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 – …)
  – BelGer – Nemo (2006 – 2007)
• 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
• 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


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


Offshore grids and supergrid …

What will the future grids look like?

Offshore Grid Proposal by Statnett (Source Statnett, 2008)

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

Vision of High Voltage Super Grid (Source: Dowling and Hurley, 2004)

KEMA Ocean grids

Airtricity

Czisch – Supergrid for renewable energies

Tradewind

Desertec
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 $\approx$ AC frequency
  - Changes when 'consumption' $\neq$ '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’?

![Diagram of DC grid with slack converter]
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’)

![Diagram of DC voltage control system](image)
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 margins (slack outage)
  - Current limits (‘sharing’)

![Diagram of DC voltage control system with AC and DC converters, slack converter, and voltage/current limits markers.]
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*
• DC grid power flow equations:

\[ P_{dc_i} = 2U_{dc_i} \sum_{j=1 \atop j \neq i}^{n} Y_{dc_{ij}} \cdot (U_{dc_i} - U_{dc_j}) \quad \text{with power-voltage droop} \]

\[ I_{dc_i} = \sum_{j=1 \atop j \neq i}^{n} Y_{dc_{ij}} \cdot (U_{dc_i} - U_{dc_j}) \quad \text{with current-voltage droop:} \]

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

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

• Defining modified active power vector,

\[ X_{dc} = \begin{bmatrix} P_{dc_1} & P_{dc_2} & \cdots & P_{dc_k} & I_{dc,0_{k+1}} & \cdots & I_{dc,0_l} & P_{dc,0_{l+1}} & \cdots & P_{dc,0_m} & 0 & \cdots & 0 \end{bmatrix}^T \]

\[ \text{slack} \quad \text{P-control} \quad \text{U-I droop} \quad \text{U-P droop} \quad \text{outage} \]

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

\[ \left( U_{dc} \frac{\partial X_{dc}}{\partial U_{dc}} \right)^{(j)} \cdot \Delta U_{dc}^{(j)} = \Delta X_{dc}^{(j)} \]

\[ \Delta X_{dc_i}^{(j)} = \begin{cases} 
P_{dc_i}^{(k)} - P_{dc_i} (U_{dc}^{(j)}) & \forall i: 2 < i \leq k \\
I_{dc,0_i} - I_{dc,0_i} (U_{dc}^{(j)}) & \forall i: k \leq i \leq l \\
P_{dc,0_i} - P_{dc,0_i} (U_{dc}^{(j)}) & \forall i: l \leq i \leq m \\
-P_{dc_i} (U_{dc}^{(j)}) & \forall i: m < i \leq n 
\end{cases} \]
Modeling VSC HVDC Systems

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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

\[ P_s^* + \rightarrow K_P \left(1 + \frac{1}{\tau_{P,s}}\right) \rightarrow i_{cq}^* \]

\[ u_{dc}^* + \rightarrow K_{dc} \left(1 + \frac{1}{\tau_{dc,s}}\right) \rightarrow i_{cq}^* \]

\[ u_{dc} \rightarrow \Delta P_s \rightarrow i_{cq}^* \]

(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

\[
C_{dc} \frac{du_{dc1}}{dt} = i_{dc1} - i_{cc},
\]
\[
C_{dc} \frac{du_{dc2}}{dt} = i_{dc2} + i_{cc},
\]

DC line dynamics:

\[
L_{dc} \frac{di_{cc}}{dt} = u_{dc1} - u_{dc2} - R_{dc}i_{cc}.
\]
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

![Diagram showing steady-state and dynamic interactions with values and graphs illustrating power and voltage changes over time.]

- Active power $P_1$ (p.u.): Various values are shown with corresponding time evolution graphs.
- DC Voltage $u_{dc}$ (p.u.): Graphs illustrating voltage changes over time with various lines indicating different scenarios.
- Line currents $i_{x}$ (p.u.): Graphs showing current changes over time with different lines for different scenarios.

The diagrams and graphs provide a visual representation of how steady-state and dynamic behaviors interact within the system, emphasizing the analysis of power and voltage dynamics over time.
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.