Inclusion of a White-Box Transformer Model in EMTP-RV

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EMTP-RV User Conference, Perpignan, France, June 21, 2019.

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Background

Transformer manufacturers

- In-house software for calculating internal voltage stresses during lightning impulse test ("white-box model").
- Parameters calculated based on detailed design information
- Proprietary software

CIGRE

- Recommends that manufacturers start delivering transformer wide-band models to customers (JWG A2/C4.52: ongoing).

Objective

- Demonstrate the inclusion of a white-box (detailed) transformer model in EMTP-RV

- Emphasis on
  - User friendliness
  - Computational efficiency

About the work

- **Collaboration between SINTEF and Rte** (Cesar Martin)

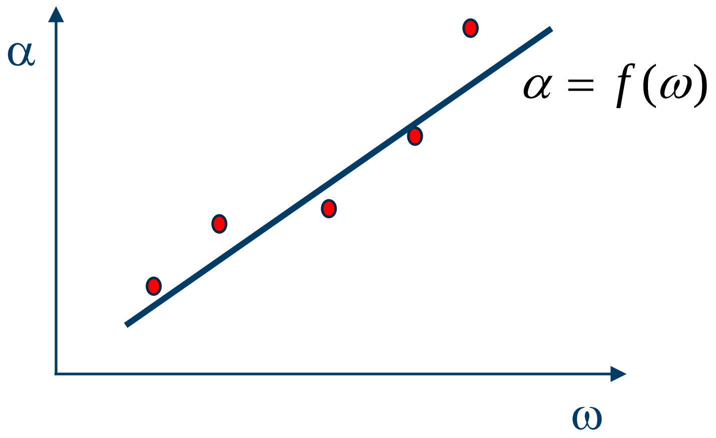
- **Support from Norwegian Research Council and Norwegian utilities**
  (project no. 207160/E20)

White-box transformer model*

- State-space model with **A** diagonal
- Multi-port, admittance formulation

$$\mathbf{L}, \mathbf{C} \quad \Rightarrow \quad \begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{v}_{\text{ext}} \\ \mathbf{i}_{\text{ext}} &= \mathbf{C}_1\mathbf{x} + \mathbf{D}_1\mathbf{v}_{\text{ext}} \\ \mathbf{v}_{\text{int}} &= \mathbf{C}_2\mathbf{x} \end{aligned}$$

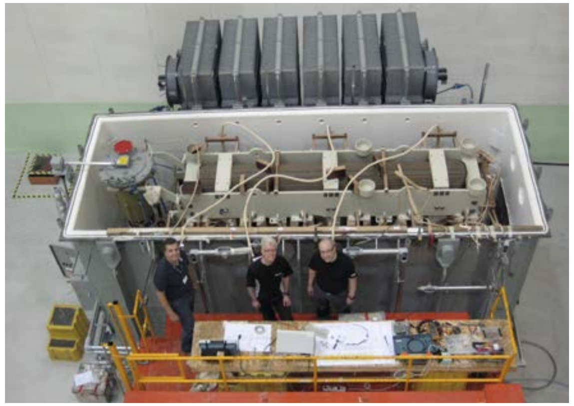
- Damping by modifying real part of **A** according
  to empirical damping curve ("Fergestad" approach)

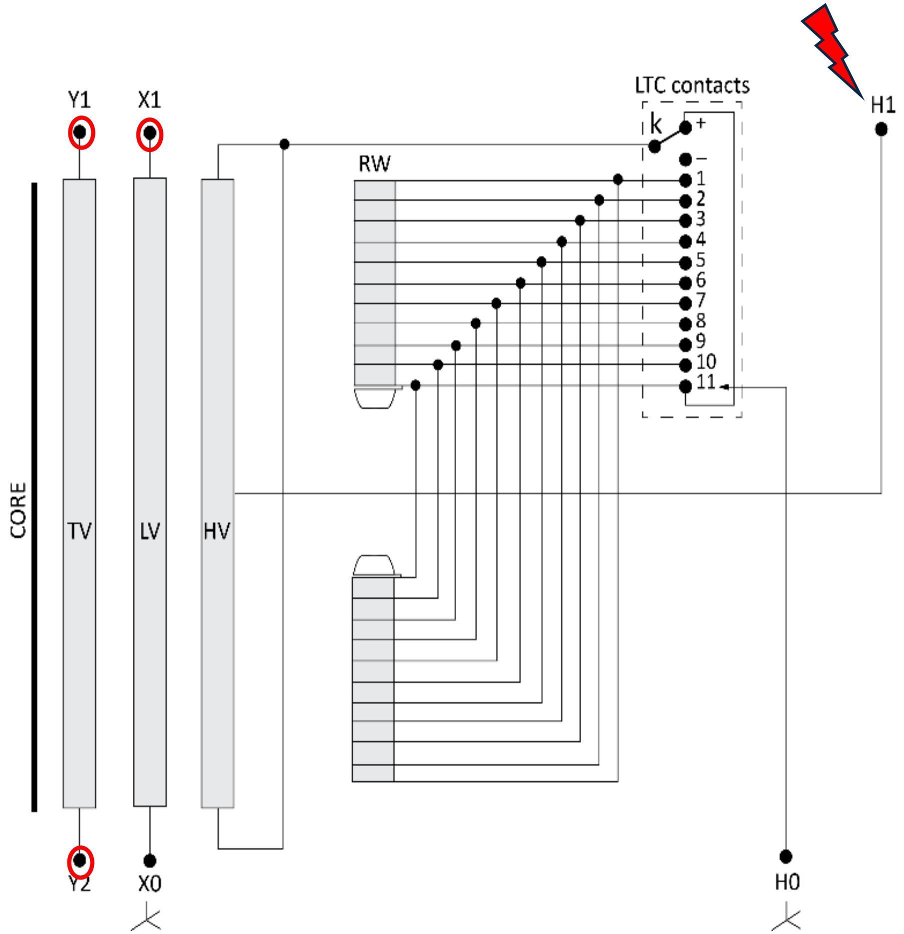


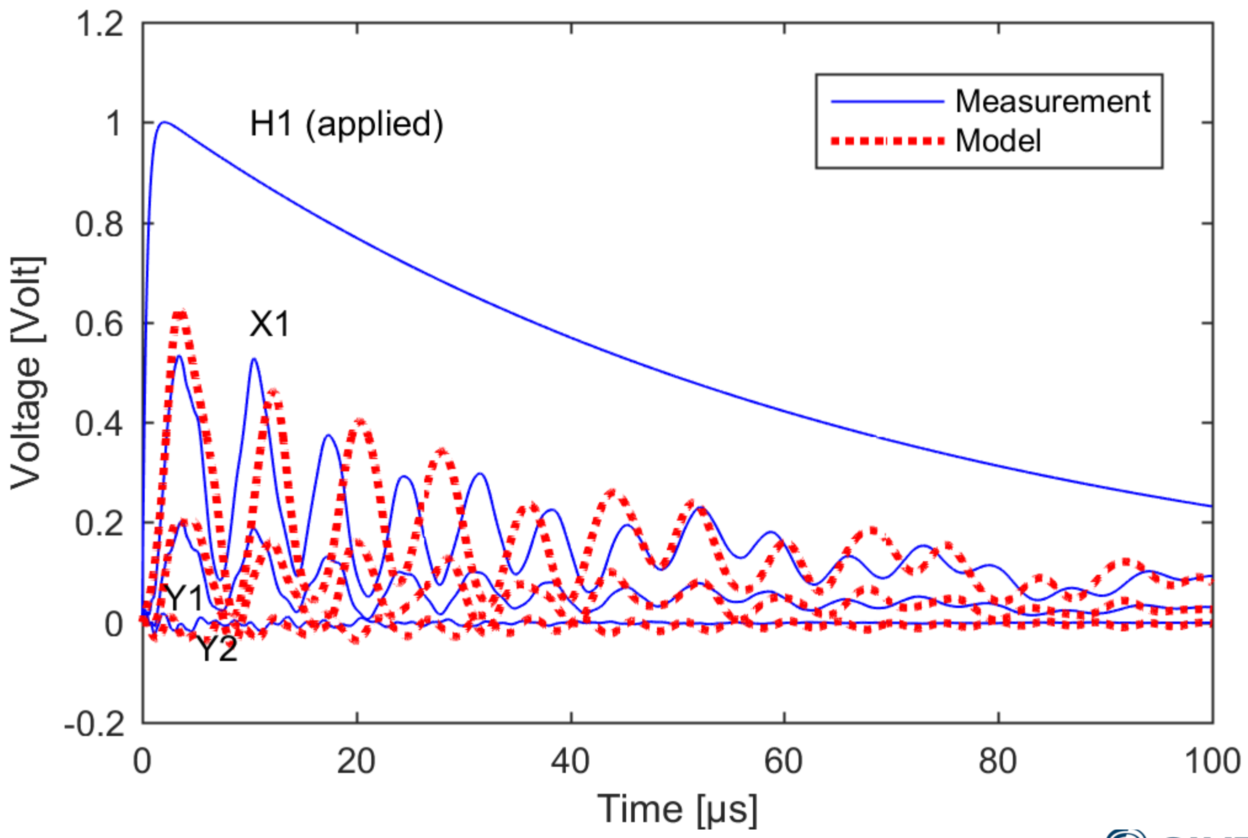
* B. Gustavsen, A. Portillo, "A damping factor-based white-box transformer model for network studies", *IEEE Trans. Power Delivery*, vol. 33, no. 6, pp. 2956-2964, Dec. 2018.

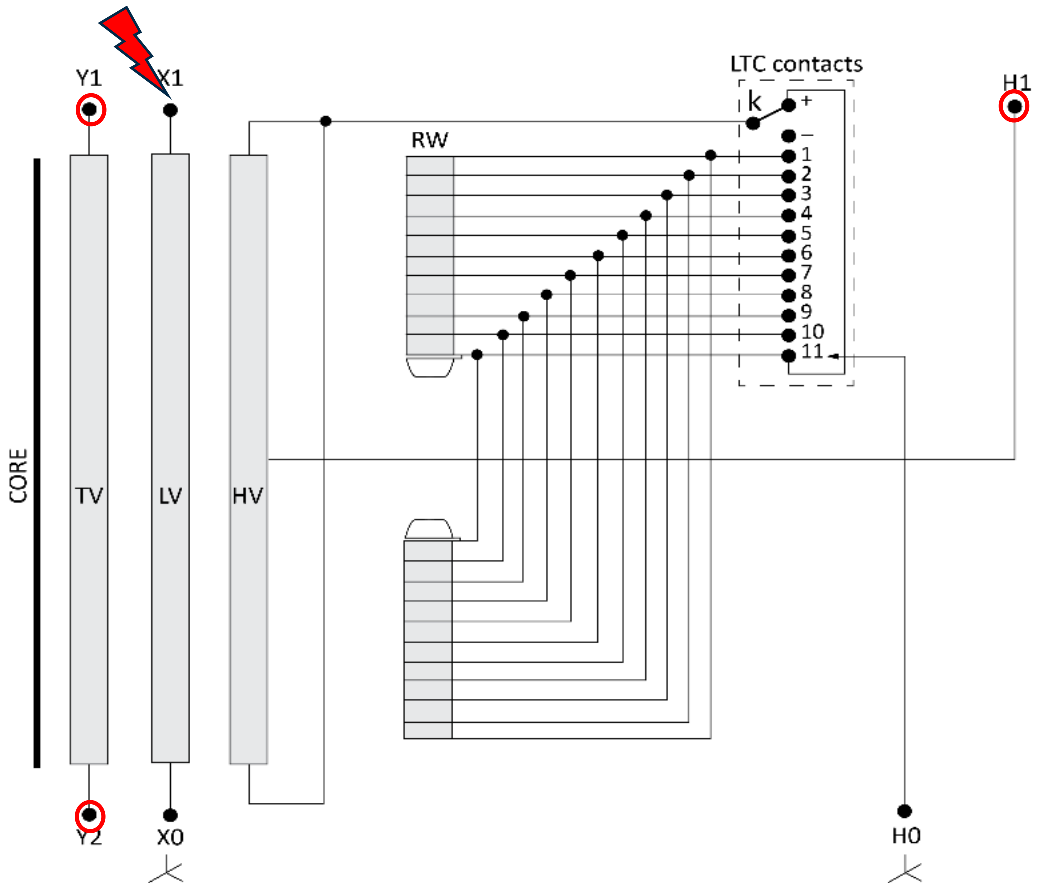
Resulting model can give ok accuracy

$\left(50\ \text{MVA},\ 230/\sqrt{3},\ 69/\sqrt{3},\ 13.8\ \text{kV}\right)$

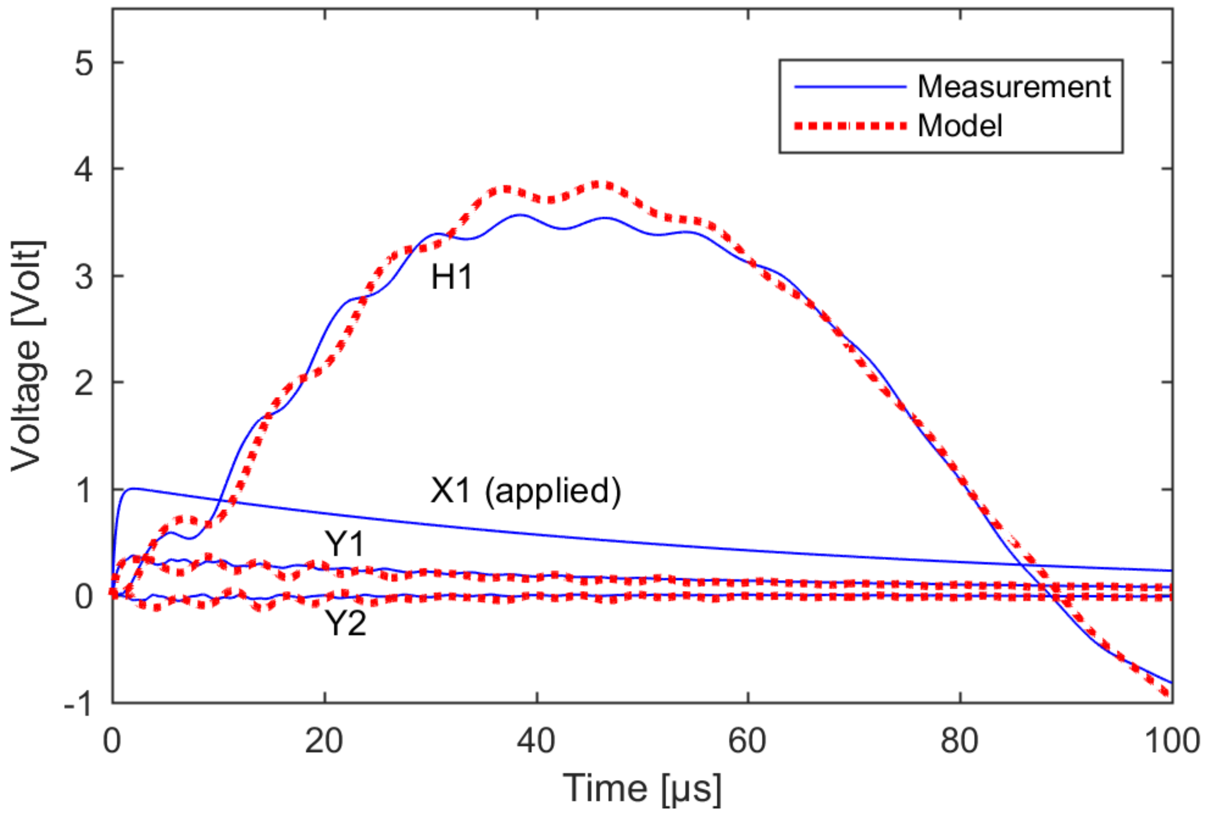








Y1
X1
LTC contacts
k
+
–
1
2
3
4
5
6
7
8
9
10
11
H1
RW
CORE
TV
LV
HV
Y2
X0
H0



Measurement
Model
Voltage [Volt]
Time [µs]
H1
X1 (applied)
Y1
Y2
5
4
3
2
1
0
-1
0
20
40
60
80
100

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Implementation of model in EMTP-RV

Objective:

- Fully integrated model
- Utilize model file format as proposed by CIGRE JWG A2/C4.52 (ongoing)
- Demo simulation of overvoltage stresses

Inclusion of model in EMTP-RV time domain simulation

1. Reading model parameters from formatted text file
2. Conversion from complex to real-only parameters/variables
3. Discretization (trapezoidal rule)
4. Inclusion in EMTP-RV (coding)
5. User interface
6. Internal node voltages: Plotting tool

1. Reading model parameters from formatted text file (CIGRE A2/C4.52)

dimensjoner

```
write(n1) !n.o. external terminals
write(n2) !n.o. internal node voltages
write(N1) !n.o. real poles
write(N2) !n.o. complex poles
```

D

```
write('D:')
for i=1:n1
  for j=1:n1
    write(D(i,j))
  end
end
```

A

```
write('Poles:')
for i=1:N1        !real elements
  write(A(i,i))
end
for i=N1+1:2:N1+N2    !cmplx pairs, 1st of
  write(real(A(i,i)))
  write(imag(A(i,i)))
end
```

B

```
write('B:')
for j=1:n1          !columnwise
  for i=1:N1        !real elements
    write(B(i,j))
  end
  for i=N1+1:2:N1+N2 !cmplx pairs, 1st of
    write(real(B(i,j)))
    write(imag(B(i,j)))
  end
end
```

C

```
write('C:')
for i=1:n1+n2     !row-wise
  for j=1:N1      !real poles
    write(C(i,j))
  end
  for j=N1+1:2:N1+N2 !cmplx pairs, 1st of
    write(real(C(i,j)))
    write(imag(C(i,j)))
  end
end
```

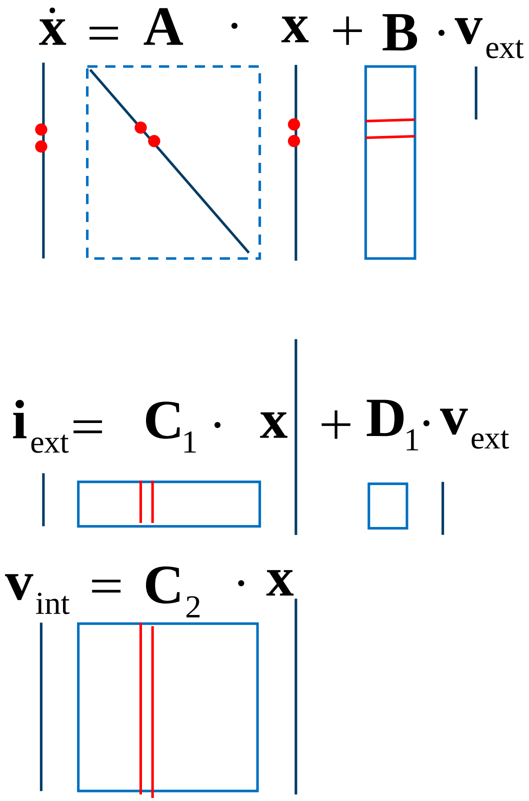
```
write('Labels:');
for i=1:n1+n2
  write(labels(i));
end
```

Node number mapping

(Replace 'write' with 'read')

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{v}_{\text{ext}}$$
$$\mathbf{i}_{\text{ext}} = \mathbf{C}_1\mathbf{x} + \mathbf{D}_1\mathbf{v}_{\text{ext}}$$
$$\mathbf{v}_{\text{int}} = \mathbf{C}_2\mathbf{x}$$

2. Conversion from complex parameters to real parameters



Complex pair (diagonal)

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} a & 0 \\ 0 & a^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \mathbf{b}^T \\ \mathbf{b}^H \end{bmatrix} \mathbf{u}$$

$$\mathbf{y} = \begin{bmatrix} \mathbf{c} & \mathbf{c}^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_1 \end{bmatrix}$$

complex-valued

$$\mathbf{T} = \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}$$

2x2 block

$$\begin{bmatrix} \dot{\tilde{x}}_1 \\ \dot{\tilde{x}}_2 \end{bmatrix} = \begin{bmatrix} \mathrm{Re}\{a\} & \mathrm{Im}\{a\} \\ -\mathrm{Im}\{a\} & \mathrm{Re}\{a\} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} + \begin{bmatrix} 2\,\mathrm{Re}\{\mathbf{b}^T\} \\ -2\,\mathrm{Im}\{\mathbf{b}^T\} \end{bmatrix} \mathbf{u}$$

$$\mathbf{y} = \begin{bmatrix} \mathrm{Re}\{\mathbf{c}\} & \mathrm{Im}\{\mathbf{c}\} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix}$$

real-valued

A-matrix gets 2x2 blocs on its diagonal

Computations in real arithmetics much faster than in complex arithmetics!

3. Time domain discretization

Continuous time

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{v}_{\text{ext}}$$
$$\mathbf{i}_{\text{ext}} = \mathbf{C}_1\mathbf{x} + \mathbf{D}_1\mathbf{v}_{\text{ext}}$$
$$\mathbf{v}_{\text{int}} = \mathbf{C}_2\mathbf{x}$$

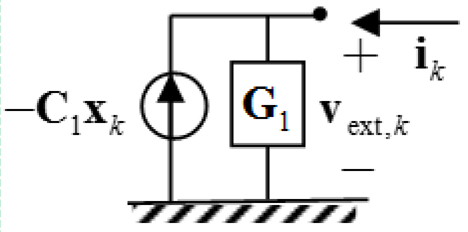
Discrete time

$$\frac{\mathbf{x}_k - \mathbf{x}_{k-1}}{\Delta t} = \bar{\mathbf{A}}\frac{\mathbf{x}_k + \mathbf{x}_{k-1}}{2} + \bar{\mathbf{B}}\frac{\mathbf{v}_{\text{ext},k} + \mathbf{v}_{\text{ext},k-1}}{2}$$
$$\mathbf{i}_{\text{ext},k} = \bar{\mathbf{C}}_1\mathbf{x}_k$$
$$\mathbf{v}_{\text{int},k} = \bar{\mathbf{C}}_2\mathbf{x}_k$$

$$\mathbf{x}_k = \boldsymbol{\alpha}\mathbf{x}_{k-1,} + \boldsymbol{\beta}\mathbf{v}_{\text{ext},k-1}$$
$$\mathbf{i}_{\text{ext},k} = \bar{\mathbf{C}}_1\mathbf{x}_k + \bar{\mathbf{G}}_1\mathbf{v}_{\text{ext},k}$$
$$\mathbf{v}_{\text{int},k} = \bar{\mathbf{C}}_2\mathbf{x}_k + \bar{\mathbf{G}}_2\mathbf{v}_{\text{ext},k}$$

"Recursive convolution"

Norton equivalent
(for interfacing)



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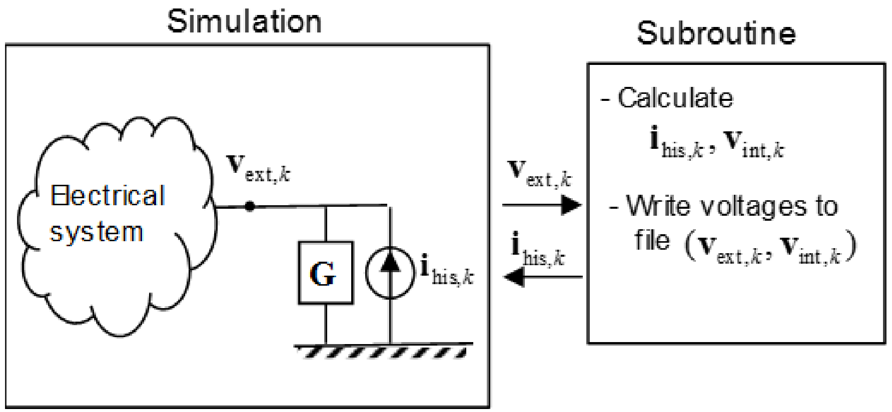
4. Coding and interfacing with EMTP-RV



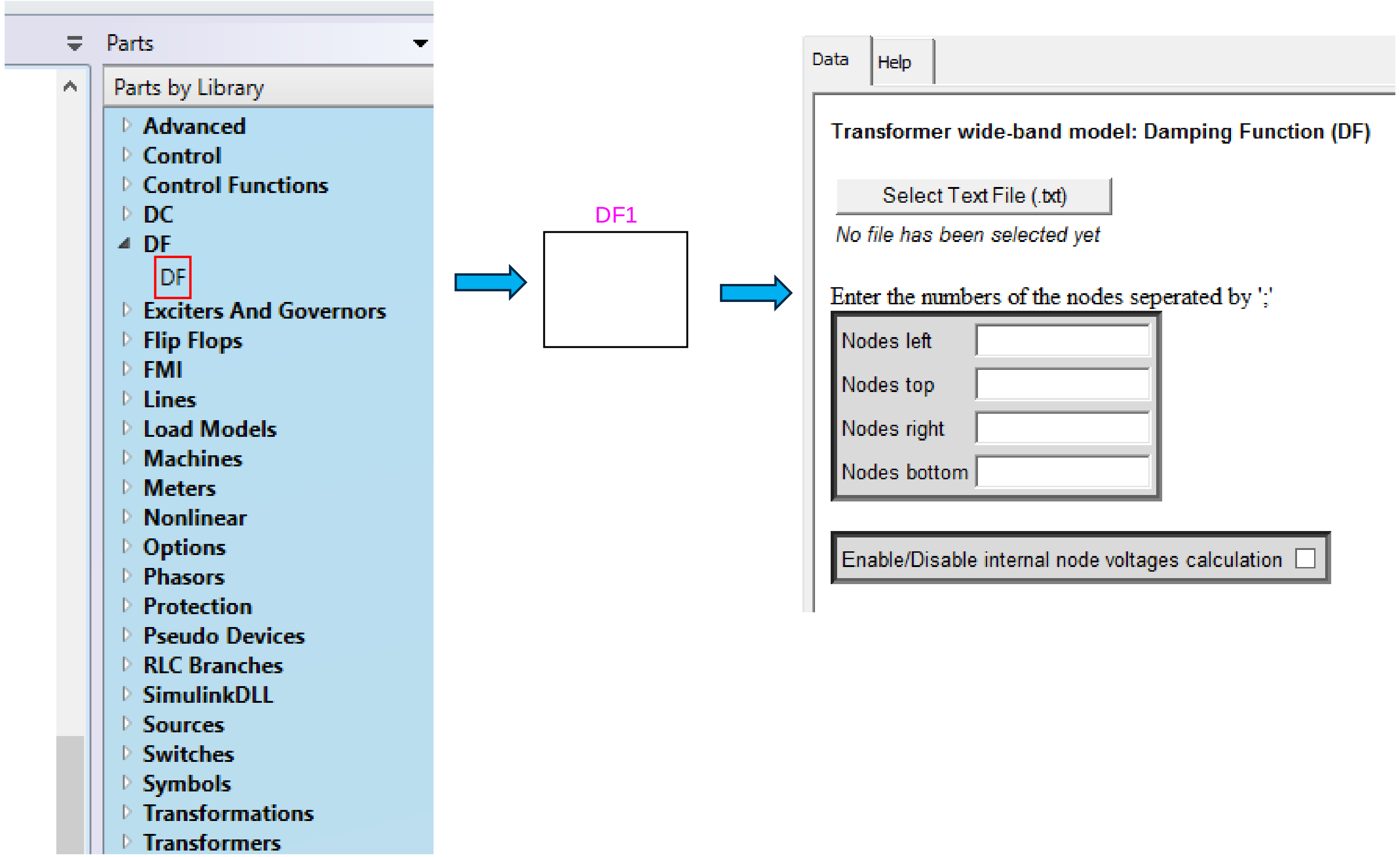
Calculations

- Model coded as a Fortran 90/95 subroutine
- Included in EMTP-RV as DLL (Dynamic-link library)
- Dynamic memory allocation
- Subroutine responds to calls from EMTP-RV main program
    - Initialization, update history current soure, frequency scan,…
- Very fast computations

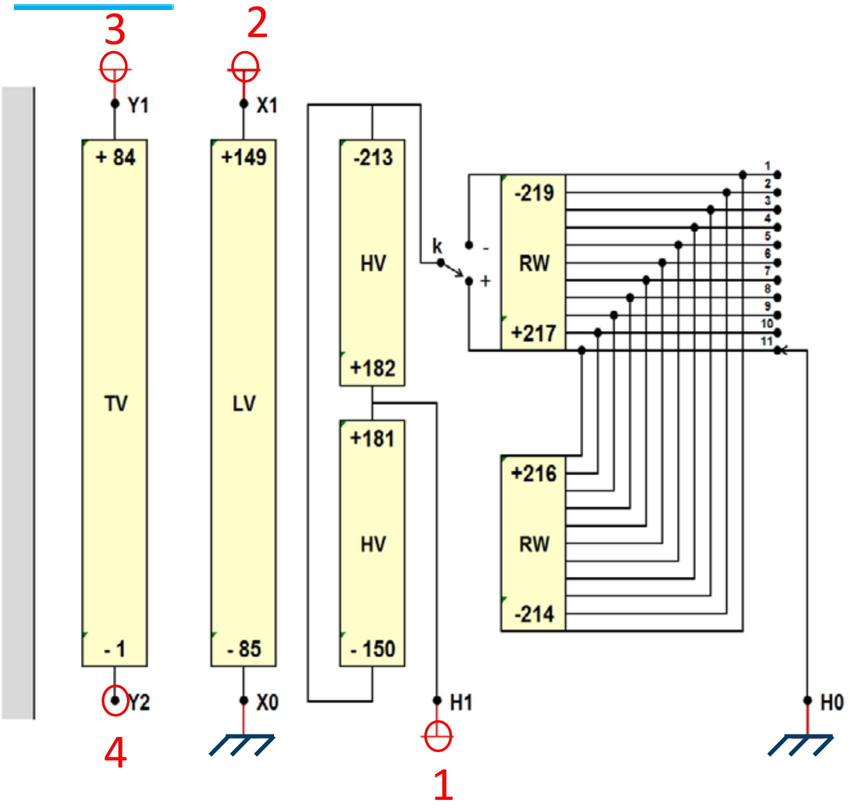
User interaction

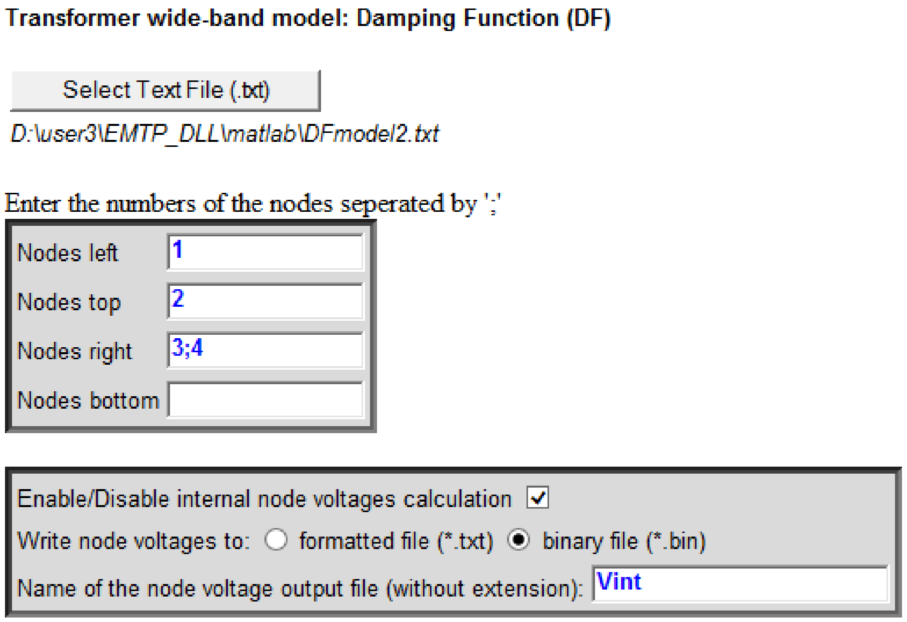
- User interaction via component interface (javascript), provided by Rte
    - File input
    - Pin position
    - Output file (internal voltages)

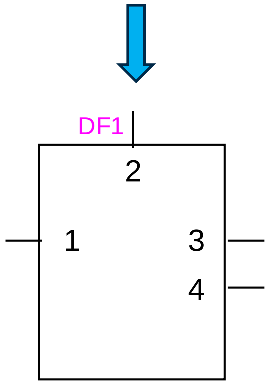
5. User interface



Example: 1ph- 3-winding transformer (50 MVA, $230/\sqrt{3}$, $69/\sqrt{3}$, $13.8\ \text{kV}$)







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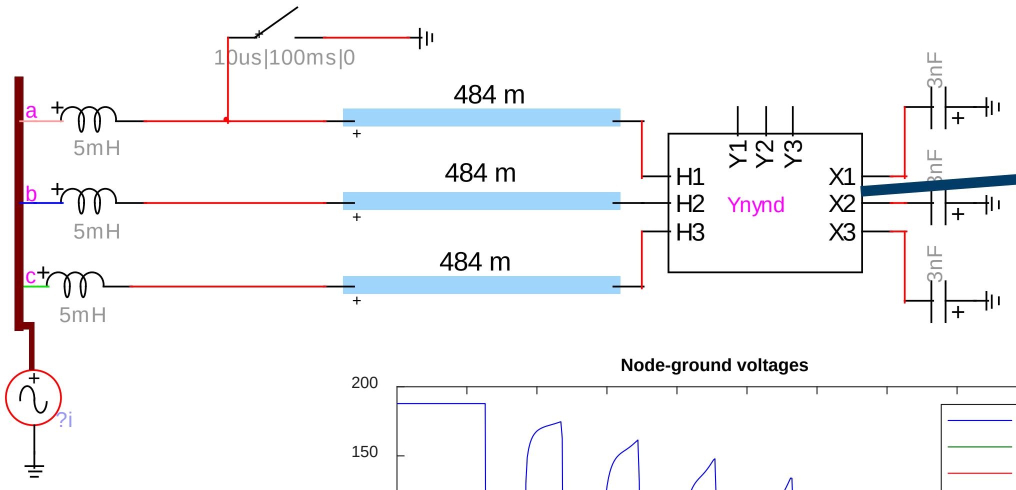
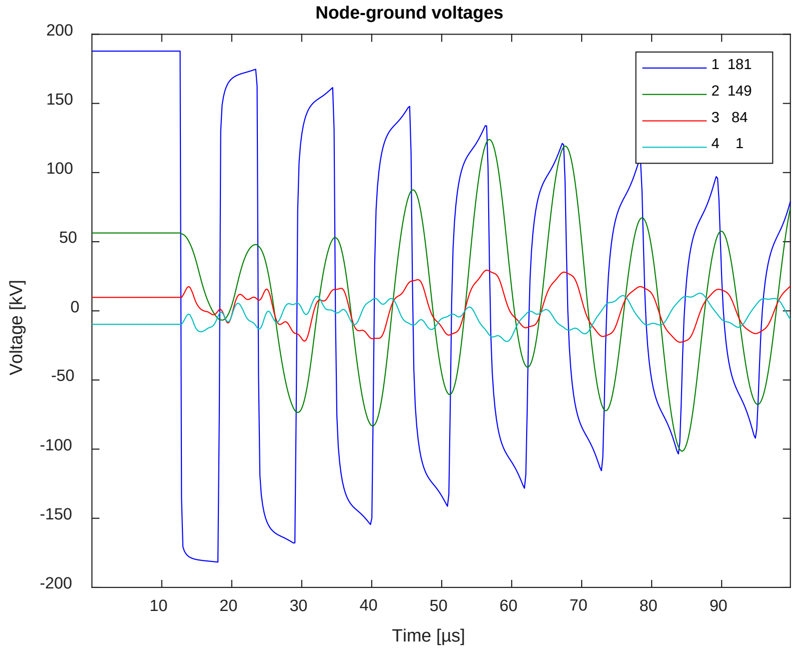
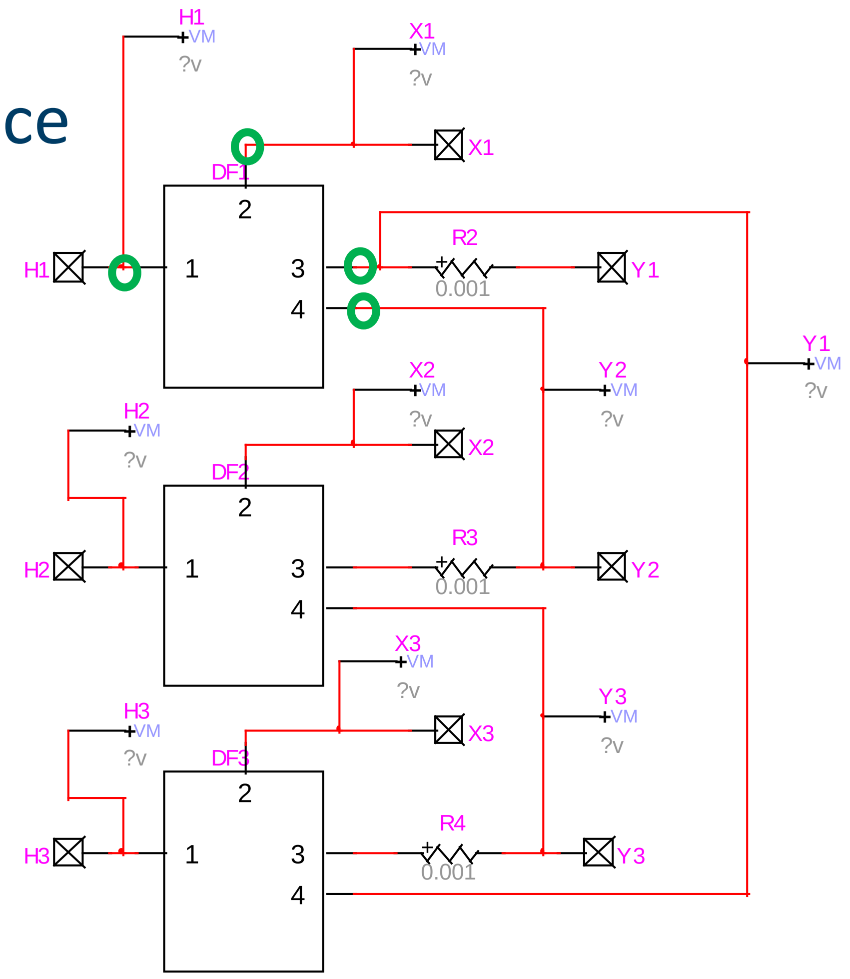
Example: Ground-fault initiation and resonance

Apply ground fault at t=10 µs







CPU-tid: (5000 time steps)

- 0.46 sec (without internal voltages)
- 2.1 sec (with 213 internal voltages)

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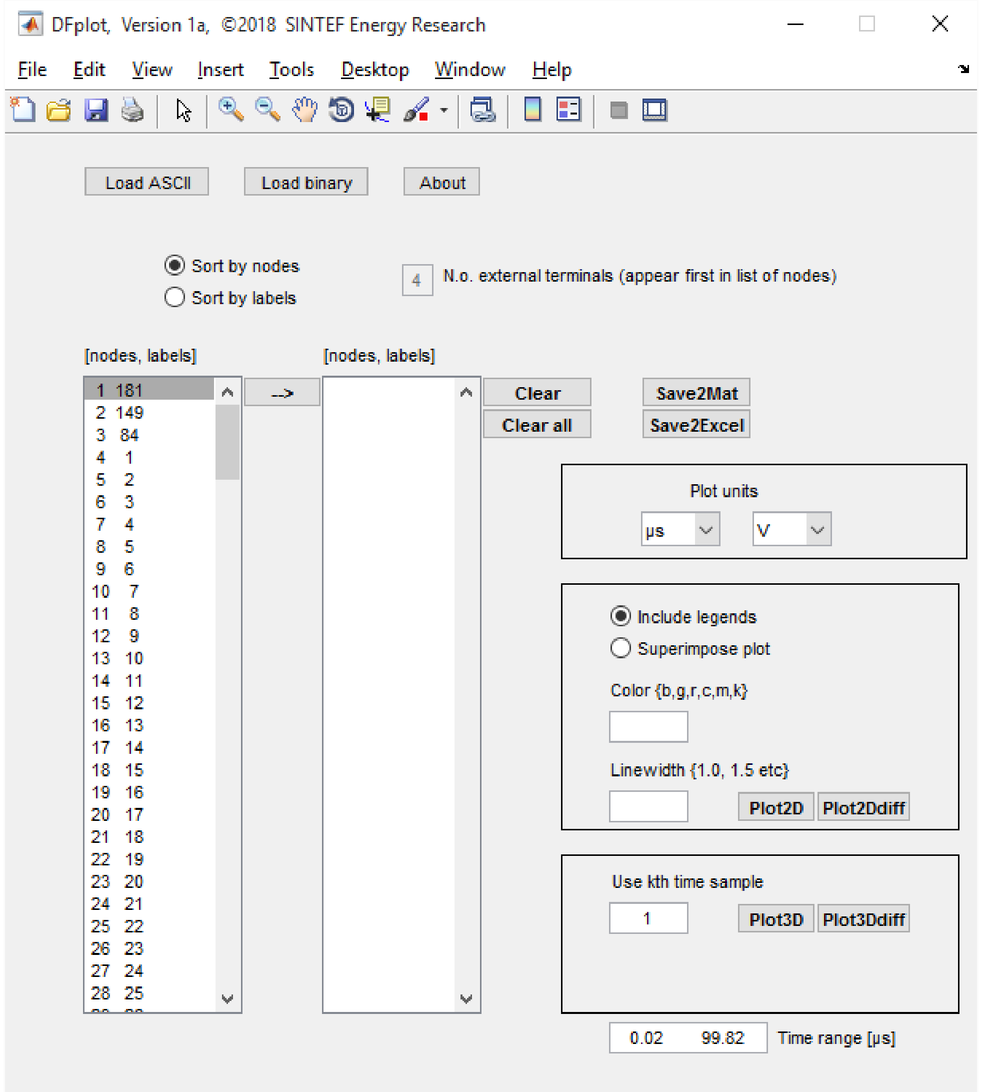
6. Internal node voltages: Plotting tool



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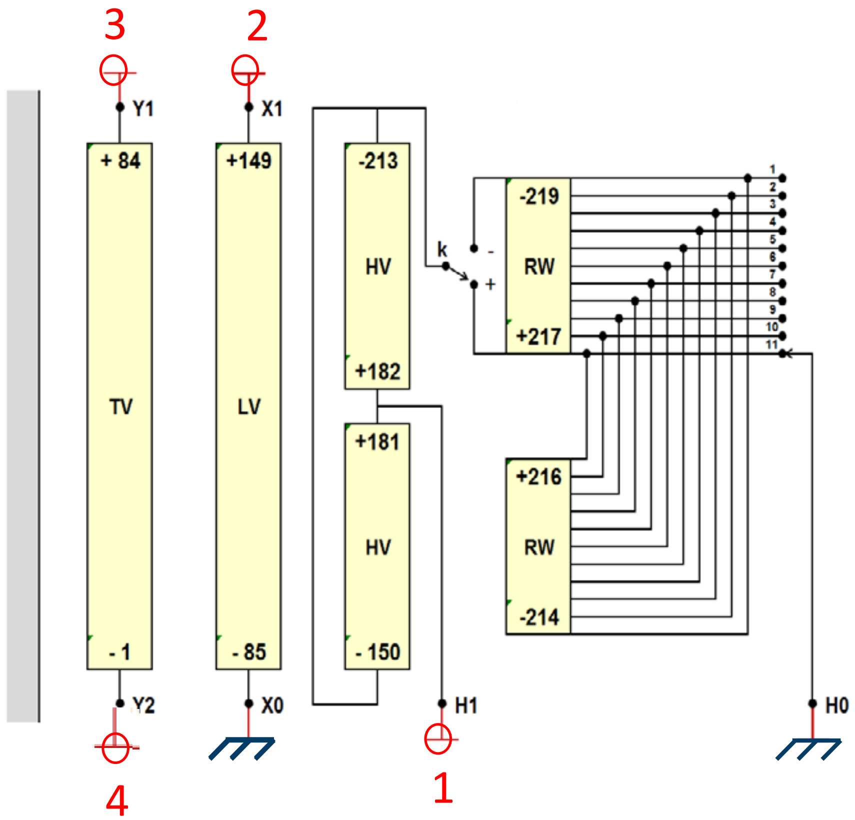
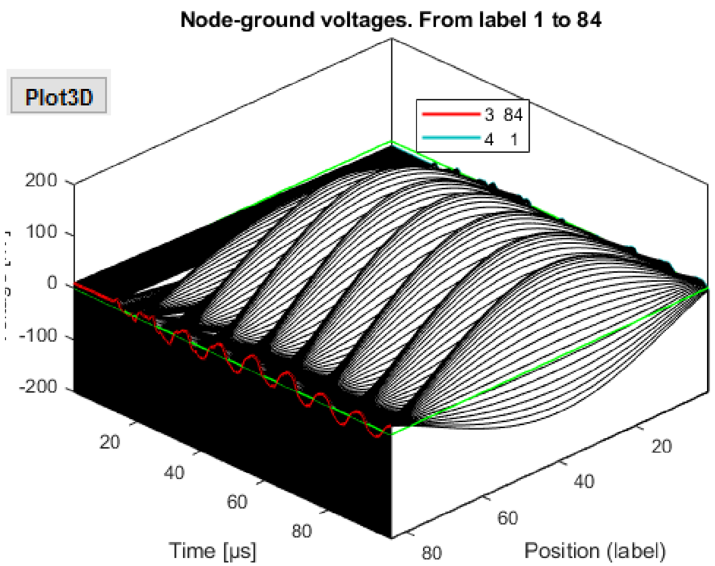
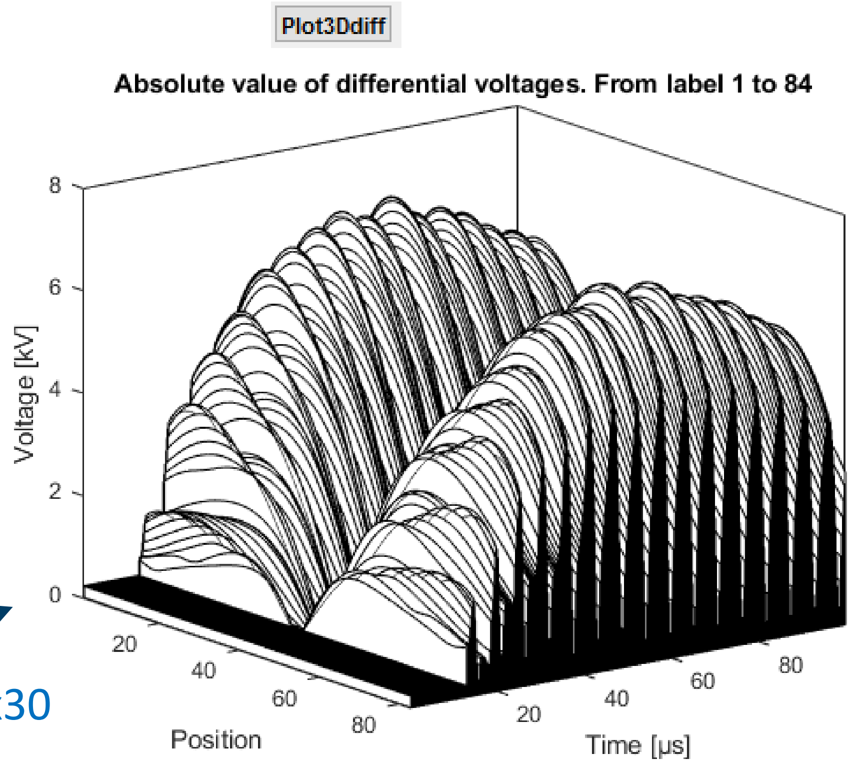
Tertiary winding: nodes 1-84







Voltage magnification vs. 60 Hz: x30

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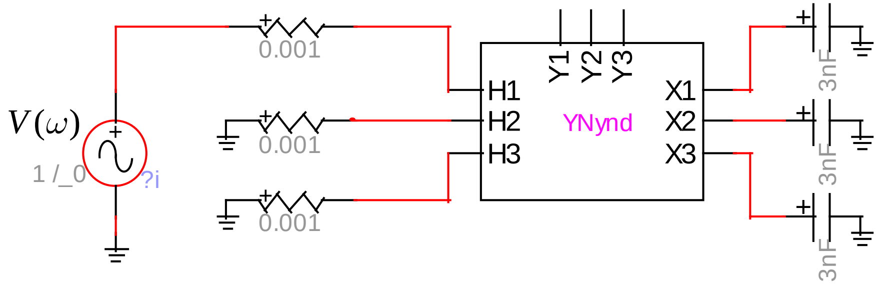
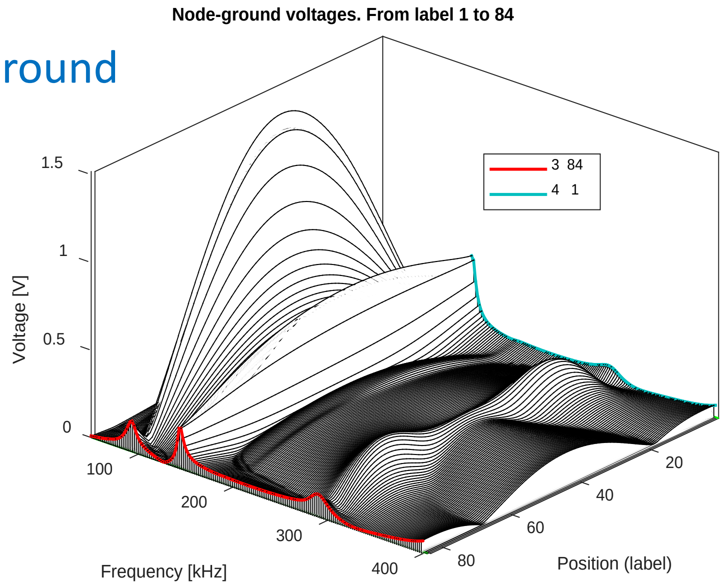
Predicting worst-case cable length

- Frequency sweep calculation in EMTP-RV
- Plot of internal voltages vs. frequency



Node-ground



Peak at 92 kHz

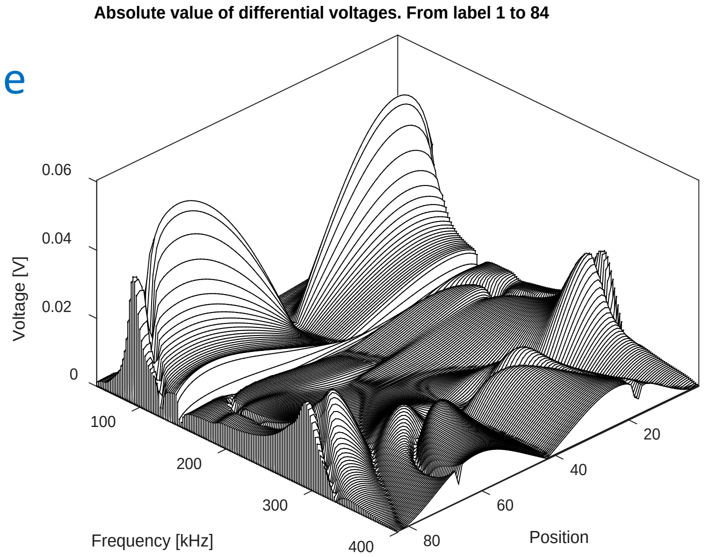
$$f_{\lambda/4} = \frac{v}{4l}$$

Cable open-end resonance frequency

$$\downarrow$$

$$l = \frac{v}{4 f_{\lambda/4}} = \frac{1.78 \cdot 10^8}{4 \cdot 92000} = 484 \text{ m}$$

Node-Node



Documentation*

Time Domain Implementation of Damping Factor White-Box Transformer Model for Inclusion in EMT Simulation Programs

Bjørn Gustavsen, *Fellow*, *IEEE*, Cesar Martin, and Alvaro Portillo, *Senior Member*, *IEEE*

*IEEE Trans. Power Delivery, early view on ieeeXplore

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Conclusions

- One particular white-box model (damping factor –DF) has been developed

- Inclusion in EMTP-RV: DLL-code + user interface

- Input: Model parameters, read from file (CIGRE JWG A2/C4.52 format)

- Calculates both external and internal overvoltages
    - extremely fast simulation
    - steady-state initialization

- Output: Dumps internal voltage to text file

- Visualization/analysis of internal voltage distribution by separate program (Matlab)