This document gives an overview of the HVDC Control System. The key for understanding how an HVDC transmission operates is to know the basic principles of the HVDC Control system functions.

The basic principles highlighted in this report are:

- the DC current / DC voltage characteristics of an HVDC transmission
- the cooperation between the HVDC transmission converter terminals
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1. INTRODUCTION

The major advantage of an HVDC transmission is its built-in ability to control the transmitted power between the sending and the receiving converter terminals, the former called **rectifier** and the latter **inverter**.

This **controllability** can be utilized for the stabilization of the connected AC network, to control the frequency of a receiving, islanded network and to assist the frequency control of a generator, connected to the HVDC transmission rectifier.

The reactive power, that the HVDC converter consumes, is depending on the values of the control angles. Thus, the exchange of the reactive power between the converter and the AC network can be controlled and the AC voltage can be stabilized.

Also, combined active and reactive power generation can be applied when found advantageous.

This report will cover the control fundamentals for the HVDC converters and the transmission itself.

2. BASIC CONTROL PRINCIPLES

The basic concept to control an HVDC transmission is the possibility to set the DC voltage across the converter valve bridge and the transmitted power by varying the phase position of the gate control pulses to the converter valves.

Figure 1 shows a simple diagram for a monopolar HVDC transmission. The voltage of the rectifier is indicated by \( U_{d1} \) and the inverter by \( U_{d2} \). The polarity of the voltage \( U_d \) across the bridge is defined and it should be noted, that to make the inverter valves conduct the rectifier must set up a higher voltage than the inverter.
2.1. The exchange of power between rectifier and inverter

The normal configuration used for HVDC is a 12 pulse bridge converter. In a 12 pulse converter two 6 pulse converters are connected in series with one valve bridge being provided, with a Y/Y connected transformer and the other with a Y/D connected transformer. Figure 2 presents the 12 pulse converter bridge and its single line diagram symbol.

![12 pulse converter and its single line diagram]

The power delivered to the DC circuit from the rectifier is

\[ P_{dR} = U_{d1} \times I_d \]  (1)

The DC current \( I_d \) is determined by the voltage difference between rectifier and inverter and by the line resistance \( R_d \)

\[ I_d = \frac{U_{d1} - U_{d2}}{R_d} \]  (2)

and

\[ P_{dR} = \frac{U_{d1}(U_{d1} - U_{d2})}{R_d} \]  (3)

The DC line has normally a low resistance \( R_d \) and accordingly \( I_d \) is very sensitive to the converter voltage variations. Only a small change in voltage (\( U_{d1} - U_{d2} \)) is needed to cause an increase or a decrease in the DC current.

Equation (3) gives the power delivered by the rectifier. The power absorbed by the inverter is obtained by replacing the first \( U_{d1} \) in (3) by \( U_{d2} \)

\[ P_{di} = \frac{U_{d2}(U_{d1} - U_{d2})}{R_d} \]  (4)

The difference between \( P_{dR} \) and \( P_{di} \) is equal to the losses in the DC circuit, i.e. mainly the line losses.

\[ P_{dl} = P_{dR} - P_{di} = R_d \times I_d^2 \]  (5)

By establishing a DC current feedback loop in one of the converter stations, normally in the rectifier and by making the inverter determine the DC voltage, a basic HVDC transmission system is obtained.
level, that a preset DC current can be delivered to the inverter.

The current control can be performed by either the rectifier or the inverter with a principle, that the current is always controlled by one of the converters and the voltage determined by the other.

3. \( U_d/I_d \) CHARACTERISTICS FOR THE HVDC CONVERTER

3.1. The \( U_d/I_d \) characteristics

Assuming that the rectifier in Figure 1 is having the current control and the current order set to the value \( I_0 \).

The \( U_d/I_d \) characteristics is now determined by the equation

\[
U_d = U_{dio} \times \cos \alpha - (d_i + d_r) \frac{I_d}{I_{dN}} \times U_{dioN}
\]

The firing angle \( \alpha \) is a parameter influenced by the control system to keep the DC current equal to the preset reference.

The second term in the right member is the voltage drop in the converter transformer with \( (d_i + d_r) \) directly representing the impedance of the transformer.

\( U_{dio} \), with rated value \( U_{dioN} \), is the no-load DC voltage obtained with \( \alpha = 0 \).

For the discussion below we assume the steady state conditions, meaning that the AC bus voltages \( U_{ac1} \) and \( U_{ac2} \) are constant.

Supposing, that the inverter voltage \( U_{d2} \) is high, the rectifier will try to force the ordered current through the DC circuit by decreasing the firing angle \( \alpha \), which may in turn reach its minimum limit in the region of 5 degrees. If \( U_{d2} \) is very high, the maximum available value of \( U_{d1} \) will perhaps not be high enough, even with an \( \alpha = \alpha_{\text{min}} \) to make the inverter valves to conduct. No DC current will flow and we are somewhere above point A on the \( U_d \) axis in the following diagram.

Static \( U_d/I_d \) characteristic of a converter

It should be noted that the sign of the voltage of the characteristics shown in Figure 4 is so defined that it is positive when the cathode side of the valve bridge is positive. When discussing the cooperation between the rectifier and the inverter, the sign must be changed so that it is referred to the line instead of the bridge.

Decreasing \( U_{d2} \) means that we will sooner or later have a current flowing. At first, the current will be lower than the preset value, although the control system orders a minimum \( \alpha \).

We are moving now on section A-B in the \( U_d/I_d \) characteristics above. The term \( U_{dio} \times \cos \alpha \) in equation (6) is now constant and the slope of the characteristics within section A-B is determined by the converter transformer.

Reaching point B means that the current is equal to the preset current order \( I_0 \).
Without a current control system and with a further decreasing inverter voltage $U_{d2}$ the current would have exceeded the current order $I_0$.

With a decreasing $U_{d2}$ the rectifier voltage $U_{d1}$ is now adapted to it by increasing $\alpha$ and we are now moving on the vertical line B-C-D in the $U_d/I_d$ characteristics.

When $U_{d2} = 0$, the firing angle $\alpha$ in the rectifier is around 90 degrees and no power is transmitted. When $U_{d2}$ decreases further into the negative region no dramatic change in operation will occur in the corresponding converter. As long as $\alpha$ can be increased, the rectifier can control the current also with an opposite polarity on the DC circuit. Now the rectifier is absorbing power from the DC circuit and the inverter.

The current control system can still increase $\alpha$ and we can move downwards along the line B-C-D until we reach a maximum at point D. This $\alpha_{\text{max}}$ value is determined by the minimum permitted value for the extinction angle $\gamma$ and the present overlap angle $u$.

If the current through the rectifier should increase further, $\alpha$ must decrease as a consequence of that the overlap angle must increase. However, the extinction angle is kept constant by the converter firing control system (CFC). Thus, when the current increases further, we move along the line D-E which is the focus for the constant extinction angle $\gamma$ in the $U_d/I_d$ characteristics.

The characteristics A-B-C-D-E is the basic form of the $U_d/I_d$ characteristics for an HVDC converter for both the rectifier and the inverter operation.
3.2. Combined characteristics for a rectifier and an inverter cooperating on a DC line

Monopolar HVDC transmission

The definition criteria for the converter to operate either as rectifier or inverter is, that the converter with the highest DC current will operate as rectifier and the other as an inverter.

The rectifier has been provided with a current feedback control system consisting of a current control amplifier (CCA), a converter firing control system (CFC) and a control pulse generator (CPG). The inverter is also supplied with a control system of a similar kind as shown in Figure 5, even if the inverter current control is not activated in this basic mode of operation. However, a CFC and a CPG are needed to apply some form of control which can be used to obtain a fixed DC voltage.

Assume now, that the two converters with identical control systems are having the transformer winding ratios chosen so, that the current order for the inverter is slightly lower than for the rectifier. The two \( U_d/I_d \) characteristics will result now as shown in Figure 6 below.

The current control system corrects the firing angle \( \alpha \) by increasing it when the DC current exceeds the current order \( I_0 \). The correction is equal for both the rectifier and the inverter.

If both the rectifier and the inverter are energized on the AC side and deblocked, meaning that they are started, we will find that the rectifier delivers more current to the inverter than it requests.
The current order relation will be now $I_{01} > I_{02}$. The inverter will resist the DC current increase by increasing the firing angle $\alpha$ to reach the area of $\alpha > 90$. The inverter voltage $U_{d2}$ will now be negative on the cathode side of the 12 pulse bridge and will further increase in that direction meaning, that the inverter will generate a positive voltage on the DC line and is thus operating as an inverter. To force the ordered current $I_{01}$ through the DC line and to maintain the rectifier operation the rectifier must establish a higher positive voltage, the cathode side of the converter being positive.

To illustrate the cooperation between the rectifier and the inverter in the static $U_d/I_d$ characteristics, let us redefine the sign of the voltage across the inverter $U_{d2}$ so that it is positive when the line is positive. This means that the characteristics for the inverter shown in Figure 6 should be turned around the $I_d$-axis.

By doing so, the diagram shown in Figure 7 is obtained and if we disregard the DC line voltage drop ($U_{d1} - U_{d2}$) we notice that an operation point A has been established. Here the rectifier controls the current and the inverter determines the voltage by the constant extinction angle $\gamma$ control.

### 3.3. Power reversal by changing the relation between the current orders

The Figure 7 is also used to illustrate the power reversal of an HVDC transmission. The current order for the rectifier is decreased from $I_{01}$ to $I_{01}'$ so that $I_{01}' < I_{02}$. Note, that there is no intersection point in the first quadrant, between the new characteristics of the rectifier and the unchanged characteristics of the inverter. However, we can find one, the point B in the fourth quadrant indicating that the polarity of the line voltage has changed. This means, that the rectifier is now operating as an inverter and inverter as a rectifier. The converter with the highest current order is operating as a rectifier.

The current order change which made the order of the former rectifier lower than that of the former inverter, obviously caused a power reversal of the HVDC transmission meaning, that the polarity of the DC line voltage was changed while the direction of the DC current flow remained unchanged.

This method of a power reversal can be used if a fastest possible power reversal is required. However, the speed of the reversal cannot easily be controlled by this method.

Although, one of the converter stations may request the fastest possible reversal in an emergency situation, the assisting station may not be able to confront such a shock in power change. Therefore, the power reversal is normally carried out by a three step procedure. The power is first ramped down to either zero or minimum power, followed by an interstation control sequence ordered reversal of the transmission direction and finally the power is ramped up in to the chosen level in the...
new direction. In this type of procedure the ramping speed is normally set by an operator.

3.4. The principle of current margin control

The reason for providing the inverter with a complete current control system has not been explained yet. As demonstrated in Figure 8 the earlier discussed operation point A can still be obtained, if the inverter can operate only in the constant extinction angle γ control mode of operation. The line 11-7-6 is the characteristics for the inverter operating in this mode.

![Static Ud/Id characteristics](statch3.vsd)

Figure 8

However, if we suppose that the AC voltage in the rectifier network drops the α minimum characteristics will fall below the constant extinction angle γ characteristics. Thus, the rectifier Ud/Iδ characteristics will change from 1-2-5 to 3-4-5 and no operation point between the rectifier and the inverter characteristics is established. This means, that the inverter voltage Ud2 is too high for the rectifier to be able to force a current through the DC circuit. Thus, the power transmission is made impossible.

Instead, if the inverter is provided with a current control mode as discussed earlier and indicated by the sections 6-7-8-9 in Figure 8, a new intersection point between the rectifier and the inverter characteristics is established at B in the diagram. In this operation mode the DC current is controlled by the inverter and the voltage is determined by the rectifier.

This basic control mode for HVDC has been called the current margin control principle of the fact, that the inverter current control system is given a current order, which is lower than that of the rectifier by an amount called the current margin Δ I. Practically the two stations are given equal current orders but the Δ I order is subtracted in the inverter. Δ I order is normally a constant value in the region of 10% of the rated current.

We conclude from the discussion above that with the use of the current margin control principle the station with the highest maximum voltage will control the current and the station with the lowest will determine the voltage.

![Static Ud/Id characteristics](statch4.vsd)

Figure 9

A modification according to Figure 9 of the inverter Ud/Iδ characteristics has been applied in HVDC systems. This modification, called the positive slope section between B and A, was originally introduced to avoid that the nearly parallel characteristics of the two converters, α minimum for the rectifier and the minimum extinction angle γ for the
inverter, to coincide for unfavorable combination of the rectifier and inverter AC voltages.

The positive slope has importance for the stability for the current control system. When the inverter is operating in the constant $g$ mode, the rectifier sees the inverter as a negative impedance, at least for lower frequencies in the DC current fluctuations the characteristics 7-6 in Figure 8 has a negative slope, meaning that the voltage across the inverter decreases with an increasing current.

3.5. Influence from the DC line resistance when considering the static $U_d/I_d$ characteristics

The DC line resistance was neglected in the above static $U_d/I_d$ characteristics. For a more accurate presentation both the rectifier or the inverter characteristics should be compensated by the line voltage drop $R_dI_d$. In the following Figure 10 the inverter $U_d/I_d$ characteristics is compensated by adding the $R_dI_d$.

![Static Ud/Id characteristics](image)

**Figure 10**

3.6. Dynamic aspects on the $U_d/I_d$ characteristics

In the discussion above about $U_d/I_d$ characteristics it was assumed, that the AC voltage and thereby $U_{dio}$ are constant and not depending on the variations of the DC current. With this assumption the slope of the inverter characteristics for constant $\gamma$ is constant and negative according to the second term in equation (9).

Practically $U_{dio}$ is never constant, but follows the non-zero frequency, DC current variations, because the connected AC network has an impedance higher than zero ohm. Thus the dynamic slope of the inverter constant $\gamma$ characteristics can be considerably more negative than the static slope determined by the coefficient $(d_x-d_r)U_{dioN}/I_{dN}$ in equation (10).

The consequence is that the higher the AC network impedance is, meaning the weaker the network is, the more influence the AC network has on the stability of the current control system and the more important is the choice of the static positive slope for the section B-A in the inverter characteristics according to Figure 9.

Equation (6) above,

$$U_d = U_{dio} \times \cos \alpha - (d_x - d_r) \frac{I_d}{I_{dN}} \times U_{dioN}$$

This leads to the expression

$$U_d = U_{dio} \times \cos \phi - (d_x - d_r) \frac{I_d}{I_{dN}} \times U_{dioN}$$

normaly used for the voltage across the inverter.
4. THE BASIC HVDC CONTROL SYSTEM

The control system illustrated in Figure 5 is the basic control system needed to operate an HVDC transmission. To differ between the rectifier and the inverter operation, both stations are provided with equal control functions with only some individually preset parameters. Both stations are given equal current orders, but the current margin $\Delta I$ order is subtracted in the inverter to make the effective current order in that station lower than in the rectifier.

4.1. Converter Firing Control System

The Converter Firing Control system receives a current order $I_0$ and sends out firing pulses (CP) in such a way that the ordered current is maintained. The dynamics of the HVDC transmission system is determined primarily through the settings of the Voltage Dependent Current Order Limiter (VDCOL) and the Current Control Amplifier (CCA).

4.1.1. Voltage dependent current order limitation (VDCOL)

When the DC voltage is low the current order is reduced by a current order limiter. The purpose of this function is to prevent instability in AC voltage, which can occur when a high current is forced into a weak inverter AC network. Further, it is used to achieve a controlled recovery without commutation failures.

To assist the AC system in recovering from faults, the reactive power consumed by the converters must often be limited. This is carried out by the VDCOL that reduces the transmitted DC current at low DC voltage.

![Converter firing control](image-url)

**Figure 12**

The characteristics of the limiter shown in Figure 12 has a fixed minimum and a maximum limitation of a slightly more complex structure. The break point $U_{dl}$, below which the current order is reduced, when the voltage is decreasing, can be different depending on the application. When the receiving AC network is very weak it can be suitable to locate $U_{dl}$ very close to $U_{AN}$, but in more normal cases $U_{dl}$ may be 50-70% of the rated voltage.

The DC voltage response is filtered in an asymmetrical lowpass filter before controlling the maximum limitation of the current order. The filter has different time constants for the decreasing and the increasing voltage and the time constant for the former is normally considerably lower than for the latter.

The control systems in both the rectifier and the inverter are provided with current order limiters and the time constants can be separately set for the two stations.
4.1.2. The current control amplifier (CCA)

The output signal from the current control amplifier is a reference for the delay angle and used as an input order to the firing control system.

The signal can be directly proportional to $\alpha$ or it can be a function of it. It should be limited to a region just outside the allowed region for $\alpha$, between an $\alpha$ minimum and an $\alpha$ maximum value.

The CCA is needed for the current feedback loop. It should have enough high gain to adjust the current order $I_0$ with the current response and a suitable dynamics to make the current control system stable and fast.

4.1.3. Firing Control

The objective of the firing control is to convert the ordered firing angle $\alpha$ to firing pulses, which are further transferred to the converter valves of the corresponding phase and within a correct interval. The firing angle being between the $\alpha = \alpha_{\text{min}}$ to $\alpha = \alpha_{\text{max}}$, the latter being determined by the minimum extinction angle $\gamma$ limit. The permitted changes of the firing angle are depending on the operation mode.

Thus, the most important task of the Firing Control is to make sure, that the firing instant does occur within the designed time limitations for the thyristor valves. For example, to avoid too fast changes at low $\gamma$ in regions, where the commutations may become unsuccessful. This is accomplished through the following features.

- The AC voltage has to reach a certain level ($U_{\text{MIN}}$, corresponding to $\alpha$ approximately 5 degrees at normal voltage) across the thyristor valve to enable firing. For inverter operation, the value (ALPHA MIN) is set to approximately 90 degrees, to prevent reversed voltage and thereby reversed power.

- Predictive extinction angle (AMIN) control ensures that the extinction angle $\gamma$ is kept above the minimum value, normally 17 degrees, to minimize the risk of commutation failures.

4.1.4. Control Pulse Generator (CPG)

The firing control orders the control pulse generator (CPG) to generate the gate control pulse signals individually to every valve in the converter.

In normal current control the $\alpha$ order from the current control amplifier CCA is directly turned into the correct phase position of the gate control pulse signals. The CPG distributes the control pulses to the correct thyristor valves. For each valve, one control pulse is sent, i.e. for a twelve pulse bridge, 12 pulses are sent per cycle. Furthermore, block, block with the bypass pairs, deblock and selection of the bypass pairs are also performed in
this system. The orders are received from either the pole sequences or from the protections.

4.2. Converter firing control

Operation modes

As discussed earlier, the current order $I_0$ to the inverter is lower by the current margin $\Delta I$ than that in the rectifier. Thus, the current delivered by the rectifier is higher than the current required by the inverter. The inverter tries to counteract that by increasing the firing angle $\alpha$. If the rectifier is capable of forcing the ordered current through the inverter, the $\alpha$ will reach its maximum value, determined by the minimum extinction angle $\gamma$ and the CFC will operate in the extinction angle $\gamma$ control mode of operation.

If the rectifier is not having sufficiently high maximum voltage, for instance caused by a low AC voltage, the inverter will take over the current control. The current through the rectifier will now be lower than the current order, by the current margin $\Delta I$. To be able to deliver the ordered current the intent is to decrease $\alpha$ as far as possible. Thus, the minimum delay angle $\alpha$ mode of operation is obtained from the current control amplifier output.

The CFC is thus able to operate in whichever of the following modes determined by the CCA:

- minimum delay $\alpha$ angle control
- constant DC current control
- minimum extinction angle $\gamma$ control
- constant DC voltage control
5. OTHER HVDC CONTROL FUNCTIONS

Overview of Voltage and Angle Reference Calculation (VARC)

5.1. Voltage and angle reference calculation (VARC)

The objective of the Voltage and Angle Reference Calculation function (VARC) is to ensure that the DC voltage $U_d$, the extinction angle $\gamma$ and the firing angle $\alpha$ will be within design limitations during the steady state conditions. This is done by calculating reference values for the DC voltage, $\gamma$ and $\alpha$, which are then sent to the Tap Changer Control (TCC). The DC voltage and the gamma reference values will also be sent to the converter firing control (CFC).

The $U_d$, $U_d \delta_0$ and angles are coordinated between the two stations for various operation modes and power levels.

The DC voltage, which is the same in both stations, except for the voltage drop across the DC line resistance, is controlled by the (VARC). Telecommunication is used to calculate the resistance of the line. Since the DC voltage is controlled in one station, the resistance is used to ensure a proper voltage control. During telecommunication outages the calculated resistance value is frozen.

5.2. Tap Changer Control (TCC)

The Tap Changer Control, (TCC) system is designed to control the Load Tap Changers of the converter transformers. The objective of the (TCC) is to keep the ordered $\alpha$, $\gamma$ and DC voltage at the preset values determined by the (VARC).

The tap changers operate much slower than the basic control function, acting on the control angle $\alpha$. One tap changer step takes some seconds to execute. Thus, there is no risk for interference between the basic converter control function and the tap changer control systems. One step
gives a change of 1-1.5% of rated value in the valve side voltage.

The tap changers in the inverter in the extinction angle $\gamma$ control are normally used to control the voltage on the DC line. The voltage response measured by a voltage divider is compared to an order, $U_{dio}$. For a significant difference between the two signals, the tap changer control system (TCC) orders increase or decrease of the valve side voltage. Because of the stepwise character of the tap changer, the control system must be provided with a dead band. To bring the voltage back to the reference value and thus avoid hunting, the dead band should have a width of at least one tap changer step.

When the inverter takes over the current control, the DC voltage tap changer control must be locked.

The voltage in the rectifier end of the line can be controlled by adding a proportional amount of the line voltage drop, $R_d \cdot I_d$ to the measured inverter end voltage.

In the rectifier the (TCC) is normally used to keep the firing angle $\alpha$ as close as possible to the rated value, which normally is chosen to 15 degrees. To keep the term $U_{dio} \cdot \cos \alpha$ in the expression (6) constant, at varying rectifier AC voltage, the current control system responds to it by changing $\alpha$. The (TCC) system in the rectifier compares an $\alpha$ response signal to a reference value and at a significant deviation it orders the tap changer to step and change $U_{dio}$. The control characteristics must include a dead band also here and $\pm$ step of 1.25% from rated value corresponds to a region from 12° to 17.5° in $\alpha$.

### 5.3. Reactive Power Control (RPC)

The purpose of the Reactive Power Control (RPC) is to control properties in the AC network connected to the converter station. The quantity to be controlled is either the AC bus voltage ($U$-control) or the reactive power exchange with the AC system ($Q$-control). To prevent excessive harmonics to enter into the AC system the (RPC) should also make sure that a sufficient amount of filters is connected. These tasks are performed by switching on and off the AC filters and shunt banks.

The harmonic filtering properties will be supervised by a function (Min filter) in the (RPC), that monitors the number of the connected filters. This number is compared to the number of filters, that is required for the present operating situation. To make sure, that the filtering performance requirements are met, the necessary amount and type of filters will depend on the operation mode and on the DC power level. To avoid overloading the filter, a higher priority function (Abs Minfilt) is included.

To avoid overvoltage, two functions are implemented in the (RPC) called $Q$-maximum and $U$-maximum. These functions disconnect the AC filters and the shunt capacitors to prevent a protective action at overvoltage. The functions are also active in the manual mode. The $Q$-maximum acts to prevent an overvoltage to occur, at for instance a pole trip, while the $U$-maximum disconnects AC filters to reduce an already existing high AC voltage.

In $Q$-control, the RPC will switch the AC filter banks to keep the reactive power exchange with the AC network to a preset value and within specified limits.

In $U$-control, the AC voltage will be controlled directly by the RPC AC filter switchings.

The Abs Minfilt has the highest priority of the RPC functions, since it prevents from overloading the filters and thereby also from filter and pole trips. The $U$- and $Q$-maximum functions have second and third priority, since they protect against the
overvoltage. The fourth priority is the Min filter function and finally, the control functions have the lowest priority.