Improvement of Commutation Failure Prediction in HVDC Classic Links

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BACHELOR’S THESIS

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Summary

In this thesis, an evaluation of the existing control system for ABB’s HVDC Classic Links is performed in order to investigate whether a possible improvement to commutation failure prediction is possible and to be recommended.

The thesis starts with a theoretical approach to the complexity of consequences of increasing the extinction angle ($\gamma$) in order to prevent commutation failure in inverter operation, which is later confirmed through using the simulation software PSCAD to evaluate coherence between simulation results and theory.

Dynamic power studies are performed through simulations in the electromagnetic time domain transient tool PSCAD in order to establish a possible improvement to the existing commutation failure prediction today used in ABB control systems for HVDC applications.

The thesis shows three possible detection signals to quickly detect increased risk for commutation failure within 1 ms after fault initiation. It addresses issues of network strength and robustness. The detection can be made by utilizing existing control system signals for recording zero-crossing times of the valve voltages, the sum of the AC voltage phases and to detect phase shifts using the error signal of the internal PLL-algorithm.

Several points of interest are presented in the thesis for a successful implementation of an improved predictor algorithm. Simulations show how there are limits to when an angle increase may be effective concerning point-of-wave of the AC voltages as well as point-of-wave in the extinction angle ($\gamma$) transient, where an effective use of an improved predictor is limited to areas between 0-54° and 144-216° on the AC voltage cycle.

The extent to which an extinction angle ($\gamma$) contribution is effective without giving consequences which leads to network collapse is highly related to the strength of the connected AC system and there might be applications in which an increase in ($\gamma$) is not to be advised.
Preface

This thesis represents the end of my education in electric power technology at University West. I want to thank Pablo Rey for accepting my request of writing a Bachelor’s thesis for the system design department; it is with great thanks to the collaboration of ABB AB in Ludvika that I am able to present this work.

My supervisors at ABB AB have been extremely helpful, and many discussions have resulted in taking the thesis work to the final revision. Thanks therefore, to Fredrik W Jansson, and Boris Nordström for helping not only with software issues, and finding particular signals from the control system – but to offer advice and input on results as they came.

I would also like to place thanks to Per Holmberg, at the department of system design, for his willingness to engage in the thesis and to share with me his knowledge of commutation behaviour in HVDC Classic links.

For three years of engaging my interest in electric power and for spurring for future learning, I’d like to thank the engineering department at University West. My supervisor at the University, Fredrik Sikström, Doctor in electro technology, has been very helpful in taking his time to read through the thesis and offer suggestions of improvement. I am grateful that he has shown interest for the field of electric power technology and I very much appreciate his involvement.

As a last note, I would like to give special thanks to, Anna-Karin Christiansson, Doctor in feedback control, for waking my interest for control systems and for stimulating my eagerness for learning more in this field.
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A. Signal Observations
B. HVDC theories and concepts
### Abbreviations and Symbols

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<tr>
<th>Abbreviation/Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current, voltage prefix</td>
<td>kV</td>
</tr>
<tr>
<td>AMAX</td>
<td>The firing angle (α) maximum</td>
<td></td>
</tr>
<tr>
<td>AMIN</td>
<td>The extinction angle (γ) minimum</td>
<td></td>
</tr>
<tr>
<td>CFPREV</td>
<td>Commutation Failure Prevention</td>
<td></td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current, voltage prefix</td>
<td>kV</td>
</tr>
<tr>
<td>dx</td>
<td>Relative inductance direct voltage drop</td>
<td>p.u.</td>
</tr>
<tr>
<td>Erms</td>
<td>RMS value of the AC voltage</td>
<td>kV</td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>I_d</td>
<td>Direct current</td>
<td>kA</td>
</tr>
<tr>
<td>I_o</td>
<td>The ideal direct current</td>
<td>kA</td>
</tr>
<tr>
<td>I_{rectifier}</td>
<td>The rectifier current rush</td>
<td>kA</td>
</tr>
<tr>
<td>I_{cable}</td>
<td>The cable de-energization current</td>
<td>kA</td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
<td>H</td>
</tr>
<tr>
<td>P</td>
<td>Active Power</td>
<td>MW</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
<td></td>
</tr>
</tbody>
</table>
\( Q_{\text{absorption}} \) Reactive power absorption of the converter station MVA

R Resistance \( \Omega \)

S Apparent Power MVA

Scr Short Circuit Ratio

\( U_d \) Direct Voltage kV

X Reactance \( \Omega \)

\( \alpha, \text{Alpha} \) The firing angle \( ^\circ / \text{radians} \)

\( \gamma, \text{Gamma} \) The extinction angle, or voltage-time area \( ^\circ / \text{radians} \)

\( \mu, \text{Overlap} \) The overlap angle \( ^\circ / \text{radians} \)

**Glossary**

**Clarke’s transform**

Also known as the \( \alpha \beta \gamma \) transformation, the Clarke transform is a mathematical transformation method to simplify power analysis by transforming the three-phase currents into two-phase orthogonal stator axis.

**System values**

The system parameters most relevant to the HVDC control analysis. In this thesis these are listed in diagrams in the following order: AC voltage, Wye-currents, Delta-currents, DC current, Power rating, and the commutation angles \( (\alpha), (\mu), \text{ and } (\gamma) \).
1 Introduction

This Bachelor’s thesis is the end of a 180 ECTS program in electrical engineering and even though this thesis is pointed towards a broad audience, it is recommended that the reader of this text is familiar with general power technology theories [1,2] as well as feedback control [3] and HVDC technology [4]. The thesis features an appendix with basic HVDC concepts and theories for the interested, see appendix B.

It is recommended that the thesis be printed in colour to fully appreciate the illustrative diagrams and graphs featured.

1.1 Background

The main part of an HVDC Classic transmission link is the thyristor valve hall and transformers, jointly often referred to as the converter station. A link always got one set of identical converter stations; one for converting the alternating current (AC) system parameters to direct current (DC), called rectifying, and one for inverting the DC parameters back to AC again, called inverting. Hence, the two stations making up a link are generally called the rectifier and the inverter respectively.

When the converter station is energized and fully connected to a feeding AC grid, the operation of the station is performed by controlling the firing of the thyristor valves at correct times through optical fibres. By delaying the firing of the valves, one can consequently determine the rated voltage level [5].

The thyristor module is very sensitive to voltage bias. When a commutation occurs, a second thyristor is fired and forces the first to get a negative bias, and thus get switched off. However, this negative bias has to remain for a certain time period (see Figure 1:1) for the thyristor to successfully extinguish in order to not cause a failure of the transmission.

This time area is called the voltage-time area [6], and is very important, especially in the inverter of the HVDC station where the firing angle (α) is ideally held around 130-140°. Adding an overlap (µ) of 17-20°, the remaining voltage area, expressed as the extinction angle (γ), becomes very limited.
Disturbances in the AC network can cause voltage drops and phase shifts in the voltages [7]. This in turn can cause the voltage-time area to be insufficient, and cause what is called a commutation failure. A commutation failure causes a short circuit of the valve bridge where the power transfer will go down to zero – causing outages in the connected AC network.

Keeping a large voltage-time area can be difficult hence it also means a lower voltage output as well as a higher current, which in turn increases the converter reactive power consumption. The desire to maintain an adequate voltage-time area while still keeping the reactive power supply requirement and voltage ratings down places tough constraints on the control system [8].

When a large phase shift occurs in the grid, there are instances where the present control system fails to detect and successfully prevent commutation failures from occurring. Phase shifts are a problem that has occurred through the vast expansion of HVDC technology, and where several transmission links are connected to the same AC grid, creating a so called multi-infeed HVDC system (see Figure 1:2).
It has been shown that HVDC installations in combination with a weak AC grid have resulted in commutation failures to spread to other links in the area [9]. It is therefore preferable to improve the possibility to detect and react to disturbances that could lead to commutation failure caused by influence of other HVDC transmissions.
1.2 Overview of previous works


The thesis implements the theoretical discussion in the papers from ABB AB (former ASEA), USA. The presented predictor uses amplitude measurements of the Wye-phase voltages as well as $a\beta$-parameters from Clarke’s transform (see Glossary for further explanation) in order to recognize voltage drops and asymmetrical occurrences.

The resulting predictor, called the CFPREV function, does not detect phase angle changes in the network, and thus there are commutation failures that the predictor can not prevent.

Pre-study (2010).

A pre-study [13] was performed in the summer of 2010 at ABB AB concerning commutation failures in a weak multi-infeed network. The study was presented in a report at University West in August 2010 and features an evaluation of reported data from commutation failures, and a developed ramp function to simulate the behaviour of a HVDC Classic control system during these faults.

The resulting simulator was developed using data from fault reports stored in ABB’s disturbance and outage reports’ database [14]. The evaluation of the commutation failures showed that the majority (66.67 %) of the reported faults caused a collapse of the Delta-bridge. The analysis showed that the fault type is most likely a phase-to-phase fault when looked upon on the Delta-side of the converter. Fault evaluation also indicated that the commutation failures are most probably due to positive phase shifting in the zero-crossings of the valve voltages.

The pre-study also features a discussion for a concept model for possible improved commutation failure prediction in the controls, as well as a future work assessment for which this Bachelor’s thesis is built upon.

1.3 Purpose/Goal

The goal of the thesis is to evaluate the current control system in HVDC Classic, and to establish whether a possible improvement to the commutation failure prediction function is liable, and under which circumstances an improvement can be made.

A part of the thesis is also to find and implement an algorithm to prevent commutation failures during phase shifts in the AC network on the inverter side of
the HVDC link. This includes finding appropriate input and output signals while keeping transmission stability.

1.4 Limitations

The commutation failures that are being considered are only those that cause a decreased commutation margin/voltage-time area. The work was built upon a model of a bipolar HVDC Classic link (two standard links in parallel). However, the thesis was limited to only one of the two poles. In order to mitigate possible disturbances from the other pole, all control actions have been done equally to both poles of the link.
2 Description of Software

Different computer software has been used for evaluation, simulation and development. This chapter gives a short description of software used during the thesis work.

In the text the following expression is used to denote the voltage-time area: “extinction angle (γ)”. Due to the nature of two of the software used in this thesis (namely TOP and TFRplot, both described in the following), the diagrams from these two programs are unable to depict the symbol ‘γ’. Therefore, many of the diagrams will instead denote the signal as “Gamma”.

Please note that all software requiring license and/or purchase have been provided by ABB AB.

2.1 PSCAD

PSCAD is an electromagnetic time domain transient simulation tool from Manitoba HVDC research centre [15]. The software is used by ABB AB to, among other things, simulate and prepare the control systems for their HVDC projects.

In this thesis PSCAD is used to simulate the controls of a bipolar HVDC Classic link in order to address the control systems’ behaviour during faults and to evaluate changes done in the control system files through the means of simulation.

2.1.1 Xdebug

Xdebug 0.501 is a software application, which at ABB, is implemented in PSCAD in order to easy monitor signals that are not directly displayed in PSCAD.

The software is used in this thesis to verify HiDraw signals and collecting data from the control system simulations in PSCAD.

2.2 HiDraw

HiDraw is a graphical code generating tool developed by ABB AB [16]. It uses graphical function-block representation of control applications for the HVDC control system and produces code in C or assembly language from the finished pages.

In this thesis HiDraw is the software in which the algorithm an improved commutation failure predictor will be built and implemented with the existing control system. The generated code is compiled to be used in PSCAD for testing and verification.
2.3 TOP
TOP, The Output Processor, is a freeware from Electrotek Concepts [17]. TOP is a tool for graphical analysis of data from monitors and computer simulations in power and energy applications.

In this thesis TOP is the primary software in which calculations and analysis of data from simulation in PSCAD is performed.

2.4 TFRplot
TFRplot is software used to present data from formats such as comptrade, and PSCAD among several others, in a diagram setting easy to configure.

In this thesis, TFRplot is used to present data from simulations, primarily of main circuit data that is readily presentable without further calculative analysis, for which TOP is preferable.
3 Model Setup

In this chapter the network conditions and model setup for the thesis are identified.

3.1 Network Conditions

Three different AC network representations have been evaluated. The networks were modelled with a short circuit ratio corresponding to approximately 1500, 2000, and 3360 MVA respectively.

The network strength is represented by the short circuit ratio ($Scr$) (see Table 3:1). For this work, a stronger network is defined as having a $Scr$ larger than three. The short circuit ratio is calculated according to Eq. (3:1) and is the relation between the apparent power $S$ and active power $P$ (in MVA and MW respectively).

$$Scr = \frac{S}{P}$$  \hspace{1cm} (3:1)

Table 3:1. Network configurations evaluated.

<table>
<thead>
<tr>
<th>$P = 480$ [MW]</th>
<th>Network 1</th>
<th>Network 2</th>
<th>Network 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$ [MVA]</td>
<td>1440</td>
<td>2000</td>
<td>3360</td>
</tr>
<tr>
<td>$Scr$</td>
<td>3.0</td>
<td>4.2</td>
<td>7</td>
</tr>
</tbody>
</table>
3.2 HVDC Systems

The HVDC link configuration used is a bipolar Classic link (see Figure 3:1); however, only one pole will be considered for this thesis as in compliance with the limitations stated in section 1.4.

The base parameter settings are as listed in Table 3:2 and are equal to both poles of the HVDC link and relevant to all network configurations described in Section 3.1.

![Figure 3:1. Main circuit representation](image)

1) Converter bridges with representation of converter transformers.
2) AC filters and DC filters.
3) DC smoothing reactors.
4) DC lines and cables.

<table>
<thead>
<tr>
<th>Base parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Power, $P$</td>
<td>MW</td>
<td>250</td>
</tr>
<tr>
<td>Base voltage, $E_{rms}$</td>
<td>kV</td>
<td>165</td>
</tr>
<tr>
<td>Frequency, $f$</td>
<td>Hz</td>
<td>50</td>
</tr>
<tr>
<td>Relative inductance direct voltage drop, $dx$</td>
<td>p.u.</td>
<td>0.11</td>
</tr>
</tbody>
</table>
The controls for the HVDC link are represented using HiDraw code. The HiDraw drawings used to create the software for the control functions included in the simulations are equivalents to those used in commissioned projects.
4 Methods

This chapter explains the methods that were used in the thesis. It explains equations and settings to evaluate the control system as well as a theoretical approach to the consequences of increasing the extinction angle in the inverter of a HVDC Classic link.

4.1 Consequences of increasing the extinction angle – a theoretical approach

Increasing the extinction angle ($\gamma$) can be critical, especially in inverter operation. In order to not get a commutation failure one will have to fire at an earlier moment than usual and thus causing a voltage magnitude drop which in turn can have negative consequences on the operation.

The three commutation angles $\alpha$, $\gamma$, and $\mu$ are sharing a 180 degree half period. The two angles that can be relatively controlled are the firing angle ($\alpha$) and the extinction angle ($\gamma$) (for more information on the commutation process see appendix B). Increasing the extinction angle ($\gamma$) has an indirect effect on the overlap ($\mu$) which the following discussion will show.

Increasing the extinction angle ($\gamma$) is done by subtracting an angle reference from the firing angle ($\alpha$), thus moving the firing instant backward from its otherwise predetermined value. In Figure 4:1 there is an example with two diagrams depicting the angle relationship before and after an extinction angle ($\gamma$) increase in an ideal system, where the overlap angle ($\mu$) (and thus the direct current) is said to be constant.

Diagram 1:4a show the firing angle ($\alpha$) “Alpha” to be 130 degrees, the overlap angle ($\mu$) “Overlap” being 35 degrees, and the extinction angle ($\gamma$) “Gamma” equal to 15 degrees (180 degrees in total).

The extinction angle ($\gamma$) would be increased by lowering the firing angle ($\alpha$) with the corresponding value. The result is diagram 4:1b in Figure 4:1 on the following page. The angle relations have then been shifted accordingly and the firing angle ($\alpha$) is now equal to 127 degrees, the overlap angle ($\mu$) 35 degrees, and the extinction angle ($\gamma$) equal to 18 degrees.
The figures above illustrate the angle relations in an ideal shift of the extinction angle (γ) and lowering of the firing angle (α).

When the thyristor fires earlier it causes the DC voltage amplitude to decrease according to principles of AC/DC conversion. The sudden decrease in voltage will have several consequences on the system. The overlap angle (μ) is, for example, tightly connected to the DC current and in contrast to the ideal situation – the overlap angle (μ) will also differ in accordance to current changes. It is a frail situation, where increasing one parameter can have profound negative effects working against the goal one wishes to achieve. The three main consequences of increasing the extinction angle (γ) are decreased voltage, increased current, and reactive power consumption.
**Decreased voltage**, \(U_d\), is the result of firing the thyristor valves earlier relative to the voltage rating before the increase of the extinction angle (\(\gamma\)). A lower voltage rating means a lower power rating on the transmission, which increases the economic losses of the HVDC link.

**Increased current** is a consequence of the decreased voltage. The sudden drop in voltage amplitude will cause the DC current, \(I_d\), to increase in order for the system to remain at the stated power rating, \(P\), of the station. However, this does not occur proportionally as suggested by the ideal steady-state expression:

\[
P = U_d \cdot I_d
\]  
(4:1)

The DC current consists of three main components, where the first is linearly proportional:

\[
I_o = \frac{P}{U_d}
\]  
(4:2)

\(I_o\) = The ideal DC current, see \(I_d\) in Eq. (4:1)

The other two components are exponential due to current rush from, primarily, two sources:

1. The voltage decrease in the inverter will cause a voltage difference between the rectifier station and the inverter; causing a current rush and thus adding a second component, \(I_{\text{rectifier}}\), seen in Eq. (4:3), to \(I_d\).

\[
I_{\text{rectifier}} = \frac{\Delta U}{R}
\]  
(4:3)

\(\Delta U\) = Voltage difference between the inverter and rectifier stations

2. Many HVDC links are connected via cable connection; due to the de-energizing of the cable’s capacitive abilities a third component, \(I_{\text{cable}}\), will be added to \(I_d\).

While in reality there are more factors in \(I_d\)’s development due to extinction angle (\(\gamma\)) increase, it would be too complex to express them in a mathematical formula. The tree components stated above are the main components which will have the largest effect on the resulting current Eq. (4:4).

\[
I_d = I_o + I_{\text{rectifier}} + I_{\text{cable}}
\]  
(4:4)

The firing angle (\(\alpha\)) is related to the DC voltage, the overlap angle (\(\mu\)) is related to the DC current rating. The overlap (\(\mu\)) is dependent upon the transformer inductance, therefore, an increased DC current enlarges the overlap (\(\mu\)) needed to complete the commutation process. Figure 4:2 shows an example of the angle relations after an increase in the extinction angle (\(\gamma\)).
The angle relation after an increase in the extinction angle ($\gamma$) results in a lower extinction angle ($\gamma$), 16 degrees, than intended from the original situation illustrated in Figure 4:1 (which was 18 degrees). Increasing the extinction angle ($\gamma$) can therefore result in either positive or negative consequences depending upon the network parameters and DC current dependencies.

**Reactive power consumption.** The transformer in the converter station of a HVDC link is a large consumer of reactive power. The consumption is affected by increasing the extinction angle ($\gamma$). Because of the current rush created by decreased voltage (on both the DC and AC side of the converter), the current through the transformer is also increased. The increased current through the transformer results in a larger amount of reactive power in the transformer windings.

The reactive power is normally stabilized with capacitor banks on the AC side of the transformer; however, the level of the reactive power consumption, $Q_{\text{absorption}}$, is negatively relative to the DC voltage rating, see Eq. (4:5). Hence increasing the extinction angle results in decreased voltage, the reactive power from the filters will decrease despite the increased consumption of the transformer due to the fact that the filter settings are scaled to the voltage rating.

$$Q_{\text{absorption}} = P \cdot \sqrt[2]{\left( \frac{U_{d0}}{U_d} \right)^2} - 1$$  \hspace{1cm} (4:5)

$U_{d0} =$ No load DC voltage

In weak networks, this could easily cause a collapse of the AC connected network, thus, great precaution has to be taken to how much the extinction angle ($\gamma$) can be increased, without causing too much negative consequences.
4.1.1 Complementary simulations
A simulated system response to an increased overlap (µ) compared by the extinction angle (γ) increase was made to complement the theoretical approach. It is of great interest to estimate the resulting extinction angle (γ) caused by the current rush.

The simulation was made by making an angle increase at steady-state with no application of fault. Simulations were done at all established network strengths with increments of one degree over a total (where applicable) of 10 degrees, and simulation results were noted based off the maximum overlap angle (µ) as reference.

4.2 Detection algorithm
The main work consisted of developing an algorithm for detecting a possible commutation failure, handling of detection parameters, and giving the correct output signal response. The work was divided into three separate parts: identifying possible input variables, developing an algorithm for processing, and finding the correct output parameters for affecting the system.

4.2.1 Liable input parameters
In the pre-study performed in the summer of 2010, it was established that the most suitable parameter for detecting increased possibility of commutation failures through phase shift is the zero-crossing times of the valve voltages. There was also a discussion whether the Phase Locked Loop (PLL) used to calculate the next firing also could be used for detection, because the PLL bases its prediction on the zero-crossings. However, it has been decided in collaboration with my supervisors at ABB AB, Fredrik W Jansson and Boris Nordström, that the PLL respond is too slow in order to work as a possible input.

After discussion with several colleagues at ABB AB, two other possible input signals were decided to be worth considering besides the signals of the zero-crossings. The first is the signal already used by the existing predictor algorithm measuring the sum of the three phase voltages; the second is the error signal of the PLL.

The PLL works to synchronize the firing with the AC voltages. In order to do so, it constantly measures the difference between its own prediction and the actual voltage. The difference between the two is an error signal which is fed to a PI-controller that keeps the internal control system in phase with the AC network. While it has been decided that the PLL as a whole works too slowly, the error signal is a direct continuous response of how well the control system and the network are synchronized.

All three signals; the zero-crossings, the sum of the voltages, and the PLL error signal (ERROR_PLL) were monitored during simulation of a phase-to-ground fault in accordance with system parameters as explained in Section 3.3.1. The challenge was to
see whether any of the signals showed enough signs for a possible detection, and if so, to find an appropriate detection level.

4.2.2 Concept model

The next step is to develop a more detailed concept model for the processing of the input signals to the algorithm. The idea was to complement the existing predictor with a new algorithm rather than replacing it, hence the existing predictor was used as a reference for handling of the signals.

The model revolves around increasing the extinction angle (γ) for a satisfactory amount to prevent commutation failure. Phase shifts expressed in degrees is easier to comprehend; therefore a conversion between degrees and radians was needed. The most important part was to find an appropriate scaling of the angle relative to the detection levels from the input signals.

4.2.3 Output parameters

The existing predictor outputs the angle deviations to two parameters; AMAX and AMIN. Since the goal of the algorithm is to increase the extinction angle (γ), the output parameters will remain the same. The algorithm connects its outputs to the existing predictor, making it an integrated part of the CFPREV function in the control system.

AMAX is the maximum value of the firing angle (α). In inverter operation, the firing angle (α) normally resides at this value in order to keep stability of the current control.

AMIN is the minimum allowed voltage-time area (or the extinction angle (γ)). By increasing this value you will lower the value of where which firing must at the latest occur in order to complete a successful commutation between two thyristor valves.

4.3 System reaction to extinction angle increase

The biggest part of this thesis has been to examine how the system responds to an increase of the extinction angle (γ). As discussed in Section 4.1, there are several consequences of increasing the voltage-time area. The impact depends on the strength of system; a weak network suffers more quickly than a strong network.

For the purpose of finding an appropriate scale setting for the signals to AMIN and AMAX in the algorithm, several simulations were performed to see how the system reacts to an angle increase while under a phase-to-ground fault that does not, but nearly, causes a commutation failure. This was done to see whether an extinction angle (γ) increase will mitigate the effect of the fault, and if so, what levels of increase give the best system response.
4.3.1 System parameters

In PSCAD, the HVDC link is represented by network equivalents with infinite sources (see Figure 4:3), and a simplified control system interface. Three main system parameters needed to be calculated, others were tuned to fit with the general transmission ratings of the link (see Section 3.2).

![Figure 4:3. Settings of the infinite source of the network equivalents as a part of the HVDC link simulation in PSCAD.](image)

The settings for each predetermined network are calculated with the assumption that the X/R relation (the relationship between the reactance, X, and the resistance, R) is equal to 10, and from what follows from Eq. (4:6):

\[
X = \frac{Erms^2}{S[MVA]} = 2 \cdot \pi \cdot f \cdot L
\]

\[
L = \text{Inductance [H]}
\]

\[
f = \text{Frequency [Hz]}
\]

\[
Erms = \text{Base voltage [kV]}
\]

The tuning of the Erms signal to 165 kV was done through monitoring of signals from PSCAD. When the steady state system is configured, a phase-to-ground fault is applied using the built in fault module (see Figure 4:4) found in the PSCAD master library.
The phase-to-ground fault impedance is tuned to cause approximately 10% decrease of the Erms signal. This is because (1) the pre-study (see Section 1.2) showed slight or none decrease in voltage amplitude, (2) and the existing CFPREV function has a detection level of AC voltage amplitude drops of 14%. By configuring the fault to cause only a 10% drop, it resembles not only the issue of phase shifts, but also combined phase shift and voltage drops that is not detected today.

The base setting for the fault can be viewed in Table 4:1. The tuning of the fault impedances was made through scaling the base values (see Table 4:1) to the desired level.

Table 4:1. Phase-to-ground fault impedances scaled off base values.

<table>
<thead>
<tr>
<th></th>
<th>Base Values</th>
<th>$\Delta r$: 3.0</th>
<th>$\Delta r$: 4.2</th>
<th>$\Delta r$: 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>R [ohm]</td>
<td>2.1</td>
<td>25.2</td>
<td>12.6</td>
<td>7.35</td>
</tr>
<tr>
<td>L [H]</td>
<td>0.055</td>
<td>0.66</td>
<td>0.357</td>
<td>0.1925</td>
</tr>
</tbody>
</table>

4.3.2 Simulations

In order to simulate an increase in the extinction angle ($\gamma$), modifications to both the PSCAD simulator and the HiDraw code have to be done. The degree of increase for the extinction angle ($\gamma$) had to be accessible for settings from within the PSCAD environment. By making use of the already available communication interface modules between PSCAD and HiDraw (see Figure 4:5), a new data signal connection was added by re-using existing function blocks and settings.
Several more function blocks were added from the communication interface to create a conversion from degrees to radians, and adding the resulting signal directly to the AMIN and AMAX from the existing CFPREV function.

It was desired to investigate if there were any difference in the system response depending on when the failure was added relative to one period of the voltage. A time-logic (see Figure 4:6) in the HiDraw code, with a signal accessible from Xdebug, enabled the possibility to simulate a fault, and a preventive action, without re-compile the coding when changing time intervals.

Simulations were performed and analyzed in the PSCAD environment and TOP with the following main focus areas: (1) extinction angle increase, (2) point-of-wave differences, and (3) symmetrical/unsymmetrical AMIN.

The first focus was to investigate how much of an increase to the extinction angle ($\gamma$) could be made before causing a commutation failure as the angle increase was made 0.1 ms after fault initiation.

Because the AC voltage is a sine curve, it was of interest to find out whether the time of the angle, relative to the AC voltage point-of-wave, could give a different result.
The second focus on the simulations was therefore to look at the significance of point-of-wave. Simulations were made in PSCAD with the help of Xdebug to alter the fault initiation time as well as the angle time settings to cover a 360 degree period corresponding to 20 ms with increments of 1 ms (or 18 degrees.)

The third focus has to do with the AMIN function at present. When an angle contribution to AMIN is done, it is symmetrically added to all valves during one period. Decreasing AMIN for a period of time (20 ms) could worsen the effect due to consequences discussed in Section 3.1. By investigating the disabling of the symmetry control, to let the AMIN contribution only affect the next valve to fire, a possibility of a less negative system response could be evaluated.
5 Results

In this section, results from the algorithm and the simulations with an increased extinction angle ($\gamma$) will be presented. All simulations have been performed originating from a fixed system setting where only the time of the fault and the value of extinction angle ($\gamma$) have been varied.

5.1 Consequences of increasing the extinction angle – complementary simulations

Below are results related to Section 4.1, where a theoretical approach to consequences of increased extinction angle ($\gamma$) is discussed. The following subsections compares simulation results with the theoretical discussion by simulating an increased extinction angle ($\gamma$) in the case of three defined network strengths under a steady-state operation of the link.

5.1.1 Network strength, Scr, 3.0

The system at this ratio is extremely critical (as discussed in Section 4.1), which Figure 5:1 illustrates. To make a positive impact, the contribution to AMIN and AMAX needs to be a minimum of three degrees. The result of the extinction angle ($\gamma$) increase up to one degree even results in a negative response with a decreased angle (note that in Figure 5:1 the graph may look constant; however, the increase of one degree is 0.1 degrees lower than the steady-state value of 16.88 degrees.) The reason for the negative result at one degree is most likely due to the current rush from the DC cable being so large that it pushes the extinction angle down rather than up.
Improvement of Commutation Failure Prediction in HVDC Classic Links

Figure 5:1. Maximum angles from AMAX and AMIN of a system with a Scr of 3.0.

X-values show the level of angle contribution added to the nominal reference values of AMIN and AMAX, while Y-values represent the resulting degrees of the angles for the overlap (μ) and extinction angle (γ) respectively. While the result of the extinction angle (γ) simulations lags behind of the increased overlap (μ) at small degrees, the system quickly becomes unstable. Already after two degrees, the angles increases more rapidly and an angle contribution above five degrees is highly unwanted due to severe control instability.

5.1.2 Network strength, Scr, 4.2

At a Scr of 4.2, the system is more stable than in the case of a Scr of 3.0. Moreover, you can increase the angle contribution up to (and above) 10 degrees without causing instability in the control, see Figure 5:2.
X-values show the level of angle contribution added to the nominal reference values of AMIN and AMAX, while Y-values represent the resulting degrees of the angles for the overlap (μ) and extinction angle (γ) respectively. The increase in extinction angle (γ) and overlap (μ) are more or less proportional until an angle contribution of more than eight degrees. The sudden increase in gamma indicates that the system is starting to accelerate towards instability.

### 5.1.3 Network strength, Scr, 7

Results of having a very strong network is illustrated in Figure 5:3. The overlap (μ) increases with a relatively low slope compared to the weaker networks in Section 5.1.1 and 5.1.2, while the extinction angle (γ) increases faster.
X-values show the level of angle contribution added to the nominal reference values of AMIN and AMAX, while Y-values represent the resulting degrees of the angles for the overlap ($\mu$) and extinction angle ($\gamma$) respectively. The angles show no sign of exponential increase, indicating that the system remains stable for contributions up to at least 10 degrees.

### 5.2 Algorithm concept

The most important issue was to determine which signals that could work as detection of an increased risk of commutation failure. It was necessary to find signals that could register detection fast enough, and the algorithm also had to execute quickly. The time frame, which was estimated and observed during the pre-study (see Section 1.2), was limited to a maximum of 5-10 ms for an adjustment to be able to have any chance of preventing a commutation failure in the bridge.

In the following sections, liable input and output parameters along with an algorithm concept model will be presented.

#### 5.2.1 Input parameters

The three signals mentioned in Section 4.2.1 were all analyzed and presented in diagrams using the software TOP. All three signals showed deviations from normal values, and possible detection within 5 milliseconds seems valid under the assumption that normal deviations are below what has been observed in the following figures.
All simulations performed were made by adding a phase-to-ground fault in accordance with system settings described in Section 4.3.1 at a time of 0.1 seconds. The fault persisted through 0.1 second after which the system settles to steady-state.

The first signal evaluated was ERROR_PLL. Due to the synchronization of the PLL function with AC voltages, the deviations could be either positive or negative depending upon the AC voltage period. In order to find a liable detection level, only the signals’ absolute value was looked at for possible detection, see Figure 5:4.

![Figure 5:4](image)

Figure 5:4. The absolute value of ERROR_PLL with a Scr of 3.0.

While the signal clearly shows deviation from its ideal value of zero, with a fault signal well over 0.05 radians, the possibility of using ERROR_PLL as detection signal for the algorithm is dependent upon how much the observed deviation, seen in Figure 5:4, differs from normal deviations of the signal. So far, normal fluctuations do not seem to be larger than 0.014 radians (see Figure 5:5) relative to the absolute value of ERROR_PLL.
ERROR_PLL represent the difference in phase between the PLL control function, and the AC network. Therefore, being dependent upon phase shifts, the signal remains robust to differences in voltage ratings and the detection levels remain approximately the same for all three network strengths.

The second signal to be analyzed was the sum of the AC voltage phases. During a phase shift, it is reasonable to argue that the sum would differ from its ideal value of zero. In Figure 5.6, there are both quick and apparent deviations; normal fluctuation appears to be non-existent.
The signal of the summarized phase voltages is very dependent upon disturbances in the AC voltage. Even though the signal is represented in per unit values, great fluctuation in the AC voltages may still complicate detection of increased risk for commutation failure.

The last signal to be analyzed to be a possible input signal was the zero-crossing times. In the control system, there are twelve zero-crossing times; one negative and one positive for each valve (corresponding to one 6-pulse bridge). The positive and negative signal each represent when the valve voltage changes polarization, by adding the two signals for each valve, the half-period interval can be extracted. The nominal interval for a half-period in a 50 Hz network being 10 ms, the signals can be plotted and observed for deviations from that value, see Figure 5:7.
Figure 5:7 show clear changes in the half-time periods already at one ms after applied fault (see graph U14Y). It is at this time still unknown how normal fluctuations of the half-time period look like.

Data from simulations of network strengths with $Scr$ of 4.2 and 7 is stored and available at ABB AB, Ludvika.

### 5.2.2 Algorithm concept model

The algorithm concept model can be viewed in Figure 5:8. The algorithm is based upon the existing CFPREV function, and is intended to work as follows:

The detection of an increased possibility for commutation failure is based on the input signals from Section 5.1.1. When one or more of the signals show differentiation from normal deviations, the function is triggered. The function $H(s)$, represent where the input signals are to be converted into a representative value of the extinction angle ($\mu$) contribution to be made. The conversion is dependent upon system parameters and settings need to be addressed for each individual
implementation. The algorithm scaling to an extinction angle ($\mu$) contribution would have to be relatively low, (if compared to the existing CFPREV contribution which gives a value of more than 10 degrees) which will be seen by the results presented in Section 5.2.

**Figure 5.8. Algorithm concept model.**

### 5.3 System reaction to extinction angle increase

In this section, results concerning the evaluation of system response to an extinction angle ($\gamma$) increase are presented. The simulations in this section, concerning the system response, are done during the appliance of the phase-to-ground fault, see section 4.3.1. Several limitations and dependencies restrict the improvement of the commutation failure algorithm.

#### 5.3.1 Possible commutation failure prevention relative to point of wave

Several simulations of point-of-wave dependency of the fault occurrence showed clear limitations in fault prevention.

Figure 5:9 illustrates the areas of one period sine curve of fault occurrences for which commutation failure prevention could be possible. The results are similar for all network strengths investigated with little or none difference.
The dark blue areas on the voltage curve in Figure 5:9 depict where a preventive action for commutation failure might be possible. The areas illustrate angles between 0-54, and 144-216 degrees; in radians, the corresponding areas are between 0-0.942, and 2.513-3.769 radians respectively.

The results are approximate in accordance to the determined simulation settings (see Section 4.3.2). The limitations reflect the sensitivity of the system, where a large fault current will inevitably lead to commutation failure in the converter.

### 5.3.2 Simulation results of extinction angle increase level

The amount of extinction angle (γ) increase is very dependent upon the network strength of the connected AC system as seen in Section 5.1. It is only at the highest evaluated network strength (with a Scr of 7) that the contribution to the extinction angle (γ) could be effectively larger than one degree.

In Figures 5:10-5:11 below, the results of the simulation and the contributions’ effect on system parameters can be observed for settings corresponding to the Scr of 7. The figures illustrate how the system remains stable even at 10 degrees extinction angle (γ) contribution. The behaviour of the system is stable throughout the increase from 0-10 degrees; data is stored and available at ABB AB for future reference.

Take note that the line currents in coming diagrams have the following titles:

- Wye line currents are denoted ca_r/s/t
Delta line currents are denoted $c_b r/s/t$

The observant will also see that the currents in the diagrams have been given the unit kV, which is incorrect. The correct unit should be kA.
Figure 5:10a. Main circuit parameters and significant signals of system response to a zero degree contribution with a $\delta_{cr}$ of 7.
Figure 5:10b. Main circuit parameters and significant signals of system response to a zero degree contribution with a $\Delta r$ of 7.
Figure 5:11a. Main circuit parameters and significant signals of system response to 10 degrees with a $\Delta \theta$ of 7.
Figure 5.11b. Main circuit parameters and significant signals of system response to 10 degrees with a $\Delta \alpha$ of 7.
The results show decreased system values, values relevant for HVDC control analysis in this thesis (see Glossary for specification), as the contribution is increased. However, the simulations have been performed with fixed extinction angle contribution, so the system does not return to its normal steady-state values.

One can see, looking specifically at the graph of $I_d$, how it increases in a stable manner. It goes up in a smooth curved formation and then quickly returns to steady-state after fault clearance. Similar behaviour can be seen for the line currents as well. Erms show a lower minimum value as the extinction angle ($\gamma$) is increased. This is expected behaviour, since it is in line with AC/DC conversion principles of effects from decreasing the firing angle ($\alpha$).

One can also see a difference in the commutation angles that relates to the complementary simulations of the theoretical approach in Section 5.1. A higher AMIN/AMAX contribution to the extinction angle ($\gamma$) does not result in the same initial decrease in the resulting angle as a lower does (see the “Gamma_S2P2” signal in Figure 5.7.) This is consistent with the simulations on the weakest network with a $Scr$ of 3.0 in Section 5.1.1 which indicates problems with too low angle contribution.

Similar simulations were performed for network strength 3.0, and 4.2. The weakest network, 3.0, quickly turns unstable – an angle contribution of only one degree to the control system results in commutation failure.

The network strength, at $Scr$ of 4.2, does not reach commutation failure until an angle contribution of 10 degrees is added. However, the system response show increased instability in the system at angle contribution values of approximately eight degrees. The sign of instability can best be viewed in the graph of $I_d$ where one can see a difference in the curvature from that of a stable transient event, see Figure 5:12. Data diagrams concerning $Scr$ 3.0 and 4.2 are summarized and can be viewed in appendix A, whereas complete data is available at the system design department at ABB AB in Ludvika.
The results are similar to those of the initial simulations in Section 5.1.2 where a growing instability was detected around an eight degree extinction angle (γ) increase. In Figure 5:12 there are two graphs of the DC current, \( I_d \). The top graph (from file “_Scr_4_2_2.inf”) show \( I_d \) with a two degree extinction angle (γ) contribution, whereas the bottom graph (from file “_Scr_4_2_9.inf”) show \( I_d \) with a nine degree extinction angle (γ) contribution. There is a difference in the curvature, which the diagrams display, where in the bottom graph; the current rush at approximately 0.125 sec. This rush will grow more apparent as the angle is further increased; however, in the network with a \( Scr \) of 4.2, the system collapses at 10 degrees.

It is not as much the algorithm that fails in its contribution to the extinction angle (γ). It is rather the current rush that causes the system to collapse. Figure 5:13 show the extinction angle (γ) “Gamma” from simulations of the weakest network with \( Scr \) of 3.0; the algorithm successfully increases the extinction angle (γ) from approximately 8.22 to 9.48 degrees after the initiation of the fault as well as the angle contributions to AMIN and AMAX.
The above figures are equal in that they display the transient sine wave-like behaviour of the extinction angle during fault. Readings of the extinction angle (γ) value before fault are made at the purple line seen in diagram which tells of a steady-state value of 16.9002 degrees. The value of interest is the minimum value at the first cycle of the sine wave formation, illustrated by the green line seen in Figure 5:13a. The minimum value at fault with zero degree angle contribution (Figure 5:13a) is 8.22421 degrees, whereas the corresponding value at fault with one degree angle contribution (Figure 5:13b) is 9.48607 degrees.

The above results illustrate the approximate increase of one degree in the extinction angle (γ), which was contributed through addition to the AMIN and AMAX parameters as seen in Section 5.2.3 on output parameters.

5.3.3 Symmetry control of AMIN evaluation

Due to the results from the simulations in Section 5.3.2, the evaluation of the symmetry control and its impact on the extinction angle (γ) is limited to the highest defined network strength.

Results show that disabling the symmetry of AMIN will have an impact on the extinction angle (γ). In Figure 5:14, two graphs depicting the extinction angle (γ) are superimposed and filtered with a low-pass filter for better visualization. The blue graph shows the extinction angle (γ) with enabled symmetry control, while the black
graph show a simulation with the same level of increase but with the symmetry control disabled.

Note that it is due to the filtering of the signal that the graph seems to begin at zero; a corresponding diagram with the non-filtered signals can be viewed in appendix A.

Figure 5:14 illustrates a large difference in mean values between having the symmetry control enabled or disabled. The difference ranges approximately between 10 – 30 % in favour of a disabled symmetry control, except during the initial milliseconds where an enabled symmetry control gives a marginally lower mean value. However, it is the consequential action after the initial angle deviation that is most critical in order to keep the current rush to a minimum.
6 Discussion

In this section the results represented in Section 5 are discussed further. Limitations in the simulation model, network strength differences and possible complications to detection signals are addressed in Section 6.1 while thoughts for future work and focus points are expressed in Section 6.2.

6.1 Result commentary and discussion

This discussion is parted into two sections: (1) Algorithm concept model, and (2) Simulation results and extinction angle contribution limits for easier navigation.

6.1.1 Algorithm concept model

It is still unclear how quickly an improved preventive function has to execute. According to Per Holmberg, an expert on commutation behaviour at ABB AB, it is most likely necessary to execute within five milliseconds from fault occurrence in order to be effective due to the systems sensitiveness as well as the limited time from fault initiation to commutation failure that is about 10-20 ms. This puts large constraints on not only the detection, but also on the size and complexity of the algorithm.

Caution needs to be taken when establishing detection levels so that they are both selective and robust. This can be difficult in weak networks where, for example, the frequency is able to fluctuate in larger range compared to a strong network. It could be wise to consider using the three evaluated detection signals in combination with each other rather than separate.

The simulations have shown very little disturbances in the signals during steady state. Depending upon the connected AC system and disturbances in the network the signals can be more or less stable. You would want to have an algorithm that remains robust against normal deviations. Therefore, it is highly unwanted, that a future algorithm based on detection signals presented in this thesis, to give an extinction angel (γ) contribution during other disturbances that is not related to an increased possibility for commutation failure.

6.1.2 Simulation results and extinction angle contribution limits

The simulation results reveal significant differences in behaviour depending upon the network strength of the AC system. An implementation of an improved algorithm for commutation failure prevention is more limited the weaker the network is.

The physical limits of the control system parameters are narrower in a weaker AC system than in a strong system. It could be preferable to not make an AMIN/AMAX contribution in networks that are extremely weak.
It is important; however, to remember that the \( \text{Scr} \) values evaluated in this thesis are based upon a relatively high \( dx \)-value of the transformers (0.11 per units); the reason for the high \( dx \)-value is mainly due to the control system model that was used which is a relatively old version. Today, normal \( dx \)-values for transformer design lies around 0.6 per units.

An interesting result was found in Section 5.1.1 and 5.3.2 which indicates that the extinction angle (\( \gamma \)) contribution is subject to possible negative results to the resulting voltage-time area if the angle is too low. It is a necessity to find a level that is as low as possible but still enough to give the wanted positive effects and to not further increase the possibilities of commutation failure. The fact that the results could be seen not only in the weakest network, as suggested in Section 5.1.1, but also in stronger network configurations is a strong indication that the level of angle contribution can be too low, as well as too high, and that an appropriate point of operation needs to be found. This point is most likely subject to specific network settings and parameters.

It is an interesting notion that the results concerning point-of-wave dependency relative to the AC voltage also seem to be revealed in the extinction angle (\( \gamma \)) signal “Gamma.” As can be seen in the diagrams of, for example, the symmetry control of AMIN in Section 5.3.3, the extinction angle (\( \gamma \)) signal “Gamma” has a sine wave formation during transient events.

Figure 6:1 show an extinction angle (\( \gamma \)) from the simulations of the network with a \( \text{Scr} \) of 3.0, where a one degree contribution to AMIN and AMAX was made.
If the instant where the sine wave formation begins is denoted zero degrees (0.101 in Figure 6:1), and we move forward more than 54 degrees/0.003 sec (see Section 5.3.1), we end up with a larger instant difference to the signal as the steady-state value correlates to the sine wave. The amplitude of the sine wave is dependent upon the amount of contribution made to AMIN and AMAX; therefore, a larger contribution will give bigger initial amplitude change in the “Gamma” signal.

These observations suggest that point-of-wave might also be an issue when looking at the extinction angle (γ), and not only related to the AC voltage. The extinction angle (γ) suffer from physical limitations, where a signal value below seven degrees is not physically possible for the thyristors used in HVDC Classic configurations due to a minimum voltage-time area needed for the thyristor to regain voltage block capabilities.
6.2 Recommendations for further research and development

Further tests concerning the robustness and sensitivity of the detection signals presented in this thesis ought to be performed to distinguish detection from normal fluctuation and fault tendencies.

Due to limited time, a complete algorithm for testing could not be developed. However, the thesis suggests possible improvements to commutation failure prevention, even though a fully developed algorithm and testing of it is necessary.

Results from Section 5.3.1 alone, does not suggest that the point-of-wave, relative to the AC voltage, is dependent upon angle contribution level whilst it seems to be of outmost importance concerning the extinction angle transient discussed in Section 6.1.2. A deeper investigation of the extinction angle (γ) and its relations to point-of-wave has not been performed in this thesis; however, it is a point that ought to be addressed.

An investigation to establish possible values of the angle contribution limits relative to different network strengths and settings is also needed.

7 Conclusions

The results presented in this thesis support the improvements of the commutation failure predictor in HVDC Classic Links. Several dependencies have been established and suggested for a successful implementation.

Further investigations and developments are needed to reach an implemental version of the modified algorithm. For this purpose, this thesis and supporting internal documents and simulation data are available at ABB AB, Ludvika.
References


A. Signal Observations

Section 5.3.2 Simulation results of an increase in the extinction angle ($\gamma$)

On the following pages are summarized data equal to that represented in Section 5.3.2 though corresponding to system network strengths of 3.0 and 4.2 respectively.

Please take note, that in the diagrams, the line currents for the Wye-phases are denoted ca_r/s/t, whereas the Delta-phases are denoted cb_r/s/t.
Figure A:1a. Main circuit parameters and significant signals of system response to a zero contribution with a $\Delta \sigma$ of 3.0.
Figure A:1b. Main circuit parameters and significant signals of the system. The response to a zero degree contribution with a $\Delta \tau$ of 3.0.
Figure A.2a. Main circuit parameters and significant signals of the system. The response to one degree contribution with a $\Delta \alpha$ of 3.0.
Figure A.2b. Main circuit parameters and significant signals of the system. The response to one degree contribution with a $\Delta \theta$ of 3.0
Figure A.4a. Main circuit parameters and significant signals of the system. The response to a zero degree contribution with a $\text{Scr}$ of 4.2.
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Figure A-4b. Main circuit parameters and significant signals of the system. The response to a zero degree contribution with a $Scr$ of 4.2.
Figure A:5a. Main circuit parameters and significant signals of the system. The response to a two degree contribution with a $Scr$ of 4.2.
Figure A:5b. Main circuit parameters and significant signals of the system. The response to a two degree contribution with a $\Delta \alpha$ of 4.2.
Figure A.6a. Main circuit parameters and significant signals of the system. The response to a nine degree contribution with a $\Delta \Phi$ of 4.2.
Figure A.6b. Main circuit parameters and significant signals of the system. The response to a nine degree contribution with a $Scr$ of 4.2.
Figure A:7a. Main circuit parameters and significant signals of the system. The response to 10 degree contribution with a $\text{Scr}$ of 4.2.
Figure A:7b. Main circuit parameters and significant signals of the system. The response to 10 degree contribution with a $\Delta r$ of 4.2.
Section 5.3.3 Symmetry control of AMIN evaluation

Figure A:8. Non-filtered extinction angle (γ) signals.
B. HVDC theories and concepts

1. History

HVDC technology began its development in the early 1900s. ABB AB (ASEA at the time) has been an active player with nearly 50 years of work until today [18]. The very first commercial HVDC transmission was ordered by the Swedish state from ASEA to be used to transfer power between mainland Sweden and the isle of Gotland off the east coast.

The transmission was in operation by 1954 [19] and at the time, the converter bridges were made up by mercury arc valves in order to convert between AC and DC with connection to a control system via vacuum tubes.

In the 1970's the mercury arc valves were replaced by the thyristor bridges that are still used in HVDC Classic links. This was a significant development in the HVDC technology. The use of thyristors reduced not only the size of the converter stations but also its overall complexity [20]. Together with the developments in computer technology, HVDC stations have come to be a very powerful and reliable transmission concept, and have become more competitive compared to other means of energy transport.

2. Why HVDC?

HVDC technology is transmission of power through DC voltage. Transmitting DC has advantages compared to transmitting AC for a number of reasons: (1) Losses during transmission is significantly lower (DC has no reactive component) which ultimately leads to less economic costs in transmission. The losses are said to become such a huge advantage over traditional AC transmission that when overhead lines are longer than 50 km, or if it is a cable transmission, DC has lower economic costs concerning maintenance and operation of the transmission link. (2) Less environmental impact can be achieved by using overhead lines for DC transmission rather than AC transmission. While AC transmission needs three parallel going lines, one for each phase, DC transmission only needs two. (3) The fact that it is DC transmission makes the required air space between the lines smaller due to lack of reactive currents. This ultimately leads to less required space for overhead lines and better preservation of the environment.

3. Converter Stations

There are generally twelve thyristor valves in a converter station, ordered in two so called 6-pulse bridges in a Graetz-bridge formation coupled in series. The valves are fed by two three-phase transformers with the configuration shown in Figure B:1; Wye-Wye and Wye-Delta respectively.
The reason for this configuration is mainly due to the positive effects on harmonics as well as it enabling higher DC voltage amplitude and thus increasing the power capability of the link. Positive consequences on the harmonics are obtained through the use of one Wye-Wye and one Wye-Delta transformer. Due to the 30 degree shift between Wye and Delta parameters, one effectively eliminates both the 5\textsuperscript{th} and the 7\textsuperscript{th} harmonic \[21\] from the system.

4. The Commutation Process

The valves convert the current by means of commutation between several valves constructed in a greatz bridge formation, see Figure B:2. The commutation process is a matter of stepping through the upper and lower bridge-part in the following manner, where two valves always conducts simultaneously to create a closed circuit:

\[
1 \& 2 \rightarrow 3 \& 2 \rightarrow 3 \& 4 \rightarrow 5 \& 4 \rightarrow 5 \& 6 \rightarrow 1 \& 6 \rightarrow \ldots
\]

This commutation process is usually represented in valve voltages with the following subscripts: \(U_{V12}, U_{V32}, \ldots, U_{V16}\).
Figure B.2. Commutation process.