BASIC OPERATION CHARACTERISTICS OF CAPACITOR COMMUTATED CONVERTERS

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Abstract - Most of the recent HVDC systems consist of line commutated converters. The demand of reactive power is supplied by filter or capacitor banks which are connected on the primary side of the converter transformer. This conventional design is well known and proven during last decades. However, such conventional converters suffer commutation failures when they operate as inverter at a weak AC system.

A series capacitor between converter transformer and thyristor valves (CCC: Capacitor Commutated Converter) can improve the immunity of inverter against commutation failure. This paper investigates the CCC design which only demands a little enhancement of the conventional design but with additional advantages. The CCC concept is applied to a modern HVDC Back-to-Back scheme. The basic steady state characteristics are analyzed under various practical design aspects. Digital simulations are performed to confirm some basic behavior of CCC converter. The goal of this study to determine basic relationships between the main design parameters of a CCC converter with focus on the industry applications.

Keywords - HVDC, CCC, Series capacitor

1 INTRODUCTION

The current design of HVDC systems based on 6-pulse line commutated converter bridges is well proven but has some disadvantages. The strong dependence to the line commutation voltage makes the conventional converter sensitive to commutation failures. Large filter banks are required for the compensation of the consumed reactive power, which may cause high over voltages in case of sudden load rejection and weak AC system. HVDC links connected to weak AC networks need special design to avoid frequent commutation failures.

To prevent or minimize the previously mentioned disadvantages, there have been various design modifications of the conventional converter proposed in the past. Back in the late 60's there was concept modification presented in [1], called the Capacitor-Commutated-Converter (CCC). This concept was selected for this investigation, because it is only a small enhancement of the conventional converter design, by inserting series capacitors between the converter transformer and the graze bridge as shown in figure 1, but has significant advantages in the practical operation.

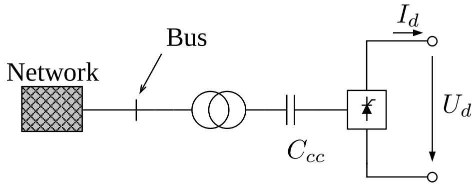

Figure 1: CCC converter concept

2 THE CCC BASICS

The major motive for using the converter concept with series capacitors is to provide additional commutation voltage and for the reduction of reactive power. In contrast to HVDC-converters using the conventional design, with switchable shunt-capacitor banks on the primary converter-transformer side, here the capacitors are connected in series directly between the transformer and the converter-bridge as can be seen in fig. 1.

Due to their electrical position, the series capacitors directly take influence on the voltage of the commutation circuit and therefore to the commutation process itself.

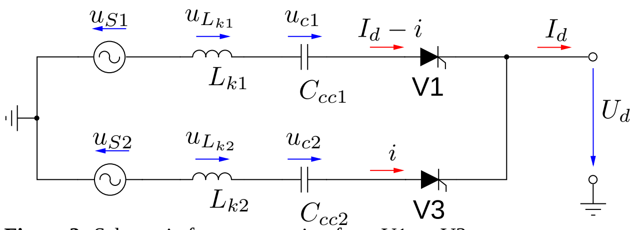

Figure 2: Schematic for commutation from V1 → V3

According to the above shown circuit, valid for the commutation from valve V1 to V3, of the CCC converter its basic operation behavior during commutation can be investigated. Assume i as the increasing current of the on-going valve V3 leads to an decreasing current $I_d - i$ of the off-going valve V1. Therefore the potential difference of the inductance of the transformer ($u_{L_{k1}}$) has changed sign and thus the transformer inductance L_{k1} and L_{k2} can mathematically be combined into one term $2L_k$ (assuming both transformer reactances are balanced). However, during commutation process both phase-voltages u_{S1} and u_{S2} can also be interpreted as the line voltage (U_L). This results into the following DEq:

$$i'' + \frac{i}{L_k C_{cc}} = \frac{I_d}{2L_k C_{cc}} - \frac{U_L\ \omega}{\sqrt{2}\ L_k} \cos(\omega t + \alpha_N) \quad (1)$$

One solution of this DEq with the initial condition $i(\omega t = \mu/\omega) = 0$ for the current at the end of the commutation process (period μ) of the off-going valve V1 futures the first basic CCC-equation:

$$A\ \cos\left(\frac{\omega_0}{\omega}\mu\right)+B\ \sin\left(\frac{\omega_0}{\omega}\mu\right)+\frac{I_d}{2}- \\ -\frac{\sqrt{2}\,U_L\,\omega}{2L_k(\omega_0^2-\omega^2)}\cos(\alpha_N+\mu)=0 \quad (2)$$

To determine the constant A the DEq is solved under the initial condition $i(\omega t=0)=I_d$ at the beginning of the commutation process, which gives:

$$A=\frac{I_d}{2}+\frac{\sqrt{2}\,U_L}{2L_k(\omega_0^2-\omega^2)}\cos\left(\alpha_N\right) \quad (3)$$

Because of series connection, the line current of the converter-bridge is the charging current of the series capacitors. A positive line current will charge the capacitor to its positive maximum ($\hat{u}_c$) and vice versa according to figure 3.

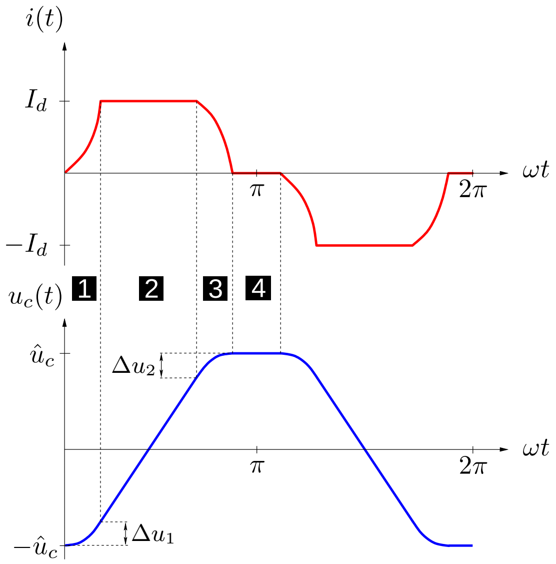

Figure 3: Current & voltage at capacitor

This charging procedure is of linear mode (during time-section 2) with the exception of the commutation margin μ. During this period (e.g. 1 and 3) non-linear charging of the capacitors is done. Additionally, this non-linear charging is different for on- and off-going current due to fact that on- and off-going currents are different. Therefore the non-linear timevariant part of the capacitor voltage is named Δu_1 for the on-going and Δu_2 for the off-going charging period μ.

Considering Kirchhoff's law, one can write for the commutation circuit presented in figure 2 (see also its description):

$$u_{S1S2}+2L_k\frac{di}{dt}+u_{c2}-u_{c1}=0 \quad (4)$$

By using the initial conditions of the capacitor voltages at the beginning of the commutation process, one next solution of the DEq delivers constant B. At the beginning of the commutation procedure form valve V1 to V3 capacitor C_{cc1} is at the end of the positive linear charging process 2. Following up is the non-linear charging of the off-going current, which finally charges the capacitor to $+\hat{u}_c$. However, at the beginning of the commutation procedure C_{cc1} is therefore charged to $u_{c1}=\hat{u}_c-\Delta u_2$.

Capacitor C_{cc2} has reached the end of the non charging periode during valve V3 was not conducting. Up to that state it has been charged to its negative maximum (beginning of time-section 1), this means it is charged to $u_{c2}=-\hat{u}_c$. Now one solution of the DEq yields the second constant B:

$$B=\frac{\pi\ I_d}{3\left(\frac{\omega}{\omega_0}\right)}-\frac{\Delta u_2}{2L_k\omega_0}-\frac{\sqrt{2}\,U_L\,\omega_0}{2L_k(\omega_0^2-\omega^2)}\sin(\alpha_N) \quad (5)$$

Practical computation of constant B is difficult due to the presence of the unknown variable Δu_2. This unknown can be eliminated with help of the initial conditions of the capacitor voltage at the end of the commutation process (see also figure 3). At this instant capacitor C_{cc1} is charged to its maximum positive voltage $u_{c1}=+\hat{u}_c$ (end of time-section 3). While capacitor C_{cc2} is at the end of the non-linear charging period 1 and thus charged to $u_{c2}=-\hat{u}_c+\Delta u_1$. Theses initial conditions yield to the solution of the DEq:

$$-\ A\ \sin\left(\frac{\omega_0}{\omega}\mu\right)+B\ \cos\left(\frac{\omega_0}{\omega}\mu\right)+ \\ +\frac{\sqrt{2}\,U_L\,\omega_0}{2L_k(\omega_0^2-\omega^2)}\sin(\alpha_N+\mu)- \\ -\frac{2\,\frac{\pi}{3}\frac{I_d}{\omega\ C_{cc}}-\Delta u_1}{2\ \omega_0\ L_k}=0 \quad (6)$$

Analysis of the above shown equation makes clear, that one of both variables (Δu_1 or Δu_2) is always present in the CCC equation. Its connection can be computed via the overall capacitor voltage $2\hat{u}_c$ which is splitted into three sections. Two non-linear components Δu_1 and Δu_2 and one linear component between two overlap-intervals ($\mu<\omega t<2\pi/3$). Therefore one of both variables can be expressed by:

$$\Delta u_2=\frac{I_d\ \mu}{\omega\ C_{cc}}-\Delta u_1 \quad (7)$$

The series capacitors consequently produce a voltage phase-shift relatively to the supply voltage ("U_1" at fig. 4). This phase-shift is not a constant value due to the fact that the capacitors are charged by the non-constant line-current i of the converter bridge. This line-current itself is in general dependently from the firing-angle α and the overlap-angle μ.

Due to the phase-shifting effect of the series capacitors it is necessary to differ between transformer-side and valve-side angles. Therefore transformer-side values are abbreviated "N" and valve-side values are indexed "V". The phase shifting of the voltage is the main advantage of the CCC converter concept, especially for the inverter mode of operation. It is possible to operate the CCC-inverter at higher ($\alpha_N > 150°$) firing-angles than the conventional inverter, while the extinction angle at valves can be kept at same value. Higher firing angles at inverter result in a lower consumption of reactive power according to the conventional converter theory (see also fig. 5).

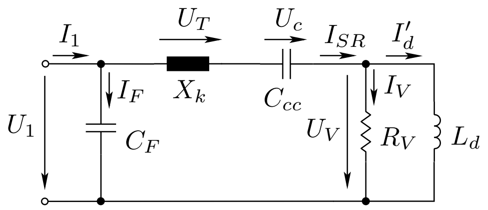

Figure 4: The CCC-converter's single-phase schematic

The general differences between the conventional converter and the CCC-concept are also presented in fig. 5. Usually the series-capacitor (C_{cc}) compensates the converter-transformer reactance (X_k). Therefore the valve-voltage (U_V) is higher than the network-voltage (U_1) and phase-shifted towards the line-current, which leads to a low power-factor (φ).

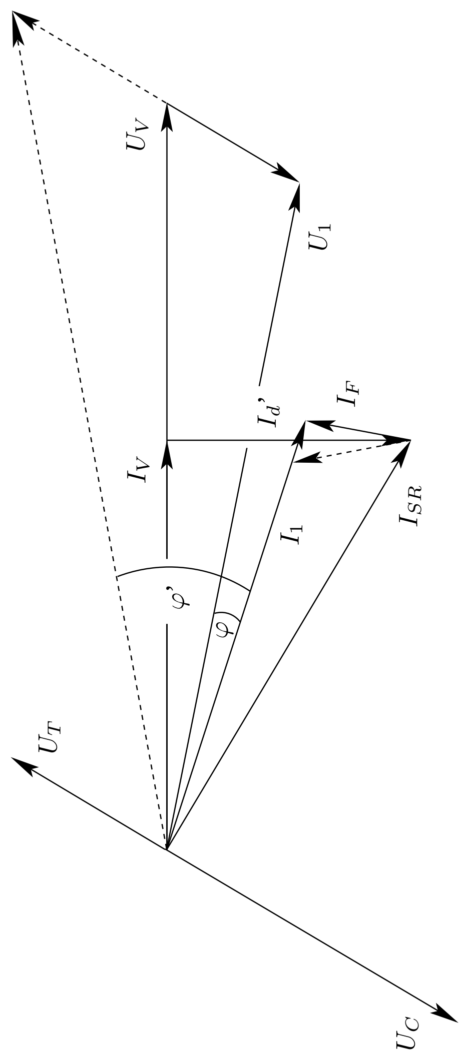

Figure 5: Vector-diagram of the CCC-converter

For the purpose of comparison the voltages of the conventional converter are plotted in dotted lines. Obviously the power-factor (φ') is much higher than before. Fig. 5 therefore shows the reduced demand for reactive power of the CCC-converter. The short-circuit current of the CCC-converter is much lower ($\approx$ 5 p.u.) than of the conventional converter ($\approx$ 12 p.u.) due to the compensated transformer reactance. This lower "replacement" reactance of the converter transformer causes a reduced overlap-angle, which has a negative impact on the AC current-harmonics. In particular the characteristic harmonics may be significantly higher.

3 Design Criteria

The modified commutation process of the CCC-converter has large impacts on the extinction-angle. This provides substantially improvement for the inverter-mode operation of the converter. Figure 6 shows the line-voltage (u_{L1}, u_{L2}, u_{L3}) and the valve voltage (uv_1, uv_2, uv_3), which is the sum of the line-voltage and the capacitor voltage. It can be seen how the series capacitors shift phase angle of the voltage.

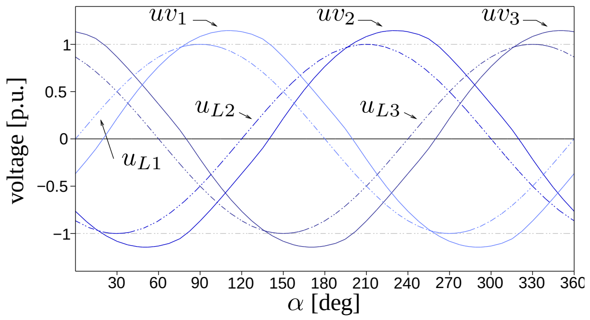

Figure 6: The voltage-shifting process of the CCC-converter

As the extinction angle of valves is referred to the valve voltage (solid-line voltage in fig. 6), it is possible to operate the CCC-inverter at higher firing-angles (α_N) than the conventional inverter, by using the same extinction-angle (γ_V). Higher firing-angles result in a lower consumption of reactive power, but also in a higher direct voltage on the DC-side. As shown in figure 5.

The vector diagram of the CCC-converter in figure 5 shows clearly, that the series capacitors does not only shift the phase angle of valve voltage (U_V), they also increase the magnitude of it, which can also be observed in figure 6. The valves in a CCC will be stressed with a higher voltage. Therefore the value for the series capacitors shall be selected in coordination with other equipment.

Further improvement by the series capacitors is the reduced power rating of the converter transformers, because less reactive power needs to be transmitted. As a result the transformer voltage-ratio has to be adapted accordingly. The smaller the capacitor, the more voltage-shifting is done and more extinction-angle (γ) is "generated" which can be computed by considering the commutation circuit after commutation took place.

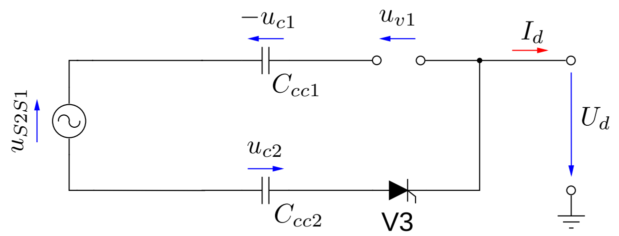

Figure 7: Commutation-circuit after valve V1 is off

Due to the difference between network-side and valve-side one can compute two different extinction-angles. The network-sided is calculated like in conventional converter theory:

$$\gamma_N = \pi - \alpha_N - \mu \tag{8}$$

The valve-sided extinction-angle can be calculated according to figure 7, showing the commutation circuit at the end of the commutation process when valve V1 is off. Voltage differences are displayed according to the positive indication of direction. Kirchhoffs law indicates that $u_{S2S1} + u_{c1} - u_{v1} - u_{c2} = 0$. As analyzed above, in this state capacitor C_{cc1} is charged to its positive maximum $u_{c1} = \hat{u}_c$ but its indication of direction has changed. This has been taken into account by its negative sign in figure 7. The actual voltage of capacitor C_{cc2} depends on the overlap-angle μ:

$$u_{c2} = -\hat{u}_c + \Delta u_1 + \frac{1}{\omega\, C_{cc}} \int_0^{\xi} I_d\, d\omega t \tag{9}$$

Where $0 \leq \xi \leq 2\pi/3 - \mu$. With the line voltage $\sqrt{2}\, U_L\ \sin(\omega t + \alpha_N + \mu)$ and the condition that $u_{v1} = 0$ at $\omega t = \xi = \gamma_V$ because of zero crossing of the valve voltage at this moment, it yields:

$$\sqrt{2}\, U_L\ \sin(\gamma_V + \alpha_N + \mu) + \\ + 2\, \frac{\pi\, I_d}{3\, \omega\, C_{cc}} - \frac{I_d\, \gamma_V}{\omega\, C_{cc}} - \Delta u_1 = 0 \tag{10}$$

Figure 8 illustrates formula (10) and the influence of the capacitor values to the extinction-angle. The increased extinction-angle makes it possible to use larger firing-angles and therefore to reduce the reactive power demand.

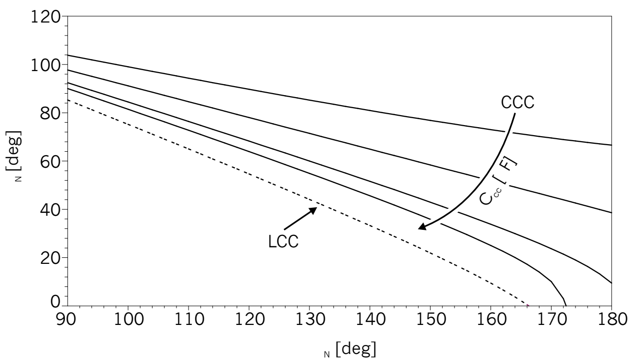

Figure 8: Extinction-angle $\gamma_N = f\,(C_{cc}, \alpha_N)$

Another important point is about the valve-voltage and the arisen problems. If the value for the series-capacitors (C_{cc}) is too low, the voltage at the vales becomes excessive (see fig. 9). If the capacitance is selected too high, the desired benefit of the series compensation disappears and therefore the reactive power demand is as high as the conventional converter. The chapter "DIGITAL SIMULATION" explains the iterative process of selecting the capacitance.

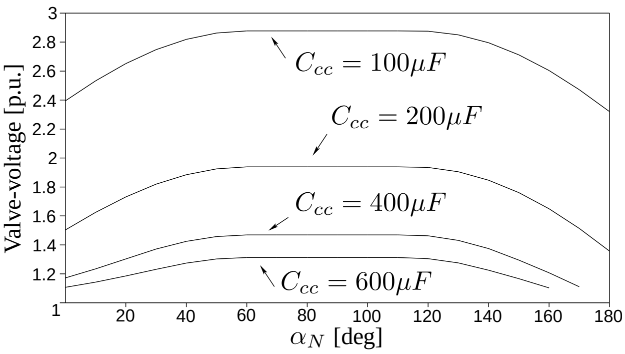

Figure 9: Valve-peak-voltages

Selecting the capacitance for practical operation shall consider the voltage stresses at the valves. On the other hand, the increase of the valve voltage by the series capacitors is partially off set by the transformer ratio. Following example demonstrates this effect: for the CCC converter example described in the next chapter a capacitor value of $C_{cc} = 410\mu F$ leads to an increase of voltage stress of 0.4 p.u. in worst case (see figure 9), but on the other hand the transformer-voltage is reduced by 0.124 p.u. (see also table 1).

Investigations described above analyzed only the AC voltage relations on the series capacitors. There is also a DC voltage contribution U_{db} of the series capacitors. In order to determine DC voltage, the arithmetic mean of the capacitor voltage has to be computed. Figure 3 shows that only time periods ❶to ❸are of interest, ❹gives no contribution because it appears two times each periode 2π with alternating sign.

$$U_{db} = 2 \cdot \frac{3}{2\pi} \left[\frac{1}{2} \int_0^{\mu} u_{c2}(\psi)^{❶} d\psi + \right. \\ \left. + \int_{\mu}^{\frac{2\pi}{3}} u_{c2}(\psi)^{❷} d\psi + \frac{1}{2} \int_0^{\mu} u_{c2}(\psi)^{❸} d\psi \right] \tag{11}$$

Voltage of sections ❶and ❸has to be multiplied by ½ because during commutation procedure capacitor voltage is splitted up into both phases.

$$\begin{aligned} u_{c2}(\psi)^{❶} &= -\hat{u}_c + \frac{1}{\omega\, C_{cc}} \int_0^{\psi} i\; d\omega t \\ u_{c2}(\psi)^{❷} &= -\hat{u}_c + \Delta u_1 + \frac{1}{\omega\, C_{cc}} \int_{\mu}^{\psi} I_d\; d\omega t \qquad (12) \\ u_{c2}(\psi)^{❸} &= \hat{u}_c - \Delta u_2 + \frac{1}{\omega\, C_{cc}} \int_0^{\psi} (I_d - i)\; d\omega t \end{aligned}$$

The DC voltage-contribution of the series-capacitors can therefore be computed according to the formula:

$$U_{db} = \frac{3}{\pi}\left[\left(\frac{2\,\pi}{3} - \mu\right)\Delta u_1 - \frac{\Delta u_2\,\mu}{2} + \right.$$
$$\left. + \frac{I_d\,\mu}{3\,\omega\,C_{cc}}\left(\frac{9\,\mu}{4} - \pi\right)\right] \quad (13)$$

In general, the maximum contribution to the DC voltage occurs at small firing-/extinction-angle for rectifier and inverter operation respectively. Like other voltage drops caused by the inductive and resistive load (e.g. d_x, d_r) the voltage contribution of the series capacitors can be understood as the relative voltage drop $d_{xc} = U_{db}/U_{di}$. This relative voltage contribution can be as high as the resistive voltage drop (d_r) of the converter station or even greater (app. 1%...2% of $U_{DC_{rated}}$), as shown in figure 10.

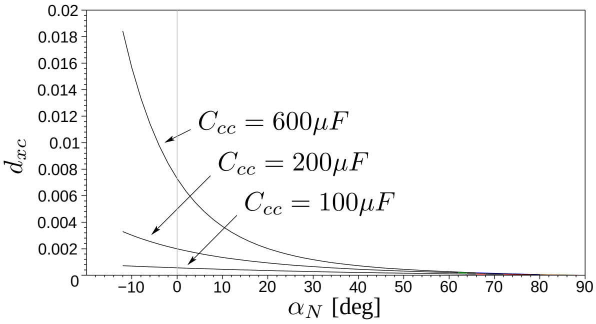

Figure 10: Rel.-Voltage contribution of the series-capacitors

The voltage contribution of the series capacitors can be integrated into the conventional converter theory to calculate the total DC-voltage as follows:

$$U_{d\alpha CCC} = \frac{3\,\sqrt{2}\,U_L}{\pi}\,\left(\cos(\alpha_N) - d_x - d_r + d_{xc}\right) \quad (14)$$

Because the commutation current i of the CCC-converter is no longer a function of the transformer reactance only (resistive component neglected), it can directly be influenced by the value of the series-capacitors C_{cc}. This has a significant impact on the transient current stresses of the valves during a valve short-circuit inside the converter itself. In this case the first complete period of the fault current i is of interest.

The amplitude of the short-circuit current (represented by equation (1) and plotted in fig. 11 for the in chapter "DIGITAL SIMULATION" selected capacitor value) of the CCC-converter is lower than for the conventional (LCC) design. In comparison to the conventional converter, the current of the CCC-converter crosses the zero line much earlier than the conventional converter does. This means, a negative valve voltage occurs much eatlier at the valve than in conventional design. The longer time period of negative valve voltage makes a safe blocking of the valve possible which wouldn't always be secured at the conventional converter.

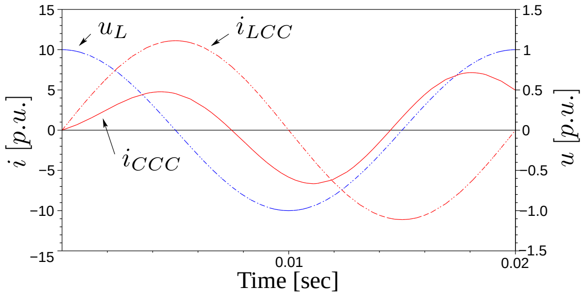

Figure 11: Short-circuit current of converter

Because the transformer-reactance (X_T) and the series capacitor have a resonance frequency, it is important to ensure this resonance frequency at a distance from the values of the fundamental frequency or other harmonic frequencies to avoid high over-currents. Furthermore it is possible to influence the peaks of the short-circuit current directly through the selection of the reactance values. This means it is possible to select the values in order to fit the short-circuit characteristics of the converter to other (e.g. external) conditions.

4 DIGITAL SIMULATION

The basic CCC equations (2), (5), (6) and (7) are used to determine the essential steady state values of a back-to-back link in the CCC configuration. This calculation is done using the software MAPLE and is based on the data of a typical conventional HVDC 500 MW back-to-back station which is now remodeled in the CCC arrangement. The basic calculation data is presented in the appendix.

The HVDC system consists of two six-pulse bridges which are connected in delta-star-configuration to the converter-transformer on the AC side. Because of the DC side series connection of both bridges, the basic values are computed for one six-pulse bridge of the converter only. To get comparable values to the conventional design, the fundamental data of the DC- and AC-side is capped constant.

To make use of the advantages of the series-capacitor design, the reactive power demand of the HVDC converter shall be reduced to about 20% or less of the conventional design at Q=142 MVAr. Additionally, the extinction-angle is increased to about $\gamma_V = 20°$ for more safety margin. This conditions have been computed under the aspects mentioned in the last section "DESIGN CRITERIA". Table 1 shows the calculated steady-state values.

The results of this base-case study show that a series capacitance of $C_{cc} = 410\mu F$ and a firing angle of $\alpha_N \approx 170°$ on the network side of the inverter is required, to reduce the reactive power demand to 20% of the conventional converter. Using the same capacitor for the rectifier operation, at $\alpha_V = 20°$ ($\alpha_N = -7,1°$) the reactive power demand is only about 10 MVAr (app. $7,4\%$). Lower firing angle may even lead to negative reactive power, which means the converter generates reactive power. For this base-case study the CCC-converter uses $C_{cc} = 410\mu F$ with the corresponding angle-relations according to table 1 for the subsequent investigations.

CCC rectifier			
DC voltage:	$U_{d\alpha}$	=	$80,676kV$
AC voltage:	U_{sec}	=	$60,0kV$
Firing-angle:	α_V	=	$20°$
	α_N	=	$-7,1°$
Extinction-angle:	γ_V	=	$142,8°$
	γ_N	=	$170°$
Overlap-angle:	μ	=	$17,2°$
Series-capacitor:	C_{cc}	=	$410\mu F$
DC Power:	P	=	254,1 MW
Reactive Power:	Q	=	10 MVAr
Power-Factor:	φ	=	$2,2°$

CCC inverter			
DC voltage:	$U_{d\alpha}$	=	$-80,676kV$
AC voltage:	U_{sec}	=	$60,0kV$
Firing-angle:	α_V	=	$142,8°$
	α_N	=	$169,9°$
Extinction-angle:	γ_V	=	$20°$
	γ_N	=	$-7,1°$
Overlap-angle:	μ	=	$17,2°$
Series-capacitor:	C_{cc}	=	$410\mu F$
DC Power:	P	=	254,1 MW
Reactive Power:	Q	=	19,4 MVAr
Power-Factor:	φ	=	$4,37°$

Table 1: CCC-converter-data for a steady-state

4.1 Dynamic Response of CCC Converter to Sudden Voltage Steps

For the digital simulation of the dynamic behavior of the CCC-converter the software *EMTDC/PSCAD* was used. The *cigre-benchmark-model* [2] has been used as base and been modified by adding series capacitors. To demonstrate the benefits of the CCC-configuration, the behavior during a commutation-failure has been simulated. The extinction angle at the inverter side of the HVDC link has been monitored. For comparative study, the nominal commutation process of the CCC-inverter is plotted in figure 12.

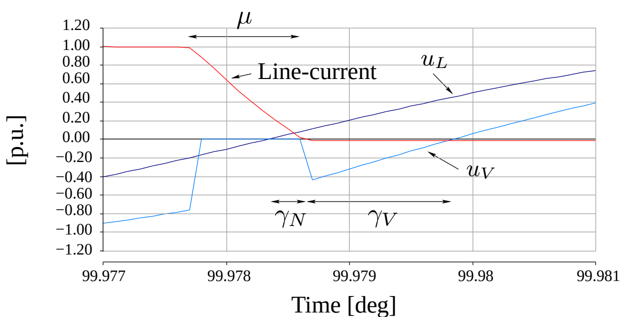

Figure 12: CCC-inverter mode

In most cases, a commutation-failure is caused by a voltage drop on the AC network. Here, the amplitude of the AC network was dropped down of about 8% of $U_{AC_{rated}}$ in the simulation, such voltage reduction may result in commutation failure of conventional converter.

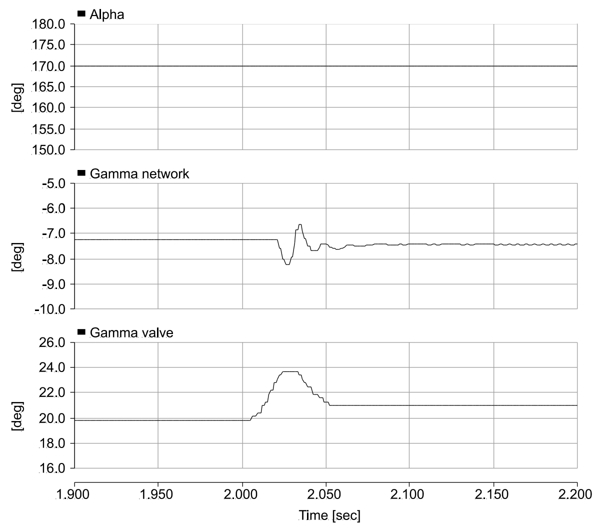

Figure 13: Graph of AC voltage-drop reaction of the CCC-converter

For this simulation the firing-angle (α = “Alpha” at fig. 13) is kept constant to make the impact of the voltage-drop on the extinction-angle (γ_V = “Gamma valve” at fig. 13) more obvious.

As can be seen in figure 13, the voltage-drop increases the valve-sided extinction-angle of the CCC-converter. This happens because the reduced AC-voltage results in an increasing of DC line current, as the DC-voltage at rectifier is controlled at constant value. The increased line current influences the charging of the series-capacitors. The voltage contribution of the series-capacitors to the valve voltage becomes higher. The series-capacitors add more voltage to the commutation-process which results in a more shifted supply voltage inside the commutation circuit than before and consequently the extinction-angle is increased.

In contrast to the conventional converter the AC voltage drop here does not cause a commutation-failure because the extinction-angle was increased by the CCC-inverter itself. This operational behavior makes the CCC-converter suitable and attractive especially for weak AC networks.

4.2 Steady State Reactive Demand of CCC at Various Loads

It is known for the conventional HVDC converter that the reactive demand is approximately 50% of the active DC load. However, for the CCC converter the steady state reactive power demand can be kept at low value over the whole load range. For this reason the reactive power demand was monitored on the AC side of the inverter for different loads during simulation.

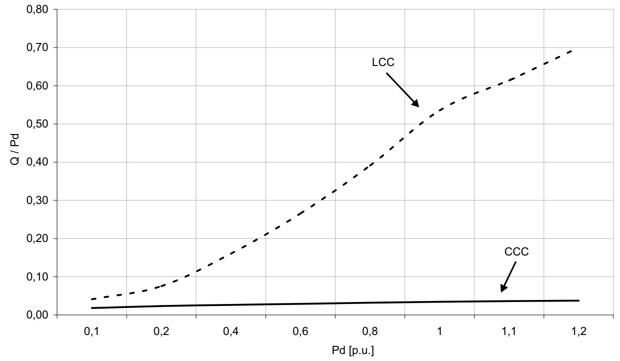

Figure 14: Reactive power demand of the CCC-converter

It can be seen, that even large changes in the transmitted DC power do not actually effect the reactive power demand of the CCC-converter in contrast to the conventional converter. Conventional converters use large filter banks on the AC-side of the converter transformer for the compensation of the reactive power. These capacitor filter banks are only stepwise switch-able in relation to the reactive power demand and may result unfavorable voltage steps at switching. The CCC-converter can avoid this problem due to its relative constant and low reactive power demand, which only needs small filter banks and switching is likely not needed.

4.3 HARMONIC CURRENTS OF CCC

The Fourier-analysis of the phase current is done for one phase only due to the symmetry between the phases. The results of the Fourier-analysis is presented in figure 15.

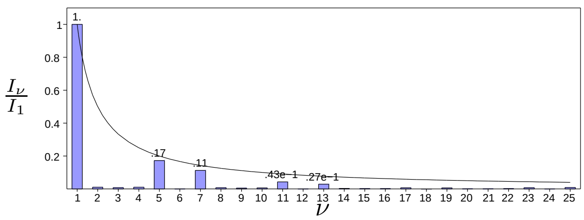

Figure 15: Fourier-analysis of the line current

As stated in the previous sections, the harmonics have “relative” high amplitudes and in fact theses amplitudes are quit near to the worst case of zero overlap-angle (for comparison with the relation $I_\nu/I_1 = 1/\nu$, displayed in fig. 15 as solid line). The increased harmonic currents may require more effort for harmonic filtering such as sharply tuned filters or active filters.

5 CONCLUSIONS

The series capacitor in a CCC converter shows substantial impact on the commutation process. Analysis of its basic behavior showed that CCC provides advantages for practical operation in spite of some side effects.

A set of basic CCC equations has been affiliated from the commutation process and was analyzed under practical aspects in detail to be able to calculate basic parameters for a preferred steady state.

The reduced overlap-angle, derived from the influence of the series capacitors to the commutation procedure, causes higher harmonic currents than the conventional converter does. The phase shifting of voltage due to the series-capacitors gives the possibility of using greater or smaller (inverter or rectifier respectively) firing-angles for a low reactive power demand. This demand of reactive power remains even low during large changes in transmitted DC power. Because of the small reactive power demand, smaller AC filters can be used which has positive impact on the voltage steps at switching.

Another feature of the CCC-converter for practical operation is its inherent immunity against commutation-failures caused by voltage drops of the AC network, which has been demonstrated by simulation in this paper. This behavior favors the selection of the CCC-concept to be used in HVDC links connected to weak AC networks.

The CCC-converter concept complements well to the conventional converter design.

6 APPENDIX

Acknowledgment: The results presented in this paper are mainly from a bachelor thesis from Uni. Flensburg, Germany. The major part of work has been carried out in Siemens, Power Transmission and Distribution Group, in Erlangen Germany.

Fundamental calculation data of the conventional converter:

			rec.	inv.
DC Power	P_d	MW	252	250
DC current	I_d	A	3150	3150
DC voltage	$U_{d\alpha}$	kV	80	80
Firing-angle	α	deg	15	
Extinction-angle	γ	deg		17
Overlap-angle	μ	deg	23	22
Trans. leakage	u_k	%	0,18	0,18
Ind. voltage drop	d_x	%	0,09	0,09
Res. voltage drop	d_r	%	0,004	0,004
Overall volt. drop	$d_{x\ tot}$	%	0,094	0,094
Trans. rated power	S_n	MVA	305	305
Sec. trans. voltage	U_{sec}	kV	68,5	68,5
Pri. trans. voltage	U_{pri}	kV	400	400
Frequency	f	Hz	50	50
Reactive-power	Q_{DC}	MVAr	135	142

Symbols:

U_d	DC-voltage	Q	Reactive power
U_L	Line-voltage	P_d	Active power
I_d	DC-current	ω_0	$1/\sqrt{L_k C_{cc}}$
L_d	Smoothing-reactance (DC)		
L_k	Transformer-inductance		
R_V	Resistant for simulation of converter losses		

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