Chapter 6

Capacitor Commutated Converters for HVDC Systems

6.1 CAPACITOR COMMUTATED CONVERTERS

This “new” HVDC converter configuration has been discussed about for more than 50 years! One of the earliest studies of this configuration was first carried out in the 1950s [1]. A more detailed investigation into the operation of this circuit was reported in [2]. In the late 1970s and early 1980s, studies with the parallel capacitor version were reported [3,4,5,6]. However, due to practical limitations with the valve ratings, these studies did not lead to any actual installations.

After a brief period of activity [3,4] while some attempt was made to consider the system implications of such a converter (Figure 6-1), references to this converter configuration disappeared from the research field for a while since it offered a more costly and “difficult” operational alternative to the line commutated converter (LCC). However, in the early 1990s, the CCC configuration [5] was resurrected again due to a number of reasons:

- Problem of voltage ratings of valves became less of a constraint financially (due to increasing ratings and decreasing valve costs),
- Management of reactive power and high performance harmonic filtering could be dealt with independently due to the development of the continuously tunable ac filter and active filters, and
- Utility demands for operation with increasingly weaker ac systems has meant that commutation with LCCs has become much more unpalatable.
The CCC is characterized by having capacitors inserted in between the converter transformer and the converter valves. Thus, this capacitor is in series with the leakage impedance of the transformer and the main valves. This has a two-fold effect:

- The capacitor provides a forced commutation facility to the main valves (as explained earlier in another chapter), and
- The capacitor compensates for the leakage inductance (or reactive power demand) of the converter transformer.

Sizing of the commutation capacitor, therefore, becomes a very important criteria as it impacts on the above two effects. A too-small capacitor will cause a large overvoltage across the capacitor (and valves), and not compensate sufficiently for the leakage inductance to result in a lagging current drawn from the ac bus. A too-large capacitor will result in low overvoltages and over-compensate for the demanded reactive power and might even draw a leading current from the ac system. However, a too-large capacitor also has a cost penalty associated with it. Common design practise suggests that an economical capacitor size would be to cause, say, a 10% overvoltage across the capacitor (and valves) as well as compensate for the reactive power demand to present a unity power factor to the ac bus. This design criteria maintains the cost of the valves at a reasonable level.

Figure 6-1: CCC circuit diagram
The capacitor voltage $v_C$ is directly proportional to the dc current $I_d$, the (fixed) time $t$ of conduction of the valve and inversely proportional to the size of the capacitor $C$, i.e., $v_C = (I_d \cdot t)/C$. Since $v_C$ increases with $I_d$, this results in an increase of the dc voltage. This is in direct contrast to the case of a conventional LCC working at minimum extinction angle control where the dc voltage decreases with increase in $I_d$. This feature, therefore, results in a positive inverter impedance characteristic for the CCC providing improved dynamic stability (Figure 6-2). Therefore, the CCC can operate with very weak ac networks, and it can also tolerate a sudden drop of 15-20% in the ac bus voltage without suffering a commutation failure.

The capacitors are protected against overvoltages by parallel ZnO varistors.

![Figure 6-2: Comparison of LCC and CCC stability](image)

### 6.1.1 Reactive Power Management

A comparison between the reactive power management of a LCC and a CCC are shown in Figure 6-3. The LCC serves the same need by means of switchable shunt capacitor banks. Since the CCC provides reactive power compensation $Q$ proportional to the load current $I_d$ of the converter, the need for switchable banks is eliminated. Consequently, ac filters are needed only for harmonic filtering; so their design can be optimized for this duty alone. Typically, only about 13% of the reactive power is required to be supplied by this minimal filter.
In the past, one of the problems of high-performance ac filters (which were sharply-tuned using small capacitor banks) was to keep them in tune while being subjected to daily component and frequency variations. This problem was resolved by use of a continuously tuned reactor which is controlled by a dc current fed into a control winding mounted perpendicular to the main winding, enabling continuous adjustment of its inductance and thus continuously tuning the filter branch.

### 6.1.2 Thyristor Valve Modules

To optimize the cost of the thyristor valves (and the dc side equipment), the nominal dc current is optimized to be as close to the limit of the thyristor current rating at the permitted valve cooling limit. This permits the rated dc voltage to be kept low to achieve the rated dc power. A low dc voltage rating is beneficial for a compact modular valve housing as air clearances can be kept small.

![Diagram of Line Commutated Converter and Capacitor Commutated Converter](image.png)

*Figure 6-3: Reactive power management comparison between CCC and LCC [15]*
The thyristor valves are air-insulated at atmospheric pressure and installed in modular valve housings. Each valve module contains two single valves, i.e. three modules for a 6-pulse converter. The thyristor valves are suspended from the ceiling and easily accessible for maintenance purposes. The surge arresters across the valves are also included in the housings.

6.2 CONTROLLED SERIES CAPACITOR CONVERTER (CSCC)

A modification of the CCC configuration has been proposed [6] where the series capacitor is re-located to be beyond the filter bus and in series with the source impedance (Figure 6-4a). This arrangement can be considered as an amalgamation of the CCC and LCC configurations, and the results obtained from steady state and dynamic performances confirm this. The advantage of this configuration is that the converter is a standard LCC.

In addition, the series capacitors can be controlled similar to a thyristor controlled series compensation (TCSC) scheme (Figure 6-4b). This variant is called the “Controlled Series Capacitor Converter” (CSCC).

6.3 COMPARISON OF CCC AND CSCC

A detailed steady state and dynamic performance comparison of the two systems was carried out in [6].

6.3.1 Steady State Performance

For the purposes of comparison, the two systems shown in Figures 6-1 and 6-4 are connected to a 300 kV ac bus and provide equal amounts of reactive power (116 MVAr referred to the 300 kV bus) from the ac filters and with the same value (22°) for the steady-state extinction angle of the valves at rated conditions. The dc systems in either case are rated at 500 kV, 1.6 kA.
A. Extinction Angle Characteristics:

One advantage of these topologies is that the series capacitors assist in the commutation process. Thus the apparent extinction angle viewed from the 300 kV ac bus bar can approach very small, or even negative values depending on the size of the selected series capacitor. The apparent extinction angle $\gamma_{app}$ is the electrical angle corresponding to the time at which the valve turns off to the positive zero crossing of the corresponding apparent
commutation (line-line) voltage on the ac bus bar. The actual extinction angle $\gamma_{\text{act}}$ is larger because the real commutation voltage is the sum of the line-line ac bus bar voltage and the series capacitor voltages. The selected operating point has a value for $\gamma_{app} = 2^\circ$, which corresponds to an actual $\gamma$ of 22°. The small value of $\gamma_{app}$ results in an improved power factor and diminishes the requirement for shunt reactive power compensation.

Because the voltage on the series capacitor actually increases with dc current, the natural tendency for the extinction angle on an increase in dc current is to increase. This is the converse of the situation for the conventional converter in which an increase in dc current decreases $\gamma$, thereby bringing the converter closer to its commutation failure limit. This characteristic of the CCC or CSCC options is very favorable particularly for long cables. In these cases, a sudden lowering of inverter ac voltage, say due to a remote ac fault results in a sudden increase in dc current. The current controller on the rectifier has a negligible effect on this over-current which is primarily due to a discharge of the cable capacitance. The probability of commutation failure is reduced due to the natural tendency for $\gamma$ to increase with increasing dc current.

Theoretical relationships found in [1,4] of the real extinction angle as a function of dc current for the CCC and CSCC options are plotted (Figure 6-5) assuming a control mode of constant $\gamma_{app} = 2^\circ$. It is noted that the extinction angle increases with dc current and that either option gives essentially the same result.

![Figure 6-5: Comparison of actual and apparent extinction angles [6]](image-url)
B. Maximum Available Power:

Assuming the inverter to be in Constant Apparent Extinction Angle (CAEA) control ($\gamma_{app} = 2^\circ$), a theoretically calculated plot of dc voltage versus dc current (Figure 6-6) shows that the dc voltage for both the CCC and CSCC options has a much smaller slope as compared with the conventional LCC case.

![Figure 6-6: DC voltage versus dc current for CEA control mode [6]](image)

This gives a much larger value for Maximum Available Power (MAP) as compared to a LCC (operated at a typical $\gamma = 18^\circ$), as seen from the theoretically calculated curves in Figure 6-7. If the dc system is operated in the power-control mode, points on the power curve beyond the MAP point are unstable. In fact, for the given system short circuit ratio, the rated operating point would be past the stability limit of 1.5 kA (0.94 pu) for the conventional option. This stability limit is increased to 2.35 kA (1.44 pu) and 2.2 kA (1.34 pu) with the CCC and CSCC options respectively.

C. Converter Valve Voltage Stress:

The valve voltages in the case of the CCC are higher than those for a conventional bridge [1,4]. The converter itself is of the conventional type in the CSCC option. However the steady state voltage on the converter (ac filter bus) is higher (327 kV) than the rated voltage (300 kV) of the system bus. It turns out that considering the transformer turns ratio, the final valve volt-
ages with the CSCC option is the same as in the CCC option at rated conditions. However, for operation with higher ac bus voltages, when the slightly different tap changing regimes for the two options are taken into account, the CCC option is seen to require a somewhat larger valve voltage rating.

D. Harmonics and Filtering:

Since the ac filters are required only for harmonic elimination and not for reactive power support, the MVAR rating of the filter is reduced to very small values, which results in a very narrow passband. To keep the filter in tune for frequency or component variations, one option is to have a continuously tuned filter [4]; another option is to use active filters [11]. Unlike the conventional case, neither option requires filter bank switching for variations in the load over the full range of operation which simplifies the switchyard design. In this study, the filter MVAR rating is selected to be about 15% of the rated dc power.

On account of the smaller overlap angles that results because of the additional commutation voltage provided by the capacitors, the dominant current harmonics (11th and 13th) generated in both options are typically higher than that for the conventional dc installations. Table 6-1 shows the characteristic converter current harmonic magnitude for the CCC and CSCC options at the rated operating point. The CSCC appears to have a smaller harmonic content when compared with the CCC option.
6.3.2 Transient Performance

In this section, comparisons with respect to the performance under transient conditions such as load rejections and ac system faults are discussed.

A. Load Rejection Over-voltages:

Due to the smaller reactive power demanded from the filter bus, both CCC and CSCC options have considerably smaller load rejection over-voltage as compared with a LCC. This is particularly so for a weak ac system in which the equivalent impedance of the ac system is large [10]. For the test system, studies indicate that the magnitude of the load rejection over-voltage for the CCC and CSCC are approximately the same (1.17 pu), but are smaller than the over-voltage for the LCC case (1.4 pu).

B. Three Phase AC Bus Fault:

Typical faults were applied to the two options -- the LCC and CCC -- in order to evaluate the recovery performance of the two systems [12]. No special controls were modeled in this exercise. Figure 6-8 shows (a) dc voltage, (b) dc current and current order, and (c) inverter ac bus voltages for the LCC and CCC options respectively.

The fault is applied at 0.05 ms into the run and has a 5 cycle duration. After an initial over-current, the dc current is brought to zero due to the VDCL action taken at the rectifier end. The nature of the recovery, i.e. peak over-current, over-voltage and recovery is very different in both options.

The LCC option exhibits a slightly under-damped transient during the fault, but has a smooth recovery. The CCC option is more damped during the fault period, but has a small oscillation during the recovery. Both options restore the power to 90% within 150 ms after fault clearing. It is noteworthy that the CSCC option (not shown here) has a similar behavior as the CCC option.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Harmonic #</th>
<th>11</th>
<th>13</th>
<th>23</th>
<th>25</th>
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<td>CCC</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSCC</td>
<td>166.3</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>LCC</td>
<td>140.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-1: AC current harmonics [6]
C. Single Phase Remote AC Fault:

One of the shortcomings of the LCC when used in a long dc cable system is that ac side voltage reductions can cause the dc cable to discharge, transiently increasing the dc current in the inverter. The natural instantaneous effect of a current increase is a loss of commutation margin and hence an increased probability of commutation failure. The CCC and CSCC options have the opposite tendency, in that the instantaneous response to a current increase is an increase in the extinction angle.

In this case, the performances of the LCC and CCC options are compared with the application of a remote ac fault. The dc system is modeled as a long cable, which would discharge into the inverter because of the resulting reduced ac voltage. The inherent characteristic of the converter of increas-
ing $\gamma$ for increasing dc current allows the CCC option to operate successfully through the fault. The single phase fault is simulated by connecting an impedance to the converter bus so as to reduce the Thevenin source voltage by 20%. Results are shown in Figure 6-9.

The CCC option easily rides through the disturbance without suffering a commutation failure with full power recovery within 200 ms. During the fault, a second harmonic current is observed in the dc current; this is a characteristic of an unbalanced fault of this type. The LCC option, however, suffers a commutation failure and requires the assistance of the VDCL protection to reduce the current order.

It is noteworthy that the CSCC option (not shown here) has a similar behavior as the CCC option.

Figure 6-9: Single phase remote ac fault - LCC & CCC options [12]
D. Valve Short Circuit Over-current:

For rectifier operation with the CCC option, the series capacitor significantly reduces the valve short circuit current. In the CSCC option, the series capacitor is not directly between the filter bus and the converter valves, and consequently the short circuit current is larger than in the CCC option. Nevertheless, as shown in Figure 6-10, the magnitude and duration of this current is still smaller than that of the valve short circuit current in a conventional converter.

The performance of the CCC and CSCC options is very similar for steady state as well as transient operation. The maximum valve voltage and the ac current harmonics for the CSCC option are lower than the CCC option. On the other hand, the CCC option in rectifier operation exhibits a smaller valve short circuit current.

![Figure 6-10: Valve short circuit currents][6]

6.4 GARABI INTERCONNECTION BETWEEN ARGENTINA - BRAZIL

The first commercial installation of the CCC type was at the 1100 MW Garabi back to back (BB) interconnection between the 500 kV systems of Argentina and Brazil [13]. Since the Argentinian system is at 50 Hz while the Brazilian system at 60 Hz, a BB frequency converter installation was necessary. Furthermore, since the short circuit levels at the converters were
low, a CCC option was selected to provide the enhanced stability for the ac systems due to the forced commutated converters. A second interconnection of another 1100 MW is under construction. A single line diagram and an aerial view of the installation is shown in Figure 6-11.

Figure 6-11a: Single line diagram of CCC at Garabi [13, 14 and ABB]

Figure 6-11b: Aerial view of CCC at Garabi [13, 14 and ABB]
The principal reasons for opting for the CCC option were:

- Switchable shunt filter banks were not required and replaced by the series capacitor bank to compensate for the reactive power,
- The CCC alternative provided a dynamically more stable operation with the weak ac systems,
- Since the series capacitor’s impedance is typically several times greater than the transformer’s leakage impedance, it reduced the valve currents during dc side short circuits allowing optimization of the transformer and valves, and
- The power factor, seen from the ac bus, could be kept close to unity, or even become positive during certain operating ranges.

Since this installation provides a ground breaking departure from conventional BB stations, some of its unique and innovative aspects are discussed next.

### 6.4.1 Valve Stresses

Due to the higher impedance of the capacitor as compared to the leakage impedance of the transformer, the short circuit currents are considerably reduced (by a factor of between 2-3 times) in the CCC concept as compared to the LCC. This allows the transformer and valve current ratings to be optimized for lower cost.

On the other hand, the voltage across the commutation capacitor results in higher peak voltages across the valves. The capacitors themselves need to be protected from overvoltages by means of Zn0 varistors across them.

Since the series capacitor reduces the overlap angle due to compensation of the leakage inductance of the transformer, switching voltage stresses and losses are reduced.

### 6.4.2 AC Switchyard

The reactive power management of the CCC is far superior when compared to a LCC. The elimination of the switches for reactive power compensation equipment simplifies the design, layout and space requirements of the ac switchyard. Since no ac breakers or disconnects, apart from the energizing purposes (Figure 6-12) are needed, system reliability is improved.
6.4.3 AC Filters

Since the reactive power requirements of the station are now mostly met by the series capacitors, the filtering requirements can be uniquely met by the ac filters. Typically, the ac filters of a CCC provide less than 15% of total converter reactive power demand as compared to about 55% for a LCC. This means that the ac filters need to be high performance units to optimize the costs. Therefore, electronically controlled filters which are sharply tuned (Q factor ~ 150, and therefore lower losses) can be used for the 11th and 13th characteristic harmonics, which are the dominant harmonics for a 12-pulse converter. By contrast, conventional band pass filters have to be equipped with damping resistors to give a broad characteristic to allow them to perform within the frequency and component value variations (Figure 6-13).
Since the CCC acts like a static compensator, giving smooth continuous control of voltage and power flow, the minimum size of the ConTune filters help to keep load rejection overvoltages within limits. Therefore, switching banks are not needed.

The adjustable reactors of the filters are Continuously Tuned (hence the trade name “ConTune”) by a dc current fed into a control winding mounted perpendicular to the main winding (Figure 6-14) and coil arrangement.

**Figure 6-13:** Comparison of conventional Damped filter and ConTune filter

**Figure 6-14:** ConTune filter (a) structure and (b) linearity [15]
The dc current in the control winding influences the magnetic flux in the iron core. A stable control design is achieved due to the high linearity of the rate of change of inductance with dc current, as shown in the figure.

The control loop (Figure 6-15) requires measurement of the ac bus voltage and the filter current to derive the phase angle between them. The control loop then controls the dc current to obtain zero phase shift between the harmonic voltage and current.

![Control circuit of ConTune filter](image)

**Figure 6-15: Control circuit of ConTune filter**

Since no physically moving parts (Figure 6-16) are required for changing the inductance, the equipment enjoys high reliability and limited maintenance requirements.

The filter reactor is the component that controls the tuning of the filter. The reactor consists of four main parts: the coil, the insulating tube, the core and the control winding. A small cooling fan is used to maintain a compact size for the reactor.
6.4.4 Thyristor Valves Modules

To minimize the cost of the valves and dc equipment, the dc current is kept as high as possible within the thermal capabilities of the thyristor and cooling system. This means that for a given dc power, the dc voltage can be maintained low permitting a small air clearance requirement resulting in a compact modular design for the valve housing.

The thyristor valves are air insulated at atmospheric pressure and installed in modular valve housings. Each valve module contains either two or more single valves, which implies up to 6 valve modules per 12 pulse converter. The thyristor valves are suspended from the ceiling and are easily accessible for maintenance purposes. The housing also contains the surge arresters connected across the valves. (Figure 6-17).
6.4.5 Modular Design Benefits

The modular design of the BB station results in saving of time and cost due to following factors:

- No need for a valve hall, control and service buildings. Therefore, the design and cost of the civil structure is kept to a minimum,
- Installation/commissioning time can be reduced considerably since most of the assembly/testing work is performed at the factory,
- A standardized design of the equipment reduces the number of spare parts required which facilitates storage and handling of spares, and
- The modular converter station is compact enough to be fitted into an existing right of way of a typically 400 kV ac line.
6.5 CLOSING REMARKS

The cost of a CCC is presently more than a comparably rated LCC by a factor of about 25%. This cost differential is likely to decrease with time as the cost of the valves will continue to decrease. However, the CCC offers features that the LCC cannot. For this reason, the CCC offers an attractive solution for inter-connecting weak ac systems, and for dc systems with a long dc cable.

6.6 ACKNOWLEDGEMENT

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6.7 REFERENCES


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