

# HVDC CAPACITOR COMMUTATED CONVERTERS IN WEAK NETWORKS

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## Summary

Capacitor Commutated Converters (CCC) were introduced to the HVDC market in the end of 1990 and have been in commercial operation since 1999. Several installations around the world have been taken into operation with excellent operational performance. Until today CCC has been used only for Back to Back installations. However for DC Cable Installations CCC has been discussed for a number of HVDC projects since the CCC concept has operational advantages for installations with long DC cables.

The main advantages with CCC for all types of HVDC installations appear in converters in weak ac systems, especially in the receiving end (Short Circuit Ratio, SCR, below 2). CCC offers a better performance than a conventional HVDC system for such network conditions.

In many cases for a multiterminal HVDC system, at least one inverter often operates with lower rating than the other terminals, and is also often connected to a weak ac network. A CCC configuration for that terminal would result in an improved performance for the whole HVDC system since the risk of commutation failures at ac network disturbances is lower for CCC and the stability is better for CCC compared to conventional converters.

This paper deals with CCC's operational benefits for inverters connected to weak networks.

## Main operational advantages of the CCC

The reactive power consumption of a conventional HVDC converter is around 50% of the active power. Compensation is provided by switching an appropriate number of filters/shunt banks to the ac bus of the converter. Normally, the size of a filter or capacitor bank is restricted by the ac system requirements on reactive power unbalance and voltage step. The unbalance is not normally allowed to exceed a specified tolerance range. This results often in many filter/shunt banks to be switched in/out when the active power is changed especially if the ac network is weak.

Operation of the CCC is based on the principle that the commutation capacitors, connected in series between the converter transformer and the HVDC valve (Figure 1), make an additional contribution to the commutation voltages of the valves. As a result of this additional voltage contribution, considerably less reactive power is required by the converter compared to a conventional converter. Furthermore, the contribution grows with the converter load, and this compensates the growth of reactive power consumption in the transformers and the converting process. For a CCC no shunt reactive power units are

needed, only filters taking care of the generated harmonics are needed i.e. no need to switch shunt banks in and out for reactive power compensation when the active power is changed (Figure 2).

The CCC also results in the inverter station performing more reliably and with better dynamic stability and CCC is less sensitive to commutation failures at disturbances in the connected 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 during turnoff increase.

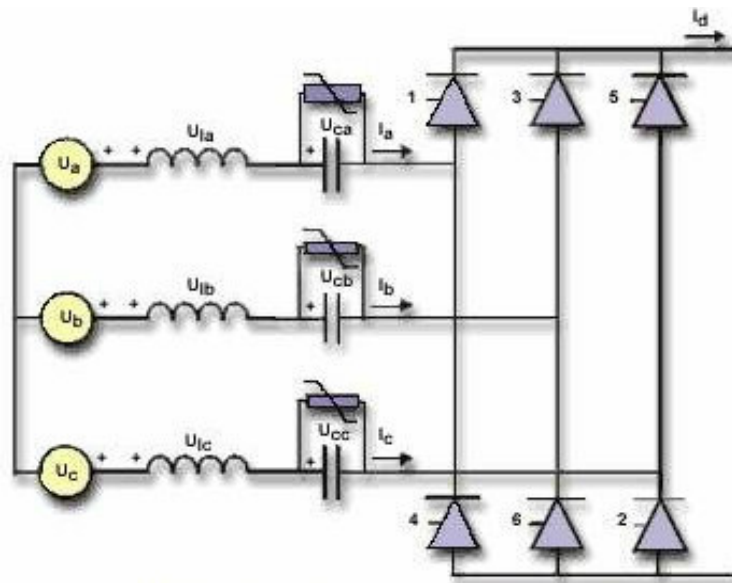


Figure 1. The CCC main circuit configuration

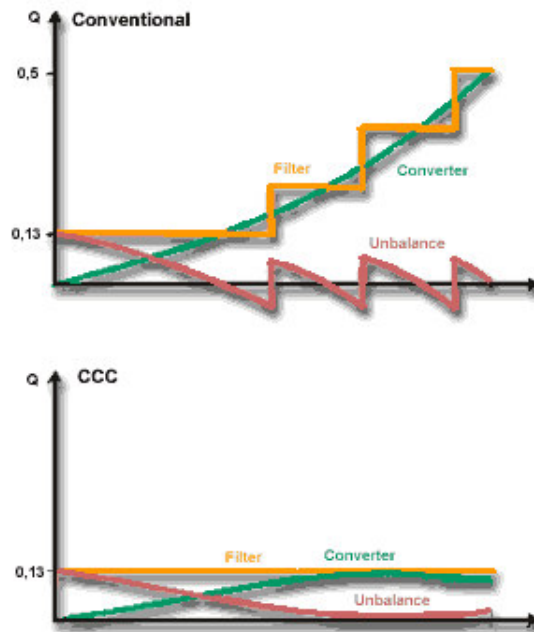


Figure 2. Reactive power conditions for conventional converter vs. CCC

### Commutation voltage and commutation margin

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

In a CCC converter, the contribution from the voltage in the series capacitors will shift the phase of the voltage applied to the valve, and, in contrast to a conventional inverter, the phase angle in the CCC inverter is always smaller than the actual commutation margin at the valve 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 (Figure 3). This allows the turn-off to be delayed in relation to the bus

voltage by  $\gamma_{ac}$  while maintaining the minimum commutation margin  $\gamma'$  between current zero-crossing and the valve voltage zero-crossing,

The commutation margin  $\gamma'$  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. 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 p.u. current, with the same firing angle in each case. The commutation interval (overlap angle) is largely unaffected by the increased current, as shown in Figure 4b.

The duration of the negative valve voltage is longer with the increased current, as shown in Figure 4c. The reason for this behavior is the increased voltage contribution from the commutation capacitors when the direct current increases, resulting in favorable lagging of the commutation voltage. A phasor diagram in Figure 4a illustrates this.

$I_a, I_b, I_c$  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  
 $\gamma_{ac}$  Firing angle in relation to system voltage  
 $\gamma'$  Firing angle in relation to valve bridge

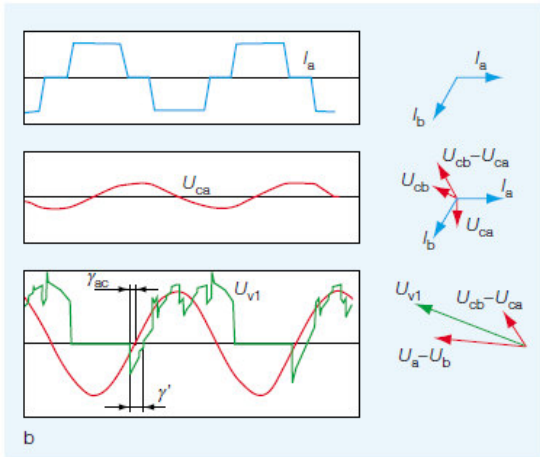
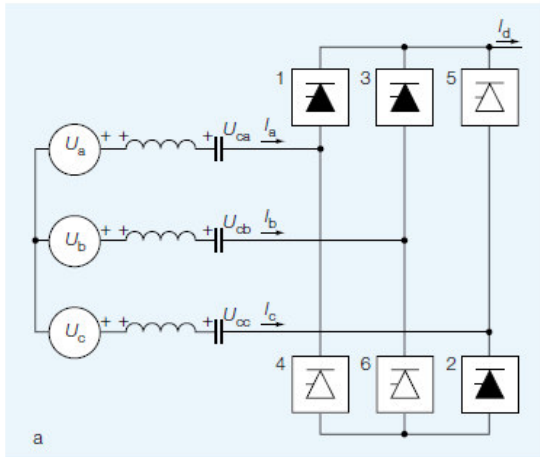
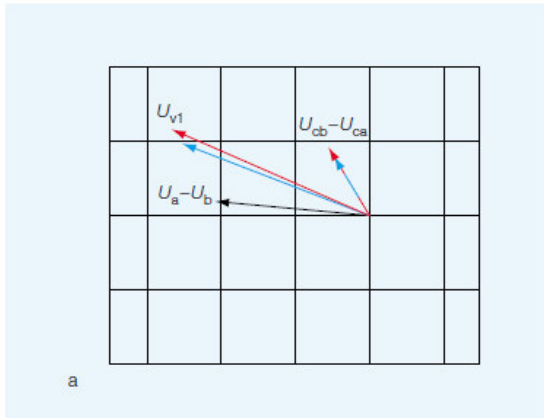
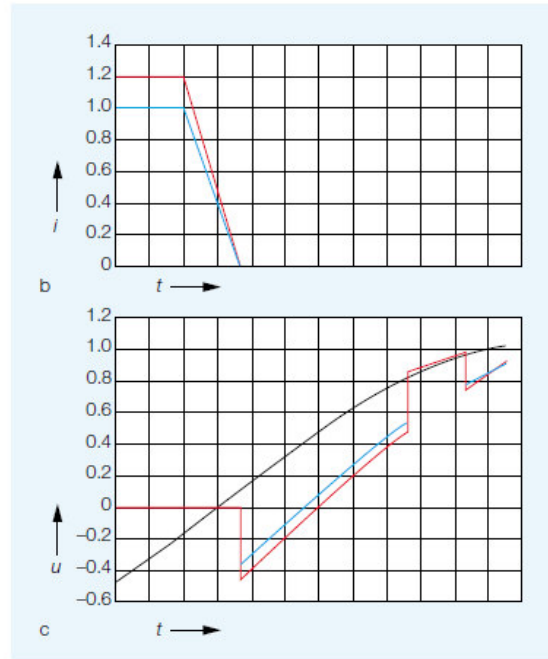


Figure 3. Basic Circuit of CCC.

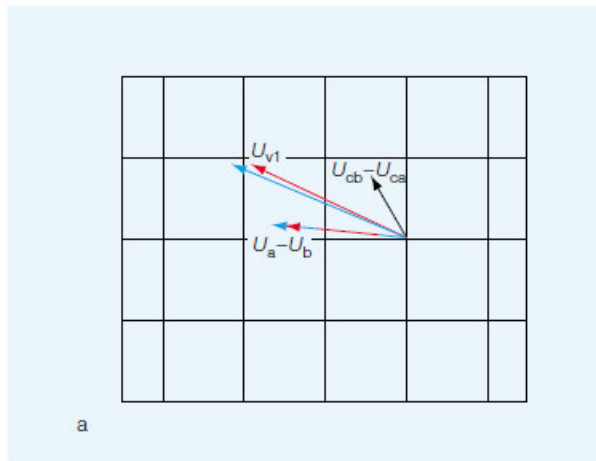


Commutation voltages for a CCC valve at nominal current (blue) and 1.2 pu current (red)

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



Figures 4 a - c. Commutation voltages for a CCC valve at nominal current (blue) and 1.2 pu current (red)



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

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

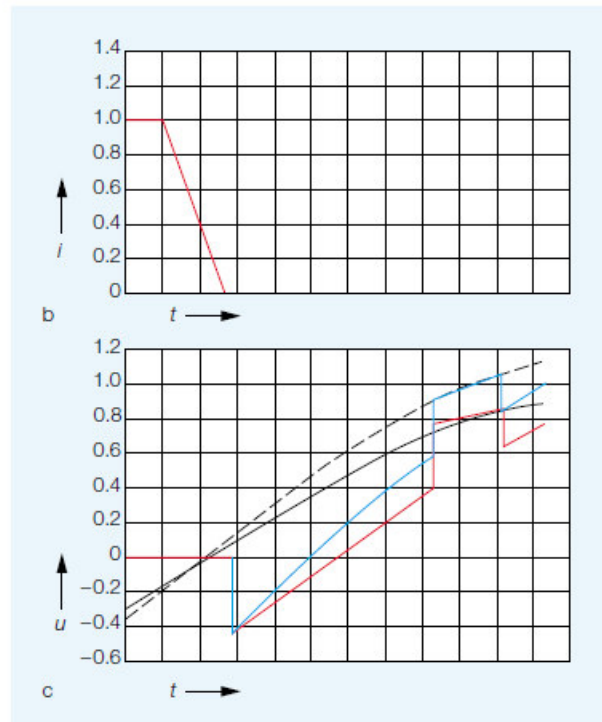


Figure 5 a – c. Commutation voltages for a CCC valve at nominal current (blue) and 0.8 pu current (red)

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 is shown in Figure 5 by a comparison of the characteristics for a nominal AC voltage with those for a drop to 0.8 p.u. AC voltage, with the firing angle being the same in both cases. The commutation interval (overlap angle) is for the most part unaffected by the reduced AC voltage, as shown in 5b. The duration of the negative valve voltage is longer with a lower AC voltage, as can be seen in Figure 5c, ensuring the proper commutation. This is because the capacitor voltage becomes proportionally higher when the bus voltage drops. The relationship is also illustrated by a phasor diagram of the fundamental frequency voltage components. 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 negative impedance as seen from the DC side. In cases with a weak AC bus (i.e., 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, giving rise to 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 inverter**

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 slightly positive impedance.

Another favorable feature of the CCC is its transient reactive power characteristic, as illustrated in Figure 6. The figure shows the behavior for a sudden change in dc current from a steady state at 1.0pu. If the load increases, the reactive power consumption will decrease, as shown in Figure 6a. The reason 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.

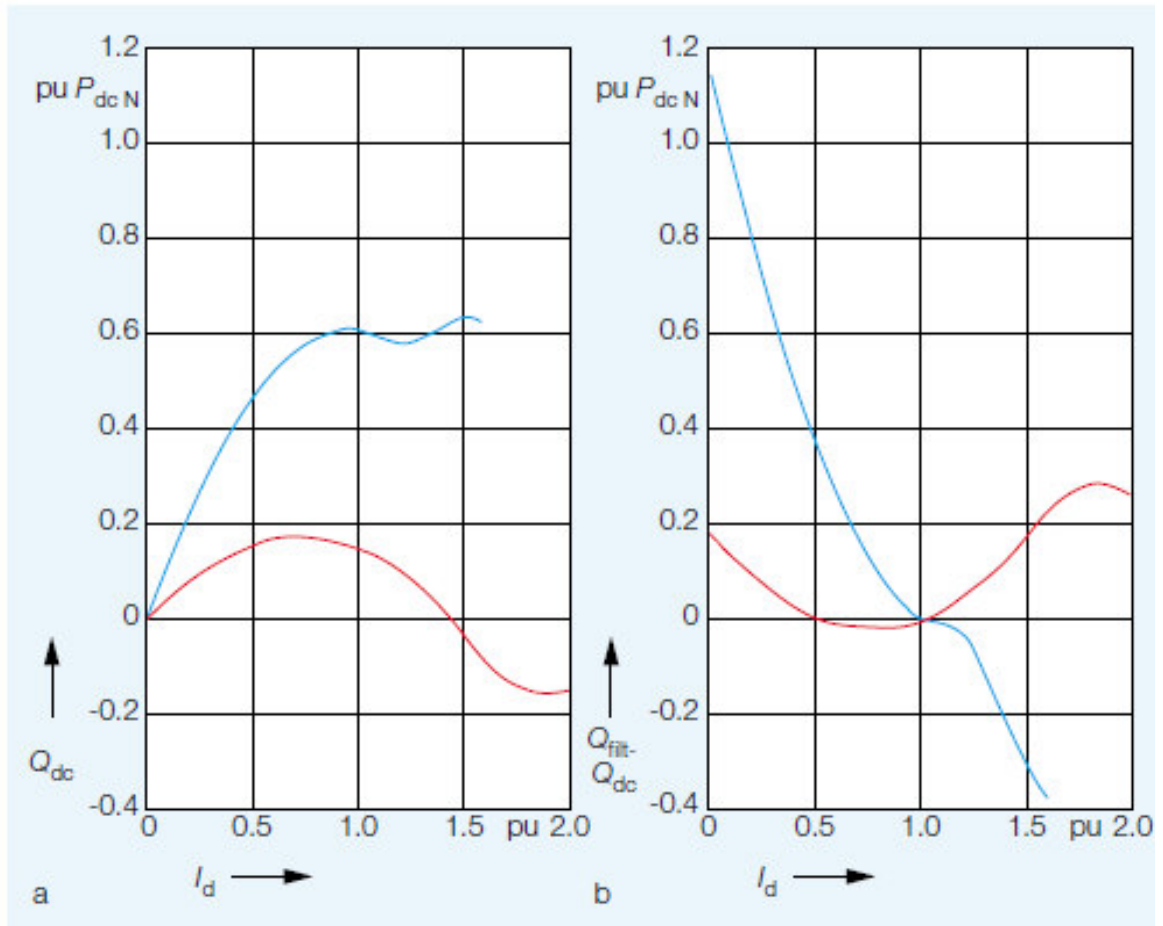
In the case of the conventional converter, reactive power consumption increases with an increase in current. However, Figure 6a shows that consumption stagnates, the reason being that the bus voltage in the network in question collapses and the active power actually decreases for further current increase. Figure 6a shows that a CCC in combination with its 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, as shown in Figure 7. Similarly to Figure 6, this figure shows the behavior for a sudden change in dc current from a steady state at 1.0pu.

The power transmission capability of a given network is greater with capacitor commutated converters than with conventional technology, as clearly Figure 7 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 (i.e., increased direct current).

For a given weak network (e.g., 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. In the case of direct current above the MAP, the transmitted power decreases with an increasing direct current, and power control becomes unstable. For the CCC in the example considered, the MAP is 1.75, i.e. 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. The favorable properties of the CCC are explained by the fact that the HVDC power influence on the bus voltage is only moderate. The power for the CCC can thus be increased from 1 p.u. to 1.5 p.u., with the bus voltage dropping by only 2 percent. With a conventional converter, an increase in power from 1 to 1.2 p.u. 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 p.u. compared with nearly 1.4 p.u. for the conventional converter. The reason for the power above the MAP dropping despite the increase in current is that the bus voltage decreases. 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 is amplified by the large reactive power deficit.



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

$I_d$  Direct current

$P_{dcN}$  Nominal power

Figure 6. Reactive power consumption and reactive power balance in a conventional HVDC system and a CCC-based system

**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**

$I_d$  Direct current

$P_{dcN}$  Nominal power

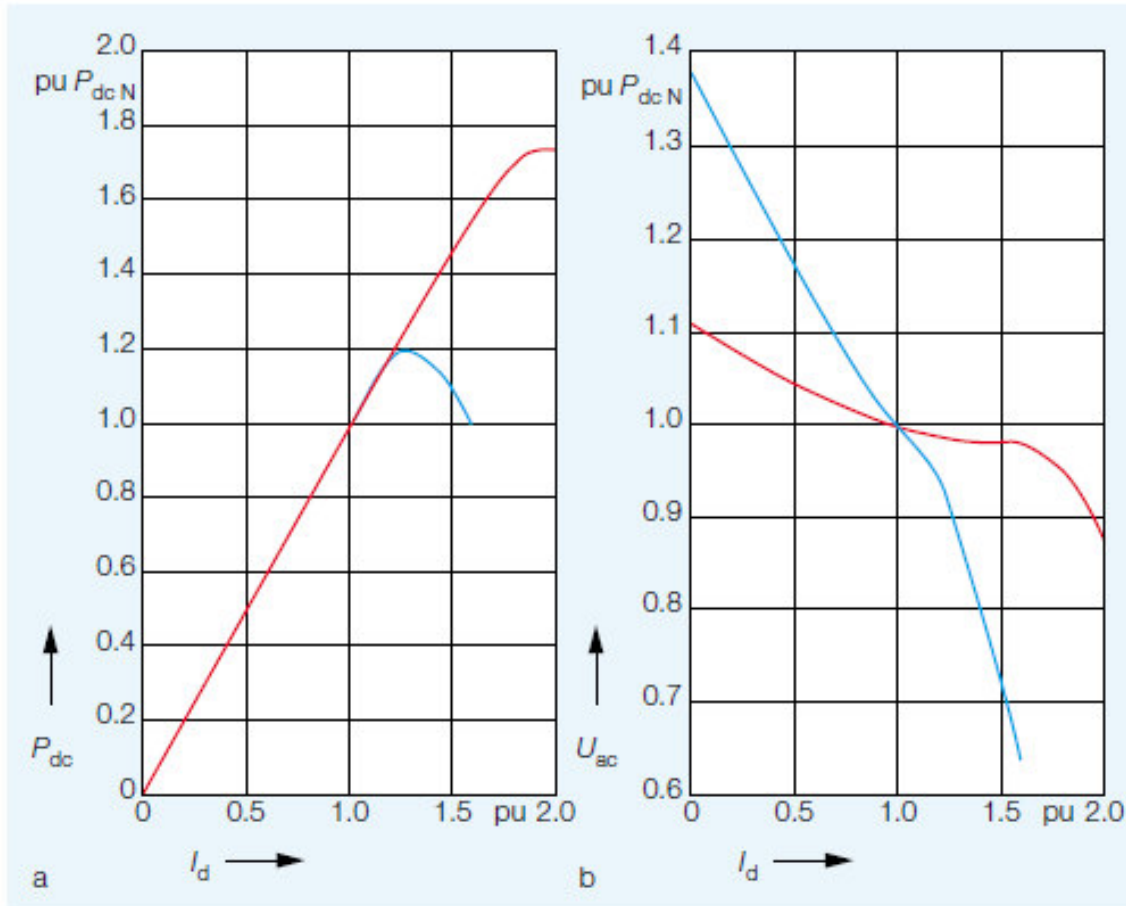


Figure 7. Transmitted power and AC voltage system voltage of a conventional HVDC system and a CCC-based system

### CCC and remote system AC 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. With a direct current above 1.4 p.u., 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 weak AC networks ( $SCR < 2$ ), 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. 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.

### **Behavior under load rejection conditions**

Another significant difference between a conventional HVDC station and a CCC based station concerns their behavior in the event of load rejections. Load rejection in the inverter is possible due to a temporary interruption of transmission, for example if a fault occurs on or near the rectifier bus. The inverter does not then consume any reactive power and the excess reactive power generated in shunt connected capacitive elements causes an overvoltage. The series connected capacitive elements stop producing reactive power automatically when the current goes down. The low reactive power consumption of the CCC results in only a small surplus occurring upon load rejection. The overvoltage with a CCC system is therefore much lower than with a conventional HVDC system, as illustrated in Figure 7.

### **Low-order harmonics resonance**

A conventional HVDC station is equipped with a relatively large set of filters and capacitor banks 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) of low harmonic order from the converter, thus giving risk to resonance. The risk of low-harmonic resonance is minimized with the CCC, since it requires a significantly smaller filter capacitor.

### **Increased utilization of HVDC by using CCC**

The introduction of CCC has increased the possibility to use conventional HVDC transmission systems. An HVDC system incorporating CCC can be a solution for transmission projects which were not considered to be feasible in the past due to weak AC networks. With CCC, the inverter is much more stable, even in cases of large, rapid load fluctuation during power transmission. This performance characteristic is ideal not only for Back-to-Back systems, but also for Long DC cables, Operation at weak AC systems.

For multiterminal systems a commutation failure in one inverter will create a short interruption (200 – 300 ms) of the total power transfer of that pole, even for the terminals not creating the commutation failure. Using CCC inverter for the terminal connected to a weak AC system will improve the total system performance since it is more stable and more robust against commutation failures that may be caused by network disturbances.

In short, CCC supports HVDC transmission with the following features:

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