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Published in:

Proceedings of the 8th WSEAS International Conference on Electric Power Systems, High Voltages, Electric Machines (POWER '08)

Publication date:

2008

Document Version

Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Bak, C. L., & Søgaard, K. (2008). Single-phase AutoReClosure ARC failure on 400 kV combined cable/overhead line with permanently connected shunt reactor. In *Proceedings of the 8th WSEAS International Conference on Electric Power Systems, High Voltages, Electric Machines (POWER '08): Recent advances in electric power systems, high voltages, electrical machines* (pp. 118-127). WSEAS Press.

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Single-phase AutoReClosure ARC failure on 400 kV combined 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 likelihood of having a successful single-phase autoreclosure ARC in such a combined cable/OHL line.

Keywords — 400 kV cable, single-phase autoreclosure, shunt reactor, resonance, mutual coupling

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 behavior 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.

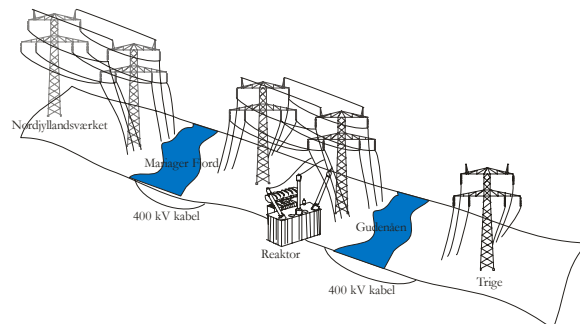


Fig. 1. The combined OHL/cable line between Aarhus (Thrige TRI) and Aalborg (Nordjyllandsværket NVV).

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.

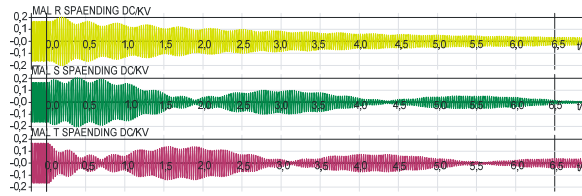


Fig. 2. Phase voltages for the 400 kV line NVV-TRI when performing last-end disconnection. Timescale horizontal 6,5 s between bars and voltage peak before instant of switching (before left bar) equal to 335 kV

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 successful single-phase ARC take place in such type of combined line with a permanently connected shunt reactor? One would perhaps expect that mutual coupling between the phases in the reactor would leave the single phase under ARC in a non-energized state and in this way give rise to an unsuccessful ARC. Can reliable simulation models be created and used to predict such behavior for existing and future lines? This paper presents results of a Masters Thesis by Kim Søgaard analyzing such combined OHL/cable systems. A former paper [7] describes detailed the modeling, simulation and verification approach whereas this paper describes more specifically analysis and results of the single-phase ARC behavior of such combined cable/OHL line. 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 [7] and section XXX. Subsequently the simulation model is changed slightly to allow for simulating single-phase ARC with the focus on analyzing dynamic voltage and current in the faulted phase during an ARC cycle. This is followed by an analysis of the possibility to sustain an arc in the faulted place and it is concluded, for this specific system layout, that successful ARC should be expected.

2 System description

A. The line

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

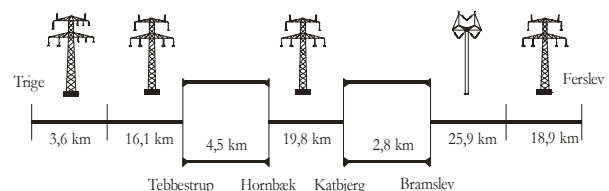


Fig. 3. Line configuration for the analyzed 400 kV cable/OHL line

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. The line is protected with distance relays and differential relays (backup) with possibility for both single- and three phase ARC. During single phase to ground faults single phase ARC is applied with a dead time of app. 0,8 s. Insulators of the OHL has a length of 4,3 m

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.



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

Figure 4 shows the shunt reactor. The reactor core is 5-limbed and it possesses airgaps in the three phase core legs in order 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 single-phase ARC behavior of the 400 kV combined cable/OHL line, suitable models of each component of the system (OHL, cable and shunt reactor) must be used. A detailed modeling in PSCAD/EMTDC of the entire line using already available models for cable and OHL is created. Shunt reactor models (which take into account mutual coupling) are not available in PSCAD/EMTDC so such a model is created and verified [7]. The models of each component will be discussed briefly in the following sections. Further explanations to the models can be found in [1] and [7].

A. 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.

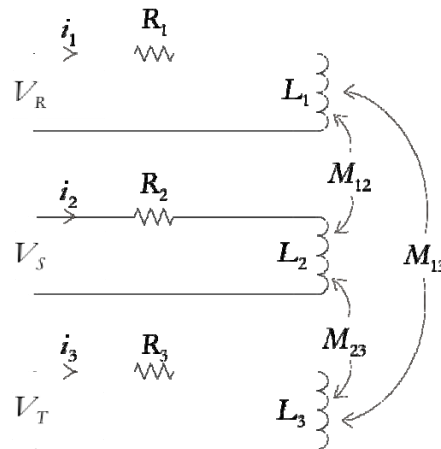


Fig. 5. Shunt reactor equivalent scheme model

The equations (1) are written on the basis of the laws of Kirchhoff and represent 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.

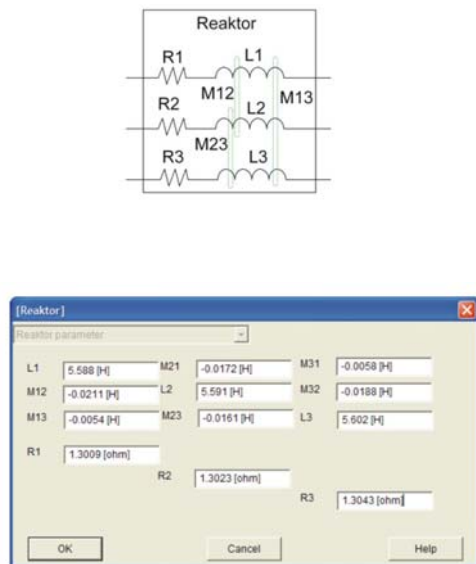


Fig. 6. Shunt reactor implemented in PSCAD/EMTDC

This model is verified with ABB test report data [1] and [7] and has proven to be accurate.

B. 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]. Energizing of the line is accomplished by means of an ideal voltage source and a circuit breaker element. Cable section screens are connected according 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 7, 8 and 9.

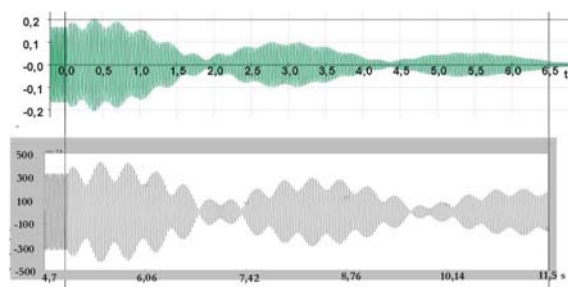


Fig. 7. Results from PSCAD/simulations compared to measurements of last-end switch off of the 400 kV line TRI-FER, phase R. Peak voltage before instant of switching (both graphs) is 335 kV

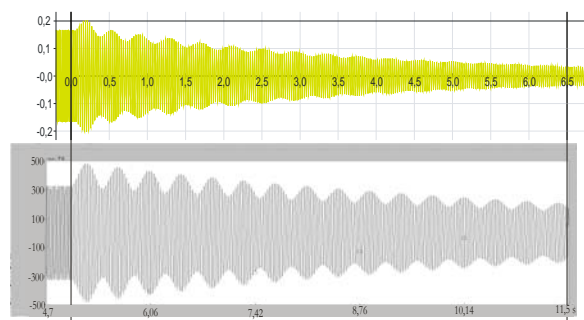


Fig. 8. Results from PSCAD/simulations compared to measurements of last-end switch off of the 400 kV line TRI-FER, phase S. Peak voltage before instant of switching (both graphs) is 335 kV

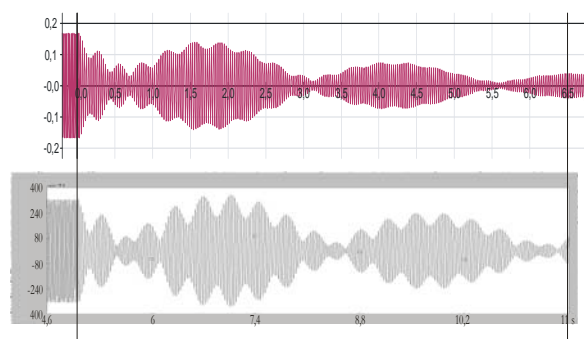


Fig. 9. Results from PSCAD/simulations compared to measurements of last-end switch off of the 400 kV line TRI-FER, phase T. Peak voltage before instant of switching (both graphs) is 335 kV

C. Discussion of last-end switch off simulation results vs. measurements

Although the results in figures 7-9 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. On the basis of the before mentioned verification of the model of the combined 400 kV cable/OHL line it seems justified to use the model for simulating and predicting single-phase ARC behavior.

D. Simulation of single-phase ARC

The combined line is protected with a double relay system (distance and differential) with phase selective ARC. Ordinary OHL transmission systems (without permanently connected shunt reactor) possesses only mutual couplings between phases caused by mutual inductance and mutual capacitance, where the last mentioned can be neglected in the present study. Speculations within Energinet.dk resulted in this present investigation as it was considered a possible problem that the shunt reactor was a possible source of energization of the ARC-

switched off phase in such a way that the ARC cycle would fail.

In order to validate the entire model of the 400 kV combined cable/OHL line for simulating single phase ARC comparison between simulation and measurement is conducted. Figure 10 shows the measured phase voltage during single-phase ARC.

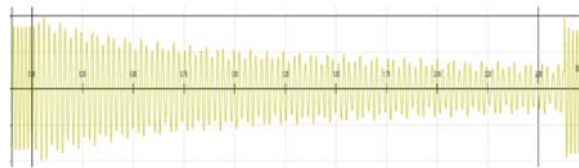


Figure 10: Phase voltage during single phase ARC for the 400 kV line NVV-TRI. Timescale horizontal 2,5 s between bars and voltage peak before instant of ARC is equal to 335 kV

As can be seen from figure 10 the phase voltage of the phase during ARC dead time has a lower frequency than 50 Hz. The fundamental frequency is 36,9 Hz and modulated with a non-constant frequency. The fundamental frequency around 36 Hz stems from the resonance circuit formed by the shunt reactor inductance and the total shunt capacitance of the entire line (both OHL and cable), as the phase during ARC is switched off the power frequency and thereby resonates freely with its natural resonance frequency. The origin of the non-constant frequency modulation can be deduced looking at figure 11, which is a zoom of the single phase voltage during ARC plotted together with the two other healthy phase voltages (these are not switched off as this is single-phase ARC)

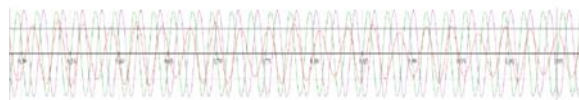


Figure 11: Phase voltages of the three phases during single phase ARC (red curve). The graph covers 0,55 s and the peak phase voltage of the healthy phases is equal to 335 kV.

Recovering laws of induction reveals that the random, non-constant modulation of the phase under ARC originates from the induced voltages from the healthy phases. It can be noted from figure 11 that there is a close connection between the 50 Hz sinusoidal voltage phase

angle of the healthy phases and the 36 Hz amplitude of the single phase under ARC in such a way that the highest peaks of the single phase ARC voltage corresponds to instants of phase angle for both healthy voltages giving rise to a maximum superimposed (induced magnetically) voltage on the the 36 Hz decaying single phase. So; to summarize, voltage of the sick phase under ARC origins from the trapped charge of the resonant circuit of this phase slowly decaying with a frequency equal to the resonant frequency superimposed with voltage induced from mutual couplings of the three-phase circuit, hereunder the shunt reactor.

The PSCAD/EMTDC model is used to simulate the same ARC incident as described above and shown in figure 10. This is shown in figure 12.

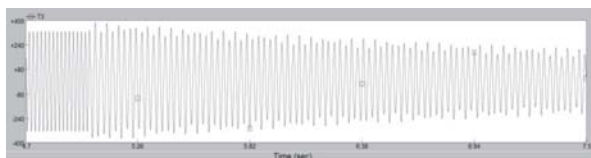


Figure 12: Simulation of single phase ARC phase voltage to be compared with measurement in figure 10.

Frequency of simulated phase voltage is app. 35 Hz (compared to measurement app. 37 Hz) and same random behaviour of modulation can be seen, although damping is seen to be less than in measurement. As the purpose of this investigation is a worst case estimation of the possibility of a successful ARC, the damping of the simulation can be regarded as being of less importance on the first hand. The fact that the voltage is less damped will in hand give rise to a larger current in the arc of the faulted phase and thereby represent worst case. As real life yields more damping and thereby less current the likelihood of a successful ARC is thus higher than for the simulation.

The ground fault can happen several places on the combined 400 kV cable/OHL line. Only atmospherically originated (lightning) surges are considered so faulted locations are limited to the OHL sections. Furthermore ARC on cables gives no reason, because such faults are permanent. The five cases shown in figure 13

have been simulated concerning dynamic ground fault current through an arc of negligible impedance and worst location (highest current) has been further analyzed concerning ability to sustain an electric arc in the faulted location.



Figure 13: Five different fault locations cases of the 400 kV combined cable/OHL line NVV-TRI.

A result for the current in the faulted location for case 1 is shown in figure 14.

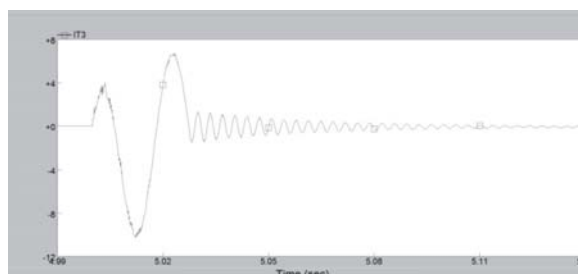


Figure 14: Fault current to ground of the faulted phase, case 1. The ground fault happens at $t = 5,0$ s and is switched off at $t = 5,02$ s. Vertical axis scaling in kA.

The peak of the current (after switch-off) is seen to be app. 1,4 kA. This will be used to estimate further, whether an electric arc can continue to burn in the faulted place.

The peak fault current of all five cases of figure 13 is stated in table 2.

Case	1	2	3	2	1
$I_{\text{fault}} [\text{A}]$	1401	870	539	715	726

Table 2: Peak fault current of the faulted phase during ARC for the five cases shown in figure 13.

An electric arc can be modelled with equation (2) [8]

$$U_{\text{arc}} = \Delta U + E_{\text{arc}} \cdot l_{\text{arc}} + \frac{1}{I_{\text{arc}}} (\alpha + \beta \cdot l_{\text{arc}}) \quad (2)$$

where U_{arc} is the voltage of the arc, ΔU is the voltage drop of anode and cathode, E_{arc} is the field strength of the arc, l_{arc} is the length of the arc and α and β are anode/cathode material

specific constants and I the current through the arc. An electric arc possesses resistance according to [9]

$$R_{arc} = \frac{28700 \cdot l_{arc}}{I^{1.4}} \quad (3)$$

Using the RMS value of $I = 1401/\sqrt{2}$ and an arc length $l_{arc} = 4,3$ m yields $R_{arc} = 7,9 \Omega$. The law of Ohm gives an expected voltage drop across the arc equal to

$$U_{arc} = R_{arc} \cdot I = 7,9 \cdot 1401/\sqrt{2} = 7813 \text{ V} \quad (4)$$

Inserting this in (2) and solving for l_{arc} using proper constants for α , β , ΔU and E_{arc} assuming iron as electrode material for the arc (arc across i.e. insulator string) [8] yields a maximum arc length (critical length) equal to 3,1 m, which is less than the minimum possible arc length equal to 4,3 m across the insulators (related to the Basic Insulation Level BIL of the 400 kV system) so the likelihood of the arc being able to burn continuously seems quite small. Furthermore several factors all affecting arc burning ability points in the direction of the above estimation being a worst case:

- Calculation based on peak current
- Arc reigniting not considered
- Arc extension not considered
- Actual arc resistance not considered when simulating arc current
- Arc current decaying AC so conditions for arc burning will in time get worse

The general assessment must be that the likelihood of an unsuccessful ARC caused by energization of the faulted phase during ARC through mutual couplings (including shunt reactor) of the combined cable/OHL line seems very small. Therefore ARC can be used at the line in question.

4 Conclusions

This paper has shown the analysis of a shunt reactor compensated combined 400 kV overhead line/cable transmission line during single-phase ARC. Main focus has been put on the possibility of having a failing ARC cycle as a consequence of the energization of the faulted

phase by the shunt reactor mutual coupling between phases during the ARC dead time not leaving the faulted place deionised sufficiently to secure a successful reclosure. This is accomplished by means of a detailed PSCAD/EMTDC simulation model used for simulating faulted place current to ground during ARC dead time. The ability of this current to be able to sustain an electric arc in the faulted place has been evaluated using empiric equations for the arc characteristic and it has been shown that the arc would not be expected to continue burning during ARC dead time. Therefore single-phase ARC is expected to be successful for the 400 kV transmission line in question. The nature of the dynamic behaviour of the system is complex and no general guidelines can be given of whether ARC will be successful for such combined systems or not, but this study shows the necessity for studying the dynamic behaviour of such combined system more detailed during the planning period using time-domain simulation tools already in the design phase.

Suggestions for further work could be:

- Including arc characteristic in simulation model
- Design of an intelligent detection of necessary ARC dead time securing sufficient deionisation
- Full scale test measurement

5 Acknowledgement

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

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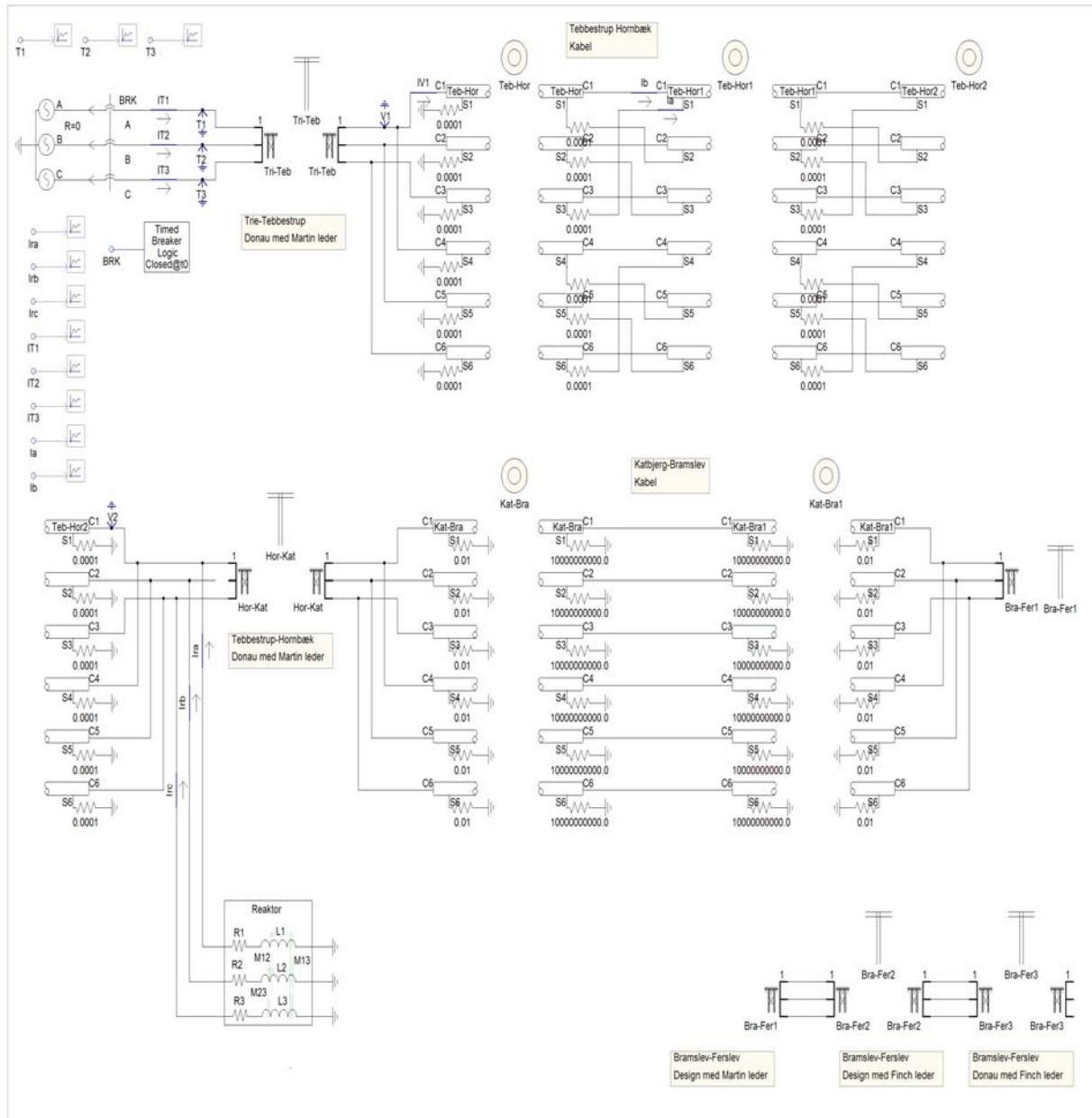


Fig. 17. PSCAD/EMTDC simulation model of entire 400 kV line TRI-FER during last end switch off. This is the fully modelling of the 400 kV combined overhead/cable line shown in figures 1 and 2, including the shunt compensating reactor placed as shown approximately in the middle (at Hornbæk, see fig. 1 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 7-9 comparing measurements and simulation.
