Switching surge generation when disconnecting combined 400 kV cable/overhead line with shunt reactor

Presented at WETS'07

on 28 June 2007

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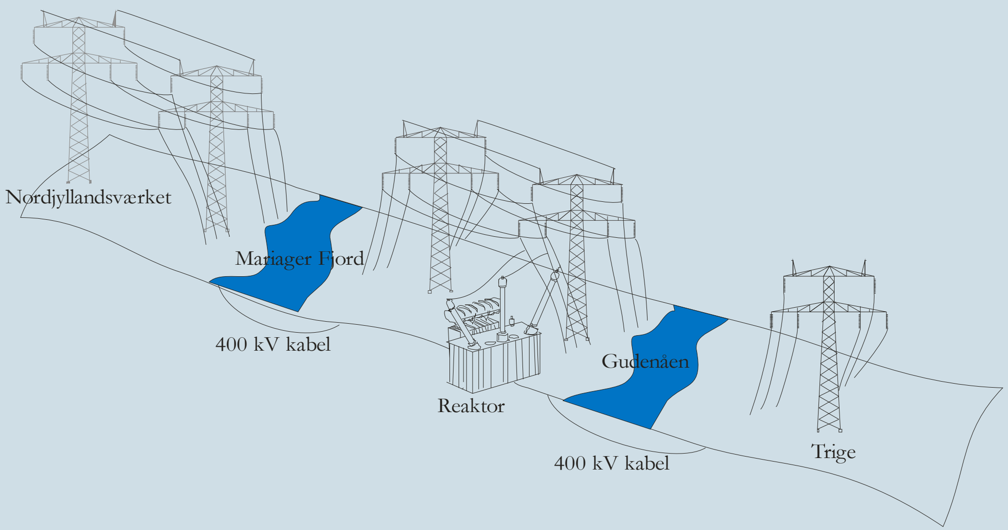
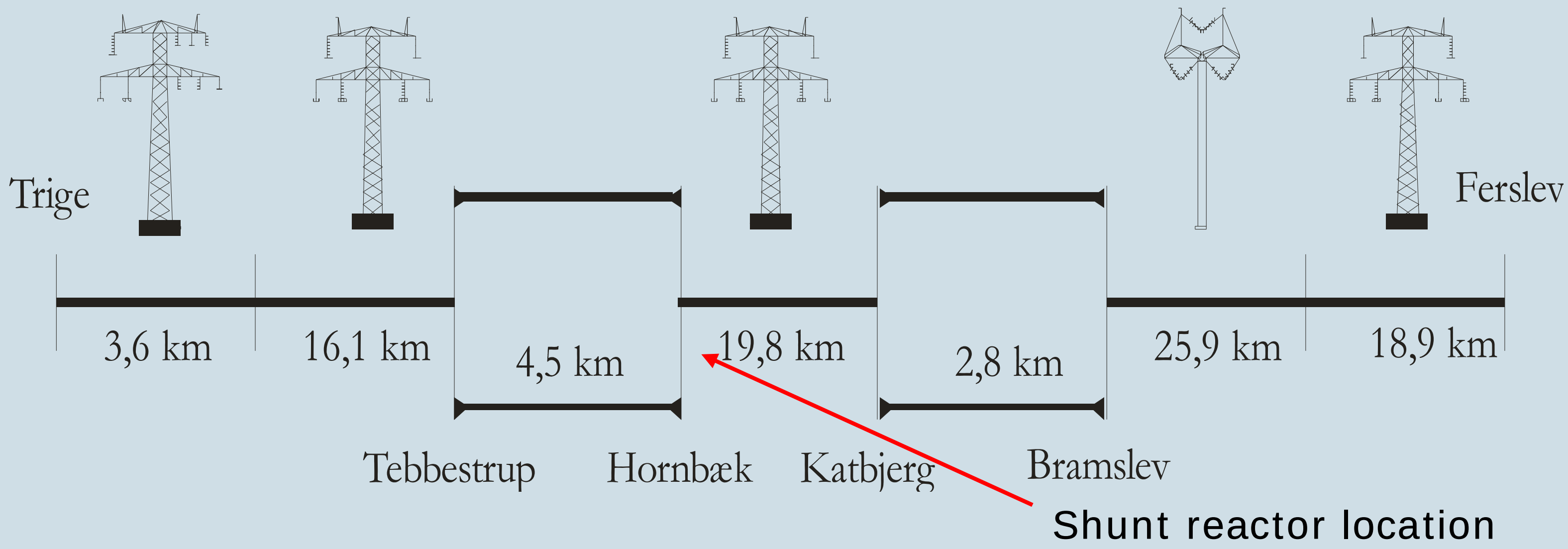
Introduction

- Danish TSO Energinet.dk has designed and constructed a new 400 kV transmission line between the cities Aarhus and Aalborg, app 90 km.
- Two cable sections (4,5 km and 2,8 km) are used to cross areas of natural beauty.
- Reactive power of the cable sections is compensated by a three-phase shunt reactor



The 400 kV OHL/cable line TRI-FER

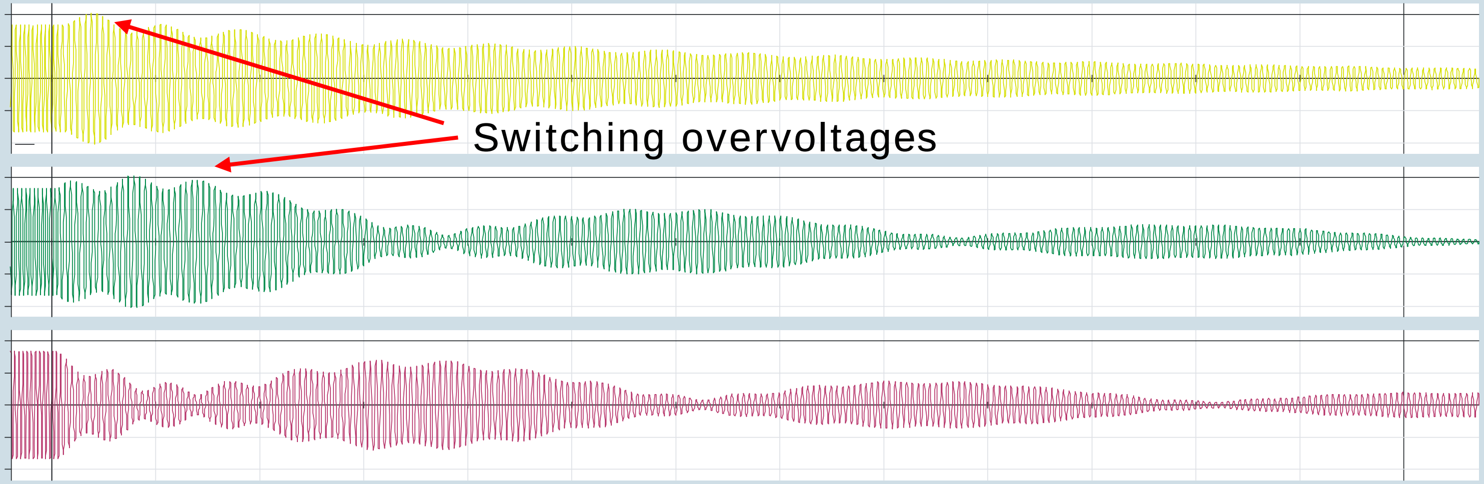


- Cable sections are double Al XLPE 1200 mm2 and capacitance 0,18 µF/km per cable

- Three-phase shunt reactor (100 Mvar) is permanently connected in Hornbæk

Voltage during last-end disconnection

- During commissioning of the line, measurements of phase voltages revealed that after switching off the last end of the line:
- The frequency of the decaying voltage lowers to resonant frequency, app. 35 Hz
- Two lower frequencies appear, app. 3 Hz and 0,4 Hz
- Switching overvoltages are present



Questions

- What causes these overvoltages and where do the frequencies come from?

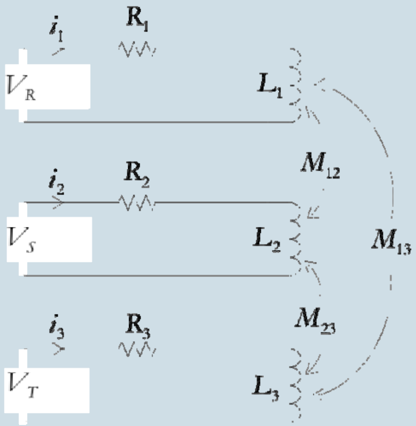
- What is the physical explanation of the decaying voltage waveforms?

- Is it possible to create reliable simulation models to predict such behavior in the design phase?

Modeling and simulation

- 400 kV, 100 Mvar shunt reactor model

The reactor core is 5-limbed with airgaps in the three phase core legs.



$$V_R(t) = R_1 i_1 + \frac{di_1}{dt} L_1 + \frac{di_2}{dt} M_{12} + \frac{di_3}{dt} M_{13}$$

$$V_S(t) = R_2 i_2 + \frac{di_2}{dt} L_2 + \frac{di_1}{dt} M_{21} + \frac{di_3}{dt} M_{23}$$

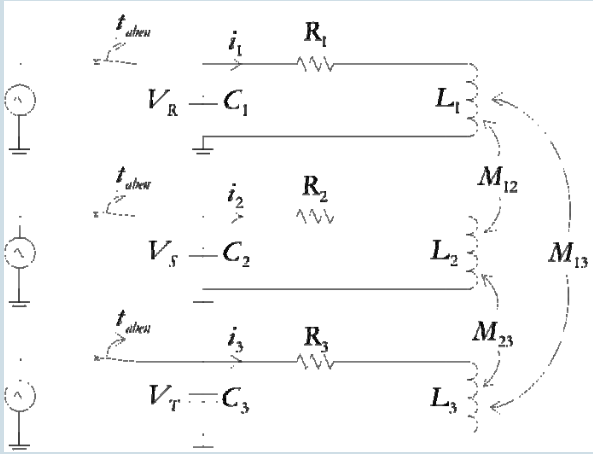
$$V_T(t) = R_3 i_3 + \frac{di_3}{dt} L_3 + \frac{di_1}{dt} M_{31} + \frac{di_2}{dt} M_{32}$$

Mutual inductance is evaluated on the basis of test report single phase voltage tests, where one phase is energized and the voltage is measured at the other two phases.

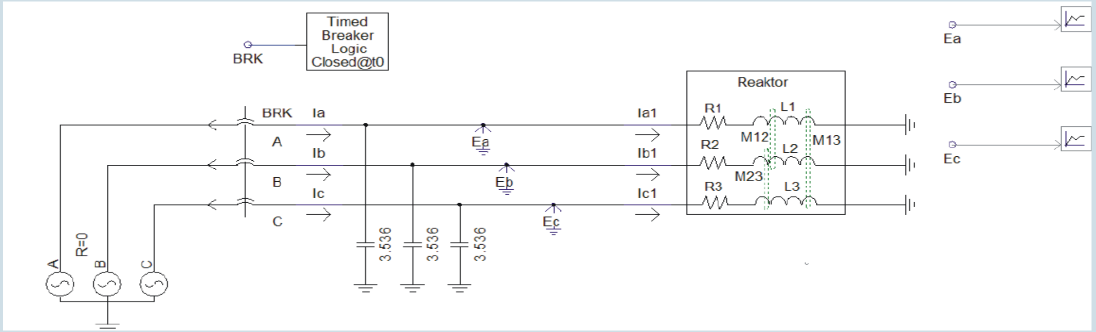
			Fase R	Fase S	Fase T
Fase R	1,3009 Ω	5,588 H		-0,0172 H	-0,0058 H
Fase S	1,3023 Ω	5,591 H	-0,0211 H		-0,0188 H
Fase T	1,3043 Ω	5,602 H	-0,0054 H	-0,0054 H	

Modeling and simulation

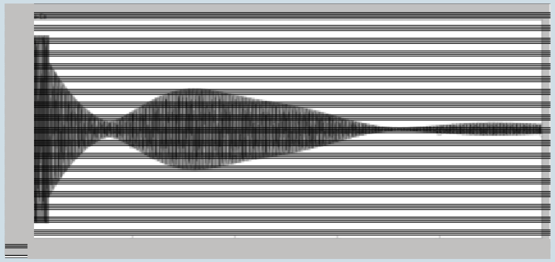
- Simplified model of last-end switching



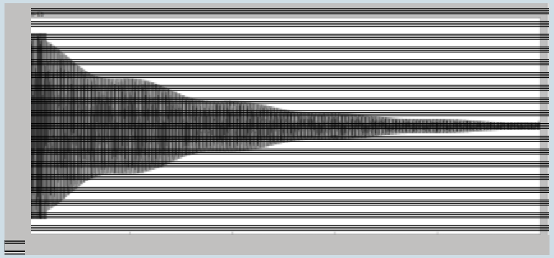
R_1=1.3	C_1=3,536	L_1=5,5		M_{21}=-0,02	M_{31}=-0,0058
R_2=1.3	C_1=3,536	L_2=5,5	M_{12}=-0,02		M_{32}=-0,02
R_3=1.3	C_1=3.536	L_3=5.5	M_{13}=-0.0058	M_{23}=-0.02	



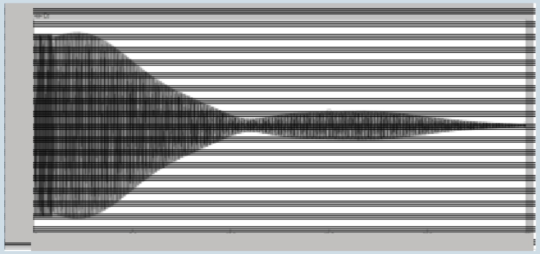
Phase voltage R



Phase voltage S



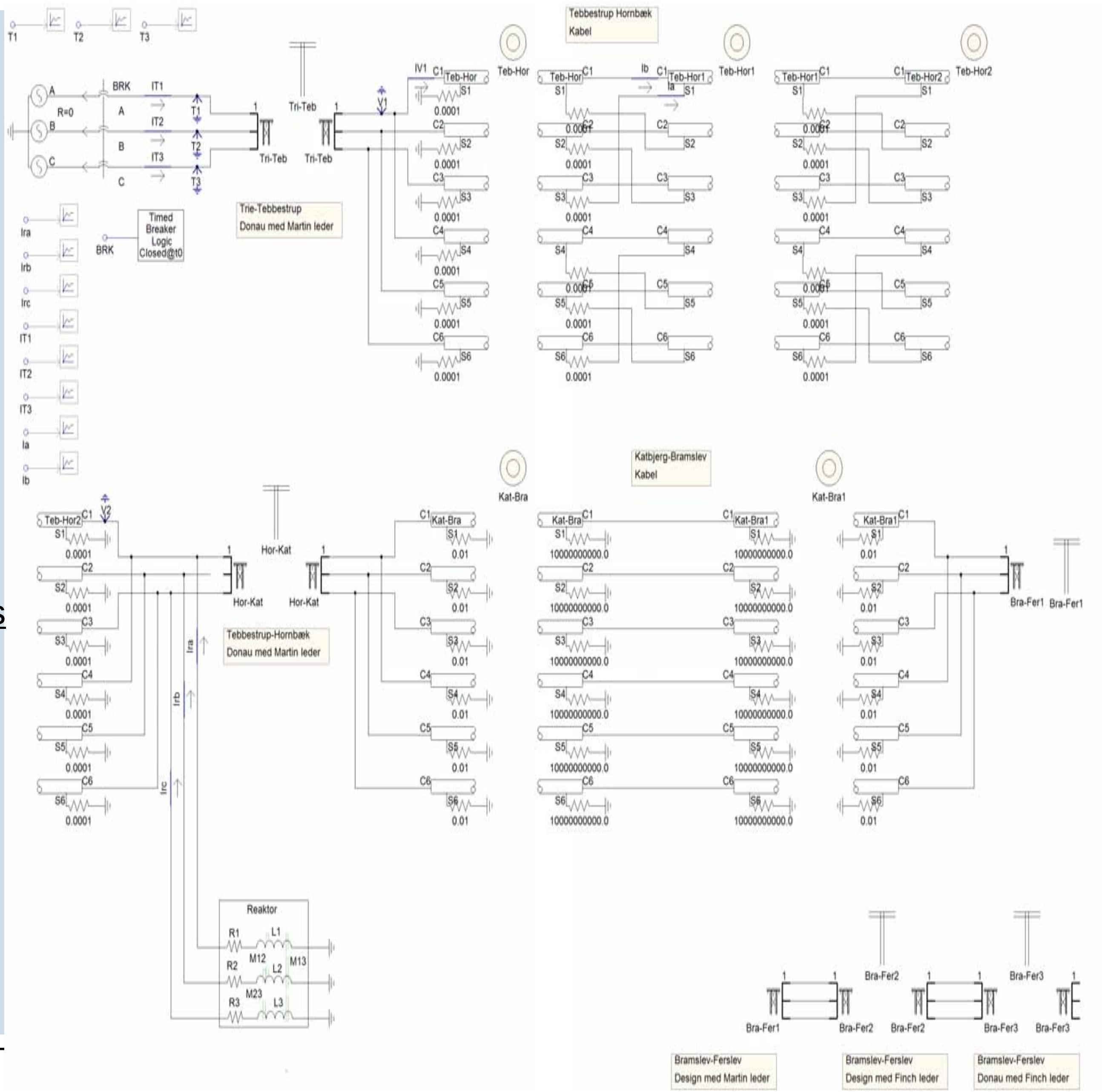
Phase voltage T



Using this simplified model the frequency beating can be reproduced

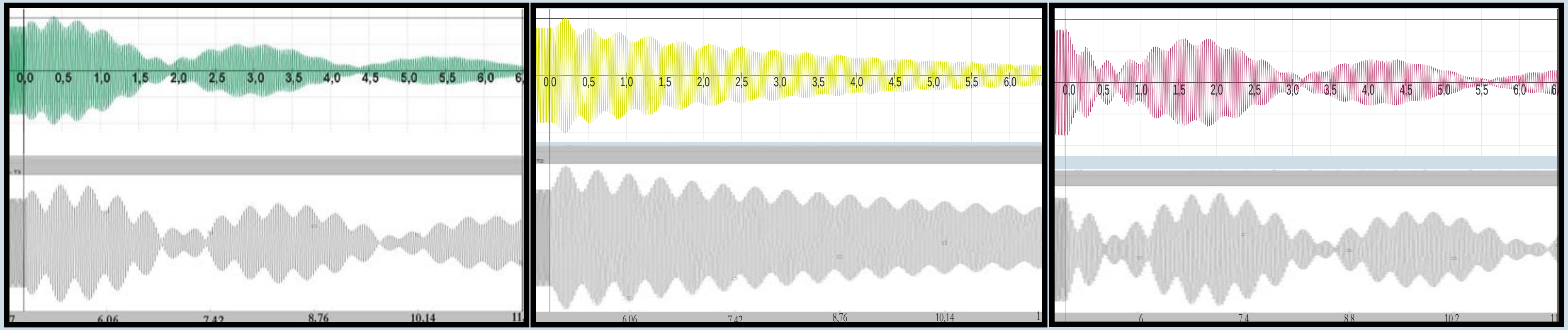
PSCAD model of entire OHL/cable line

- Cable sections with cross-bonding and open screen
- Shunt reactor model (unequal phase self inductances and unequal mutual inductances
- <u>The same instant of switching as in measurements</u>



Simulation vs. measurement results

Phase R Phase S Phase T



Simulated fundamental $f_{res,sim}$ = 34 Hz and measured after switch off $f_{res,meas}$ = 36 Hz.

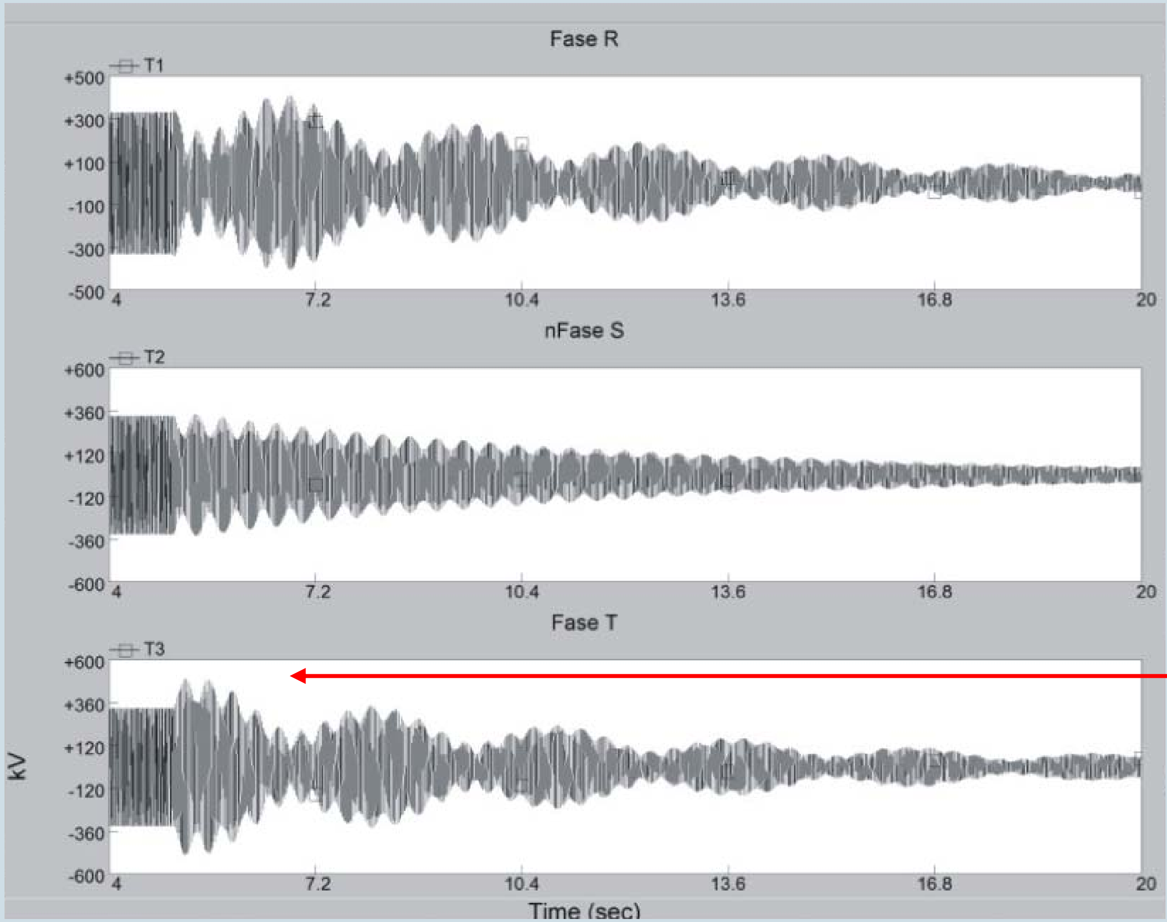
Simulated modulating frequency one in the range $f_{mod1,sim}$ = 3,2 – 2,4 Hz for all three phases whereas measurement yields $f_{mod1,meas}$ = 2,8 Hz.

Simulated second modulating frequency $f_{mod2,sim}$ = 0,37 – 0,36 Hz for phase R and T (S no second modulating frequency) and measured $f_{mod2,meas}$ = 0,4 Hz.

Damping in simulation too small: shunt reactor iron losses (hysteresis and eddy current), leakage current of OHL, corona of OHL and dielectric losses of the cables.
Voltage transformers will tend to discharge the line.

Simulation results

- Maximum switching overvoltage amplitude



Switching off at voltage peak gives worst case switching overvoltage.

Max. overvoltage
455 kV (132 %)

Conclusions

The differences in appearance for the three phases is due to the slightly different resonant frequencies of each phase (caused by reactor and line asymmetries) coupled by mutual couplings (also unsymmetrical – both inductively and capacitively) between phases and thereby added.

Adding sinusoidal signals with slightly different frequency yields such frequency beating.

In this way numerous shapes and appearances (frequencies, amplifications, attenuations) can appear.

Symmetry of the system should improve the situation.

Damping must speed up the decay and thereby lower both duration and amplitude of such switching overvoltages.

Switch-off resistors in combination with the circuit breaker would assist in remedying the problem.

Low mutual couplings will also remedy the problem as the modulation will not take place if voltages are not induced (both capacitively and inductively) from phase to phase.