Capacitor commutated converters for HVDC systems

HVDC 2000 is the name given by ABB to a new generation of high-voltage DC power transmission systems based on the capacitor commutated converter, or CCC. The concept, which has been mainly of academic interest for many years, has now become reality on account of numerous special features offered by the CCC. Capacitor commutated converters perform better than conventional converters and are less sensitive to AC system disturbances.

Essentially, the CCC is an HVDC converter with a commutation capacitor between the converter transformer and the valve bridge **1**. With this configuration, the capacitor stresses are low as both the operating current and the overcurrents are controlled by the valve bridge.

Main advantages of the CCC

Operation of the CCC is based on the principle that the commutation capacitors make an additional contribution to the commutation voltages of the valves. As a result of this additional contribution, considerably less reactive power is required by the converter. The shunt capacitors needed to supply additional reactive power can be reduced to a small filter bank.

ABB recently developed a new method for the automatic tuning of harmonic filters, thanks to which the converter harmonics can also be filtered using a filter bank that generates only a low reactive power. The CCC concept and the new, tuned filter therefore make an ideal combination [1].

The small filter bank provides the required reactive power compensation over the entire operating range from minimum to maximum load. As a result, there is no need to switch filter banks in and out of circuit, as is the case with a conventional converter **2**.

The reactive power consumption of a conventional HVDC system is much higher than that of a CCC-based system. Compensation is provided by switching an appropriate number of filter units into the circuit. Normally, the size of the units in a filter or capacitor bank is restricted by the system requirements. The unbalance is not normally allowed to exceed a specified tolerance range.

Per-Erik Björklund
Tomas Jonsson
ABB Power Systems

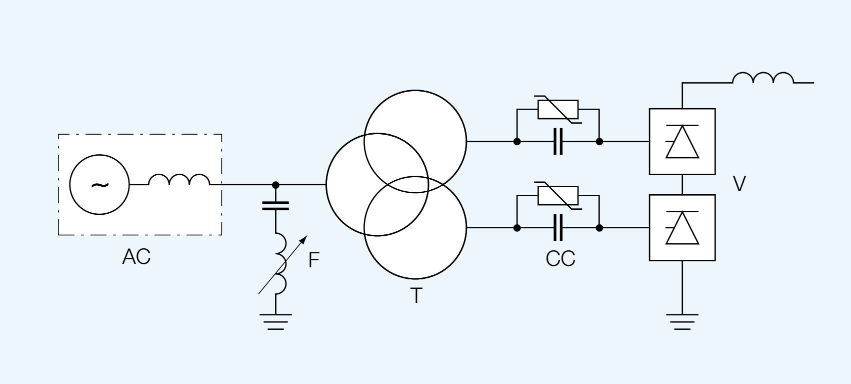
The CCC also results in the inverter station performing more reliably and with better dynamic stability. This is especially true when the inverters are connected to weak AC systems and/or long DC cables. The main reason is that the risk of commutation failure is smaller due to the CCC-based system being less sensitive to disturbances in the AC network.

The CCC configuration results in the main circuit components being subjected to different stresses. As a result of the contribution from the commutation capacitors, the operating voltage of the valve bridge increases while its short-circuit current decreases. The CCC has lower no-load losses than a conventional converter, since the converter transformer can be designed with a lower rated power. This is possible because the CCC minimizes the reactive power flowing through the transformer. On the other hand, operating losses are slightly higher since the harmonic currents and the valve voltage steps increase during turn-off.

The introduction of the CCC has made it easier to design an HVDC transmission link **3**. Among other things, the number of AC circuit-breakers can be reduced as only one filter bank is needed. The total equipment costs are consequently lower.

Commutation voltage and commutation margin

An HVDC valve in inverter mode requires a negative commutation voltage (ie, a voltage in the reverse direction) for a certain period of time in order to ensure satisfactory turn-off. The duration of this negative commutation voltage is usually defined as the angle γ, and is termed the commutation margin. For a conventional converter in inverter mode, the phase angle between the zero crossing of the valve current (turn-off) and the bus voltage zero crossing is



Single-line diagram of a monopolar HVDC transmission system with capacitor commutated converter **1**

AC *AC power system*
F *Filter*
T *Converter transformer*
CC *Commutation capacitor*
V *Valve bridge*

identical to the valve commutation margin γ. In contrast, the phase angle in the CCC inverter is always smaller than the commutation margin, and only equal to it when the current is zero.

The smaller phase angle with the CCC is explained by the additional voltage contributed by the capacitors to the valve commutation voltage. This allows the turn-off to be delayed in relation to the bus voltage while maintaining the minimum commutation margin **4**.

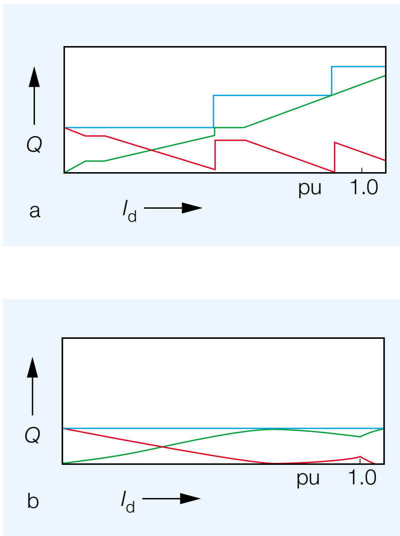
The commutation margin γ' for a CCC inverter can be defined as the angle between the valve current zero crossing (turn-off) and the voltage zero crossing.

An increase in the direct current-results in a larger commutation margin, while the overlap angle remains almost constant **5**. The response by the CCC to an increase in current can be illustrated by comparing the characteristics for nominal current with the characteristics for 1.2 pu current, with the same firing angle in each case. The commutation interval (overlap angle) is largely unaffected by the increased current, as shown in **5b**. The duration of the negative valve voltage is longer with the increased current, as the graph in **5c** shows. The reason for this behaviour is the higher voltage contribution from the commutation capacitors when the direct current increases, resulting in favourable lagging of the commutation voltage. A vector diagram **5a** illustrates this well.

Reactive power compensation in a conventional HVDC converter station (a) and for a CCC-based station (b) **2**

Blue *Filter*
Green *Converter*
Red *Unbalance*

Q *Reactive power*
I_d *Direct current*



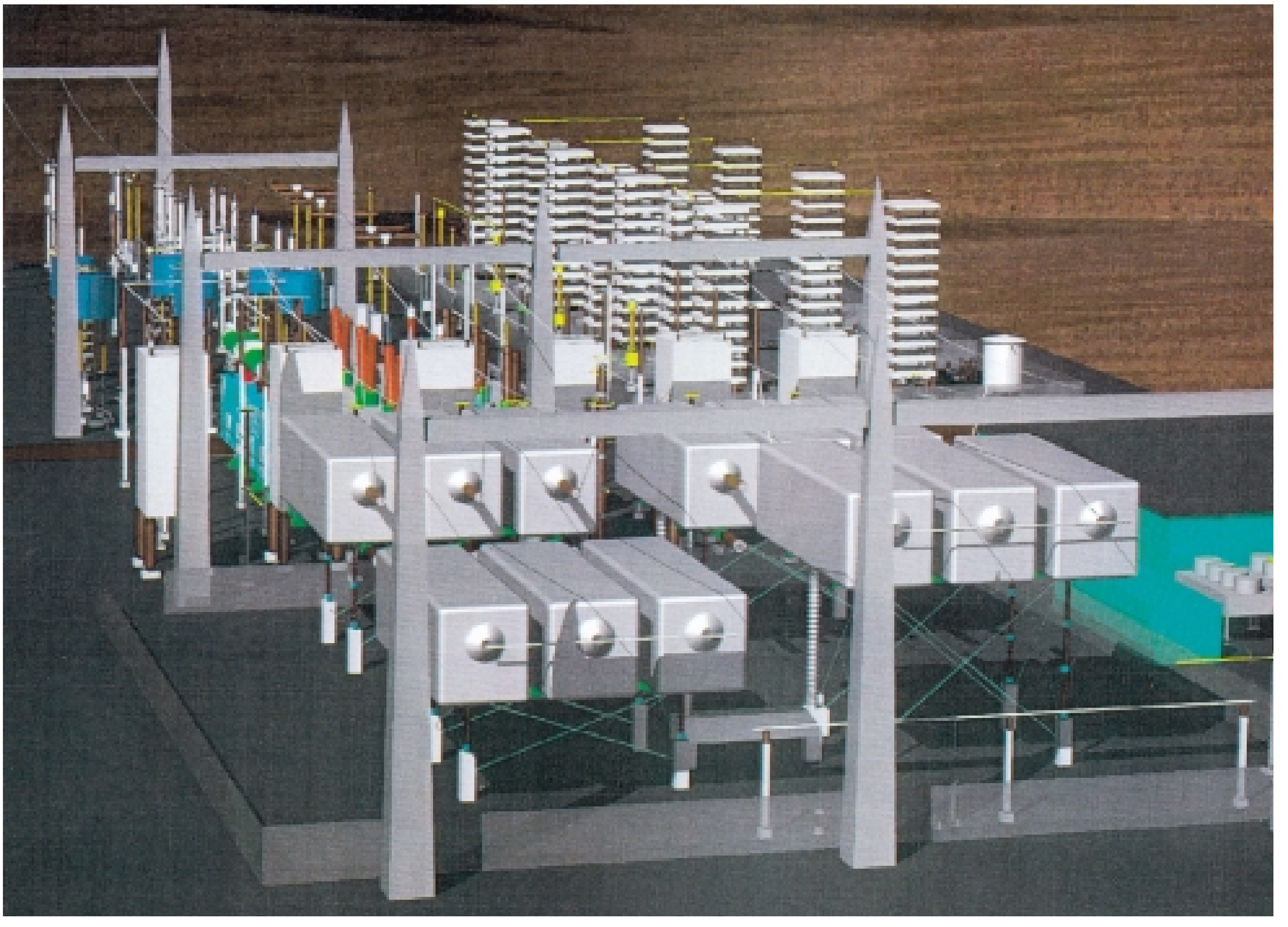
The commutation margin also increases when the bus voltage decreases, since the commutation capacitor voltage is then proportionally higher than the bus voltage.

The response of the CCC to a drop in the AC voltage can be shown by a comparison of the characteristics for a nominal AC voltage with those for an 0.8 pu AC voltage (the firing angle is the same in both cases) **6**. The commutation interval (overlap angle) is for the most part unaffected by the reduced AC voltage, as shown in **6b**. The duration of the negative valve voltage is longer with a lower AC voltage, as can be seen in **6c**. This is because the capacitor voltage becomes proportionally higher when the bus voltage drops. The relationship is also illustrated by a vector diagram of the fundamental frequency voltage components **6a**.

Successful commutation may still be possible even if the AC voltage is close to zero, since all of the commutation voltage is then supplied by the capacitors.

Stability of a conventional inverter

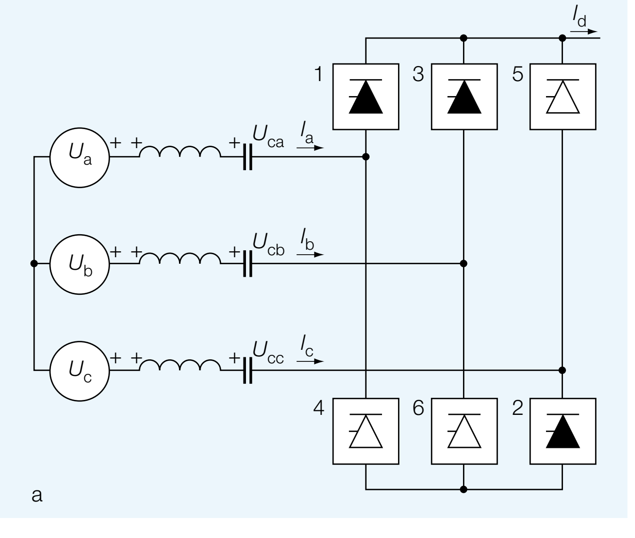
A conventional inverter is normally controlled such that the commutation margin stays constant. When the direct current is increased, the commutation needs more time and must therefore begin earlier. The available AC voltage is consequently utilized to a lower degree and the DC voltage decreases. This can be characterized as the inverter having a negative impedance as seen from the DC side. In cases with a weak AC bus (ie, a bus with high impedance), the increase in direct current will produce a drop in the bus voltage. The result will be a further drop in the DC voltage, giv-

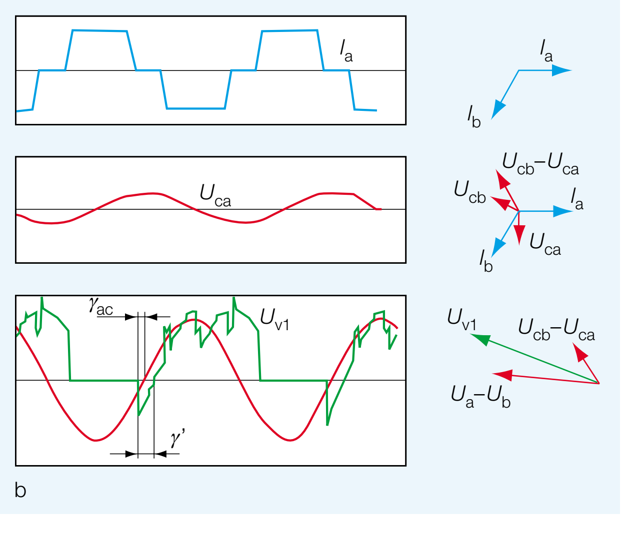


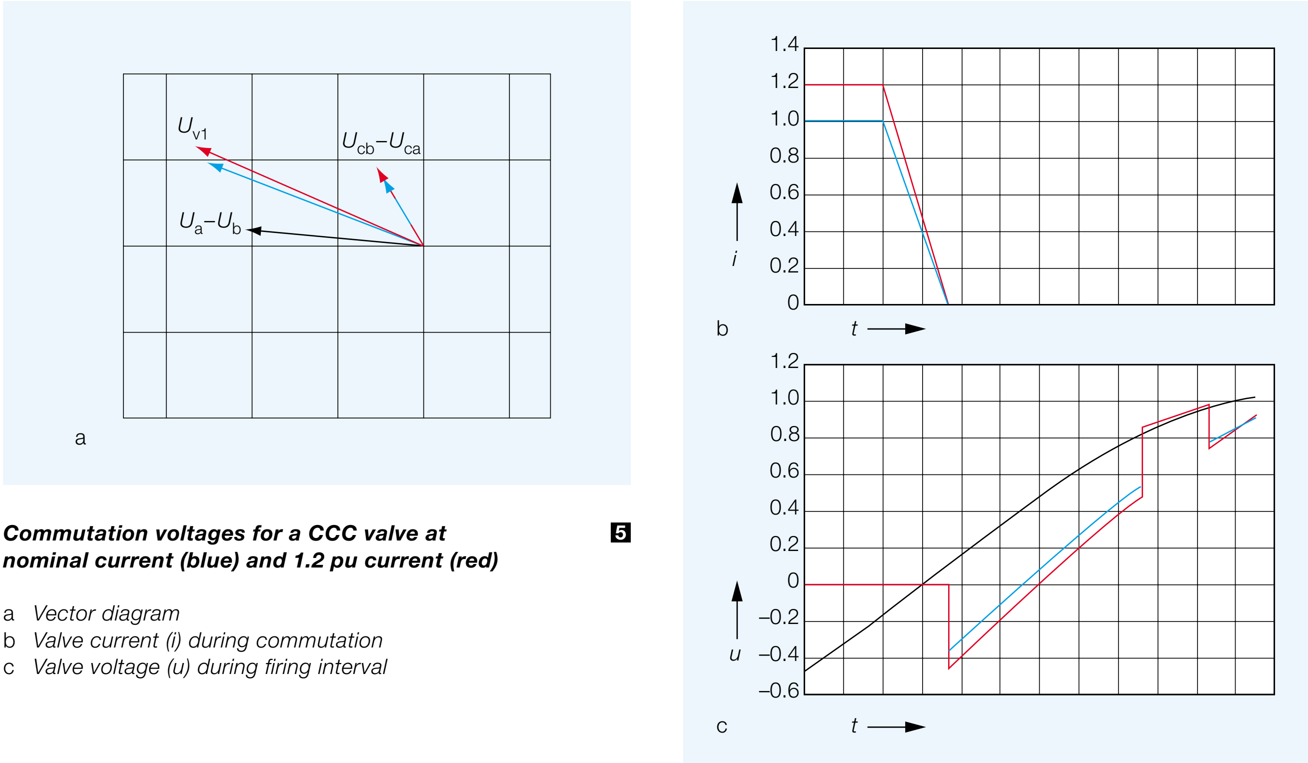
Model of a converter station corresponding to the HVDC 2000 concept **3**

Basic circuit of the capacitor commutated converter **4**

I_a, I_b, I_c	*Alternating currents*
I_d	*Direct current*
U_a, U_b, U_c	*Alternating voltages*
U_{ca}, U_{cb}, U_{cc}	*Voltages across commutation capacitors*
U_{v1}	*Voltage, valve 1*
γ_{ac}	*Firing angle in relation to system voltage*
γ'	*Firing angle in relation to valve bridge*







Commutation voltages for a CCC valve at nominal current (blue) and 1.2 pu current (red) **5**

a *Vector diagram*
b *Valve current (i) during commutation*
c *Valve voltage (u) during firing interval*

ing rise to a stronger negative impedance.

The strong negative impedance of the inverter results in less stable HVDC transmission. This is because a transient increase in the direct current – which can be the result of a small reduction in the bus voltage in the receiving network – is amplified by the increasing voltage difference between the rectifier and the inverter. Satisfactory stability is achieved by a high-speed controller that keeps the direct current from the rectifier at a constant value.

Improved stability with the CCC

In the case of a CCC-type inverter with a constant commutation margin, the DC voltage will be constant (or will increase slightly) when the direct current is increased. This is primarily because the commutation capacitors provide additional commutation voltage in proportion to the direct current. Thus, seen from the DC voltage side, the CCC inverter appears to behave as a slightly positive impedance.

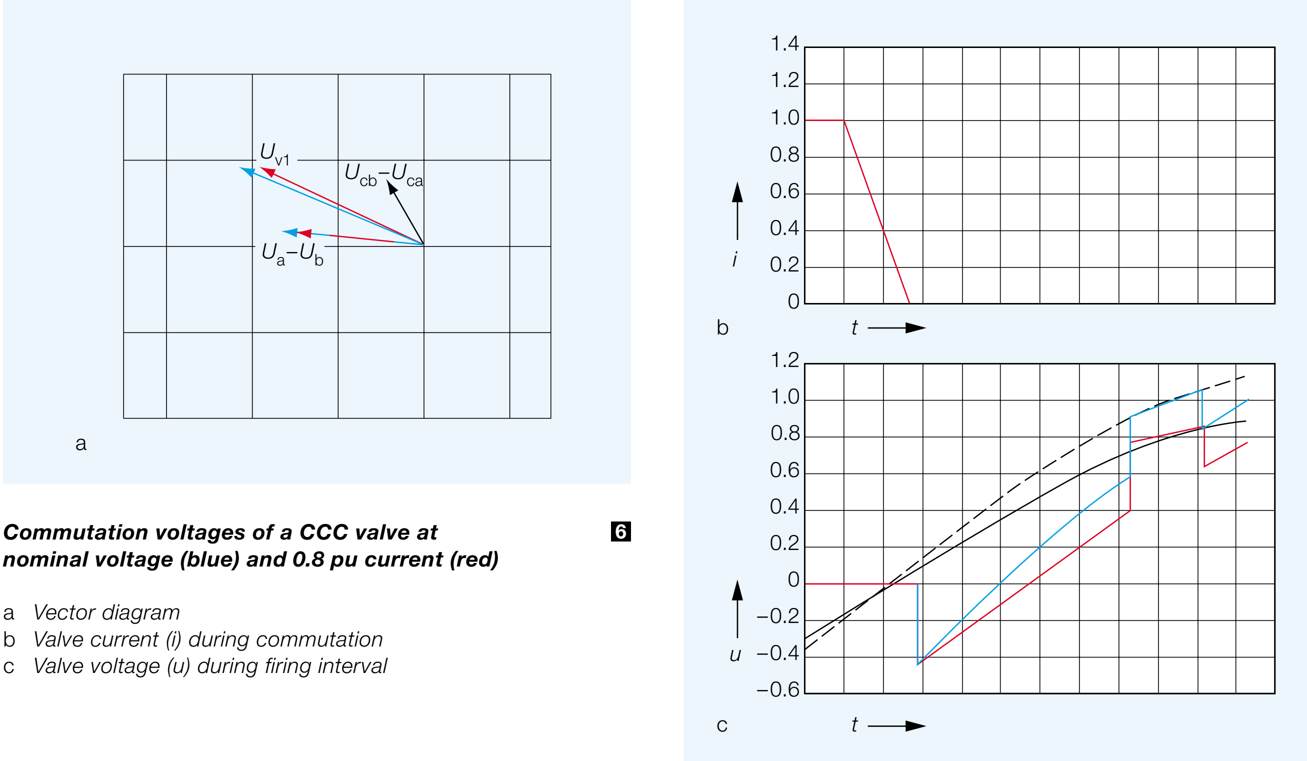
Another favourable feature of the CCC is its reactive power characteristic **7**. As the load increases (starting from the nominal value and with the CCC working as an inverter), the reactive power consumption will decrease **7a**. The reason for this is that the increased current results in an increased voltage boost from the commutation capacitors. By allowing a delay in the firing, the commutation margin can be kept constant. A further increase in the current causes the CCC to begin generating reactive power.

In the case of the conventional converter, reactive power consumption increases with an increase in current. However, **7a** shows that consumption stagnates, the reason being that the bus voltage in the network in question collapses and the active power decreases.

7b shows that a CCC in combination with AC filters supports the network with reactive power in cases of overload. With the conventional converter there is a large deficit under overload conditions and a large surplus when the load is low. One contributing factor is the load-dependent variation of the bus voltage **8**.

The power transmission capability of a given network is greater with capacitor commutated converters than with conventional technology, as **8** clearly shows. This increase is possible because of the improved stability, being due to the reactive power requirement decreasing instead of increasing for an increased supply of active power to the AC network (ie, increased direct current).

For a given weak network (eg, with a short-circuit ratio of 2), the margin to the maximum available power (MAP) is much larger with a CCC than with a conventional converter.



Commutation voltages of a CCC valve at nominal voltage (blue) and 0.8 pu current (red) **6**

a *Vector diagram*
b *Valve current (i) during commutation*
c *Valve voltage (u) during firing interval*

In the case of direct current above the MAP, the transmitted power decreases with an increasing direct current **8a**, and power control becomes unstable. For the CCC in the example considered, the MAP is 1.75, ie the power can be increased by 75 percent from the nominal working point without stability problems. For a conventional converter, the MAP is 1.2, allowing a power increase of only 20 percent with maintained stability.

These favourable properties of the CCC are explained by the fact that the influence on the bus voltage is only moderate. The power for the CCC can be increased from 1 pu to 1.5 pu, the bus voltage dropping by only 2 percent **8b**. With a conventional converter, an increase in power from 1 to 1.2 pu will cause the voltage to drop by 6 percent. Load rejection (interrupted power transmission) will cause the CCC voltage to increase to only 1.1 pu, compared with nearly 1.4 pu for the conventional converter.

The reason for the power above the MAP dropping despite the increase in current is that the bus voltage decreases **8b**. This decrease is due to the weak network receiving insufficient reactive power at such a high current value. In the case of the conventional converter, this phenomenon will be amplified by to the large reactive power deficit **7**.

CCCs and remote system faults

A CCC-type inverter will counteract an AC voltage collapse in the event of a remote system fault, while a conventional converter would be more likely to accelerate such a collapse. If there is a fault in the remote system the source voltage will drop slightly. This voltage drop in the inverter results in the direct current increasing.

For a conventional HVDC system:

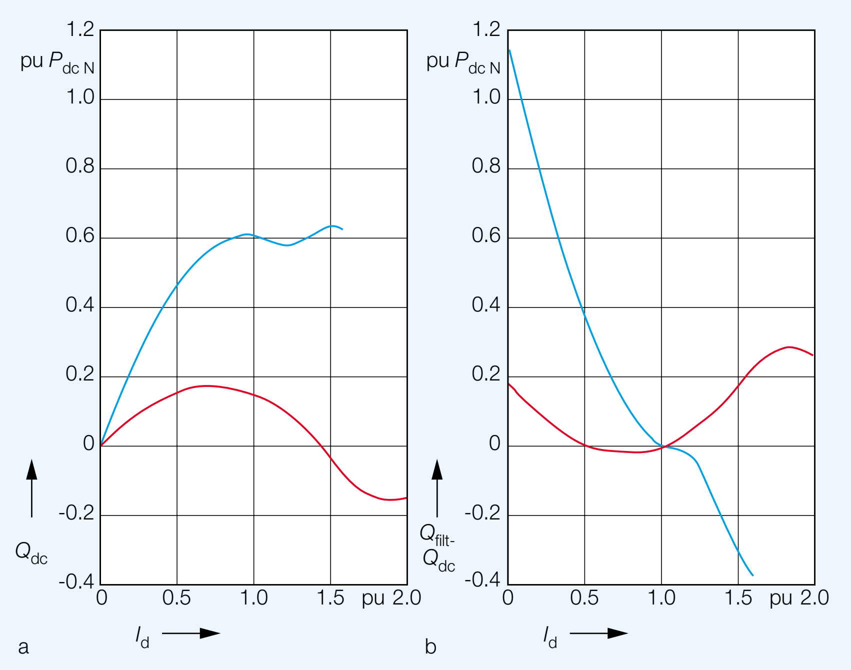
- The reactive power consumption increases with increased current.
- The increased consumption of reactive power further reduces the system voltage.
- There is a risk of voltage collapse.

In the case of a CCC-based system, on the other hand, reactive power consumption decreases when the direct current is increased, and the CCC can be controlled with the minimum commutation margin thanks to the extra voltage obtained from the commutation capacitors **7**. With a direct current above 1.4 pu, the converter will even supply reactive power to the system. Thus, the total reactive power asset of a CCC station, including the shunt filter, will be positive, which will counteract AC voltage collapse.

The CCC and weak AC networks

In many so-called ‘weak’ AC networks, the voltage fluctuates both strongly and rapidly. The CCC is the ideal choice for such systems, as it is stable and can handle large, fast changes in the network supply.

Voltage stability is influenced by the reactive power consumption of the inverter. The total reactive power consumption of a CCC station, unlike that of a conventional station, drops at high currents **7**. Since the AC system can be supported with reactive power, the CCC is able to transmit more power without the short-circuit rating of the AC network having to be increased **8**.

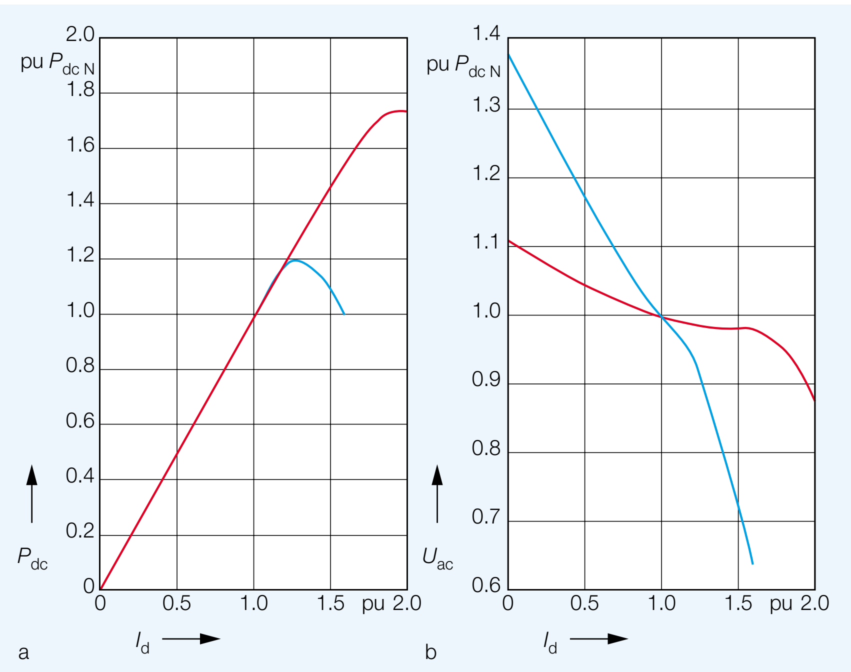


Reactive power consumption Q_{dc} (a) and reactive power balance Q_{filt}-Q_{dc} (b) of a conventional HVDC system (blue) and a CCC-based system (red) for transient variation around the nominal working point in inverter mode **7**

I_d Direct current *$P_{dc\,N}$ Nominal power*

Transmitted power P_{dc} (a) and AC system voltage U_{ac} (b) of a conventional HVDC system (blue) and a CCC-based system (red) for transient variation around the nominal working point in inverter mode **8**

I_d Direct current *$P_{dc\,N}$ Nominal power*



The CCC and long DC cables

CCCs also offer advantages when long DC cables are to be used. CCC-based installations not only ensure stable transmission but also, unlike conventional stations, have no need for the following features:

- Larger inverter commutation margins
- Larger reactive power resources

A long DC cable in a transmission system acts as a large capacitor. In the event of a transient drop in the system voltage in the inverter, for example due to a remote fault in one phase, the DC cable will partially discharge into the AC network via the inverter.

Because of the high cable capacitance, the transient current increase at the inverter end is not immediately detected at the rectifier. This delay means that the rectifier does not immediately begin reducing the direct current. Even if the rectifier did respond instantaneously and cut off the current, the rectifer would not be able to discharge the cable, which is consequently still discharged at the inverter end. When the inverter has not been designed to respond quickly and increase its DC voltage as soon as the current increases, the AC voltage will collapse. The CCC has this inherent defence feature. By counteracting the current increase it improves the stability of the HVDC transmission.

Behaviour under load rejection conditions

Another significant difference between a conventional HVDC station and a CCC-based station concerns their behaviour in the event of load rejections. Load rejection in the inverter is possible due to a temporary interruption of transmission, for example when a fault occurs on the rectifier bus. The inverter does not then consume any reactive power and the excess reactive power causes an overvoltage. The low reactive power consumption of the CCC results in only a small surplus occurring upon load rejection. The overvoltage with a CCC-based system is therefore much lower than with a conventional HVDC system 8.

Low-order harmonics resonance

A conventional HVDC station is equipped with a relatively large filter and capacitor bank connected to ground. Parallel resonance between the capacitors to ground and the network inductance can occur in weak (high-impedance) networks. This can coincide with non-characteristic harmonics[1)] of a low-harmonic order from the converter, thus giving rise to resonance.

The risk of low-harmonic resonance is minimized with the CCC, since it requires a significantly smaller filter capacitor.

Optimum utilization of the AC voltage

Optimum utilization of the AC voltage is achieved by operating the converter with small firing angles to obtain a power factor close to unity:

$$\cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}}$$

Any change in the DC voltage due to network voltage fluctuation in the inverter has to be counteracted by the rectifier through a change in the control angle, resulting in the active and reactive power also changing 9.

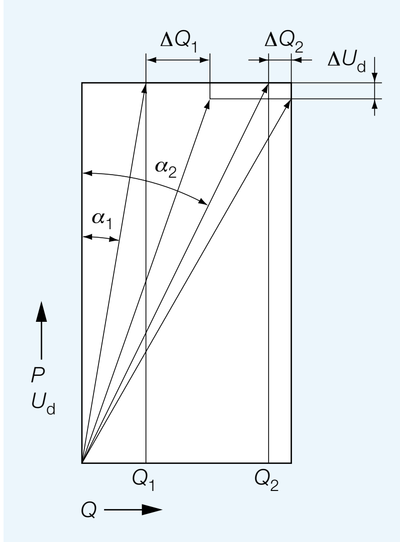
The same principle also applies to variations in the AC voltage of the converter. Operation with small firing angles results in a low nominal reactive power requirement and a high power factor. On the other hand, the variation in reactive power will be larger due to the bigger change in the firing angle that is necessary to counteract the variation in voltage.

Unbalanced capacitor voltages

The commutation performance of the inverter deteriorates when the capacitor voltages are in a state of unbalance. Any transient change in the direct current will cause the current to change during subsequent conduction intervals, resulting in different peak values for capacitor voltages in different phases (ie, unbalance). One result of this is that different valves in the converter have different commutation voltages, and consequently different commutation margins. The variation in commutation voltage also leads to additional fundamental frequency components in the DC voltage. Any unbalance between the phases in the commutation capacitor voltages can be detected by measuring the fundamental frequency component of the DC voltage. The results of the measurement are then used by the CCC controls to overcome the unbalance through:

- A temporary reduction of the firing angle (inverter operation only) to maintain the minimum commutation margin required for the most critical valve.

1) Non-characteristic harmonics are caused by asymmetry between the phases in power system components or voltages



Change in reactive power consumption for a change in power system voltage. 9
The variation in the reactive power consumption in the case of a voltage fluctuation ΔU_d is greater with a small firing angle (α_1) and low reactive power consumption (ΔQ_1) than with a larger firing angle (α_2).

α Firing angle under ideal commutation conditions

- Modulation of the firing angle to enhance the restoration of the balanced capacitor voltages.

Commutation capacitors

The steady-state voltage of the commutation capacitor is directly proportional to the direct current, since the capacitor is charged and discharged by this current (depending on which valves are conducting) 4, 10.

The commutation capacitor voltage contains the fundamental frequency voltage and the six-pulse AC harmonics. Commutation capacitor overvoltages are limited by ZnO varistors 1, 11.

A commutation capacitor is designed to withstand the maximum continuous direct current as well as given overloads. Since the operating current across the capacitor and the power demand on the varistor are relatively moderate, the commutation capacitor can be made very compact. For example, each phase takes up only a few square meters of the switchgear installation 11.

Valves

The steady-state voltage of a valve is made up of the AC system phase-to-phase voltage and the contribution from two commutation capacitors, one in each phase. The contribution by the commutation capacitors reaches its peak at commutation.

Since a margin is needed for the current control in the rectifier, there is a surplus of commutation voltage at the nominal working point. This results in a firing angle which is larger than for a conventional HVDC converter. The larger firing angle, which results in higher extinction voltage steps, will, in combination with the shorter commutation interval, lead to higher commutation overvoltages. Consequently, higher demands are made on the damping circuits and valve arresters. For an optimum design, the valve arrester voltage rating must be increased to a value which is typically 10 percent higher than that for a conventional HVDC converter.

The commutation capacitors reduce the currents in the event of a valve short circuit in the rectifier. The short-circuit current quickly charges the capacitors, so that a counter voltage is built up which lowers the peak value of the fault current.

Insulation coordination

The insulation level on the valve side of the converter transformer is determined by the arresters in the valve bridge and the varistor of the commutation capacitor. For a 400-500 kV DC transmission system, the insulation level of the transformer will be 100-300 kV higher than for a conventional HVDC converter.

Thus, with CCC-based systems, the insulation coordination is influenced by the commutation capacitors, the converter valves and the converter transformer.

Harmonics

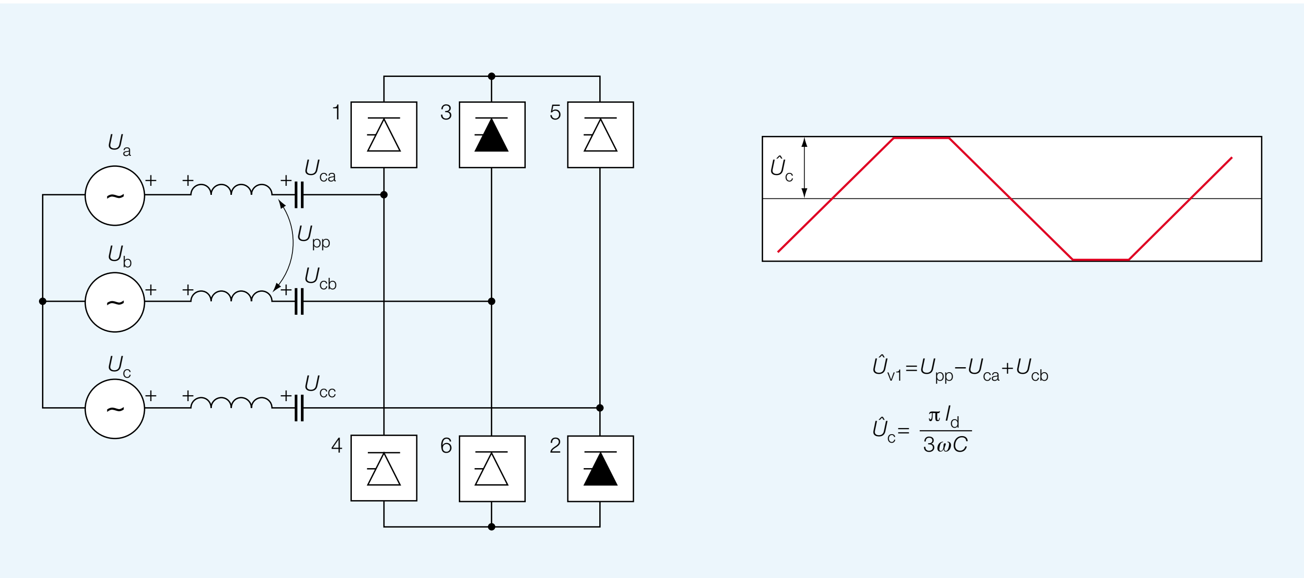
Harmonic generation in the CCC, both on the AC and on the DC side, is greater than in the conventional HVDC converter. This calls for better filtering, which is provided by incorporating active DC filters and automatically tuned AC filters [1].

Ground faults and the commutation capacitor

A ground fault between the commutation capacitor and the transformer in the low-voltage valve bridge causes the capacitor to be discharged via the valve. If the valve is grounded either direct in the converter station or through the neutral bus and a high-frequency filter capacitor, this discharge can be critical. To reduce the load on the valve, a small damping reactor can be incorporated in series with the valve connection to the neutral bus.

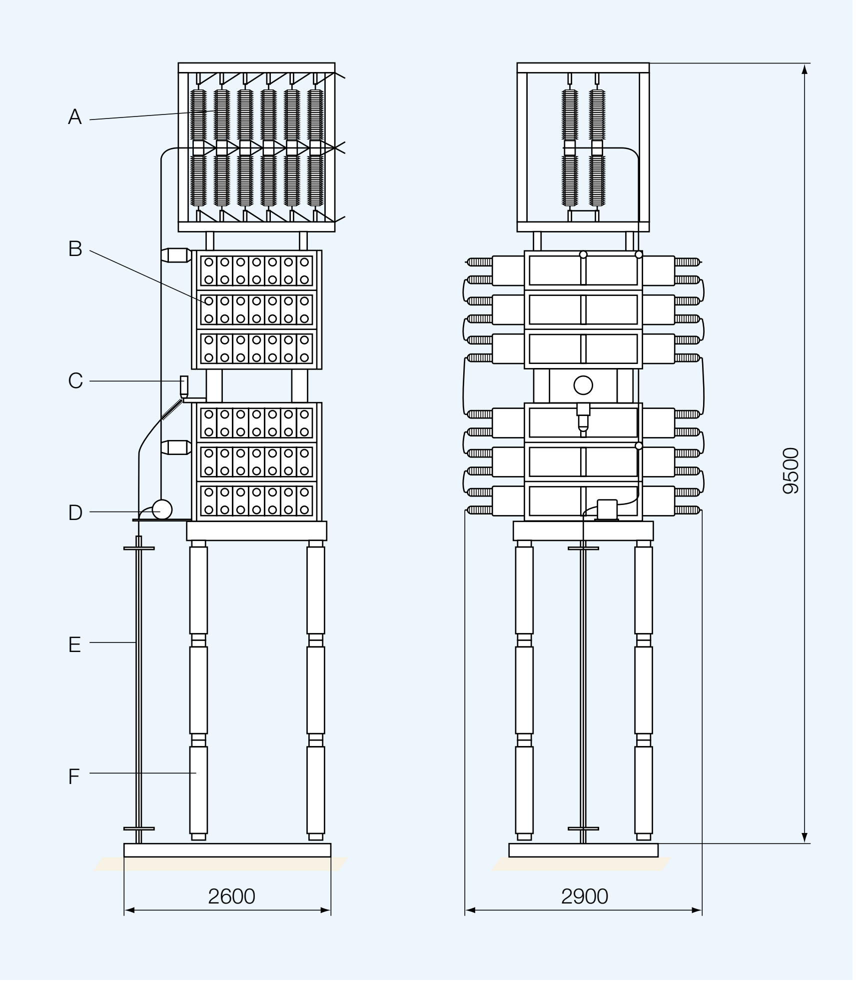
The steady-state voltage of a commutation capacitor is directly proportional to the direct current. 10

U_a, U_b, U_c *Alternating voltages*
U_{ca}, U_{cb}, U_{cc} *Voltages across commutation capacitors*
U_{v1} *Voltage across valve 1*



Commutation capacitor unit, typical design **11**

A *ZnO varistor with PEX insulators*
B *H-connected capacitor cans for unbalance detection*
C *Unbalance protection OCT*
D *Surge counter*
E *Fiber optic link*
F *Support insulator*



CCC concept for HVDC 2000

The availability of capacitor commutated converters radically alters the question of how and when HVDC transmission systems can be utilized. An HVDC system incorporating CCCs can be a solution for transmission projects which were not considered to be feasible in the past. With CCC, the inverter is much more stable, even in cases of large, rapid load fluctuation during power transmission. This performance characteristic is ideal for long DC cables, weak AC systems and where remote faults can occur. In short, CCCs support HVDC transmission with the following features:

- Better immunity to commutation failures
- Lower reactive power consumption
- No need for switched filter and capacitor banks
- Lower overvoltages when load rejections occur
- Less sensitive to low-order harmonic resonance

A CCC-based system requires fewer AC circuit-breakers than a conventional HVDC transmission system. In addition, it simplifies the AC switchgear and other equipment, thereby lowering the cost of their maintenance.

The CCC, together with the other components that make up the HVDC 2000 concept, creates a platform for lower capital and operating costs as well as better transmission performance for HVDC schemes.

Reference

[1] B. Ärnlöv: HVDC 2000 – a new generation of high-voltage DC converter stations. ABB Review 3/96, 10–17.

Authors' address

Per-Erik Björklund
Tomas Jonsson
ABB Power Systems AB
P.O. box 703
S-77180 Ludvika
Sweden
Fax: +46 240 782 720