PERFORMANCE EVALUATION OF AN HVDC LINK WITH A CAPACITOR COMMUTATED INVERTER CONNECTED TO A VERY WEAK RECEIVING AC NETWORK

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The capacitor commutated converter (CCC) is a new type of HVDC converter topology which shows promise for use in long distance transmission via cables. This technology is, thus, a potential candidate for use in HVDC transmission across large bodies of water. In this paper the technology of Capacitor Commutated Converters (CCC) is presented and the advantages of the CCC for high power transmission are shown. The transient performance evaluations are presented using PSCAD/EMTDC. The system is derived from the first CIGRÉ HVDC Benchmark model. The results demonstrate the superior performance of a CCC link, when connected to a very weak AC system in terms of increased transmission capacity and improved stability of the AC network.

K e y w o r d s: HVDC transmission, CIGRE HVDC Benchmark model, CCC inverter, very weak receiving AC system

1 INTRODUCTION

Conventional HVDC converters have a serious limitation in that they rely on the AC network voltage for the turn-off of the thyristor valves. The robustness of the AC network is therefore of critical importance for proper operation of such converters. Buseman [1] introduced already in 1954 an HVDC-topology, which utilises series capacitors for generating a portion of the voltage required for thyristor valve commutation. This HVDC-converter topology is referred to as the Capacitor Commutated Converter (CCC) and has been reported on by several other authors [2–5]. Other types of artificially commutated converters have also been discussed in literature [6]. The CCC converter; which only recently has been made available by manufacturers, appears much less dependent on the AC network strength and on other network disturbances for successful valve commutation. Therefore, it should offer an attractive alternative to conventional DC transmission, particularly when the converter is applied in extremely long DC cable transmission or feeds a weak AC network.

The main focus of this paper is therefore to examine the dynamic performance of an HVDC CCC-inverter connected to a very weak AC system. The first CIGRÉ HVDC Benchmark model [7, 8] is used as a test system. Results obtained confirm the superior performance of the CCC in applications involving very weak AC systems. The simulation results are presented using PSCAD/EMTDC.

2 THE CAPACITOR COMMUTATED CONVERTER

A capacitor commutated converter (CCC) is a conventional HVDC converter provided with commutation capacitors between the transformer and valves, as shown in Fig. 1. The basic function of this concept is that the capacitors contribute to the valve commutation voltage. This contribution makes it possible to operate the CCC with much lower reactive power consumption compared to the conventional converter. Further, CCC gives a more robust and stable dynamic performance of the inverter station, especially when inverters are connected to weak AC systems and/or long DC cables. Increased commutation margins can be achieved, without increasing the reactive power consumption of the converter station, by reducing the capacitance of the commutating capacitors in order to increase their contribution to the commutation voltage [9].
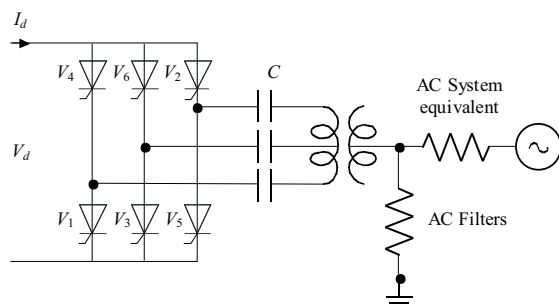

Fig. 1. The CCC HVDC

In the CCC it is necessary to distinguish between the apparent extinction angle (γ') and the real extinction

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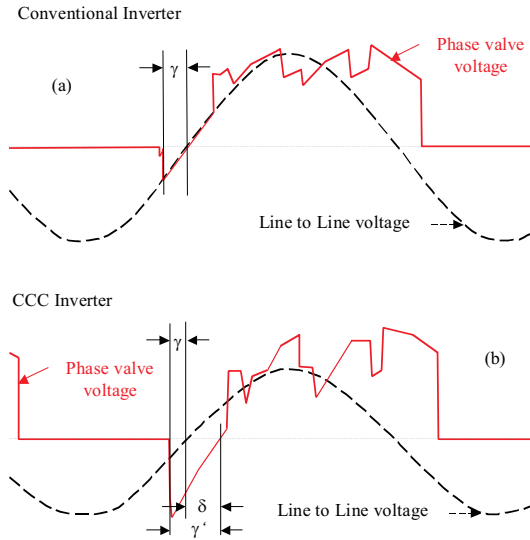
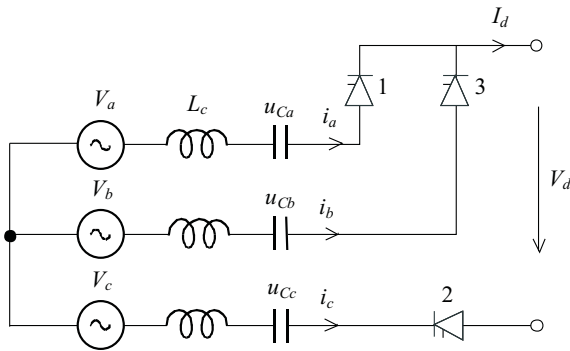**Fig. 2.** AC bus voltage and valve voltage waveforms: (a) — conventional inverter, (b) — CCC inverter

Fig. 3. Equivalent CCC circuit during commutation from valve 1 to valve 3 (non-conducting valves not shown)

angle (γ) as shown in Fig. 2. In the conventional HVDC converter, the extinction angle y is defined as the electrical angle corresponding to the time at which the valve turns off to the positive zero-crossing of the line-to-line voltage at the ac converter bus, is given by

$$\gamma = \pi - (\alpha + \mu) \qquad (1)$$

where α is the inverter firing angle, and μ is the overlap angle. However, in the case of the CCC this measurement does not take into account the capacitor voltage and is therefore not a measure of the real extinction angle. It is therefore referred to as the apparent extinction angle (γ')

$$\gamma' = \pi - (\alpha + \mu) + \delta. \qquad (2)$$

The commutation margin-angle γ' in the CCC inverter is the angle between the end of commutation and the valve voltage positive zero crossing. Where δ is the phase-lag angle between the AC bus voltage and thyristor valve voltage Fig. 2.

Due to its reliance on the additional capacitor voltage the CCC has contrary to the conventional the ability to

operate at a firing angle or at an extinction angle at very small or even negative angles with the choice of suitable series capacitors. The CCC has thus, the ability to produce reactive power both in the rectifier and the inverter operation mode.

3 THE CCC COMMUTATION DURING OVERLAP

Figure 3 shows the equivalent converter circuit during commutation from valve 1 to valve 3.

The instantaneous line-to-line voltages of the AC sources are taken as:

$$V_{ac} = V_a - V_c = \sqrt{3}V_m \cos(\omega t + 30°),$$
$$V_{ba} = V_b - V_a = \sqrt{3}V_m \cos(\omega t - 90°), \qquad (3)$$
$$V_{cb} = V_c - V_b = \sqrt{3}V_m \cos(\omega t + 150°).$$

The mesh equation for the commutation loop from valve 1 to valve 3 is

$$V_b - V_a + u_{cb} - u_{ca} = L_C \frac{di_b}{dt} - L_C \frac{di_a}{dt}. \qquad (4)$$

Using equation (3) and taking into account that the direct current is constant this can be written as

$$\sqrt{3}V_m \sin(\omega t) + u_{cb} - u_{ca} = 2L_C \frac{di_b}{dt}. \qquad (5)$$

Under normal operating conditions, the capacitors in phase (a) and (b) are charged in such a way as to accelerate the commutation. Unfortunately, the capacitor voltages themselves depend again on the current i_b:

$$C\frac{du_{ca}}{dt} = -i_a = i_b - I_d, \qquad (6)$$
$$C\frac{du_{cb}}{dt} = -i_b. \qquad (7)$$

An analytical solution is presented in [2]. A much simpler solution which is nonetheless quite accurate will therefore be developed here based partly on [10].

We have assumed by symmetry that the capacitors charge to a maximum/minimum voltage of $+\hat{V}_C/-\hat{V}_C$. The total excursion of capacitor voltage from peak to peak is:

$$\hat{V}_C = \frac{\pi}{3\omega C} I_d. \qquad (8)$$

Integrating equation (5) over the interval of overlap and inserting the boundary conditions $i_b(\omega t = \alpha) = 0$ and $i_b(\omega t = \alpha + \mu) = I_d$ yields

$$\frac{\sqrt{3}V_m}{2\omega L_C I_d}\big(\cos\alpha - \cos(\alpha+\mu)\big) + \frac{\mu}{6\omega^2 L_C C}(2\pi - \mu) = 1. \qquad (9)$$

This equation is transcendental and needs to be solved for μ numerically. However, it can be further simplified
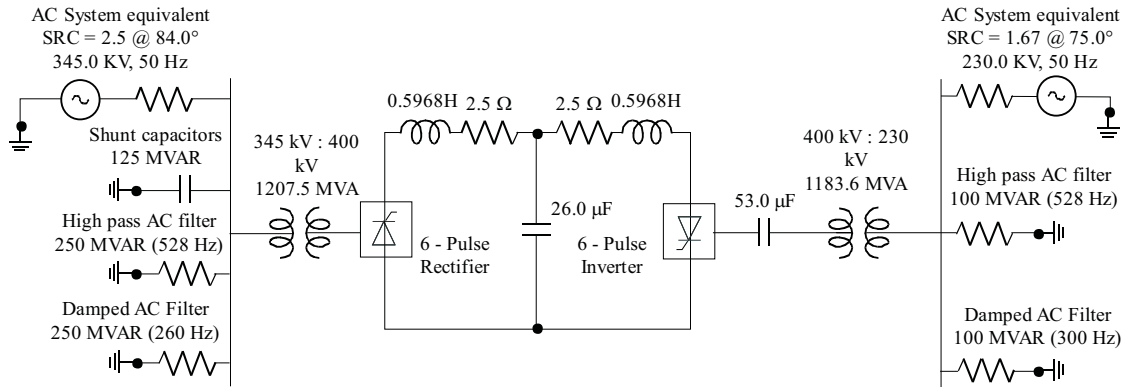
Fig. 4. HVDC Link

by approximating $\cos(\alpha + \mu)$ with a second-order Taylor series

$$\cos(\alpha + \mu) \approx \cos\alpha - \mu\sin\alpha - \frac{\mu^2}{2}\cos\alpha. \quad (10)$$

Equation (9) then reduces to a quadratic equation in μ with the solution

$$\mu \approx \frac{\sqrt{4A + B^2} - B}{2A} \quad (11)$$

where

$$A = \frac{\sqrt{3}V_m}{2\omega L_C I_d}\frac{\cos\alpha}{2} - \frac{1}{6\omega^2 L_C C}, \quad (12)$$

$$B = \frac{\sqrt{3}V_m}{2\omega L_C I_d}\sin\alpha + \frac{2\pi}{6\omega^2 L_C C}. \quad (13)$$

4 SYSTEM UNDER STUDY

A 1000 MW (500 kV, 2 kA) DC interconnection is used to transmit power from a 345 kV, 2500 MVA, and 50 Hz network to 230 kV, 1670 MVA, and 50 Hz network, with a capacitor commutated inverter. This system is derived from the first CIGRE benchmark model with some modifications to facilitate the study of the system (6-pulse converters), as shown in Fig. 4. In contrast to the conventional HVDC transmission system the reduced extinction angle, due to the additional commutation voltage supported by the CC, leads to a decreased consumption of reactive power. So the AC filter capacitors can be smaller and the quality of the filters can be improved. It is practical to limit the size of the capacitors to a value allowing extending the firing angle range at the inverter up to 180° [5].

The capacitance of the CC used in this model is determined to $C = 53\,\mu\text{F}$. The AC networks, both at the rectifier and CCC-inverter end have a Short Circuit Ratio (SCR) of 2.5 and 1.67 respectively, which is defined as

$$SCR = \frac{S_{MVA}}{P_{dc}} \quad (14)$$

where S_{MVA} is the short circuit capacity of the connected AC system, and P_{dc} is the rating of the converter terminal in MW.

The following SCR values can be used to classify an AC system [10]:

a) a strong AC system is categorized by an $SCR \geq 3$.
b) a weak AC system is categorized by $2 \leq SCR < 3$.
c) a very weak AC system is categorized by an $SCR < 2$.

4.1. The AC systems

The AC networks, both at the rectifier and inverter end, are modelled as infinite sources separated from their respective commutating buses by system impedances. The impedances are represented as R–$R//L$ networks having the same damping at the fundamental and the third harmonic frequencies. The impedance angles of the sending end and the receiving end systems are selected to be 84° and 75° respectively.

4.2. DC system

The DC line parameters were chosen to represent a high voltage cable of about 100 Km length. High capacitances normally give rise to more problems as far as DC control settings are concerned.

4.3. The Converter transformers

The two converter transformers are modelled with three-phase transformer (Two-Windings). The parameters adopted (based on AC rated conditions) are considered as typical for transformers found in HVDC installation such as leakage $X_C = 0.18$ pu.

4.4 AC filters and capacitor banks

On AC side of 6-pulse HVDC converter, current harmonics of the order of 5, 7, 11, 13 and higher are generated. Filters are installed in order to limit the amount of harmonics to the level required by the network. In the conversion process, the converter consumes reactive power, which is compensated in part by the filter banks and the rest by capacitor banks of 625 Mvar on the rectifier side, and 200 Mvar on the inverter side.
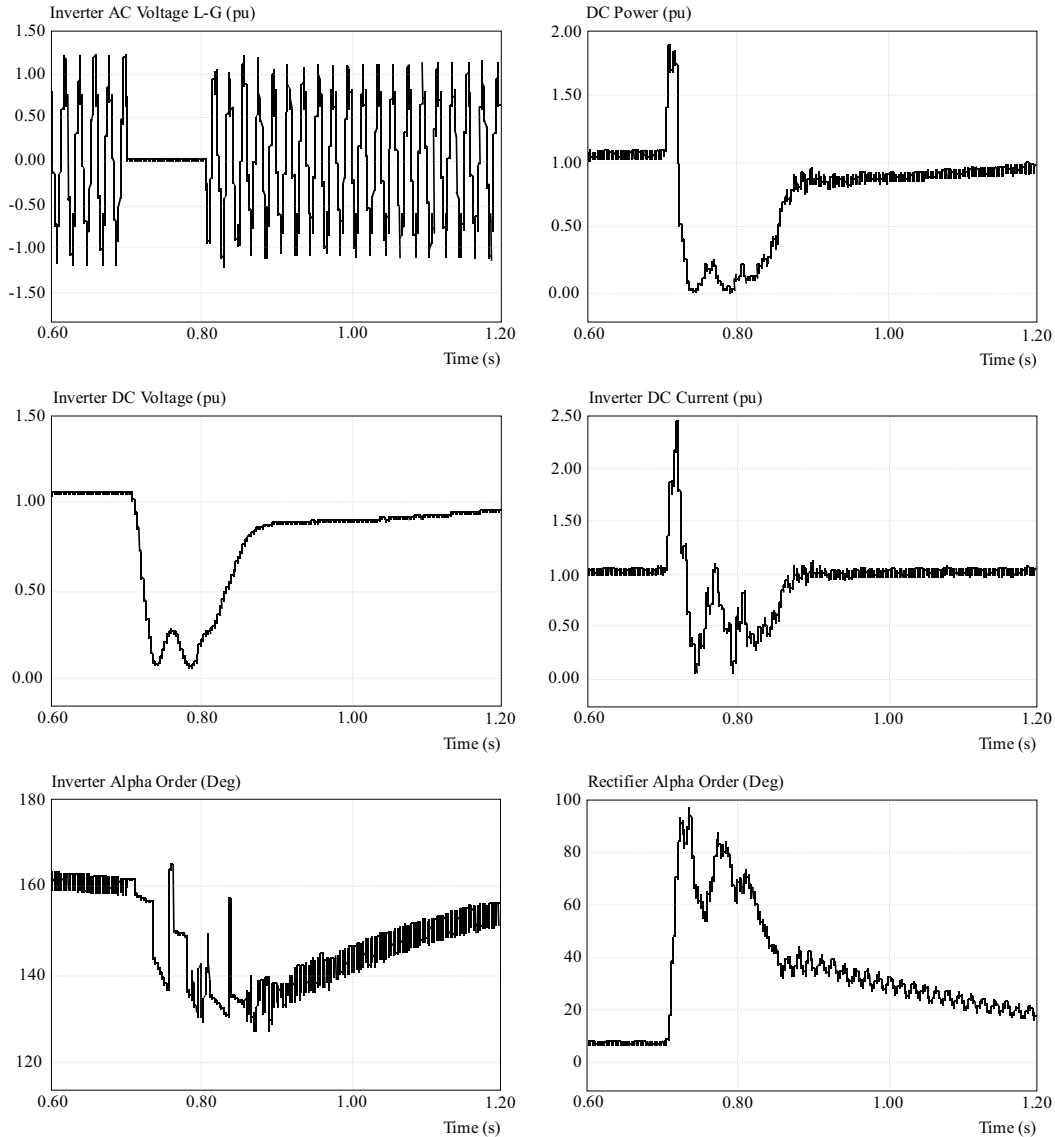
Fig. 5. Single phase-to-ground fault at inverter side

4.5 Control system

In normal operation, the rectifier controls the current at the Id_ref reference value whereas the inverter controls the voltage at the Vd_ref reference value. Another important control function is implemented to change the reference current according to the value of the DC voltage. This control named Voltage Dependent Current Order Limits (VDCOL) automatically reduces the reference current (Id_ref) set point when VdL (Vd line) decreases (as for example, during a DC line fault or a severe AC fault). Reducing the Id reference currents also reduces the reactive power demand on AC network, helping to recover from fault [11, 12].

5 STEADY–STATE PERFORMANCE

5.1 Reactive power consumption

It is known for the conventional HVDC converter that the reactive demand is approximately 50 % of the ac-

tive 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. It can be seen, that even large changes in the transmitted DC power do not actually affect 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 step-wise switch-able in relation to the reactive power demand and may result unfavourable voltage steps at switching. The CCC-converter can avoid this problem due to its relative constant and low reactive power demand, where switching is not needed.

5.2 Maximum available power (MAP)

The power transmission capability of a given network is greater with capacitor commutated converters than
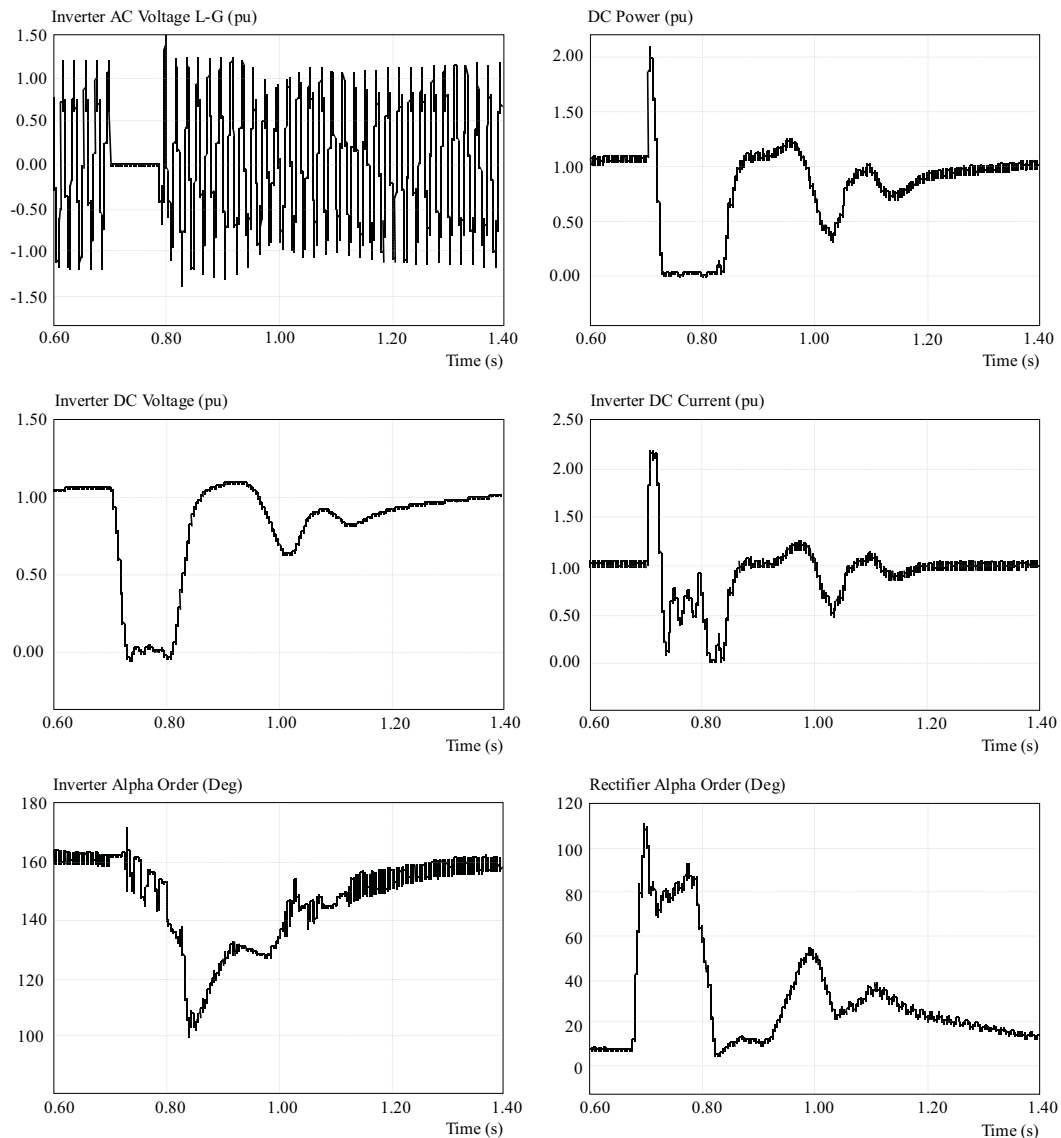
Fig. 6. Three phase-to-ground fault at inverter side

with conventional technology as clearly shows in [13]. 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).

6 DYNAMIC PERFORMANCE

In this section the following types of disturbances are examined in this paper
1. Single phase-to-ground fault at the inverter side.
2. Three phase-to-ground fault at the inverter side.
For each of the transient case considered above, plots of DC power, rectifier firing angle, and the inverter AC voltage, DC current, DC voltage, and firing angle, are given.

6.1 Single phase-to-ground fault at inverter side

The fault was applied to the A-phase of the inverter bus, and the duration of the fault was 5 cycles (100 ms).

Results of this study are shown in Fig. 5. The test system has a short circuit ratio (SCR) equal to 1.67 at the inverter side, which is very low. Employing a conventional converter in such a weak AC receiving system would not be feasible due to control instability.

When this fault is applied at $t = 0.7$ s (cleared at $t = 0.8$ s), the AC voltage drop causes commutation failures, which are represented in the simulation as a short circuit across the inverter. The dc current then rapidly rises. During the fault period, the VDCOL reduces the current order to its minimum value. The VDCOL action allows system recovery, avoiding voltage collapse due to the otherwise high reactive power consumption of the inverter after fault clearance. The system recovers in approximately 0.1 s.

The recovery time is defined as the time from fault clearing to the instant at which 90 % of the pre-fault DC power is restored.

B. Three phase-to-ground fault at inverter side

A three-phase-ground was applied to the three phases of the inverter bus at $t = 0.7$ s. The duration of the fault was 4 cycles (80 ms). Results of this study are shown in Fig. 6.

When the fault is applied, due to a sudden reduction in the inverter DC voltage there is overshooting in DC current of magnitude 2.2 pu. The rectifier current controller attempts to reduce the DC current by increasing the firing angle of the rectifier. The rectifier therefore goes into the inverter region. The DC current reduces to a low average value as determined by the VDCOL. After the fault clearing at $t = 0.78$ s, the VDCOL operates and rises the reference current to 1 pu. The system recovers in approximately 0.3 s after fault clearing.

6 CONCLUSION

The transient behaviors of a CCC inverter feeding a very weak AC system were investigated by modeling the first CIGR benchmark model using PSCAD/EMTDC.

The capacitor commutated converter has many beneficial features that make it attractive for use in an HVDC transmission system connected to a very weak receiving AC system. The effectiveness of these features can be studied using steady-state and transient analyses. The CCC is superior to the conventional inverter in its low reactive power demand. Moreover, the maximum power transmission capability (MAP) is greater with capacitor commutated converters than with conventional technology.

The transient analysis shows that the CCC-HVDC system demonstrates a good behavior following a single phase-to-ground and a three phase-to-ground fault at a very weak receiving AC network. However, employing a conventional converter in such situation would not be feasible.

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