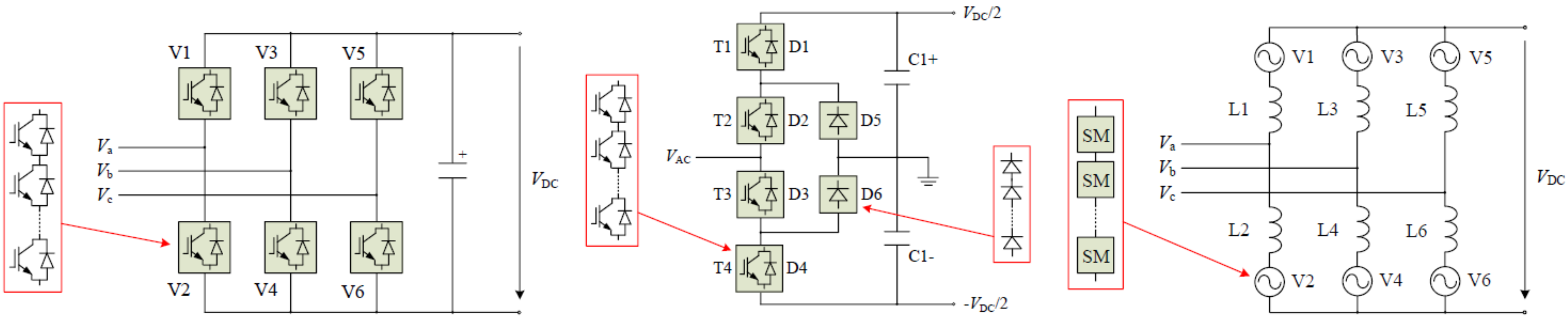


(a)



(b)

Converter Topologies I



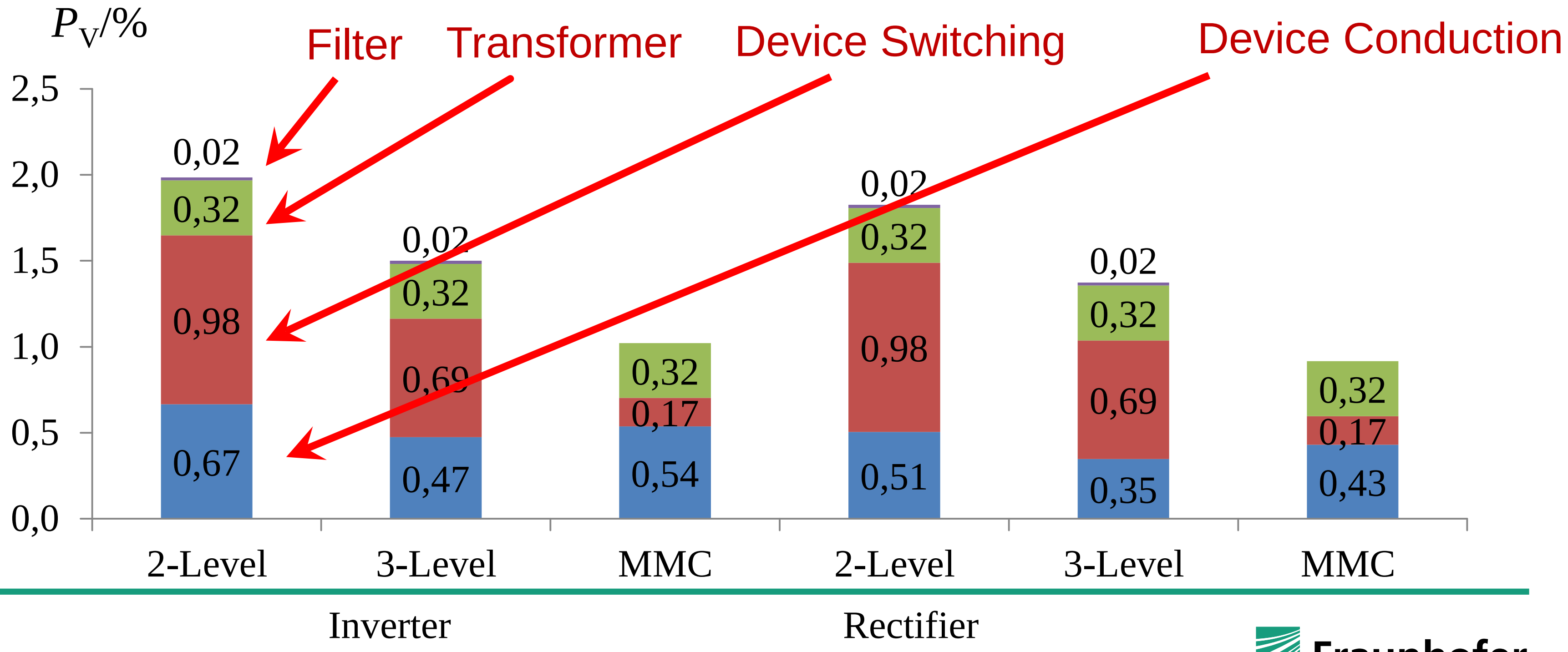
(a) (b) (c)

- Two-level converter (a)
  - Analytical derivation for device current possible
- Three-level converter/neutral point clamped (b)
  - Analytical derivation for device current possible
- Modular multi-level converter/MMC (c)
  - Analytical approx. according to IEC draft standard possible

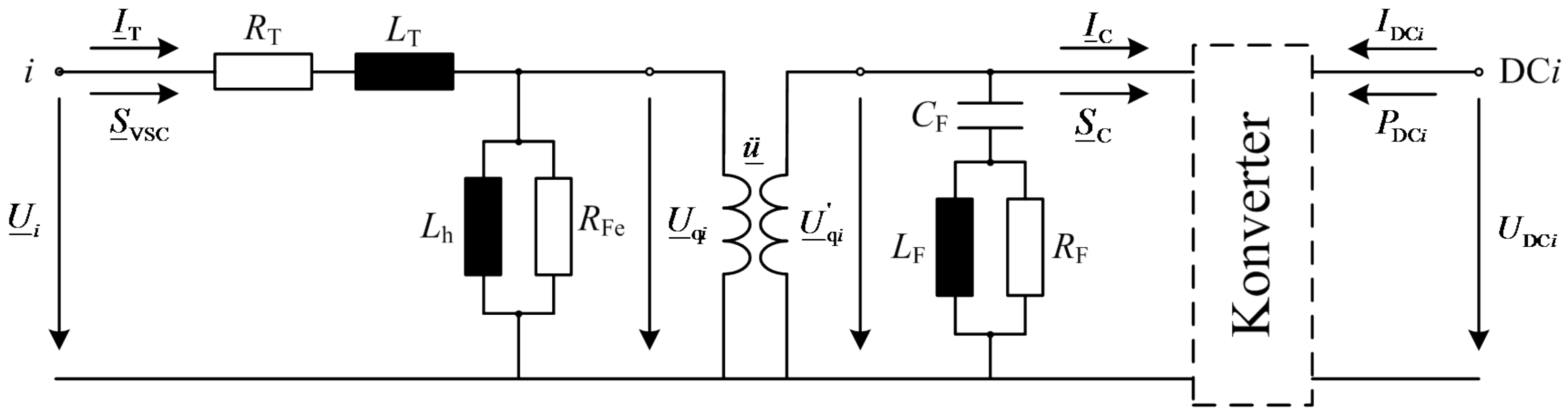
Converter Topologies II

Topology	2-Level	3-Level	MMC
Switching frequency	1150 Hz	1150 Hz	150 Hz
IGBT-Module	5SNR 13H2500	5SNA 1300K450300	CM1500HG-66R
Transformer	yes	yes	yes
Filter	yes	yes	no

- 350 MW Point-to-Point transmission example at **nominal conditions**:



Interconnection with the Power Flow

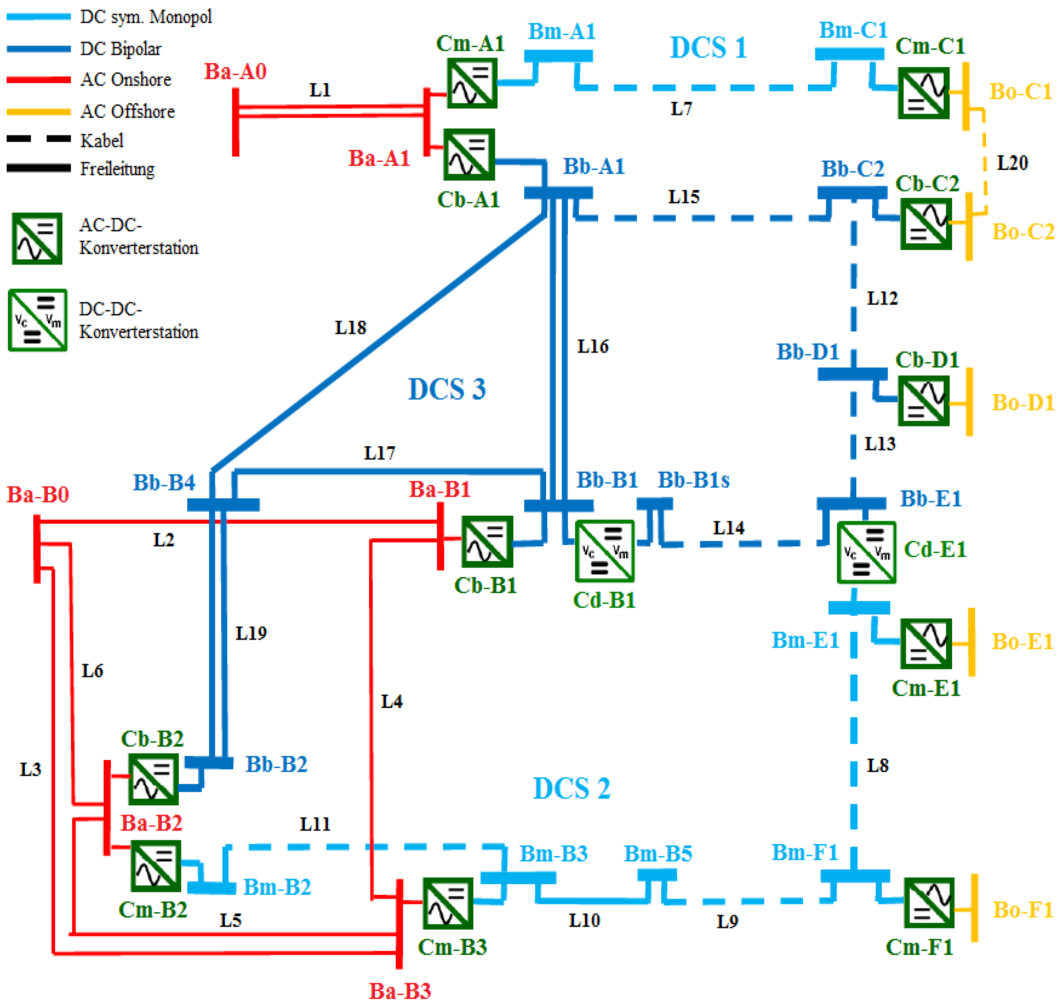


- Assessment of arbitrary operating points
- Converter losses as described
- Filter losses using filter design/dimensioning approach
- Transformer losses with load-independent and load-dependent losses

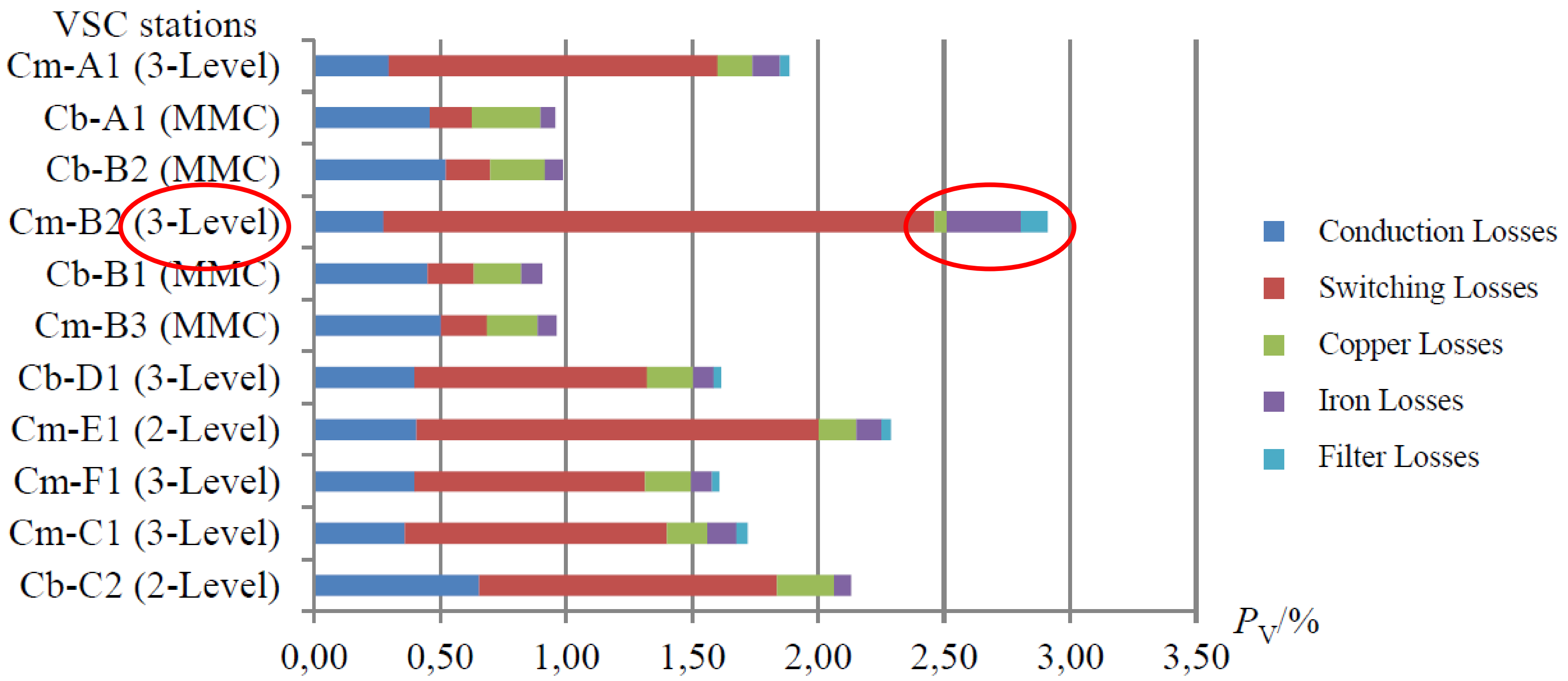
Study Case: CIGRE B4 DC Test System I

- Modular **expansion planning** of offshore grid is assumed
- Technology **development** during expansion assumed

VSC	Topology	IGBT module
Cm-A1	3-Level	5SNA 1300K450300
Cb-A1	MMC	CM1500HG-66R
Cb-B2	MMC	CM1500HG-66R
Cm-B2	3-Level	5SNA 1300K450300
Cb-B1	MMC	CM1500HG-66R
Cm-B3	MMC	CM1500HG-66R
Cb-D1	3-Level	5SNA 1300K450300
Cm-E1	2-Level	5SNR 10H2500
Cm-F1	3-Level	5SNA 1300K450300
Cm-C1	3-Level	5SNA 1300K450300
Cb-C2	2-Level	5SNR 13H2500



Study Case: CIGRE B4 DC Test System II



- Converter Cm-B2 only utilized by 17% in the given scenario
- Switching losses (no-load losses) are dominant and lowering efficiency

Next Steps

- Improving the efficiency of the calculation algorithm
- Detailed integration of converter capabilities into the algorithm
- State-estimation of AC/DC systems including effect of synchronized measurements
- Sensitivity analysis for estimating AC/DC interactions during power system operation
- Lifetime estimation using the load model and evaluating long-term thermal load-cycles for robust long-time planning
- Reliability analysis utilizing the lifetime estimation and different scenarios

RAVE Offshore Wind R&D

International Conference on R&D for Offshore Wind Energy in the North Sea

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Call for abstracts coming soon!

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Main Research Activities:

- Offshore Power System Planning and Operation
- Power System Dynamics Considering Renewables

Backup Power Flow

- Stationary conditions
- Non-linear problem: Newton-Raphson-Verfahren
- Vector of state-variables $\boldsymbol{x}_\mathrm{N}$:

$$\boldsymbol{x}_\mathrm{N} = [\delta_1 \cdots \delta_i \cdots \delta_n \; u_1 \cdots u_i \cdots u_n]^\mathrm{T} = [\boldsymbol{\delta} \; \boldsymbol{u}]^\mathrm{T}$$

- Grid and node powers decomposed in active and reactive parts:

$$\Delta \boldsymbol{p} = \boldsymbol{p}_\mathrm{N} - \boldsymbol{p}_\mathrm{K} = \boldsymbol{0} \qquad \Delta \boldsymbol{q} = \boldsymbol{q}_\mathrm{N} - \boldsymbol{q}_\mathrm{K} = \boldsymbol{0}$$

- Vector of active and reactive power mismatches $\Delta\boldsymbol{y}$: $\Delta \boldsymbol{y} = \left[\Delta \boldsymbol{p} \; \Delta \boldsymbol{q}\right]^\mathrm{T}$
- Partial derivatives

$$\boldsymbol{J} = \begin{bmatrix} \dfrac{\partial \Delta \boldsymbol{q}}{\partial \boldsymbol{\delta}} & \dfrac{\partial \Delta \boldsymbol{q}}{\partial \boldsymbol{u}} \\ \dfrac{\partial \Delta \boldsymbol{q}}{\partial \boldsymbol{\delta}} & \dfrac{\partial \Delta \boldsymbol{q}}{\partial \boldsymbol{u}} \end{bmatrix}$$

$$\Delta \boldsymbol{x}_{\mathrm{N},v+1} = -\boldsymbol{J}_v^{-1} \Delta \boldsymbol{y}_v$$

$$\boldsymbol{x}_{\mathrm{N},v+1} = \boldsymbol{x}_{\mathrm{N},v} + \Delta \boldsymbol{x}_{\mathrm{N},v+1}$$

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