Transient analysis of transformers and cables for offshore wind connection

Bjørn Gustavsen
SINTEF Energy Research
Trondheim, Norway

Wind power R&D seminar – deep sea offshore wind:
Outline

- Modeling of transformers and cables
- High-frequency transformer-cable resonance
- Wind power
PART I:  
Modeling of transformers and cables
High-frequency transformer modeling (black box)

1. Characterize the transformer by its frequency domain behavior at its external terminals

2. Identify a model which emulates the behavior of the transformer, as seen from the terminals.
Terminal characterization by admittance matrix

\[ i = Y_n v \]

\[
\begin{bmatrix}
I_1(\omega) \\
I_2(\omega) \\
\vdots \\
I_n(\omega)
\end{bmatrix} =
\begin{bmatrix}
Y_{11}(\omega) & Y_{12}(\omega) & \cdots & Y_{1n}(\omega) \\
Y_{21}(\omega) & Y_{22}(\omega) & \cdots & Y_{2n}(\omega) \\
\vdots & \vdots & \ddots & \vdots \\
Y_{n1}(\omega) & Y_{n2}(\omega) & \cdots & Y_{nn}(\omega)
\end{bmatrix}
\begin{bmatrix}
V_1(\omega) \\
V_2(\omega) \\
\vdots \\
V_n(\omega)
\end{bmatrix}
\]
Measurement of admittance matrix

- Network analyzer
- Connection box
- Coaxial cables
- Current sensor

Built-in current sensor (Pearson)
Modeling via rational functions

The rational model is compatible with EMTP-type circuit simulators
Procedure for rational fitting

1. Calculate a rational model using Vector Fitting

\[ Y(\omega) \approx \sum_{m=1}^{N} \frac{R_m}{j\omega - a_m} + D \]

2. Enforce passivity by residue perturbation

\[ \Delta Y = \sum_{m=1}^{N} \frac{\Delta R_m}{s - a_m} + \Delta D \geq 0 \]

\[ eig(Re\{Y + \sum_{m=1}^{N} \frac{\Delta R_m}{s - a_m}\}) > 0 \]

\[ eig(D + \Delta D) > 0 \]

Matrix Fitting Toolbox

http://www.energy.sintef.no/produkt/VECTFIT/index.asp
High-frequency cable modeling

1. Characterize the cable by its per-unit-length series impedance matrix $Z$ and shunt admittance matrix $Y$

\[
Z(\omega) = R(\omega) + j\omega L(\omega)
\]
\[
Y(\omega) = G(\omega) + j\omega C(\omega)
\]

2. From $Z$ and $Y$, calculate parameters for a frequency-dependent traveling wave model.

This modeling capability is available in EMTP-type programs.

Main challenge: calculate $Z$
- Analytical expressions
- Finite Element
PART II:
Cable-transformer high-frequency resonance

Demonstrate that transients on the high-voltage side of a transformer can cause excessive overvoltages on the low-voltage side.

Identify critical cable-transformer configurations that lead to high overvoltages.
Voltage ratio, from high to low

At high frequencies, the voltage ratio is governed by stray capacitances and inductances, not ampere-winding balance.

50 Hz → voltage ratio ≈ 0.02
2 MHz → voltage ratio ≈ 2

A 2 MHz sinusoidal voltage would produce a 100 p.u. overvoltage
Laboratory measurement

Before connecting cable to transformer

After connecting cable to transformer

~24 p.u. overvoltage !!
Measurement-based model of transformer

- Frequency sweep measurements of $Y(\omega)$
- Model extraction by Matrix Fitting Toolbox

$$Y(\omega) \approx \sum_{m=1}^{N} \frac{R_m}{j\omega - a_m} + D$$
Measurement-based model of 27-m cable

Model extraction by Matrix Fitting Toolbox

\[
\begin{bmatrix}
    i_1 \\
    i_2
\end{bmatrix} =
\begin{bmatrix}
    y_a & y_b \\
    y_b & y_a
\end{bmatrix}
\begin{bmatrix}
    v_1 \\
    v_2
\end{bmatrix}
\]

\[
y_b = \frac{b}{R(a - 1)}
\]

\[
y_a = -\frac{y_b}{a}
\]

\[
Y(\omega) \approx \sum_{m=1}^{N} \frac{R_m}{j\omega - a_m} + D
\]

\[y_a, y_b\]
Simulation vs. measurement

**High-voltage**

Step voltage

30 Ω

**Low-voltage**

Cable (27 m)

Before connecting cable to transformer

After connecting cable to transformer

SINTEF Energy Research

B. Gustavsen, 2010
Max. overvoltage vs. cable length

– State-of-the art frequency-dependent traveling-wave type model obtained from geometry.

<table>
<thead>
<tr>
<th></th>
<th>Radius [mm]</th>
<th>Thickness [mm]</th>
<th>Resistivity [Ω·m]</th>
<th>$s_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase conductor</td>
<td>9.25</td>
<td></td>
<td>3.36E-8</td>
<td></td>
</tr>
<tr>
<td>Semiconductor</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>3.4</td>
<td></td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Semiconductor</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheath conductor</td>
<td>0.4</td>
<td></td>
<td>1.72E-8</td>
<td></td>
</tr>
<tr>
<td>Jacket</td>
<td>2</td>
<td></td>
<td>2.3</td>
<td></td>
</tr>
</tbody>
</table>

– Compute max. overvoltage on low-voltage side for alternative cable lengths
Ground fault.
Max. overvoltage vs. cable length

Overvoltage in p.u. of applied voltage

20 m cable (open LV)

Overvoltage in p.u. of applied voltage

Cable length [m]

0 20 40 60 80 100

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

Maximum overvoltage [p.u.]

Open

C=1 nF  R=400 Ω

20 m cable (open LV)

~43 p.u. overvoltage !!

Time [µs]

0 1 2 3 4

V_3  V_4  V_5  V_6

Excitation
Switching overvoltages (1)

- Several parallel cables connected to bus
- Combined characteristic impedance much lower than that of connection cable
- Bus appears as "stiff" voltage seen from connection cable

Closing CB results in oscillating voltage on cable
Switching overvoltages (1)

\[ V_A \]

\[ V_1 \]

\[ V_5 \]

\[ V_6 \]

\[ V_4 \]

\[ \text{~20 p.u. overvoltage !!} \]
Switching overvoltages (2)

- Two cables of equal length coupled to the same busbar
- One cable is live

\[ V_{\text{bus}} \]

\[ V_1, V_2, V_3 \]

\[ V_4, V_5, V_6 \]

\[ T1 \]

\[ 11 \text{ kV} \]

\[ 230 \text{ V} \]

\[ 1, 2, 3, 4, 5, 6 \]

\[ \sim 25 \text{ p.u. overvoltage} !! \]
Switching overvoltages (3)

\[ V_{bus} \]

\[ V_1, V_2 \]

\[ V_3 \]

\[ V_6 \]

\[ 1 \, \mu F \]

\[ 11 \, kV \]

\[ 230 \, V \]

\(~43 \, \text{p.u. overvoltage}!!~\)
Note:

- Other transformers may have resonances at much lower frequencies.
  → Overvoltages will occur with longer cables.

Voltage ratio for a 410 MVA generator transformer (434 kV / 21 kV)
PART III:
Relevance to wind power
Switching overvoltages

- Radials of nearly equal length
- Energizing a branch → oscillating overvoltage on WT transformer HV side
- In the case of short radials (< 1km), the oscillating overvoltage has frequency above 50 kHz
- High overvoltages may result on WT transformer LV side by resonance
Ground fault initiation can cause an oscillating overvoltage in the cable.

- Frequency depends on fault location
- High overvoltages may result on WT transformer LV side by resonance
Notes

- The actual overvoltage on the WT LV side is strongly dependent on the network on the LV side

- A complete model must be developed
Conclusions

- High-frequency interaction between the wind turbine transformers and the cables can lead to excessive overvoltages the transformer LV side.
- The phenomenon can be triggered by ground fault initiation and by switching.
Electromagnetic Transients in Future Power Systems.
Phenomena, Component Stresses, Modeling

A JIP project (KMB) between SINTEF and industry partners (2011-2015)

New partners are welcome!
Contact: bjorn.gustavsen@sintef.no
Objective

Develop and demonstrate tools for the evaluation of land-based and offshore power systems in order to ensure increased reliability of the supply and minimize the risk for failures due to unexpected interactions. This will be achieved with the development of computational models of grid components for assessing transient voltages and currents in power grids.

1. Assessment of trends in power systems related to new network topologies and component technologies.

2. Develop wide-band component models and modelling procedures for power grids components: transformers, cables, circuit breakers, and instrument transformers. These models should be ready to work out-of-the box, allowing for wide-spread application by non-expert users.

3. Demonstrate how such models can be applied for determination of transients in future power systems. Overvoltage levels, currents, protective relaying, penetration of harmonics.