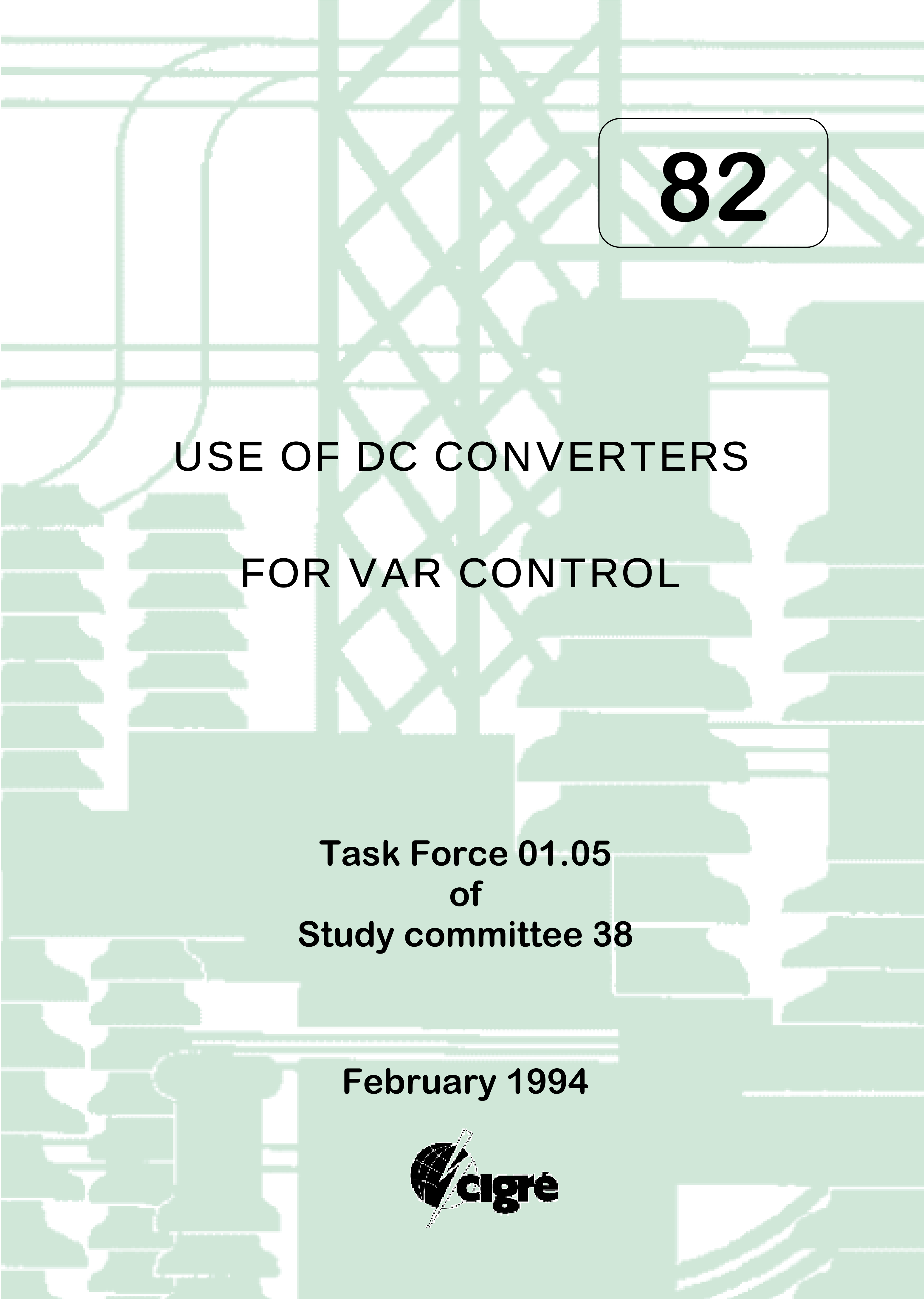

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USE OF DC CONVERTERS FOR VAR CONTROL

Task Force 01.05
of
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FOR VAR CONTROL

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(Power System Analysis & Techniques)

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Use of DC Converters for var Control

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PREFACE

This brochure is intended as an application guide for system planners and operators as well as equipment engineers, who want to evaluate control strategies for DC converters.

This brochure starts with an explanation of DC converter capabilities and how this can be evaluated for var control.

Impact from disturbances, etc. are explained and models for analytical studies are shown. Lastly, the application of var control is discussed and as an example, a DC converter with var control is compared with a converter station including a static var compensator (SVC) for var control.

The brochure contains 12 appendices with a detailed explanation of specific subjects discussed in the main report. These appendices are useful to experts in the specific fields and can be read independently of the main brochure.

ABSTRACT

The fast control of DC converters can be used to determine a control strategy useful for reactive power and voltage control in the AC network. The brochure deals with var control on DC converters and concludes that the performance can be similar to static var compensators (SVC) added to the converter station for this purpose. A novel feature is an analysis of the var range usable for converter control. It is found that the range depends highly on the active power through the converter. Curves for normal converters and for converters specially designed for this application are considered. The steady-state area for converter var control is significantly reduced from the theoretical area available, and the area available for dynamic control is between those limits. A substantial disadvantage is that natural commutated converters always absorb reactive power, which implies that the average value of the reactive power absorption will have to be increased to have a control range for var control. For the forced commutation type converter currently being investigated this is not the case, but only natural commutated converters are considered in this paper. For establishing a desired control strategy and for finding optimal parameters for var control, careful system studies have to be made and models for such studies are summarized.

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1. INTRODUCTION

Most transmission components such as lines and transformers have simple and passive performance in the power system. Contrary to this the performance of DC converters is very dependent on their inherent controls. Both the static and dynamic performance of DC converters are determined by the controls. This means that we can elaborate the control strategy of the DC converter in such a way that characteristics useful for the AC network are obtained. Normally priority is given to active power control, but in some cases var control can also be of interest.

Of course we cannot change the natural properties of DC converters, which properties are that they absorb reactive power whether in rectifier or in inverter operation. They also produce harmonics, wherefore AC filters are required to absorb some of these harmonics at the same time as they generate some of the var absorbed by the converter. But the exchange of reactive compensation is mostly determined by needs of the AC system.

The object of this paper is to explain how DC converters can be used for var control, and how the performance can be compared with other reactive power sources. The paper gives guidance to system planners and operators to minimize interactions of the AC/DC system with respect to voltage control and var optimization. Unwanted interactions due to harmonics, commutation failure, etc., are also considered.

Only natural commutated converters are considered in this paper.

2. DC CONVERTER CAPABILITIES

2.1 Introduction

Figure 1 shows the capability diagram or PQ diagram for an HVDC converter where the converter transformer taps and the AC system voltage are assumed constant. By capability diagram we understand a diagram similar to those used for generators and indicating the area available for control of active and reactive power by the converter.

In curve 1 (rectifier) the DC voltage is kept constant at its maximum value, and the power is controlled by the current.

In curve 2 the inverter is operated at the minimum control angle ($\gamma \sim 15\text{-}17°$) which is a compromise between the wish to reduce var absorption and limit the occurrence of commutation failure to values that are small and considered acceptable.

Together curves 1 and 2 represent the control characteristics with the lowest var absorption by the converters. These types of control are therefore often used in actual schemes in order to minimize losses, and because they provide for the least expensive converters. We refer to them as the basic control schemes.

Curve 3 represents a situation where the DC current is kept constant at its maximum value.

Within the area enclosed by curves (1), (2) and (3), the converter controls can in theory be made to act, very fast if necessary, in order to improve the operation of the combined AC/DC system. Additional control strategies can be implemented to act on AC or DC variables, or both, in order to control the flow of active and reactive power, the AC voltage or the frequency.

As example curve 4 in Figure 1 shows a case where the converter is operated with constant absorption of reactive power. Curve 5 with constant active power shows a case where the reactive power absorption can be changed by e.g. an external control to keep the local voltage constant while the active power transfer remains constant. Such control strategies should follow the requirement from the AC network.

2.2 Steady state DC converter capabilities

In practice many factors will reduce the area available for controls. Appendix 1 gives a detailed explanation of the factors important to the capability of reactive power absorption in DC converters, and how these factors limit the area available for control.

In theory it is straight-forward to design the converters for steady state operation with a consumption of reactive power which is higher than normal, but it has a significant impact on the price of the converter station due to the following factors:

If the reactive consumption should be increased by increasing the control angle, α or γ, the AC voltage on the valve side of the converter transformer must also be increased to retain the normal DC voltage and thereby full transmission capacity. It is then quite clear that the valves must be designed for higher voltage than for a normal optimum design. This has a direct impact on the valve price and converter losses as the number of thyristors and other components in the valves will increase. It also affects the price of the arresters across the valves, because the commutation over-shoots increases as well as the number of jumps which occur at firings and extinctions.

The conclusion is that the components in the damping circuits must be rated for higher power dissipation if the converters are to be operated with increased control angles and the valve price will go up. The valve cooling capacity must also be higher for increased power dissipation within the valve and this will also affect the price. The increased reactive power at rated active power also means an increased apparent power and by this an increased rating of the converter transformer. Further, operation with large control angles at rated current leads to an increased amount of harmonics on both the AC and the DC side, and this results in more expensive AC and DC filters.

To this it should be added that a frequent variation of U_{dio} by stepping the tap-changer leads to increased demands for maintenance on the tap-changer which also must be taken into consideration when judging the total extra costs.

In Appendix 1 these factors are analyzed in detail. From this appendix, Figures 2a and 2b show an example of the allowed areas of operation in the PQ diagram (shadowed). Figure 2a represents a normally designed converter ($\alpha_{max} = 25°$, $\gamma_{max} = 30°$ and $U_{diOmax} = 1.05 \cdot U_{diON}$. ($U_{diO}$, U_{diON} = a specific DC variable and its rated value which is proportional to the ideal, no-load voltage on the valve side of the converter transformer)). For the rectifier the maximum limit is composed of (from the left) the maximum ($\alpha + \mu$) curve, the maximum U_{dio} curve (note the break-point at $p \simeq 0.8$ p.u.), the maximum apparent power curve and the vertical line at $p = 1$ p.u. which corresponds to rated direct current. For the inverter the maximum limit is defined by the maximum U_{dio} and the maximum apparent power curves and the minimum limit is the minimum γ curve. Figure 2b represents a converter specially designed for an increased reactive consumption ($\alpha_{max} = 35°$, $\gamma_{max} = 40°$ and $U_{diOmax} = 1.2 \cdot U_{diON}$). In this case the upper limit of the allowed area for the rectifier is determined by the U_{diOmax} curve. From the example in Figure 2b we note that the range available for var control can be extensively increased, if needed even more than the area in Figure 2b.

As shown in Figure 1 (curve 6) there is normally a minimum current limit determined by operational needs. This limit can also be reduced to very small values if needed.

2.3 Converter transformer tap control

The PQ diagram of Figure 1 is valid only for given voltage conditions of the AC network and the tap selected on the tap-changing transformer. As an example, Figure 3 shows two diagrams with the same parameters at the same system voltage for the lowest and the highest tap of the tap-changing transformer. If the operating conditions change, e.g. through switching of lines or change in DC transmission power, fast control can adjust voltage to previous conditions. The new operating point for continuous operation is normally no longer in economic operating range, which is characterized by low losses and required reserves in reactive power control.

Returning the converter to the economic operating range can be done via the converter transformer's tap changer control, which adjust the new AC voltage on the valve side of the converter transformer in such a way that the operating range of the converter can be used to its full extent. Time delay between the steps of the tap changer is in the range of a few seconds. Another way is to switch shunt reactive elements (filters, capacitors and inductors).

2.4 Temporary DC converter capabilities

For steady state operation with increased reactive power as discussed above we suppose that it goes on for "infinite time" and we can control the reactive power in such a way that it affects only one converter station or one AC network at a time. The reactive power absorption capability in steady state is however rather limited.

Transient or short time operation with increased reactive power consumption is however something different. HVDC valves are according to IEC 700 tested with large control angles ($\alpha = 90°$) and high current for considerable time intervals (0.5 to 1 minute). Capability diagrams for utilization of temporary increased reactive power consumption, which must also include the time as independent variable, can be calculated in actual cases, but the issue is too complex to present generally valid temporary capability diagrams. It should be noted that converters can be specially designed to fulfil required AC system needs.

However, the reactive consumption of a converter can be considerably increased for a limited time by increasing the control angle, α or γ. But as the converter transformer tap-changers cannot be used in this case it is unavoidable that the other converter station is also affected as the direct voltage is decreased when α or γ is increased, and this may be acceptable or not. In a voltage controlling converter station the increased consumption is achieved simply by decreasing the voltage reference or increasing the control angle (α or γ) reference. Then the current controlling converter station must increase α or γ in order to keep the direct current equal to the reference value. In a current controlling converter station, α or γ can not be directly increased locally in a fast way to increase the reactive consumption. Instead the other station must first decrease U_d and by this force the current controlling station to increase the control angle. Thus it is clear that if it is not possible to use the tap-changers in the converter transformer, the reactive consumption can not be increased in one converter station without increasing the consumption in the other station too.

It is important to note that the control affects the converters in the sending and the receiving end in a "symmetrical" way, because if one converter is controlled to absorb more reactive power (P_{DC} = constant implies U_{DC} decrease and I_{DC} increase), the converter in the other end will experience a similar increase in the absorption of reactive power due to the increased current.

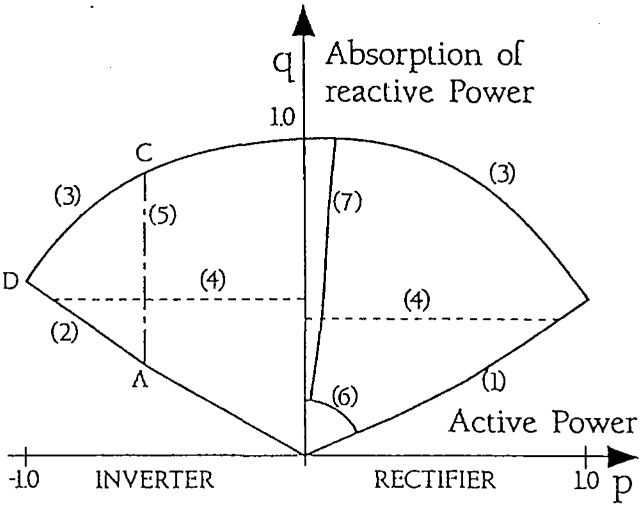
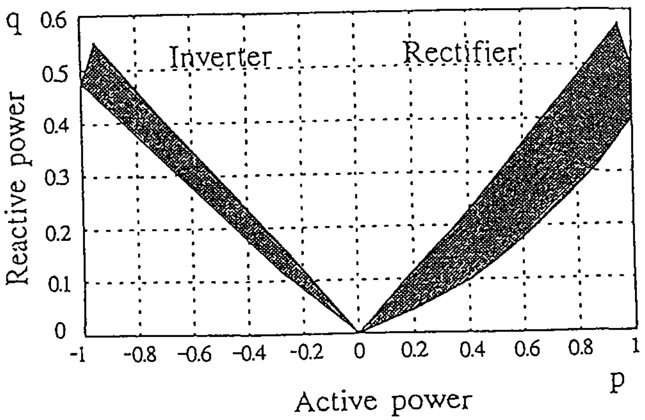


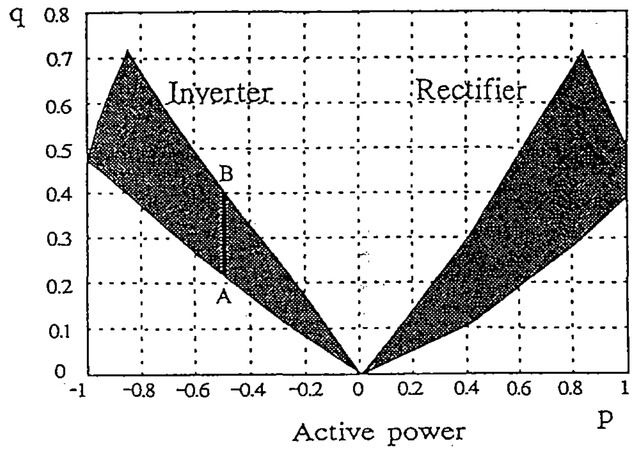
Figure 1. Capability diagram of DC converter terminalwith different control strategies

(1) Constant DC voltage control and minimum control angle (α min.)
(2) Constant minimum control angle (γ min.)
(3) Constant DC current control.
(4) Constant reactive power control
(5) Constant active power control
(6) Minimum direct current
(7) Maximum control angle (α max.)



γ_{min} = 16° and γ_{max} = 30°; α_{min} = 5° and α_{max} = 25°

Figure 2a - Area of operation in the PQ diagram for a normally designed DC converter (U_d fixed = 1 p.u. and U_{di0max} = 1.05 x U_{di0N}). Both q and p are in p.u. values related to the nominal active power of the inverter.



γ_{min} = 16° and γ_{max} = 40°; α_{min} = 5° and α_{max} = 35°

Figure 2b. Area of operation in the PQ diagram for a DC converter designed for operation with increased control angle and U_{di0} (U_d fixed = 1 p.u. and U_{di0max} = 1.2 x U_{di0N}). Both q and p are in p.u. values related to the nominal active power of the inverter.

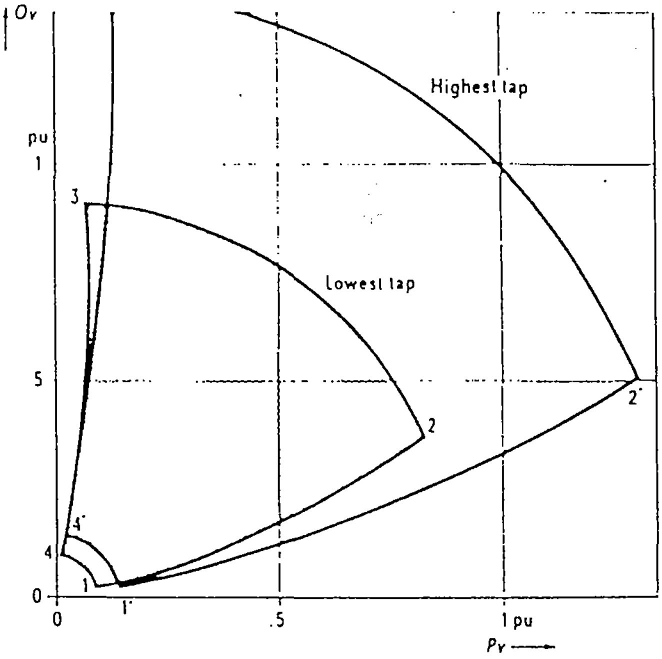


Figure 3. PQ diagram of a DC converter with different taps of the converter transformer. By the tap changer it is possible to operate the DC converter with rated values and thereby minimum losses at minimum and maximum AC voltage conditions.

3. THE DC CONVERTER USED FOR VOLTAGE CONTROL

3.1 Introduction

For investigations in the AC power system using the converter station for voltage control, curves showing the ability of stabilizing the voltage can be of value. We assume that we want to stabilize the AC voltage at the inverter keeping the active power constant at 0.5 p.u., cf. curve A-C in Figure 1. This can be done making a DC control characteristic as shown in Figure 4, where the slope of the curve from A to C is made by the DC control. As explained in Figure 2 the area available for steady state var control is limited. In the example in Figure 2b the stationary control range is limited to the line A-B (0.2-0.4 p.u.). Both the stationary control characteristic A-B and the temporary B-C is shown in Figure 4 by a fulldrawn and a dotted line respectively. This is a steady-state characteristic similar to that of a static var compensator (SVC). Doing this the converter can control the local voltage, which can be seen in the following way (consider the AC voltage the independent variable):

We start in point A at 1 p.u. voltage. If the AC voltage at the inverter increases, the DC control will make the inverter absorb more reactive power, and by doing so it will stabilize the local AC voltage. If the voltage keeps increasing, the voltage controller will eventually reach its end value in point B where the DC current has reached its maximum steady state value. The DC current limiter will then keep the DC current constant, which will limit the Var absorption for further voltage increase until the converter is switched off at its maximum voltage. For a limited time it is possible to absorb even more reactive power (curve B-C in Figure 4).

If the AC voltage decreases from 1 p.u., the converter will reduce its var absorption and by doing so it will stabilize the voltage until the voltage controller reaches its end value in point A, where the control angle γ is at its minimum value. Further decrease in the AC inverter voltage will result in an increase of the DC current to keep the active power constant. A condition for controlling decreasing voltage is of course that the converter is biased to run at a point between A and B in Figure 4.

The operating limits (maximum DC current for overvoltages and minimum control angle for undervoltage) can be extended by the use of the tap changers.

Using the converter transformer taps we are able to adjust the converter transformer to any AC voltage within the control range of the taps as shown in Figure 5. This means that we can fix the voltage controller to run in a condition where a needed control range in direction of either var absorption or generation is available. This also means that when the controller reaches its end value in either point A or point B in Figures 4 and 5, the taps can be adjusted to make the converter remain here in spite of further change in the AC voltage.

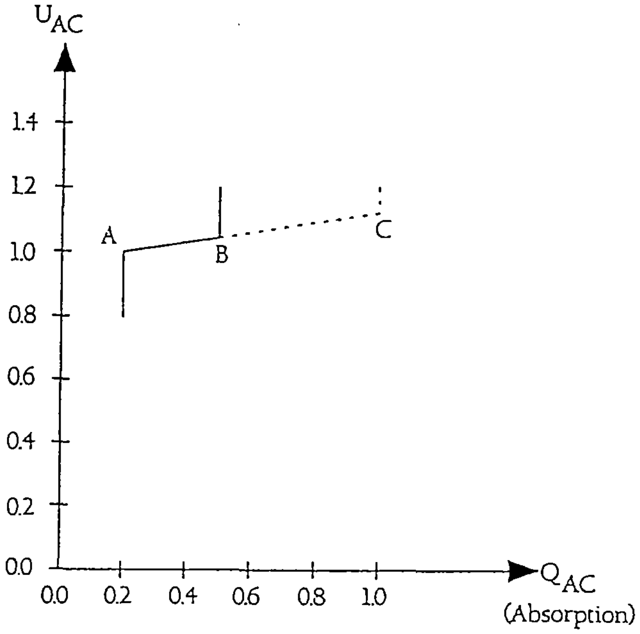


Figure 4. Voltage control at the inverter keeping the power constant at 0.5 p.u. (curve A-C in Figure 1 and curve A-B in Figure 2b). Note that the diagram is drawn in a way which is common practice for SVC plants, i.e. with u_{AC}, which is normally the independent variable, as the ordinate.

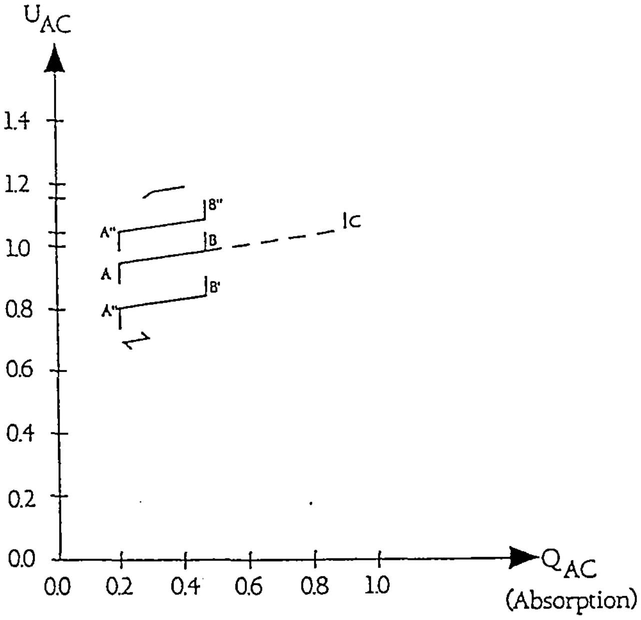


Figure 5. Adjusting the voltage controller to the actual AC voltage by use of the converter transformer taps.

3.2 Steady state control characteristics

We know from the previous chapter and from Appendix 1 that the available steady state control area is quite limited, from the area shown in Figure l.

We have also seen that an important characteristic is that the potential reactive power control range of a DC converter is very dependent on the active power transfer.

However when it comes to getting an impression of the voltage stabilization effect of a DC converter, PQ curves as shown in Figure 2 are not very suitable. To get a better impression of this, Appendix 2 analyses how the PQ curves derived from Appendix 1 can be converted into U/Q curves, which are normally used for SVC. In this case, contrary to SVC where the active power is zero, we have to introduce the active power through the converter as a parameter. Figure 6 shows an example of U/Q curves showing the available area for voltage control with the active power through the converter as parameter. The example is slightly different from Figures 2a and 2b (see α_{max}, γ_{max}, U_{diOmax}). Furthermore the direct voltage U_D is permitted to be lower than 1 p.u. Finally the rectifier and inverter are of equal size. From the example in Figure 6 we notice that the inverter has an inherent var control range between 0.1 p.u. (at p = 0.2 p.u.) and 0.26 p.u. (at p = 0.5 p.u.) and the rectifier a little less. For controlling the local AC voltage the effect is equal to an SVC with the same control range.

3.3 Concept of DC converter control

The inherent voltage control characteristic can be obtained by adding an overall control characteristic to the DC converter control. How this is done is explained in Appendix 3. In principle, it is done by keeping P and U as the overall controlled parameters in the DC converter control.

As explained in Appendix 3 other overall control modes are of course usable, such as fU (frequency - voltage), which seems favorable in small isolated networks.

3.4 Dynamic control

The converter controls can be used for AC voltage control during load changer, reactive equipment switching, fault clearing and load rejection. This control is done by acting on the direct currents or on the DC voltage, or on both at the same time.

The tap changer cannot help in this control because it is too slow (a few seconds).

The control of the temporary overvoltage due to load rejection is discussed in section 4.5.

The use of the converter to control the AC bus voltage has been extensively adopted in back-to-back installations, because information can be obtained from the inverter and the rectifier simultaneously. This type of control can also be used in point-to-point transmission, but in this case the reliability is decreased because of the need to rely on telecommunications.

The control of the AC voltage changes due to the switching of shunt reactive elements can also be done by limiting the size of the capacitor or filter to be switched. An example of this is summarized in Appendix 4.

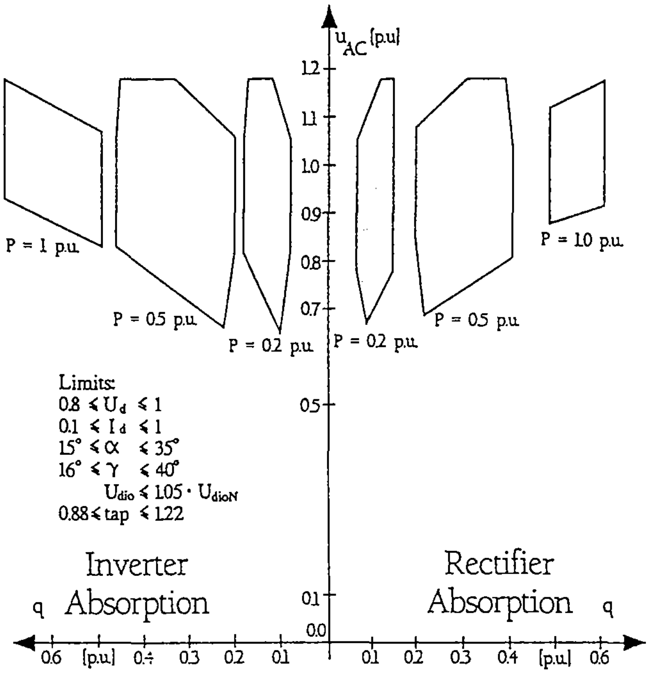


Figure 6. Example of U-Q curves showing the available area for voltage control with the active power through the converter as parameter.

3.5 Other considerations in using DC converters for voltage control

Normally, the operating point at continuous operation is chosen in such a way that losses of transmission are as low as possible, which means operating with low firing angle and maximum DC voltage. In the schemes with voltage/reactive power control the operating point with rated transmission power should normally provide some margin in firing angle to change converter reactive power consumption by voltage changes. This implies a certain increase in rating for DC equipment in the range of a few percent and also increase in losses. On the other hand, however, continuous operation with the increased control angle at the inverter means additional security margin against commutation failures.

Back-to-back link. In many cases both AC systems to which the DC back-toback station is connected are weak. The voltage and reactive power control according to the change in PQ converter diagram on one side produces change in voltage and current of the DC circuit and consequently the change in operating point of the other converter influencing the connected AC system. Control can therefore not depend only on the conditions in one system, as the control action on one side could produce voltage change on the other side. In this case control should weight both influences and use a compromize strategy. However, it means that the fast voltage control in one system has certain restrictions in effectiveness as it also has to take care of the voltage change in the other system.

However, with the help of a tap changer control and switching of reactive power elements the unsymmetrical conditions of both AC sides can be equalized, and the new optimum operating point for continuous operation can be reached.

Long distance transmission. In principle, the voltage and reactive power control can be used for long distance transmission in the same way. However, it differs in some important ways from a back-to-back station, viz.

- communication between both terminals is needed to coordinate control actions of both converters if major changes in active and reactive power are required. This means slower response of the control compared to the back-to-back station. Without communication (e.g. because of an outage) voltage and reactive power control can be effected only in a small range (within the current margin). It is not recommended, however, to change the current order without communication. The current margin is normally fixed to the minimum value. If it is lost, the DC voltage collapses and much larger disturbances appear in both AC systems.
- The voltage and reactive power control in a larger range means operating with lower DC voltage and higher DC current. This can have a substantial influence on transmission losses and should therefore be used only temporarily or justified by other advantages due to economic considerations.
- Interference from harmonics can disturb telephone communications.

4. RECOVERY FROM DISTURBANCES, HANDLING OF RESONANCES AND LOAD REJECTIONS

This chapter is about the undesired interactions in AC/DC systems. It summarizes transient AC voltage conditions in relation with DC converters. It covers both the overvoltage and the undervoltage aspects as well as the transmission of power by the DC system during and immediately after faults in the AC network.

4.1 Impact of DC faults

The immediate impact on the AC system of a fault on the DC side is not as severe as that of a fault directly on the AC system itself. The impact is felt indirectly and is different for faults on the DC line than for converter equipment faults. For a converter fault, the equipment must be taken out of service. This results in the permanent loss of a pole. In monopolar installations (e.g. back-to-back stations and submarine cables), this causes the loss of DC transmission and both locations in the AC network(s) must be capable of withstanding this loss. Where continuous ground or sea return current is not acceptable, DC links must be bipolar. Then the impact of a DC equipment fault is less severe because only half the trans-mission capability is lost. The impact on the AC system can be reduced further by the use of control strategies that overload the remaining pole. Theoretically, the power on the remaining pole can be doubled without causing undue impact on the AC voltage because the reactive compensation of the faulted pole can remain connected and compensate for the increased reactive power consumption. The short time overload capability of the converters is the practical limit. In some instances it is more advantageous to pay for the extra cost of a substantial overload capability than to reinforce the AC network to make it capable of withstanding the loss of DC transmission.

In the case of a DC line fault the normal protection strategy is to assume that the fault affects external insulation only and can be cleared by reducing the DC voltage to zero for a period sufficiently long (200 to 500 msec) to allow de-ionization of the air and re-establish the voltage withstand capability. If the restart attempt is not successful, a second sequence can be initiated with a longer delay, and possibly a restart at reduced DC voltage and hence reduced power. This multiple restart strategy is possible only if the AC system can withstand the loss of transmission for the longer duration. During the restart attempts, the reactive compensation remains connected, at both ends, while no DC power is transmitted. This is equivalent to a full load rejection which as discussed in subsection 4.5 below, can result in severe overvoltage conditions.

A special DC fault is a "commutation failure" which acts as a temporary short circuit of a valve, which should have been switched off. Examples of how commutation failure influences the AC system is summarized in Appendix 5. The conclusions in this Appendix are as follows:

- Both the rectifier and the inverter side are influenced by a commutation failure. The transferred disturbances are severe when the rectifier AC network is weak.
- The fundamental wave active power drops to low values during the failure on both rectifier and inverter side.
- The fundamental wave reactive power on the rectifier side becomes more inductive with increasing DC current and the fact that the rectifier bridge is in controlled operation.
- It is not possible to derive a general rule for the fundamental wave reactive power at the inverter because the bridge is not in controlled operation during the commutation failure.
- The recovery of the converter from commutation failures depends on the specific behaviour of control design and cannot be quantified for a general case.

Such aspects, together with specific mitigation strategies, are beyond the scope of this paper.

4.2 Impact of AC faults

During a fault in the AC network, a DC system can maintain some power transmission capability, depending on the AC voltage conditions and depending if the fault affects only the rectifier or the inverter or both.

Modern converters operating as rectifiers can transmit approximately 30% power during a phase-to-ground fault at the converter station. For symmetric faults, the power transmitted can be proportional to the AC voltage unless it is deliberately limited by control action (voltage dependent current order limiter).

If the fault affects the AC voltage at the inverter, there will be a commutation failure. Depending on the amount of distortion in the AC voltage, there may be persistent commutation failures, resulting in no transfer of power by the DC during the fault. In the best of cases, the average power transmitted during the fault is substantially reduced because of the reaction of the DC to recover from the commutation failure.

In Appendix 6 it is calculated how faults and switching in the AC network influence the DC converter. The calculation concerns the influence between normal frequency changes in amplitude and phase angle as well as transients. The conclusion does not give an answer to the risk of commutation failures but it emphasizes the factors influencing the risk of commutation failures.

As mentioned above the typical impact of commutation failure is calculated in Appendix 5.

The severity of the impact on the AC network(s) of this loss of DC transmission during the fault depends on whether the DC system is an asynchronous tie or if the DC line transmits power in parallel with an AC system. In this latter case, the power not transmitted by the DC during the fault overloads the AC network and could lead to a voltage collapse situation. On the other hand, the transient overload capabilities of the DC link can be used after the fault is cleared to enhance the transient stability of the AC system by modulating the power to help damp oscillations or by using the overload capability of the DC as a braking resistor.

4.3 Recovery from faults

The recovery of the integrated AC/DC system after a fault is inherently limited by the characteristics of the power circuit, but the quality of this response can be influenced directly by the control strategy adopted. As a general guide recovery to 90% of prefault transfer level can be accomplished in 100 to 300 milliseconds. However, if the SCR is less than 3.0 after fault clearing, the effects on the AC voltage of magnetizing inrush currents can be large and the impact of the recovery must be softened by restarting at a lower power level typically 80% in the 100-300 msec) followed by a slower rise towards 100%. The slower recovery is usually not significantly detrimental to the performance of the network, specially if the AC network has sufficient inertia to maintain transient stability. Too rapid a recovery can lead to the DC system drawing excessive reactive power from the AC network, thereby hindering post-fault AC voltage recovery.

Altogether the recovery should be adapted to the AC system needs.

4.4 Operation under low AC voltage conditions

Because of the AC voltage sensitivity to reactive power variations, the operation of a DC converter may become precarious under low voltage conditions. However, following the loss of AC network elements such as a main transmission line, the converter controls provide the ability to reduce both the power transfer and the reactive power absorption by the converter in a way that is compatible with the AC system capability and requirements. The criteria for such power runback operation of a specific HVDC installation can result from system transient stability studies as well as from AC voltage control or voltage stability studies.

4.5 Temporary overvoltages

Temporary AC system overvoltages can occur at the terminals of HVDC systems due to converter blocking, load rejections, AC fault clearing, DC faults and other disturbances. Because of the potential for damaging utility and customer equipment as well as the impact on DC converter station design and cost, it is essential that suitable temporary overvoltage control measures are included in the design of any HVDC system.

Surplus reactive power leads to voltage increase. The worst overvoltage condition is when the reactive compensation remains connected following a complete DC load rejection from full load conditions. The term "temporary overvoltage" refers to the complete waveform which consists of the fundamental frequency component and the superimposed oscillatory components resulting from AC network transients and possible low-order harmonic (LOH) resonances.

4.5.1 Fundamental-frequency overvoltages

The fundamental-frequency component is due to the mismatch between the supply of reactive power and the instantaneous reactive demand by the DC converter and the AC system. Figure 7 gives calculated results of fundamental-frequency overvoltages for rectifier and inverter operation as a function of the SCR, with the impedance angle of the network as a parameter. It shows that for equivalent AC network strengths, temporary overvoltages in the rectifier mode are normally more severe than in inverter mode, as the voltage drop of the active power on the AC network impedance produces an additional increase of overvoltage.

Fundamental-frequency voltage variations may also occur as a result of generator angle swings stimulated by faults or DC system power flow disturbances.

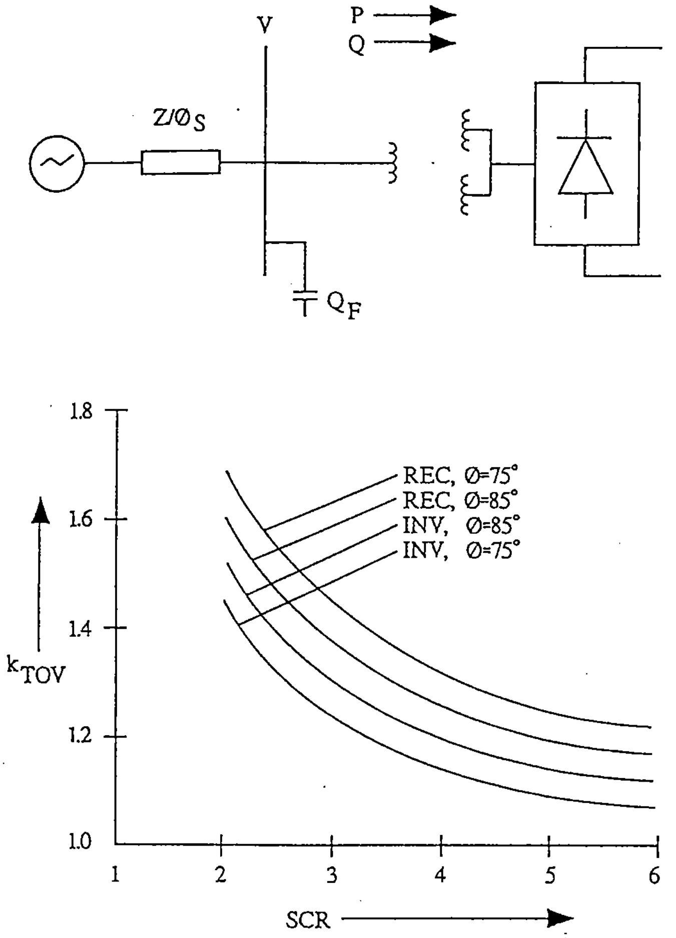


Figure 7. System configuration and results of a simplified calculation for overvoltage factor k_{tov} at blocking of DC substation over SCR assumptions:

$P_d = \pm 1$ p.u.
$Q_d = 0.6$ p.u.
$Q_f = 0.6$ p.u.
$\emptyset = 75°$ and $85°$

The reactive power consumption of a DC converter can be controlled by increasing the firing angle if the station is designed for reactive power and voltage control. Following a fault on the AC network with the resultant temporary blocking of the DC transmission, overvoltages can be limited if the DC restarts immediately. Nevertheless for the design of the equipment the most severe case must be taken into account. This is when the DC is not deblocked and the full overvoltage occurs. It is then necessary to limit the initial transient overvoltage to acceptable value using metallic-oxide arresters until a controlled reaction can be initiated.

The temporary overvoltages can be reduced apart from converter controls by such different means as the use of synchronous compensator, static var compensator, metal-oxide arresters, switching of shunt capacitors and AC filters connected to the busbar of the DC station or the addition of low-order harmonic filters. It should be noticed that if metal-oxide arresters are used to suppress fundamental frequency overvoltages the cause of overvoltage should be removed before the heating energy generated in metal-oxide arresters exceed its capacity.

Appendix 7 gives two examples of modern HVDC systems where special actions are used for the control of AC overvoltages resulting from load rejection.

4.5.2 Transient overvoltages

In the case of a fault in the AC network and subsequent blocking of the converters, even higher overvoltages can occur than at load rejection. Indeed at the recovery of the system, transient voltage components according to the natural resonance of the network are superimposed on the load rejection overvoltage. Figure 8 shows a temporary overvoltage at fault clearing when the DC remains blocked.

Also during re-energization of the converter transformers and other nearby transformers, high inrush currents can occur. If the harmonic components of this current meet resonance conditions in the network, harmonic voltages of high magnitude lasting for several seconds are superimposed on the operating voltage.

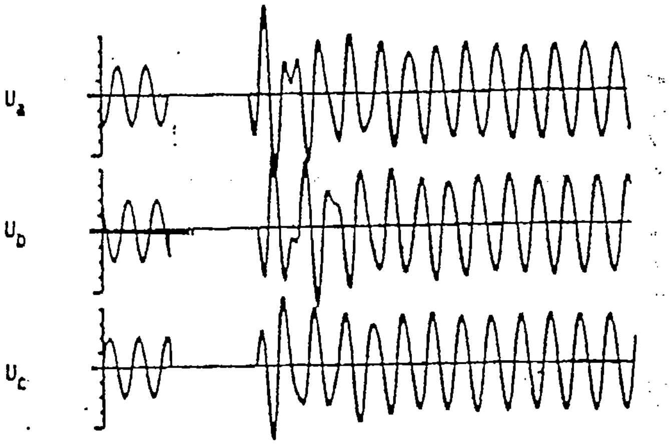


Figure 8. Temporary overvoltage at fault clearing without restart of DC transmission (SCR = 2.4)

4.5.3 Low-order harmonic resonances

The connection of capacitive shunt devices in order to supply the reactive power consumed by the converters reduces the Thevenin impedance of the network seen by the converter. If the short circuit power level of the network is low with respect to the operating power level of the DC converters, then the first natural resonance will be close to the second or third harmonic. The presence of nearby loads will normally provide sufficient damping such that these resonances will not create unacceptable overvoltage conditions.

Low-order harmonic resonances voltage components are created by interactions between non-characteristic harmonic currents injected by the converters during disturbances, harmonic currents injected by saturated transformers and the system harmonic impedance. If the HVDC system remains in operation, the system net impedance at the AC bus is affected by the DC system characteristics and controls.

Transients overvoltages can then be controlled to a certain extent by the influence of the converter. The worst case of low-order harmonic resonance overvoltage occurs when the AC system and the filters form a parallel resonant circuit tuned to the 2nd, 3rd, 4th or 5th harmonic. This may happen at minimum load as compared to fundamental frequency overvoltages which result from full load rejection.

5. MODELS FOR LOAD FLOWCALCULATIONS, TRANSIENT STABILITY CALCULATIONS AND LOCAL VOLTAGE CONTROL

The TF's opinion on requirements for DC models for planning of AC systems are summarized in Appendix 8.

Furthermore the TF have analyzed the replies to a questionnaire on the need for models for transient fundamental frequency studies of AC/DC interactions. The analysis is summarized in Appendix 9. The detailed analysis is available from the TF members. The analysis indicates that many user's claim the need for more detailed models, especially concerning the control system.

For load flow studies and for voltage stability studies Figures 2 and 6 give a good impression of how the control range and its dependence on the active power through the converter influence the use of converters for controlling the reactive power.

For transient stability analysis and fixing of control parameters, Appendix 10 describes a digital model, which can be used for power system planning studies.

If the available control strategies, e.g. var control, are to be used, detailed system studies are to be recommended in the planning stage to optimize the control parameters to the AC system needs. An extensive and general HVDC model to be used for such studies is described. In weak networks with risks for voltage stability, and to analyse the impact of faults, it is important to study the response of all major variables. For such studies the model summarized in Appendix 10 can be used.

6. CONSIDERATIONS ON USING DC CONVERTERS FOR VOLTAGE CONTROL COMPARED WITH OTHER SOURCES

The system requires reactive power to control the system voltage during the day, the year and in connection with disturbances. Sometimes reactive power is also used as a preventive measure, e.g. to avoid transient instability when faults have occurred. These system requirements can be divided into three parts, viz.

- one part to keep a needed voltage profile below the low daily, weekly and yearly variation of the load,
- one part needed for continuous voltage control, and
- one part needed for fast and/or frequent voltage control actions.

We have here demonstrated the DC converter suitability for voltage control by showing U/Q curves with the control range. For comparison Appendix 11 shows the similar U/Q curves for other reactive power sources, such as generator, synchronous generators and SVC.

Let us consider the DC converter potential for voltage control in connection with the system needs.

6.1 The DC converter used for the daily voltage control

Typically this control is carried out by switching in or out reactors or condensers 2-4 times a day. Under maximum load a need normally exists for additional condensers to compensate for the reactive load. The DC converter is not suited for this application simply because it always absorbs reactive power.

Under low load, or more exact if the transmission network is lightly loaded, a need often exists to reduce the voltages in the transmission network. The DC converter is well suited for this kind of operation, first because it normally is connected to a central busbar in the transmission network, and second because the DC converter in these situations normally also is lightly loaded, which implies that there is a relatively large margin for absorbing reactive power. The alternative is shunt reactors switched to the high-voltage grid. In some cases investment in reactors can be avoided. Anyway the DC converter in voltage control can replace reactors under repair and limit the number of switchings. Finally, the size of shunt-reactors can be extended using the fast DC voltage control to compensate in part for the voltage drop when switching in the reactor.

Appendix 4 describes this in more detail in an example where filters, capacitors and reactors are switched independently of the active power transfer. In this case, the fast voltage control facility of the DC converter is used to reduce the voltage change in connection with the switchings.

The U/Q diagram is valuable, when the gain in the DC voltage controller is fixed and for illustrating the converter function for the system operator, incl. its limitations.

6.2 The DC converter used for continuous voltage control

This application is very useful for weak systems with high system impedance, because the DC converter can act as an SVC to stabilize the voltage, as we have seen in chapter 3. By this control it is possible to stabilize any weak system under the assumption that the other side is strong. Of course, nothing is free in this world. Here the burden of stabilizing the weak network is sent to the other end of the HVDC connection, and, of course, this end must be strong enough and also willing to accept this. As previously explained, the influence on the other end of the DC link is only temporary as the steady state conditions can be equalized by the tap control of the converter transformer.

The area needed for continuous voltage control is dependent of the equivalent impedance of the AC network. Appendix 4 gives an example of how the planner can determine the area needed for continuous operation in the PQ diagram in the converter.

The alternative is to use SVC or synchronous condensers. These have the advantage that they can be used on one side without any influence on the other side, and that they can be used when the converter is out of operation or disturbed.

6.3 The DC converter used for reactive power reserve

To distinguish from the previous example we here think of need, which in principle is discontinuous and sometimes called reactive power reserve. Often this need is connected with the active power through the converter, e.g. when the system is in need of active power from the converter without increase of the absorption of reactive power from the converter (curve 4 in Figure 1). As change in active power is not treated in this paper, this important feature of DC converters are not treated further in this paper.

The DC converter is not very suited for delivering pure reactive power for instance to improve transient stability. The reason for this is that in order to have reactive power reserve in direction generation, the converter will have to be operated continuously at a high control angle and therefore with sustained increased losses.

As previously explained, the influence on the other end of the DC link is only temporary as the steady state conditions can be equalized by the tap control of the converter transformer.

In direction absorption, the reactive power reserve on the DC converter is extensive and useful to handle load rejections as explained in chapter 4.6.

6.4 Other considerations

As explained in chapters 2 and 3 the range for control of reactive power is limited and dependent on the power through the conver-ter. As explained in chapter 3, this means that the equipment in some cases must be designed larger to have control capacity at full load. As the voltage control facility is often only needed part of the year, perhaps one tenth, when the short circuit capacity is at its lowest, the inherent overload capacity in active power is available in the rest main part of the year. Further, in the first years of operation, where one system is weak, it may be useful to have a margin for reactive power control. Later, when it is useful, this margin may be used for uprating of the active power transfer by investing in other voltage stabilizing sources (SVC), if needed at that time. Planned in this way the DC converter can be more flexible to meet future needs.

Switching between two control concepts (γ_{min} and PU mode) for the DC converter is not a problem in practice as explained in Appendix 3.

6.5 Comparison between DC converter for voltage control and DC converter with SVC

Using voltage control on DC converters can be illustrated by the two examples shown in Figure 9. The assumption is that we need to transfer 1.0 p.u. active power, and for the continuous voltage control we need 0.25 p.u. reactive power under minimum short-circuit conditions. In example 1 this is obtained by uprating the DC converter and in example 2 by adding a SVC. Appendix 12 gives a more detailed explanation of how an increased var control range is obtained.

Figure 9 also summarizes the overall advantages and disadvantages of using the two different kinds of var control, which have to be taken into consideration in addition to the cost evaluation where the cost of the SVC (ex. 2) has to be compared with the cost of uprating the DC converter (ex. 1). The cost comparison will normally favour the last solution.

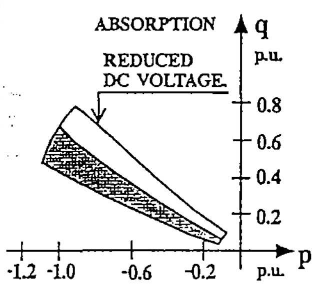
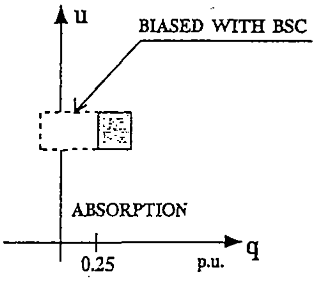
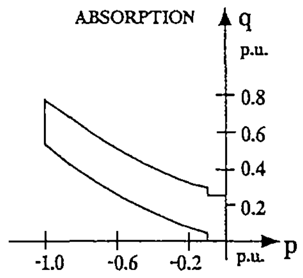
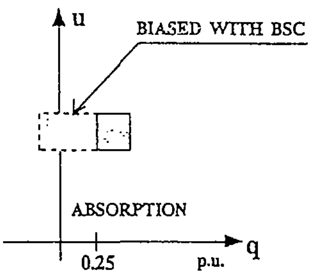
System need under Sc min: P = 1.0 p.u. Δq_{cont} = 0.25 p.u.	AREA FOR STEADY STATE INVERTER PERFORMANCE.	AREA FOR DYNAMIC CONTROL AT P=1.0 p.u.	ADVANTAGES	DISADVANTAGES
EX. 1 Pmax = 1.11 p.u. Smax = 1.24 p.u. Udomax = 1.12 p.u. γ max ≈ 32° HVDC control concept : var control $\gamma_{min} < \gamma < \gamma_{max}$ $U_{dio} < U_{diomax}$			1. Inherent approximate 0.11 p.u. continuos overload of active power (with reduced var control) 2. Temporary overload capacity in absorbing reactive power.	1. Increased losses when control area is used. 2. Control range is dependent on the active power flow through the converter and is particularly reduced at low power. 3. The fast reactive power control influences temporarily the reactive power at the other terminal.
EX. 2 Pmax = 1.0 p.u. Smax = 1.11 p.u. Udomax = 1.05 p.u. (γ max = 24°) SVC = - 0,25 p.u. HVDC control concept : Min γ control			1. Var control is independent of the active power. 2. Can be biased to run at minimum SVC losses (with ± SVC) 3. Var control is independent of HVDC operation. 4. Var control does not influence the other converter. 5. SVC can be used on DC converter blocking to reduce overvoltages.	1. Losses in SVC. 2. Need more space.

Figure 9 - Comparison between DC converter with voltage control and DC converter with SVC.

7. CONCLUSION

The fast control of DC converters can be used to achieve a control strategy useful for the AC network.

The full half-circle PQ area limited by the maximum converter current is in practice limited both for temporary and especially for steady state conditions. The steady state limitations are shown in the example in Figure 2 for 1 p.u. DC voltage. (A larger area can be obtained by reducing the DC voltage). The temporary limitations are not quantified in this paper.

This demonstrates that voltage control of the local AC network is an available and in some cases useful option for DC conver-ter control. Such cases are where static var compensators (SVC) or synchronous condensers would otherwise have been needed for continuous control of the AC voltage and where load rejections in the AC network cause overvoltages. The example shown in chapter 6 can give the reader an overview of the advantages and disadvantages of using DC converter var control.

If the available control strategies are to be used, detailed system studies are to be recommended in the planning stage to optimize the control parameters to the AC system needs. A model for such studies is summarized in Appendix 10, and Appendix 9 summarizes the evaluation of the answers to a questionnaire of what utilities find important for modelling in system studies.

Undesired interactions from disturbances, resonances, load rejections, etc. are to be carefully looked at in actual schemes.

Finally, it should be mentioned that more precise studies are required to keep the active power constant while the converter control controls the AC voltages in actual power systems. This item is recommended for further studies.

APPENDIX I

CAPABILITY OF REACTIVE POWER ABSORPTION IN DC CONVERTERS

by Göte Liss and Ture Adielson, Sweden

I.1 INTRODUCTION

An HVDC convertor of the conventional type, the so called line commutated convertor, does always absorb reactive power when in operation. This is the case irrespective of whether it operates as rectifier or inverter. The reactive absorbtion is normally strongly dependent on transmitted active power. It also depends on a number of other variables and on some parameters in the HVDC system.

The HVDC convertor has theoretically a relatively large capability to control and absorb reactive power, at least when the direct current is high, but this demands special control principles for the whole HVDC transmission system and can not be attained without paying for increased capability of the convertors. For convertors not specially designed for increased reactive absorption, the capability is more moderate at least in steady state operation.

Further development of the conventional convertor will not change this situation very much. However, if and when other types of convertors, especially forced commutated convertors with extinguishable (GTO-type) thyristor valves, will be available for HVDC applications much more advanced reactive power control can be performed. The convertor can in this case both generate and absorb reactive power without affecting or being dependent on transmitted active power. This type of convertors can already now be delivered for smaller d.c. applications, but for full-size HVDC transmissions more research and development still remains.

The normal way of operating an HVDC system is to keep the direct voltage constant in the rectifier end of the d.c. line by convertor transformer tap-changer control in the inverter. By this the voltage can be kept as high as possible in order to minimize the line losses. The system is sometimes designed to keep U_{di0} constant using the tap-changer, U_d in this case being kept constant by varying γ in one way or the other.

In this report the reactive absorption capability for an HVDC convertor is discussed and approximative "capability charts" are presented.

It has not been the intention to cover in detail the matter of how to control the HVDC convertors in order to utilize the inherent reactive absorption capability but some basic aspects are accounted for. It should be stressed here that the maximum values for reactive absorption presented in this report are only examples and can not be guaranteed for a specific project.

I.2 GENERAL ASPECTS

There are a few important relations which can be used for calculation of steady-state characteristics in an HVDC transmission:

$$P_d = U_d \cdot I_d \;; \qquad \text{...(1)}$$

$$Q_d = \frac{U_{dio} \cdot I_d}{4} \cdot \frac{\sin 2\alpha - \sin 2\,(\alpha + \mu) + 2\mu}{\cos\alpha - \cos(\alpha + \mu)} \;; \qquad \text{...(2)}$$

$$U_d = U_{dio} \cdot \cos\alpha - (d_x + d_r) \cdot \frac{I_d}{I_{dN}} \cdot U_{dioN} \;; \qquad \text{...(3)}$$

$$\cos\alpha - \cos(\alpha + \mu) = 2 \cdot d_x \cdot \frac{I_d}{I_{dN}} \cdot \frac{U_{dioN}}{U_{dio}} \;; \qquad \text{...(4)}$$

$$\alpha = \pi - \gamma - \mu \;; \qquad \text{...(5)}$$

These relationships refer to a specific convertor and the variables and parameters are:

U_d	direct voltage.
U_{di0}, U_{di0N}	a specific HVDC variable, and its rated value, which is proportional to the ideal, no-load voltage on the valve side of the convertor transformer ($U_{di0}=3\sqrt{6}\cdot U_{ph}/\pi$ if the winding ratio of the convertor transformer is $\tau=1$).
d_x	a parameter proportional to the short-circuit impedance of the convertor transformer ($d_x=0.5\cdot x_k$).
d_r	represents the resistive losses in the convertor transformer.

I_d,I_{dN}	direct current and rated direct current respectively.
α	delay angle.
μ	overlap angle (calculated from equation (4)).
Q_d	absorbed reactive power.
P_d	transmitted d.c. power referred to the rectifier.
γ	the extinction angle.

By using equation (5) it is easy to derive expressions which are directly related to inverter operation:

$$U_d = U_{dio} \cdot \cos\gamma - (d_x - d_r) \cdot \frac{I_d}{I_{dN}} \cdot U_{diON} \quad ; \qquad ...(6)$$

$$\cos\gamma - \cos(\gamma + \mu) = 2 \cdot d_x \cdot \frac{I_d}{I_{dN}} \cdot \frac{U_{diON}}{U_{dio}} \quad ; \qquad ...(7)$$

Equation (2) above is the exact expression for reactive power absorbtion in an HVDC convertor and is used together with equations (1) and (3) for calculating Q_d as a functin of P_d. The delay angle α can be used as a parameter. However, equations (3) and (4) must be used for solving for the overlap angle μ which also appears in (2) and to be able to do that we must decide how to control the convertor, for instance, should we use the tap-changer to keep U_d or U_{di0} constant. These two cases have been investigated and graphs for Q_d as function of P_d have been calculated and are discussed below.

The reason for the overlap angle μ to appear as a variable in the expression for the reactive power absorption is that it is directly related to the convertor transformer short-circuit impedance via the parameter d_x as shown in equations (4) and (7) above. If the transformer impedance is zero the current can commutate instantaneously from one valve in the valve bridge to the next and the phase current lags the a.c. voltage by exactly α degrees. For a real transformer with a short-circuit inductance greater than zero it takes some time for the current in a just fired valve to grow from zero to a value equal to the current on the d.c. line, i.e. there is a commutation process which takes some time ($t_\mu=\mu/\omega_0$). A consequence of this is that the fundamental frequency component of the phase current lags the voltage by an angle larger than α but less than (α+μ).

For a convertor transformer without impedance equations (2) to (4) are simplified to:

$$U_d = U_{dio} \cdot \cos\alpha \quad ; \qquad ...(8)$$

$$\mu = 0 \quad ; \qquad ...(9)$$

$$Q_d = P_d \cdot \tan\alpha \quad ; \qquad ...(10)$$

The calculations below have been performed with d_x=7% and d_r=0.5%. Variables are in per unit with U_{dN} as base, i.e. $I_{dN}=P_{dN}/U_{dN}$, by which U_{dioN} is obtained from equation (3) for nominal values on the other variables. Nominal U_d for the inverter is here defined as 1-r_{dN} (r_{dN} being the nominal d.c. line voltage drop, $r_{dN}=R_d \cdot I_{dN}/U_{dN}$. r_{dN}=5% is choosen here). Thus the nominal values for U_{dioN}, in per unit with U_{dN} as base, are obtained from the following relations. For the rectifier it is:

$$1 = U_{dioNR} \cdot (\cos\alpha_N - (d_x + d_r)) \quad ; \qquad ...(11)$$

and for the inverter:

$$1 - 0.05 = 0.95 = U_{dioNI} \cdot (\cos\gamma_N - (d_x - d_r)) \quad ; \qquad ...(12)$$

It is worth to mention here that a good approximation for equation (2) exists and is:

$$Q_d = P_d \cdot \sqrt{(\frac{U_{dio}}{U_d})^2 - 1} \quad ; \qquad ...(13)$$

This expression gives a value which is 1 to 2 per cent higher than the correct one in normal operation. It offers, however, a good understanding of how different parameters and variables affect the reactive absorbtion of the convertor. It is clear that, for constant P_d, the reactive power absorbtion is manipulated only by varying the quotient U_{di0}/U_d. Q_d can be increased at constant U_d and constant P_d (i.e. also constant I_d) by increasing U_{di0}, but to attain this, i.e. to keep U_d constant at increasing U_{di0}, equations (3) and (6) indicates that α or γ must increase. Thus it is possible in this case to increase Q_d without increasing I_d.

Q_d can also be increased by decreasing U_d with U_{di0} constant. To do that however, I_d must be increased to keep P_d constant.

We also see from equation (13) that if Q_d should be kept constant when U_{di0} is constant and the active power is reduced the only way to solve it is to reduce U_d and this can only be done by increasing α (in rectifier operation) or γ (in inverter operation).

From this discussion we understand that whatever we do to operate with increased reactive power, at least in steady-state operation, we must pay for higher rating for the valves and possibly also for the convertor transformers. High U_{di0}, large α (or rather α+μ as discussed below) or γ as well as high current result in valves and convertor transformers with higher rating then normally. It also increases the cost for filters.

It should be mentioned here that for only a few HVDC projects it has been requested and economically justified to design the convertor station equipment for significantly increased absorbtion of reactive power. This is the explanation for the normally designed convertor being optimized for minimum absorbtion of reactive power. Notice also here that we are talking about real steady-state operation which means "infinte time" by definition. Operation with increased reactive absorbtion during limited time is discussed in last paragraphs of this report.

I.3 INCREASED APPARATUS STRESSES CAUSED BY OPERATION WITH HIGH REACTIVE ABSORPTION

It is straight-forward to design the convertors for steady state operation with higher than normal absorbtion of reactive power, but it has a significant impact on the price for the convertor station. It can be interesting to see in which way it affects the price. However, a complete and detailed account for all the relations which must be considered for such a design would carry too far for this report and so a simplified handling of the subject follows below.

If the reactive absorbtion should be increased by increasing the control angle, α or γ, the a.c. voltage on the valve side of the convertor transformer, i.e. U_{di0}, must also be increased to retain $U_d=1$ p.u. and full transmission capacity. It is then quite clear that the valves must be designed for higher voltage than for a normal optimum design. This has a direct impact on the valve price as the number of thyristors and other components in the valves will increase. It also affects the price for the arresters across the valves. To this it should be added that a frequent variation of U_{di0} by stepping the tap-changer leads to increased demands for maintenance on the tap-changer which also must be taken into consideration when judging the total extra costs.

Further, it is indicated above that α (in rectifier operation) or γ (in inverter operation) must normally be increased to obtain increased reactive power. This has also an influence on the valve price which can be understood by referring to Figure 1. Figure 1a shows the voltage across a valve fired at $\alpha = 15°$, i.e. a rectifier valve, and Figure 1b the voltage across an inverter valve with $\gamma = 16°$.

The size of commutation over-shoots in the valve voltages depend on α and γ. These over-shoots affect the power dissipation in the arresters across the valves, especially at increased voltage due to partial or full load rejection, and must be considered when designing these arresters.

The commutation over-shoot indicated by b1 in Figure 1b gives the highest valve voltage in inverter operation. If now γ is increased from 17° the commutation associated with the over-shoot at b1 (this over-shoot comes at the end of the overlap) will move to the left in relation to the sinusoidal part of the valve voltage and the top of the over-shoot will reach a maximum value for a specific γ-value greater than 17°. If γ is further increased the maximum of the over-shoot will go down again. We understand from this that the stresses on the valve arresters will increase when γ is increased and if the arresters have to be uprated to handle higher power dissipation it will have an impact on the convertor station price.

Another typical property of the valve voltages, as seen in Figure 1, is a number of jumps which occurs at firings and extinctions. These jumps cause transient power dissipation in the valve damping circuits and the thyristors and are decisive for the rating of the components involved.

The conclusion is that the components in the damping circuits must be rated for higher power dissipation if the convertors are to be operated with increased control angles and the valve price will go up. The valve cooling capacity must also be higher for increased power dissipation within the valve and also this will affect the price. The increased reactive power at rated active power also means an increased apparent power and by this an increased rating of the convertor transformer for which the transformer must be designed. Further, operation with large control angles at rated current leads to an increased amount of harmonics on both the a.c. and the d.c. side and this results in more expensive a.c. and d.c. filters.

I.4 STEADY-STATE OPERATION WITH CONSTANT DIRECT VOLTAGE

As just mentioned the reactive absorbtion of the convertor can be increased, for a given value of transmitted power P_d and constant U_d, by increasing U_{di0} and the delay angle α. For a normally designed convertor, i.e. not intentionally designed for increased reactive absorbtion,this can not go very far because the maximum voltage across the valve and the losses in the valve circuits will increase with increasing reactive absorbtion. If an increased convertor cost is accepted, the convertor can be designed for steady-state operation with higher U_{di0} and α. Similar aspects are valid for inverter operation; high U_{di0} and γ means high reactive power absorbtion. It is also clear that if the convertor is designed for higher than normal absorbtion of reactive power at rated active power, the convertor transformer with its tap-changer will be more expensive.

In Figures 2a to 2f, graphs of Q_d as function of P_d are presented for different values of α (rectifier operation) and γ (inverter operation) and for different values of constant U_d. For Figures 2a and 2b, $U_d=1$ p.u., for Figures 2c and 2d, $U_d = 0.9$ p.u. and for Figures 2e and 2f, $U_d=0.8$ p.u.. In the first quadrant, which corresponds to rectifier operation, the reactive absorption is limited on the lower side by the locus for minimum α. This locus has been calculated for $\alpha = 5°$ which is a normal minimum value. A current controlling rectifier can not be operated in steady-state at minimum α because there is no control margin for the current control system to increase U_d in the case of a disturbance. There should also be a lower limit defined by a locus for minimum direct current but this is of minor importance for the general discussion in this report and has not been presented.

It should be noted that P_d in Figures 2a to 2f is transmitted power referred to the rectifier end of the d.c. line and that it is positive when the power goes out from the convertor on the d.c. side.

Q_d is also calculated for a nominal value of $\alpha=15°$ and for $\alpha=25°$ or $\alpha=35°$. There is of course no universal maximum value for α but 25° at rated current is reasonable for a convertor not specially designed for increased reactive absorbtion. $\alpha=25°$ represents one upper limit for reactive absorbtion at rated current. Q_d has also been calculated for a minimum γ=16° and maximum values of 30° or 40°. γ=30° is a reasonable maximum value for a normally designed convertor. The corresponding curves are shown in the second quadrant of Figures 2a to 2f. The curves in this figures have been calculated for a power range from 0 to a maximum value corresponding to 1 p.u. in I_d.

It should be noted that the large voltage jump in the valve voltage across a rectifier valve, a1 in Figure 1a, comes at the extinction of the valve and accordingly the size of it depends on the angle ($\alpha + \mu$). Thus the maximum α related to the maximum stresses on the valve in rectifier operation at varying P_d should be derived from the value on ($\alpha + \mu$) at maximum (or rated) current rather than being kept constant. This would give a higher value for the maximum allowed reactive power absorbtion for P_d less than 1 p.u. Also this is a little conservative as it is possible to increase α slightly more with decreasing direct current, but we disregard this here for the reason of simplicity. Figure 3 shows the reactive power absorbtion of a rectifier for constant α=25° (curve 1) and for constant ($\alpha + \mu$) (curve 2) corresponding to α=25° at rated power and we see that the difference in reactive absorption is about 0.1 p.u. in the middle of the active power range. Curve 2 in Figure 3 is included also in Figures 2a to 2f as curve 4.As mentioned earlier U_{di0} must increase when γ or α increases in order to keep U_d constant and the maximum allowed U_{di0} will accordingly define one further upper limit. Curves $Q_d(P_d)$ for constant U_{di0} equal to maximum values of $1.05 \cdot U_{di0N}$ and $1.15 \cdot U_{di0N}$ have been calculated for both rectifier and inverter operation (see the text to the right of Figures 2a to 2f).

Concerning the upper limit the conclusion is that it may be determined either by the maximum ($\alpha + \mu$) or maximum U_{di0} curve in rectifier operation and by maximum γ or maximum U_{di0} in inverter operation.

Note here that U_{di0} varies along a constant α locus in rectifier operation and constant γ locus in inverter operation, and it increases with increasing P_d. The reason is that U_{di0} must be increased with increasing I_d (or P_d, which is the same) to compensate for the increasing transformer voltage drop, i.e. for the term $(d_x+d_r)\cdot(I_d/I_{dN})\cdot U_{di0N}$ in equation (3) or the the corresponding term in equation (6), in order to keep U_d constant which was an assumption for the calculations. As mentioned earlier, U_{di0} is proportional to the valve side a.c. voltage of the convertor transformer and the increase in U_{di0} for increasing P_d, when moving along a constant α (or γ) locus, must be performed by changing the winding ratio in the transformer. Thus the tap-changer will step when moving along the constant α (or γ) locus. The variations in U_{di0} is shown in Figure 4.

For the constant ($\alpha + \mu$) locus in rectifier operation, U_{di0} increases with decreasing P_d. This is understood if we combine equations (3) and (4) to obtain:

$$U_d = U_{di0} \cdot \frac{\cos\alpha + \cos(\alpha + \mu)}{2} - d_r \cdot \frac{I_d}{I_{dN}} \cdot U_{di0N} \quad ;...(14)$$

The last term in the right member is small, because the presence of the factor d_r, and can be neglected here. Then we see from equation (14) that if ($\alpha + \mu$) is constant and as α increases with decreasing P_d, U_{di0} must increase with decreasing P_d. This is also illustrated in Figure 4 in which also the constant ($\alpha + \mu$) locus has been shown in each rectifier diagram.

One more upper limit for reactive power absorbtion in the convertor should also be defined. This is the locus for constant apparent power, which is a part of a circle in the Q_d/P_d diagram and which passes through the points of nominal operation, α=15°, $P_d=P_{dN}$ in the first quadrant and γ=16°,$P_d=-P_{dN}$ in the second quadrant (for U_d=1 p.u., i.e. in Figures 2a and 2b). It should be noted that in Figures 2 and 4 the graphs in the second quadrants are not continuations of the graphs in the first quadrant as, according to equations (11) and (12), U_{di0N} is not equal for rectifier and inverter operation. This explains the discontinuity in the constant-S curve in Figure 2 and the constant-I_d curve in Figure 6. Note that a constant-current locus can not be included in Figures 2a-2f as these Figures are celculated for constant U_d; P_d can not be varied if both I_d and u_d are constant.

Thus the allowed area of operation in the Q_d/P_d diagram is limited by loci for minimum α (minimum γ in inverter operation), maximum ($\alpha + \mu$) (maximum γ in inverter operation), maximum U_{di0} and maximum or rated apparent power and this area is not very large for a normally designed convertor.

In Figures 5a and 5b the allowed areas of operation in the P_d/Q_d diagram are shown shadowed. Figure 5a represents a normally designed convertor with an α_{max}=25° as rectifier or γ_{max}=30° as inverter and $U_{di0max}=1.05 \cdot U_{di0N}$. For the rectifier the maximum limit is composed of (from the left) the maximum (α+μ) curve, the maximum U_{di0} curve (note the breake-point indicated by A at $P_d \approx 0.8$ p.u.), the maximum apparent power curve and the vertical line at P_d=1 p.u. which corresponds to rated direct current. For the inverter the maximum limit is defined by the maximum U_{di0} and the maximum apparent power curves and the minimum limit is the minimum γ curve. Figure 5b represents a convertor designed for an increased reactive absorbtion with α_{max}=35° , γ_{max}=40° and, to make U_{di0max} decisive for the upper limit, $U_{di0max}=1.2 \cdot U_{di0N}$. In this case the upper limit of the allowed area for the rectifier happens to be determined by the maximum U_{di0} curve.

I.5 STEADY-STATE OPERATION WITH CONSTANT DIRECT VOLTAGE AND U_{di0}

Graphs have been calculated for constant $U_{di0}=U_{di0N}$ and constant U_d=1.0, 0.9 and 0.8 p.u. To keep these variables constant, α in the rectifier and γ in the inverter must increase with decreasing direct current as indicated in equations (3) and (6). This mode of operation is understood if we start at $I_d=I_{dN}$ and decrease I_d. Equations (3) and (6) indicate that α or γ must increase with decreasing I_d to keep U_d constant when U_{di0} is constant. If U_d in the rectifier is to be kept constant by varying γ in the inverter, i.e. increasing γ when I_d is decreased, the d.c. line voltage drop must be lower than the d_x voltage drop in the convertors. If the latter is not the case, γ must be decreased when I_d is decreased and accordingly γ must be greater γ minimum in operation with rated current. Thus this type of control is practical only when the line voltage drop is lower than the d_x voltage drop in the convertors.

At rated power, $P_d=P_{dN}$, α or γ and I_d have their nominal values. It should be noted that the curves $Q_d(P_d)$ for constant U_{di0} ($=1.05 \cdot U_{di0N}$ or $=1.15 \cdot U_{di0N}$) have been presented as upper limits in Figures 2a to 2f. In Figure 6, $Q_d(P_d)$ is shown for U_d=1.0, 0.9 and 0.8 p.u. This indicates that the reactive power can be varied by changing U_d. When U_d is decreased with constant P_d, Q_d will increase as seen in the Figure 6. However, this means that I_d also must increase. In practice the current must not exceed the nominal value or some steady-state over-load maximum value. For that reason the locus for constant I_d=1 p.u. has been calculated and presented in Figure 6 as an upper limit for Q_d. With reduced direct voltage the control angles α and γ will increase considerably as shown in Figures 7 a and b.

The constant U_d loci in the first quadrant of Figure 6 are very close to, but not exactly, straight lines as equation (2) was used (they would have been straight lines if the approximative formula, equation (13), had been used). This is not the case in the second quadrant of the same Figure. The reason for this is that P_d and the constant U_d are referred to the rectifier end of the line, which in this case is supposed to have a resistance of 5% ($r_d=0.05 \cdot (U_{dN}/I_{dN})$).

I.6 STEADY-STATE CONTROL SOLUTIONS

It is not the intention to go deep into principles for HVDC control in this report, but basic aspects of interest for reactive power control are worth to be mentioned.

In steady-state control of reactive power the convertor transformer load tap-changer can be included in a slow feedback control loop by which the reactive power can be controlled locally in each convertor station without affecting the other station.

Consider the most normal way of controlling an HVDC transmission. In this case the rectifier controls the direct current by a controller which acts on the delay angle α and the tap-changer is used to control the U_{di0} so that α is kept close to the nominal value (e.g. 15°). The inverter is in this normal mode of control operated on constant γ and the tap-changer is used, in a feed-back loop, to control the direct voltage (e.g. referred to the rectifier end of the line).From this it is clear that a slow reactive power control function can be established in the rectifier by including a controller which varies the α reference in the tap-changer control loop. If, for instance, increased reactive power is requested the controller orders α to increase and this results in increased U_{di0}. This process will not disturb the inverter as the latter determines the direct voltage.

If it is requested that the reactive power should change faster in the rectifier than what could be attained by operating the transformer tap-changer, the direct voltage must be decreased by increasing γ in the inverter. In this case it is unavoidable that the inverter is also affected.

Increasing the reactive power in an inverter operating with constant γ control is performed by increasing the reference for γ. If this is done slowly enough so that the tap-changer, which controls the direct voltage, can follow,the rectifier will not be affected as the tap-changer controller will restore the direct voltage by increasing U_{di0}. If the inverter is in feed-back voltage control the tap-changer is used to keep γ close to a nominal value and a steady-state change of reactive power can be done by changing the γ reference.

Although not discussed specifically here it should be noted that the tap-changer range is a limiting factor for increasing the absorbtion of reactive power because it limits the possibility to increase U_{di0}. Thus it has an influence similar to the maximum U_{di0} limit.

I.7 CONVERTOR TRANSFORMER TAP-CHANGER ASPECTS

An HVDC convertor transformer is normally, and with very few exceptions, provided with a load tap-changer. The reason for this is that the valve-bridge voltage should have a specified value to attain optimal operation conditions in steady-state operation or for very slow variations in d.c. line loading and in the a.c. voltages. "Optimal operation conditions" here refers to highest possible direct voltage, U_d, to minimize the d.c. line losses, to operate with suitable control angles, α and γ, in order to avoid an unnecessarily high absorbtion of reactive power, which of course is the normal design target, and to avoid too low α for control purposes.

The tap-changer is connected to the a.c. side winding of the transformer because this winding has a grounded neutral and this is not the case for the valve-side winding. Thus stepping down the tap-changer means that the valve voltage increases.

The tap-changer range is normally determined by the magnitude of normal a.c. voltage variations and by the voltage variations along the d.c. line caused by the direct current variations. The tap-changer is used to control the direct voltage by varying the valve voltage up to a specified maximum value which should be reached even with lowest steady-state a.c. voltage and down to a specified minimum valve voltage to be obtained also with highest steady-state a.c. voltage.

There is of course always a nominal tap position corresponding to a nominal transformer winding ratio, $\tau=\tau_N$, which gives a nominal $U_{di0}=U_{di0N}$ for nominal a.c. voltage $U_n=U_{nN}$. If a maximum $U_{di0}=U_{di0max}$ should be obtained with the lowest $U_n=U_{nmin}$ the lowest tap position τ_{min} is defined by:

$$\tau_{min} = \frac{U_{nmin}}{U_{di0max} / (3 \cdot \sqrt{6} / \pi)} \quad ; \qquad \text{...(15)}$$

and to get U_{di0} equal to a specified minimum value U_{di0min} the highest tap position, τ_{max} should correspond to a winding ratio of

$$\tau_{max} = \frac{U_{nmax}}{U_{di0min} \ / \ (3 \cdot \sqrt{6} \ / \ \pi)} \quad ; \qquad \text{...(16)}$$

The tap position corresponding to τ_{min} is of interest for reactive power control as it is associated with U_{di0max} and by this with increased reactive power absorbtion. τ_{max} is not so interesting here because we can not decrease reactive absorbtion significantly below the level at rated operation but it may be of importance to keep U_d at rated value when Id decreases.

I.8 Q/U DIAGRAMS FOR AN HVDC CONVERTOR

The reactive power generation (or absorbtion) capability of power system components is sometimes expressed as the a.c. voltage as a function of the reactive power, i.e. as Q/U diagram. This can be done also for an HVDC convertor as shown in Figure 8. The rectifier diagrams shown here, which have been calculated for constant U_d and P_d and for the extreme positions of the convertor transformer tap-changer, should be considered as examples only. For Figure 8a both U_d and P_d were set to 1 p.u. and for Figure 8c, 0.7 p.u. was used for both. It should be noted that no α or U_{di0} restrictions have been considered when calculating the capability areas in Figure 8. However, the variations in α and U_{di0} are shown separateley in Figures 8b and d and from this it can be understood that the net capability areas are strongly restricted in accordance with the discussion in earlier sections of this report.

I.9 TEMPORARY REACTIVE POWER CONTROL

For steady-state operation with increased reactive power as discussed above we suppose that it goes on for "infinite time" and we can control the reactive power in such a way that it affects only one convertor station or one a.c. network, at a time. The reactive power absorption capability is however rather limited.

Transient, or short time, operation with increased reactive power absorbtion is however something different. HVDC valves are according to IEC 700 tested with large control angles (α=90°) and high current (1 p.u.) for considerable time intervals (0.5 to 1 minute). Capability diagrams for utilization of temporary increased reactive absorbtion, which must include also the time as independent variable, are not available and can accordingly not be presented here. However some examples of transient reactive power control is discussed below.

The reactive absorbtion of a convertor can be considerably increased for a limited time by increasing the control angle, α or γ. However, as the convertor transformer tap-changers can not be used in this case it is un-avoidable that the other convertor station is also affected as the direct voltage is decreased when α or γ is increased, and this can be accepted or not, in the general case it can not be accepted. In a voltage controlling convertor station the increased absorbtion is achieved simply by decreasing the voltage reference or increasing the control angle (α or γ) reference. Then the current controlling convertor station must increase α (or γ) in order to keep the direct current equal to the reference value. If the HVDC transmission is transmitting less then maximum active power an existing active power controller will increase the direct current in order to restore the power when the voltage is decreased and this will contribute to increased reactive absorption. In a current controlling convertor station, α or γ can not be directly increased locally in a fast way to increase the reactive absorbtion. Instead the other station must first decrease U_d and by this forcing the current controlling station to increase the control angle. Thus it is clear that if it is not possible to use the tap-changers in the convertor transformer the reactive absorbtion can not be increased in one convertor station without increasing the absorbtion in the other station too.

The reactive absorbtion of a convertor as a function of α (for the rectifier) or γ (for the inverter) has been calculated with constant I_d as parameter and with $U_{di0}=U_{di0N}$. The result is presented in Figures 9a and 9b. These diagrams indicate that the convertor has about the same reactive absorbtion at 0.45 p.u. direct current and 90° control angles as for nominal control angles (α=15° or γ=16°) and 1.0 .u. 7%. This property is useful in some emergency situations as will be seen below.

I.9.1 Small signal reactive control at filter and shunt-bank switching

Reactive compensation equipment in an HVDC convertor station often consists of a number of a.c. filter banks and capacitor shunt-banks, i.e. not only of one large filter bank which always is connected. One reason for this may be stringent requirements on reactive control and exchange of reactive power between the convertors and the a.c. network. The size of the banks may also be limited by the maximum allowed a.c. voltage steps at bank switching which is especially important if the short-circuit level of the a.c. network is low.

A form of angle (α or γ) control of reactive power can be applied to minimize the consequences on the a.c. voltage quality at filter switching. The basis for this is to compensate the reactive power change in the convertor station when a filter is connected or disconnected by a corresponding change in reactive absorbtion in the convertor itself by increasing or decreasing the control angle as simultaneously as possibly.

Thus, if a filter or shunt-bank is going to be disconnected the total reactive compensation is reduced and a negative step in a.c. voltage will result. If the reactive absorbtion of the convertors could be decreased at the same time, the total effect on the voltage would be small. Such a procedure requires that γ (the procedure is normally most interesting in the inverter) is suddenly decreased which of course is not possible if the convertors are operating in minimum γ mode. However, if the bank switching is planned it is possible to prepare for it by slowly increasing γ by a suitable amount and when the bank is switched off, γ is decreased again to the nominal value in a step. The problem to be solved is of course to do the two thing simultaneously enough although some tolerances is normally acceptable.

When a filter or a shunt-bank is connected to the a.c. bus and the reactive compensation increases, no preparation is needed. γ can be suddenly increased to increase the converter reactive absorption when the bank is switched and than slowly brought back to its nominal value. However, here it must be noted that for an unintelligent bank-switching procedure, i.e. with no synchronization to the a.c. voltage and without pre-insertion resistors, inrush current into the bank may give more serious disturbance than the theoretical voltage step caused by the increased reactive generation when the filter is connected.

I.9.2 Reactive power control by combined convertor control and bank switching

When the reactive power or the a.c voltage is controlled only using a.c. filters and shunt banks the control will be discrete and the convertor reactive absorbtion is exactly compensated only in a limited number of points within the range from zero to rated power.The combination of bank switching and convertor control, in such a way that the bank switching control itself always gives reactive over-compensation which is completely or partially eliminated by convertor control with increased α or γ, can be a practical solution when a low exchange of reactive power with the a.c. network is required. It is a question here whether this is a steady-state or temporary reactive control; during a power ramping process it is normally not possible to use the tap-changer and the control angle reactive control will affect both networks. It may be necessary to design the convertor station equipment for increased reactive absorbtion in this case.

I.9.3 Reducing temporary over-voltages by convertor reactive power control

Temporary faults in one power system may cause unacceptable load-rejection over-voltages in the other power system, especially if the a.c. network is weak, i.e. has a low short-circuit capacity. If, for instance, such a serious fault occurs in the inverter a.c. network that the inverter can no longer commutate, two valves will continue to con-duct as long as the commutation voltage is missing and U_d will be zero because of that. The rectifier will react to this by increasing α to about 90° to control the direct current to a value equal to the reference signal. If now a significant current order remains when the direct voltage is close to zero — the current order is normally reduced by a cur-rent order limiter when the voltage goes down — the recti-fier will absorb reactive power despite the active load re-jection on the d.c. line. Now it is interesting to refer again to Figure 9, discussed above, from which it was concluded that the reactive absorbtion of a convertor operating at α or γ close to 90° and with 0.45 p.u. current has a reactive absorbtion equal to the absorbtion for the convertor when operating at nominal angle and rated direct current. Thus the rectifier absorbs enough reactive power to avoid dangerous over-voltages despite the active load rejection.

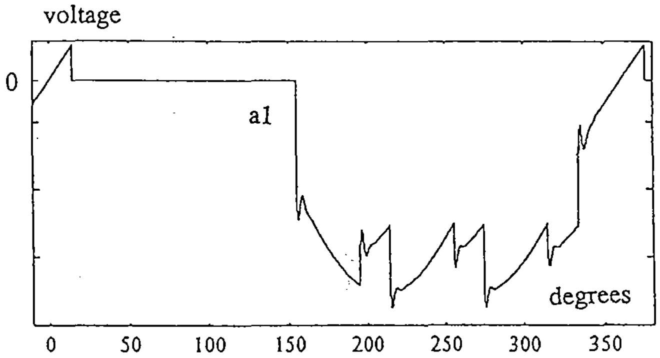
The same procedure could also be applied in the inverter at a serious fault in the rectifier a.c. network. If the inverter, in such a situation, would be allowed to operate with an α slightly below 90°, i.e. operating in the rectifier region, the effect would be the same. However, an inverter is normally provided with an α minimum limitation of around 100° for preventing the inverter from going into rectifier operation. This is done to prevent the inverter from feeding current into a ground fault on the d.c. line by which it would be impossible to extinguish the fault from the rectifier. For a line transmission, fast and safe information from the rectifier about the a.c. fault would be necessary to be able to selectively reduce the α_{max} limitation in the inverte from 100° to below 90° for this type of event. The method is not applied to-day for HVDC line transmissions.

In a back-to-back scheme, on the other hand, the method can be used and it is used in some transmission systems of this kind.

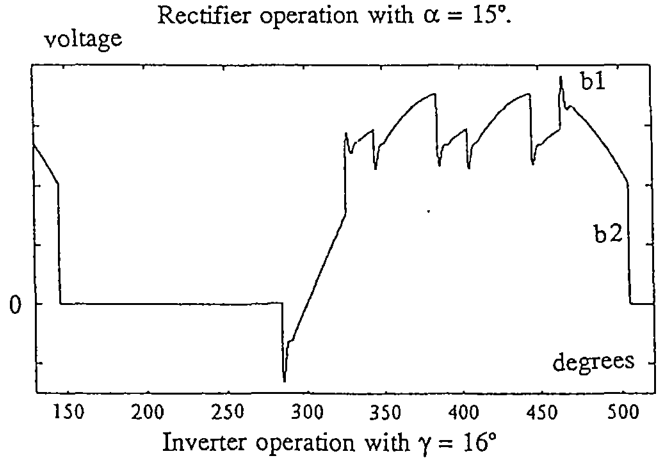
As some load-rejection over-voltage normally can be accepted it is not necessary to operate with as much as 0.45 p.u. current in the discussed cases.

REFERENCES

"Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities. Part I: AC/DC Interaction Phenomena". Produced by the Joint Task Force of CIGRÉ WG 14-07/IEEE WG 15.05.05.



Rectifier operation with $\alpha = 15°$.



Inverter operation with $\gamma = 16°$

Figure 1. Valve voltages for rectifier and inverter operation

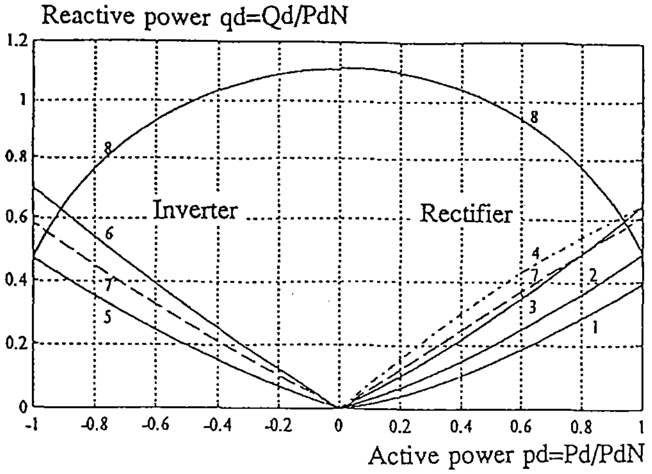


Figure 2a. Reactive power absorption of a normally designed convertor. Constant U_d = 1.0 p.u.

1: $\alpha = 5°$
2: $\alpha = 15°$
3: $\alpha = 25°$
4: $\alpha+\mu$ = const.
5: $\gamma = 16°$
6: $\gamma = 30°$
7: $U_{diOmax} = 1.05 \cdot U_{diON}$
8: S = const. = 1 p.u.

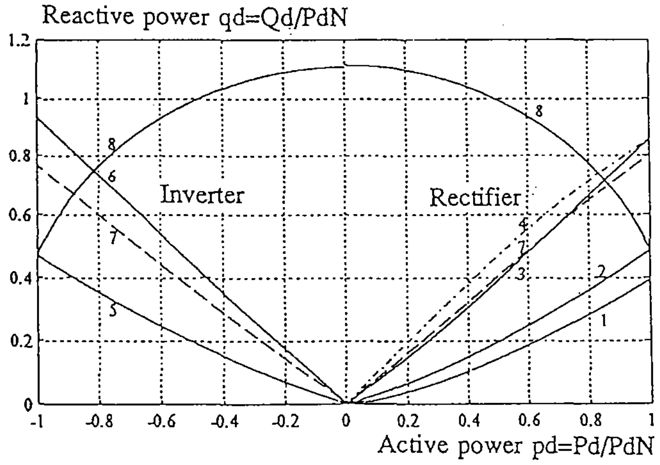


Figure 2b. Reactive power absorption of a convertor designed for operation with increased control angles and U_{dio}. Constant U_d = 1.0 p.u.

1: $\alpha = 5°$
2: $\alpha = 15°$
3: $\alpha = 35°$
4: $\alpha+\mu$ = const.
5: $\gamma = 16°$
6: $\gamma = 40°$
7: $U_{diOmax} = 1.15 \cdot U_{diON}$
8: S = const. = 1 p.u.

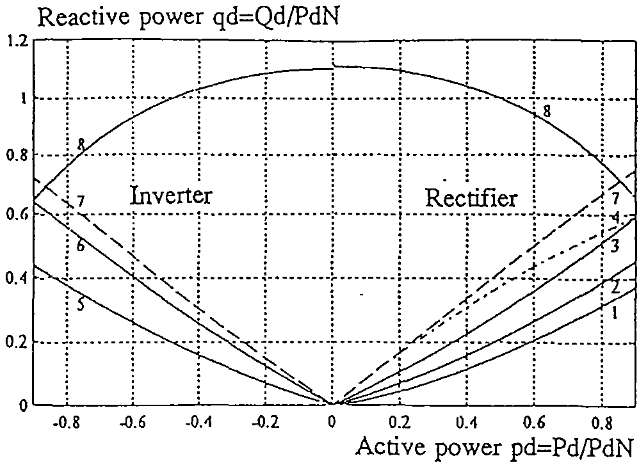


Figure 2c. Reactive power absorption of a normally designed convertor. Constant U_d = 0.9 p.u.

1: $\alpha = 5°$
2: $\alpha = 15°$
3: $\alpha = 25°$
4: $\alpha+\mu$ = const.
5: γ = 16o
6: $\gamma = 30°$
7: $U_{diOmax} = 1.05 \cdot U_{diON}$
8: S = const. = 1 p.u.

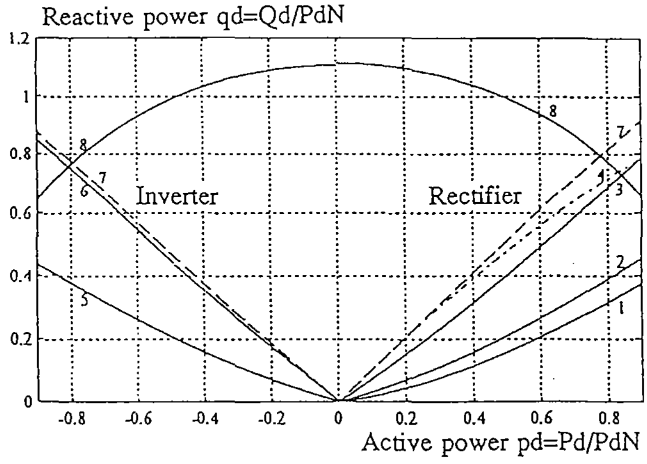


Figure 2d. Reactive power absorption of a convertor designed for operation with increased control angles and U_{dio}. Constant U_d = 0.9 p.u.

1: $\alpha = 5°$
2: $\alpha = 15°$
3: $\alpha = 25°$
4: $\alpha+\mu$ = const.
5: $\gamma = 16°$
6: $\gamma = 30°$
7: $U_{diOmax} = 1.05 \cdot U_{diON}$
8: S = const. = 1 p.u.

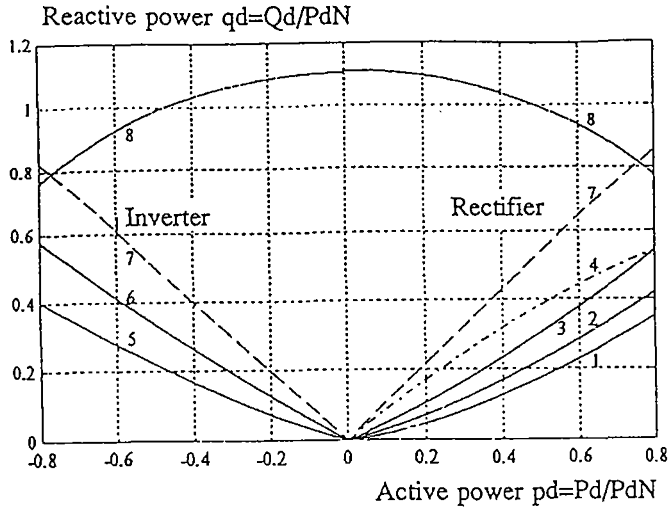


Figure 2e. Reactive power absorption of a normally designed convertor. Constant $U_d = 0.8$ p.u.

1: $\alpha = 5°$	5: $\gamma = 16°$
2: $\alpha = 15°$	6: $\gamma = 30°$
3: $\alpha = 25°$	7: $U_{diOmax} = 1.05 \cdot U_{diON}$
4: $\alpha + \mu$ = const.	8: S = const. = 1 p.u.

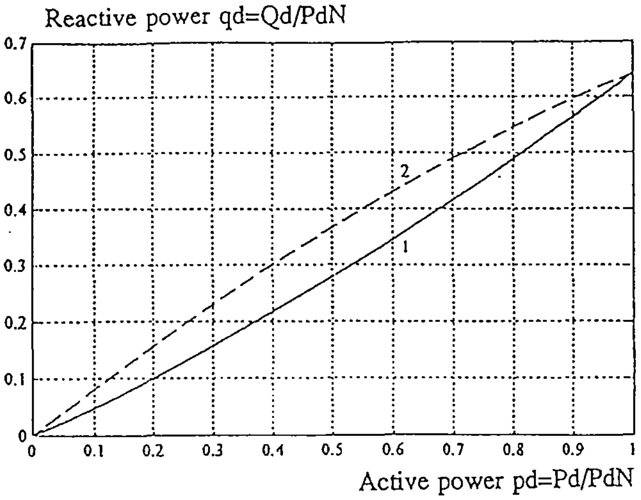


Figure 3. Comparison of reactive power absorption of a normally designed convertor operated on constant α and constant $\alpha + \mu$. Constant $U_d = 1$ p.u.

1: $\alpha = 25°$
2: $\alpha + \mu$ = const.

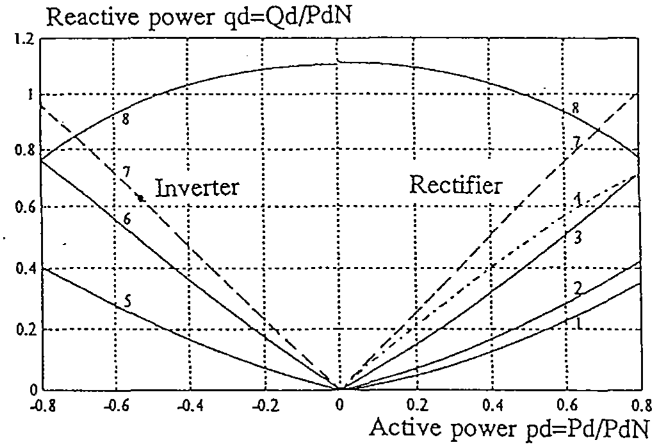
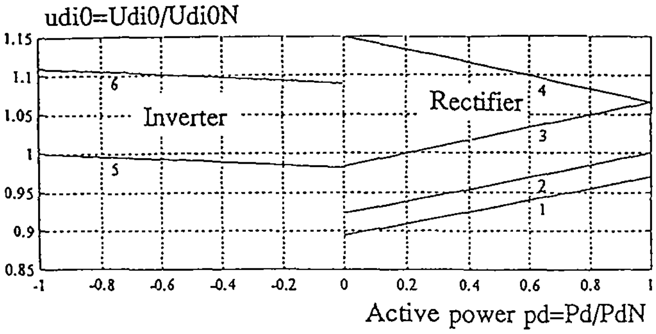


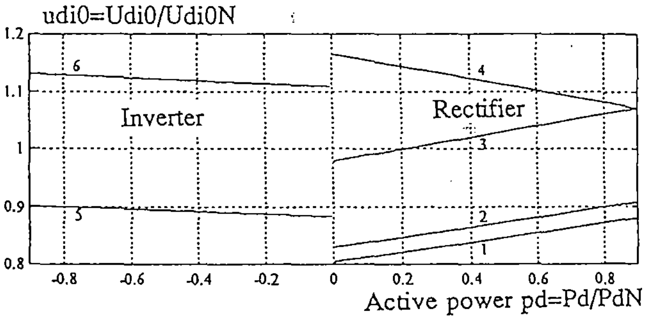
Figure 2f. Reactive power absorption of a convertor designed for operation with increased control angles and U_{diO}. Constant $U_d = 0.8$ p.u.

1: $\alpha = 5°$	5: $\gamma = 16°$
2: $\alpha = 15°$	6: $\gamma = 40°$
3: $\alpha = 35°$	7: $U_{diOmax} = 1.15 \cdot U_{diON}$
4: $\alpha + \mu$ = const.	8: S = const. = 1 p.u.



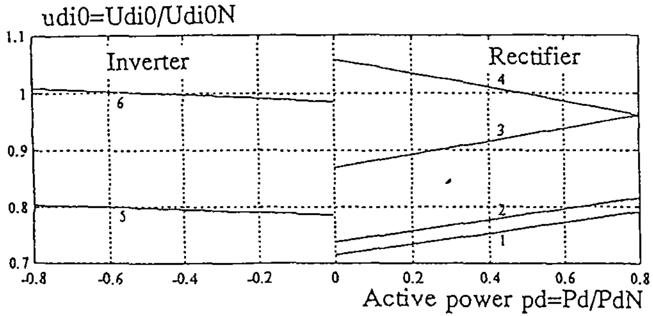
4a. $U_d = 1.0$, $\alpha_{max} = 25°$, $\gamma_{max} = 30°$.

1: $\alpha = 5°$ 4: $\alpha+\mu$ = const.
2: $\alpha = 15°$ 5: $\gamma = 16°$
3: $\alpha = 25°$ 6: $\gamma = 30°$



4b. $U_d = 0.9$, $\alpha_{max} = 35°$, $\gamma_{max} = 40°$.

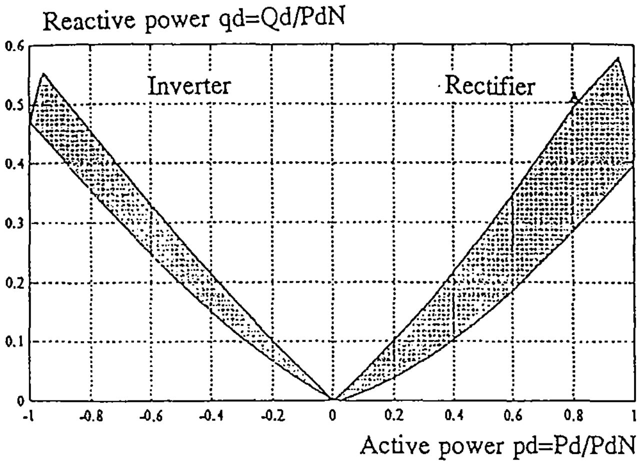
1: $\alpha = 5°$ 4: $\alpha+\mu$ = const.
2: $\alpha = 15°$ 5: $\gamma = 16°$
3: $\alpha = 35°$ 6: $\gamma = 40°$



4c. $U_d = 0.8$, $\alpha_{max} = 35°$, $\gamma_{max} = 40°$.

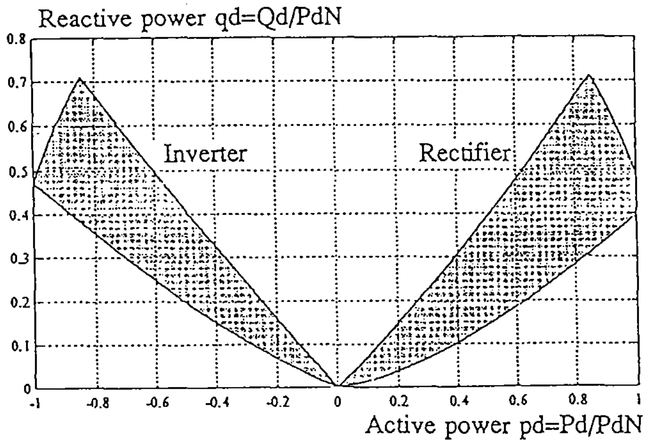
1: $\alpha = 5°$ 4: $\alpha+\mu$ = const.
2: $\alpha = 15°$ 5: $\gamma = 16°$
3: $\alpha = 35°$ 6: $\gamma = 40°$

Figure 4. Variations along the constant α, constant (α + μ) and constant γ curves in figure 1.



$\gamma_{min} = 16°$ and $\gamma_{max} = 30°$; $\alpha_{min} = 5°$, $\alpha_{max} = 25°$.

Figure 5a. Area of operation in the P_d/Q_d diagram for a normally designed convertor. $U_d = 1$ p.u. and $U_{diOmax} = 1.05 \cdot U_{diON}$.



$\gamma_{min} = 16°$ and $\gamma_{max} = 40°$; $\alpha_{min} = 5°$, $\gamma_{max} = 35°$.

Figure 5b. Area of operation in the P_d/Q_d diagram for a convertor designed for increased reactive absorption. $U_d = 1$ p.u. and $U_{diOmax} = 1.2 \cdot U_{diON}$.

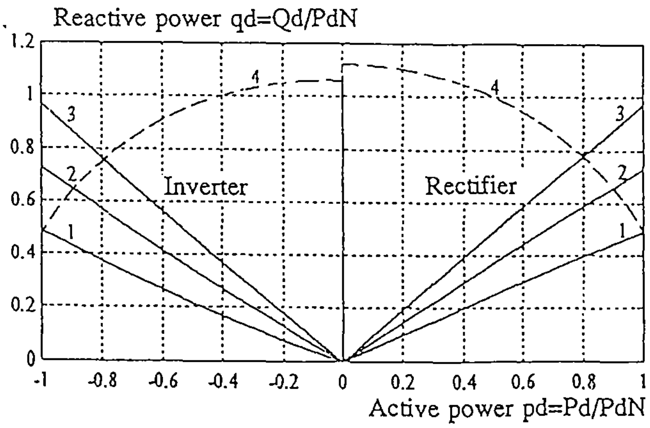
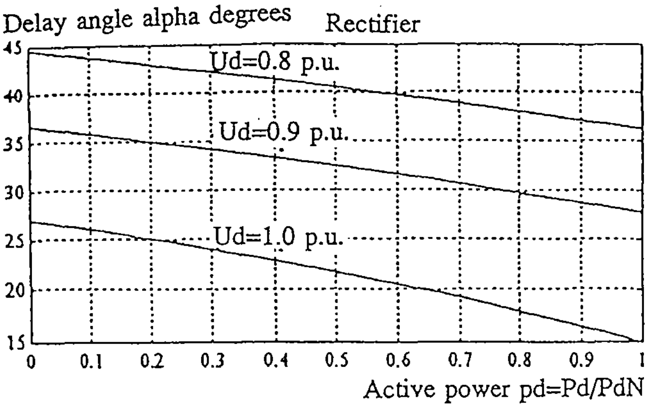
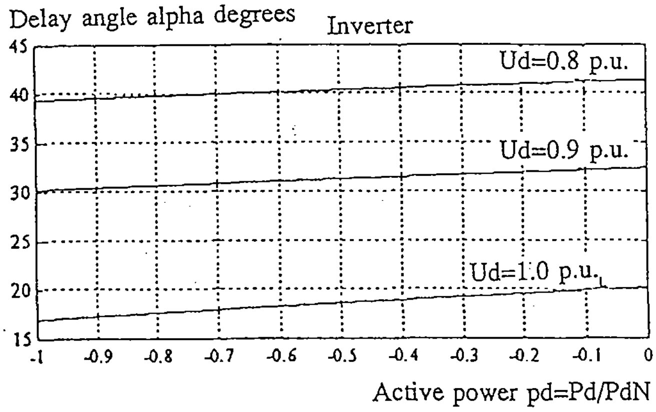


Figure 6. Reactive absorption of an HVDC convertor. Constant U_{dio} ($=U_{diON}$) and constant U_d.

1: $U_d = 1.0$ p.u 3: $U_d = 0.8$ p.u
2: $U_d = 0.9$ p.u 4: $I_d = 1.0$ p.u

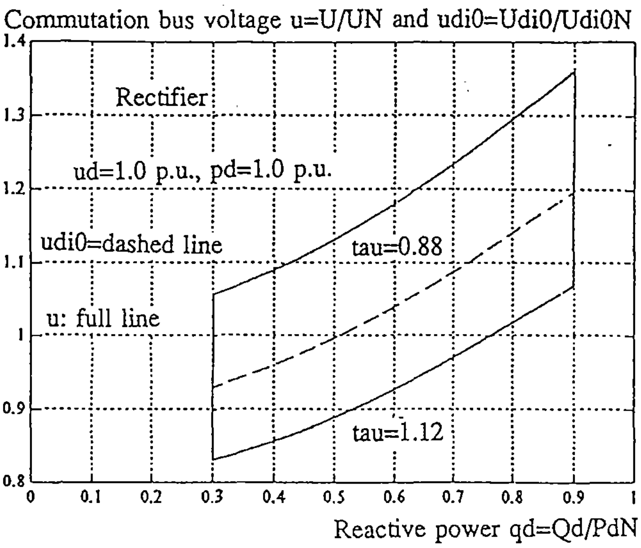


a) Rectifier, variation in α

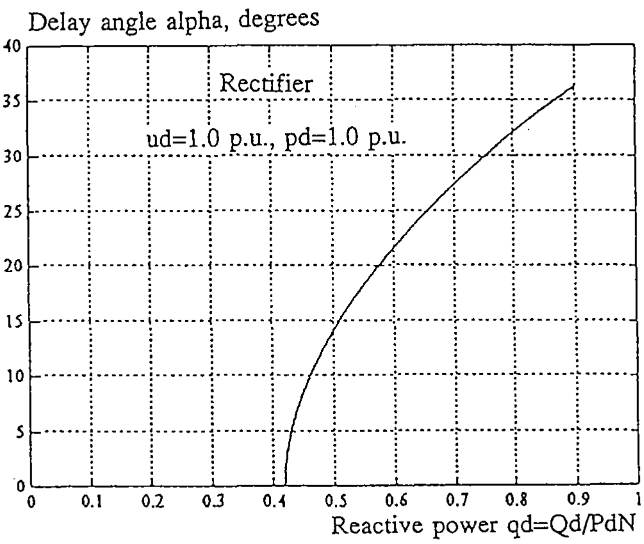


b) Inverter, variation in γ

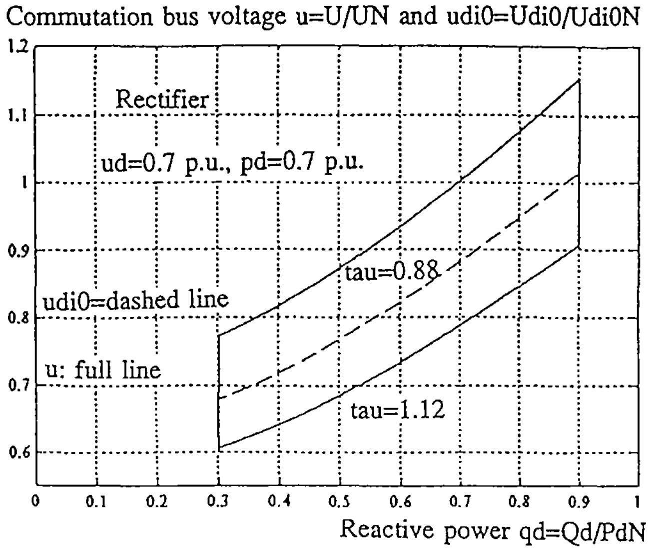
Figure 7. Variation in α and γ along the constant U_d curves in figure 4.



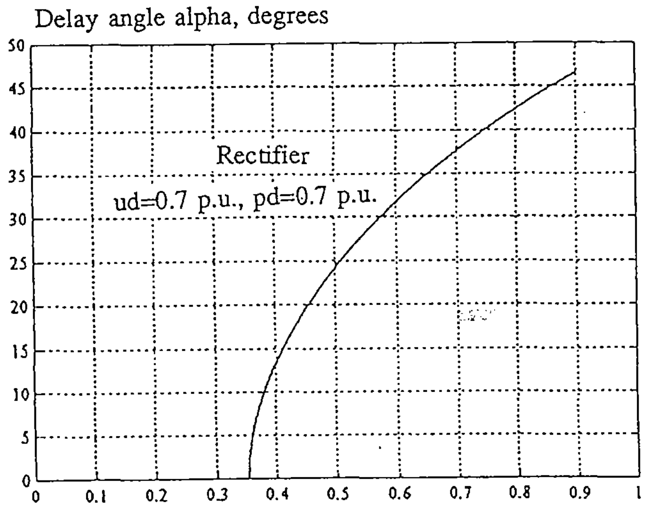
8a. $U_d = U_{dN}$ and $P_d = P_{dN}$



8b. $U_d = U_{dN}$ and $P_d = P_{dN}$



8c. $U_d = U_{dN}$ and $P_d = P_{dN}$



8d. $U_d = U_{dN}$ and $P_d = P_{dN}$

Figure 8. Steady-state Q/U-diagram for an HVDC convertor.

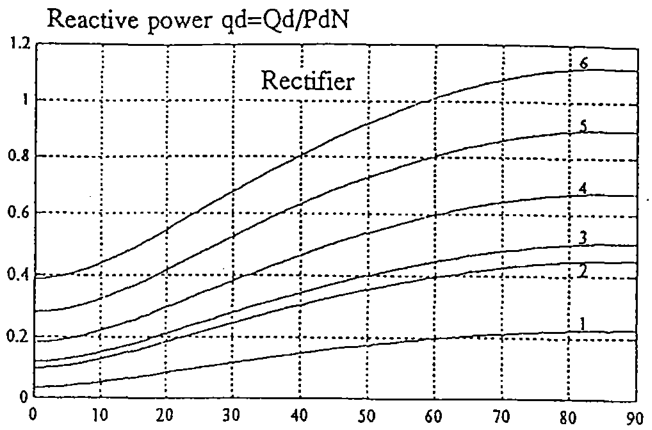


Figure 9a. Reactive power absorption of a rectifier as a function of α with $U_{diO} = U_{diON}$.

1: Id = 0.2 p.u 4: Id = 0.6 p.u
2: Id = 0.4 p.u 5: Id = 0.8 p.u
3: Id = 0.45 p.u 6: Id = 1.0 p.u

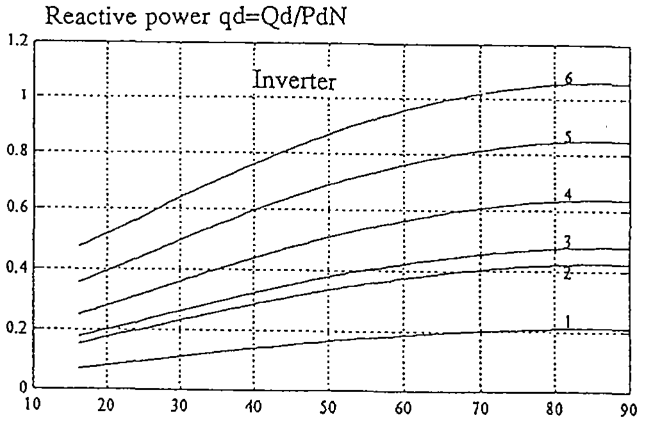


Figure 9b. Reactive power absorption of a rectifier as a function of γ with $U_{diO} = U_{diON}$.

1: Id = 0.2 p.u 4: Id = 0.6 p.u
2: Id = 0.4 p.u 5: Id = 0.8 p.u
3: Id = 0.45 p.u 6: Id = 1.0 p.u

APPENDIX II

CAPABILITY OF REACTIVE POWER ABSORPTION IN DC CONVERTERS

by Torben Østrup, Denmark

Summary

The report describes the possibilities of changing the reactive power of a DC converter in the steady state when the active power is held constant.

The diagrams, called QU diagrams, are constructed for the network side of the converter transformer. The diagrams do not include the reactive power from the filters but do include the effect of the tap changer of the converter transformer. Data for a typical DC link have been used.

The QU diagrams have the network voltage at the vertical axis and the reactive power of the converter at the horizontal axis.

Conclusion

The steady state reactive power range for a fixed active power is strongly dependent on the limits applied for the different parameters. However, in general the range is small for a full loaded converter and for a converter with small active load. For a converter having an active load of 0.6 - 0.9 p.u. the reactive power range is largest and can typically be about 0.3 p.u.. However, for fixed active power transfer, the DC voltage must be reduced to obtain the largest reactive power absarption within the range. The range is smaller than that of a typical generator, but the DC converter can maintain the range even for rather low AC voltages.

For small active power transfers, the reactive power range can be made large by use of large control angles. However, it is necessary at the same time to reduce the voltage at the DC link because the difference between the per unit values of the AC voltage and the DC voltage becomes large.

For a full loaded converter, a larger reactive power range can only be obtained by dimensioning the converter for it. This is quite similar to the properties of a generator.

II.1 QU DIAGRAMS FOR A CONVERTER

In order to be able to judge the possibilities of controlling the reactive power absorption of a converter in the steady state, it is desirable to have diagrams showing the possible range of reactive power absorption for varying AC network voltages but fixed active power transfer. Such QU diagrams also make it possible to compare the properties of the DC converter with those of other devices which can control the reactive power such as generators and SVCs.

The QU diagrams described here are made for the network side of the converter transformer. The network AC voltage is on the vertical axis and the reactive power on the horizontal axis, while the active power is used as a parameter. Figure 1 shows the diagram of the converter station. The filters are not included in the investigated system.

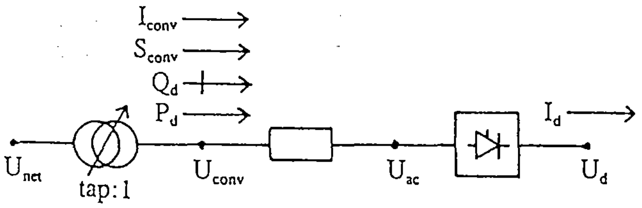


Figure 1 - Diagram of converter station.

The construction of the QU diagrams is based on litt. [1] and [2]. Appendix II.1 summarizes the basic equations and the data for the example used in this report.

II.2 STATIC LIMITS

The permissible area of operation in the static QU diagram is bounded by curves where certain AC or DC parameters reach their steady state limits. Which parameters that will define the boundary can depend on the design of the converter. In this chapter, the possible limitations are mentioned and the choice used for the examples in this report is given.

II.2.1 DC network parameters

The DC current, I_d, is not allowed to exceed its nominal value, 1 p.u., in the steady state. A minimum value of I_d is also present, typically 0.1 p.u.. The limits used for I_d here is $0.1 \leq I_d \leq 1.0$.

The DC voltage, U_d, is not allowed to exceed its nominal value, 1 p.u., in the steady state. A minimum value of U_d has been selected to 0.8 p.u.. A major reason to have this minimum U_d is to avoid operation with large control angles. In chapter 3, specific limits are used for the control angles making the lower limit of U_d of less interest. With the selected limits of the angle, the minimum U_d of 0.8 p.u. mainly has the effect of restricting large consumptions of reactive power at low network voltages which are situations of little interest. In chapter 4, the effect of omitting the minimum U_d is investigated. The limits used for U_d here are $0.8 \leq U_d \leq 1.0$.

II.2.2 Converter parameters

The delay angle α can be kept continuously at about 5°. However, to have a proper dynamic control range, the steady state minimum α is chosen to the nominal value, which here is 15°. A maximum α is required in the steady state due to the created harmonics. A fairly large value of 35° is used here. In chapter 4, operation without a maximum α is investigated. The limits used here are $15° \leq \alpha \leq 35°$.

The extinction angle, γ, has a lower limit of typically 16° to secure the commutation. Maximum γ is typically a little higher than maximum α. The limits used for γ here is $16° \leq \gamma \leq 40°$.

The ideal no load direct voltage, U_{diO}, is an expression of the voltage applied to the thyristors. Therefore, an upper limit exists for this voltage. The limit used here is $U_{diO} \leq 1{,}05 \cdot U_{diON}$, where U_{diON} is the nominal value.

No limits are used for the apparent power, S_{conv}, on the AC side of the converter. Eventual limits are more correctly based on the current.

However, neither for the AC converter current, I_{conv}, a limit is used. For an ideal converter, the AC current is simply proportional to the DC current independent of the reactive power consumption. For a real converter, the AC current varies a little because the overlap angle is changed when the reactive power consumption is changed. This effect is disregarded.

No limits have been used for the AC voltage at the converter, U_{conv}. It is assumed that the limits of U_{diO} will be the most restrictive.

II.2.3 Transformer parameters

No limits are used for the apparent power of the converter transformer equal to S_{conv}. It is assumed that the thermal properties of the transformer will not limit the utilization of the converter. (The rated transformer power which is used in Appendix I for the determination of the parameter d_x is about 6% greater than the apparent power for the converter at rated conditions).

For the same reason, no limits are used for the transformer current.

The network voltage, U_{net}, will in reality have an upper limit of typically 1.05-1.1 p.u.. However, this limit is not fixed by the converter station and is therefore disregarded here.

The transformer tap range has been selected to $0.88 \leq tap \leq 1.12$. With this range, the rated point of operation of the converter as well as full load operation with a 5% higher U_{diO} (and thereby higher reactive consumption) can be achieved or network voltages in the range $0.93 \leq U_{net} \leq 1.06$. This is a typical normal operating range for a transmission network.

II.2.4 Summary of the static limits used

$0.1 \leq I_d \leq 1.0$
$0.8 \leq U_d \leq 1.0$
$15° \leq \alpha \leq 35°$
$16° \leq \gamma \leq 40°$
$\text{UdiO} \leq 1.05 \cdot U_{diON}$
$0.88 \leq tap \leq 1.12$

No limits for S_{conv}
I_{conv}
U_{conv}
U_{net}

In chapter 4, the influence of exceeding some of the limits is investigated.

II.3 TYPICAL QU DIAGRAMS

For a converter with the data given in Appendix I, the QU diagrams are shown on Figure 2.

The reactive power range is small for a full loaded converter and for a converter with small load. However, in the active power range of about 0.6-0.9 p.u., a significant variation in the reactive power absorption can be obtained, although the range is still smaller than for a generator. It should, however, be noticed that generators are nearly always dimensioned with $\cos \phi < 1$ in order to increase the allowable range of Mvar-production.

The heights of the diagrams depend to a high degree on the tap range of the converter transformer. With the chosen tap range, the maximum reactive power range is maintained down to low network voltages = 0.8-0.85 p.u. The maximum network voltage is the same for all the figures. It is determined by the maximum tap and the maximum U_{diO}.

Figures 3 and 4 show details from the construction of the QU diagrams for $P_d = 1$ and 0.8 respectively. The two figures show diagrams without limits for minimum α and

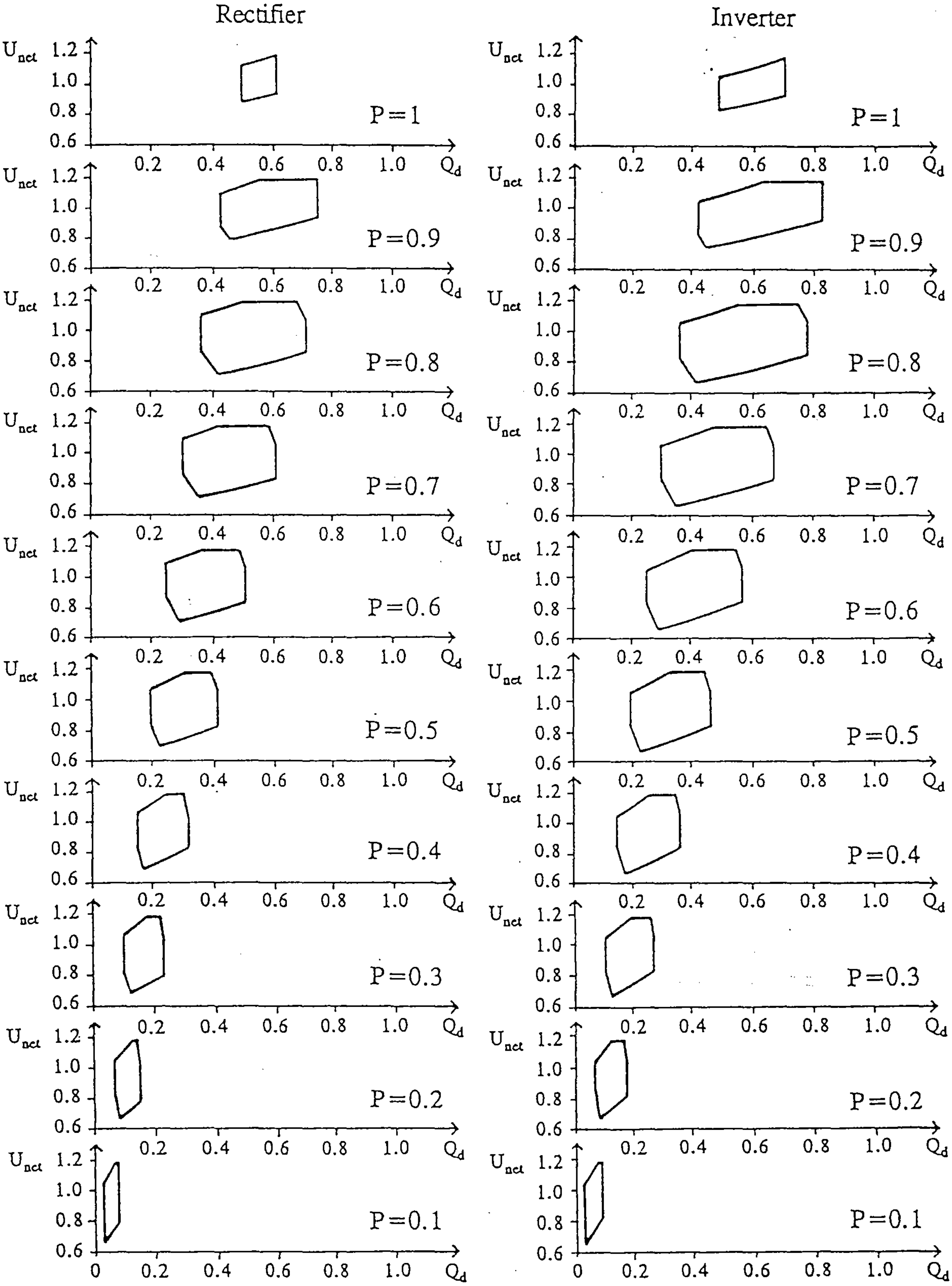


Figure 2. QU-diagrams for a typical DC converter.

$0.1 \le I_d \le 1.0$
$0.8 \le U_d \le 1.0$
$15° \le \alpha \le 35°$
$16° \le \gamma \le 40°$
$UdiO \le 1.05 \cdot U_{diON}$
$0.88 \le tap \le 1.12$

No limits for S_{conv}
I_{conv}
U_{conv}
U_{net}

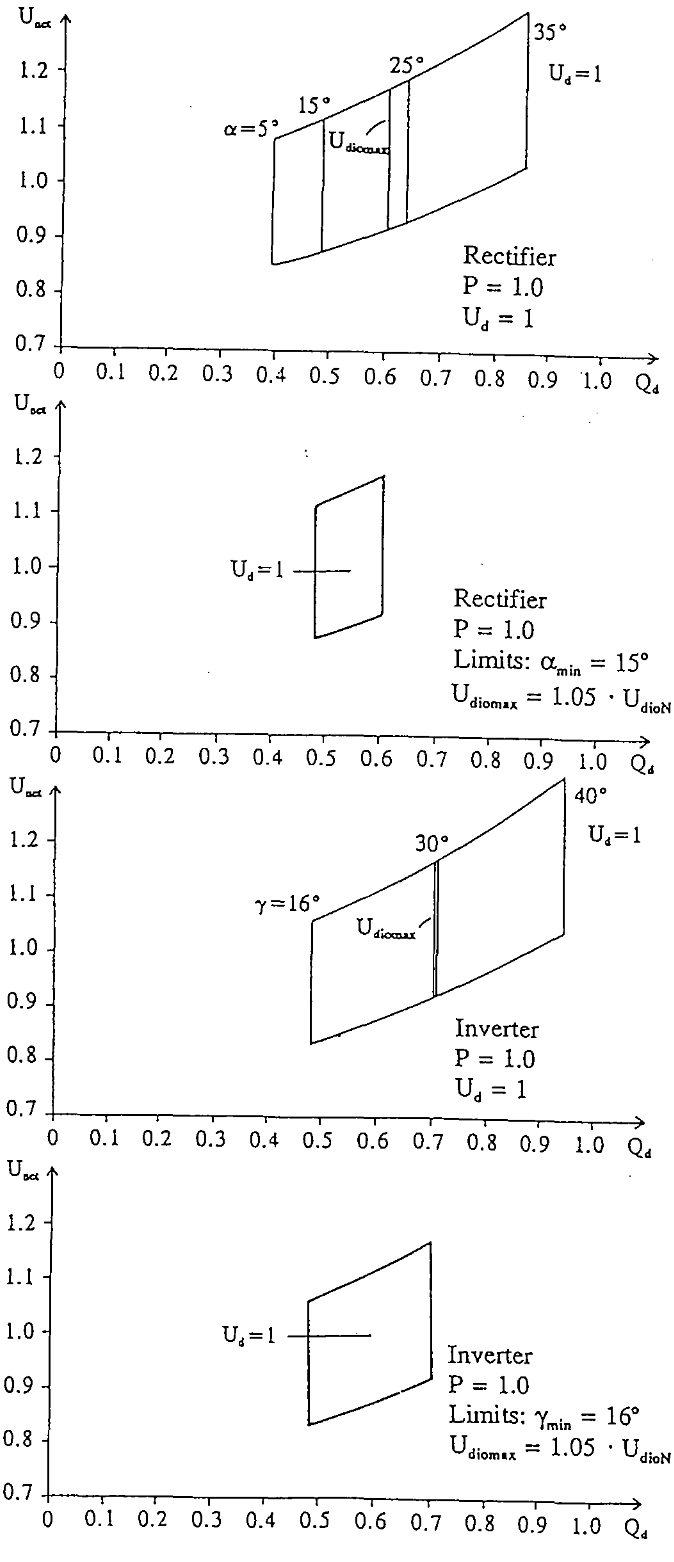


Figure 3. QU-diagrams for a typical DC converter.

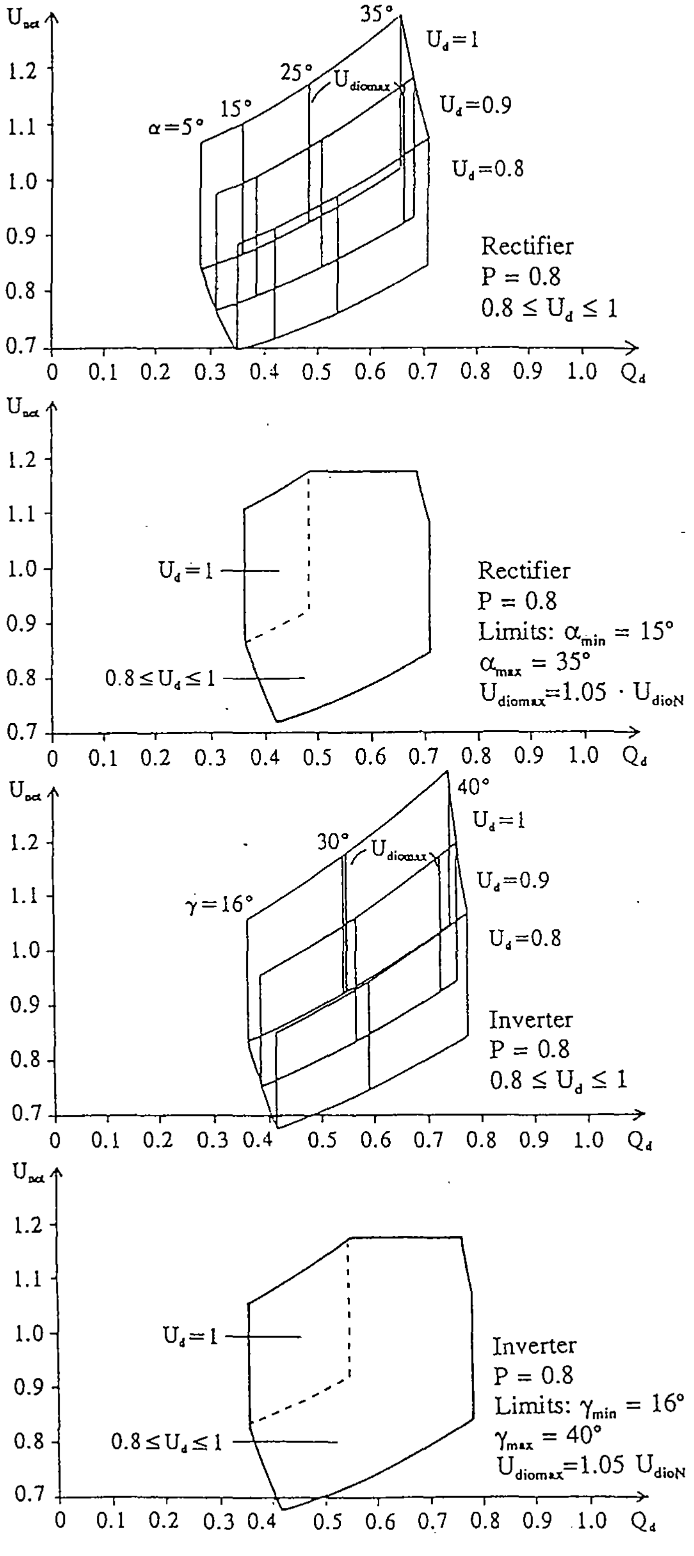


Figure 4. QU-diagrams for a typical DC converter.

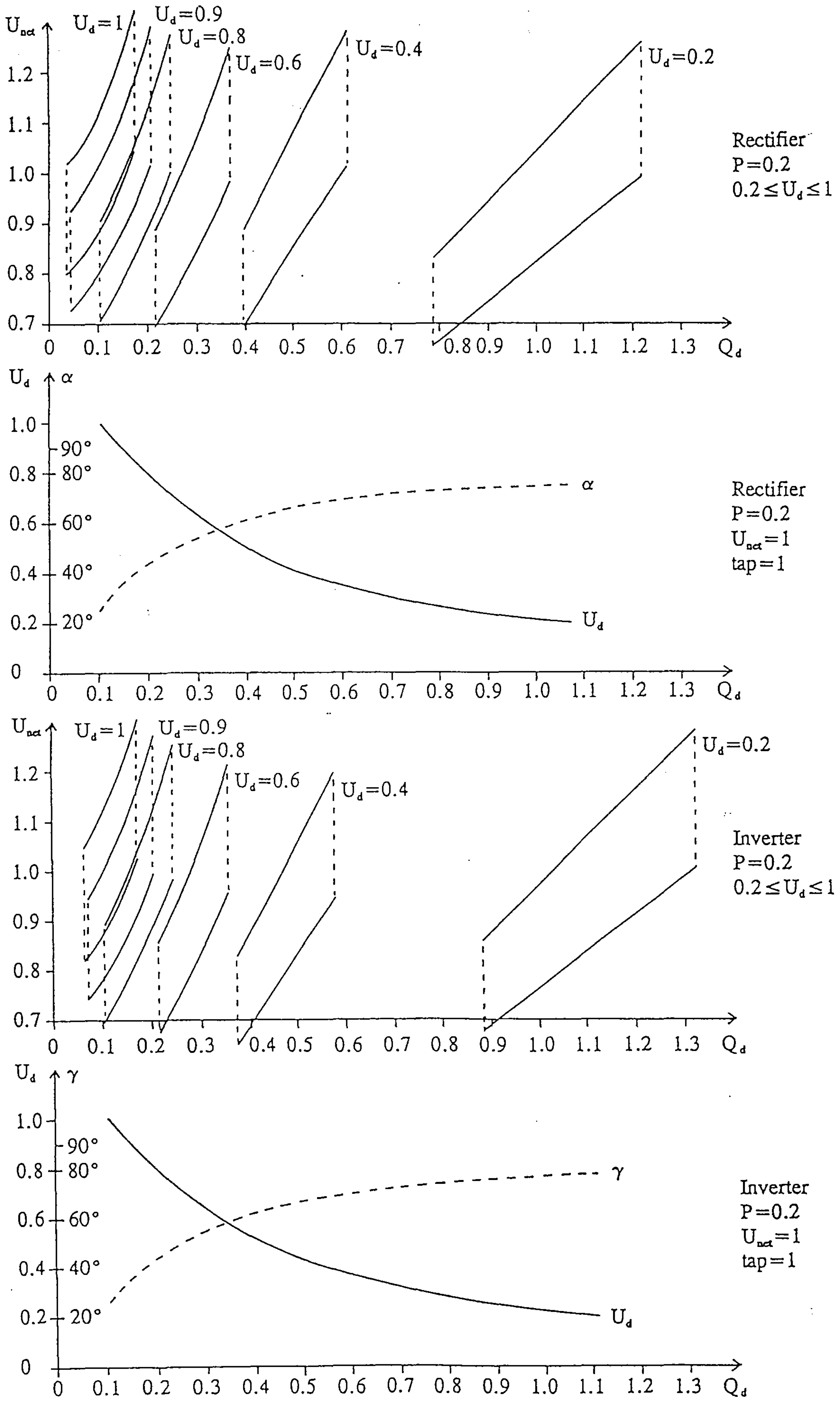


Figure 5. Diagrams for use of low U_d and large α and γ.

maximum U_{dio} for both rectifiers and inverter and the QUdiagrams as they appear, when allowance is made for all the limits mentioned in chapter 2.

Figure 3 with $P_d = 1$ is simple, as U_d must be 1 p.u. to keep $I_d \leq 1$. In the model used with the taps located at the network side of the converter transformer, the curves for constant α, γ and U_{dio} become vertical lines.

In Figure 4, the possible areas of operation are shown for $U_d = 1.0$, 0.9 and 0.8. A decrease in U_d moves the area towards lower network voltages and higher reactive power absorption. The limit set by maximum U_{dio} becomes less important when U_d becomes smaller. In the total allowed area of operation is indicated the parts which can be used with $U_d = 1$. These are rather small. For the major part of the allowed areas, U_d has to be decreased.

II.4 USE OF LARGE CONTROL ANGLES FOR SMALL ACTIVE POWER TRANSFERS

For small active power transfers, the range of reactive power variations on Figure 2 is very small. Use of larger control angles could therefore be desirable to be able to absorb larger amounts of reactive power.

However, the sole use of larger control angles only gives a minor increase in the reactive power range. This is because the curves for constant U_d and constant tap in the QU diagrams become quite steep. The reason for this is that I_d is constant because P_d is constant. Therefore, also I_{conv} is nearly constant and a large increase in Q_d will require a large increase in U_{conv} and thereby in U_{net}. As the possible increase in the AC voltages is very limited, U_d must instead be decreased if large amounts of reactive power are to be absorbed.

Figure 5 shows the possible areas of operation for $P_d = 0.2$ and $0.2 \leq U_d \leq 1$.

Further, the variation in α, γ and U_d is shown as a function of Q_d for fixed nominal values of U_{net} and tap.

It appears that it is possible to get very large variations in Q_d. However, α and γ very rapidly become large; they reach 50° at Q_d about 0.25 p.u.. Also U_d rapidly becomes smaller.

II.5 SUMMARY

The QU diagram for a typical DC converter shows that the range in which the reactive power absorption can be varied in the steady state is very small for a full loaded converter and for a converter with low load.

For a converter operating with an active load of 0.6-0.9 p.u., the range for the reactive power variations is 0.25-0.4 p.u., which is less than for a generator but still quite much, as the rated power of DC links is often high. The DC voltage must be reduced to obtain the largest reactive power absorption within the range.

The full range for the reactive power variations can be maintained down to low system AC voltages of 0.8 - 0.85 p.u. (except when the DC link is at full load) for reasonable tapchanger intervals on the converter transformer.

For low active power transfers, it is possible to absorb larger amounts of reactive power if large control angles are used together with low DC voltages.

At full load, only a certain overdimensioning can create a larger interval for the reactive power absorption. This is similar to the properties of a generator.

II.6 LITERATURE

[1]: "Reactive Power Control in HVDC", by G. Liss and T. Adielson, Appendix I.

[2]: "A Digital Model of an HVDC System for System Planning Studies", by T. Adielson and G. Liss, Appendix X.

[3]: "Guide for Planning DC Links Terminating at AC System Locations having Low Short-Circuit Capacities. Part I: AC/DC Interaction Phenomena," by CIGRÉ WG 14.07, 1992.

Appendix II.1: Basic equations and data used for the construction of the QU diagrams

II.1.1 Rectifier and transformer equations

The following diagram is used for construction of the QU-diagrams for the network side of the transformer:

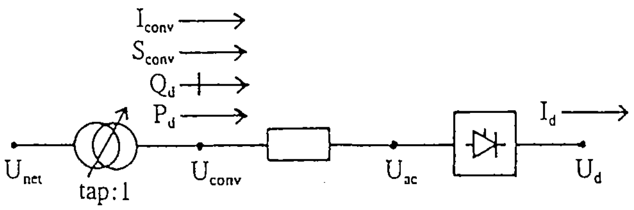


Figure 1. Diagram of converter station

For the rectifier, the following equations are used (taken from litt. [1]):

$$(1)\quad U_{dioN} = \frac{U_{dN}}{\cos\alpha_N - (d_x + d_r)}$$

$$(2)\quad I_d = \frac{P_d}{U_d}$$

$$(3)\quad U_{dio} = \frac{U_d + (d_x + d_r) \cdot \frac{I_d}{I_{dN}} \cdot U_{dioN}}{\cos\alpha}$$

$$(4)\quad \mu = \arccos\left(\cos\alpha - 2 \cdot d_x \cdot \frac{I_d}{I_{dN}} \cdot \frac{U_{dioN}}{U_{dio}}\right) - \alpha$$

$$(5)\quad Q_d = P_d \cdot \frac{\sin 2\alpha - \sin 2(\alpha + \mu) + 2\mu}{2(\cos^2\alpha - \cos^2(\alpha + \mu))}$$

$$(6)\quad S_{conv} = (P_d^2 + Q_d^2)^{1/2}$$

$$(7)\quad U_{conv} = \frac{U_{di0}}{U_{di0N}} \cdot U_{convN}$$

$$(8)\quad I_{conv} = \frac{S_{conv}}{U_{conv}}$$

$$(9)\quad U_{net} = U_{conv} \cdot tap$$

The voltages, active and reactive powers, currents and transformer quantities are shown at the figure 1.

The subscript N indicates nominal values.

The rest of the quantities are

α = delay angle

μ = overlap angle

U_{di0} = no load direct voltage, proportional to U_{conv}

d_x = ½ X_t for a reasonable choice of converter transformer. (Litt. [2], S_{tN} = rated transformer power = $\pi/3 \cdot I_{dN} \cdot U_{di0N}$).

d_r = parameter representing the transformer and converter losses.

II.1.2 Inverter equations

The inverter equations differ a little from those used in litt. [1]. Here, it is presumed that the inverter is identical with the rectifier and thereby has the same rated values, including U_{di0N}.

For the inverter equations (3), (4) and (5) is modified. U_d and P_d are still the values at the rectifier. The corresponding values for the inverter (with suffix I) are smaller due to the DC line resistance.

$$(10)\quad U_{dI} = U_d \left(1 - r_{dN} \cdot \frac{I_d}{I_{dN}} \cdot \frac{U_{dN}}{U_d}\right)$$

$$(11)\quad P_{dI} = U_{dI} \cdot I_d$$

Equation (3) is replaced by

$$(12)\quad U_{di0} = \frac{U_{dI} + (d_x - d_r) \cdot \frac{I_d}{I_{dN}} \cdot U_{di0N}}{\cos\gamma}$$

Use of

$$(13)\quad \alpha + \gamma + \mu = \pi$$

changes (4) into

$$(14)\quad \mu = \arccos\left(\cos\gamma - 2 \cdot d_x \cdot \frac{I_d}{I_{dN}} \cdot \frac{U_{di0N}}{U_{di0}}\right) - \gamma$$

and (5) into

$$(15)\quad Q_d = P_{dI} \cdot \frac{\sin 2\gamma - \sin 2(\gamma + \mu) + 2\mu}{2 \cdot (\cos^2\gamma - \cos^2(\gamma + \mu))}$$

In the equation (6), P_d is substituted by P_{dI}.

$$(16)\quad S_{conv} = (P_{dI}^2 + Q_d^2)^{1/2}$$

In the equations for the inverter, the signs have been adjusted so that I_d, U_{dI}, and P_{dI} are all positive values.

The two new quantities in the equations are

γ = extinction angle

r_{dN} = nominal DC-line voltage drop

II.1.3 Data used for the construction of the QU diagrams

The data used are typical examples for a DC link.

I_{dN} = 1 p.u.

U_{dN} = 1 p.u.

α_N = 15°

γ_N = 16°

r_{dN} = 0.05

d_x = 0.07

d_r = 0.005

U_{convN} = 1 p.u.

tap = 0.88 - 1.12

APPENDIX III

MODES OF OPERATION FOR DC CONVERTER STATIONS INCL. CONCEPT OF THE DC CONVERTER CONTROL

by Dr. M. Erche and D. Povh, Germany

III.1 INTRODUCTION

An HVDC link or transmission is a local but nevertheless a very important equipment in an AC system. It has to meet the requirements coming from the AC system and not vice versa.

HVDC converter stations with resonant circuits and, if necessary, static var compensators can

- feed active power to or draw it from an electrical power system
- supply or consume reactive power.

In principle they can act like a power plant but with two basic differences:

A positive one:

- control of an HVDC converter station is very fast in the range of some halfwaves.

A negative one:

- active power can not be produced or consumed in a DC link but must be delivered or taken over by the neighbouring power system at the same instant at which it is needed or surplus in the interconnected system. Nevertheless in multiterminal HVDC systems distribution of the loads is free within the ratings of the stations.

HVDC converter stations can be used for power exchange, reserve holding and stabilization duties as well as for power frequency control, reactive power and voltage control in three phase AC systems especially with low short-circuit capacity.

A long HVDC transmission normally supplies a more or less strong system compared to the capacity of the transmission itself. The active power is coming from a remote power plant and the reactive power requirements of the converter stations are kept small to minimize losses. Their main purpose is to transmit low-priced energy to load centres.

On the other hand, DC links and short HVDC transmissions are mostly located between weak systems or at least connecting a weaker system to a stronger one. Their main purpose is power exchange and reserve holding more than power transmission. Since weak systems more often have problems with stability or power oscillations, reactive power and voltage control, special features of HVDC converter stations can be applied with little increase of costs.

An HVDC converter station in an AC system can be compared to a power plant at the same location. The above mentioned characteristics of a converter station are similar to those of a power plant. If the partner behind the DC link is a strong AC system, the HVDC converter station does even more than a power plant.

III.2 CONTROL MODES IN AN INTERCONNECTED AC/DC SYSTEM

The active and reactive power behaviour of a DC link with a weak system is shown by reference to the scheme in Figure 1. A short-circuit capacity S_{SC} from the system is present at the DC link connection point. The load $\underline{S}_L$ is covered by the DC link ($\underline{S}_{DC}$) and the system ($\underline{S}_N$). The remote system is assumed to have a fixed source voltage $\underline{E}$, while the voltage $\underline{U}$ is present at the DC link connection point. The short-circuit capacity S_{SC} and the load $\underline{S}_L$ are treated as known data.

The table in Figure 2 shows the various criteria (modes) which can serve as the basis for planning and operating a system of this type.

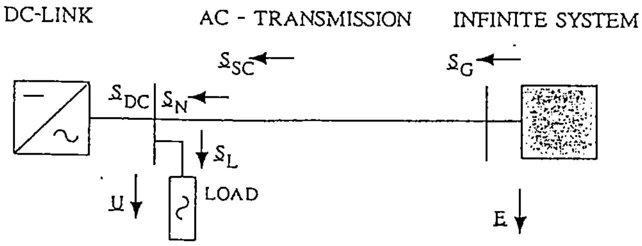


Figure 1. Principle scheme of an interconnected AC/DC system.

In an AC system, the active power P influences mainly the transmission angle ϕ and the power frequency f in the system, whereas the reactive power Q has most influence on the voltage U. Therefore there are two "pairs of twins" in the modes for operation - P with f or ϕ and Q with U which can be exchanged one with another. In principle, there are four modes of operation for a DC link just as for a power plant: PQ, PU, fU and ϕU.

Mode	Controlled variables	Effect
PQ	P_{DC}, Q_{DC}	Active power specified Reactive power to minimum
PU	P_{DC}, U	Active power specified Voltage controlled
fU	f, U	Frequency controlled Voltage controlled
ϕU	$< \underline{E} - < \underline{U}$, U	Transmission angle controlled Voltage controlled

Figure 2. Main control modes of operation in an interconnected AC/DC system.

III.2.1 PQ mode

The PQ mode is normally used in DC converters where the active power of the DC link is specified (e.g. by contract) and the reactive power is kept to a minimum to keep investment and losses down.

III.2.2 PU mode

With rather small additional investment a reactive power control of the converter station can be used for voltage stabilizing at the busbar by influencing the reactive power balance in the system. This is practically equal to the control mode normally used in generator units.

The reactive power control of the station can be supported by external elements, such as filter circuits, shunt capacitors, shunt reactors or even static var compensators. These can operate independent or in cooperation with the converter station control system.

III.2.3 fU mode

Like a power plant a DC converter station can also be used for load - frequency control. The active power P_{DC} is controlled depending on the frequency in the system, the reactive power can independently be used for voltage control.

III.2.4 ϕU mode

This may be a very important mode for the future. Changes in the active power P_{DC} will have influence on the transmission angle, changes in the voltage U will have influence on the voltage profile in the system. The stability of a long distance transmission and the active and reactive power load flow in a meshed system can be improved. Higher ratings up to the thermal limits may be envisaged.

III.2.5 Other modes

DC converter control is very flexible. The active power P can be replaced by the frequency f or by the transmission angle ϕ, the reactive power Q by the voltage U. So the equivalent modes fQ (for fU) and ϕQ (for ϕU) would be possible but nevertheless of minor importance.

III.2.6 Application of the PU mode

The PU mode is of a special importance mainly in systems with low short-circuit capacity. For the PU mode, Figure 3 shows an example (with constant busbar voltage U) of the system and load-dependent reactive power requirements Q_{DC} as a function of the active power P_{DC} supplied to drawn from the AC system.

The power limits for a maximum transmission angle between the system voltage $\underline{E}$ and the busbar voltage $\underline{U}$ of 20 degrees or 25 degrees are also entered.

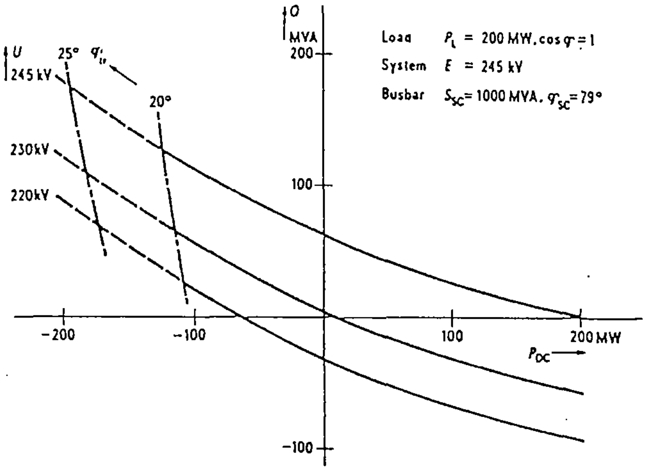


Figure 3. Reactive power requirements of a weak AC system connected to a DC link.

The short-circuit capacity S_{SC} at the busbar was set at 1000 MVA, and the load $\underline{S}_L$ was set at 200 MW with p.f. = 1. The voltage in the infinite system is E = 245 kV. It can be seen from Figure 3 that there is a reactive power change amounting to about 8.5 ... 9 MVA per % voltage change in the PQ range used, and so there is still no risk of voltage instability. The reactive power requirement can be made available in coarse steps by the reactive power elements already mentioned and can be continuously adjusted by the reactive power control of the DC link.

III.3 PRINCIPLE SCHEME FOR HVDC ACTIVE AND REACTIVE POWER CONTROL

Figure 4 shows the block diagram of a control system with which all the modes in Figure 2 can be realized. Also the requirements of the system in Figure 3 can be covered, provided that sufficient reactive power compensation (filters, switched capacitors and reactors) is installed on both sides of the converter station.

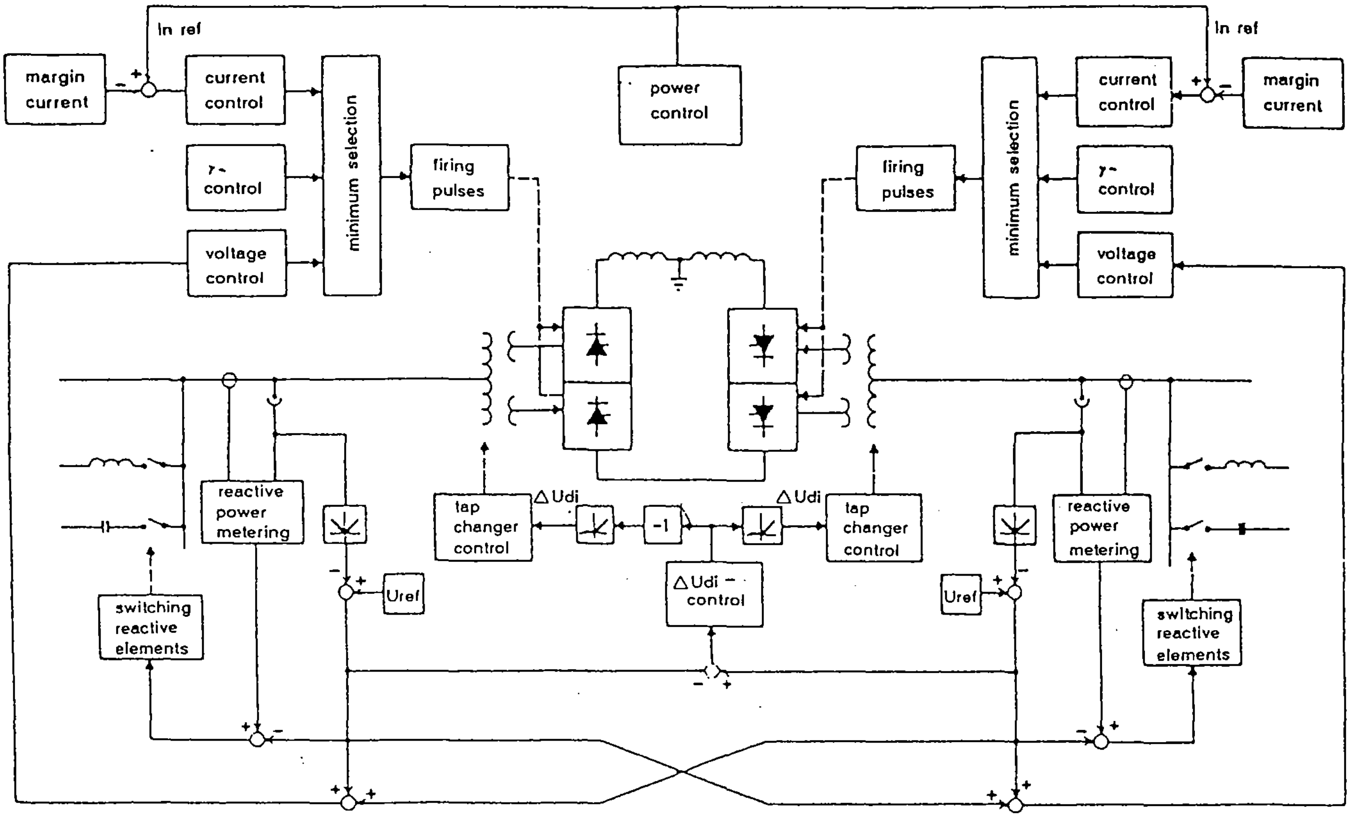


Figure 4. Example of block diagram of the control system for a back-to-back DC link designed for var control.

The control system includes:

- Firing angle control on the rectifier side
- Extinction angle control on the inverter side
- Tap changer control on both sides) steady state
- Switching reactive elements on both sides) only

with steady state and dynamic influence on:

- Active power transmission
- Reactive power on both sides
- Operating point.

Two of any of these values can be chosen for dynamic influence, the other ones for steady state influence only.

How the control can be used in a real scheme is shown in Figure 5. The reactive power requirements of both systems for a power transmission of 200 MW from west to east are met by both converters with the aid of compensation means. Transmitted active power, voltage level at the busbars and reactive power needs by the system are specified by the operator.

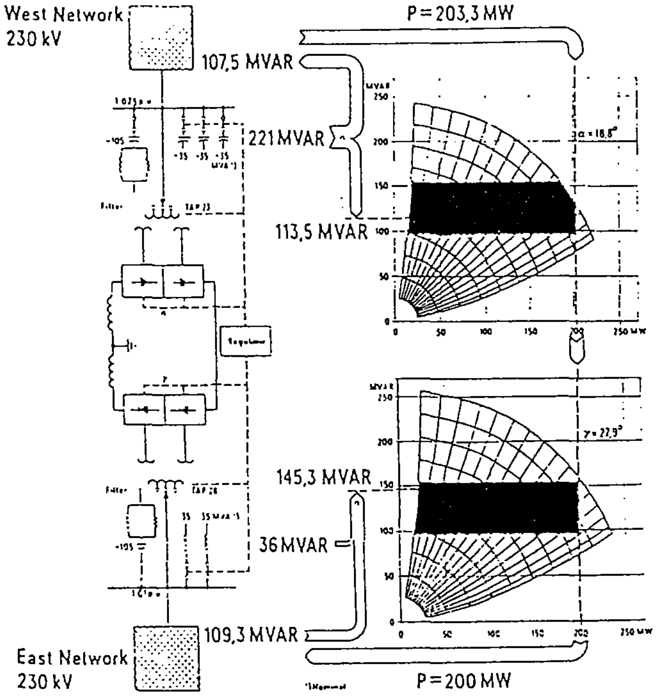


Figure 5. Active and reactive power flow of a back-to-back DC link operating in PU mode. The black area is the operation area specified due to system needs.

APPENDIX IV

PRINCIPLES OF VOLTAGE CONTROL AND ACTIVE POWER CONTROL BY DC CONVERTER COMBINED WITH FILTER, CAPACITOR AND REACTORS

by Dr. M. Erche, Germany

Active power control at minimum losses and voltage control are mentioned in the chapter "Modes of operation". In this chapter the continuous dynamic voltage control at constant active power will be described and compared with active power control at minimum losses.

IV.1 CONTINUOUS VOLTAGE CONTROL

The upper part of Figure 1 shows the reactive power requirements of the system presented in Appendix 3 for the constant voltage levels 220, 230 and 245 kV at the DC link busbar. Only capacitive reactive power is needed in rectifier operation and also mainly in inverter operation of the DC link. As can be seen in the converter diagram rectifier and inverter need additionally reactive power in the range of about 50 % of the transmitted active power. The DC filters deliver the basic reactive power which is not sufficient in the rectifier operation, but too much in the inverter operation. Consequently capacitors are added in the rectifier mode, a reactor in the inverter mode.

The operating points of the converter are determined in such a way that dynamic voltage control at constant active power is possible between 220 kV and 245 kV without switching capacitors or reactor. An example for the reactive power balance at the operating point for 230 kV and modulation up to 245 kV at about -140 MW active power (export) is given in the figure. The filter and two capacitors are switched on.

The "lift" (decrease of reactive power in the rectifier) is smaller than the necessary changes of reactive power in the system to move from the 230 kV curve to the 245 kV curve. The reason is the increase of reactive power delivered by filter and capacitors at the higher voltage level (see legend to Figure 1).

For rectifier and inverter operation the operating points and control areas have been calculated and introduced in Figure 1. Filter and three capacitors are necessary to ren der full dynamic voltage control in the rectifier operation (export up to -200 MW). No switching of reactive power elements is necessary in the inverter operation.

About 15 % more rating above 200 MW is necessary to have the full control range at 200 MW rated power of the DC link. In the rectifier operation a full range modulation would require an additional capacitor at -200 MW but that would of course not be justified for such a small area to increase the voltage to 245 kV.

IV.2 ACTIVE POWER CONTROL AT MINIMUM LOSSES

For comparison reasons the same diagram (Figure 2) has been made for active power control at minimum losses with reduced rated power but unchanged filter, capacitor and reactor ratings.

Firing and extinction angle are constant at a minimum of about 15°. By switching capacitors or reactors the voltage can be kept steady state between 220 and 245 kV. Only two capacitors are necessary compared to three at voltage control.

With the same rating of filter, capacitors and reactors as used for voltage control there is an overlap in the voltage range in the rectifier operation. If for the DC link only the mode of active power control at minimum losses is specified probably number and size of the capacitors could be reduced.

Dynamic voltage control is only possible below the rated power by higher reactive power consumption of the DC link that is equivalent to voltage reduction only.

IV.3 CONCLUSIONS

There are many criteria for dimensioning a DC link and its equipment which are dealt with in this report. Some of them in the connection with continuous and dynamic voltage control should be mentioned briefly:

- Continuous steady state and dynamic voltage control requires a higher rating of the DC link including reactive power equipment.
- The converter diagrams are depending on voltages and transformer tap changer positions in both systems.
- Dynamic reactive power and voltage control are not independent in both systems. There must be a good coordination especially in the case where both systems are relatively weak.
- Minimisation of losses requires operation at lowest possible firing and extinction angles. Nevertheless the minimum values of these angles must be respected due to security of operation.
- Dimensioning of the transformers requires consideration of voltages, saturation and overload.

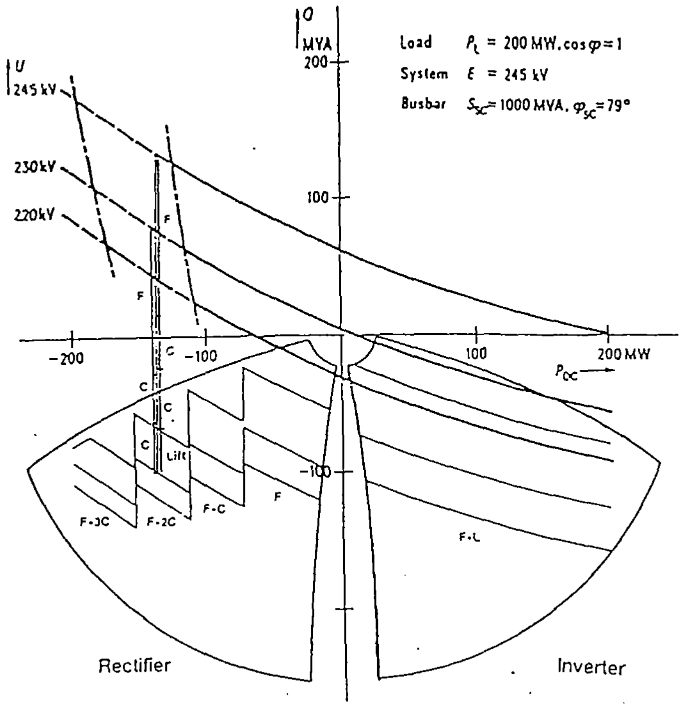


Figure 1. Principles of continuous voltage control by DC converter combined with filter, capacitors and reactors.

	220 kV	230 kV	245 kV
F Filter	-96.1	-105	-119
C Capacitor	-32.0	-35	-39.7
L Reactor	32.0	35	39

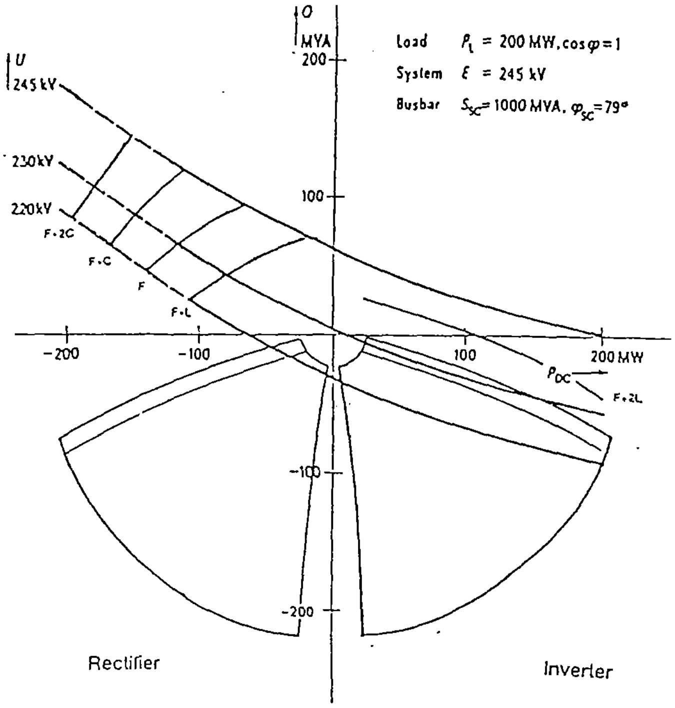


Figure 2. Principles of active power control (minimum losses) by DC converter combined with filter, capacitors and reactors.

	220 kV	230 kV	245 kV
F Filter	-96.1	-105	-119
C Capacitor	-32.0	-35	-39.7
L Reactor	32.0	35	39

APPENDIX V

COMMUTATION FAILURES IN DC SYSTEMS AND THEIR EFFECTS ON THE FEEDING AC SYSTEMS

by Dr. J. Rittiger, Germany

for CIGRÉ WG 14.05

(Summarized here with the permission of
the chairman, Mr. Göran Anderson, Sweden)

V.1 INTRODUCTION

This section illustrates calculations on detailed model of two point transmission. It should show the voltages, currents and powers in order to show impact of a commutation failure on the AC system. As discussed in previous sections commutation failure always leads to a DC short circuit in at least one of the inverter valve bridges, so that the direct current driven by the rectifier increases until the rectifier controls are reacting according to their control parameters. This means that commutation failures produce transient changes in the active and reactive power of the DC scheme.

Commutation failures which result from a switching operation in the inverter AC network or from loss of firing pulses at the inverter are simulated and analysed. Furthermore, voltages and currents in the valve groups are investigated to explain how a commutation failure develops and to further illustrate the phenomena discussed in the previous section.

V.2 SIMULATION MODEL

Simulations presented in this section are made by electric transient program. Figure 1 shows the investigated configuration based on the CIGRÉ Benchmark Model [1]. The HVDC system is a 250 MW (250 kV, 1000 A) cable trans mission with a cable length of 130 km, where the DC cable is represented by 40 π-equivalents.

The valve representation includes snubber circuits. The converter transformer model also takes saturation effects into account. The control parameters were modified compared to [1] (I_d-controller: $k = 0.4$, $T = 30$ ms; γ-controller: $k = 0.2$, $T = 50$ ms). In the controls there were no additional measures implemented to avoid commutation failures.

The AC network representation consists of the AC filters and the feeding AC system.

The feeding AC systems are modelled as a source and an equivalent impedance according to the short circuit capability. On the rectifier side, the short circuit ratio (SCR) was 2.5 for all calculations. On the inverter side, calculations were made for SCR 2.5 and 10.0.

V.3 VALVE VOLTAGES AND CURRENTS DURING COMMUTATION FAILURE

For the following simulations, SCR on the rectifier and the inverter side was 2.5, assuming relatively high impedance AC networks.

Figure 2 shows the voltages and currents of one inverter six-pulse group during a commutation failure caused by the switching of a large reactor in the inverter AC network. The extinction angle of the inverter before the switching operation was 17°. It can be seen that there is a commutation failure from valve 1S+ to 1T+ and from valve 1S- to 1T-, because the negative voltage time areas of the 1S+ and 1S- valve voltages are zero as a result of the change in commutation voltage angle (mark a in Figure 2). The six-pulse group is short circuited for 25-30 msec so that the DC group voltage drops to zero.

Figure 3 shows the same switching operation with a temporarily increased extinction angle of 23° (e.g. $\Delta\gamma = 6°$). It can be seen that the negative voltage time area of the valve 1S+ decreases after the switching operation but it is still present and enables to finish the commutation process (mark a in Figure 3). The temporary increase of extinction angle before the known switching operation (e.g. switching of reactors or filters) can help to maintain normal HVDC operation.

More frequent, however, are unforeseeable switching events or faults in the inverter AC system for which there is no opportunity to increase γ in advance of the disturbance. In these cases it is highly dependent on the strength of the AC fault or the switching event, whether a commutation failure will occur or not. In the case of a weak AC network with high frequency of switching events and faults, an increased extinction angle for steady state operation can be chosen to increase DC system reliability, accepting a higher converter rating and increased active power losses.

Figure 4 shows a commutation failure after the loss of a firing pulse in the valve 1R+, so that the valve 1T+ cannot commutate the current to the valve 1R+. At the same time the valve 1T- is conducting and the six-pulse group is short circuited.

V.4 ACTIVE AND REACTIVE POWER DURING COMMUTATION FAILURES

The interaction between the HVDC and the AC network concerning active and reactive power of the converters are discussed below. In Figures 5a/b - 8a/b, the most important quantities for the rectifier and inverter sides for different SCR of the inverter AC network are measured.

Each figure shows the following rectifier and inverter quantities:

U_R: Phase voltage R at the busbar
U_S: Phase voltage S at the busbar
U_T: Phase voltage T at the busbar
I_R: Converter 12-pulse current phase R
I_S: Converter 12-pulse current phase S
I_T: Converter 12-pulse current phase T
I_d: Direct current
U_d: DC voltage at the converter bridges
P_d: DC power $I_d * U_d$
P: Active power of the converter
Q: Reactive power of the converter

Figure 5: Commutation failure caused by a switching operation (SCR = 2.5 at the inverter)

Figure 6: Commutation failure caused by a firing pulse loss (SCR = 2.5 at the inverter)

Figure 7: Commutation failure caused by a switching operation (SCR = 10 at the inverter)

Figure 8: Commutation failure caused by a firing pulse loss (SCR = 10 at the inverter).

Some general conclusions are possible:

- The rectifier AC network is also strongly influenced by a commutation failure, especially when the rectifier SCR is low. It can be seen that during the commutation failure the busbar voltages on the rectifier side are severely distorted (Figure 5a).

- The active power drops to zero or even a power reversal occurs, depending on control parameters.

- The total reactive power on the rectifier side becomes inductive during the commutation failure because of two effects: During the commutation failure, the capacitive power of the filters decreases according to the drop in the busbar voltage and the inductive power demand of the rectifier converter increases.

- On the inverter side, the fundamental frequency active power decreases to low values. For the reactive power demand on the inverter side no general rule can be derived. This can be explained because the converter group is not in controlled operation during the commutation failure, and the current, which is unbalanced between phases, is flowing more or less arbitrarily according to the time of the fault occurrence and the resonance conditions in the inverter AC network.

- On both sides, harmonics have a great influence on active and reactive power demand. This influence is high for SCR = 2.5. In this case the inverter AC network and the filters have a strong resonance near the third harmonic (150 Hz).

From the simulation results it can be seen that the active power recovers within a few cycles after the commutation failure. However it must be noted that this is highly dependent on the choice of control parameters.

V.5 CONCLUSION

The active and reactive power demand of the HVDC converters depends strongly on time of fault occurrence, SCR and resonances in the AC networks.

More specifically:

(a) The rectifier side is also influenced by a commutation failure. The transferred disturbances are severe when the rectifier AC network is weak.

(b) The fundamental wave active power drops to low values during the failure on both rectifier and inverter side.

(c) The fundamental wave reactive power on the rectifier side becomes more inductive with increasing DC current and the fact that the rectifier bridge is in controlled operation.

(d) It is not possible to derive a general rule for the fundamental frequency reactive power at the inverter because the bridge is not in controlled operation during the commutation failure.

(e) The recovery of the converter from commutation failures depends on the specific behaviour of control design and cannot be quantified for a general case. Such aspects, together with specific mitigation strategies, are beyond the scope of this paper.

REFERENCES

[1] FGH, 1988; Paper presented to CIGRÉ WG 14-02. Simulator studies of HVDC controls with a proposed Benchmark Model.

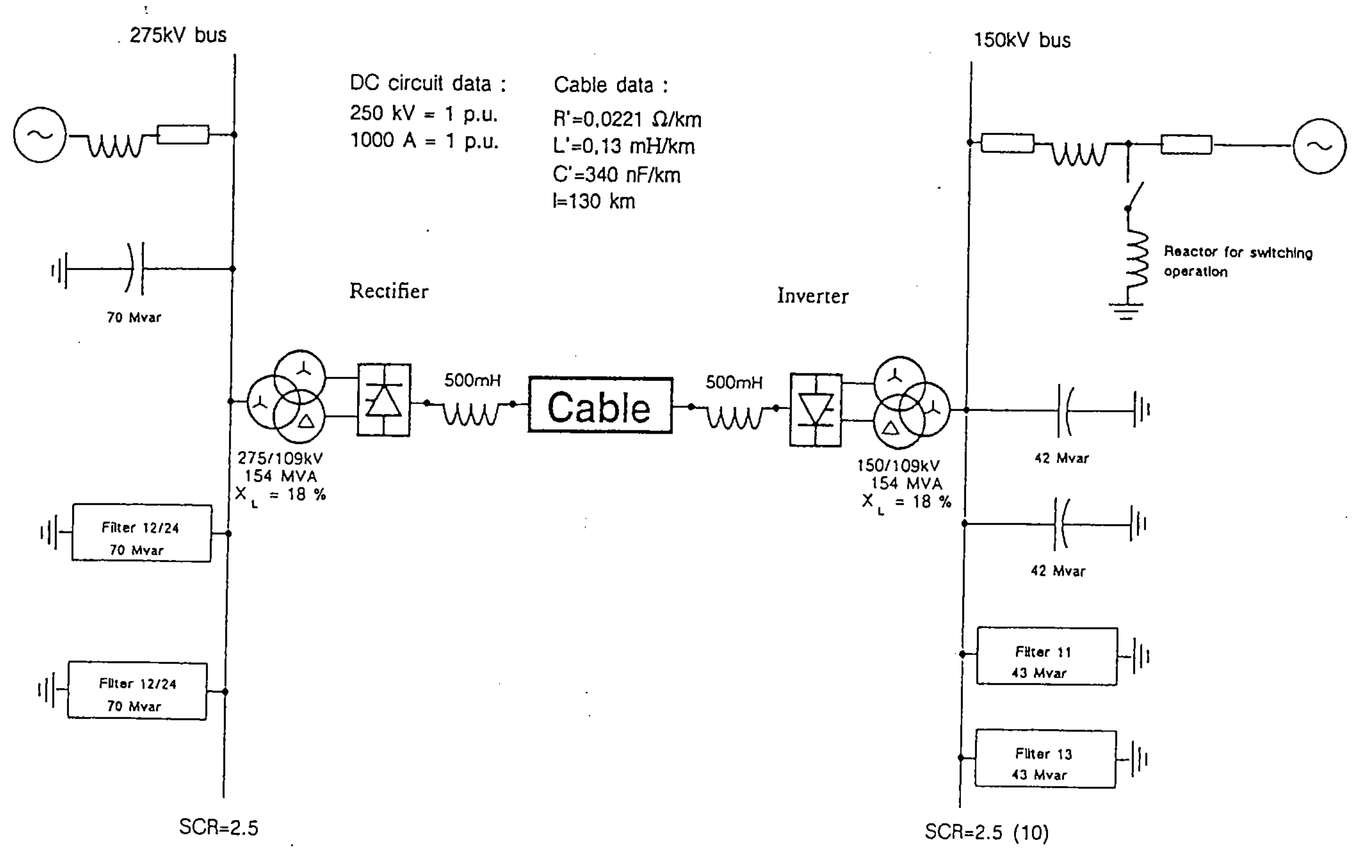


Figure 1 : Representation of HVDC system to study the effects of commutation failures

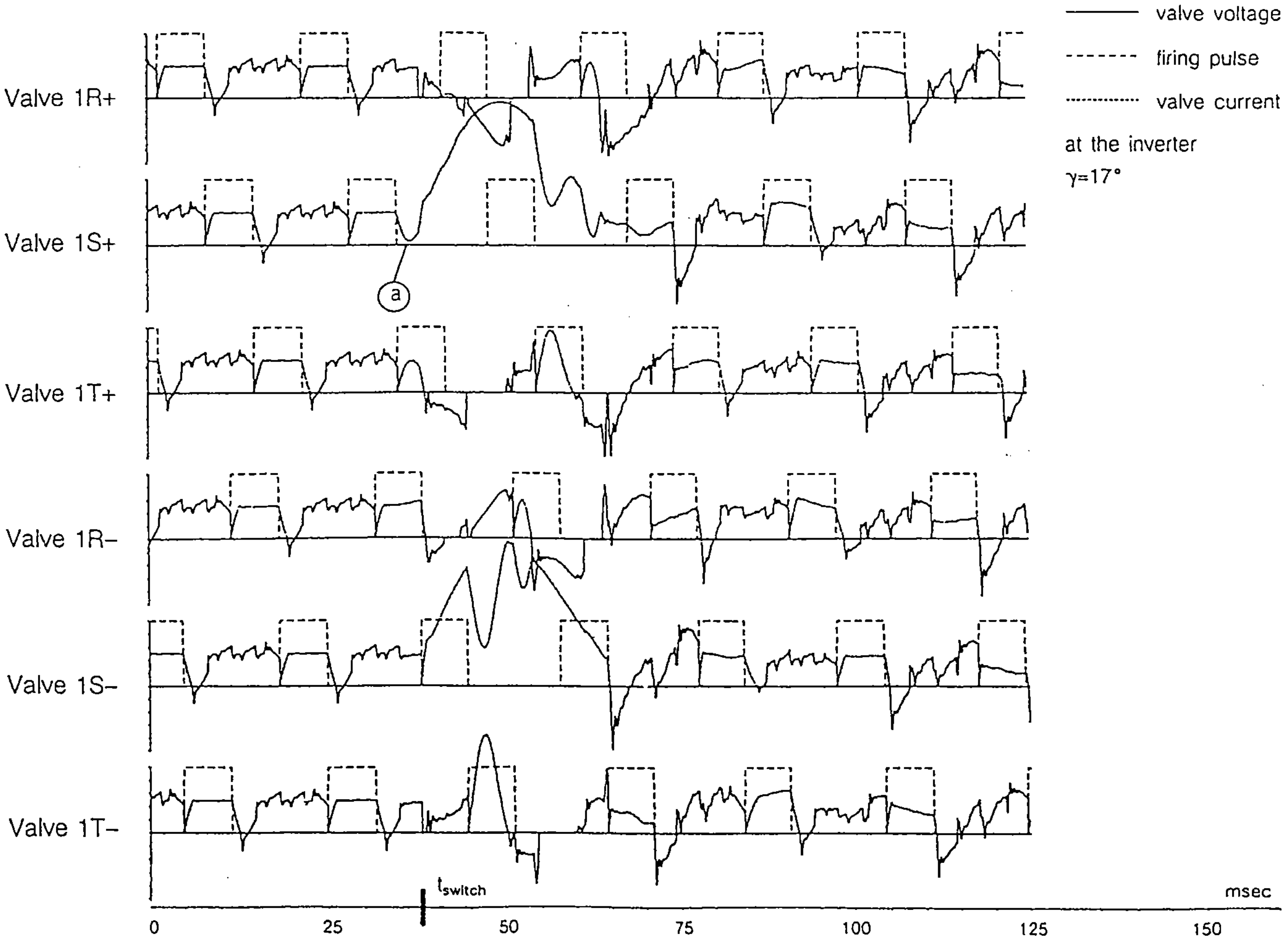


Figure 2 : Commutation failure after a switching operation (SCR=2.5)

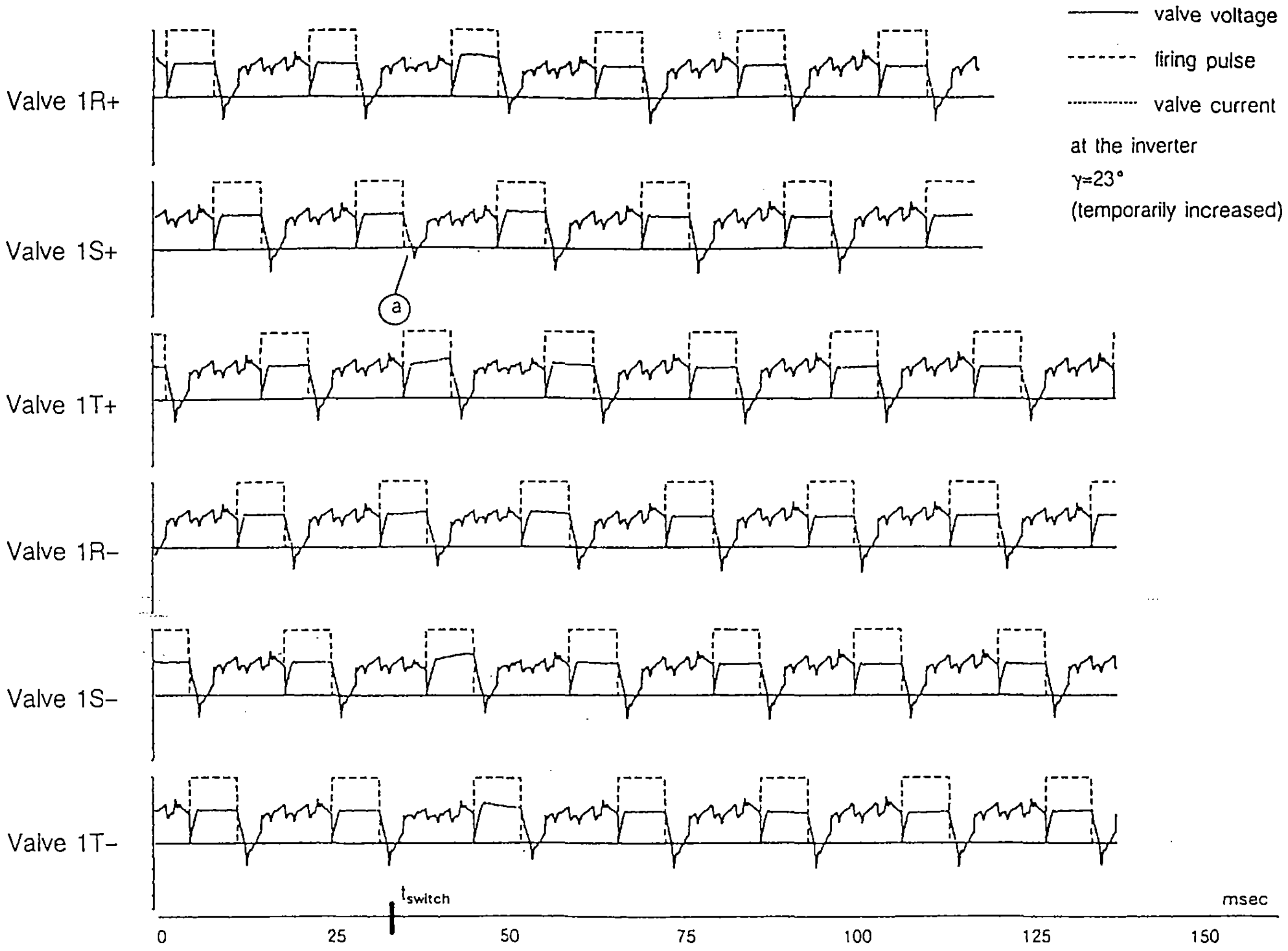


Figure 3 : Switching operation with increased extinction angle (SCR=2.5)

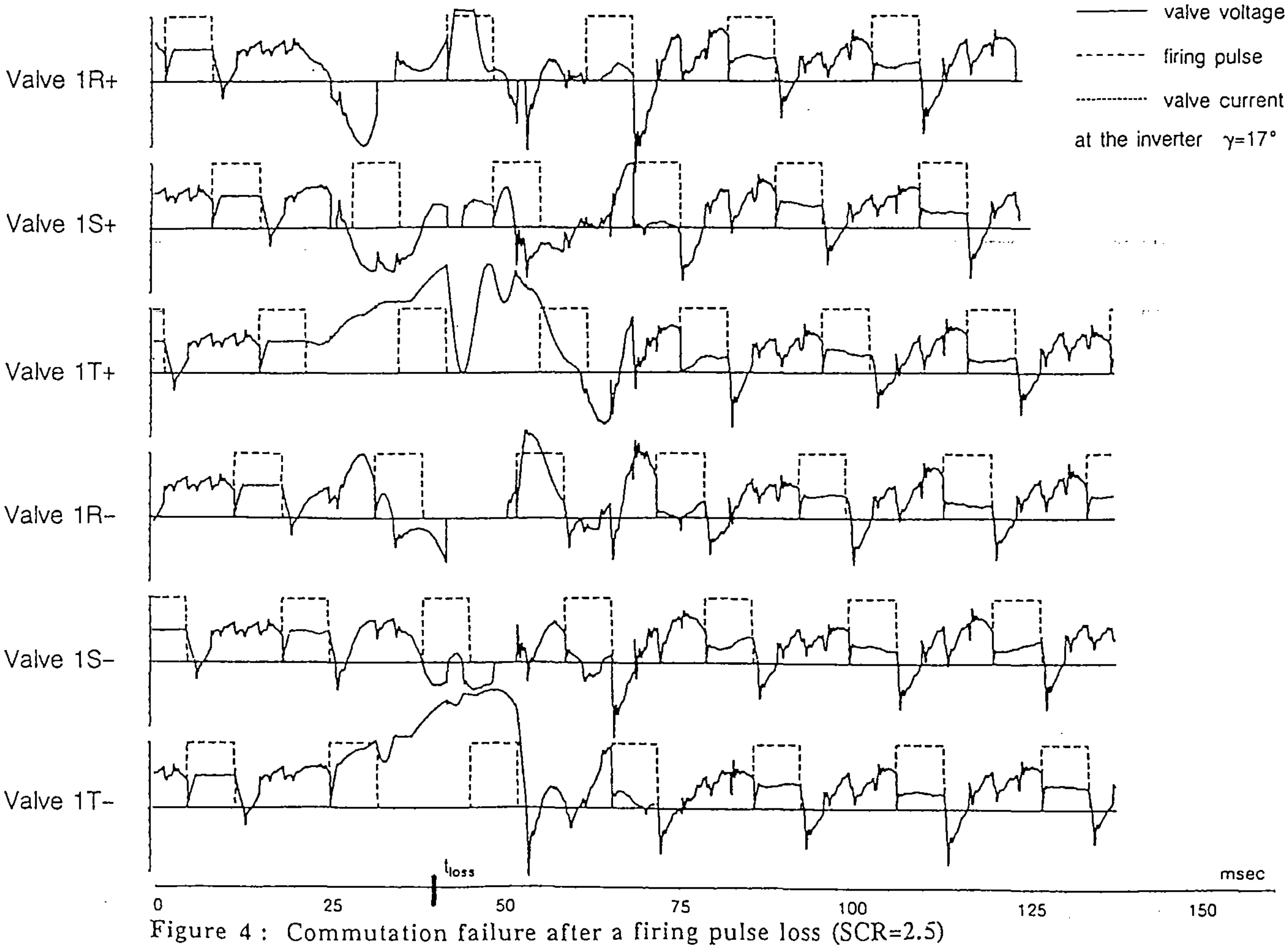


Figure 4 : Commutation failure after a firing pulse loss (SCR=2.5)

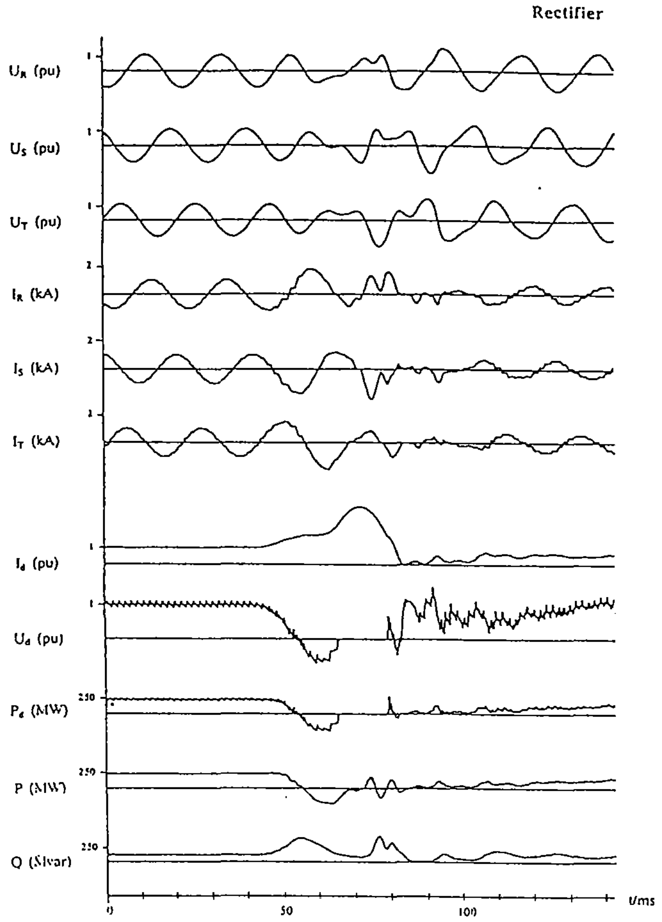


Figure 5a : Switching operation (SCR=2.5)

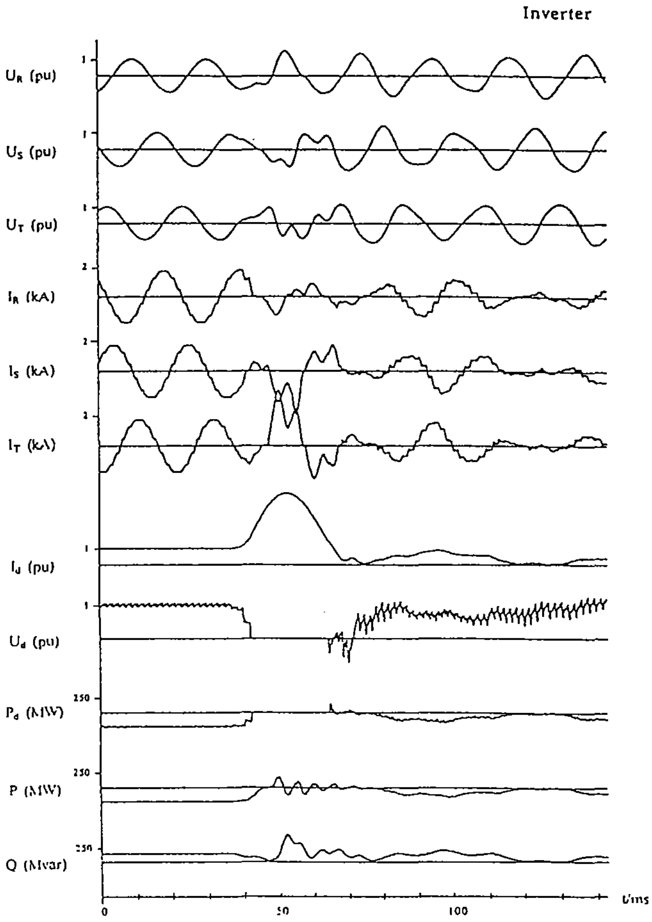


Figure 5b : Switching operation (SCR=2.5)

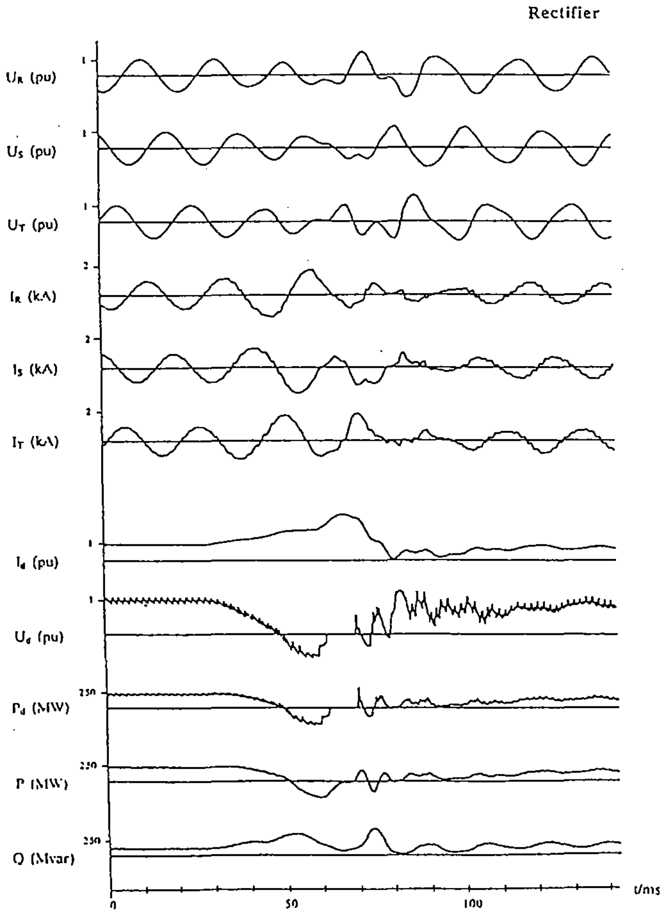


Figure 6a : Firing pulse loss (SCR=2.5)

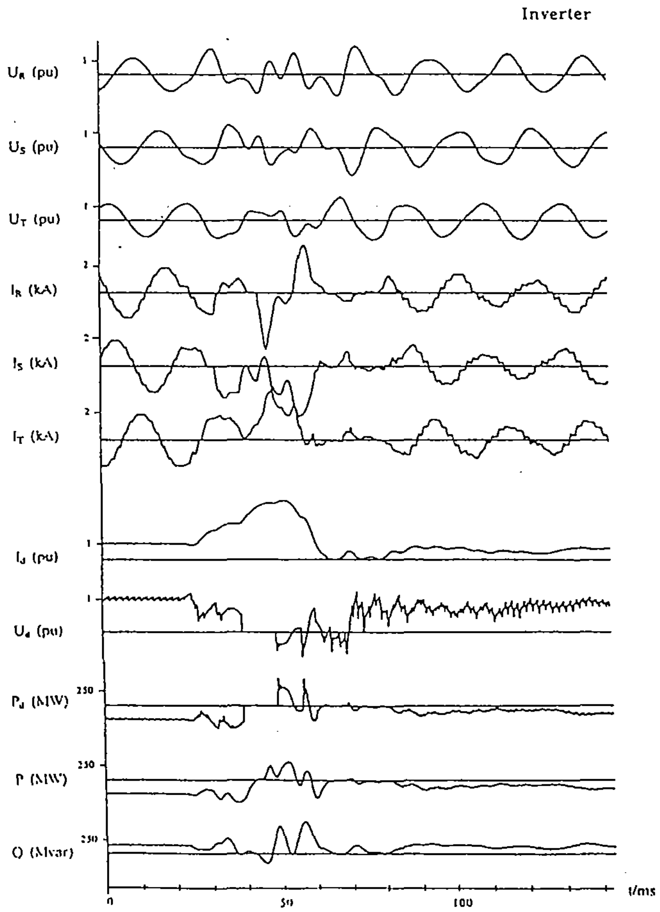


Figure 6b : Firing pulse loss (SCR=2.5)

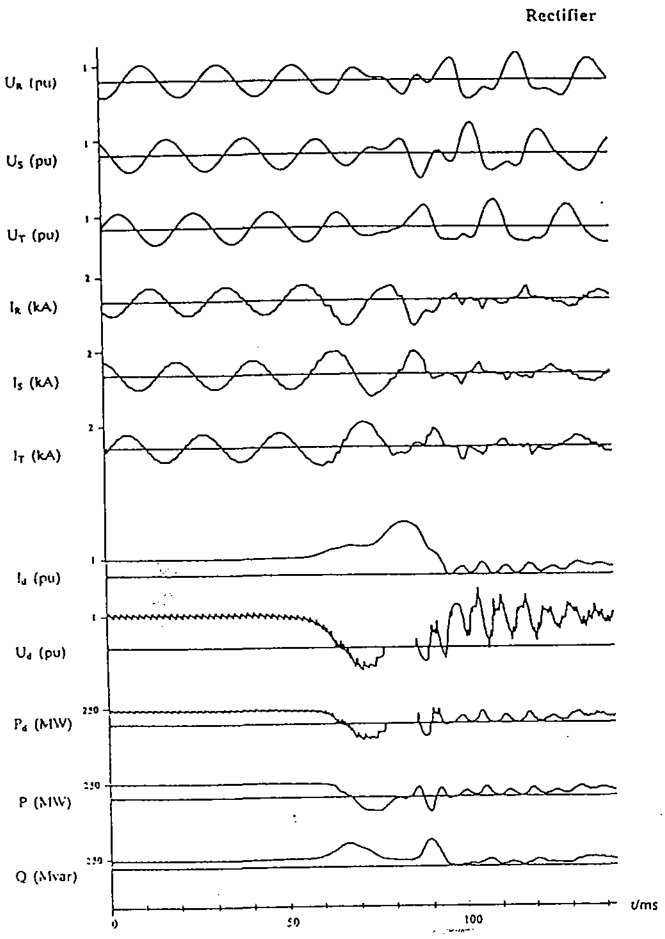


Figure 7a : Switching operation (SCR=10)

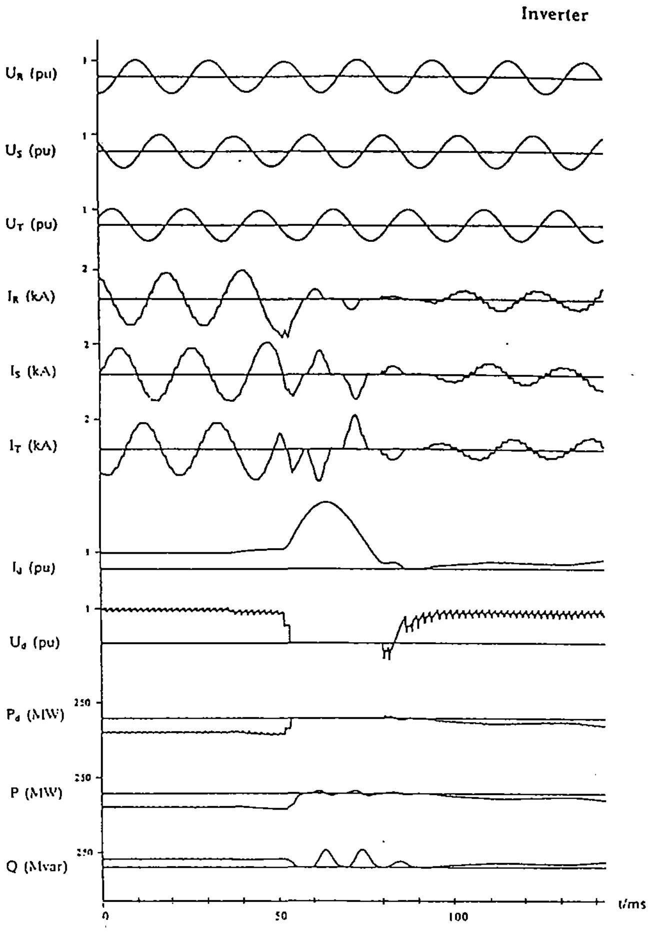


Figure 7b : Switching operation (SCR=10)

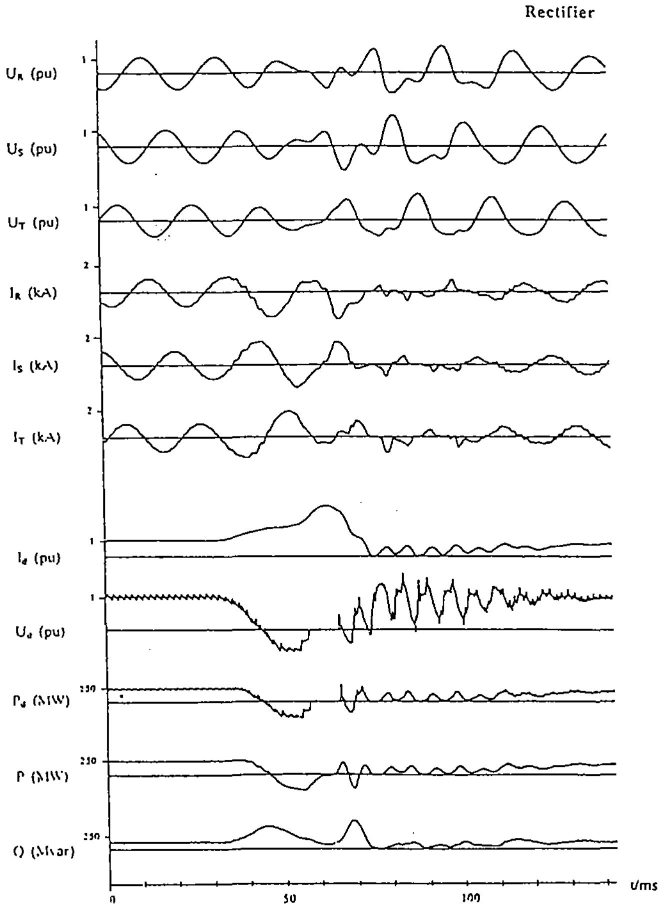


Figure 8a : Firing pulse loss (SCR=10)

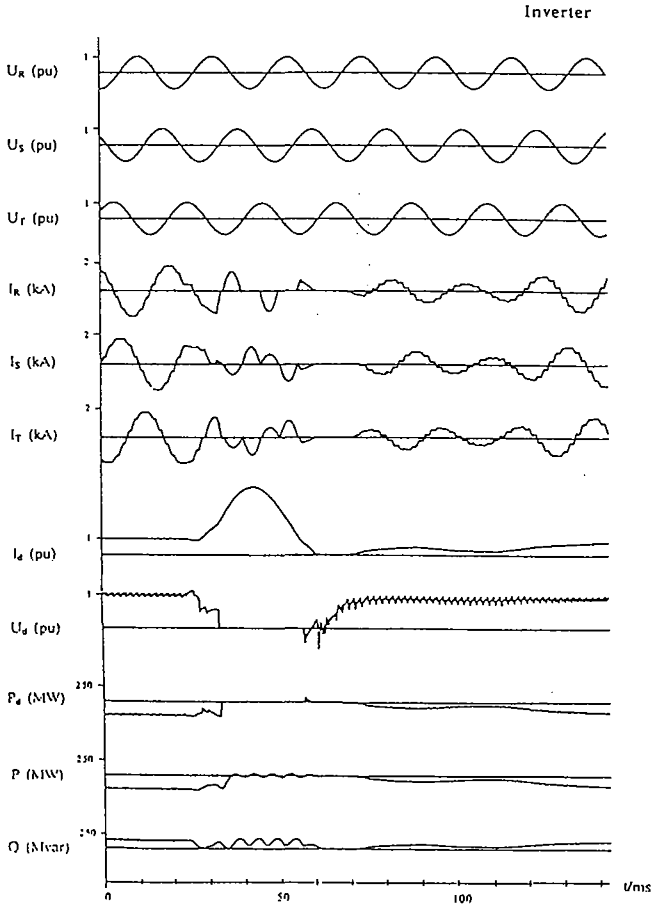


Figure 8b : Firing pulse loss (SCR=10)

APPENDIX VI

VOLTAGE CHANGES IN PHASE ANGLE AND AMPLITUDE AS WELL AS TRANSIENTS IN CONTEXT WITH SWITCHING OPERATIONS AND FAULTS

by Dr. M. Erche, Germany

VI.1 VOLTAGE QUALITY IN THE NETWORKS

Users of electric power demand both network operation that is as fault-free as possible and voltage that is of high quality. This means at constant frequency a practically constant voltage with low harmonic content. In view of sensitive consumers, even short-time voltage fluctuations must be kept to a minimum in terms of amplitude and phase angle, with it no longer being possible in the short-time range to distinguish between fluctuations in frequency or in phase angle. Electronic devices, especially power electronics components in drive systems and in HVDC transmission inverter operation, are sensitive to sudden changes in voltage in the millisecond range.

Fig. 1 shows values of the extent and frequency of voltage changes in electrical networks at consumer-close voltage levels. As most voltage fluctuations are caused by the consumers themselves, it is the lower limits of the range illustrated which apply with regard to the permissible voltage changes in the (consumer-remote) high and very-high-voltage network. If large consumers are connected there, attention is paid as early as the planning and equipment design stages to the necessity of keeping within prescribed voltage fluctuation limits.

VI.2 CAUSES OF VOLTAGE CHANGES IN THE HIGH-VOLTAGE NETWORK

With an electrical network being operated at a particular frequency, good voltage quality means that, in addition to the frequency, the amplitude and phase angle of the voltage also remain largely constant. In a high-voltage network, however, a certain noise level is superimposed on the operating frequency voltage. This noise level indeed comes partly from the subordinate voltage levels, but its occasionally conspicuous values are caused in the high-voltage network itself.

VI.2.1 Operational switching activities

Changes in the amplitude and phase angle of the operating frequency voltage are caused in a high-voltage network mainly by:

- Switching of lines. This includes the opening or closing of rings in the network or of connections to other networks.

- Switching of loads. Substantial variable loads connected to the high-voltage network, e.g. arc furnaces, are generally so designed that impermissible voltage changes cannot occur. Other substantial loads are switched in and out either in steps or continuously via converters. Solely in the event of faults in the network, e.g. incorrect tripping on faults, can the shedding of major loads result. In this case too, switching back in takes place where possible in small steps at a time.

- Switching of transformers. Even transformers under no load conditions when switched in rush-wise take up for a good number of seconds heavily distorted currents up to the order of the rating of the transformer. This can result in not only substantial voltage changes, but also in electronic devices being affected by harmonics.

VI.2.2 Faults in the network

Sudden brief faults in the network can lead to a considerable reduction in the voltage quality.

- The failure of power plants, of external feed sources or of HVDC infeeds can lead to changes in the load flow and, in an unfavourable case, to active power deficits in the system. In the event of power plant failure, the network shows the same behaviour as is the case with the switching of major loads.

- Short-circuits. More than 90 % of short-circuits in a high-voltage network are single-phase earth faults. Even multi-phase faults are generally initiated by a single-phase earth fault. As these faults substantially affect the active and reactive power balance in the network, every effort must be made to prevent further malfunctioning of equipment (with escalating con-sequences) during a short-circuit. In the following, ideas are therefore centered around earth faults.

- Power swing, subsynchronous resonance. Usually following faults in the network, power swing can occur with relatively low-frequency influence on voltage amplitude and phase angle. The control system of the HVDC transmission must be able to resist these swings or even to counteract them. They are therefore not covered in this context.

VI.2.3 Reactive power control

The reactive power control changes the reactive power balance, thus the reactive power flow in the network too and also the voltage control in line with magnitude and phase:

- Switching of coils or capacitors. Sudden reactive power changes lead to sudden voltage changes too. These processes are treated in the same way as is the case with the switching loads. The magnitude of the switched units depends on the permissible voltage changes in the network.

- SVC. With Static Var Compensators, reactive power can be continuously controlled. Sudden voltage changes, which are to form the subject of this report, are thereby avoided.

- Transformer tap changers. Transformers are controlled in short steps, so that the voltage changes chaused therby have no negative effect.

VI.3 EFFECTS OF VOLTAGE CHANGES IN THE NETWORK

VI.3.1 Influences on Consumers

- Electronic devices, especially computers, without uninterruptible power supply and with insufficient energy storage in the power pack, can have their operation adversely affected by voltage dips. Control electronics may also be susceptible to incorrect interpretations of frequency and voltage; this can in turn lead to wrong inputs.

- With speed-sensitive machines, such as are used in the textile industry and elsewhere, especially periodic voltage changes can lead to substantial quality deficiencies in the products.

- In inverter operation and in the event of major voltage and phase angle changes, the power electronics are susceptible to commutation failure, which would lead to a temporary interruption of HVDC transmission. As, for example, in the event of an earth fault a three-phase connection can still carry 60 to 70 % of the previous load, the complete failure of HVDC transmission under the same fault conditions is scarcely acceptable to the operator of a three-phase network.

- The light intensity of many lighting fittings depends heavily on the voltage and can therefore vary quite significantly as a result of minor changes. The quality of lighting at a place of work and also in households is therfore one of the main reasons for the limiting of voltage changes in normal, low voltage network operation.

VI.3.2 Influence on network equipment

- HVDC transmission in inverter operation. HVDC transmission is, as mentioned, sensitive in inverter operation to sudden voltage amplitude and phase angle changes and is a major aspect of these statements.

- Protection malfunction. Phase angle changes can give the impression of short-time frequency changes and thus for example lead to the tripping of load-shed relays.

VI.4 POWER FREQUENCY VOLTAGE CHANGES

VI.4.1 Voltage changes in the event of switching of loads and reactive power elements

In the normal switching of loads, switch-in and switch-out occur equally often. Larger loads are switched in steps or continuously (converters). Several larger loads are of course not intentionally switched in together; they can however as a result of false tripping or in connection with a network fault be switched out and in the event of short-circuit interruption switched back in after a few hundred ms. This shows that intentional switching operations lead to relatively minor voltage changes, whereas in particular in the event of uncontrolled load shedding, considerable voltage changes - usually increases - can occur.

Fig. 2 shows a general equivalent circuit diagram for calculating voltage changes in the event of load changes. The network impedance ZSC is derived from the short-circuit power SSC, which is determined mainly by the impedances of the generators, transformers and lines up to the point in question. This short-circuit impedance is mainly inductive. The load impedance ZL is at a normal load level approximately ohmic, but in the case of reactive power elements purely capacitive. These include non-loaded cables, which count as capacitive loads. The voltage U on the load is, referred to the EMF voltage E in the network, dependent on the ratio of these two impedances.

In Fig. 3, magnitude and phase angle of the voltage change are superimposed on the ratio of the short-circuit power to the load. The parameter is the angle of this ratio, which with an inductive load can be negative, with ohmic load is still below 90° and with capacitive load reaches almost 180°. Owing to the mainly inductive short-circuit impedance, the switching of inductive or capacitive load leads to substantial voltage changes (with various signs) but to relatively minor changes in angle. Conversely, when an ohmic load is switched, the change in the magnitude of the voltage is small, but the change in the phase angle considerable.

Assuming that with frequent load switchings the magnitude of the voltage is not supposed to change by more than 1 %, a switched ohmic load must not be substantially greater than about 2 % of the short-circuit power. Much more serious however is the problem with the switching of the reactive power elements, which have to be switched in relatively small steps if sudden voltage changes are not avoided right from the start by means of a continuously controllable static Var compensator. Voltage changes continously regulated over several periods are handled by the electronics without trouble and generally tolerated by the other consumers.

The switching of greater ohmic loads leads to conspicuously greater changes in angle than is the case with the switching of inductive or capacitive loads. The remaining consumers however register these changes in angle less than the changes in the magnitude of the voltage; the electronics must adjust itself to this.

VI.4.2 Transfer switching in the network

Transfer switching operations in the network can have many reasons:

- Changes in the network constellation in order to improve either the load flow or the power plant generation schedule, or to reduce losses, etc.

- Commissioning and removal from service, e.g. for maintenance of cables, transformers, switchgear, etc.

- Corrective switching in order to avoid greater faults.

The equivalent circuit illustrated in Fig. 4 can therefore describe the process only in principle.

A load centre is fed from a power plant via two connections. The short-circuit impedance and, derived therefrom, the short-circuit power and the voltage change are calculated for the network with both connections or, in the event of an interruption in the lower feeder, with only one connection.

An example involving the following assumptions

$Z_2/Z_1 = Z_3/Z_1 = 0.5$ and
S.C.R. $Z_L/Z_1 = 5$ angular difference $(Z_L/Z_1) = -75°$

produces when the ring is opened a voltage change of -2.2 % and a phase angle change of -2.3° and shows that even where the switched connection has a relatively high share of the short-circuit impedance and with a low short-circuit ratio, the voltage change even in the vicinity of the switched connection is still relatively small.

VI.4.3 Single-phase line-to-earth fault

As already mentioned, single-phase line-to-earth short circuit is the most common fault in a high-voltage network. Usually as a result of an insulation fault, a conductor incurs a connection with earth and acquires zero potential; the potential for the other two lines is increased. If the short-circuit occurs in line R, the voltage of line S lags somewhat, and that of line T leads. During the fault, U_R at the fault location is zero. The three line-to-earth voltages in a real system including the transients are shown in Fig. 5.

This oscillogram shows the voltages in the network, but not the voltages behind the transformer on the converter of an HVDC transmission system. There the zero voltage is absent; at the converter itself only the two voltages in the positive and negative phase sequence system occur. The resulting voltage changes will be more closely examined in the following.

The equivalent circuit for calculating the currents and voltages in the event of single-phase earth fault in symmetrical components is shown in Fig. 6. The formulae for the operating frequency voltages in the three lines before and during the fault together with their symmetrical components are also listed.

By way of example with $Z_o/Z_1 = 3$ and angular difference $Z_o/Z_1 = -15°$ the three line-to-earth voltages were calculated and shown in Fig. 7 as an oscillogram. It corresponds (without transient phenomena) approximately to the network in Fig. 5, but without the transients. U_R becomes zero, U_S and U_T are increased in the amplitude. U_S becomes lagging and U_T becomes leading compared to the voltages before the fault.

The symmetrical components of the three line-to-earth voltages are superimposed in Fig. 8 on the ratio Z_o/Z_1. They can, for example, be quickly calculated by the space vector method immediately after occurence or shutdown of a fault.

The short-circuit impedance of the network, the positive phase sequence impedance Z1, is largely inductive. The same applies to the zero component with a somewhat greater ohmic proportion. The ratio of both impedances therefore has a slightly negative impedance angle. The magnitude of Z_o/Z_1 can be below 1 in stations with many earthed transformers; the normal value is however in the range 2 to 3 and can with long lines exceed this value somewhat. Overall therefore, in an evaluation of the diagrams, ratios Z_o and Z_1 in the range of approximately 1 to 4 are necessary in solidly grounded systems.

Fig. 9 shows the three voltages of the lines R, S and T to the (non-earthed) neutral point behind the transfomer on the converter in terms of magnitude and phase. Although the line R is faulted, the voltage U_R attains even at small Z_o/Z_1 ratios 50 % and more of the normal star voltage. The voltages U_S and U_T are based on the differential phase angle between the impedances Z_o and Z_1. The phase angles of the three voltages can also attain substantial values at a low Z_o/Z_1 ratio. However, the interaction of magnitude and phase angle of voltage is significant since both together determine the intersections of the instantaneous values of the operating frequency voltages which are so important for commutation in the converter in inverter operation.

The effect of this is shown in Fig. 10. The three voltages U_R, U_S and U_T appear in the oscillogram without zero component. It can be seen that the voltage in line S dips somewhat in magnitude and is somewhat leading in the phase angle. The voltage in line R dips considerably more, producing overall a shift forward of the intersection of the two voltages U_R and U_S. Communication is therefore unfortunately hampered at the first intersection of the voltages U_R and U_S after the earth fault has occured Nevertheless a quick reaction could be based on definite criteria in the transient phenomena and in the power frequency changes when a single phase earth-to-ground fault has occured within about 1 to 2 ms.

The next commutation between the lines T and R then takes place somewhat later.

It can be clearly seen that the absence of the zero component has fundamentally changed the voltage shape in comparison with the line-to-earth voltages illustrated in Fig. 5.

VI.4.4 Two phase line-to-earth fault

Some accidents in high voltage transmission lines or in substations can cause two phase line-to-earth faults. Depending on the ratio Z_0/Z_1, the voltages between the faulted phases and the neutral, which are responsible for commutation failures, are reduced to less than 50 % of the star voltage (Fig. 11). The phase angles are shifted by about 60° (Fig. 12). The leading (faulted) phase is delayed, the following phase advanced. Reductions in the amplitude and phase shifting may influence the next commutation. Whether this influence is positive or negative should be decided by converter specialists.

VI.4.5 Influence of the fault location

Previous ideas paid attention to locating the fault. In practical terms, the faults in the network are distributed more or less uniformly, with the result that the voltage deviations, e.g. at the place of installation of an HVDC transmission system, are considerably less in the event of a fault at a great distance from the busbar than for a fault directly on it. The figures stated are therefore limit values.

VI.5 TRANSIENT PHENOMENA IN THE CONTEXT OF SWITCHING OPERATIONS AND FAULTS

Switching operations and faults in the system generally lead to a temporary or lasting change in the operating frequency voltages and currents in the system. If these processes take place over a very short time, the result is a transient phenomenon. Its magnitude will depend on the change in the amplitude and in the phase of the operating frequency voltage or current respectively. The frequency of the transient phenomenon depends on the inductances and capacitances of the system, on the damping of the losses, especially in the cables and lines, but also on the loads.

Regardless of the nature of the fault or of the switching operation, the transient phenomena proceed similarly. It is therefore sufficient here to describe this procedure by way of a single example, without going into detail on the difference between possible faults and switching operations.

Load shedding, which can lead in the system to temporary overvoltages, increases in the operating and low-frequency voltages, will not be dealt with closely here. It tends to be rare and is generally separately investigated where it can occur in connection with HVDC transmission.

VI.5.1 Single-phase equivalent circuit

Inductances are found mostly in the series arm of the system. Exceptions are shunt reactors and loads, which are however usually of such high impedance that they have only slight influence on the higher-frequency transient phenomena. Capacitances are usually found in the shunt arm. An exception are series capacitors, which must however always be handled separately where transient phenomena are concerned.

Loads are not incorporated in this equivalent circuit, as their impedance is at least 5-10 times greater than the series impedance. They usually have a damping influence.

The equivalent circuit is single-phase. In the three-phase circuit, the principle of the transient phenomenon is unchanged. The latter circuit has more elements than the single-phase circuit and therefore tends in the event of asymmetrical fault to lead to multiple frequency transient phenomena.

The single phase basis circuit (Fig. 13a) can be represented by its equivalent voltage source (Fig. 13b) or by its equivalent current source (Fig. 13c). The equations for the three most important values in the circuit are shown in the illustration. These three circuits are also the basic form of the equivalent circuits for two poles. The simple circuit is also the most simple form of the iterative network (Fig. 13d), which represents a multiple frequency network. The series connections of parallel resonant circuits (Fig. 13e) and the parallel connection of series resonant circuits (Fig. 13f) are partial break connections, the behaviour of which is absolutely identical with that of the iterative network. They are used for example for calculating the transient recovery voltage or of the transient phenomenon in the short-circuit current. The two latter connections give no indication of the processes in the system itself; the iterative network is therefore used as an example in the following.

VI.5.2 Example for calculation of the transient phenomenon

The iterative network is a special form of the meshed network. So as not to have too many parameters, all inductances and capacitances have been equalized. The following values have been incorporated in the circuit:

Operating frequency $f = 50$ Hz

Series inductance $X_L = 20$ [Ohm] $L = 63.7$ mH

Loss resistance R = 4 [Ohm]
(non-frequency-dependent)

Natural frequency of the
half element $f_e = 500$ Hz

Parallel capacitance C = 1.59 µF

The following resonance frequencies can be calculated:

Parallel resonances (natural frequencies of the parallel resonant circuits)

$f_{p1} = 309$ Hz $f_{p2} = 809$ Hz

Series resonances (natural frequencies of the series resonant circuits)

$f_{r1} = 500 \text{ Hz} = f_e$ $f_{r2} = 1500$ Hz

It can be seen that the lowest series resonance concurs with the resonance frequency of the half element. The lowest parallel resonance is below this value.

VI.5.2.1 Closing the short-circuit

When the short-circuit is initiated, the voltage at the fault location returns to zero (Fig. 14: U_1). The operating frequency portion of the voltage increases as the distance from the fault location becomes greater, and remains of course at the voltage source itself (U_1 to U_3). The first series resonance frequency 500 Hz can be clearly seen in the short-circuit current and in the voltages inside the iterative network.

VI.5.2.2 Opening the short-circuit

When the short-circuit is closed, the current is interrupted in its zero. The returning voltage clearly shows the first parallel resonance frequency. For the voltage at the fault location, the oscillogram calculated shows a noticeable jump, caused by the sudden superimposition of a partial voltage on the input inductance. Under natural conditions, this pure inductance does not exist, but rather there is a piece of line, the natural frequncy of which appears instead of this voltage jump (broken curve).

VI.5.3 Results

- The voltage proceeds from its momentary value before the switching operation or fault always in the direction of the new momentary value of the operating frequency voltage at the same point in time after occurrence of the fault.

- The transient phenomenon often begins with a higher frequency oscillation of low amplitude, which is quickly damped.

- The transient phenomenon is as a rule dominated by the lowest resonance frequency of the system. In a connecting operation, this is the series resonance frequency; in a disconnecting operation it is the (somewhat lower) parallel resonance frequency.

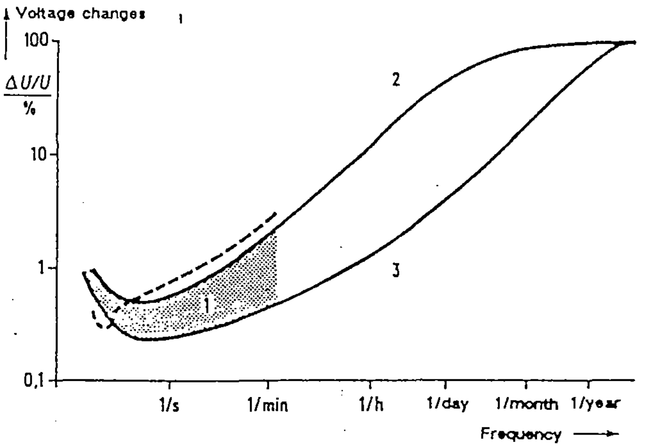
- In the system itself, frequencies below the first parallel or series resnance are also initiated.

- The amplitude of the transient phenomenon can be increased by resonance in the system itself. The amplitude can even be greater in the system than at the location of the switching operation or fault.

- In a meshed network, multiple frequency phenomena occur, with behaviour which is in principle similar.

- The higher frequencies are more quickly damped than the low ones.

The oscillograms shown were worked out with weak damping. The transient phenomena in the system are as a rule very much more strongly damped. The illustrated phenomena refer to fault initiation and fault clearing. In load switching, the operating frequency voltage changes are very much less (Fig. 15); the same then applies of course to the transient phenomena too. Here it should merely be shown that in the great majority of cases, the transient phenomena proceed with the resonance frequencies calculable in the systems, and in accordance with a quite definite schema.



1 Industrial networks with periodical surge load
2 Upper limit: Mainly rural networks
3 Lower limit: Public and industrial networks with good voltage quality
---- Maximum values to IEC TC 77 (proposal)

Fig. 1: Frequency of voltage changes in electrical networks

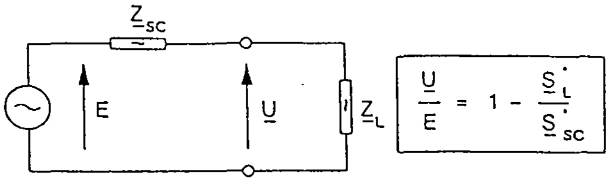


Fig. 2: Equivalent circuit and calculation of voltage changes when a load is switched in (switching out analogous)

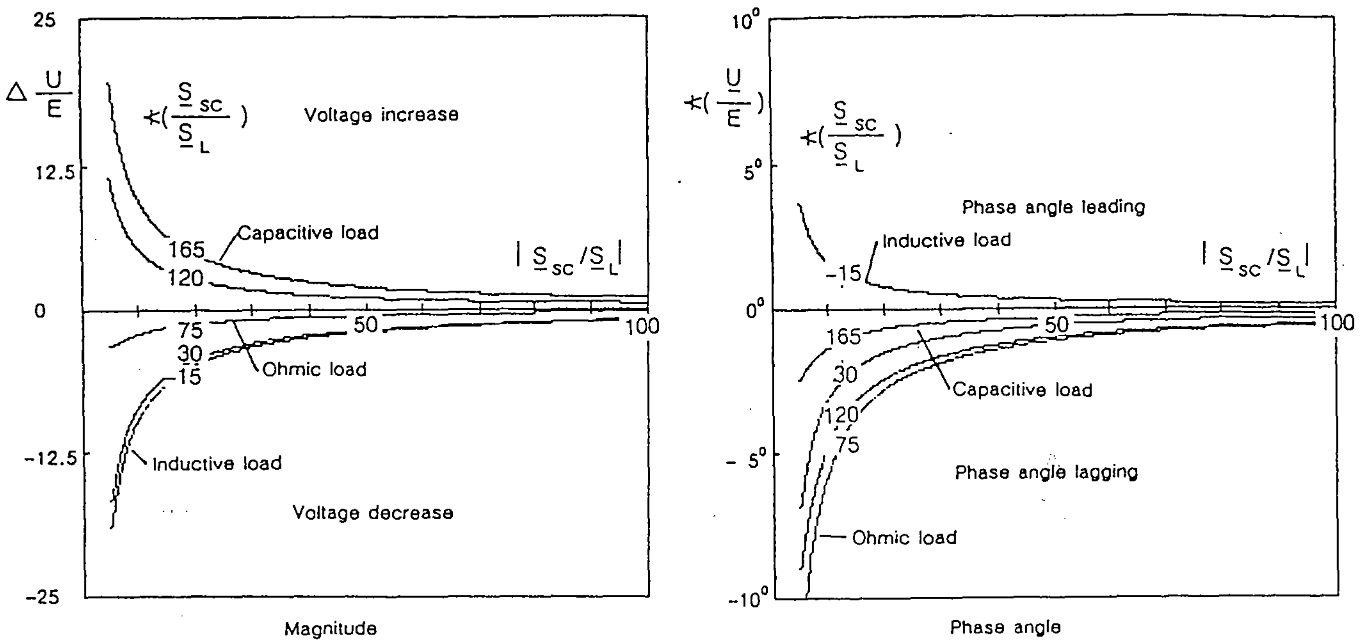
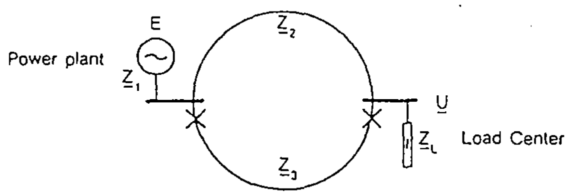


Fig. 3: Power frequency voltage changes caused by load changes as a function of the short circuit ratio

S_{SC}/S_L = Short circuit power / Load

U/E = Voltage after / before switching in of a load



closed <- Connection 3 -> open

$$\underline{Z}_{sc} = \underline{Z}_1 \cdot \left(1 + \frac{\underline{Z}_2}{\underline{Z}_1} \cdot \frac{1}{1 + \frac{\underline{Z}_2}{\underline{Z}_3}}\right)$$

$$\underline{Z}'_{sc} = \underline{Z}_1 \cdot \left(1 + \frac{\underline{Z}_2}{\underline{Z}_1}\right)$$

Voltage ratio: ring open / closed

$$\frac{\underline{U}'}{\underline{U}} = \frac{1 + \frac{\underline{Z}_{sc}/\underline{Z}_1}{\underline{Z}_L/\underline{Z}_1}}{1 + \frac{\underline{Z}'_{sc}/\underline{Z}_1}{\underline{Z}_L/\underline{Z}_1}}$$

Fig.4: Equivalent circuit and calculation of voltage changes when a ring is opened

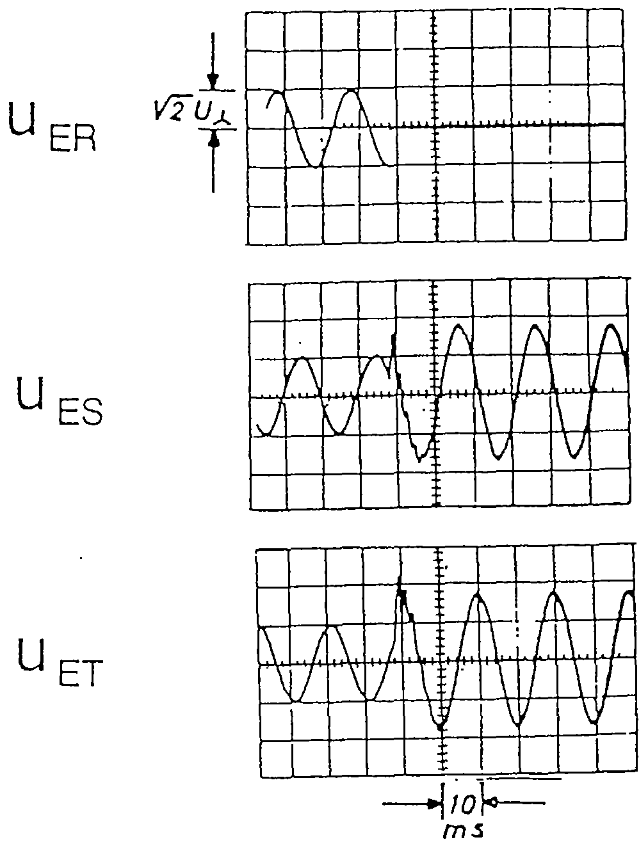
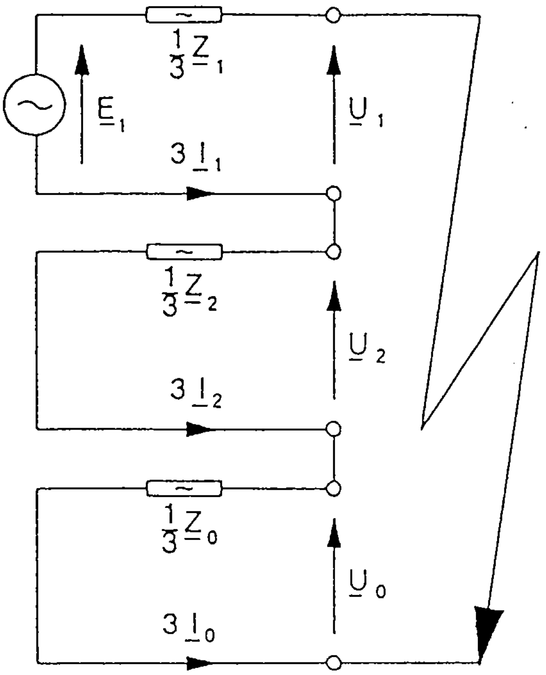


Fig. 5: Line to earth voltages at fault location in the event of an earth fault in the network with low resistance neutral point earthing



Voltages at operation with no fault

Line-to-earth voltages

$$\frac{\underline{U}_R}{\underline{E}_{⅄}} = \underline{E}_{⅄}$$

$$\frac{\underline{U}_S}{\underline{E}_{⅄}} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$

$$\frac{\underline{U}_T}{\underline{E}_{⅄}} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$

Symmetrical components

$$\underline{U}_0 = 0$$

$$\underline{U}_1 = \underline{E}_{⅄}$$

$$\underline{U}_2 = 0$$

Relations between line-to-earth voltages and their symmetrical components

$$\underline{U}_R = \underline{U}_0 + \underline{U}_1 + \underline{U}_2$$

$$\underline{U}_S = \underline{U}_0 + a^2\underline{U}_1 + a\,\underline{U}_2$$

$$\underline{U}_T = \underline{U}_0 + a\,\underline{U}_1 + a^2\underline{U}_2$$

Line-to-earth voltages and their symmetrical components during fault

$$\frac{\underline{U}_{RE}}{\underline{E}_{⅄}} = 0$$

$$\frac{\underline{U}_{SE}}{\underline{E}_{⅄}} = \frac{-\frac{\underline{Z}_0}{\underline{Z}_1}\left(\frac{3}{2} + j\frac{\sqrt{3}}{2}\right) - j\frac{\sqrt{3}}{2}}{2 + \frac{\underline{Z}_0}{\underline{Z}_1}}$$

$$\frac{\underline{U}_{TE}}{\underline{E}_{⅄}} = \frac{-\frac{\underline{Z}_0}{\underline{Z}_1}\left(\frac{3}{2} - j\frac{\sqrt{3}}{2}\right) + j\frac{\sqrt{3}}{2}}{2 + \frac{\underline{Z}_0}{\underline{Z}_1}}$$

$$\frac{\underline{U}_1}{\underline{E}_{⅄}} = \frac{1 + \frac{\underline{Z}_0}{\underline{Z}_1}}{2 + \frac{\underline{Z}_0}{\underline{Z}_1}}$$

$$\frac{\underline{U}_2}{\underline{E}_{⅄}} = \frac{-1}{2 + \frac{\underline{Z}_0}{\underline{Z}_1}}$$

$$\frac{\underline{U}_0}{\underline{E}_{⅄}} = \frac{-\frac{\underline{Z}_0}{\underline{Z}_1}}{2 + \frac{\underline{Z}_0}{\underline{Z}_1}}$$

Star voltages without $\underline{U}_0$ during fault

$$\frac{\underline{U}_R}{\underline{E}_{⅄}} = \frac{\frac{\underline{Z}_0}{\underline{Z}_1}}{2 + \frac{\underline{Z}_0}{\underline{Z}_1}}$$

$$\frac{\underline{U}_S}{\underline{E}_{⅄}} = \frac{-\frac{1}{2}\frac{\underline{Z}_0}{\underline{Z}_1}\left(1 + j\sqrt{3}\right) + j\sqrt{3}}{2 + \frac{\underline{Z}_0}{\underline{Z}_1}}$$

$$\frac{\underline{U}_T}{\underline{E}_{⅄}} = \frac{-\frac{1}{2}\frac{\underline{Z}_0}{\underline{Z}_1}\left(1 - j\sqrt{3}\right) - j\sqrt{3}}{2 + \frac{\underline{Z}_0}{\underline{Z}_1}}$$

Fig. 6: Equivalent circuit in symmetrical components for the calculation of the voltages and currents in single phase line to earth faults

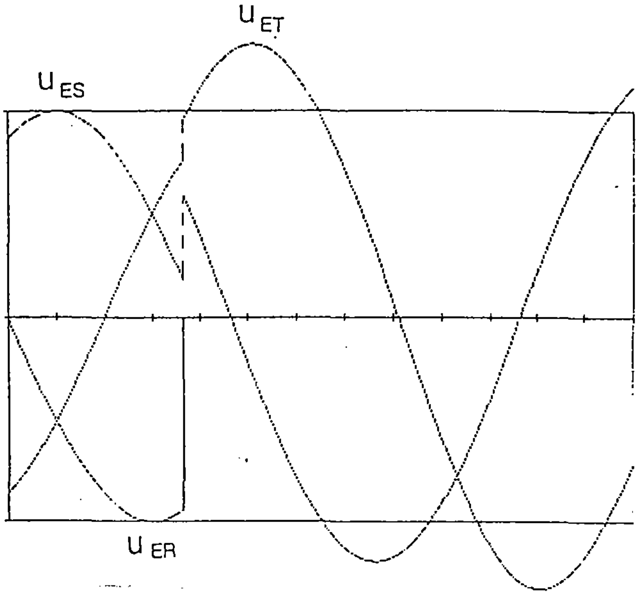


Fig. 7: Power frequency line to earth voltages in the event of a single phase line to earth fault
$Z_0 / Z_1 = 3$, $<(\underline{Z}_0 / \underline{Z}_1) = -15^0$

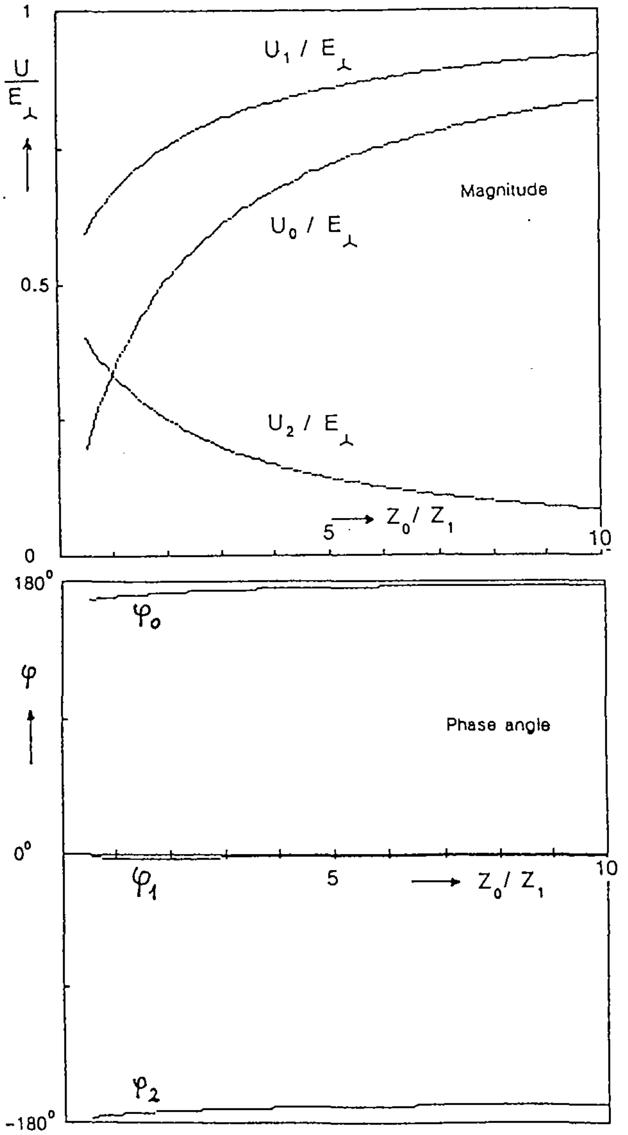


Fig. 8: Symmetrical components of the line to earth voltages in the event of a single phase line to earth short circuit. $<(\underline{Z}_0 / \underline{Z}_1) = -15^0$

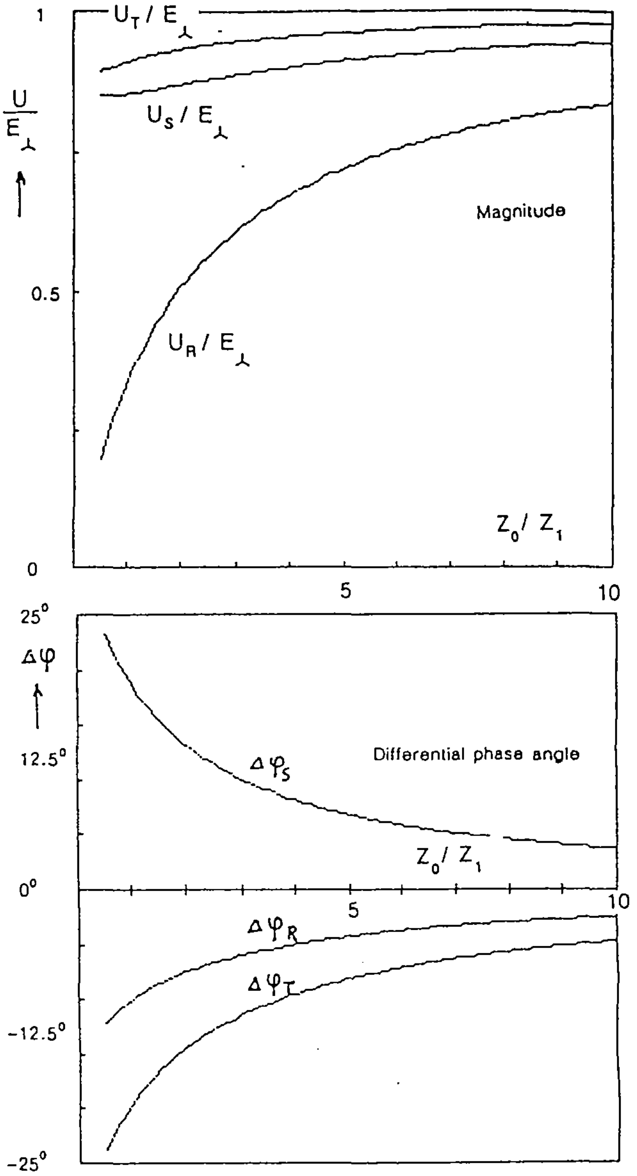


Fig. 9: Star voltages (without $\underline{U}_0$) behind the rectifier transformer in the event of a single phase line to earth short circuit
$<(\underline{Z}_0 / \underline{Z}_1) = -15^0$

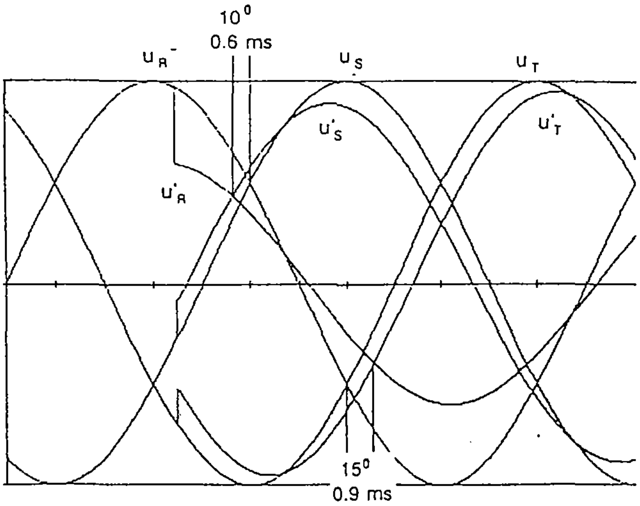
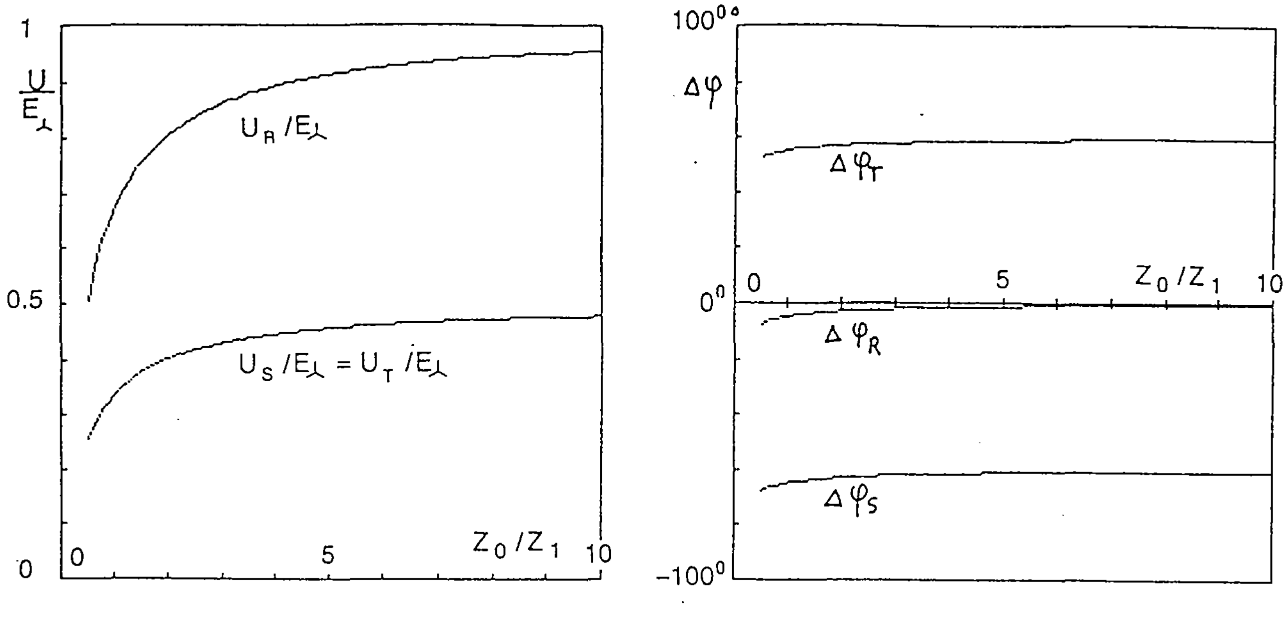


Fig. 10: Star voltages (without $\underline{U}_0$) behind the rectifier transformer in the event of a single phase line to earth short circuit
$Z_0 / Z_1 = 3$, $<(\underline{Z}_0 / \underline{Z}_1) = -15^0$



Magnitude

Differential phase angle

Fig. 11: Star voltages (without $\underline{U}_0$) behind the rectifier transformer in the event of a two phase line to earth short circuit $<(\underline{Z}_0 / \underline{Z}_1) = -15^0$

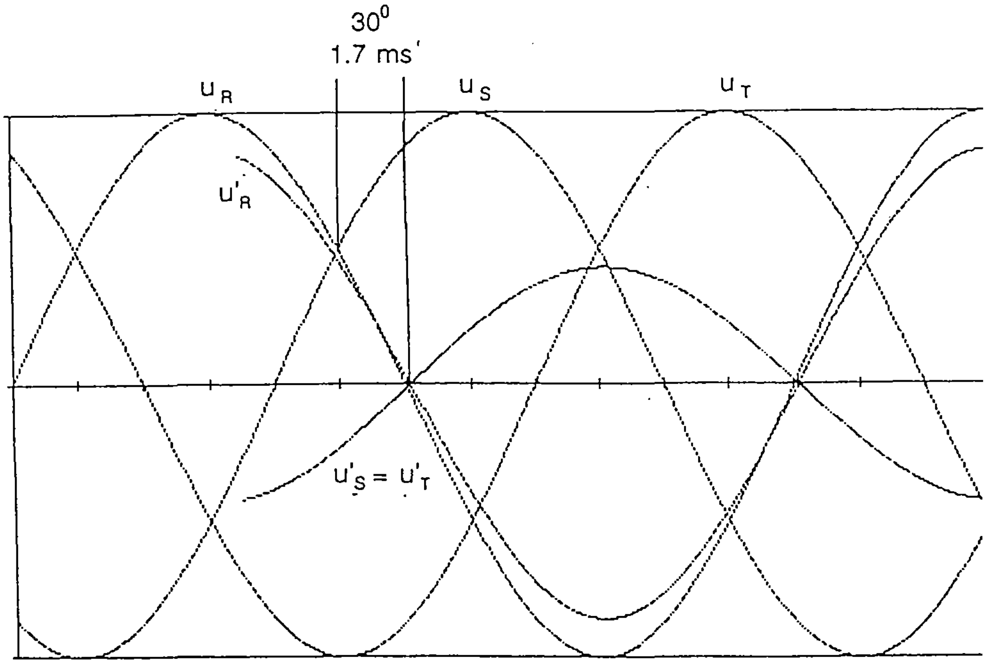
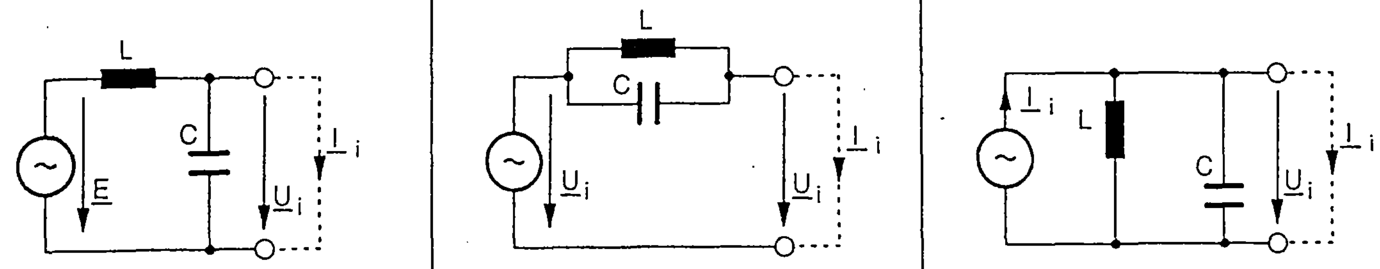


Fig. 12: Star voltages (without $\underline{U}_0$) behind the rectifier transformer in the event of a two phase line to earth short circuit
$Z_0 / Z_1 = 3$, $<(\underline{Z}_0 / \underline{Z}_1) = -15^0$

a) Single phase basic circuit

b) Equivalent Voltage Source

c) Equivalent Current Source



$$\underline{Z}_i = \frac{j\,w L}{1-w^2 LC} = \frac{j\,w L}{1-\left[\frac{f}{f_{res}}\right]^2}$$

$$\underline{U}_i = \frac{E}{1-\left[\frac{f}{f_{res}}\right]^2} = \underline{I}_i \bullet \underline{Z}_i$$

$$\underline{I}_i = \frac{E}{j\,w L} = \frac{\underline{U}_i}{\underline{Z}_i}$$

Partial Break Connections

d) Iterative Network

e) Series Connection of Parallel Resonant Circuits

f) Parallel Connection of Series Resonant Circuits

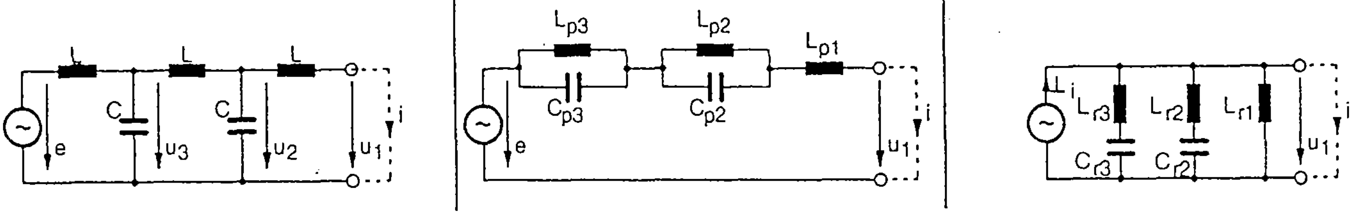


Fig. 13 : Principle circuits for the calculation of transients

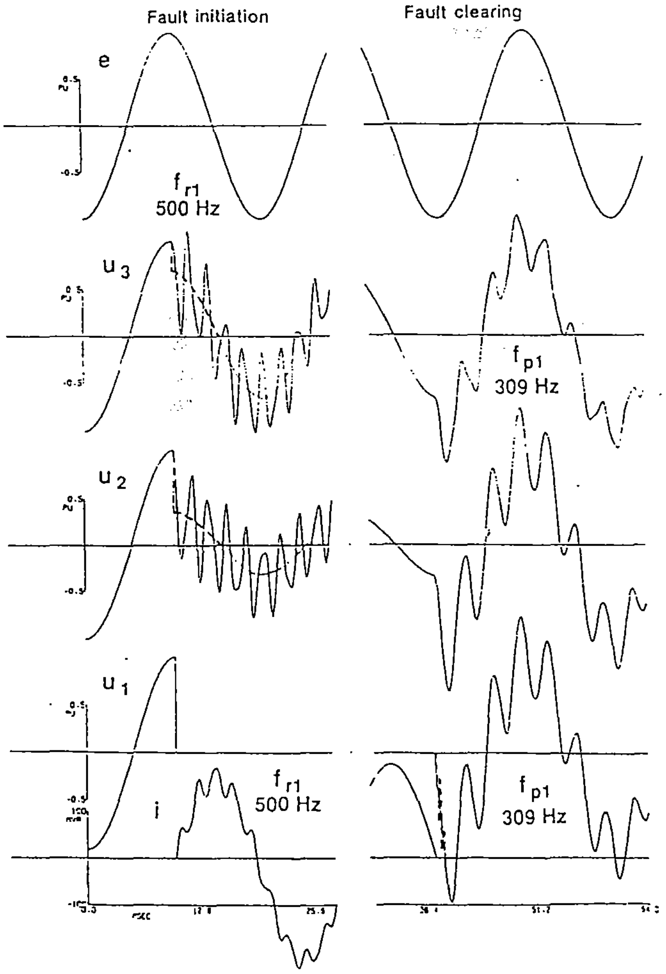


Fig. 14: Voltages and current at fault initiation and fault clearing.
u_1, u_2, u_3 corresponding to location in figure 13 d.

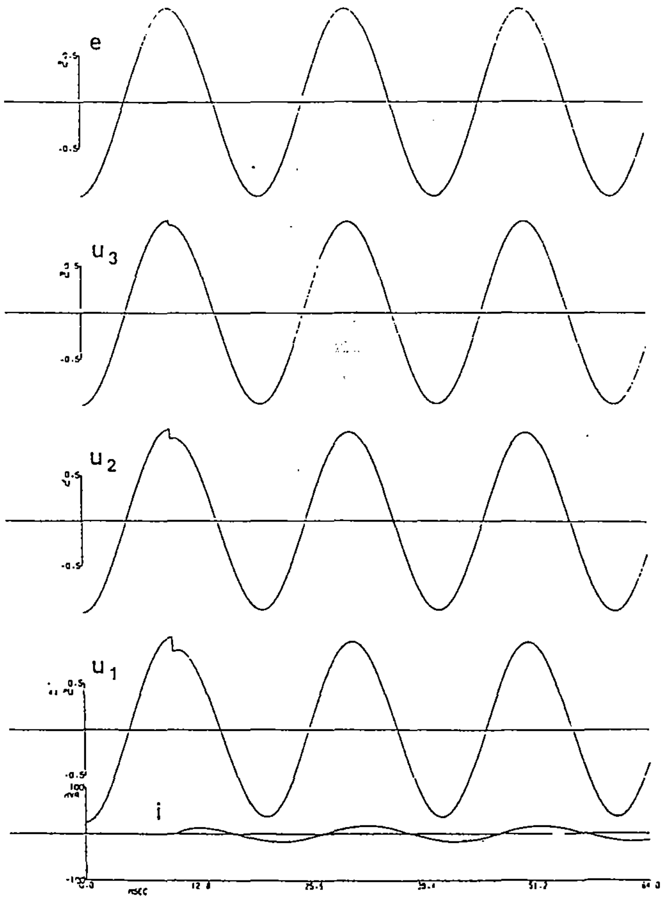


Fig. 15: Voltages and current at load switching
u_1, u_2, u_3 corresponding to location in figure 13 d

APPENDIX VII

TWO EXAMPLES OF HANDLING LOAD REJECTIONS IN LOW SCR CONDITIONS

by Jacques Lemay, Canada

This appendix describes design and operating experience data for two of the HVDC projects where AC voltage control can be demanding because of low SCR conditions.

For further information on operating experience is referred to a number of papers published by Study Committee 14.

1. Miles City: This 200 MW back-to-back station has low SCR conditions on both sides.

1.1 Temporary overvoltages. The total shunt capacitive reactive power compensation required for converter operation and AC voltage support is 188 Mvar on the east side and 218 Mvar on the west side where temporary overvoltages could be as high as 1.55 pu following DC load rejection, if nothing is done to reduce them. The strategy is a combination of permanently connected zinc-oxide varistors together with a fast post-disturbance restart of the converters to consume reactive power. The following temporary overvoltage limits were specified:

- within 2 cycles	1.4 pu
- after 250 msec	1.2 pu
- after 600 msec	1.05 pu

The overvoltage control strategy is as follows:

- the initial overvoltage is limited by a customized multi-column zinc-oxide device (discharge energy rating of 8.75 MJ)
- the converter operation is restored within two cycles after a fault is cleared to meet the specified overvoltage limits by var demand
- the station is tripped if the DC restoration is not successful.

1.2 Recovery of the DC power from AC faults. Further to the control of overvoltages, power is restored to 90% of the predisturbance level in approximately 200 msec. For the loss of key 230 kV lines on either side, the recovery time is increased to 400-500 msec, and the transfer is limited to 175 MW.

1.3 Voltage changes due to switching. The maximum size of reactive bank is 15 Mvar to limit the instantaneous change in voltage. In the steady-state the inverter operates in a regular mode and switches reactive elements to prevent the AC voltage from deviating more than 1% from a voltage reference.

2. Sidney: This 200 MW back-to-back station has strong SCR on both sides (8.6 on the east side and 5.2 on the west side). The loss of a main 230 kV line on the west side reduces the SCR to 2.25.

2.1 Temporary overvoltages. The specified limits are 1.25 pu within two cycles and 1.15 pu within 250 msec. These values are met by the use of metal oxide varistors that are switched by circuit breakers. The switching of the varistors has to be coordinated with other switching actions in the AC system as well as with the converter controls. The varistor energy rating is based on the expected recovery time of the converter: they are designed to accommodate one 80 msec discharge period (successful DC restart), followed by a second period of 140 msec (unsuccessful restart), for a total rating of 28 MJ per phase.

2.2 Power modulation. Power modulation to damp the rotor swings of a nearby generator is activated in response to generator shaft speed deviations. The power is ramped down to reduced transmission limits for the loss of key AC lines on either side. Ramping is also used as a backup for the case where the microwave signal from the generating station is lost after the modulation process has been activated.

2.3 Harmonic interaction. During commissioning a potential for harmonic resonances near the fifth and seventh harmonics were discovered in the eastern network. Additional monitoring equipment was installed and DC transmission is stopped to protect the nearby generator if the fifth or seventh harmonic currents are excessive as indicated by firing angle imbalance or special harmonic relays.

APPENDIX VIII

REQUIREMENT FOR DC MODEL FOR PLANNING OF AC SYSTEMS

by Dag Holmberg and Per Olav Lindström, Sweden

VIII.1. INTRODUCTION

Within CIGRÉ Task Force 38-05-05 a simplified model of HVDC transmission has been discussed. The model should be used for studies where the influence from the HVDC on the AC system shall be analyzed.

The aim is to get a model with results that are not deviating too much from the results from a more detailed model. The model should be as common as possible.

This simplified model is therefore general and is not representing any particular HVDC system or manufacturer. The model shall be used to study the voltage, frequency and power flow in the AC systems for the following cases:

a) Commutation failure with or without AC fault at the inverter
b) AC faults at the rectifier
c) Internal HVDC faults, temporary or permanent
d) a-c) in combination with power modulation or overload.

From the power system's point of view, the only interesting parameter is the consumed active and reactive power in the converters.

The easiest way to model an HVDC transmission is by loads at the rectifier and inverter buses. With such a model, severe contingencies as blocking, commutation failure, overload, etc. may be studied with acceptable accuracy. The drawback is that the user must control all changes manually. This paper describes a model which is rather simple to use but gives results with good accuracy for planning studies.

VIII.2 USER-SUPPLIED DATA

The number of parameters should be as few as possible in order to facilitate the use of the model. Parameters that are needed for system studies or substantially influences the results shall be defined by the user. The following shall the user be able to choose or define:

a) Side for DC current control (rect. or inv.)
b) Rated power [MW]
c) Actual power [MW]
d) Rated DC voltage for the converter controlling the voltage [kV]
e) DC line resistance [ohm]
f) Ratio for converter transformer. An appropriate value is calculated automatically by the model if zero is given by the user.
g) Reactance for converter transformer [%]
h) α-min at steady state [°]
i) α-min during dynamic simulation [°]
j) γ-min at steady state [°]
k) γ-min during dynamic simulation [°]
l) Switch for manual blocking, unblocking, commutation failure, etc.
m) Overload capacity [%], see fig. 1
n) Delay time before overload is ramped down [s], see fig. 1
o) Time for ramp down of overload to nominal power [s], see fig. 1

Typical values for the parameters shall be given in the documentation of the model.

VIII.3 DESCRIPTION OF THE MODEL

Parameters which do not vary too much or parameters that do not influence the results may be built into the model and given normal values. Thereby the user does not need to care for these parameters and he can concentrate his efforts on parameters interesting for the AC system. The following may be built into the model without limiting the usefulness of the model:

a) 12-pulse converters
b) Rating of converter transformer is calculated using the rated DC power and an appropriate power factor
c) Number of steps for tap changer, ± 10
d) Step size for tap changer, 1.25 %
e) Current margin, 10 %
f) α-max and γ-max for steady state condition is set so stable operation is achieved

g) Voltage dependent current order limiter, VDCOL. A typical curve is used. The overload capacity shall be reflected in the VDCOL function.

VIII.4 CONTROL ACTIONS

The local converter controls and the associated response of DC current and voltage are rapid in relation to the time scale of simulations.

The modelling of DC transmission recognizes three distinct types of action by the controls:

a) Normal regulation of DC converter operation to maintain specified constant power transfer with coordination of rectifier and inverter current setpoints.

b) Temporary overriding of DC converter normal operating setpoints in response to disturbances of AC system voltages during faults or internal DC faults.

c) Modulation of the DC power setpoint by a supplementary signal. For example frequency control or damping of system oscillations.

a) Normal operation

Transformer taps are adjusted if the firing angles are outside the steady state limits. The taps are normally not adjusted during dynamic simulations. The user sets the power order in MW while the model internally works with current order.

b) Disturbances

Commutation failure

The model shall not have any logic for determination of commutation failure. The reason is that the commutation depends on individual phase-to-ground and phase-to-phase voltages and these are not available in dynamic simulations which consider the positive sequence only.

The control actions at commutation failure should be initiated by the user. He should set the switch (see above) to a certain value. The model shall then reset the switch and simulate a commutation failure. It shall be possible to simulate consecutive commutation failures by setting the switch several times.

AC faults at rectifier

A drop of the AC voltage results in decreased DC voltage at the rectifier when the α-min limit is hit. The voltage at the inverter is therefore decreased so the DC current continues to flow. The inverter has a practical maximum limit of α of about 105°. Large voltage drops at the rectifier leads therefore to zero power transfer. For small and moderate voltage drops, the VCDOL will limit the DC current and thereby the DC power.

When the fault is disconnected and the AC voltage recovers, the power shall be automatically restored by the control system. The user shall not need to take any actions for the control of the HVDC for this kind of disturbance.

HVDC faults

Internal faults in the HVDC transmission are studied by manual blocking. The power is automatically restored by the control system when the HVDC is unblocked. The user changes the switch in order to block or unblock the DC transmission.

c) Modulation

Special control like frequency control, reactive power control or power system oscillation damping shall not be implemented in the simplified model. Such devices may be modelled by separate models and their output shall be added to the [illegible] order of the HVDC model. This additional signal shall be in effect also during power recovery.

d) Overload

The overload capacity specified by the user shall be limited in time during dynamic simulations. Figure 1 shows the definition of the delay time and ramp down time. The overload "protection" is trigged when the actual DC current exceeds the rated DC current. After the delay time, the maximum current limit is ramped down to rated DC current. An example is shown where the actual current is reduced to nominal current by the current limit.

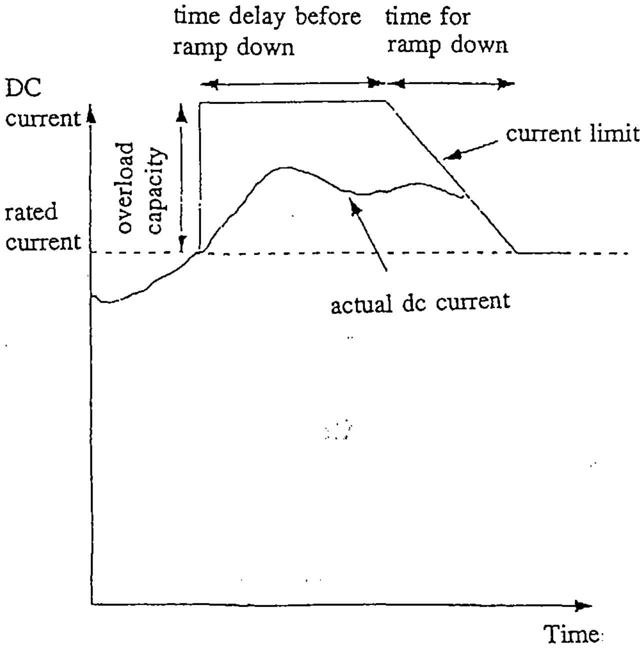


Figure 1. Overload capacity and ramp down.

APPENDIX IX

EVALUATION OF THE QUESTIONNAIRE: "TRANSIENT FUNDAMENTAL FREQUENCY STUDIES FOR AC SYSTEM ASPECTS OF AC/DC INTERACTIONS"

by H.L. Thanawala and J.C.W. Corcoran, U.K.

IX.1 INTRODUCTION AND GENERAL REMARKS

Replies have been received from 24 participants to the questionnaire on fundamental frequency transient ac/dc interaction studies issued in 1991. A summarised analysis of the replies is given here and it is believed that it yields useful information under the five main headings under which the 27 questions were posed. These headings are:

A. Purpose and topics of the studies
B. Programs and experience
C. System modelling
D. Representation of controls
E. Future developments.

The original questionnaire included considerable detail, suggesting possible forms of answer under each question. These suggestions were not mandatory but were intended to act as prompts where required. In Appendix A an abbreviated form of the questionnaire is given in which the 27 questions are recorded, with only examples of the suggested answer topics.

In the original analysis of the answers the results were presented in 27 tables, one for each question, each table having 24 columns representing answers from the 24 participants. The answers to the question in a particular table were indicated down the left hand side of the table - one per row - and a cross (or some other indicator) was placed in each box representing an answer from a particular respondent. An example is shown as Table 1, indicating answers to Question Number One. Since the presentation in this form requires 27 such tables the main points of the replies are summarised here for brevity in one small Table (2) together with notes in the following sections, where the 27 questions are considered in the five groups A to E indicated earlier. A list of the organisations and individuals who responded to the questionnaire is given in Appendix B.

In many places respondents not only answered the questions but provided useful additional notes and elaborations. It is not possible to do justice to these in this brief document but some of the points made are included in the summarising notes which follow.

IX.2 NOTES ON THE ANALYSIS

The 27 questions are now considered briefly in groups in an attempt to summarise the most obvious or interesting features of the answers. An overall observation that may first be made concerns the difference between the trends of answers when these were given as options in the questions and when each respondent gave their own. In the first case the 'matrix' of X's in a Table such as Table 1 is very full - presumably because most organisations are interested in the main subjects. In the second case the 'matrix' is sparse because individual replies are all at least a little different, indicating the variety of problems identified by different groups.

It is also evident that, inevitably, different organisations are at different stages of studies of the types under consideration and the replies of course reflect this. It is to be hoped that the form of the total of replies will assist the recognition of topics which appear most important to those with great experience. Some organisations acknowledge their replies to be based on what they expect to do later.

Group A: Questions 1 to 3 - Purposes of Studies

These questions concern the main study topics, and the principle system disturbances of interest; also the related subject of the real time period over which it is desirable for particular studies to run during calculation.

Results showed that there is a large consensus of agreement on the main topics that should be addressed and the disturbances most needing to be simulated to evaluate ac/dc interactive system effects. These are largely those subjects which one would expect for overall design purposes but some authors have pointed to topics of particular concern in their own work, and these may help to remind other workers of unexpected features. Main and other frequent replies are indicated in Table 2 with the numbers of respondents giving each type of reply in parenthesis following it.

Regarding study times (question 3) many replies gave, of course, ranges for typical studies and overall ranges were as follows:

Transient stability	2 to 10 seconds
Swing damping	10 to 20 seconds
Frequency transients	10 to 60 seconds
TOV	1 to 5 seconds

Load shedding, run back and sub-synchronous resonance studies each had one reply. The associated times were 2.5, 5 and 50 seconds respectively.

Group B: Questions 4 to 6 - Programs and Experience

In answer to these questions a large variety of digital computer programs were indicated, covering both transient stability type of calculation and calculations of EMTP-type for higher frequency effects. It is clear that both PSS/E, a transient stability analysis program, and EMTP, an electromagnetic transient program, are favoured by a number of users. In fact these are the only 'named' programs identified by more than one respondent.

Similarly the large number of physical simulators in use is of interest but equally a significant number of organisations are not yet availing themselves of such techniques. Four organisations indicated use of simulators developed in-house.

Question 6 both overlaps and complements questions 1 and 2 but serves to highlight some additional topics of concern. These included 'Loss of DC interconnection, Delayed clearing of a close fault, Dynamic interaction, New generator integration, Series compensation, SSR and multi-terminal links.

Group C: Questions 7 to 11 - System Modelling

These concern the important topic of system modelling and bring out the fact that while the most usual type of program for study clearly is that applying positive sequence phasors (i.e. a program of 'transient-stability' type) for conducting AC/DC dynamic performance studies there is some use also of programs of EMTP type, employing full three-phase differential equations.

There is justifiable concern to be able to more accurately model the effects on the DC link of single-phase ac system faults and to predict the onset of commutation failure. The need to be able to accurately model dc link effects while conducting ac system studies emerges here and in later questions. Question 11 points to this and so do the questions on control representation in Section D. The use of User-defined modelling or of a program of EMTP type is favoured by three respondents in each case. The answers to question 8 indicate a large diversity of approaches to methods for unbalanced faults.

The types of program in use of course affect the answers to question 9 on the parameters included when representing the dc line between convertors for different types of study. DC network modelling by R, R/L and R/L/C all seem to be nearly equally favoured (R = 10 replies, R/L = 10 and R/L/C = 13). Distributed parameters were mentioned (by two) as appropriate to EMTP type work. Table 2A shows the replies.

The subject of interfacing ac system and dc link representation is addressed in question 10 and the replies indicate that in most cases, for the type of fundamental frequency transient studies being dealt with, steady state convertor equations are used to iterate injected currents and dc voltages across the interface. The number of correspondents using full 6 or 12-pulse bridge models or simulators seems lower than might be expected (7).

Integration of full link representation and standard ac transient study methods is being raised in some answers to these and later questions. The use of a physical simulator or EMTP-type program as an additional facility is clearly considered by some in question 11 to be highly desirable. Four employ such additional facilities for weak ac systems, and eight regard some use as a necessity; five employ such facilities as an additional check.

Group D: Questions 12 to 21 - Representation of Controls

The use of a simplified model, with 'instantaneous' control of dc link parameters is from the replies a debatable issue. Eleven investigators have replied that they do not use such a model; some evidently do. One respondent, who gives useful additional notes, points to the need to carefully confirm the use of 'instantaneous' controls when the dc link is the more important (or 'more powerful') element in the studies, but feels that the simplified model is accurate enough when the aim is the assessment of system behaviour. Where the ac system is weak, lack of control representations in the dc link model can be a problem as the effects of frequency variations will not be sensed.

A variety of different features of simplified control models used is indicated in the answers to question 13 but a few replies draw attention to standard models such as CDC4 or 6. In question 14 the assessment of likely commutation failure is addressed together with convertor model changes used to deal with it, but in most cases it seems that these issues are very difficult to deal with directly. Methods of assessment of the occurrence of commutation failure tend to be by monitoring of ac (or dc) voltage and cos γ. Simulation may be by inverter bypass (five replies). No approximate methods of these types are yet fully adequate.

It is interesting that a number of respondents were able to give quantitative replies to question 15 on the value of short-circuit ratio below which they had found a simplified model to be inadequate. A value of about three seemed to be in evidence but one organisation pointed to their own situation where the long distance of transmission coupled with other effects including a low SCR can lead to very complicated effects. Question 16 was of course not applicable for some but where answered the main concerns are understandably with accuracy, confidence in a simple model and inability to observe any activity 'inside' the dc link when using a

TABLE 1
EXAMPLE OF REPLY RECORDING

A. PURPOSE AND TOPICS OF THE STUDIES

1. AIMS

Post-fault transient stability	X		X	X	X	X		X	X	X	X	X		X	X	X		X	X	X	X	X	X	X
Dynamic over-voltage/TOV		X	X	X	X	X	X	X	X	X	X			X	X	X	X	X		X	X	X	X	X
Frequency fluctuation		X	X		X	X		X	X	X	X			X	X	X	X	X	X	X	X			X
Load shedding		X	X		X				X	X	X			X	X	X	X	X		X	X	X	X	X
Frequency modulation/control			X		X	X	X		X	X	X		X	X	X	X	X	X		X	X	X	X	X
Swing damping	X		X		X	X		X	X	X	X		X	X	X	X		X		X	X	X	X	X
Danger to equipment		X	X						X	X	X			X	X	X		X		X	X	X	X	X
Control strategy		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X		X	X
Run-back			X		X			X	X	X	X							X		X	X			X
SVC requirements			X					X		X	X			X	X	X		X		X	X		X	X
Overall performance		X	X		X	X		X	X	X			X	X	X	X	X	X		X	X	X	X	X
Operation strategy				X			X																	
AC/DC parallel scheme start-up														X										
Post-fault steady state response								X																
Transient over-voltage																							X	X
Voltage stability							X				X									X				X
Sub-synchronous resonance																X							X	
Harmonic generation		X																						X
DC transient recovery								X																
System expansion				X																				
Protection operation								X																

simple model. Lack of data is also suggested as a barrier to better modelling.

Replies to question 17 on the modelling of action following a dc line fault clearly show a great variation in detail but evidently the problem is often addressed by the monitoring of voltage and the subsequent application of a predefined logic. A voltage-dependent current order limit is mentioned in six replies. In some cases (three) control action is only addressed by the use of physical simulators.

Question 18 probably brought forth the expected trend of replies, that more detailed modelling is necessary for disturbances which directly affect the dc link in such a way that special control features and responses must be considered. At least two replies said that more detailed modelling should always be used and perhaps this is the ideal. Replies to question 19 indicate that detailed controls are included by nineteen of the replying organisations either by pre-defined models or by user-defined models.

Multi-terminal dc links can it seems (question 20) be modelled by fifteen responding organisations, and two say they have very complete facilities. Some have methods partially completed or under development, but in no case is much detail indicated.

Fifteen respondents indicate that their programs cover telecommunication delays. Some detail is given as to the methods employed (e.g. represented as 'true delay' or 'transport delay').

Group E: Questions 22 to 27 - Future Developments

This group of questions, being concerned particularly with plans for future development, produced interesting replies. Each organisation, as would no doubt be expected, tends to point in question 22 to a restriction which presumably it has individually had occasion to particularly note and this should be of benefit to all concerned. There is inevitably some duplication of points between this and earlier questions, in particular where internal dc link effects are concerned. The very important questions arising for systems linked by dc to load centres a long way off or island systems connected by dc to mainland systems are mentioned here and under other headings. Examples given of other restrictions are 'Unbalanced faults difficult, Cannot study internal link effects, Cannot study SSR, Representation of commutation failure'. DC line representation and lack of MTDC facilities are also mentioned.

Combination of power frequency type dynamic programs and EMTP-type programs (see question 23) does not appear to be an intention of many organisations, but three thought it a good idea. Complementarity (with some overlap) may be the requirement rather than combination. In the answers to question 24, however, there is a call for combination and for better facilities to represent commutation failure; also for standard models from manufacturers, and particular concentration on control loop representation.

All forms of digital computer equipment are in use (question 25) - main frame, mini-computer, work station and PC, but the answers to question 26 suggest a concentration in the future on work-stations (and networking). One organisation suggests a combination of workstations and main-frame.

The concept of digital simulators (with multiple central processor units in parallel) is clearly receiving and gaining attention, although there is evidently some suspicion in one quarter that they may not be user-friendly. (Question 27).

IX.3 OVERALL SUMMARY

Table 2 gives a brief overall resumé of the replies analysed in Section 2.

APPENDIX IX.A

THE QUESTIONS
(in abbreviated form)

A. PURPOSE AND TOPICS OF THE STUDIES

1. What are your aims in conducting AC/DC system dynamic performance studies? (For example, post-fault transient stability, dynamic overvoltage (fundamental frequency temporary overvoltage TOV) etc.

2. What are the principal kinds of disturbance studied? (For example, balanced faults, load rejection, etc).

3. What is the duration of study (in secs) for the above different purposes of study (for example fault studies may be 5 sec, TOV 1 sec, frequency sec, etc)?

B. PROGRAMS AND EXPERIENCE

4. What is the name of the program used (or programs if different for the different aspects)?

5. If HVDC simulator is used, please state the manufacturer, size etc.

6. What type of studies have been carried out and what are currently being undertaken?

TABLE 2

SUMMARY OF REPLIES

Group	Heading	Main Replies	Other Significant Replies
A	Purpose and Topics	AC/DC fault transients (23) Control and frequency effects (23) Load rejection/shedding (21) Dynamic/temporary overvoltage (20) Swing damping (18) Commutation failure (16) SVC requirements (12) Run-back (10)	Voltage stability (4) Danger to equipment (14) Generator trips (5) Typical study times quoted: TOV 1-5 sec Transient stability 2-10 sec Swing damping 10-20 sec Frequency transients 10-60 sec
B	Programs and Experience	17 named programs mentioned, plus 4 'in-house' 14/24 replies quoted PSS/E 6/24 replies quoted EMTP Studies of all likely types being undertaken or to be undertaken	9/24 quote simulators 5/24 do not use simulators 6/24 mentioned modulation or control as a study type
C	System Modelling	18/24 use +ve sequence phasors 8/24 use 3 phase differential equations SS convertor equations used by most for AC/DC interaction (question 10) AC/DC interaction needs further attention	Unbalanced SC difficult (Many different approaches) Physical simulator very desirable See Table 2a for use of DC tie models (question 9)
D	Representation of Controls	Use of instantaneous control debatable: If AC system stronger - OK If DC system stronger - need more detailed controls Assessment of commutation failure (CF) by monitoring voltage and cos γ (4 answers) CF modelling needs further attention	Simple models need validating and are restrictive. (Many types used) Representation of controls important for large disturbances to link Some organisations can handle MTDC links Simulator necessary for some work Detailed controls modelled by most (some pre-defined, some user-defined)
E	Future Developments	Many individual restrictions (see text) Not much (but some) interest in combining TS and EMTP types - use in complementary way Need to improve 'control' representation	Work stations favoured for future but all forms of computer in use now Digital simulators being developed

TABLE 2A
(Question 9 Answers)

9. MODEL OF DC NETWORK

Tie not represented	X			X																X				
No restrictions																					X			
(a) Resistive		S	I			A		D	A	DF			A		I			P			P			
(b) Resistive, inductive		D	X				FL	D		GR	B				C						O		B	X
(c) R, L, C		D					D	DE			M	OC		A		ER		D	A		C	A	X	X
(d) Distrib parameters		D						E													W			
Not applicable																	X							
Not answered					X																			

Key:
A = All
B = Back to back
C = Cable
D = Dynamic
E = EMTP-type
F = Frequency
G = Danger
I = Initial (or simple)
L = Load rejection
M = MTDC
O = Overhead line
P = Power flow
R = Subsynchronous resonance (SSR)
S = Steady state
W = Switching overvoltage
X = 'Applies' (as in other tables)

C. SYSTEM MODELLING

7. Is the ac network modelled as positive sequence network using equivalent phasor quantities (or by full three-phase differential equations)?

8. How do you take account of ac system and convertor performance for unbalanced (e.g. one-phase) short-circuit faults?

9. For which disturbances or studies is the dc network (other than convertor bridges) modelled as:

   (a) Purely resistive?
   (b) Resistive inductive?
   (c) Resistive-inductive-capacitive?
   (d) Distributed parameter models for dc line or cable?

   (Please state for (a), (b), (c), (d) which model is adopted for which type of study, e.g. for a dc cable system the model (c) including its shunt capacitance may be considered necessary for some studies).

10. What theoretical model is used for the convertor bridge to determine its ac injected current vector and dc voltage?

    (For example, is it steady-state convertor equations,or is it the full 6-pulse or 12-pulse convertor model using topological differential equations).

11. For which studies of the fundamental frequency dynamic performance type do you consider it necessary also to employ either a physical simulator or an EMTP type program? Is it used as a necessity or as an additional check?

D. REPRESENTATION OF CONTROLS

12. For which of the studies (if any) do you use a 'simplified' control model which considers the control to be instantaneous?

13. What 'simplified' control model is used?

14. What changes (if any) to convertor model equations are employed for representing commutation failures, and how is the likelihood of commutation failure assessed by the program?

15. For what value of ac system relative strength (in terms of the SCR, i.e. short-circuit ratio) have you found the simplified model inadequate?

16. What restrictions has the simplified model imposed in your studies?

17. How are the control actions for dc line faults modelled; i.e. what aspects of low voltage current limits at rectifier and inverter are modelled?

18. When do you find a more detailed control model necessary or useful?

19. Does your program enable the detailed control model of only a pre-defined structure, or does it allow a user-defined control structure?

20. What facilities does the program provide for multi-terminal DC schemes (MTDC)?

21. Does the program cover telecommunication delays; if yes, how?

E. FUTURE DEVELOPMENTS

22. What restrictions in the available study facilities have you experienced in the studies conducted so far?

23. What future, planned or current perspectives do you have about combining in some manner the power frequency type dynamic program (i.e. transient stability program) and the EMTP type program? (For example, EMTP for modelling the ac/dc network close to the convertors and transient stability type model for the remoter part of the system including generators).

24. What improvements or other developments do you consider would be of particular benefit for future studies?

25. Do you presently run the program on a main-frame, a mini-computer, workstations or PCs, (state one or more options as actually employed)?

26. Which of the above type of computer hardware is likely to be of greater use in the near future?

27. Have you considered employing digital simulators in the near future for such studies (as distinct from physical hardware simulators presently in use and digital computer programs presently in use)? (Digital simulators employ multiple-processors (CPU) in parallel).

APPENDIX IX.B

List of responding organisations in order in which theirreplies appear in the report table columns. Left hand column corresponds to number 1

No.	Organisation	Respondent	Country
1	Elkraft	Ostrup	Denmark
2	Eskom	Hadingham	South Africa
3	ESB	Byrne	Eire
4	Statkraft	Heggland	Norway
5	Tractabel	Deuse	Belgium
6	Vattenfall	Holmberg	Sweden
7	Hitachi	Konishi	Japan
8	Westboro (Neplan & Nepsco)	Tatro	USA
9	United Power Association	Mortensen	USA
10	PTI	de Mello	USA
11	Hydro Quebec	Lemay	Canada
12	CRIEPI	Takasaki	Japan
13	Imatran Voima	Vaitomaa	Finland
14	Mitsubishi	Iyoda	Japan
15	State Elec Comm, Victoria	Bolden (via Burt, NZ)	Australia
16	EDF	Bornard	France
17	Transpower Control Group	Burt	New Zealand
18	Transpower Eng & Dev Group	Burt	New Zealand
19	Hydro-Elec Commission, Tasmania	via Burt, NZ	Australia
20	ENEL	Nicola/Pincella	Italy
21	ABB Power Systems	Adielson	Sweden
22	Bayernwerk	Gampeneider	Germany
23	FGH	Wess	Germany
24	GEC ALSTHOM	Corcoran/Thanawala	UK

APPENDIX X

A DIGITAL MODEL OF AN HVDC SYSTEM FOR SYSTEM PLANNING STUDIES

T. Adielson and G. Liss, Sweden

Summary:

The models of HVDC systems, which are presently implemented in stability programs, seem to be either too simplified to be adequate, or too detailed to be general.

The intention with this work is to propose a digital model of an HVDC system, which should be general and adequate for planning studies of dc links. It should enable a Utility to explore the properties of an HVDC system for exploiting its inherent potential to control the active power and the reactive power of the converter stations, to enhance the dynamic performance of its power system.

The modelling is focused on the properties of an HVDC system seen as a system element and the representation of the ac/dc interactions correctly. Hence, details on the internal states of the HVDC system are not reproduced.

The HVDC system model is valid for the power frequency components of ac voltages and currents, and for the mean values of dc voltages and currents, which are decisive for power flows and electromechanical transients.

Effects of harmonics are neglected. The model is valid for a multiterminal HVDC system, including series taps, and for symmetrical operating conditions.

Basic theory only is employed for the modelling of the HVDC converters. The model is here restricted to so called single overlap of the commutation of the dc current between the valves. It implies that it may not be valid for very low ac voltages and high dc currents. However, the model should be adequate for making correct conclusions about the dynamic performance of the system. The converter model can then be described by means of a rather simple equivalent circuit.

The control system of an HVDC system is represented by means of simple transfer functions of the relevant controllers:

- The Current Firing and Current Controller, which provides the delayangle to the converters and controls the dc current.
- The Current Order Limiter, which reduces the dc current for low dc voltages, and facilitates the recovery of an HVDC system after a disturbance.
- A higher level controller, Master Controller, by which the current orders to the individual converter stations are determined and coordinated.
- A Power Frequency Controller, by which the active power of a converter can be varied to control the frequency and to damp electromechanical oscillations.
- A controller for variation of the margin of commutation of an inverter, γ-Controller, by which its reactive power can be used to control and stabilize its voltage.

Disturbances in the converters, the ac and dc networks are discussed and simple representations of protective actions are proposed.

The mathematical basis of converters and controllers is given, as well as typical numerical values of their parameters.

An application example, based on the Gotland HVDC transmission is provided.

X.1 INTRODUCTION

A joint task force of CIGRE and IEEE has published an extensive "Guide for planning dc links terminating at ac system locations having low short circuit capacities":

- Part I: AC/DC system interaction phenomena.
- Part II: Planning guidelines.

The guide stresses the need to carry out adequate studies at all stages of planning and design.

In order to perform studies for the system planning, Utilities need a general and adequate HVDC system model in their software for transient stability analysis.

The HVDC system models, which are presently implemented in the stability programs, seem to be either too simplified to be adequate, or too detailed to be general.

The intention with this work is to propose a digital model of an HVDC system, which should be general and adequate for planning studies of dc links. It should enable a Utility to explore the properties of an HVDC system for exploiting its inherent potential to control the active power and the reactive power (within the design limits) of the converters, to enhance the dynamic performance of its power system. The following description is brief. For general converter theory and further details, reference is made to [1, 2, 3, 10].

X.2 REQUIREMENTS

The HVDC system model has been designed with the following basic requirements in mind:

1. The model shall focus on the properties of an HVDC system seen as an element in a power system. It shall provide the correct interaction with the other network elements. Hence, it need not reproduce the detailed internal states of the HVDC converters.
2. The model shall be consistent with those of other fast acting system elements used in transient stability programs, in particular static var systems and static excitation systems of synchronous machines.
3. The model shall be valid for the power frequency components of ac voltages and currents, and the mean values of dc voltages and currents, which are decisive for the power flows and the electromechanical transients. Hence, the effects of harmonics are neglected.
4. The model should enable a system planner to explore the dynamic performance of a system for load changes, for switching of capacitors and reactors, for load rejection, for recovery from ac and dc faults and commutation failures, and for investigation of control for enhancing the performance of the power system.
5. The model should be able to detect voltage instability, when an HVDC converter is operating at a location with low short circuit capacity. It shall be possible to study control measures for stabilizing the voltage.
6. The model should enable study of control measures for damping of active power and frequency oscillations.
7. The model should be as general and described by as few parameters as possible. Details which may reflect special design shall be avoided.

X.3 OVERVIEW OF THE CIRCUIT CONFIGURATION AND THE CONTROL

X.3.1 Main circuits

A typical circuit configuration of an HVDC station is shown in Figure 1. It consists of a number of line commutated converters, each connected between two dc nodes and an ac node on the valve side of the convertertransformer. The converters are assumed to commutate independently of each other.

The transformer is here considered as part of the ac network. It may have a tertiary winding with a synchronous condenser.

AC filters for absorption of current harmonics are normally connected on the network side of the converter transformers.

Dc reactors and dc filters for smoothing the dc current and absorption of the voltage harmonics, are normally connected on the dc side of the converters. An electrode station may be connected between a dc-neutral and the ground.

A converter station may be connected to a monopolar or bipolar dc line.

An arbitrary dc-circuit configuration should be built from basic circuit elements, converters, transformers, lines, reactors, capacitors etc, interconnected at nodes.

X.3.2 Control

The basic means for the control of an HVDC converter are the firing angle, α, of the converters and the turns ratio, η, of the converter transformers, see Figure 1. The dc voltage of a converter, and the magnitude and the phase of its ac current, relative the commutation (ac) voltage, can be varied continously and fast by means of the converter control, which determines α.

The commutation voltage of the converters can be varied in steps and slowly, by means of the LTC of the converter transformer, which determines η.

If a synchronous condenser is available, its excitation control may be used for the control of the commutation voltage of the converter, continuosly and relatively fast.

X.3.2.1 HVDC system with parallel converters

X.3.2.1.1 Systems control

In all existing commercial HVDC transmissions, the HVDC stations are connected in parallel. A parallel system is controlled according to the established current margin principle [1, 2, 3, 4, 5, 6, 7]. It implies that one converter station controls the direct voltage and the other stations control their direct currents. It is realized by having current regulators acting on the firing angles of the converters in all the poles, and selecting the current orders such that the sum of those of the rectifiers becomes equal to the sum of those of the inverters, and subtracting a so called current margin at the current regulator in an inverter or adding it at the current regulator in a rectifier. It is illustrated for a two-terminal transmission in Figure 2, and for a three-terminal system in Figure 3.

The principal effect of the current margin is that the current regulatorsincrease the direct voltage as long as all the converter stations are able to control their direct currents, because more electrical charges are then put into the system than taken out of it. The direct voltage of a converter has a maximum limit, see figure 2b and 3b. The maximum voltage is determined by the ac voltage and the minimum firing angle in a rectifier, and by the ac voltage and the margin of commutation in an inverter. When the maximum limit of the direct voltage is reached in a station, that station is no longer able to control its direct current, but acts as the slack for the other current controlling stations. Hence, the direct voltages in the system are determined by the maximum voltage of that station, and the voltage drops due to the direct currents.

The current margin principle assures that the power transmission on the dc system is maintained, even during disturbances in the connected ac systems, which may change the ac voltages such that the station with the maximum direct voltage may change.

The direct current in each station may deviate from its current order by an amount equal to the current margin at the most, during steady-state.

For the HVDC systems in Figure 2 and 3 it is assumed that the direct voltage is controlled by means of the LTC of the converter transformer in the main inverter, and that the direct current is controlled by means of the current controller in the rectifier(s). The application for an arbitrary number of parallel stations is straight-forward.

X.3.2.1.2 Station, pole and converter control

An overview of the principal controllers of a converter station, which is connected in parallel with other stations in an HVDC system, is shown in Figure 4.

Each converter has a converter firing and current controller (CFCC), which provides the firing angle, α, to the valves. It is identical for the converters connected in series of a pole. It controls the direct current to follow a current order. The input is the control error formed by the difference between the current order, I_{do}, and the actual direct current, I_d. In one station a current margin, typically about 10 % of the rated current, is also applied; It is subtracted in an inverter or added in a rectifier. It is noted that the dc and ac systems are parts of the closed loop.

The current order is obtained from a so called voltage dependent current order limiter (COL). It reduces the current order for low direct voltages during a disturbance and facilitates the recovery of the power transmission after the disturbance. .

The reference value of the current order, I_{oref}, to the COL is obtained from a master controller (MC). It also coordinates the current orders of all the poles in the system and assures that the conditions for the current margin principle is fulfilled. An HVDC-pole may be operated with constant current control or constant power control. In the latter case I_{oref} is determined by the quotient between a power order, P_o, and the direct voltage, U_d.

The ability to control the active power of an HVDC station may be used for the control of the frequency of a system, or for damping of power oscillations. Then the power order of a power controller is supplemented with the output, ΔP, from a frequency controller or a damping controller (PFC). It responds to deviations of the system frequency, Δf, the speed of a rotating machine, Δω, or the power on a tie line, ΔP_{tie}. Such controllers can also supplement the current orders for constant current control.

The ability to control the reactive power of a voltage controlling HVDC inverter, may be used for the control and stabilization of its voltage, when it is terminated at an ac system location having low short circuit capacity. It is achieved by modulating the margin of commutation, γ, by means of a voltage controller, which provides a Δγ, which is added to the normal value, γ_o. Δγ can be varied by means of an automatic voltage regulator, which responds to deviations of the ac or dc voltage, ΔU. Increased damping of the current control of an transmission, for which the rectifier is controlling the dc current, can be obtained by creating a positive slope of the dc voltage-current characteristic of the inverter, by increasing the margin of commutation in response to a decrease of the dc current, ΔI_d, [1]. In this model, the different means for the control of the margin of commutation are assembled in a γ-controller (γC).

The tap changer of the converter transformer may be varied by a regulator, (LTCC), which may control the firing angle of a current controlling rectifier, or the margin of commutation of a current controlling inverter within narrow limits, to compensate for changes of the magnitude of the ac voltage (within the limits of the tap-changer). The LTC-control is slow compared with the converter control. The LTC-regulator may also be used for control of the dc voltage of a station operating on a limit of the firing angle, see Figure 2 and 3. The dc voltage may also be controlled by means of a voltage regulator which provides the firing angle to the converters, and the LTC used to control the firing angle or the margin of commutation within narrow limits. The excitation control of a synchronous condenser may be employed for similar control as the LTC of a converter transformer, or normally, for control of an ac bus voltage.

X.3.2.2 Series HVDC tap

Power may be tapped off a pole by means of an HVDC converter connected in series with the pole. It is illustrated in Figure 5. Then the direct current through the converter is given by the power transmission on the main HVDC system. Hence, the power of a series tap has to be controlled by varying its direct voltage [8, 9]. In essence, the voltage regulator in a series tap has the similar function as the current regulator in a parallel converter.

The LTC of the converter transformer may be controlled such that the firing angle of the converters is kept within narrow limits.

X.4 OBJECTIVE AND VALIDITY OF THE HVDC SYSTEM MODEL

The model of an HVDC system, which is treated here, is intended for analysis of power flows and electromechanical transients in an electrical system. The model shall focus on the properties of an HVDC system seen as an element of an electrical power system. It shall provide the correct interaction with other elements in the power system. Hence, the HVDC system model shall be consistent with those of synchronous machines, including their excitation systems, static var compensators etc. used for transient stability studies.

For electromechanical transients it is normally sufficient to consider the power frequency component of voltages and currents in an ac network and the mean value of the voltages and currents in a dc network, as for power flows. Harmonics are neglected, since they normally have second order effects on the active and reactive power, which influence the node voltages and the speed and rotor angles of the rotating machines in the system.

Hence, the validity of this model is limited to the fundamental frequency components of voltages and currents on the ac side, and the mean values of the same quantities on the dc side of the converters. The electrical state in the ac system is then assumed to be sinusoidal. As a consequence, the ac voltages and currents are described by phasors, defined by their magnitude and phase angle. The phasors of the ac quantities and the mean values of the dc quantities will vary in time for transient conditions.

The validity of the model is limited to symmetrical conditions in the ac systems. The reason is that the representation of the HVDC-converters correctly with a phasor model for unsymmetrical conditions, typically a single-phase fault, is not feasible at the present state-of-the-art. Hence, the state in the ac system is represented by the positive sequence phasors of the node voltages.

The basic objective of the model is to provide the correct interaction between the system elements, HVDC converters, converter transformers, dc lines, dc reactors, etc. They interact with each other through their currents injected to the nodes. The node voltages of the networks are determined by the Kirchoff's law that states that the sum of the injected currents to a node is zero.

It defines an equation for each node, from which the node voltages can be solved, given the injected currents as function of the node voltages, see next section. Hence, the principal objective of the modelling is to provide the equations of an HVDC converter, which give the phasor of the fundamental component of its ac current and the mean value of its DC current, which are injected into the ac and the dc networks, respectively, as function of the phasor of the voltage of the ac nodes, the mean value of the voltage on the dc nodes, and the firing angle of the valves.

The operation of a converter group is here restricted to commutation with so-called single overlap [1, 2, 3, 10]. For normal delay angles, it is valid for ac voltages down to about 0.1 pu, assuming normal dc currents, and up to about 10 pu dc currents, assuming normal ac voltages. This restriction should not be decisive for conclusions about the dynamic performance of the system.

The direct voltage and the phase angle of the phasor of the ac current of a converter are both very sensitive to its firing angle; The differences between the dc voltages of the converters in an HVDC system determine the dc currents, and the the phasor of the ac currents of the converters determine their active and the reactive power. The control of an HVDC converter may influence the dynamic performance of a power system during and after disturbances similar to the control of synchronous machines and static var compensators. Therefore, it is of vital importance that the firing angles of the converters are determined accurately i.e. the converter control should be represented adequately; Hence, the closed loop current control of a converter has a decisive influence on the stability and dynamic performance, especially for a HVDC converter terminating at ac system locations having low short-circuit capacities, because of the sensitivity of the ac voltage to variations of the ac current, in particular its reactive component, or for a cable link.

The modelling of the transfer functions of the other items of the control system is left open to a great extent. It requires a software with a flexible modelling capability.

For most system planning studies, a symmetrical dc system configuration should be sufficient. It can be modelled by a monopolar equivalent, which however, should be built by connecting converters, dc reactors, dc lines etc. in an arbitrary multiterminal configuration.

X.5 NODES, STATE VARIABLES AND ELEMENTS OF THE AC AND DC NETWORKS

A node voltage is defined as the voltage between the node and a reference ground. A node voltage in the ac network is here the phasor of the positive sequence component of the ac voltage, i.e. a complex quantity. A node voltage in the dc network is here the mean value of the dc voltage, i.e. a real quantity.

At each node the continuity of the current (Kirchoff's current law) shall be satified. For the ac nodes it can be written:

$$\sum_{k=1}^{k=k_1} \bar{I}_{a\,jk}\,([\bar{U}_a]\,,\,[U_d]) = 0 \qquad j = 1,2,.....n_a \tag{5.1}$$

For the dc nodes:

$$\sum_{k=1}^{k=k_1} I_{d\,jk}\,([\bar{U}_a]\,,\,[U_d]) = 0 \qquad j = 1,2,.....n_a \tag{5.2}$$

where:

$[\bar{U}_a]$ is the vector of the node voltages of the ac network; it has n_a elements, and an element being the phasor of the positive sequence component of the ac node voltage.

n_a is the total number of nodes in the ac network.

$[U_d]$ is the vector of the node voltages of the dc network; It has n_d elements, and an element being the mean value of the dc voltage.

n_d is the total number of nodes in the dc network.

$I_{ajk}([\bar{U}a],[U_d])$ is the phasor of the positive sequence component of the ac current injected to the j th node from the k th system element connected to the node, as function of $[\bar{U}_a]$ and $[U_d]$.

$I_{djk}([\bar{U}_a],[U_d])$ is the mean value of the dc current injected to the j th node from the k th system element connected to the node, as function of $[\bar{U}_a]$ and $[U_d]$.

k_j is the total number of system elements connected to the j th node.

A system element may be a generator, a load, an HVDC converter, a transformer, a line, a reactor etc.

Eqs. (5.1) and (5.2) define the same number of equations as the number of unknown node voltages, and may be considered to determine the node voltages. With given node voltages, the complete state in the ac and dc networks can be determined e.g. the currents and the power flow. Therefore, the node voltages can be considered to be the state variables for the networks.

For calculation of the unknown node voltages, the model of a system element shall provide the injected current from the element to its network nodes as function of the node voltages. This functional relationship may be given as a formula, or as a set of equations, when the system element contains local state variables as well.

For an ac node, to which an HVDC converter and linear ac network elements, lines shunt filters etc, are connected, the node equation can be written:

$$[Y_a]_c^T\,[\bar{U}_a] + \bar{I}_a = 0 \tag{5.3}$$

where:

$[\bar{Y}_a]_c^T$ is the row of the admittance matrix of the ac network corresponding to the node at which the HVDC converter is connected.

$[\bar{U}_a]$ is the vector of the node voltages of the ac network.

$\bar{I}_a$ is the phasor of the fundamental frequency component of the injected ac current from the HVDC converter.

For a dc node, to which an HVDC converter and linear dc network elements are connected, the node equation can be written:

$$[Y(p)_d]_c^T\,[U_d] + I_d = 0 \tag{5.4}$$

where:

$[Y(p)_d]_c$ is the row of the admittance operator matrix of the dc network corresponding to the node at which the HVDC converter is connected.

$[U_d]$ is the vector of the node voltages of the ac network.

I_d is the mean value of the injected dc current from the HVDC converter.

$Y(p)_d$ implies that the dc network elements are represented by linear differential equations, and described by R, L, C parameters. The state changes on the dc side is relatively slow, which allows a dc line to be represented by its lumped parameters. It should be sufficient to consider only the effect of major inductances, capacitances and resistances in the dc network. Hence, for an overhead line, the shunt capa-citance may be neglected, for a cable, the inductance may be neglected, and a dc filter may be neglected.

The equations which are relevant for the modelling of an HVDC converter, i.e. for the determination of $\bar{I}_a$ I_d are treated below.

X.6 HVDC CONVERTER

X.6.1 Basics

An HVDC converter is connected between two dc nodes or between a dc node and ground, to the ac node on the valve side of the converter transformer, and to the converter control system, which provides the firing angle, α, Figure 1.

The basic unit of a converter is the line commutated 6-pulse group, Figure 6. A valve can conduct current in one direction only, and it can fire when the voltage of the anode relative the cathode is positive, $u_v > 0$. The firing instant is controlled by the delay angle α. In essence, those pair of valves, one in the upper half and another in the lower half of the 6-pulse group, are conducting which are connected to the two phases which supplies the highest voltage in the forward conduction direction. For positive sequence conditions the valves fire in the order 1-2-3-4-5-6, see Figure 6a.

For a converter, which is connected to a stiff ac voltage and for which the dc current is stiff (constant and infinitely smoothed), the instantaneous values of the dc voltage and the ac current are illustrated in Figure 6b. A valve conducts current during 1/3 of a cycle. The effect of an increase of the delay angle, assuming constant dc current, is a decrease of the mean value of the dc voltage, and an increase of the phase shift of the ac current relative the ac phase voltage.

For a converter, which is connected to an ac voltage through a transformer, its leakage inductance makes the commutations of the dc current between two valves non-instantaneous. The time for the commutation is measured by the overlap angle, u. The effect of the overlap angle is an increase of the conduction time of a valve, a further decrease of the mean value of the dc voltage, and a further increase of the phase shift of the ac current. It is illustrated in Figure 6c. The internal, sinusoidal voltage seen from the valves is called the commutation voltage, and the phase inductance seen from the ac terminals of the 6-pulse group towards the commutation voltage is called the commutation inductance. Normally, the commutation voltage is the ac voltage of the filter bus on the network side of the converter transformer.

For further details reference is made to [1, 2, 3, 10].

X.6.2 Model

X.6.2.1 Ideal converter

An ideal HVDC converter, i.e. with zero commutation inductance and a stiff dc current, can be modelled by the equivalent circuit in Figure 7.

Seen from the dc terminals it can be represented by a dc voltage source in series with a diode, the latter one to assure the unidirection of the dc current. The magnitude of the dc voltage is the mean value of the dc voltage in Figure 6b.

Seen from the ac terminal it can be represented by an ac current source. The magnitude of the ac current is the fundamental frequency component of the rectangular current in Figure 6b. The phase angle of the ac current, relative the ac voltage, becomes the delay angle, α.

The delay angle is limited between a minimum and a maximum value, α_{min} and α_{max}, respectively. A positive voltage across a valve is required to obtain a simultaneous firing of the series connected thyristors in the valve, which is decisive for α_{min}. A negative voltage across the valve is required after the extinction of the current in order to assure proper recombination of the charge carriers in the thyristors, and avoid a firing when the valve voltage becomes positive. The duration of this negative voltage is given by the margin of commutation angle γ, and $\alpha_{max} = \pi - \gamma$ for an ideal converter.

X.6.2.2 Real converter

A real converter has a nonzero commutation inductance. It modifies the equivalent circuit slightly, see Figure 8.

The noninstantaneous commutation between the valves, caused by the commutation inductance, decreases the dc voltage by an amount which is proportional to the dc current and the commutation reactance. It can be considered by an equivalent resistance, $(3/\pi)\ X_c$, in series with the internal dc voltage source of the equivalent circuit. It is added to the resistance, R_{dc}, measured between the dc terminals of the converter.

To be exact, the effect of the commutation inductance on the rate of change of the dc current should also be included. It can be considered by increasing the inductance of the dc reactor outside the converter by an amount corresponding to 1.5 - 2 times the commutation inductance per converter.

The non-instantaneous commutation between the valves modifies the shape of the ac current, see Figure 6c, which affects the magnitude and phase angle of its fundamental frequency component, i.e. the ac current source of the equivalent circuit. The equations for consideration of this effect are given in Figure 8. The commutation inductance also causes an inductive voltage drop for the fundamental frequency, between the commutation voltage and the voltage at the ac terminal of the 6-pulse group. It is considered by the commutation reactance, X_c in series with the current source.

Compared with the ideal converter, the maximum delay angle is decreased by the overlap angle, and now becomes $\alpha_{max} = \pi - \gamma - u$. Hence, it becomes a function of the magnitude of the commutation voltage and the dc current.

X.6.2.3 Main circuit parameters of a real converter

The principal main circuit parameters of a real converter are X_c and R_{dc}. These converter parameters are normally given in pu according to the following definitions [1]:

$$d_x = \frac{3}{\pi} X_c \frac{I_{dn}}{U_{dion}} \qquad (6.2.1)$$

$$d_r = R_{dc} \frac{I_{dn}}{U_{dion}} \qquad (6.2.2)$$

where:

d_x is the relative inductive direct voltage drop .

d_r is the relative resistive direct voltage drop .

I_{dn} is the rated direct current .

U_{dion} is the rated ideal no load direct voltage .

U_{dion} is normally defined for the rated conditions of the converter, and calculated from the basic relations:

$$\frac{U_{dn}}{U_{dion}} = \cos(\alpha_n) - (d_x + d_r) \textit{ for a rectifier} \qquad (6.2.3)$$

$$\frac{U_{dn}}{U_{dion}} = \cos(\gamma_n) - (d_x + d_r) \textit{ for an inverter} \qquad (6.2.4)$$

where:

U_{dn} is the rated direct voltage.

α_n is the rated delay angle for a rectifier.

γ_n is the rated margin of commutation for an inverter.

The rated voltage of the valve winding of the converter transformer, U_{vn}, is normally chosen so that:

$$U_{dion} = \frac{3}{\pi}\sqrt{2}\, U_{VR} \qquad (6.2.5)$$

The rated current of the valve winding of the converter transformer, I_{vn}, is normally defined according to:

$$I_{vn} = \frac{\sqrt{2}}{\sqrt{3}}\, I_{dn} \qquad (6.2.6)$$

Then d_x of the converter is related to the normal short-circuit reactance of the converter transformer, e_x, in pu of its rating, according to:

$$d_x = \frac{1}{2}\, e_x \qquad (6.2.7)$$

It is recommended to use the parameters I_{dn}, U_{dion}, d_x and d_r as input data for a converter, because they may be considered to be its "nameplate-quantities".

d_x is in the order of 0.06 - 0.09 pu for modern thyristor HVDC converters, and even up to 0.12 pu for old mercury-arc HVDC converters.

d_r is in the order of 0.1 d_x, and has a small influence on the performance of the system.

The delay angle and the margin of commutation are given as parameters of the control system.

X.7 CONTROL OF AN HVDC SYSTEM WITH PARALLEL CONVERTERS

X.7.1 Introduction

For the calculation of the injected currents to the dc and ac nodes of an HVDC converter, models of the controllers are needed, which ultimately provide the firing angle, α, to a converter, see section 4, 5 and 6. Basically, the firing angle of a converter is used to vary the dc voltage across its dc terminals. It is utilized by the converter control to regulate the dc current or dc voltage of a converter. The firing angle can also be controlled to vary the phase angle of the ac current to stabilize the voltage, see section 3.

The tap-changer of a converter transformer is a slow acting device. Its effect on the state of the system within a normal time for exploring stability limits and dynamic performance may be neglected. Hence, it may be kept constant on the value established for the initial steady-state condition.

The controllers are represented by their transfer functions, including limits. They are here considered as modules with defined input and output signals, and which are combined to a complete control system. The following description of the models of the controllers of an HVDC system, starts from the valves of a converter, with the converter firing and current controller and proceeds with the converter and pole control towards higher level power and systems control, see section 3 and Figure 4.

X.7.2 Converter firing and current controller (CFCC)

X.7.2.1 Model description

In an HVDC system with parallel converters, each converter is equipped with a converter firing and current controller, CFCC. A model is described by the block diagram in Figure 9.

The CFCC provides the delay angle α, which is used in the model of the converter, Figure 8.

The input to the CFCC is the the current order, I_{do}, and the measured dc current through the converter, I_d. In one converter station the so-called current margin, ΔI_{om}, is also supplied. It is added in a rectifier and subtracted in an inverter, see section 3.

The CFCC is modelled by a transfer function of PI-type, and a first order output filter. The gain of the proportional part may be modified by multiplying by the factor sin $\alpha_m(0)$/sin α_m, where α_m is the delay angle after a measuring filter, and sin α_m (0) is the value for the initial steady state. It provides linearity between a change of the dc current and the dc voltage. With a large value of the time constant T_2, linearity between a change of the dc current and the delay angle is obtained.

The minimum value of the delay angle, α_{min} can be considered to be constant. The maximum value of the delay angle varies with the direct current and the ac voltage through the overlap angle, as described in clause 6.2.2. It may also vary due to a control of the margin of commutation, if γ is used for voltage stabilization, see Figure 4.

In addition to the limits of the delay angle, limitations of its rate of change are also included. It may be needed to limit the rate of change of the reactive power of a converter and as a consequence the change of its ac voltage to improve the dynamic performance and avoid commutation failures in an inverter.

To allow a user to control the delay angle, the model should be provided with user defined control facilities, UDC, at the indicated locations. The control may be given functions of time. The may also be functions of the dc and ac voltage to enable special control for the recovery of the HVDC system after a disturbance.

X.7.2.2 Parameters of a CFCC

The principal parameters of a CFCC are K_p and T_i of the PI transfer function. They should be chosen such that the response of the direct current on a change of the current order becomes fast and well damped with a small overshoot. The following typical values may be given:

$K_p = 50 - 150°\text{el/pu of } I_{dn}$

$$\frac{1}{T_i} = 2\text{-}4°el\ /\ pu\ of\ I_{dn}\ /\ ms$$

If they are not given as a result of the design of the converter, they may be determined by simulating a step change of the current order and adjusted such that the response of the direct current fulfils the above general requirements. The time constant, T_2, is chosen very large, if linearity between a change of the delay angle and a change of the direct current should be obtained, and very small if linearity between a change of the direct voltage and a change of the direct current should be obtained.

The time constant T_1, of the measuring filter for the direct current may be a few ms or it may be neglected.

The time constant of the output filter, T_f, is typically 0.5 - 2 ms.

The minimum limit of the delay angle is a constant. The following typical values may be given:

α_{min} = 5°el for a rectifier

α_{min} = 100 - 105°el for an inverter

The maximum limit of the delay angle is determined by the actual direct current, the ac voltage and the margin of commutation. The latter one is a constant, with the following typical values for an inverter as well as a rectifier:

γ = 17°el for a 50 Hz ac system

γ = 19°el for a 60 Hz ac system

The limits for the rate of change of the delay angle may vary within a rather wide range. The following typical values may be given:

$\dot{\alpha}_{min}$ = -(0.5 - 5)°el / ms

$\dot{\alpha}_{max}$ = (1 - 10)°el / ms

The delay angle for a current controlled rectifier for rated operation, is typically α_n = 15°el.

The margin of commutation of a current controlled inverter for rated operation is typically γ_n = 21-23°el. For an inverter which operates on its maximum delay angle the values, which determine the maximum delay angle also become the rated ones i.e. γ_n = 17 - 19°el.

The current margin ΔI_{om} is typically 0.1 pu of I_{dn}.

X.7.3 Current order limiter (COL)

X.7.3.1 Model description

A principal characteristic of a current order limiter, COL, is given in Figure 10.

The COL limits the current order, I_{do}, which is provided to the CFCC, between a maximum and a minimum value. The input signal to the COL is the reference value of the current order, I_{oref}, which is obtained from a higher level current or power controller.

For normal dc voltages, the current order is limited between an absolute minimum value, $I_{do\ min}$, and an absolute maximum value, $I_{do\ max}$. For dc voltages below a given level, U_{dr}, the maximum current order is reduced linearly with the dc voltage, until it reaches a value given by a lower level, U_{ds} below which it is constant.

The reason for the COL is that it can be used to facilitate the start up of an HVDC converter, after a major disturbance, by reducing the current order to the CFCC, temporarily, The measuring filter of the dc voltage, has two time constants, one for decreasing dc voltage, T_1, and another for increasing dc voltage, T_2, $T_1 < T_2$. A dc voltage below U_{dr} is an indication on a disturbance, and the converter should be unloaded fast. When the dc volt-age is increasing, the recovery can be controlled by a suitable choice of T_2. ε is a small positive tolerance which should be chosen to avoid a switching between T_1 and T_2 for smaller oscillating components of the dc voltage.

Different values of T_2 of the individual converters in an HVDC system may be chosen, to control the speed of the recovery of the system after a disturbance.

It should be noted that a COL-characteristic may vary for different plants. The one given here, should be considered as a basic one. Other characteristics may be modelled and implemented by means of a user-defined language.

X.7.3.2 Parameters of a COL

$I_{do\ min}$, the minimum current limit, is typically 0.1 pu of I_{dn}.

$I_{do\ max}$, the maximum current limit, depends on the overload capability of the converter. Typical values may be in the range 1-2 pu of I_{dn}.
U_{dr}, the voltage below which the maximum current order is decreased, may be 0.1-0.2 pu of U_{dn}.

U_{ds}, the voltage below which the current order is constant, is normally within the range 0.5-0.9 pu of U_{dn}.

T_1, the time constant of the measuring filter of the dc voltage, for decreasing voltage, should be small, typically 10 - 20 ms.

T_2, the time constant of the measuring filter of the dc voltage, for increasing voltage, should be an order of magnitude larger, typically 50-300 ms.

X.7.4 Higher level current and power control, master control (MC)

X.7.4.1 Overview

The reference values of the current orders to the individual converters in an HVDC system of parallel converters, operating according to the current margin principle, described in section 3, are determined in a higher level controller. It is here named the Master Controller (MC). A functional diagram of a MC is shown in Figure 11.

The reference value of the current order of a converter, can be chosen independently for n-1 converters in a system with n parallel converters. It may be a given quantity, in which case the converter is considered to operate in current control mode. It may also be determined by dividing a given power order by the direct voltage of the converter, in which case the converter is considered to operate in power control mode. These alternatives are treated in the following two subclauses. The determination of the reference value of of the current order for the n:th, dependent, converter is treated in the third subclause below. Finally, typical numerical values of the parameters are given.

X.7.4.2 Current control mode of a converter

The output from the MC, to an independent converter, which is operated in the current control mode, is the reference value of its current order, I_{oref}. It is the input to its current order limiter, COL.

The input to the MC is the constant current order for the steady-state, initial power flow simulation, I_{do} (0), and an optional contribution from a controller which varies the direct current of the converter in response to changes of a frequency or a power, ΔI_{pfc}, see clause 7.5. In addition, provision should be made for a UDC input.

X.7.4.3 Power control mode of a converter

The output from the MC to an independent converter, operating in the power control mode, is also the reference value of the current order, I_{oref}.

The input to the MC is the constant power order for the steady-state, initial power flow solution, $P_o(0)$, and an optional contribution from a controller which varies the power of the converter in response to changes of a frequency or a power, ΔP_{pfc}, see clause 7.5. In addition, provision should be made for a UDC input.

The reference value of the current order is formed by dividing the resultant power order by a filtered value of the dc voltage of the converter. For too low dc voltages, typically during a disturbance, it is not meaningful to maintain the constant power control, because it would result in large currents and eventually a collapse of the voltage. Therefore, it is switched to constant current control when the voltage has decreased below a level, U_{di}, by dividing the resultant power order by a constant voltage instead, e.g. the dc voltage prior to the disturbance. The constant power control is switched back when the voltage has increased above a level, $U_{dr} > U_{di}$.

X.7.4.4 Coordination of the current orders for parallel converters

A system of parallel HVDC converters are operated according to the so-called current margin principle, see clause 3.2. Then the sum of the current orders to the rectifiers shall be equal to the sum of the current orders to the inverters. It implies that the current orders can be chosen independently in n-1 converters in a system of n parallel converters, and that the current order in the nth converter becomes dependent, see Figure 11. (It may be intended to act as the slack, but which one that will be the slack depends on the relative magnitudes of the voltages).

If $I_{oref\ n} < 0$, then the choice of the reference values of the current orders, i.e. the control, is not feasible and the execution should be terminated, and a message shall be given.

X.7.4.5 Parameters of a MC

The parameters of a MC are related to the power control mode, and to a great extent determined by the required performance. Generally, the constant power control should not be too fast, because it may cause the ac voltage to go unstable, if the converter is connected at an ac system location with a low short-circuit capacity [1]. The following typical values may serve as a guidance:

U_{di}, the voltage below which the control is switched to constant current control: 0.8 pu of U_{dn}.

U_{dr}, the voltage above which the control is switched back to constant power control: 0.9 pu of U_{dn}.

T_p, the time constant of the measuring filter: 50-500 ms.

X.7.5 Control of a power or a frequency by the active power of a converter (PFC)

The active power of an HVDC converter may be varied very fast and with large amounts, provided it can be coped with by the ac systems, to which the HVDC converters are terminated. This property may be employed to improve the dynamic performance of the system; The damping of electromechanical power oscillations may be increased, possibly the first and second swing may be influenced significantly. An HVDC link can be used for control of the frequency of an ac system i.e. to keep the balance between the load and the power infeed, typically an island without local generation.

Basically it is achieved by variation af the active power of an HVDC converter, by means of a controller in response to variations of a system frequency or a speed of a rotating machine, or the power on a tie-line. It is here named power - frequency controller (PFC), see Figure 11.

The output of the PFC forms an input to the master controller (MC) of an independent converter in a parallel HVDC system. It is ΔI_{pfc}, if the MC is in the current control mode, and it is ΔP_{pfc}, if the MC is in the power control mode.

The input to the controller may be one of the following, see Figure 4:

$\Delta P_{tie} = P_{tieo} - P_{tie}$, the deviation of an active power on a tie-line from a constant order.

$\Delta f = f_o - f$, the deviation of the frequency from a constant order.

$\Delta\omega = \omega_o - \omega$, the deviation of the angular velocity of a rotating machine from a constant order.

The transfer function of a PFC depends on the application. Hence, it is left to the user to design a suitable transfer function.

X.7.6 Control of a voltage by the reactive power of a converter (γC)

X.7.6.1 Overview

An inverter, which operates with its maximum delay angle, determined by the margin of commutation, may be used for control of its ac voltage by varying γ. Basically, the phase angle of the ac current is then varied and, as a consequence, the reactive power demand of the inverter, which affects the ac voltage, assuming a finite short circuit capacity. The active power becomes changed as well, but it is assumed to be compensated for, by a change of the magnitude of the current by means of the control of the dc current.

The variation of γ may be employed for voltage control by means of an automatic voltage regulator. Hence, an inverter may be used for ac voltage control, within its design limits, as an alternative to a static var compensator. It may be applied especially if the inverter is operating at an ac voltage location with a low short circuit capacity. Then the voltage may be unstable for a small disturbance, for instance the disconnection of a shunt capacitor. The basic mechanism is that the ac voltage decreases, which causes an increase of the dc current. Operation with a constant γ_o implies that the overlap angle increases, and, as a consequence, also the phase angle of the ac current, and hence the reactive power consumption of the inverter. It causes a further decrease of the ac voltage. The system may be stable, if the inverter is operated with constant current control. However, if it is operated with constant power control, the decreased voltage is compensated for by an increased current, which eventually will lead to a collapse of the voltage.

It may also be employed for stabilization of the current control of a HVDC link, which is performed by the rectifier and with the inverter operating on its maximum delay angle and which is terminated at an ac system location having low short circuitcapacity, by a slight modification of the dc voltage - current characteristic of the inverter.

Both controls can be modelled according to Figure 12. The modelling is described below.

X.7.6.2 Automatic voltage control

The margin of commutation, which is used for nominal conditions, γ_o is modulated with the output, $\Delta\gamma_u$, from an automatic voltage regulator, VC. The input to the VC is the order and response of the controlled voltage. It may be the ac voltage of the HVDC converter. It may also be the dc voltage of the converter, which implies a small interaction on the rest of the dc system. The effect on the static dc voltage - current characteristic is shown in Figure 12 b.

The transfer function of a VC depends on the application. Hence, it is left to the user to design a suitable transfer function. The margin of commutation may be decreased temporarily below the normal value, γ_o. The lower limit, γ_{min}, is determined by the increased risk for commutation failure. An absolut lower limit is of the order of 12° el.

X.7.6.3 Stabilization of the current control

For an inverter in an HVDC link which is operating with constant commutation margin, its direct voltage is increased for an increase of the direct current. It can be derived from the basic relations in Figure 8, or found in [1, 2, 3, 10]. Hence, the equivalent internal resistance of the inverter is negative, and contributes to a decrease of the damping of the current control, which is performed by the rectifier. A further decrease of the dc voltage is obtained due to the increased voltage drop in the ac network, as a consequence of the increased consumption of reactive power at an increase of the dc current.

The dc current control may be stabilized by varying γ in response to the change in the dc current, such that γ is decreased for an increase of the current. It implies that it causes a decrease of phase angle of the ac current, which compensates for the increase caused by the in-creased overlap angle. It has the same effect on the reactive power of the converter.

If γ is varied linearly with the dc current around the normal γ_o, then the dc voltage - current characteristic of the inverter gets a branch with a positive slope according to Figure 12c; it creates a positive internal resistance of the inverter.

The slope is controlled by the parameter $\Delta\gamma_0$, see Figure 12c. Typical values may be in the range 5-10° el.

X.8 CONTROL OF A SERIES TAP

For a series tap in an HVDC system with parallel converters, Figure 5, the direct current is given by the main transmission. Therefore, the power of a series tap is controlled by varying its direct voltage. It can be achieved by means of a regulator of PI-type, similar to the CFCC of a converter of a parallel converter, the difference being that the input are the order and the response of the dc voltage of the series tap.

Higher level control can be achieved by means of a Master Controller. For the power control mode, a reference value of the voltage is determined by dividing a power order with the direct current through the converter.

No commercial application has yet been found for a series tap.

X.9 DISTURBANCES. PROTECTIVE ACTIONS. FAULT CLEARING

Disturbances, protective actions and fault clearing represent events, which are studied to explore the performance of the system.

The protections of an HVDC system cope with disturbances within the HVDC system i.e. the converters, the dc lines and cables. They shall be coordinated with protections of equipment in the ac systems, and should not operate for disturbances in the ac systems.

X.9.1 Disturbances in a converter

X.9.1.1 Blocking and disconnection

A faulted 12-pulse converter, which is connected between a pole and neutral, is blocked and disconnected from the pole.

For a 2-terminal transmission the second converter will also be disconnected, hence the entire HVDC pole will be shut down. The effect on the ac systems can be represented by simply forcing the dc current to zero by means of the UDC of the CFCC.

For a multiterminal system the control of the converters are often employed to force the current through the faulted converter to zero, after which it can be blocked and disconnected. It is performed by temporarily forcing the rectifiers into inverter operation. It can be modelled by the UDC of the CFCC. At the restart of the system the current orders of the remaining HVDC converters have to be changed according to a new power schedule such that the conditions for the current margin principle apply.

In the future, dc circuit breakers may be employed, which then disconnects the faulted dc line, similarly to a faulted ac line.

X.9.1.2 Blocking and by-passing

A faulted converter, which is connected in series with another converter in a pole, or a faulted series tap, is blocked, by-passed on the dc side and disconnected. The principal effect is that the direct voltage across the converter and the ac current of the converter both become zero. It may be modelled by applying a short circuit between the dc terminals of the converter. If a converter is represented by an explicit number of identical series connected converters, the diconnection of a faulted one can be modelled by reducing that number by one.

Sometimes a faulted converter is taken out of service by first shutting down the HVDC system by forcing the rectifiers into inverter operation. It can be modelled by means of the UDC of the CFCC.

X.9.1.3 Commutation failure

Commutation failures may occur in an inverter, when the negative voltage across a valve, after the current has commutated to the next valve, becomes insufficient, a too small magnitude or duration, such that the valve does not block. Then the current is commutated back to the first valve, and at the later firing of the other valve in the same phase, a by-pass path for the direct current is created [1, 2]. As a consequence, the direct voltage and the ac current of the converter becomes zero. Upon detection of a commutation failure, the margin of commutation is increased temporarily, and commutation is restored after a cycle or so. Hence, a commutation failure is a temporary disturbance.

A valve voltage, which is insuffient for the blocking of a valve, may be obtained for disturbances in the ac system to which the converter is connected. Then the voltage may be distorted, its magnitude may be decreased and its phase may be changed. Hence, the possibility to detect a commutation failure for a system model with sinusoidal ac voltages is very limited. Therefore, it is left to the User to initiate a commutation failure simultaneously with a disturbance in an ac network.

The principal consequence of a commutation failure is a temporary zero of the direct voltage and the ac current of the converter. It can be modelled by applying a short circuit between the dc terminals of the converter for a specified time.

It should be mentioned that the principal influence of a commutation failure on the dynamic performance of the system, may be obtained through the subsequent fast current control of the rectifiers, which will sense an overcurrent, and their current controllers may overreact and force their direct currents to zero, temporarily.

X.9.2 Faults in the dc network

A short circuit in the dc network of an HVDC system may occur between a pole and ground, between the two poles with or without connection to the ground. It is detected by a dc line protection. In the present HVDC transmissions the protection forces the rectifiers into inverter operation by applying a large negative signal to the input summing junction of their CFCCs. Then the dc network will be discharged and the dc currents become zero, within a very short time. After a certain time the signal is removed and the HVDC system is started up. In future, dc circuit breakers may be employed, which then disconnects the faulted dc line, similarly to a faulted ac line.

A fault can be represented by applying a resistor between a pole and ground, in the similar manner as the application of a fault in an ac network.

A clearing of the fault by forcing the rectifiers into inverter operation, is modelled by means of the UDC of the CFCAs. A large negative signal is applied, and after a specified time, the fault and the signal to the CFCCs are removed.

A clearing of the fault by a circuit breaker, is modelled by disconnection of the dc line and the fault after a specified time.

X.9.3 Faults in an ac network

The general rule is to take no protective action in the converters for a fault in the ac system outside the converter station.

The model of the converters is valid strictly for symmetrical conditions in the ac systems, see section 4. Hence, the faults are restricted to 3-phase faults.

X.10 APPLICATION EXAMPLE

X.10.1 Introduction

As an example of the application of the HVDC model for system planning studies, a 2-terminal transmission is given. It is based on the Gotland HVDC link.

Descriptions of the Gotland HVDC link can be found in [1, chapter 9] and [11, 12], to which are referred. Here, the principal characteristics of the system are first given, followed by the numerical values of the principal parameters, which are needed for the model building. It should be noted that the controllers used here do not agree in all details with those in the plant, but they should be sufficiently close to provide realistic performance of the HVDC transmission system.

The Gotland link has been chosen as example of the following reasons:

- It contains a cable, the capacitance of which has a significant influence on the current control and, therefore, should be represented. It may not be required for an overhead line.
- The receiving system may be weak.
- It controls the frequency of the receiving system.

X.10.2 System characteristics

The system configuration is shown in Figure 13.

During normal conditions, the HVDC link supplies the electrical power to the loads on Gotland, without any local production. The present peak load is about 160 MW. The HVDC link is a bipolar configuration rated 135 MW, 150 kV per pole. The converter stations are interconnected by dc cables, with a length of 100 km. The link has an overload capability, which allows the peak load to be supplied by means of one pole.

Three synchronous compensators are installed in the converter station on Gotland. Without any other local synchronous machines, these synchronous compensators provides the ac voltage on Gotland. Hence, they are necessary for the commutation of the HVDC converters, and should be considered as part of the HVDC trans-mission system. The ac voltage on the 70 kV grid on Gotland is controlled by means of automatic voltage regulators of the synchronous compensators. Weak ac system conditions may be present, when synchronous compensators are out of service.

The HVDC link is operated with current control in the rectifier and with constant margin of commutation in the inverter. The direct voltage - current characteristic of the inverter is given a positive slope within the current margin, to improve the stability of the current control. In fact, the capacitance of the dc cable tends to decrease that stability.

The frequency of the electrical system on Gotland is controlled by means of an automatic frequency regulator, which provides the current order to the HVDC link.

The electrical loads on Gotland are of resident, commercial and industrial types.

The ac system at the rectifier is strong.

This example is limited to the representation of one pole and two synchronous compensators of the HVDC transmission system.

X.10.3 HVDC system

The notations used below, are defined in section 6 and 7.

X.10.3.1 Converters

Rated direct current: $I_{dn} = 0.9$ kA

Rated ideal no load direct voltage on 12-pulse basis:

Rectifier: $U_{dion} = 167.3$ kV

Inverter: $U_{dion} = 167.3$ kV

Relative inductive direct voltage drop: $d_x = 6.6\%$

Relative resistive direct voltage drop: $d_r = 0.35\%$

X.10.3.2 Converter transformers

Rated power:

Rectifier: S_n = 157.7 MVA

Inverter: S_n = 157.7 MVA

Rated voltages, (network winding/valve winding):

Rectifier: U_{nn}/U_{vn} = 135.0/123.9 kV

Inverter: U_{nn}/U_{vn} = 75.0/123.9 kV

Short circuit reactance: e_x = 13.2%

Short circuit resistance: e_r = 0.5%

X.10.3.3 Converter firing and current controller (CFCC)

Gains of the PI transfer function:

$$K_p = 120.^\circ \ el/pu \ of \ I_{dn}; \ \frac{1}{T_I} = 3.2^\circ \ el/pu \ of \ I_{dn}/ms$$

Time constant of the current measuring filter: T_1 = 0.05 s

Time constant of the linearizing filter: T_2 = 1000. s (very large)

Minimum limits of the delay angle:

Rectifier: α_{min} = 5.° el

Inverter: α_{min} = 104.° el

Margin of commutation:

Rectifier: γ = 17.° el

Inverter: γ = 19.° el

Limits of the rate of change of the delay angle:

Rectifier: $\dot{\alpha}_{min}$ = -3.4° el/ms; $\dot{\alpha}_{max}$ = 47.3° el/ms

Inverter: $\dot{\alpha}_{min}$ = -8.4° el/ms; $\dot{\alpha}_{max}$ = 3.4° el/ms

Current margin, subtracted in the inverter: ΔI_{om} = 0.09 kA

X.10.3.4 Current order limiter (COL)

Absolute maximum current limit: $I_{do\ max}$ = 1.62 pu of I_{dn}

Absolute minimum current limit: $I_{do\ min}$ = 0.1 pu of I_{dn}

Voltage below which the current order is reduced: U_{dr} = 120. kV

Voltage below which the current order is constant: U_{ds} = 50. kV

Time constant of the voltage measuring filter for decreasing voltage: T_1 = 0.022 s

Time constant of the voltage measuring filter for increasing voltage: T_2 = 0.324 s

X.10.3.5 Frequency regulator (PFC)

The transfer function of the frequency regulator is of PID-type. A block diagram, including the numerical values of the parameters, is shown in Figure 14. It measures the frequency on Gotland, i.e. the speed of the synchronous compensators, and provide a change of the current order to the Master Controller.

X.10.3.6 DC reactors and DC cable

The rectifier and the inverter have identical dc reactors, with an inductance of 0.66 H, which includes the contribution from the commutation inductance of the HVDC converters (0.06 H).

The principal parameter of the dc cable is its capacitance. For the relatively slow state changes, which are considered here, it can be represented by its lumped value, 56. µF. Its inductance can be neglected in comparison with those of the dc reactors.

The total resistance between the rectifier and the inverter is 2.5 ohm.

X.10.3.7 AC filters

The ac filters of the converter stations are represented by shunt capacitors for the fundamental frequency. They are split in two banks:

Rectifier: 35.3 + 33.1 MVAr at 135. kV

Inverter: 18.1 + 15.5 MVAr at 75. kV

X.10.4 Synchronous compensators

X.10.4.1 Machines

Two synchronous compensators are represented, with the following parameters:

Rated power (MVA) :	70.	77.
Rated voltage (kV) :	13.8	15.2
Inertia constant, H (s):	1.7	2.5
X_d (pu):	1.7	1.1
X_q (pu):	1.0	0.6
X'_d:	.33	0.29
X''_d (pu):	.16	0.15
X''_q (pu):	0.21	0.21
X_a (pu):	0.14	0.13
R_a (pu):	0.003	0.002
T'_{do} (s):	11.5	13.0
T''_{do} (s):	0.085	0.09
T''_{qo} (s):	0.23	0.29

X.10.4.2 Transformers

The parameters of the transformers of the two synchronous comepensators are, respectively:

Rated power (MVA):	70.	70.
Rated voltage (gen/netw) (kV):	12.4/75.	13.8/75.
Short circuit reactance (pu):	0.10	0.10
Short circuit resistance (pu):	0.005	0.005

X.10.4.3 Automatic voltage regulators

Each synchronous compensator has an automatic voltage regulator of the static type. A block diagram of the transfer function, including numerical values of the parameters, is given in Figure 15. It is supplied by the ac voltage at the machine terminals.

X.10.5 Receiving ac system

During normal operating conditions, the electrical load on Gotland is supplied by the HVDC inverter, without any local production. The consumers are households, shops, offices etc, the main load types of which are lighting, refrigerators and electrical heating, and industries, with a large portion of motor loads. The reactive power of the loads is compensated almost completely in the distribution networks. Here, the total load is lumped at the 75 kV bus at the inverter. It is represented by an active power, with a constant current characteristic. The frequency dependence is neglected.

X.10.6 Sending ac system

The ac system at the rectifier is strong, 2000 MVA. It is represented by a Thevenin equivalent seen from the 135 kV bus. The angle of the internal impedance is 80° el.

X.10.7 Operating parameters

A load level corresponding to the rated conditions of the dc link is chosen, i.e. with a dc voltage of 150 kV at the rectifier and a dc current of 0.9 kA. The rectifier is controlling the dc current with a delay angle $\alpha_n = 15°$ el, and the inverter is operating with a constant margin of commutation $\gamma_n = 19°$ el during steady-state conditions. The ac voltage at the rectifier is 135 kV, and at the inverter it is 75 kV.

With two synchronous compensators at the inverter, the receiving system has a high effective short circuit ratio, about 4 pu, and with one synchronous compensator it has a low short circuit ratio, about 2 pu.

X.10.8 Proposed analysis

X.10.8.1 Step change of the current order

With the gains of the current regulator given above, the response of the dc current on a step change, say 10% of the rated value, becomes fast and well damped. It is recommended to study the current response for different gains.

It may also be of interest to study the current response without the cable capacitance.

X.10.8.2 3-phase short-circuit in the rectifier

A 3-phase ac short-circuit at the rectifier decreases the dc voltage. As a consequence, the dc current decreases. For a sufficiently low ohmic fault, the dc current becomes zero. It is of principal interest to study the start up of the dc link after the fault clearing. The recovery time can be controlled by chosing different time constants of the COL in the inverter and the rectifier.

X.10.8.3 3-phase short-circuit and commutation failure in the inverter

A commutation failure may be obtained in an inverter for a relatively small decrease of its ac voltage. For a high ohmic (remote) 3-phase fault at the inverter, for which the ac voltage is reduced by 20%, a commutation failure with a duration of one cycle of 50 Hz, may be assumed. It causes zero dc voltage and ac current of the inverter. The short-circuit on the dc side creates an overcurrent. The current regulator in the rectifier may force the dc current to zero. The dc link may start up during the fault, however. When the fault is cleared, the restored ac voltage may force the dc current to zero once more, after which the dc link starts up and the prefault conditions are restored.

X.10.8.4 Investigations of the stability of the current control

The stability of the current control may be explored by disconnection and connection of an ac filter in the inverter, with and without the positive slope of the inverter dc voltage/current characteristic.

The current control becomes more stable if it is allocated to the inverter. It implies that it shall operate with a margin of commutation, $\gamma_n > = 19°$ el, say $\gamma_n = 23°$ el. The performance may be compared with that obtained above.

11. CONCLUDING REMARKS

With the HVDC model given here, and implemented in a transient stability program, a utility should be able to simulate an HVDC system and to explore its dynamic performance, in fact it may have its own digital HVDC simulator. It is recommended to model the HVDC system with a degree of detail that is consistent with the models of other system elements, and the overall requirement of the simulation.

12. ACKNOWLEDGMENT

The permission by the Swedish State Power Board to use the data of the Gotland HVDC transmission as an example for the application of this HVDC system model, is greatly appreciated.

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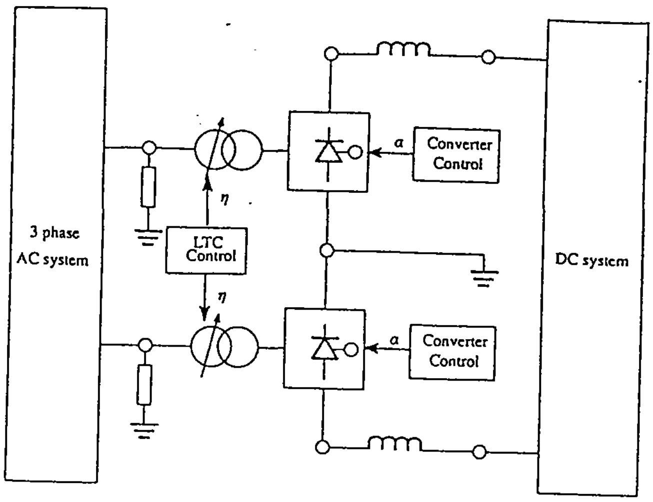


Figure 1. Typical configuration of an HVDC station

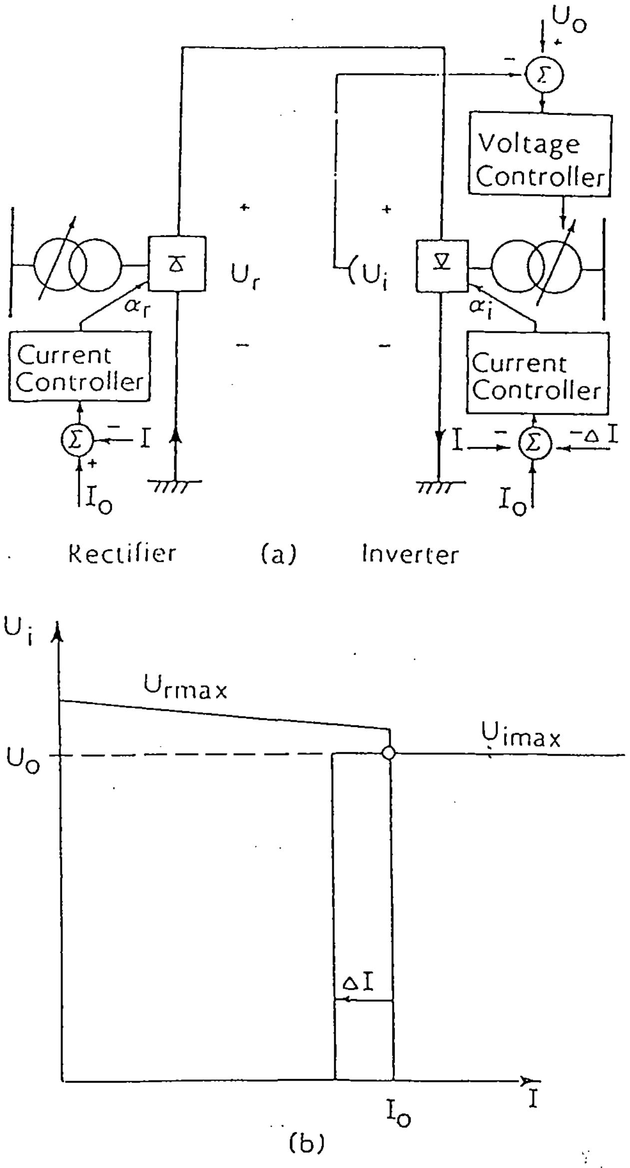


Figure 2. HVDC transmission

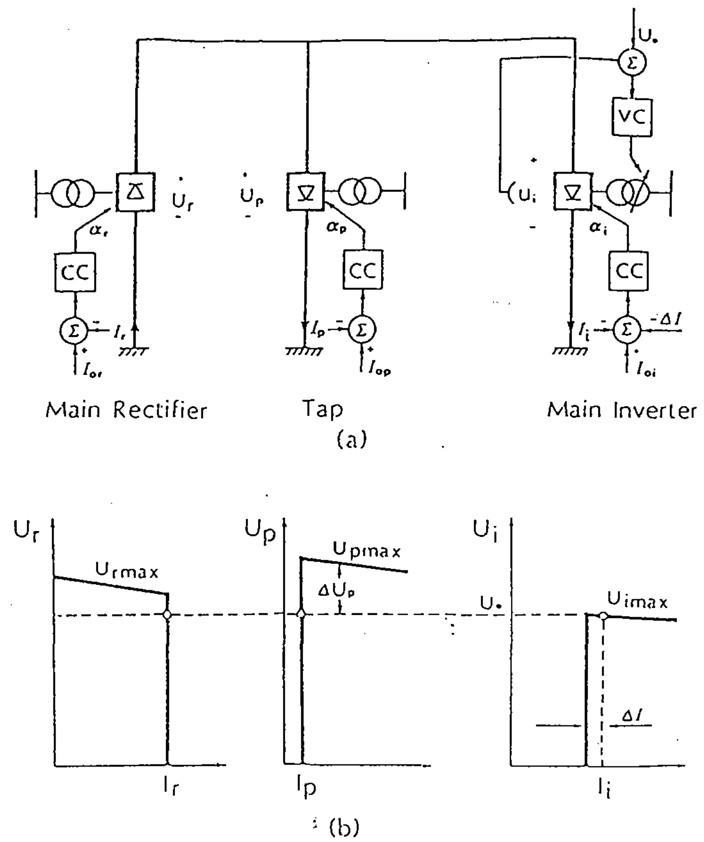
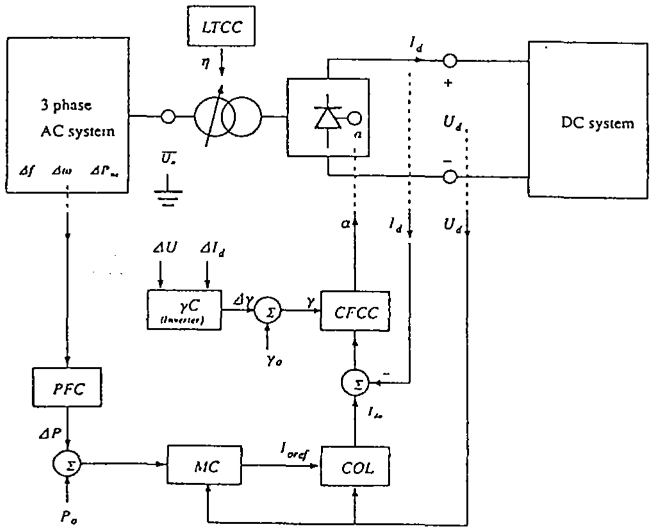


Figure 3. HVDC transmission with a parallel tap



CFCC	Converter Firing and Current Controller
COL	Current Order Limiter
MC	Master Controller
PFC	Power Frequency Controller
VC	Voltage Controller
LTCC	Load Tap Changer Controller

Figure 4. Controllers of a station in a parallel HVDC system

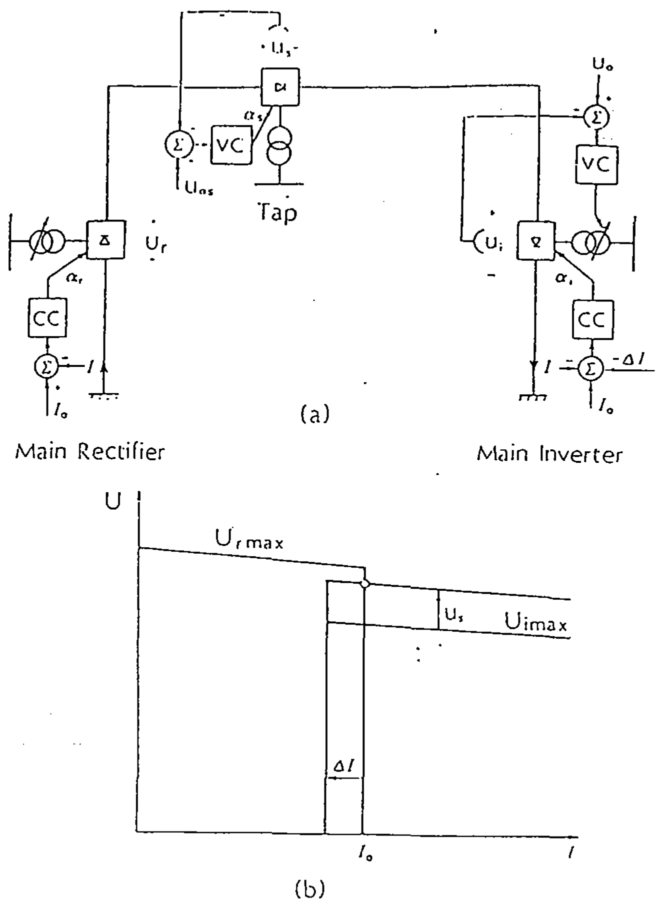


Figure 5. HVDC transmission with a series tap

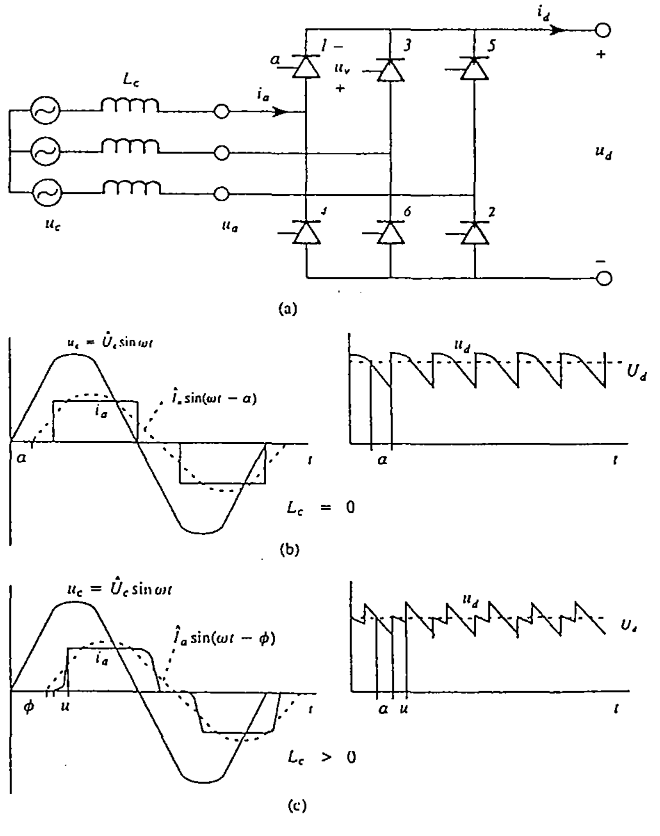


Figure 6. Basic 6-pulse group

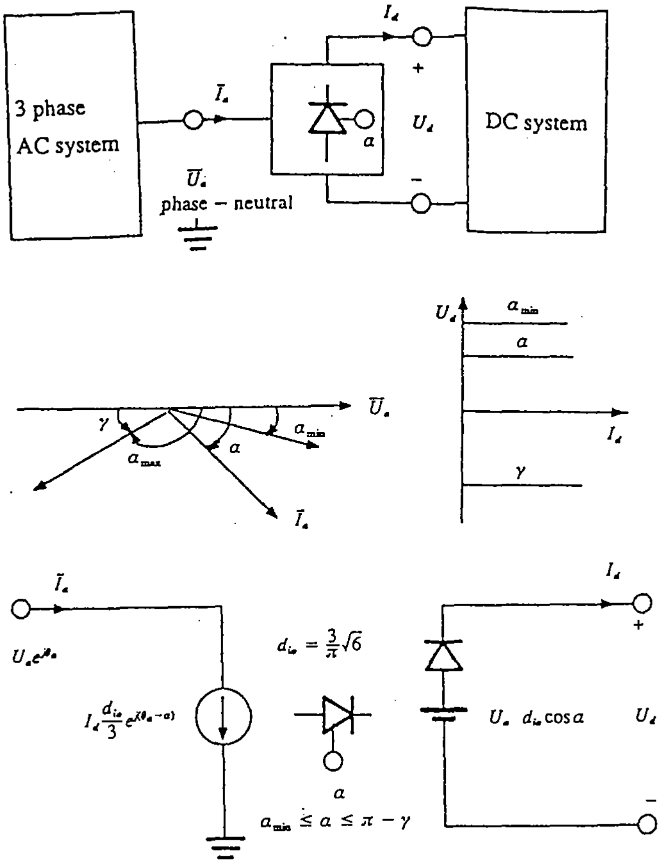
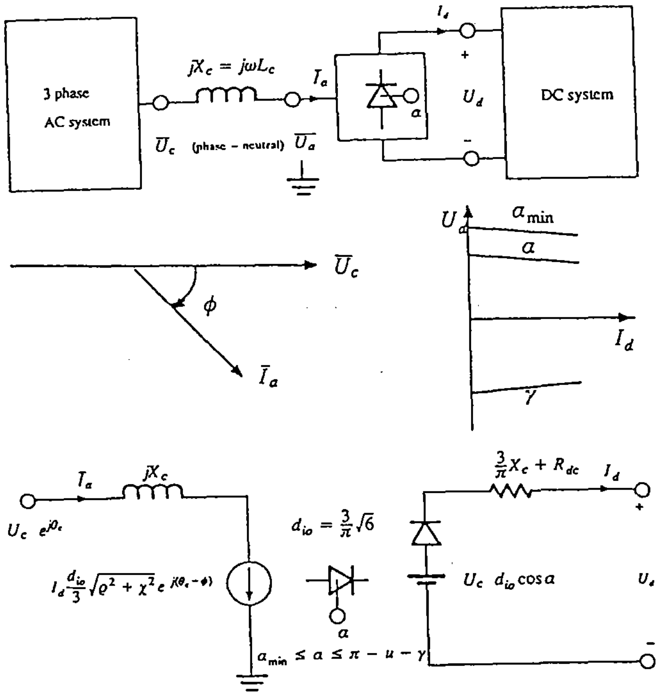


Figure 7. Circuit equivalent of an ideal, line commutated converter



$$\phi = \arctan(\frac{\chi}{\varrho}) \qquad -\pi < \phi < 0 \qquad (1)$$

$$\varrho = \frac{1}{2}[\cos a + \cos(a + u)] = \frac{U_d}{U_c \ d_{io}} \qquad (2)$$

$$\chi = \frac{1}{2}[\sin a + \sin(a + u)] + \frac{1}{2}[\frac{u - \sin u}{\cos a - \cos(a + u)}] \qquad (3)$$

$$u = \arccos(\cos a - \sqrt{\frac{2}{3}} X_c \frac{I_d}{U_c}) - a \quad 0 \le u \le \frac{\pi}{6} \qquad (4)$$

Figure 8. Circuit equivalent of a line commutated converter

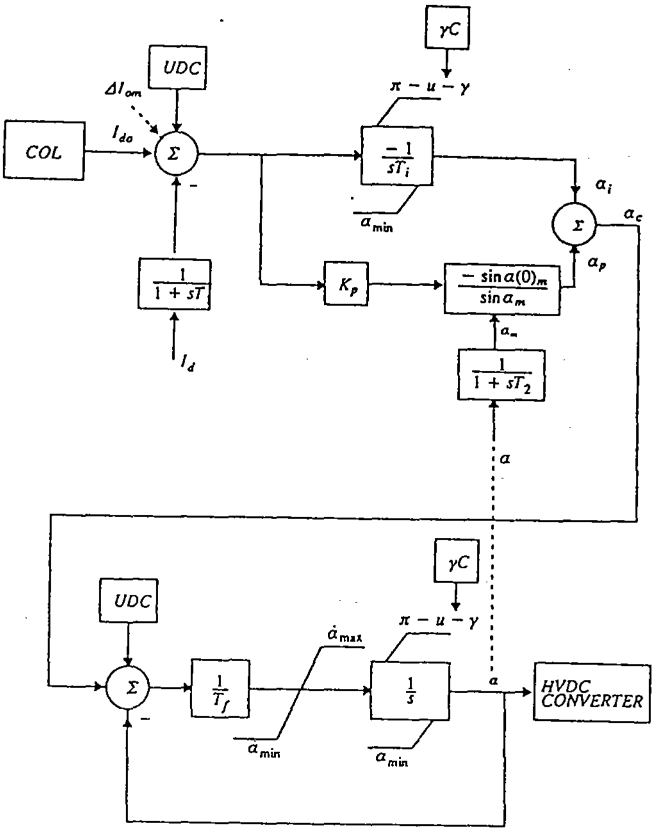


Figure 9. Converter Firing and Current Controller

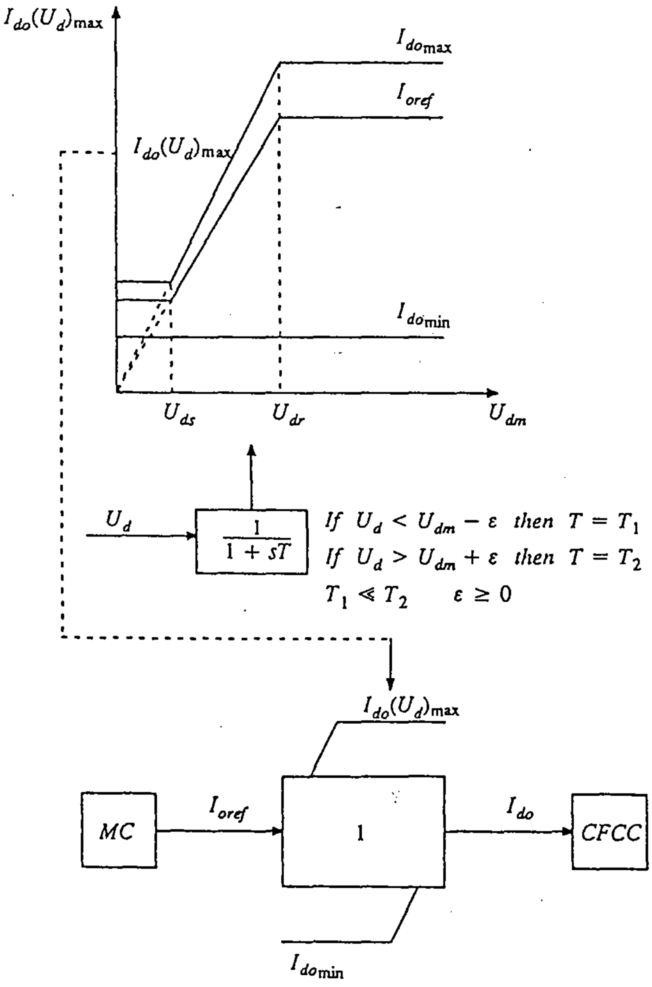
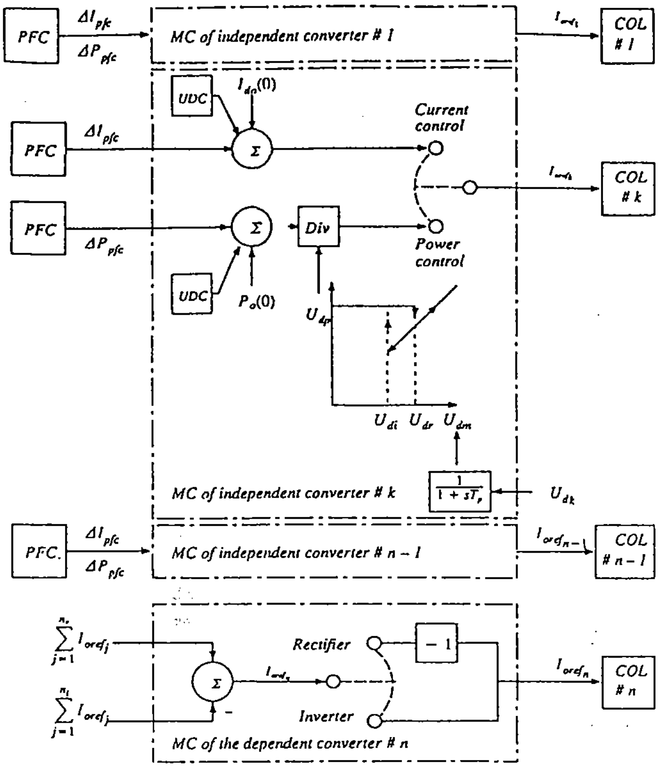


Figure 10. Current Order Limiter



$n_r =$ number of independent rectifiers
$n_i = n - n_r - 1 =$ number of independent inverters
$n =$ total number of converters

Figure 11. Master Controller of an HVDC system with parallel converters

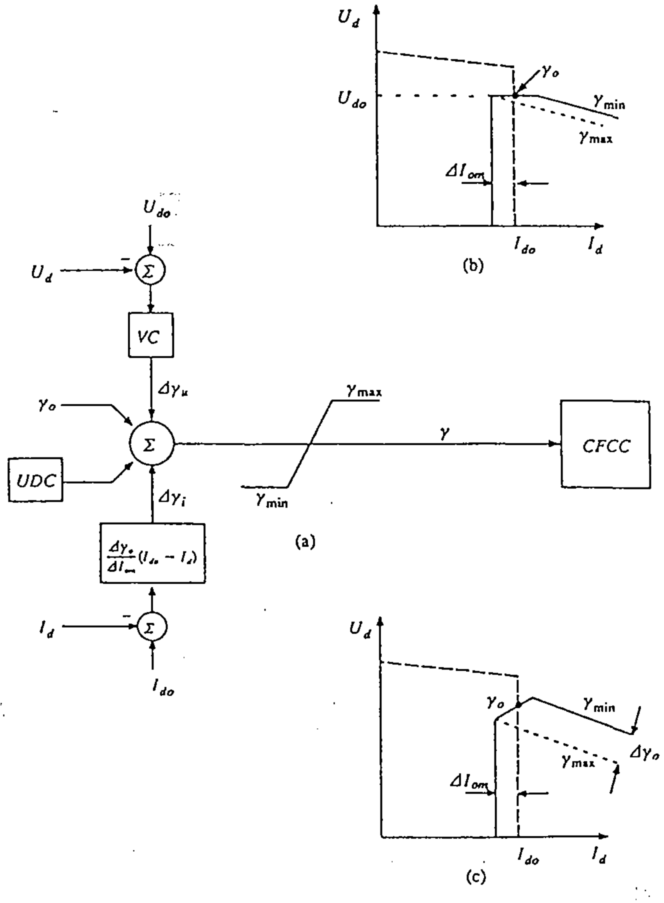


Figure 12. γ - Controller

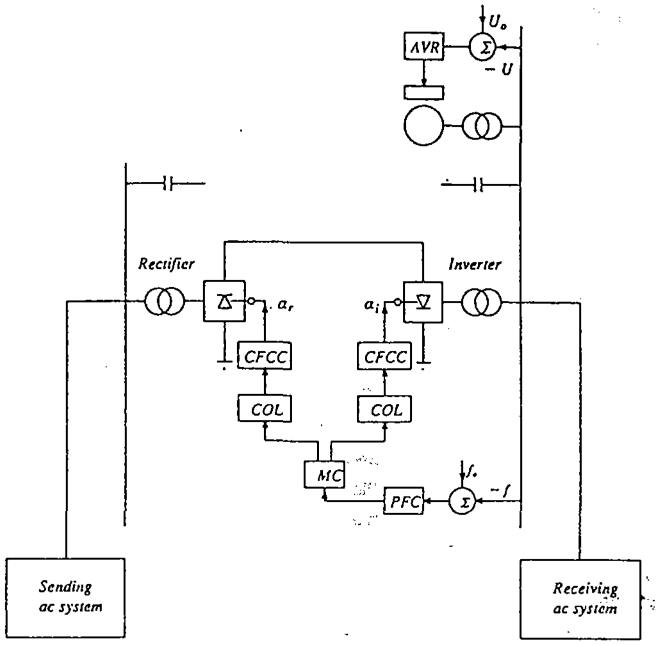
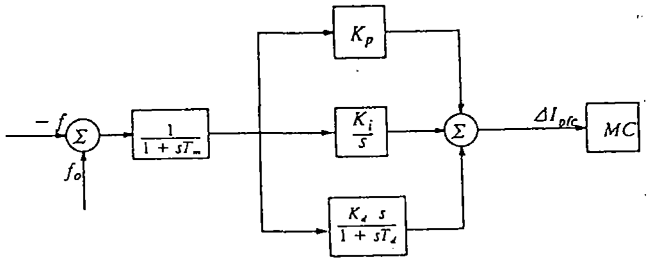


Figure 13. Application example

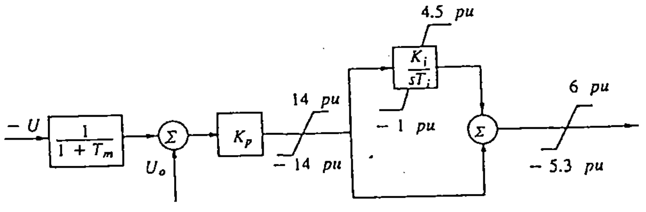


$T_m = 0.050\ s \quad K_p = 0.12\ pu\ of\ I_{dn}\ /\ Hz$

$K_d = 0.08\ pu\ of\ I_{dn}\ s\ /\ Hz \qquad T_d = 0.040\ s$

$K_i = 0.106\ pu\ of\ I_{dn}\ /\ Hz\ /\ s$

Figure 14. Frequency regulator



$T_m = 0.026\ s \quad K_p = 50.\ pu/pu \qquad K_i = 1.\ pu/pu \qquad T_i = 4.\ s$

Figure 15. Voltage regulator

APPENDIX XI
STATIC CONTROL CHARACTERISTICS FOR GENERATORS, SYNCHRONOUS CONDENSERS AND SVC

by J. Falck Christensen and T. Østrup, Denmark

XI.1 QU DIAGRAM FOR A TURBO-GENERATOR

In case of changes in a network, for example due to a fault, the active power of a turbogenerator often does not change. It is normally the voltage and the reactive power which are affected. Therefore, for many investigations on power systems, QU diagrams showing the reactive power production capability as a function of the voltage but with fixed active power are more suitable than the PQ diagrams.

The area with the possible stationary operating points for a given active power are bounded by three curves. These are the rotor current limit, the stator current limit and the rotor angle limit. (Minimum rotor current is not taken into account).

The rotor current limit will often determine the maximum reactive power production. However, for high active power production or low terminal voltage, the maximum reactive power production will be determined by the stator current limit. This is a disadvantage because while the rotor current limits are neary vertical curves, the stator current limits are rather flat curves. This means that small voltage variations can give large changes in the possible range for reactive power production.

The minimum reactive power production is determined by the rotor angle limiter. This limit is normally only of interest for high system voltages.

For a turbo-generator with high active power load, the possible range of reactive power production can become very small if the voltage becomes low.

XI.2 REACTIVE POWER PRODUCTION SEEN FROM THE NETWORK SIDE OF THE GENERATOR TRANSFORMER

Figure 1 shows examples of QU diagrams for the network side of a typical generator transformer with a reactance of 0.12 p.u. and a turns ratio of 1.

In Figure 1 are also shown curves for constant terminal voltage for the generator. These are nearly straight lines and if the voltage regulator keeps the generator terminal voltage constant the operating point of the unit will move along these lines when the network voltage varies until a limit curve is reached. When this happens, the operating point will follow the limit curve if the network voltage changes further.

The diagram for the generator at nominal active load, 0.85 p.u., shows that if the terminal voltage is reduced from 1 p.u. to 0.9 p.u. the possible range for reactive power variation is reduced from a fairly large range of 0.55 p.u. to less than 0.2 p.u.

Firstly, this shows directly that it is important to avoid low generator terminal voltages because this can severely restrict the possibility of the unit to support the network voltage.

Secondly, it indicates the importance of the turns ratio of the generator transformer. Figure 1 is drawn for a turns ratio of 1, but if this is changed it simply corresponds to move from one constant terminal voltage characteristic to another. If only voltage regulation considerations are taken into account it would be advantageous to have a tap changer on the generator transformer. This would make it possible, despite the operating situation, to maintain a generator terminal voltage of about 1 p.u. where the voltage regulation properties are normally best.

At reduced load, the reactive power can vary in wider intervals and the sensitivity to the generator terminal voltage is, although still significant, of less importance.

XI.3 GENERATORS, SYNCHRONOUS CONDENSERS AND STATIC VAR COMPENSATORS

For active voltage support in a system, three components are widely used: generators, synchronous condensers and static var compensators (SVC).

Figure 1 shows also a comparison between the voltage regulating characteristics for these three components seen from the network side of the step-up transformer.

The synchronous condenser has the same size (MVA) as the generator. Maximum rotor current is supposed to be the current at 1 p.u. load and 1 p.u. terminal voltage. Instead of a rotor angle limiter, a limit set by a minimum rotor current of 0.1 p.u. is used.

The SVC has the size of ± 0.5 p.u. The slope of the characteristic in the active range of operation has been chosen similar to those of the generator and synchronous condenser, about 0.12 p.u./p.u.

Comparison shows that the synchronous condenser has the greatest range of reactive power regulation, while the generator at rated active power has the smallest. The generator at 0.5 p.u. active load and the SVC have quite similar ranges of operation. However, it should be noted that the diagrams are for steady state operation. Dynamic properties are commented in the next chapter.

It appears also from Figure 1 that the characteristics for a given terminal or reference voltage have similar shapes in all cases.

XI.4 Dynamic properties

The limits shown in Figure 1 are the steady state limits. Some of these are related to thermal problems and these limits can normally be transgressed for a certain time. This applies to maximum rotor and stator current limits and gives an advantage to the generator and synchronous condenser compared to the SVC in case of low voltage, for instance when a voltage collapse is threatening. The possibility to overload the component even a short time increases the possibilities of counteracting a disturbance. Limits set by rotor angle or minimum rotor current cannot be exceeded.

Supervision of the reactive power production from a device and of its actual distance to the limits can provide valuable indications in case of low voltage, whether a voltage collapse is threatening or not.

Reduction of active power from a generator to obtain a larger range for reactive power production is of questionable value. To counteract a voltage collapse, the reactive power reserves must be present in the critical area where the lowest voltage occurs. Reduction of active power production in this area will increase the power import into the area and this can cause a disastrous development of the voltage collapse.

XI.5 CONCLUSION

A full loaded (0.85 p.u.) turbo-generator will normally have a rather small range for reactive power production, especially if the terminal voltage becomes low. Therefore, the turns ratio of the generator transformer becomes an important parameter. Also, therefore, the steady state voltage regulating properties of a full loaded turbo-generator is not necessarily better than that of a static var compensator at low voltages. However, the generator has an overload capability which can be used for shorter periods, and at reduced load a large reactive power range can be available even at low voltages.

XI.6 LITERATURE

[1]: "Reactive Power Production Capability Chart of a Generator" by T. Østrup, NTUA/IEEE Joint International Power Conference, September 1993, Athens.

[2]: Reactive Power Sources" by M. Erche and T. Peterson. (App. 1 of Reactive-Power comparison analysis and planning procedure). CIGRE TF 38-01-03, 1989.

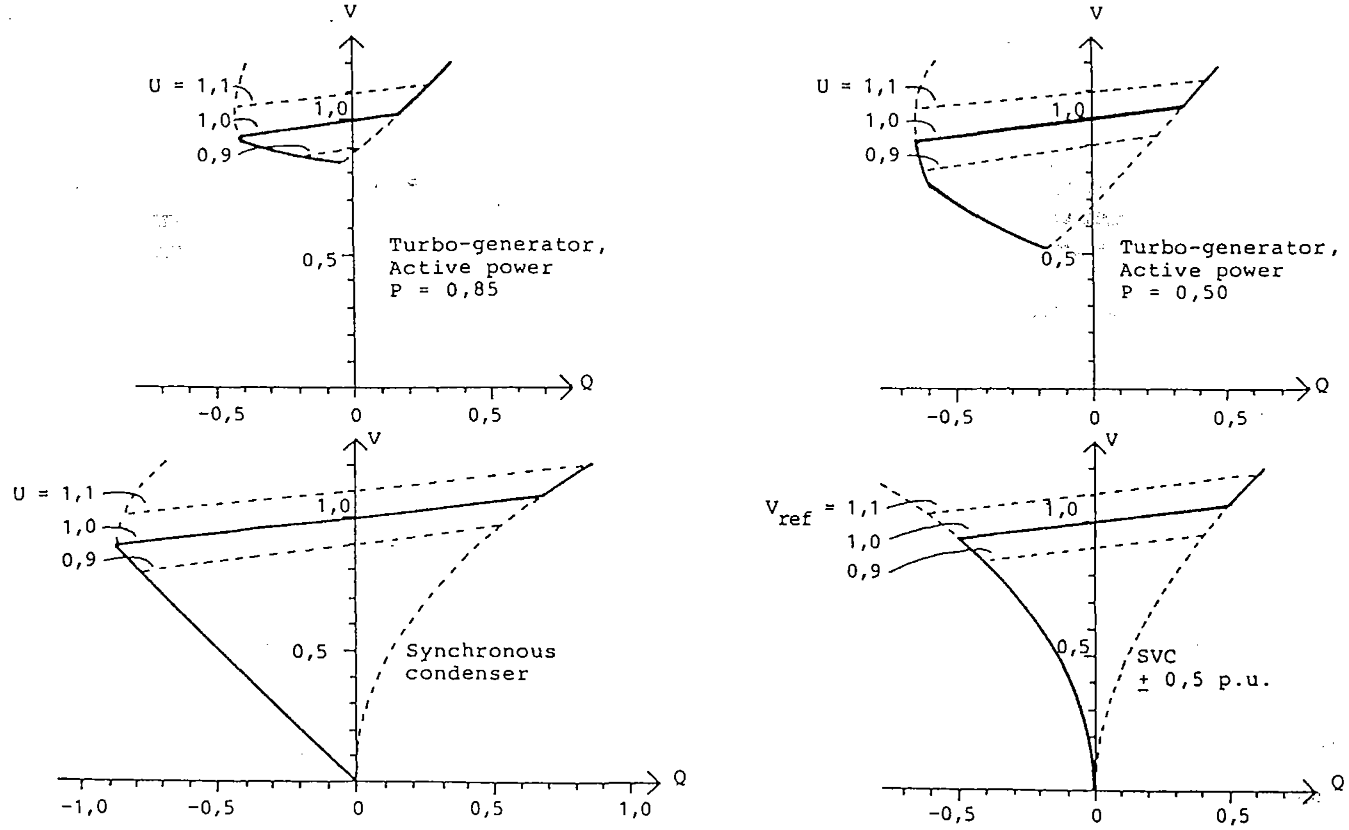


Figure 1. Voltage-reactive power diagrams for turbo-generator, synchronous condenser and SVC. The values are for the network side of the unit transformer. Positive Q is absorbed reactive power. The full-drawn curves are for generator voltage U or SVC reference $V_{ref} = 1$.

APPENDIX XII

INCREASE OF THE REACTIVE POWER CONTROL RANGE OF A DC CONVERTER

by T. Østrup, Denmark

XII.1 REACTIVE POWER CONTROL RANGE OF A DC CONVERTER

For a given active power transfer, the minimum reactive power consumption of a converter is determined by the minimum control angle, α for the rectifier, γ for the inverter. Normally, the converter is designed to absorb as little reactive power as possible. The maximum reactive power consumption is determined either by a maximum allowable control angle or a maximum allowable AC voltage across the valves, a voltage proportional to the quantity U_{dio}. For a typical DC link designed as described in litt. [1] without special reactive power control possibilities, the reactive power control range at full active power load is small for the rectifier and zero for the inverter.

XII.2 POSSIBILITIES TO INCREASE THE REACTIVE POWER CONTROL RANGE

If the reactive power control range is limited by the maximum allowable U_{dio} the Mvar control range can be increased by reducing the DC voltage, U_d. This makes it possible to use a larger control angle, which increases the Mvar consumption. The Mvar consumption is very dependent on the control angle but only to a minor degree on U_d (Litt. [1] and [2]). However, as the DC current, I_d, is increased when U_d is reduced for fixed active power transfer, the method cannot be used at maximum active power transfer. Further, use of increased control angle and reduced voltage have some drawbacks, such as increased harmonics and increased losses.

The increased Mvar range can also be achieved if the converter is designed for an increased maximum U_{dio}. Thereby the control angles and the Mvar absorption can be increased without a decrease in U_d.

A Mvar range at 1 p.u. active power transfer can also be obtained by dimensioning the DC link slightly larger. This will only give a relatively small Mvar range and for smaller active power transfers, the Mvar range is unchanged. It might therefore be desirable to combine the increased rating with the increased maximum U_{dio} or with operation at reduced U_d. The solution might be of interest where an extra amount of active power transfer is needed only a small part of the year or at a later stage in the future.

As long as U_d and I_d are not affected, the two converters of a DC link can be designed independently of one another with regard to Mvar control. Therefore, it is possible to dimension only one of the converters for an increased Mvar control range. This will then typically be a converter in a weak network and this will often be the inverter.

XII.3 SYSTEM NEEDS TRANSFERRED TO THE PQ CONVERTER DIAGRAM

Figure 1 shows a PQ diagram for an inverter designed according to litt. [1]. As curves for constant γ and for constant U_{dio} are nearly equal, the figure does not distinguish between these.

The three limit curves for the normally designed converter with $U_d = 1$ are
($S = \sqrt{P^2 + Q^2}$):

$\gamma min = 16°$
$U_{diomax} = 1.05 \cdot U_{dioN}$
$S = 1.11$ p.u.

The Mvar control range is zero for an active power transfer, P, of 1 p.u. where the reactive power, Q, is 0.48 p.u. It appears from the figure that for P = 1 p.u. the maximum Mvar control range that can be obtained for $U_d = 1$ and $U_{diomax} = 1.05 \cdot U_{dioN}$ is 0.12 p.u. independently of how large the plant is made.

In the following, a system need of 0,25 p.u. Mvar control range at P = 1 p.u. is presumed.

In figure 1, the desired possible operating point with P = 1 p.u. and Q = 0.48 + 0.25 = 0.73 p.u. is indicated together with the constant U_{dio} curve through this point. With U_d kept at 1 p.u., U_{dio} becomes $1.12 \cdot U_{dioN} \cdot \gamma$ is about 32°. For a converter designed for this U_{diomax} and with unchanged maximum I_d, the limit curves with $U_d = 1$ become:

$\gamma min = 16°$
$U_{diomax} = 1.12 \cdot U_{dioN}$
P = 1 p.u.

If the total plant is designed for the apparent power in the former mentioned operating point, P = 1 p.u., Q = 0.73 p.u. the maximum active power transfer is found as the intersection between the constant apparent power S = 1.24 p.u. circle and the γmin = 16° curve. This gives a new nominal active power P = 1.11 p.u. The limit curves for this converter become:

γmin = 16°
$U_{diomax} = 1.12 \cdot U_{dioN}$
S = 1.24 p.u.

The operating point P = 1 p.u., Q = 0.73 p.u. can be obtained with $U_{diomax} = 1.05 \cdot U_{dioN}$ by reducing U_d to 0.93 p.u. The I_d becomes 1.08 p.u. in this operating point. In figure 1, the curve for U_d = 0.93 p.u., $U_{dio} = 1.05 \cdot U_{dioN}$ is nearly identical to the curve for U_d = 1 p.u., $U_{dio} = 1.12 \cdot U_{dioN}$.

It would be natural to design the converter to be able to fully utilize the I_d = 1.08 p.u. also for U_d = 1 p.u. This will give a converter with maximum P = 1.08 p.u. However for P = 1.08 p.u., the voltage cannot be reduced, as I_d may not be increased further. An $U_{diomax} = 1.05 \cdot U_{dioN}$ gives a maximum reactive power absorption of 0.66 p.u. at P = 1.08 p.u. and a nominal apparent power of 1.27 p.u. Between P = 1 and 1.08 p.u., the minimum allowed U_d must be gradually increased from 0.93 to 1 p.u. in order to avoid an I_d greater than 1.08 p.u. The limit curves for this converter become:

γmin = 16°
$U_{diomax} = 1.05 \cdot U_{dioN}$ with U_d = 0.93 p.u.
I_d = 1.08 p.u. with $U_{diomax} = 1.05 \cdot U_{dioN}$
P = 1.08 p.u.

The illustrated methods to obtain an increased Mvar control capability are just examples. The possibilities and the most suitable ways to obtain a desired Mvar range will depend on the actual construction of a given converter. If the Mvar control is only needed for a limited time in critical situations, it may be possible to use an overload capability of the converter instead of a converter designed for continuous operation with increased Mvar absorption.

XII.4 SUMMARY

The report shows examples of how to obtain a desired Mvar control range of 0.25 p.u. for an inverter operating at a given active power transfer of 1 p.u. Increased AC voltage across the valves, increased rating of the converter and operation at reduced DC voltage have been used.

Figure 2 shows the possible areas of operation for the examples.

XII.5 LITERATURE

[1]: "Reactive power control in HVDC. Capability of reactive absorption in HVDC converters", Göte Liss and Ture Adielson, Sweden. Appendix I in this brochure.

[2]: "Reactive power capability diagram for a DC converter", Torben Østrup, Denmark. Appendix II in this brochure.

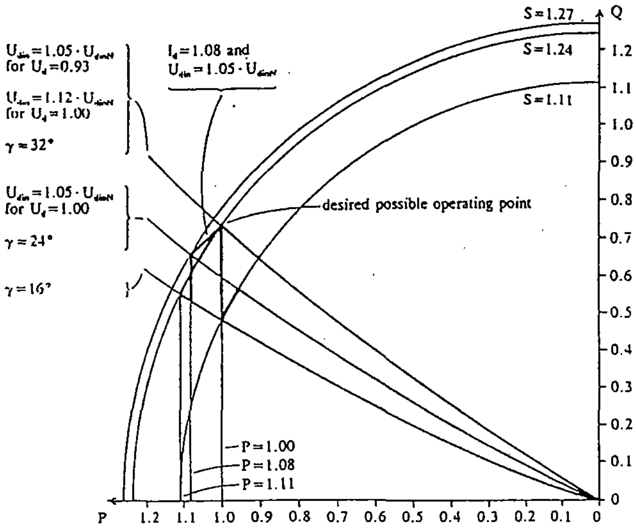


Figure 1. Limit curves in a PQ diagram for an inverter. γmin = 16°

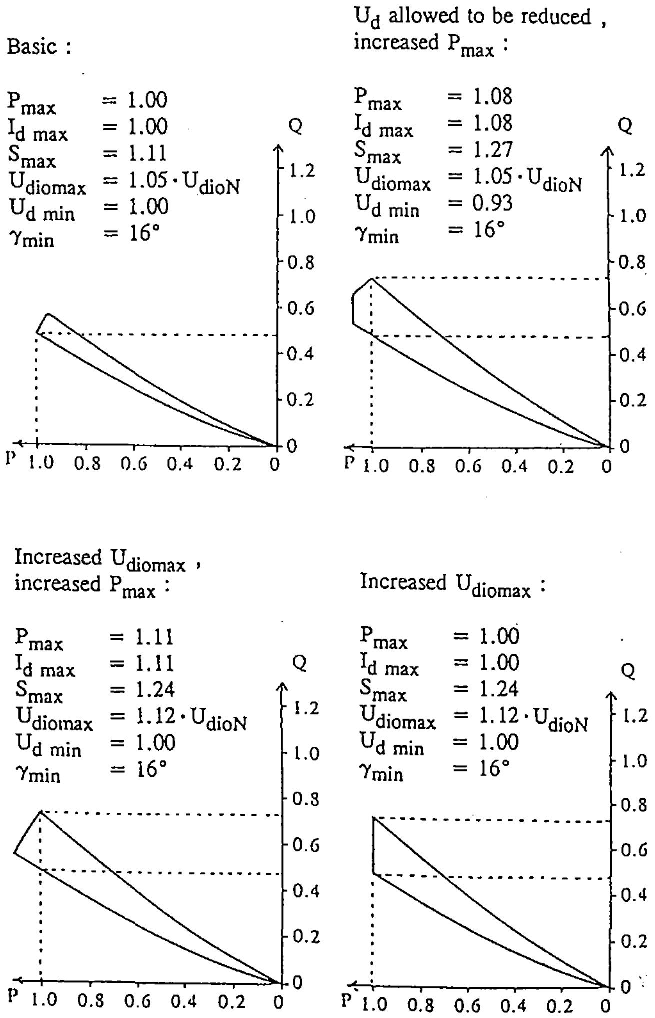


Figure 2. PQ-diagrams for an inverter.
Basic design plus three designs with a Q control range of 0.25 for a P of 1.00.

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