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Switching overvoltage when disconnecting a combined 400 kV cable/overhead line with permanently connected shunt reactor

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Abstract-- This paper demonstrates the results from a detailed study of the dynamic behavior of a shunt reactor compensated 400 kV combined cable/overhead line. This is accomplished by means of theoretical considerations, simulations and measurements. The work presented here is based on a real-life operating 400 kV power system and initiated by Danish TSO Energinet.dk after having measured the voltage of the cable/overhead line after disconnection. A particular decaying dynamic phase voltage containing voltages higher than the voltage before disconnection appeared. A simulation model for the entire system consisting of overhead lines, crossbonded cable sections and shunt reactor has been created in PSCAD/EMTDC and verified against measurements with good results. Main focus has been put on the generation of switching overvoltages. It is shown that the generation of switching overvoltages is caused by slightly different resonant frequencies of the three phases which are reflected between the phases by mutual couplings in such a way that a low-frequent modulation appears in the phase voltages.

Keywords: — 400 kV cable, disconnection, switching overvoltage, resonance, mutual coupling, shunt reactor, low frequent modulation

1 Introduction

Danish transmission system operator Energinet.dk has designed and constructed a new 400 kV transmission line between the cities Aarhus and Aalborg, app 90 km. This line is constructed as a combined overhead line/cable line. Two cable sections (4,5 and 2,8 km) are used to cross areas of natural beauty. The reactive power compensation of the cable sections are compensated by means of a permanently connected three-phase shunt reactor located app. in the middle of the line, see figure 1. Resonant behaviour can be expected from such a configuration containing capacitance from (mainly) the cable sections and inductance in the shunt reactor, especially

when switching the line free from the rest of the network.

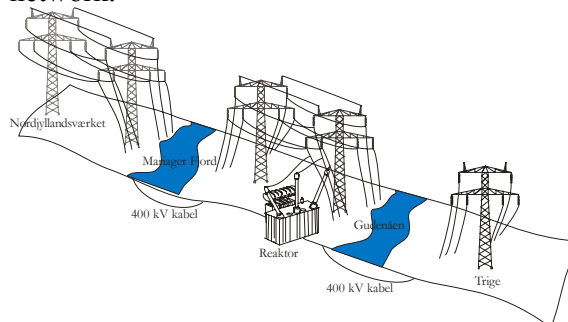


Fig. 1. The combined OHL/cable line between Aarhus (Thrige TRI) and Aalborg (Nordjyllandsværket NVV).

As the shunt reactor is permanently connected to the line, which contains shunt capacitance

from the cables, a parallel resonant circuit will start oscillating when disconnecting the line and because of the very high quality factor (very low resistance) for power systems in general and voltage will decay slowly with an oscillatory behavior. This was expected and TSO Energinet. dk has measured the dynamic decay of the phase voltages of the line when performing last-end disconnection. Such a measurement is shown in figure 2.

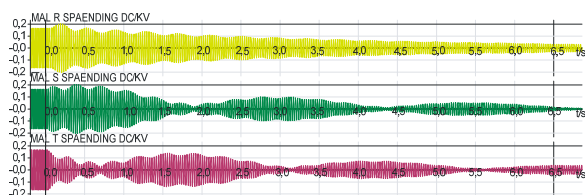


Fig. 2. Phase voltages for the 400 kV line NVV-TRI when performing last-end disconnection. Timescale horizontal 6,5 s between bars and voltage peak before instant of switching (before left bar) equal to 335 kV

As can be seen from figure 2, phase voltages decays slowly (end of graph 6,5 s) in a modulated manner. Three frequencies are recognizable; change from 50 Hz to a lower (app. 35 Hz) when switching and two modulating frequencies (app. 3 Hz for all three phases and 0,4 Hz for phase R and T). Overvoltages are visible in phase R and S. This measurement caused speculation within Energinet.dk concerning the inherent resonant nature of such line configurations as they are also used at the 150 kV transmission level and intended to be used at 400 kV more than just for this line. Can dangerous overvoltages be generated during last-end switching of such lines? And what is the electro technical explanation of such phenomena? Can reliable simulation models be created and used to predict such behavior for existing and future lines? This paper presents the main results of a Masters Thesis by Kim Søgaard analyzing such combined OHL/cable systems. A simplified three-phase equivalent circuit is set up and corresponding circuit differential equations are solved by means of the method of eigenvalues. The shunt reactor is modeled with respect to

mutual couplings. This model is verified against a similar PSCAD/EMTDC model. The equivalent circuit model shows clearly that the mutual couplings of the shunt reactor reflects the slight differences in resonant frequency of the individual phases to each other so low-frequency modulations can appear and strengthen (by adding to) or weaken (by subtracting from) the phase voltages of each of the phases. A complete model including non-symmetric mutual couplings of the OHL's and cable sections and crossbonding of the cable sheaths is put up in the PSCAD/EMTDC software including a new differential equation based model of the three-phase shunt reactor with mutual couplings. This model is verified against transient measurements of the line during disconnection and a good agreement is observed. The effect of the crossbonding of the cable sections are analyzed by means of parameter variation studies. Finally it is shown again that the origin of the modulated behavior and the overvoltages is to be found in the fact that following last-end disconnection, each phase will start resonating with its own natural frequency (which might be slightly different for the phases) and mutual couplings will reflect this between the phases so a modulated low-frequency decay of the phase voltages will appear.

2 System Description

A. The line

The combined OHL/cable line has the following configuration (see figure 3) and data:

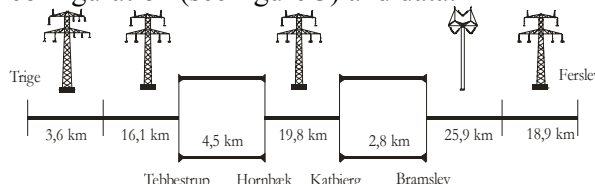


Fig. 3. Line configuration for the analyzed 400 kV cable/OHL line

Cables are single phase Al XLPE 1200 mm² and capacitance of each cable is 0,18 μ F/km and it should be noted that the cable sections consists of two parallel lines. The reactor is connected permanently in substation Hornbæk and compensates both cable sections.

B. The 400 kV shunt reactor

The shunt reactor is made by ABB, type XAN 335 TR and with a rated power of 100 MVAR. Nominal voltage 420 kV, winding star connected with a solidly grounded starpoint. Figure 4 shows the shunt reactor.



Fig. 4. 420 kV shunt reactor used for the cable/OHL line

The reactor core is 5-limbed and it possesses airgaps in the three phase core legs in order to linearize inductance.

Data for resistance, self inductance and mutual inductance are stated in table 1. 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.

	Resistance	Self inductance	Mutual inductance		
			Phase L1	Phase L2	Phase L3
Phase L1	1,3009 Ω	5,588 H		-0,0172 H	-0,0058 H
Phase L2	1,3023 Ω	5,591 H	-0,0211 H		-0,0188 H
Phase L3	1,3043 Ω	5,602 H	-0,0054 H	-0,0054 H	

Table 1. 400 kV ABB shunt reactor data

3 Modeling and simulation

In order to simulate the switching overvoltages generated at last-end witch off, suitable models of each component of the system (OHL, cable and shunt reactor) must be used. For a start a simple equivalent scheme with lumped parameters is used to illustrate the principal behavior of the system. This is followed by a detailed modeling in PSCAD/EMTDC using already available models for cable and OHL, but shunt reactor models (which take into account mutual coupling) are not available in

PSCAD/EMTDC so such a model is created and verified against test report data. The models of each component will be discussed briefly in the following sections. Further explanations to the models can be found in [1].

C. ABB shunt reactor model

The transformer reactor must be modeled sufficiently to behave as a resonant element with the ability to reflect mutual coupling effects between phases (although small). PSCAD/EMTDC does not include a standard shunt reactor model. It is customary to use a standard transformer model, but such a model does not allow defining different mutual couplings between phases, which is important for the correct behavior of the reactor model for this purpose. Neither is it possible to define self inductance separately for each phase, an issue which is important in order to simulate the correct resonant frequency of each phase. Therefore the shunt reactor is modeled on the basis of a three-phase equivalent scheme representation as shown in figure 5.

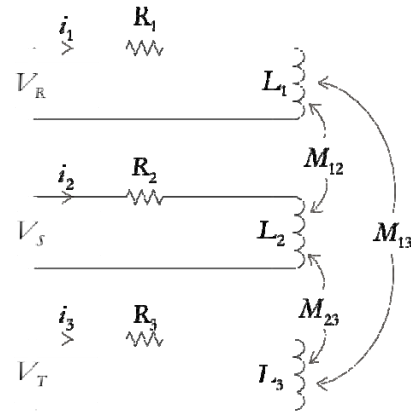


Fig. 5. Shunt reactor equivalent scheme model

The equations (1) are written on the basis of the laws of Kirchhoff and represents the shunt reactor equivalent scheme.

$$\begin{aligned}
 V_R(t) &= R_1 i_1 + \frac{di_1}{dt} L_1 + \frac{di_2}{dt} M_{12} + \frac{di_3}{dt} M_{13} \\
 V_S(t) &= R_2 i_2 + \frac{di_2}{dt} L_2 + \frac{di_1}{dt} M_{21} + \frac{di_3}{dt} M_{23} \\
 V_T(t) &= R_3 i_3 + \frac{di_3}{dt} L_3 + \frac{di_1}{dt} M_{31} + \frac{di_2}{dt} M_{32}
 \end{aligned} \quad (1)$$

This set of equations (1) is solved numerically by means of a FORTRAN routine [1] and implemented in PSCAD/EMTDC as shown in figure 6.

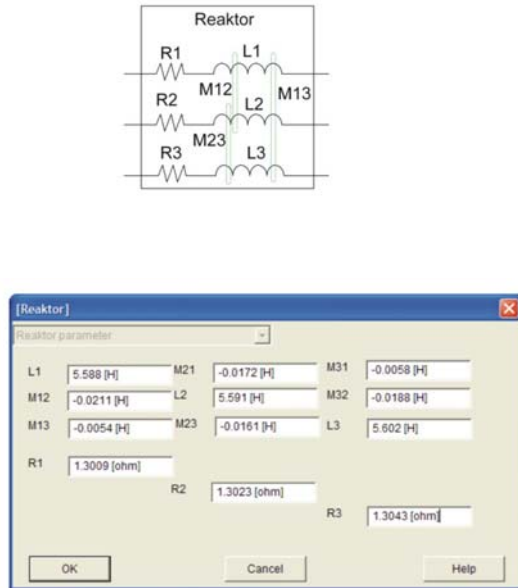


Fig. 6. Shunt reactor implemented in PSCAD/EMTDC

This model is verified with ABB test report data and has proven to be accurate.

D. Simplified model of last-end switching of TRI-FER

In order to clarify the origin of the dynamic behavior of the combined cable/OHL with the shunt reactor during last-end switch of a simplified lumped parameter model is put up and circuit equations sought solved and compared with simulations of an identical lumped parameter model in PSCAD/EMTDC. Figure 7 shows this approach. Mutual couplings and self inductance neglected for the OHL's and cables. Cable capacitance represented with one lumped capacitor. R represents winding resistance of reactor, L self inductance of reactor and M the mutual inductance between phases of the reactor. Circuit equations can be set up for figure 7, see equations (2)

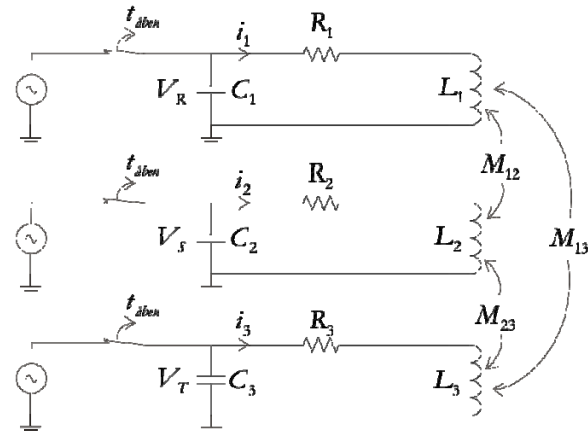


Fig. 7. Simplified representation of the line TRI-FER during last-end switch off.

$$\frac{d}{dt} \begin{bmatrix} i_1 \\ p_1 \\ i_2 \\ p_2 \\ i_3 \\ p_3 \end{bmatrix} = \begin{bmatrix} L_1 & 0 & M_{12} & 0 & M_{13} & 0 \\ 0 & C_1 & 0 & 0 & 0 & 0 \\ M_{21} & 0 & L_2 & 0 & M_{23} & 0 \\ 0 & 0 & 0 & C_2 & 0 & 0 \\ M_{31} & 0 & M_{32} & 0 & L_3 & 0 \\ 0 & 0 & 0 & 0 & 0 & C_3 \end{bmatrix}^{-1} \begin{bmatrix} -R_1 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -R_1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -R_1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_1 \\ p_1 \\ i_2 \\ p_2 \\ i_3 \\ p_3 \end{bmatrix} \quad (2)$$

The parameters used to solve the equation are:

Resistance Ω	Capacitance μF	Inductance H			
$R_1=1.300$ 9	$C_1=3,53$ 6	$L_1=5.588$	$M_{12}=-$ 0,0211	$M_{21}=-$ 0,0172	$M_{31}=-$ 0,0058
$R_2=1.302$ 3	$C_1=3,55$ 0	$L_2=5.591$	$M_{13}=-$ 0,0054	$M_{23}=-$ 0,0161	$M_{32}=-$ 0,0188
$R_3=1.304$ 3	$C_1=3,53$ 6	$L_3=5,602$			

Table 2. Parameters for solving eq. (2)

The mathematical solution of this set of equations, including the correct determination of initial conditions has been carried out [1], [3] but is tedious. Therefore some simplifications has been adopted in order to gain useful results without large mathematical/numerical difficulties. The mutual coupling between phases R and S is taken to be equal to the mutual coupling between phases S and T, moreover R and T equal to T and R. Self inductance (for reactor) and capacitance (for cable) is taken to be equal for all three phases.

Resistance Ω	Capacitance μF	Inductance H			
$R_1=1.$ 3	$C_1=3,536$	$L_1=5$.5	$M_{12}=-$ 0,02	$M_{21}=-$ 0,02	$M_{31}=-$ 0,0058
$R_2=1.$ 3	$C_1=3,536$	$L_2=5$.5	$M_{13}=-$ 0,0058	$M_{23}=-$ 0,02	$M_{32}=-0,02$
$R_3=1.$ 3	$C_1=3,536$	$L_3=5$.5			

Table 3. Simplified Parameters for solving eq. (2)

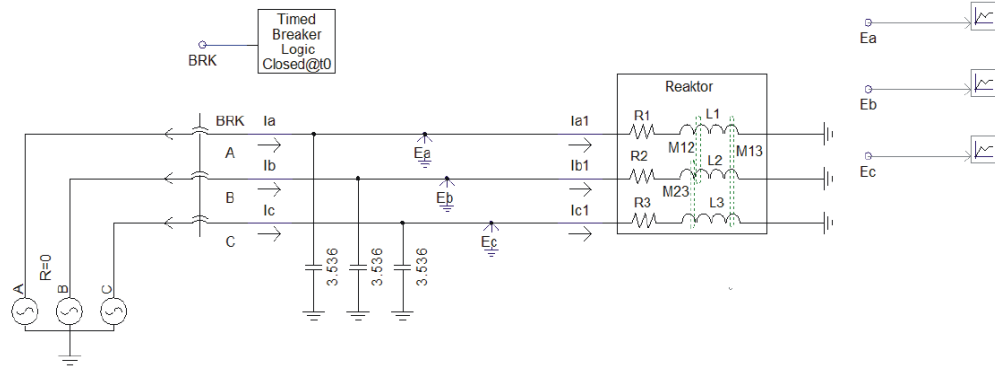


Fig. 8. PSCAD/EMTDC model to be compared with results from (2)

Numerical solution of eq. (2) calculated by means of MATLAB are compared to PSCAD/EMTDC simulation results of the same circuit, see figure 8 and presented in Figures 9-11 for all three phases R, S and T.

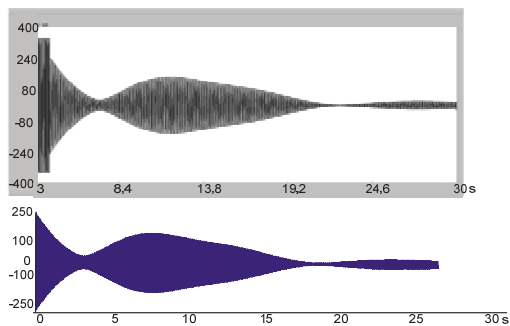


Fig. 9. Eq. (2) (lower) compared to PSCAD simulation (upper), phase R

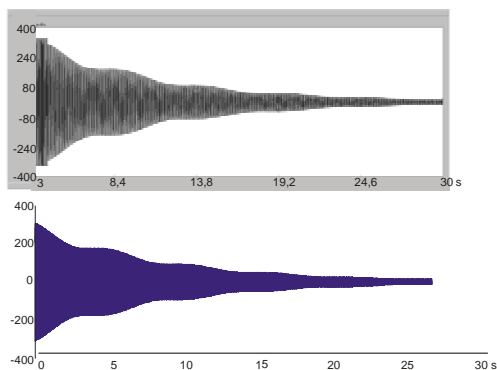


Fig. 10. Eq. (2) (lower) compared to PSCAD simulation (upper), ph. S.

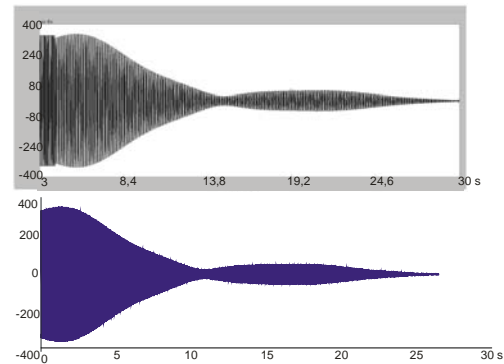


Fig. 11. Eq. (2) (lower) compared to PSCAD simulation (upper), ph. T.

As can be seen from figures 9-11 the dynamic behaviour of the system represented in figure 7 and modelled by means of eq. (2) with parameters acc. to table 3 can be simulated satisfactorily with PSCAD/EMTDC. Both “handmade” model with equivalent circuit and numerical MATLAB solving of circuit equations and PSCAD/EMTDC model show corresponding results. The main advantage of this result is that the shunt reactor model has been implemented correctly in PSCAD/EMTDC and therefore can be used together with a complete model of the total system including PSCAD/EMTDC already available, detailed models for cables and OHL’s taking into account effects such as different mutual couplings, asymmetries, groundings and crossbonding. It could have been “dangerous” to start simulating the complete system with all parameters and asymmetries present as first attempt, maybe results would not be correct. In

this way it is sought to verify the only “self-made” component, namely the shunt reactor and use it together with already well-known and proven models of OHL and cable. Results may appear more proven reliable in this way.

E. PSCAD/EMTDC model of entire line TRI-FER

The entire PSCAD/EMTDC model including cable sections and overhead line sections and the “self-made” shunt reactor model is shown in figure 17. All parameters are available in [1]. All sections are modeled with transmission line models [4] using Bergeron’s representation [4] as this is sufficient for the relative low-frequent dynamics in question here [4]. Also this model includes phase unsymmetries, which can contribute to the generation of the switching overvoltages analyzed. Energization of the line is done by means of an ideal voltage source and a circuit breaker element. Cable section screens are connected acc. to the system description using crossbonding and one-end-open screen respectively. In order to be able to compare results of the simulation with the measurements shown in figure 1 some preconditions must be fulfilled. These are:

1. Switch off is to take place when the simulation model has reached steady state.
2. Switch off in simulation has to be timed to happen at the exact same instant of the voltage and current waveform as in real life experiment in order to establish correct initial conditions for simulations. The results of the simulations compared to measurements (from figure 1) can be seen in figure 12, 13 and 14.

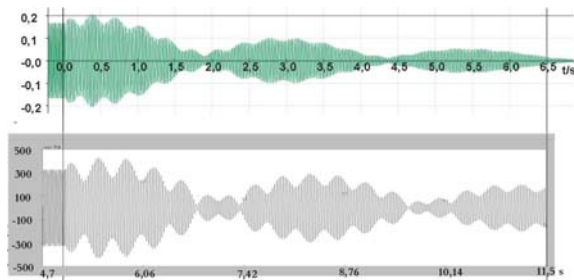


Fig. 12. Results from PSCAD/simulations compared to measurements of last-end switch off of the 400 kV line TRI-FER, phase R. Peak voltage before instant of switching (both graphs) is 335 kV

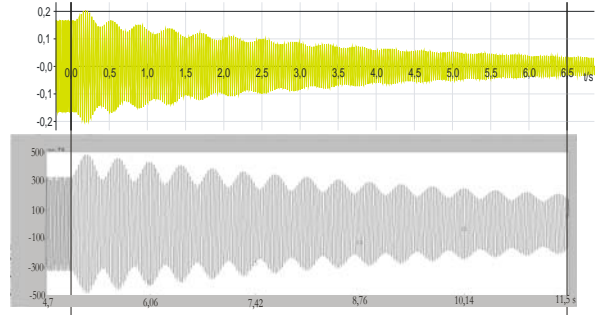


Fig. 13. Results from PSCAD/simulations compared to measurements of last-end switch off of the 400 kV line TRI-FER, phase S. Peak voltage before instant of switching (both graphs) is 335 kV

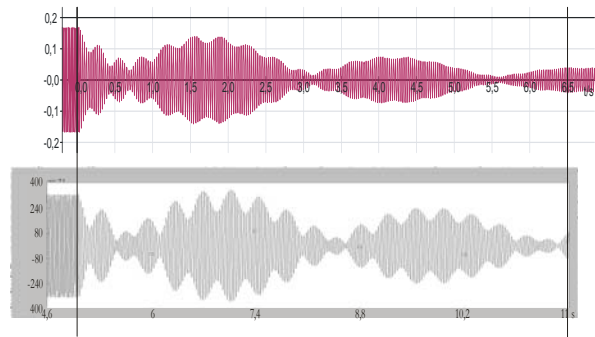


Fig. 14. Results from PSCAD/simulations compared to measurements of last-end switch off of the 400 kV line TRI-FER, phase T. Peak voltage before instant of switching (both graphs) is 335 kV

F. Discussion of results

Although the results in figures 12-14 are quite small and scaling not easily readable (readable from data file in [1]) because of the file format of the fault recorder with which the measurements are done, it is obvious that similarities exist for all three phases. Three frequencies are visible, simulated fundamental resonant frequency after switch off $f_{res,sim} = 34$ Hz and measured fundamental resonant 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 second modulating frequency $f_{mod2,meas} = 0,4$ Hz. The most dominating deviation between

measurement and simulation is to be found in the damping. Simulated results are less damped than measurements, which can be explained by non-sufficient modeling/simplification of lossy circuit elements such as e.g. shunt reactor iron losses (hysteresis and eddy current), leakage current of OHL, corona of OHL and dielectric losses of the cables. Voltage transformers connected to the line will also tend to discharge the line and thereby increase damping. The consequence is that voltage amplitude seems to high, because peaking (the hunted switching overvoltage) is caused by the modulation of the phase voltage, which happens some periods after switch off and therefore will be more affected by real-life damping than in simulation with the consequence that simulations shows too high values of overvoltage. If such damping effects are included simulations are likely to perform correct switching overvoltage estimations. Further simulations has revealed that maximum amplitude of the switching overvoltage appears for disconnection at the instant of phase voltage maximum for phase R, see figure 15.

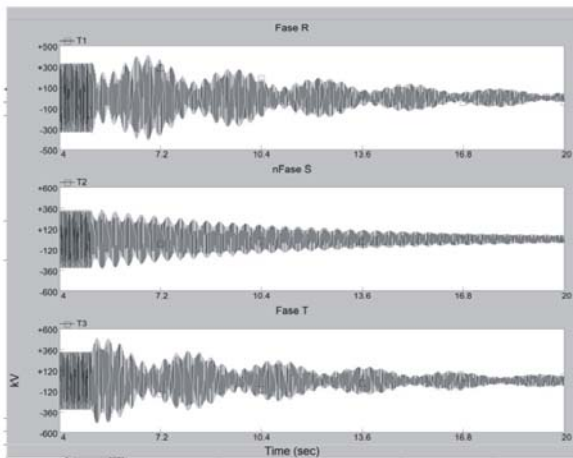


Fig. 15. Results from PSCAD/simulations with switch off at phase R voltage waveform maximum.

As can be seen from figure 15 considerable overvoltages appears for phase T, app. 32 % (455 kV compared to 343 kV). It can be shown [1] by means of circuit analysis (figure 7 and eq. (2)) that the overvoltage amplitude is inversely proportional to the square of the natural resonant frequency after disconnection given by

the resonant circuit formed by cable shunt capacitance and shunt reactor self inductance. Therefore a shift in resonant frequency towards higher values would remedy the switching overvoltage problem. This is illustrated in fig. 16, which is a simulation identical to figure 15, except that the reactor reactive power rating is increased so the resonant frequency at last-end switch off rises to 60 Hz.

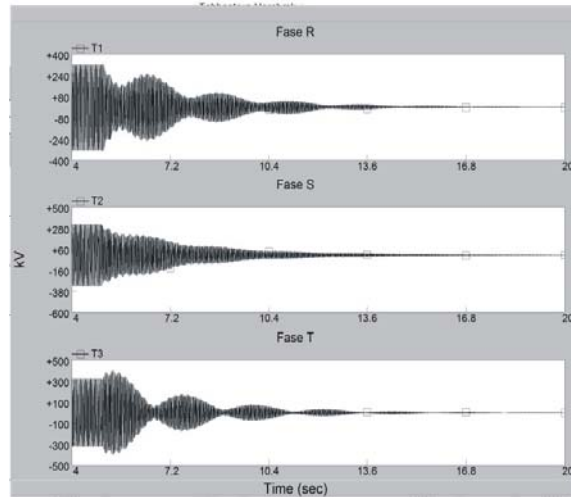


Fig. 16. Results from PSCAD/simulations with switch off at phase R voltage waveform maximum with increased reactor nominal rating so resonant frequency is 60 Hz.

Overvoltage amplitude lowers from 455 kV to 396 kV.

It can be shown [1] that the switching overvoltages during last-end switch off of shunt reactor compensated transmission lines can be ascribed to the change in reactance of the reactor when switching off and entering a (lower) resonant frequency mode. When frequency lowers reactance of reactor lowers and current increases. This current is to be taken from the charge of the shunt capacitance (cables), which in hand increases (over)voltage across these.

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 two sinusoidal with slightly different frequency yields such low-frequency modulations. In this way numerous shapes and appearances (frequencies, amplifications, attenuations) of last-end switch off voltage decay can form.

Symmetry will cause equal resonant frequencies for the three phases and thereby remedy the problem.

Damping must speed up the damping 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. This can be considered when specifying the reactor, single-phase and/or core design. Also transmission line design (tower layout and cable laying) should be kept as symmetrical as practically possible

4 Conclusions

This paper has shown the analysis of a shunt reactor compensated combined 400 kV overhead line/cable transmission line following last-end switch off. Main focus has been put on

the generation of possible long-during switching overvoltages. Such overvoltages can appear during the slowly decaying (several seconds) voltage following last-end switch off. Simulations show that for the 400 kV transmission line TRI-FER an overvoltage amplitude of 132% compared to the voltage before switch-off. Their origin (see box in sec. III D) is the resonant nature of the system formed after the switch off, combined with the system asymmetries (OHL, cable and reactor) both of the self impedance values of each phase and of the mutual couplings between phases. OHL's also contribute with asymmetrical capacitive coupling. The nature of the switch off dynamics is complex and no general guidelines can be given of how to prevent such phenomena, but it shows the necessity for studying the dynamic behaviour of such combined system after the last-end switching off, using time-domain simulation tools already in the design phase.

5 Acknowledgement

The Authors wish to gratefully acknowledge the long ongoing, valuable cooperation with Danish TSO Energinet.dk.

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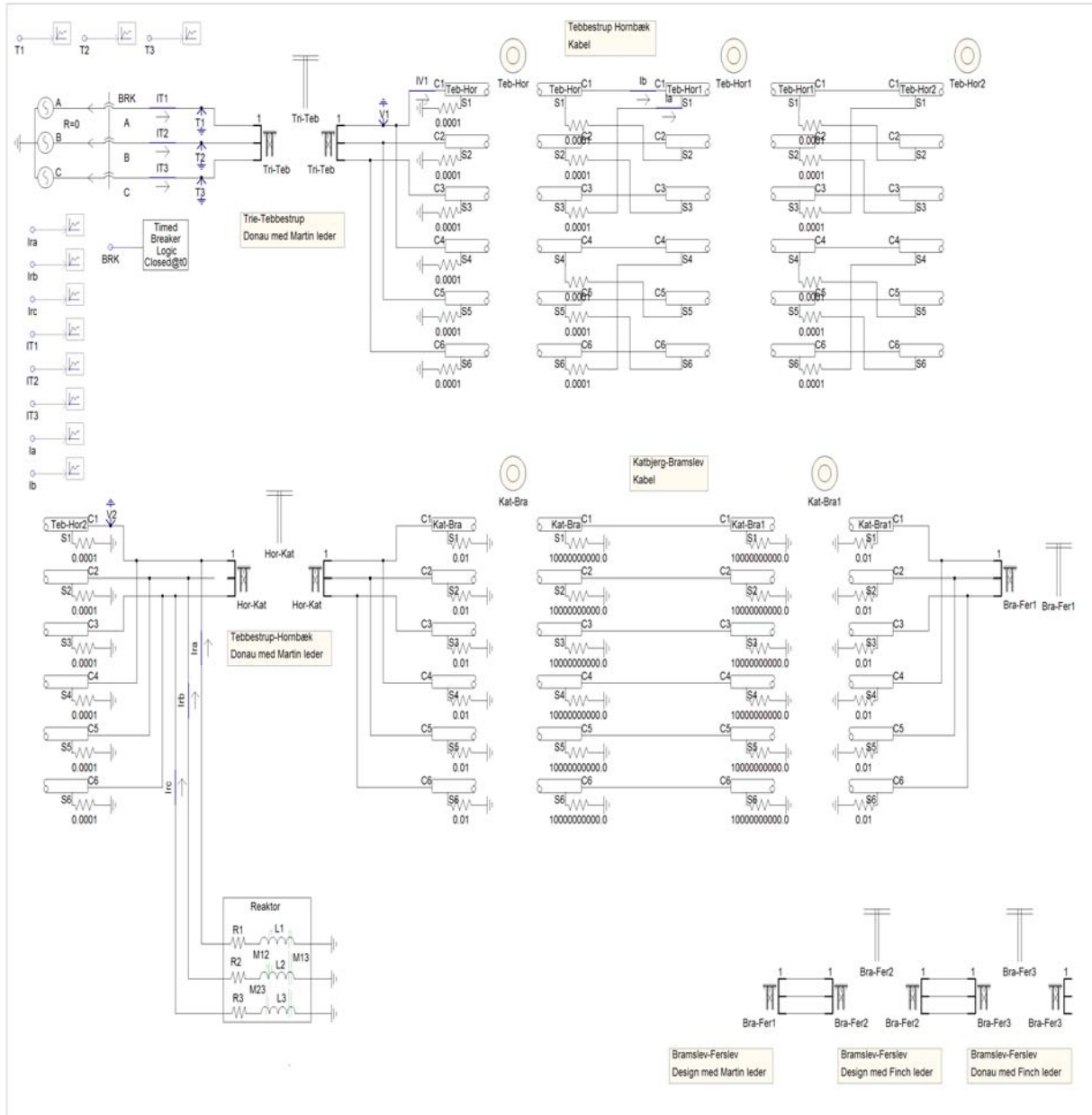


Fig. 17. PSCAD/EMTDC simulation model of entire 400 kV line TRI-FER during last end switch off. This is the fully modelling of the 400 kV combined overhead/cable line shown in figures 1 and 2, including the shunt compensating reactor placed as shown approximately in the middle (at Hornbæk, see fig. 1 and 2). OHL's are modelled using the Bergeron model with all phase conductors and ground wires represented physically as in real life using no simplifications (i.e. lines are represented as mutually coupled and non-transposed with actual unsymmetry taken into consideration). Corona and shunt leakage current not taken into consideration. Cables are modelled using Bergeron model with all single phase cables (6 per line, as 2 single phase cables are used per phase) represented as in real life using correct laying dimensions and cable internal dimensions. Cable screen is connected to ground as in real life (Crossbonding for upper cable section and one-end open for lower cable section). Dielectric losses are not modelled. The reactor is modelled with the custom made model with data as shown in figure 6. This model takes into consideration unequal

mutual coupling between phases, unequal self inductance for each phase and resistance of the windings. Iron losses (hysteresis and eddy current) are not modelled. Losses of the entire model must be lower as in real life because of the before mentioned neglecting of component losses. Therefore lower damping than in measurements must be expected. This is also demonstrated in figure 12-14 comparing measurements and simulation.
