SIMULATION OF HARMONIC PROBLEMS IN THE KRISTIANSAND HVDC STATION

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Abstract - Harmonic problems in the Kristiansand HVDC station have been analysed and identified by simulations. The most effective tool has been time domain simulation, i.e. simulation by EMTP, EMTDC and analogue HVDC simulator. For investigation of harmonic behaviour a substantial part of the ac system was modelled. The investigated case of core instability was found to involve transformer core saturation in both ends of the HVDC link. The effectiveness of counteracting the core instability by damping the dc side 50 Hz current has been verified in the HVDC simulator. Third harmonic resonance phenomena have also been simulated.

1. INTRODUCTION

Kristiansand is the Norwegian station of the Skagerrak HVDC transmission between Denmark and Norway. Kristiansand is located in an area with major generation of hydro power in southern Norway. The local load is up to around 200 MW, of which 80 percent is industrial load. The capacity of the Skagerrak HVDC transmission is at present 1040 MW. The original rating of the link is 500 MW (two poles). The third pole was commissioned in 1993. Installed filter capacity on the Kristiansand 300 kV bus is 346 Mvar, comprising four filterbanks. Additional 101 Mvar shunt capacitors are installed on the tertiary of a 300/132 kV transformer T1, see Fig. 1. For reactive power control an SVC of –200 Mvar has been in operation since 1995. The 140 MVA synchronous compensator was not in operation at any of the events with harmonic problems, which have been simulated.

The dc side consists of three line poles, pole 1 and pole 2 of the same polarity. Each line pole consists of 28 km overhead lines on the Norwegian side, 130 km submarine cable and 85 km overhead line on the Danish side. On the Danish side pole 1 and pole 2 are connected to the 150 kV system in the Tjele sub-station while pole 3 is connected to the Tjele 400 kV system. The configuration in Tjele is indicated in Fig. 4.

Occasionally significant low order harmonic distortion has been noted in Kristiansand. At some occasions the consequence has been unintended tripping of power lines by zero sequence sensitive earth fault protection. In other cases the system transformer T1 has been tripped by overload protection. It has been hard to find the causes as it has not been possible to recreate the same disturbances at field tests intended to initiate and analyse the oscillations. Simulations using EMTP, EMTDC and an HVDC simulator have been performed in order to analyse the events and to understand the mechanism behind and the conditions for the disturbances.

One event that has been investigated is how switching in of a shunt reactor in Denmark could cause trip of the 300 kV line feeding the Norwegian Kristiansand HVDC converter station via the line earth fault protection. EMTP and simulator investigation show that it is due to a core saturation phenomenon including interaction between the transformers in both ends of the HVDC link. Although the resonance frequency of the dc side, due to the long cable, is well below the fundamental, interaction between the dc side, transformer saturation on both sides and the impedance of the network on both sides, gave a somewhat negative damping of 50 Hz dc side oscillation. The triggering of the line fault protection was caused by the zero sequence fundamental current component due to the asymmetrical transformer saturation.

The phenomenon has also been replicated in an HVDC simulator, although the ac networks had to be simulated by somewhat extreme impedances. An additional damping function in the HVDC control has been proven to effectively introduce a positive damping for this core instability phenomenon.

One difficulty with this type of simulation is that it requires very long computing time. A large system has to be simulated in detail as the phenomenon involves interaction between harmonics both from the HVDC converters and from transformer saturation. Also, saturation of the transformers is built up slowly requiring long simulation time, several seconds. Furthermore, the number of parameters, which can be varied, is large and the ac network harmonic impedance is not very well known. In addition, transient
disturbance recordings from early events only show some hundreds of milliseconds, which for these phenomena are like snap shots, which do not show the dynamics. Therefore, a technique with a combination of analytic analysis and simulation has been used rather than scanning for critical cases.

2. HARMONIC INTERACTIONS

An important point regarding harmonic behaviour of an HVDC system is the interaction between the ac and the dc side of a converter. The main characteristic for this interaction is that the converter transforms a frequency on one side to other frequencies on the other side due to the commutation process. Also transformer cores have harmonic interaction, especially that a dc voltage may result in large harmonic current due to core saturation. Also other components in the system have other harmonic properties than might be expected in a first glance.

2.1 HVDC Converters

The interaction between the ac and the dc side has been quite well analysed in the literature [1][2][3]. The principle for the frequency conversion between the dc and ac side is found in Table I. It must be noted that the conversion is different for positive sequence harmonics and negative sequence harmonic on the ac side. The zero sequence harmonics are not interacting at all.

<table>
<thead>
<tr>
<th>DC Side</th>
<th>AC Side Harmonic Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, DC</td>
<td>1, Fundamental</td>
</tr>
</tbody>
</table>
| 1, Fundamental | 2, 0, DC ]
| 2       | 3                      |
| n<sub>DC</sub> | n<sub>AC</sub> = n<sub>DC</sub> + 1 |
|         | n<sub>AC</sub> = n<sub>DC</sub> - 1 |

1) The dc current is in phase-to-phase mode, but is neither negative nor positive sequence current.

In principle current harmonics on the dc side are transformed to harmonic currents on the ac side with the frequencies given by Table I. Besides there are smaller sideband harmonics of n<sub>AC</sub> ± m·p where m = 1, 2, ... and p is the pulse order of the converter, normally 12 for HVDC. The ac side harmonic voltages are transformed to dc side voltage in accordance with Table I, plus side band. Negative sequence and positive sequence voltages are transformed individually, independent of each other. Besides, the ac side harmonic voltages modulate the commutation overlap thereby directly causing ac current harmonics of the related orders, regardless of the dc side harmonic currents.

When discussing converter harmonic interaction it must be remembered that the interaction occurs both in the rectifier and the inverter at the same time. Thus, the ac networks interact with each other via the converters and dc line/cable. This interaction is influenced by the dynamics of the dc line/cable. Besides, for low order harmonics, the converter control will interact and contribute to the converter harmonic response. Furthermore, both the converter characteristics and the converter control are non-linear.

2.2 Transformer Cores

Fundamental current harmonic on the dc side is transformed to dc current on the ac side, thereby causing transformer saturation. As the dc current is injected phase-to-phase without earth mode current, the transformers will be saturated unsymmetrically resulting in different generation of harmonic currents in the different phases. As a consequence of transformer saturation, the network will be loaded by saturation current, which will have both a fundamental content and a content of all harmonic orders. The mix of harmonics is depending upon the saturation level. An important factor is that the saturation current also is a mix of positive sequence, negative sequence, and zero sequence current. Especially it must be noted that the resulting zero sequence fundamental current can be significant.

2.3 Capacitors Behind Transformers

A capacitor behind a transformer may not be seen as a capacitor from the converter ac bus. The principle is demonstrated in Fig. 2, which shows the simplified configuration and the impedance/frequency plot. The capacitor C is located behind the transformer T. L represents an inductive load on the secondary side of the transformer. The losses are represented by resistors in the figure. In the frequency plot, at increased frequency, there is at first a parallel resonance between L and C at frequency f<sub>1</sub>. At frequency f<sub>2</sub> there is a series resonance between T and C in parallel with L. It is noteworthy that a capacitor behind a transformer is seen as a capacitance from the system only at frequencies f<sub>1</sub> < f < f<sub>2</sub>. Especially for frequencies just above f<sub>1</sub> the impedance is inductive and low. Thus, capacitors behind a transformer can not be treated in the same way as shunt capacitor banks on the main bus, when estimating the system resonance frequency.

Typical examples of capacitors behind transformers are SVC:s and shunt capacitor banks and filter banks on tertiary windings. In the case that there is no parallel inductive load, the curve in Fig. 2 starts at -j<sub>∞</sub> at f=0. The total impedance is thus capacitive for f<sub>1</sub> < f < f<sub>2</sub>. It must also be remembered that a Δ-winding means that the zero sequence impedance of a transformer must be treated separately.

![Fig. 2. Capacitor Behind Transformer.](image-url)
2.4 AC System Impedance
For many applications it is sufficient to represent an ac system with a voltage behind the short circuit impedance, with impedance phase angles. However, such a representation is generally not adequate for harmonic analyses as the shunt capacitance of the lines becomes more pronounced at higher frequencies. Therefore, the shunt element must be represented. Long high voltage ac lines generate a significant amount of reactive power which to some extent is balanced by shunt reactors. Even if the shunt elements cancel each other at the fundamental frequency, they do not at harmonic frequencies, and must both be represented in a harmonic analysis. This is still more pronounced for long high voltage cables.

Besides, even if the lines are transposed and reasonably symmetrical at the fundamental frequency, they are not symmetrical at harmonic frequencies. Therefore, ac lines will transform positive sequence harmonics to negative and zero sequence harmonics. Furthermore, the ac network impedance is often not static but dynamic. The impedance varies with load changes, connected generating units, circuit configuration, etc. Consequently, it is a difficult task to correctly represent an ac network in a harmonic analysis.

3. TOOLS FOR HARMONIC ANALYSIS

The available tools for analysis are: Time domain simulation, frequency domain simulation, analytic analysis, and measurements. With the large number of non-linear circuits and harmonic transformations identified in section 2 above none of the tools available for analysis is perfect.

3.1 Time Domain Simulation
Time domain analysis is in principle suitable for the complete system with converters and other non-linearities. However, it requires a very detailed representation of all equipment and subsystems, especially converters and SVC:s. This ends up with a large system to simulate, and with the small time steps needed for simulation of converters and FACT:s, the simulations tend to be very time consuming, even in the most powerful computers currently available. Furthermore, time domain simulations can only be performed for one case at a time. Especially when looking for resonance problems the total circuit must be tuned, considering the interaction between positive, negative and zero sequence response. Besides, it may take quite long time to build up resonance harmonics, especially if transformer saturation is involved. Therefore, it is hardly practical to cover all situations by just varying the input parameters over their full range. Instead, in order to have any chance to repeat and analyse a strange behaviour in the system, it is necessary to know what to look for and concentrate on a critical range of input parameters.

3.2 Analytic and Frequency Domain Analyses
Analytic solutions are needed for obtaining understanding of different phenomena involved. However, an analytic analysis requires that the analysed system is rather simplified. Even frequency domain solutions require simplifications, that is, linearisation of non-linear functions and a very simplified converter representation. Thus, the limitation with both analytic and frequency domain analyses, is that they do not show the complete interaction of different phenomena. However, without analytic and frequency domain analyses it is very difficult to understand the mechanism and to understand the overall behaviour.

3.3 Measurements
A further and very important tool for analysis is measurements in the plant. There are some important aspects regarding measurement in the plant. As the problems tend to occur spontaneously, the triggering logic is important. The optimal solution is to get recordings even at tendencies to problem, but still with a reasonable number of recordings, so the measurement results can be properly analysed. Furthermore, the amount of recorded parameters and memory for pre-trig recordings must be sufficient for a proper analysis of the event and to trace the cause of the disturbance.

3.4 Used Method for Analysis
For analysis of the harmonic problems in Kristiansand a combination of the of the above mentioned tools has been used. The starting point is the recordings from the disturbances. From the beginning, the available recordings were limited. The transient recorders for the converters started only at converter related disturbances, etc. Consequently, the output from the transient recorders just showed the end of the event when the converter and lines eventually tripped. Consequently, if the disturbance did not affect the HVDC converters or major lines, the recorders did not start at all. The recording equipment in the Kristiansand substation has during the later years been completed with measurement of current and voltages in all strategic measuring points, and the recording equipment is also triggered at a significant increase of the harmonic level. The extended transient recording system has been of utmost importance for understanding and controlling the harmonic behaviour of the Kristiansand sub-station.

The overall simulations have been performed with time domain simulation using EMTP, HVDC simulator and EMTDC [4]. Frequency domain simulations have been used for analysing the frequency characteristics of different subsystems in order to define critical configurations for the time domain simulation. The simulations have been supported by principal analytic analysis for verification of the principle behaviour and understanding of the mechanism.

4. MODELLING
Modelling of harmonics in an ac system is a very wide subject [5]. Therefore, it is only possible to briefly describe the modelling concept found relevant and important for analysis of the Kristiansand harmonic problems. The complexity of the modelling has not been the same for all simulations. In some simulations a more simple model has been used and in other simulation the full model has been used.
The equipment and subsystems modelled are:

- HVDC converters with control systems
- Kristiansand SVC
- AC filters and transformers
- DC cables and dc lines
- Connected ac systems.

4.1 HVDC Converters

In the time domain simulation, the converters have been simulated in detail with transformers, valves, control equipment, etc. Especially in EMTDC and the HVDC simulator the used control systems are practically identical with the system used in the real plant. This is also valid considering that the Skagerrak HVDC link is a mix of two generations of HVDC technology. Pole 1 and pole 2 were commissioned 1976-1977 while pole 3 was commissioned 1993. For the frequency domain analysis the transformer impedance has been considered for the zero sequence scheme only.

4.2 SVC in Kristiansand

The Kristiansand SVC has in the time domain simulations been modelled with actual configuration including transformer, thyristor switched capacitor, thyristor controlled reactor and control equipment. The control functions and dynamics have been the same as in the plant. For the frequency domain analysis the transformer impedance has been considered for the zero sequence scheme only.

4.3 Transformers and AC Filters

The transformers connected to the 300 kV system have been modelled considering connection type, transformer reactance, and tap changer position. For the time domain studies, saturation of transformers has been modelled with an external non-linear inductance on the high voltage side of the transformers. The characteristics have been adapted to the transformer saturation characteristics.

The 300 kV filters have been modelled in detail. Shunt capacitor banks connected to the tertiary of the 300/132 kV transformer T1 have been modelled in their actual configuration. Also the ac filters on the Danish side have been modelled in detail.

4.4 DC Line

For the dc line models of the cables and overhead lines have been used in order to get an accurate response for the harmonics under investigation. The dc side smoothing reactors have been represented with linear inductances. The dc filters in Kristiansand and Tjele have been modelled in detail. For the actual investigations only the characteristics related to low order harmonics are of significance. It may be mentioned that the first resonance of the dc side alone is at around 35 Hz.

4.5 AC System

Modelling of the ac system has been the most difficult part. The problem is not to find resonances, but to find the realistic harmonic impedance of the actual system configuration. In simulations intended for verification of a principle mechanism, the ac network has been represented by a voltage behind the network short circuit impedance. When needed, shunt capacitance has been added for tuning to critical resonance. Also network losses have been modelled. Especially, the ac line capacitance was considered as a capacitance in parallel with an inductive impedance for not impacting the fundamental frequency impedance. The representation is indicated in Fig. 3.

For a more complete analysis of harmonic interaction, the southern part of the Norwegian system has been modelled in EMTDC by twenty-one ac busses, twelve 300 kV lines and two 132 kV lines. That includes also series capacitors and transposition of line. Besides, load and generation in the substations have been modelled with equivalents. All equivalents and the complete model have been verified regarding fundamental frequency characteristics.

The Danish ac system has been modelled with a voltage source behind the short circuit impedance.

5. IDENTIFICATION OF CORE INSTABILITY

The main objective of the simulations was the find the cause and the mechanism that actually caused the unintended trip. Otherwise it is not possible to be certain that the real problem, and not a hypothetical one, is countermeasured.

5.1 The Unintended Trips

In August 10, 1993, the Skagerrak HVDC station was connected with the Norwegian grid via the Kristiansand - Arendal 300 kV ac line only, due to maintenance work. At that time only Pole 1 and Pole 2 were in operation in bipolar operation mode. In conjunction with switching-in of a 400 kV shunt reactor in the Danish station Tjele, the Kristiansand-Arendal line was tripped by the earth fault protection, sensitive for zero sequence current. As the last ac line tripped, the HVDC converters also tripped, which initiated a start of the transient recorders. Besides the quite distorted ac voltages, the recordings showed about 35 A 50 Hz current superimposed on the dc current. Some hours later the same day an identical trip of the ac line occurred, but without relation to any known ac system event. With this background the event was simulated in EMTP. Each mechanism was to some extent isolated in order to get a better understanding.

5.2 Comparison with Protection Trip Criteria

One principal question was: Could 35 A 50 Hz current on the dc side of the converter cause zero sequence current on the ac side, sufficient for tripping the line protection? Simulation showed that this was the case. The simulated configuration is shown in Fig. 3. A 35 A 50 Hz current was superimposed on a constant dc current. The short circuit power at Kristiansand 300 kV bus was simulated to be 2940 MVA, which corresponds to the situation at the trip event. The impact of the line capacitance was simulated by a shunt capacitance in parallel with an inductive impedance so there was no impact on the 50 Hz short circuit power level. A shunt capacitance of about 400 MVAR gave resonance at the
second harmonic. This capacitance corresponds to the shunt capacitance of about 1200 km of 300 kV ac lines. Saturation of the converter transformers was modelled with their saturation characteristics.

![AC System Equivalent](Fig. 3. Injection of 50 Hz Current.)

When the simulation stopped after 1.1 s of 50 Hz current injection, the magnetising current of the converter transformer was in the order of 900 A, peak value, and still increasing. The unsymmetrical transformer saturation caused a zero sequence current in the ac system, i.e. the Kristiansand-Arendal line, which is higher than the protection trip level, see Table II. Thus, it was verified that the dc side 35 A 50 Hz current was sufficient for causing the trip of the ac line via transformer saturation. It was also concluded that the trip was due to fundamental frequency current rather than harmonic current. After the event, the setting of the protection has been increased.

**TABLE II. AC Line Zero Sequence Current.**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>50 Hz</th>
<th>100 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>I₀ in the simulation</td>
<td>46 A</td>
<td>58 A</td>
</tr>
<tr>
<td>Protection trip level</td>
<td>25 A</td>
<td>73 A</td>
</tr>
</tbody>
</table>

5.3 Connection of Shunt Reactor

Another sub-task was to verify that connection of a 400 kV shunt reactor in Tjele could cause significant 50 Hz current on the dc side of the Kristiansand converters. The model used for the simulation is shown in Fig. 4. The configuration corresponds to the actual situation at the trip event. The 400/170 kV transformer in Tjele was modelled as an ideal transformer. The switching-in instant of the shunt reactor was selected for obtaining a full dc offset in one phase. In the simulation the dc offset was damped out with a time constant of 3 a 4 seconds. (The shunt reactor switching was performed during commissioning of the breaker synchronising unit.)

In the simulation, the dc offset of the 400 kV reactor caused saturation of the converter transformer connected to the 170 kV system. The saturation caused a spectrum of harmonics, of which the positive sequence second harmonic current resulted in a positive sequence second harmonic voltage. Positive sequence 2nd harmonic voltage on the ac side is transformed to 50 Hz voltage on the dc side resulting in 50 Hz current. After 5.5 seconds, when the simulation stopped, the magnetising current in the Tjele converter transformers was 700 A, peak value. The magnetising current in the Kristiansand converter transformers was about 18 A peak value and increasing with a rate of 10 - 15 A per second. The 50 Hz current superimposed on the Kristiansand dc current was about 7 A.

Even if the 50 Hz current superimposed on the Kristiansand dc current was only 20 % of the value recorded in the trip, it was concluded that the simulation verified that shunt reactor switching in Tjele can cause significant transformer saturation in Kristiansand. However, the final amplitude may be depending on the network conditions. Also other simulations verified that saturation of transformers in one station could be transferred to transformer saturation in the other station. It also was considered that a significantly longer simulation time was needed for reaching the final state.

One observation is that as transformer saturation in both end of the HVDC link is interacting, the deviation between the frequencies in the two systems may have some impact. Especially as the time for build-up seems to be quite long. This aspect was not analysed any further, and generally the frequency deviation is low.

5.4 Theoretical Analyses

A theoretical analysis showed that the rectifier ac network impedance approximately can be transformed to a 50 Hz dc side impedance in accordance with Equation (1) - (3).

\[ Z_{1R} = \frac{9}{\pi^2} \left( R_R^\prime + R_{1R}^\prime + jX_{1R}^\prime \right) \]  
\[ R_{1R} = 2Z_{2R} \cos(\alpha + \frac{\pi}{2}) \cos(\alpha + \frac{\pi}{2} + \Phi_2) \]  
\[ X_{1R} = 2Z_{2R} \cos(\alpha + \frac{\pi}{2}) \sin(\alpha + \frac{\pi}{2} + \Phi_2) \]

Where:
- \( Z_{1R} \) is the rectifier ac network impedance seen at 50 Hz from the dc side
- \( Z_{2R} \) is the rectifier ac side second harmonic impedance, transformed to the valve side of the converter transformers
- \( R_R^\prime \) is the rectifier ac side dc resistance, transformed to the valve side of the converter transformers
- \( \Phi_2 \) is the phase angle of the rectifier ac side second harmonic impedance
• $\alpha$ is the converter delay angle
• $u$ is the overlap angle.

For the inverter the impedance is given by the corresponding Equations (4) - (6).

$$Z_{\text{inv}} = \frac{9}{\pi} \left( R'_{\text{inv}} + R''_{\text{inv}} + jX'_{\text{inv}} \right)$$  \hspace{0.5cm} (4)

$$R'_{\text{inv}} = 2Z'_{\text{dc}} \cos(\gamma + \frac{u}{2}) \cos(\gamma + \frac{\Phi}{2})$$  \hspace{0.5cm} (5)

$$X'_{\text{inv}} = 2Z'_{\text{dc}} \cos(\gamma + \frac{u}{2}) \sin(\gamma + \frac{\Phi}{2})$$  \hspace{0.5cm} (6)

Where:
• $Z_{\text{inv}}$ is the inverter ac network impedance seen at 50 Hz from the dc side, etc.
• $\gamma$ is the inverter commutation margin angle.

In the Skagerrak transmission both $\alpha + u/2$ and $\gamma + u/2$ are around 25 degrees. This means that when the phase angle of the rectifier ac network second harmonic impedance is above 65 degrees it contributes with a negative damping. So does the inverter ac network when the phase angle of the ac side second harmonic impedance is below -65 degrees, which normally is not the case. Consequently, the most critical situation regarding negative damping of the dc side 50 Hz oscillations is when the second harmonic impedance of the rectifier ac network is high and with a quite high impedance phase angle, and the second harmonic impedance of the inverter ac network is low. This means a situation when the rectifier network is rather weak with a resonance somewhat above the second harmonic and the inverter network is strong.

The critical situation corresponds well to the situation at the trip event, see Fig. 4. The resonance frequency for Kristiansand ac network, without considering the ac line capacitance is 145 Hz. The ac line capacitance will reduce the resonance frequency somewhat. The inverter ac network is quite strong with a short circuit power twice that of the rectifier system. Thus, it can be expected that the damping of 50 Hz oscillations was low at the trip event. It also must be remembered that even if the 50 Hz impedance damping is not negative, the additional driving 50 Hz voltage caused by the non-linear loop (DC side 50 Hz current $\Rightarrow$ Transformer saturation $\Rightarrow$ Second harmonic positive sequence current into the ac network $\Rightarrow$ AC side positive sequence second harmonic voltage $\Rightarrow$ DC side 50 Hz voltage) can cause instability. That is the phenomenon recognised as core instability. The complete interaction is shown in Fig. 5.

More about theoretical analyses can be found in the literature [1][6][7][8]. The article [8] by Burton et al. treats the transformation of impedances from the ac side to the dc side and states criteria for instability. However, the impact of transformer saturation in both stations is not considered.

5.5 Active Damping Verification in HVDC Simulator

Normally the converter control provides significant damping for the fundamental current [9]. However, the built-in damping for the fundamental currents seems not to be sufficient to prevent core instability in all situations in the Kristiansand HVDC station. In order to specifically counteract the core instability, a special 50 Hz damping control circuit was developed. The damping control is sensitive for dc side fundamental current and is fully activated if the 50 Hz current exceeds a pre-set limit. A similar function has been used in another scheme [10]. The function of the damping control has been verified in an analogue HVDC simulator, set-up for Skagerrak Pole 3. The configuration used is shown in Fig. 6.
base. With the damping control activated no core saturation occurred.

At increased ac voltage it took 80 - 85 seconds until the 50 Hz dc current started to grow to a significant value. However, the time to reach the final value from the start of the noticeable growth was only a few seconds. The damping controller prevented core instability even when the voltage was significantly higher than the voltage needed for core instability with the damping control inactivated.

At an ac system fault the core instability situation was reached immediately. Fig. 7 shows the dc voltage and dc current at a 70 ms three phase fault applied in Kristiansand. The damping control is deactivated and consequently at fault clearing the dc current is superimposed with a 50 Hz current. The amplitude is considered to be limited by nonlinearities in the converters and converter control. The time scaling is in seconds and the amplitude scaling is in p.u. of the nominal value. With the damping control the core instability is eliminated, see Fig. 8. The superimposed 50 Hz current is damped out. At the fault clearing, the transformers become somewhat saturated. Therefore, disturbance in dc current can be seen until the saturation ceases. However, there is no build up and no subsequent core instability.

6. THIRD HARMONIC RESONANCE

One of the problems to identify harmonic problems in the Kristiansand HVDC station is that there seems to be more than one mechanism for the harmonic resonance phenomena. Based on recording from another trip event simulation has been performed for simulation of a third harmonic problem too.

6.1 The Trip Events

From September 1995 up to July 1996 the transformer T1 feeding the 132 kV system in Kristiansand was tripped without any identified fault or fundamental current overloading. As the trips did not affect the HVDC link, the HVDC transient fault recorders did not start. Only in one case a transient recorder for the Kristiansand 300 kV system started. In that case about 120 A third harmonic zero sequence current could be found in 300 kV side of the transformer T1. As also the overcurrent protection of the capacitor banks connected to the tertiary winding of transformer T1 had started, it is likely that the third harmonic positive/negative sequence current was significant too. Recording of 300 kV voltages and line currents showed a significant higher third harmonic distortion in phase T than in the other phases. The transformer was tripped by the transformer overcurrent protection in phase T.

In none of the other cases the capacitor banks on T1 tertiary winding were connected. Another trip was also caused by the transformer T1 overcurrent protection in the same phase. The cause for the third trip is not known. All three trips occurred during evening hours when the load was rapidly reduced and consequently the number of hydro generators in operation was reduced with a fairly high rate.

6.2 Third Harmonic Simulation

For simulation and analysis of the expected third harmonic resonance problem a substantial part of the ac network in the vicinity of Kristiansand was modelled in EMTDC. The configuration is shown in Fig. 9. Besides the complete HVDC system with the three separate poles with complete control and the Kristiansand SVC were modelled in detail.
The Danish station Tjøle was modelled in a manner similar to the Kristiansand station with the ac network represented by an equivalent circuit. Due to the size of the modelled system and the time needed for resonance build up, each simulation shot took a fairly long time. With a 433 MHz DEC Alpha workstation the initiation up to steady state took about one hour and 1 s simulated time took 5-10 minutes.

For each sub-system the obtained impedance/frequency plot was compared with the expected values, based upon input parameter was capacitance behind transformer impedance. Thus a large number of configurations were scanned. The likelihood that one of these configurations gave resonance very close to 150 Hz was considered to be quite high. Due to the long computer calculation time it was not practically possible to scan a large number of configurations, especially as the impact of the capacitance of the connected system was rather uncertain.

With the modelled configuration the resonance frequencies were always well above 150 Hz. The reason seems to be the capacitance of the surrounding ac network. Another critical parameter was capacitance behind transformer impedance, see clause 2.3 above. However, the resonance frequency in the simulations was found to be in accordance with the impedance of the subsystems modelled.

During all the three events the load was rapidly changing and so was the impedance. Thus a large number of configurations were scanned. The likelihood that one of these configurations gave resonance very close to 150 Hz was considered to be quite high. Due to the long computer calculation time it was not practically possible to scan a large number of configurations, especially as the impact of the capacitance of the connected system was rather uncertain.

It was also found that the resonance peak for the zero sequence system in Kristiansand was quite high and sharp. An injected current of 1 A caused a total current of 33 A in the four 300 kV bus filters together. For the positive sequence system the corresponding gain was 25. The gain for transformer current in the simulation was significantly lower. With the modelled configuration the resonance frequencies were always well above 150 Hz. The reason seems to be the capacitance of the surrounding ac network. Another critical parameter was capacitance behind transformer impedance, see clause 2.3 above. However, the resonance frequency in the simulations was found to be in accordance with the impedance of the subsystems modelled.

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6.4 Countermeasures
The reason for the third harmonic problem was found to be network tuning to third harmonic, combined with low damping, especially in the zero sequence system. It was considered practically impossible to avoid network tuning to the third harmonic, a more general approach was applied. At start of a protection related to high harmonic current, a filter bank is temporarily tripped by the reactive power control system. The temporary trip of the filter will detune the system resonance during a time considered necessary for the system to be detuned.

Possible additional specific damping measures, if needed, are under consideration. The evaluation also includes consideration of possible interaction with the new HVDC converter stations under planning in the same area.

6.5 Conclusive Results
The conclusive results are:
• There is no evidence that the third harmonic resonance problem is related to core instability.
• All HVDC converters and FACTS devices contribute to the positive sequence third harmonic due to network asymmetry.
• Detuning of the system by temporary filter trip is a general countermeasure.
• No equipment failures that can explain the third harmonic problems have been identified.

7. CONCLUSIONS
Recordings from a disturbance are of utmost importance for being able to replicate the event and to understand the mechanism so that proper countermeasures can be taken for avoiding recurrence of the disturbance.

Time domain simulation is the only tool covering the complete interaction, including the non-linearities and the transformations in HVDC converters, FACTS, transformer
saturation, and transmission lines. The drawback with time domain simulation is that only one configuration can be analysed in each run.

By adjusting input parameters it is quite easy to obtain any type of instability and resonance phenomena in digital simulations. The problem is to make sure that the studied problem is the real one and not a hypothetical one. When modelling a large system, many input parameters are not well known and it is therefore difficult to configure and set of input parameter for exact replication of the real event. Due to the long simulation time for complex circuits, even with today’s computer capacity, there are practical limitations for the number of input parameter variations that can be simulated.

With recordings from the actual disturbance event as a starting point, it has been possible to identify and verify two different types of harmonic problems in Kristiansand, i.e. core instability and third harmonic resonance. The time domain simulation has been combined with analytic analysis and frequency domain simulation. A common factor is the low damping of the Kristiansand station for low order harmonics, especially in the zero sequence system. Also countermeasures have been analysed.

For analysis of low order harmonic behaviour a significant part of the connected ac system has to be modelled. Even with the substantial size of the model used, the impact of the surrounding ac system may not have been properly modelled for correct resonance frequency. The missing factors seem to be the impact of the capacitance of surrounding ac lines.

The used models have as far as practically possible been verified, and it is confirmed that EMTDC is a reliable tool for the performed harmonic simulation. However, the capacity of presently available computers makes this type of analysis very time consuming.

Regarding core instability, it has been found that core saturation in the transformers in both ends of the HVDC transmission interact, although the saturation only caused problems in Kristiansand. With some extreme parameters, core instability has also been re-simulated in an analogue HVDC simulator using the Skagerrak III set-up. The effectiveness of a damping circuit has been demonstrated.

One interesting aspect is why the problems only occur in Kristiansand but not in Tjele. There seems to be an unknown factor in Kristiansand causing unfavourable conditions resulting in the harmonic problems there in some quite rare situations. Furthermore, since commissioning of the first pole in 1976, the harmonic problems have occasionally occurred only a few times. Besides, the experience is that the studies and investigations, which in accordance with the normal praxis are performed during design and commissioning of an HVDC scheme, normally ensures stable and reliable operation over the complete operation range. The ongoing recording in Kristiansand is expected to fully reveal the secret of unknown factor in Kristiansand.

8. REFERENCES
