A Scaling method for a multi-terminal DC experimental test rig

6th HVDC Colloquium
Roskilde, 18/09/15

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1. Motivation
2. Scale-down procedure
3. Example
4. Conclusions
Contents

1. Motivation. *What/Why do we need scaling?*
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Modelling of HVDC systems

- Simulation models:
  - Not always accurate
  - Impractical simulation times in very complex systems

Alternatives

- Experimental test rigs
- Real time simulators
- Hardware-in-the-loop (HIL): Experimental test rig + Real time simulator

Problem: Experimental test rig only for a limited number of configurations and specifications
Scaling a test system

• Experimental results are reliable if the test rig is a close representation of a test system

• What does it mean to scale a system?
  – Process to represent a test system with an experimental test rig

Test rig

Run experiments

Scale-up experimental results to represent test system
Scaling a test system

HVDC system 1

HVDC system 2

HVDC system 3

Test rig

Design to match HVDC system specifications

Test rig is not designed to represent HVDC system 2 and 3

• 2 possible solutions:
  - Change configuration or specifications of test rig
  - Apply correction with VSC
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2. Scale-down procedure. *How to scale a test rig?*
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Proposed procedure

HVDC system

Test rig

Base values \( (V_{b,sys}, S_{b,sys}) \)

Base values \( (V_{b,exp}, S_{b,exp}) \)

Per-unit representation

Per-unit representation

Same cable parameters? \( \text{Yes} \rightarrow \text{Run experiments and scale-up results} \)

Same cable parameters? \( \text{No} \rightarrow \text{Apply Correction with VSC} \)
DC per-unit representation

• In DC systems, L and C are not defined as impedances due to the lack of base frequency

• *Energy method [1]*: dynamic response represented with the energy stored in L and C

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>$P_b$</td>
</tr>
<tr>
<td>Voltage</td>
<td>$U_b$</td>
</tr>
<tr>
<td>Current</td>
<td>$I_b = \frac{P_b}{U_b}$</td>
</tr>
<tr>
<td>Impedance</td>
<td>$Z_b = \frac{U_b}{I_b} = \frac{U_b^2}{P_b}$</td>
</tr>
<tr>
<td>Resistance</td>
<td>$R_b = Z_b$</td>
</tr>
<tr>
<td>Inductance</td>
<td>$L_b = 2Z_b$</td>
</tr>
<tr>
<td>Capacitance</td>
<td>$C_b = 2/Z_b$</td>
</tr>
</tbody>
</table>

Droop control correction

• In this study only the cable resistance is modified $\rightarrow$ correction of steady state results

• Droop control implemented in VSC represents:
  – Voltage source, $u_0$
  – Virtual resistance, $r_{droop}$

\[
\frac{i_{sys}}{r_{cable,sys}} = \frac{u_{sys}}{u_0} = \frac{1}{k_{droop}} \quad \text{(in per unit)}
\]

\[
i_{sys} = k_{droop}(u_{sys} - u_0)
\]
Droop control correction

- In experimental test rig the virtual resistance compensates the difference with the HVDC test system:

\[ i_{\text{exp}} = k_{\text{droop}}^* (u_{\text{exp}} - u_0) \]

\[ \frac{1}{k_{\text{droop}}^*} = \frac{1}{k_{\text{droop}}} + \frac{1}{k_{\text{add}}} = r_{\text{droop}} + r_{\text{add}} \]

(in per unit)
Droop control correction

• Estimation of results from experiments (in per-unit)
  – DC current: \( i_{sys} = i_{exp} \)
  – DC voltage: \( u_{sys} = u_0 - i_{exp} r_{droop} \)
  – DC power: \( p_{sys} = u_{sys} i_{exp} \)

• Scale-up the results from base values of the HVDC system:

\[
\begin{align*}
I_{sys} &= I_{b,sys} i_{sys} \\
U_{sys} &= U_{b,sys} u_{sys} \\
P_{sys} &= P_{b,sys} p_{sys}
\end{align*}
\]
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Application of scaling method

• **Test system**: 3-terminal VSC-HVDC scheme

- **Onshore AC grid 1**: U-I droop control
- **Onshore AC grid 2**: U-I droop control
- **Offshore Wind Farm**: Extract maximum wind power
Application of scaling method

• Experimental set-up

<table>
<thead>
<tr>
<th>Specifications of VSCs</th>
<th>Operation rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>2 kW</td>
</tr>
<tr>
<td>DC voltage</td>
<td>250 V</td>
</tr>
<tr>
<td>AC voltage</td>
<td>140 V</td>
</tr>
</tbody>
</table>
Application of scaling method

• Virtual circuits in the 3-terminal system
Application of scaling method

- Droop correction in the experimental set-up
Application of scaling method

• 3 case studies are considered to validate the method

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power of VSCs</td>
<td>800 MW</td>
<td></td>
<td>400 MW</td>
</tr>
<tr>
<td>MTDC rated voltage</td>
<td></td>
<td>±200 kV</td>
<td></td>
</tr>
<tr>
<td>Cable length 1-3</td>
<td>200 km</td>
<td>100 km</td>
<td>200 km</td>
</tr>
<tr>
<td>Cable length 2-3</td>
<td>400 km</td>
<td>500 km</td>
<td>400 km</td>
</tr>
</tbody>
</table>

• Base values and DC cable resistances in per-unit for each case study and the experimental test rig

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Test rig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base power, $P_b$</td>
<td>800 MVA</td>
<td>400 MVA</td>
<td>700 VA</td>
<td></td>
</tr>
<tr>
<td>Base voltage, $V_b$</td>
<td></td>
<td>400 kV</td>
<td></td>
<td>250 V</td>
</tr>
<tr>
<td>Resistance 1-3, $r_{13}$</td>
<td>0,0096</td>
<td>0,0048</td>
<td>0,0048</td>
<td>0,0005</td>
</tr>
<tr>
<td>Resistance 2-3, $r_{23}$</td>
<td>0,0192</td>
<td>0,0240</td>
<td>0,0096</td>
<td>0,0026</td>
</tr>
</tbody>
</table>
Results

• Comparison simulation in PSCAD with experimental results with and without the droop correction

• Initial injection of 0,3 pu from OWF.
• Increase of power to 0,6 pu.
• Droop control in GSC1 and GSC2 designed to share the same power

• DC current and voltage results
Results

- Case 1: 800 MW, l13=200 km, l23=400 km
Results

• Case 2: 800 MW, $l_{13}=100$ km, $l_{23}=500$ km

DC currents

Simulation

Experiments without correction

Experiments with correction

DC voltages

Simulation

Experiments without correction

Experiments with correction
Results

- Case 3: 400 MW, l13=200 km, l23=400 km

DC currents

Simulation

Experiments without correction

Experiments with correction

DC voltages

Simulation

Experiments without correction

Experiments with correction

[Graphs showing DC currents and voltages for Simulation and Experiments with and without correction for Case 3.]
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Conclusions

• A scaling method was demonstrated to obtain uniform steady state responses between an MTDC experimental rig and three different HVDC systems.

• The droop control correction allows representing many equivalent DC cables without using different physical elements → Increase flexibility of experimental set-up.
Any question?