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Switching Overvoltages in 60 kV reactor compensated cable grid due to resonance after disconnection

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Abstract: Some electrical distribution companies are nowadays replacing overhead lines with underground cables. These changes from overhead to underground cable provoke an increased reactive power production in the grid. To save circuit breakers the reactors needed for compensating this excessive reactive power could be directly connected to long cables. Switching both cable and reactor together will cause resonance to occur between the cable capacitance and the inductance of the cable during last end disconnection. Similar type of resonance condition is known to have caused switching overvoltages on the 400kV grid in Denmark. Therefore it is considered necessary to analyze further whether connecting a reactor directly to 60kV cable can cause switching overvoltages. A model in PSCAD was used to analyze which parameters can cause overvoltage. The switching resonance overvoltage was found to be caused by strong mutual couplings between the phases along with different resonance frequencies in the phases caused by unbalance in the grid. This is though not found to cause damaging overvoltages in a cable grid as in ENV-net's grid with the expected reactor values.

Key words: Switching Transients, Underground Cables, Shunt reactors, Resonance.

1 Introduction

Nowadays more people are in favor of removing the overhead line due to the number of disadvantages of the overhead line represents. Where some are: Corona discharge from the overhead line interferes with radio broadcast and telecommunication systems, the electromagnetic field around the cable and those cities and places of natural beauty look more aesthetic and clean without overhead line.

Due to this public pressure to remove overhead lines resolutions have been created in Denmark which limits construction of new overhead lines and expansions of existing overhead lines of 60 kV and below. Due to this the distribution companies like ENV-net in northern Jutland in Denmark tend to replace their 60 kV overhead lines with underground cables. One of the main disadvantages of this change is the large capacitance of the cables which makes the underground cable system to produce 20-30 times more reactive power than the overhead line.

A solution to the excessive reactive power production is to connect reactors into the 60 kV grid. A possibility is to connect those reactors directly to some of the cables to compensate for the reactive power production in such a way that the reactors are switched on and off along with the line and thereby reduce the changes in the reactive power balance in the grid and save cost of switchgear for the reactor. This is known to have

been done on a $400kV$ transmission line from Ferslev to Trige in Denmark [1] where the line is a combination of overhead line and underground cable.

Measurements on that line have shown resonance overvoltages up to 32 % for a period of several seconds occurs [1] after disconnection of the line. As overvoltages due to resonance are known to occur on 400 kV combined overhead underground grid it is considered of great interest to study further if similar resonance which can cause dangerous overvoltage transients occurs in a 60 kV cable grid with compensating reactors, and to analyze which parameters causes the overvoltage.

2 System description

The system used for this study is a planned 18,5 km underground cable line from 60 kV substation Ålbæk to 60 kV substation Hedebo in ENV's grid. The cables are three single phase 400mm^2 PEX cables laid in a triangle as shown in Fig 1. The capacitance of the cable is 0,19 µF/km
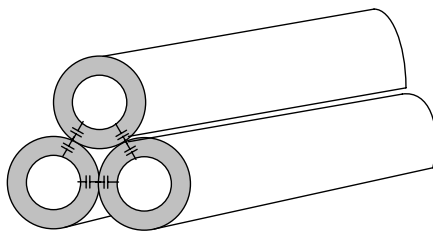

Fig. 1 Layout of the 60 kV cable

The reactive power of the cable is planned to be compensated with a reactor directly connected to the end of the line in substation Ålbæk, as shown in Fig 2.
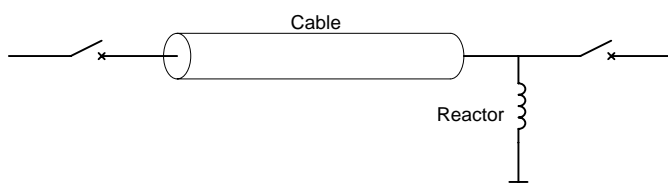

Fig. 2 Connection of the reactor and the cable

This will make the line and reactor to be switched together and will create a resonant circuit. The type

and size of the reactor has yet to be decided but it is expected that it will be around 4,5 Mvar.

As the data for the reactor is not available, data from a 40 Mvar 150 kV reactor which is available is linearly scaled down and used instead. The method for the scaling used [2] is originally for scaling transformer parameters but the similarities between reactors and transformers it is assumed usable for reactors as well. The used parameters for the reactor are found in table 1.

Table 1 Reactor parameters

Parameter	notations	Value
Winding resistances [Ω]	R_{Wa}, R_{Wb}, R_{Wc}	1,21
Magnetization resistances [Ω]	R_{Ma}, R_{Mb}, R_{Mc}	619k
Self inductances [H]	L_{Ra}, L_{Rb}, L_{Rc}	2,83
Mutual inductance phase a-b [mH]	L_{Rab}	-9,35
Mutual inductance phase a-c [mH]	L_{Rac}	-2,83
Mutual inductance phase b-c [mH]	L_{Rbc}	-9,35

3 Model of the grid

A model of a part of the grid was created in PSCAD-EMTDC as shown in Fig 3.
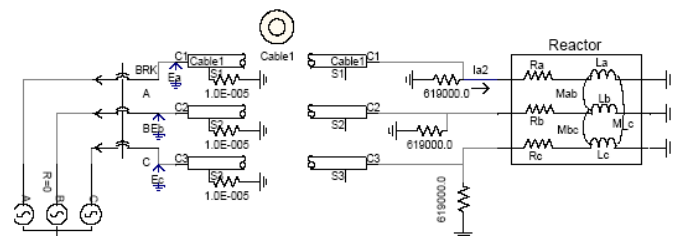

Fig. 3 Model of the system in PSCAD-EMTDC

The model is of the 18,5 km 400mm^2 PEX cable directly connected to a 4,5 Mvar reactor where the line along with reactor are switched. The model used for the cable is a frequency dependent mode model available in PSCAD which is the most advanced model available in PSCAD [3]. As no complete reactor model is available a linear model

of the reactor with mutual couplings was created in PSCAD where the electrical circuit for the reactor can be seen in Fig 4. To ensure proper implementation of the reactor model in PSCAD analytical calculations on the disconnection of the system were made where a PI model was used for the line, see Fig 5, and the differential equations for the system during disconnection were solved with eigenvalues [4] and the same model was simulated in PSCAD and the waveforms showed very good agreement.
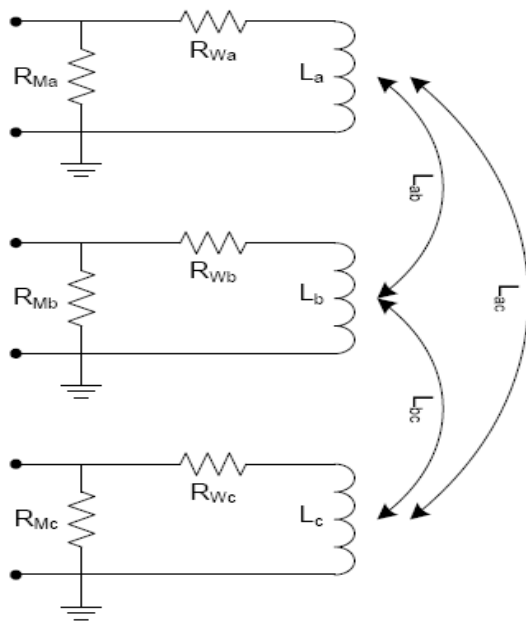

Fig. 4 Circuit diagram of reactor model

This System including a PI model for the line was compared with a more advanced frequency dependent mode model for the line shown in Fig 3. The frequency dependent mode model is well known and more advanced model for the line and considered the most suitable for the simulation. Comparing it with a simulation with a PI model is to ensure that the implementation of model parameters into the model has been done correctly as a good agreement should be between the two models at the expected frequencies. The simulated waveform from the PI model is depicted in Fig 6 and the corresponding waveform from simulation with the frequency dependent mode model is depicted in Fig 7.
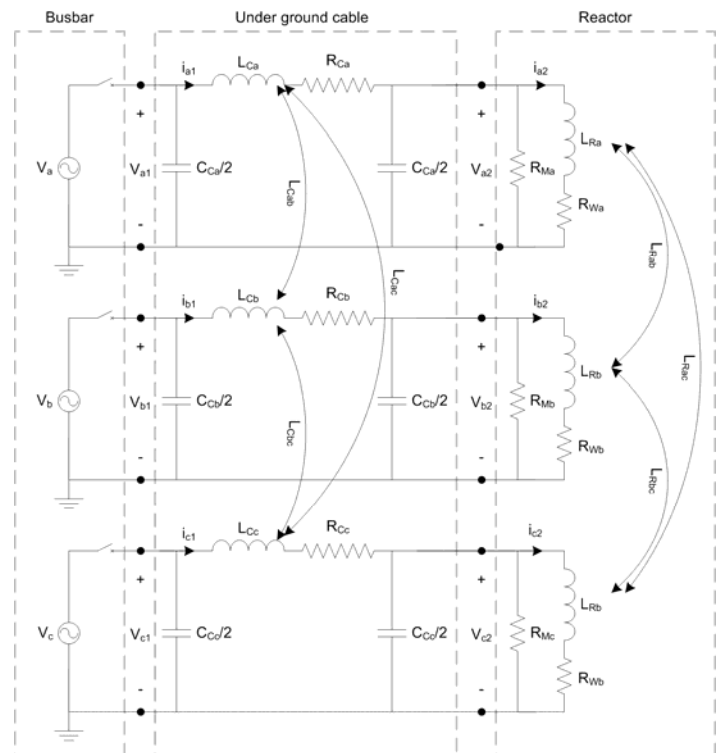

Fig. 5 Circuit diagram of the system using PI model

Comparison of the two waveforms reveals that the system with a frequency dependent mode model oscillates with frequencies around 51,8 Hz which is slightly higher than the 50,4 Hz which the system with PI mode oscillates at. This could be caused by some slight difference between the capacitance taken from the data sheet for the cable and the capacitance PSCAD calculates from the cable dimensions and the insulation permittivity. This slight difference is not expected to give any great differences in the resonance behavior of the system except slight change in the frequencies.
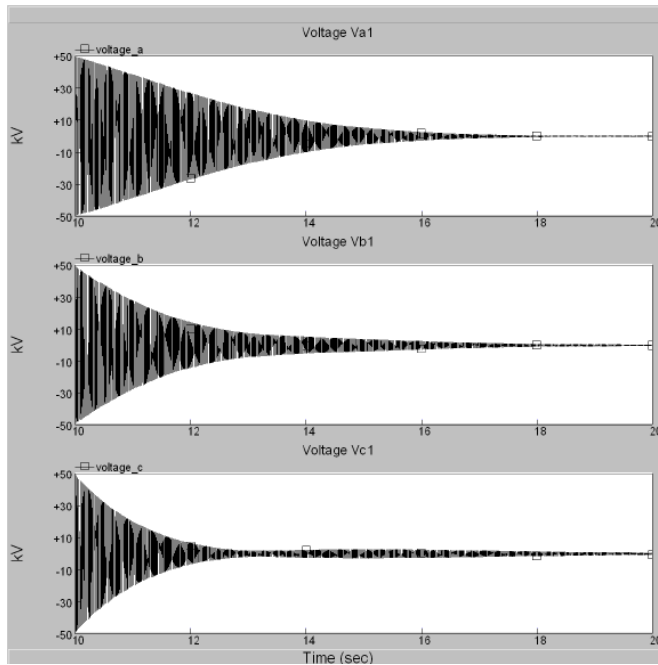
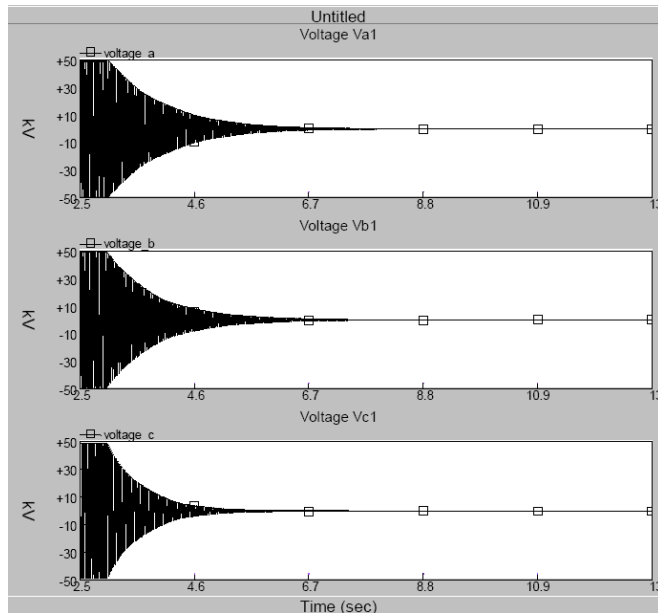**Fig. 6 Simulated voltage waveforms using PI model**

Fig. 7 Simulated voltage waveforms using frequency dependent mode model

The attenuation of the system is much more with the frequency dependent traveling wave model than with the simple model. The most likely reason is the difference in the two models in representing the cable resistance. In the PI model all the resistance in the line, R_{cable}, is concentrated in the middle of the line where approximately half of the current, I_{osc}, which is oscillating between the cable capacitance and the reactor flows. The losses in the

PI model, P_{pi}, can then be expressed as:

$$P_{pi} \approx R_{cable} \cdot \left(\frac{I_{osc}}{2} \right)^2 = \frac{R_{cable} \cdot I_{osc}^2}{4} \qquad (1)$$

In the traveling wave model half of the cable resistance is added in each end of the line [5]. In that case all the current will flow in half of the cable resistance and the losses, P_{freq}, can be expressed as:

$$P_{freq} \approx I_{osc}^2 \cdot \frac{R_{cable}}{2} = \frac{R_{cable} \cdot I_{osc}^2}{2} \qquad (2)$$

The losses in the frequency dependent model are therefore twice as large as in the PI model. Other possible cause for more losses in the frequency dependent model is that is takes into consideration the increase of losses due to proximity effect [5]. This increase in the losses is though expected to be minimal.

4 Simulation

Disconnection of the system was simulated in PSCAD and the resulting voltage waveform can be seen in Fig 8. Here no overvoltages occur and the system can therefore be expected to give no overvoltages if the reactor parameters are the same as expected.
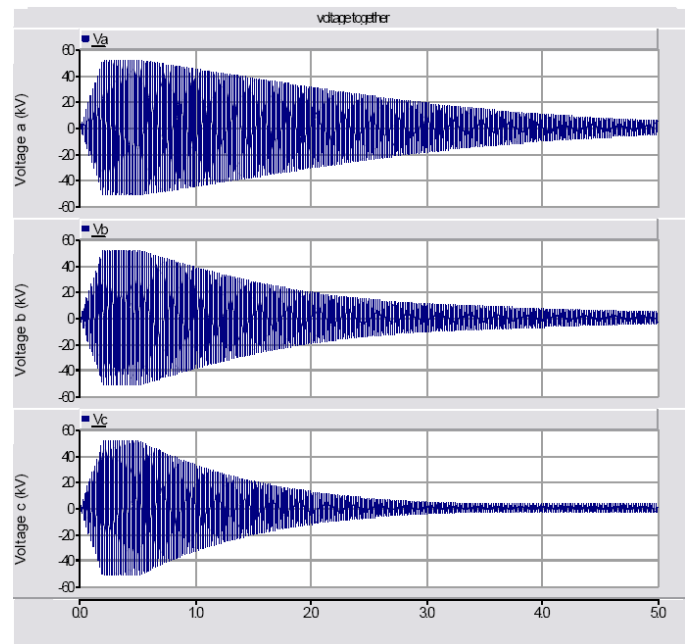

Fig. 8 Simulated voltage waveforms with expected parameter values

To gain understanding on which parameters can possibly cause overvoltages different parameters of

the system were varied. The different variable parameters are the length of the cable, the mutual inductance in the reactor and the variation of the reactor self inductance corresponding to different value of the reactor compensation. Only one of these parameters were varied at the time and the other remain fixed.

A. Variation of cable length

The length of the cable was varied during the simulation the variation of the length was from 5 to 40 km. By varying the length of the cable simulates the situation where a reactor is connected to other substations with different distant between them than Hedebo and Ålbæk. By increasing the length of the cable the total capacitance of the system increased and the influence of changes of the capacitance was studied. During these simulations no overvoltages were observed and it is therefore concluded that different cable lengths will not cause overvoltages during switching. Fig 9 shows the different phase to ground voltage with the cable length of 40Km.
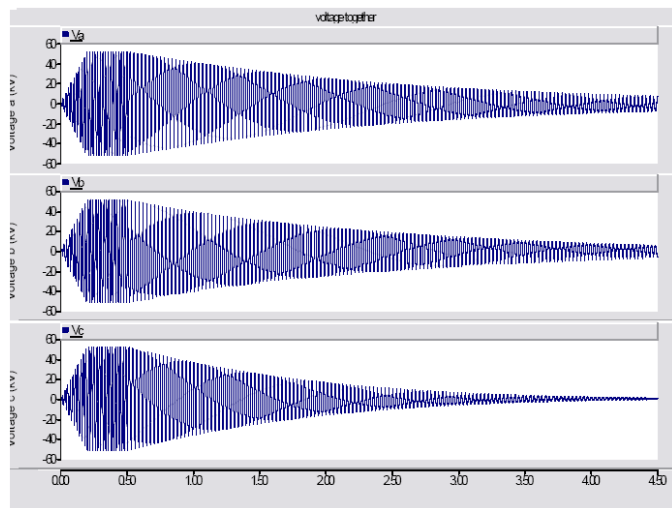

Fig. 9 Simulated voltage waveforms with 40 km cable length

B. Variation of reactor self inductance

In this simulation the self inductance of the reactor was varied. This corresponds to the case when the compensation is changed. The different values chosen to be simulated were from half times

the self inductance value to 30 times the value. During these simulations no overvoltages were observed but in the case where the inductance was reduced to half modulation started to appear in the voltage waveform as shown in Fig 10. As no overvoltages appeared it was concluded that the self inductance does not cause overvoltages in the system.
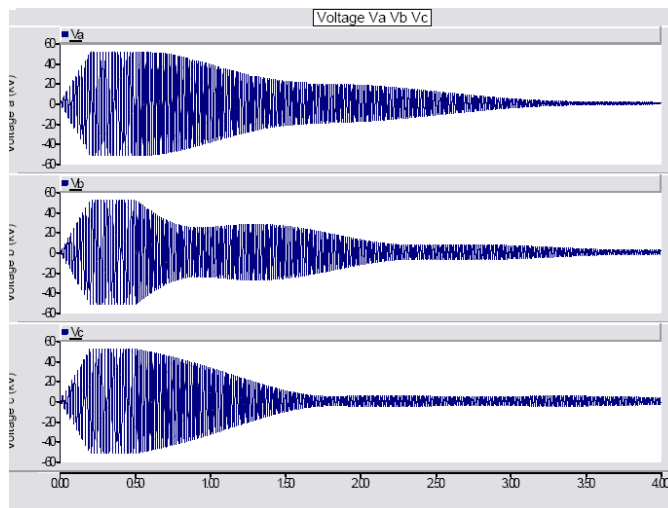

Fig. 10 Simulated voltage waveforms with half self inductance values

C. Variation of reactor mutual inductance

The mutual inductance in the reactor is varied during this simulation. The mutual inductance will be different depending on the dimensions of the reactor core. The mutual inductance was increased from 5 and up to 100 times its original value. One final simulation was then made where all the mutual inductance values were equal to the highest 100 times value that is -0,935 H.

In this simulation overvoltages appeared and table 2 shows overvoltages corresponding to different values for the mutual inductance.

Table 2 Overvoltages corresponding to different mutual inductances

Multiple of mutual inductance	Percentage of overvoltages

x4	14 %
x5	27 %
x10	29 %
x50	39 %
x100	45 %
x100(Equal between phases)	14 %

Fig. 12 Simulated voltage waveforms with mutual inductances equal to highest 100 times value

The phase to ground voltage obtained from simulation of two cases are shown in Figs 11 and 12 respectively. In the first case the mutual couplings are 100 times larger than expected. There considerable overvoltages occur and the voltage has modulated waveform. The other case is where all the mutual inductance values were equal to the highest 100 times value.

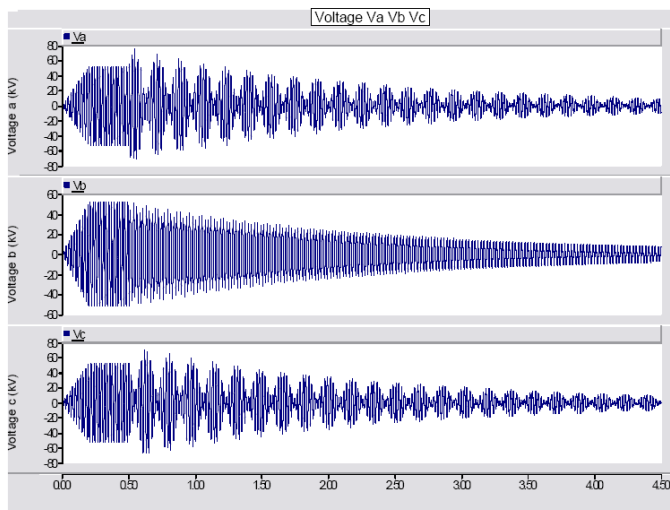During that case less overvoltage occurs and the waveforms of the voltages are not modulated.

Fig. 11 Simulated voltage waveforms with mutual inductances 100 times larger than expected
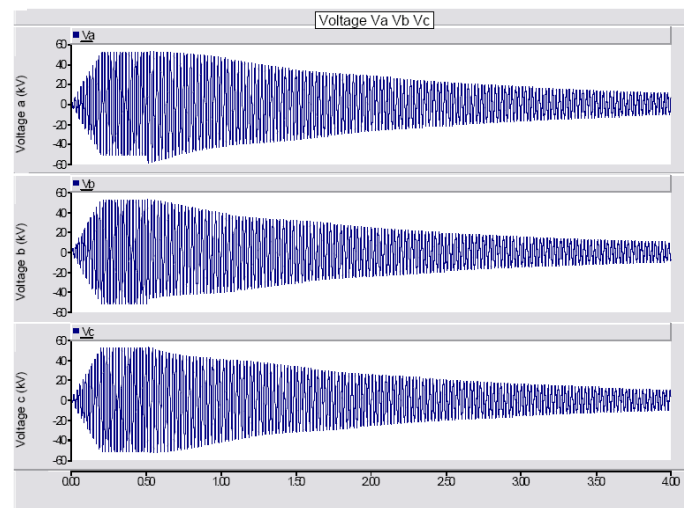
5 Origin of overvoltages

In search for the reasons of the overvoltages the impedances in the reactors are inspected. One phase of the system where the series impedances of the line and losses in the reactor are ignored can be considered as the cable capacitance connected to the reactor inductances. The voltage across the reactor can be divided into three parts; the voltages caused by the self inductance, L_a, and the two mutual inductances L_{ab} and L_{ac} as depicted in Fig 13.

This voltage before the system is disconnected can be written on vector form as three vectors with $\pm 120°$ phase shift (V_a, V_{ab}, V_{ac}) which rotate with 50Hz as depicted in Fig 14. The mutual couplings in the reactor will have negative values and therefore the vectors for the mutual couplings are shifted 180°.
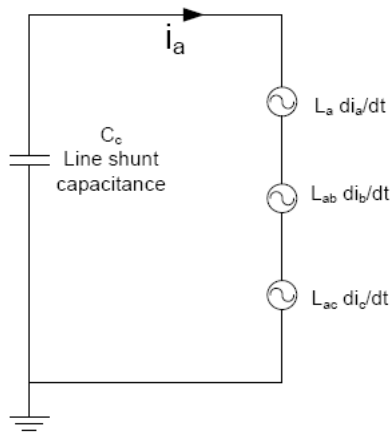
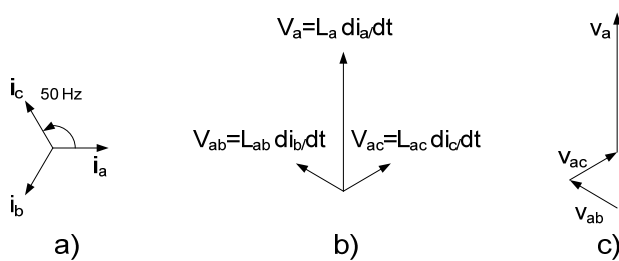**Fig. 13 Simplified circuit model of phase a**

Fig. 14 Currents and corresponding voltages across phase a of the reactor before disconnection

For the situation after the system is disconnected lets first consider a case where all the self inductances are equal and all the mutual inductances are equal as well as the cable capacitances. The disconnection is considered to occur at all phases at the same time. When the system is disconnected the voltage will be on the same form as before, all the three phases will have the same resonance frequency and therefore all the phase vectors depicted in Fig 14 will continue to rotate together but at the resonance frequency instead of 50Hz. Under these circumstances only one frequency will be on the phase and no overvoltage will occur. This is simulated case in Fig 12. For that case all the phases are not disconnected together at same instant and that causes some overvoltage to occur. This will be explained further later. If the system is not completely balanced, that is capacitance, self and mutual inductances are not equal between all phases, and the situation will be different. At very moment when the system is disconnected the voltage will consist of three

voltage vectors with ±120° phase shift, But after the system has been disconnected the three phases will have slightly different resonance frequencies and therefore the voltage sources depicted in Fig 13 will have different frequencies. This will cause the phase shift between the three voltages to change and the voltage waveform will become modulated.

The worst case scenario occurs if all the voltage align depicted in Fig 15. That will cause the voltages to exceed the nominal voltage values.
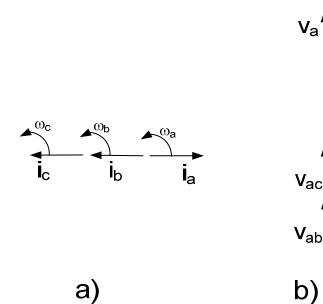

Fig. 15 Currents and voltages across phase a of the reactor where the three voltages have aligned

This difference in rotation speed of the different voltages is also the reason why there occurs a small overvoltage when the system is balanced but not all the phases are disconnected together. During the time between when the first and the last phase gets disconnected the disconnected phases will have the resonance frequency while the still connected phases will have 50Hz. This will cause the rotating vectors to rotate with different speed and in some of the phases the resulting voltage vector will become larger as the vectors align a little while in other it will become smaller. Then when all the phases have been disconnected all phase vectors will rotate with the resonance frequency and therefore no modulation will appear in the voltage.

This explanation for the overvoltages is simplified as only one phase was looked at and the amplitude of current in the other phases assumed constant while in 3 phase system modulation will appear in all the amplitude of all the three phases.

To verify that this is the cause of overvoltages the system was simulated during new cases where overvoltages are expected. First the system was

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simulated where the mutual inductances are large but the same between all the phases and the self inductance is different between phases. This is to show that unbalance caused by other parameters than the self inductance will cause overvoltages if the mutual inductances are sufficiently large to transfer the different frequencies between the phases. Fig 16 shows the voltage waveform were the mutual inductance is multiplied with 100 and made equal for all phases while the self inductance of one phase is reduced by 3,5% and increased with 3,5% on an other phase. Here overvoltage occurs and modulation appears in the waveform as expected.

The other simulation was to apply unbalanced mutual capacitors between the phases where all other parameters are kept balanced. This is a case of mind but not a realistic case as in a cable grid the mutual capacitances does not exist. This is done to estimate if mutual capacitance can also cause overvoltages in similar manner as the mutual inductance.
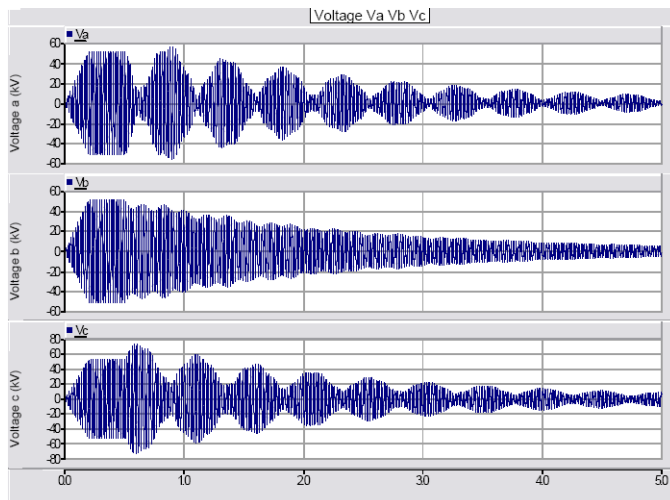

Fig. 16 Simulated voltage waveforms with strong balanced mutual inductance but unbalanced self inductance

This is interesting as that will give an idea whether the reactor, even though it is balanced and with low mutual couplings, can be connected to a system including overhead lines where the phase to phase capacitance of the overhead line is not balanced. The resulting voltages are depicted in Fig 17.
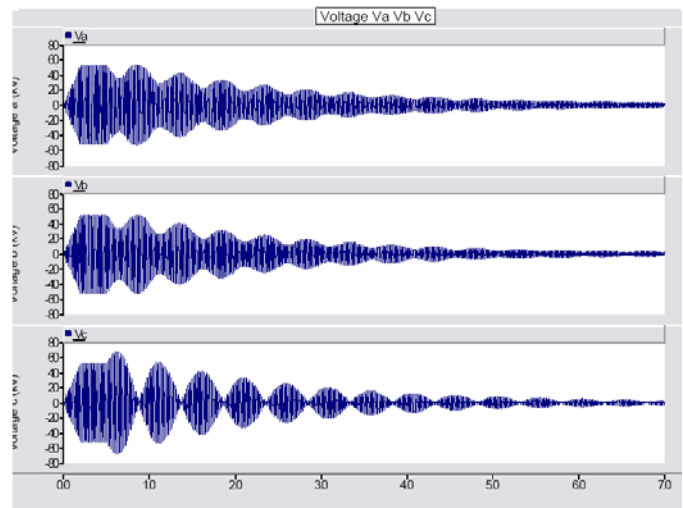

Fig. 17 Simulated voltage waveforms with unbalanced line to line capacitances

In this case the voltage waveforms become modulated and overvoltages appear. This indicates that even though the reactor compensating a system including an overhead line has low mutual coupling and is symmetrical then unbalance in the overhead line along with the capacitance between the phases can result in resonant switching overvoltage.

6 Conclusion

The result of the simulations show that in all circumstances there is no significant overvoltage during switching except when the mutual coupling of the system are significantly large and the system is unbalanced. It was also found out that with the expected reactor parameter values no harmful overvoltage will occur during switching. Assuming 63 kV operating voltage the mutual inductances of the reactor may be up to four times higher than expected before simulated overvoltages exceed the 72kV voltage level which is the highest continuous operating voltage for 60kV equipment. The conclusion of this study is that resonance overvoltages during last end switching of a line and reactor is caused by strong mutual couplings in between the phases along with different resonance frequencies in the phases caused by unbalance in the grid.

7 Acknowledgement

The authors wish to gratefully acknowledge the valuable cooperation with ENV-net and the Danish TSO Energinet.dk during the study behind this paper.

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