A COMPARISON OF CONVENTIONAL AND CAPACITOR COMMUTATED CONVERTERS BASED ON STEADY-STATE AND DYNAMIC CONSIDERATIONS

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Abstract: The Capacitor Commutated HVDC Converter (CCC) is evaluated using steady-state as well as transient analysis. The steady-state analysis indicates that the CCC device is superior to the conventional converter when operating into very weak ac-networks. This is also confirmed by electromagnetic transient simulation. However, transient simulation shows that the CCC’s performance is poorer than its conventional counterpart when recovering from unbalanced disturbances such as single-phase faults.

Keywords: Capacitor Commutated Converter, Long Cable HVDC Transmission, Weak AC Networks.

INTRODUCTION

Conventional HVDC converters appear to have a drawback in that they rely on the ac-network voltage for the turn-off of the thyristor valves. This imposes a serious limitation particularly when the converter is applied in extremely long dc cable transmission or feeds a very weak ac-network. The CCC topology (1,2) includes capacitors in series with the valve side transformer windings as shown in Fig. 1. The voltages on these capacitors aid in the commutation process thus resulting in a more robust converter, which is potentially less dependent on the ac-network strength and more robust against network disturbances. This feature makes the CCC attractive for long cable dc transmission schemes. In a conventional scheme with a long dc cable, a lowering of the inverter voltage can cause a large dc current surge due to the discharge of the capacitor, which increases the likelihood of commutation failure. The CCC, on the other hand, is better able to withstand sudden dc current increases. This technology is, thus, a potential candidate for use in long cable submarine transmission such as the HVDC-connections with cable lengths of about 600 km, which are currently in the planning stage in Northern Europe.

The paper begins with an analytical steady-state study, which is used to examine the operational characteristics for both the CCC and the conventional HVDC converter. An evaluation of the transient performance using PSCAD/EMTDC simulation is then conducted in order to critically examine the performance of the CCC in a typical cable transmission application.

STEADY-STATE PERFORMANCE

An analytical formulation is developed in order to investigate and compare the steady-state behaviour of the CCC and conventional HVDC converter topologies. This formulation allows the conduct of preliminary investigations regarding applicability and steady-state control characteristics.

The formulation represents a 6-pulse 800 MW (500 kV, 1.6 kA) inverter connected to an ac-network equivalent, as shown in Fig. 1. It consists of 14 non-linear power flow equations and 18 unknown variables, which are listed in the Appendix. The numerical solution is obtained by first specifying any four variables and then using the Newton-Raphson iteration technique.

The formulation is based on fundamental frequency quantities only. It is valid for the representation of steady-state phenomena in the time-scale after the actions of the HVDC-controls, but prior to the response of voltage controlling devices in the ac-network (such as transformer tap-changers, synchronous machines and SVCs).

As mentioned earlier, the CCC is an HVDC converter topology that shows promise for use in long distance transmission via cables. It is interesting to study the consequences of increased current when the cable capacitance discharges. This is particularly important when the inverter is connected to a weak ac-network. The analytical formulation has the capability of analysing the inverter for various control modes and for different levels of SCR. The short-circuit-ratio (SCR) is a measure of the ac-network strength via a-vis the transmitted dc-power.

Parametric plots can be generated from several successive steady-state solutions where one of the pre-specified variables is incremented from one solution to the next. Typical studies include the calculation of the Maximum Power Curve (MPC), the stability limits for the ac/dc- system and ac-voltage variations including load-rejection overvoltages as the dc-current varies.

A base case solution is required in order to produce a parametric plot. In this case $V_d=500$ kV, $I_d=2.4$ kA,
γ=20.4 degrees and Vlp=300 kV are chosen as the pre-specified variables. The base case solution represents the rated condition and is indicated in the graphs. In each parametric plot, where a given variable is plotted as a function of I\textsubscript{dc}, the transformer turns ratio n and the network equivalent voltage V\textsubscript{s} are held constant at the values found in the base case solution. Each parametric plot consists of a number of successive solutions where I\textsubscript{dc}, γ\textsubscript{app}, n and V\textsubscript{s} are the pre-specified variables and where I\textsubscript{dc} is slightly increased from one solution to the next.

The objective here is to compare the steady-state behaviour of the CCC and the conventional HVDC-converters. The comparison between the two converter types is carried out when they are connected to a relatively weak ac-network (SCR=1.82). The formulation is equally adept at handling the conventional inverter as a degenerate case with the impedance of the CCC series-capacitors set to zero.

The results presented in Fig. 2, show that the dc-voltage regulation for the CCC is far more superior to that of the conventional option as evidenced by the flatness of the voltage profile. The CCC also maintains the inverter ac-voltage closer to rated value in comparison to the conventional inverter. It is evident from the MPC-curve that that the CCC is superior to the conventional converter in terms of dc-power capability. The plots clearly show that the CCC has both a higher Maximum Available Power (MAP) and a larger dc-current stability limit in comparison to the conventional converter. Hence, the margin from the stability limit is larger in the CCC-option, indicating more robust operation. The results also show that the natural tendency for the real extinction angle is to increase when the dc-current becomes larger. This is caused by the larger series-capacitor voltage, which results in a larger real extinction angle, since the apparent extinction angle is kept constant by the controls. This characteristic of the CCC reduces the likelihood for commutation failure, particularly for long cables, where any lowering of the inverter ac-voltage results in a surge of current from the discharge of the cable capacitance.

The results obtained by the analytical study for the CCC-inverter type was verified by electromagnetic transient simulation (indicated by crosshair markers). As may be seen from the graphs, the simulated and the analytical results agree well up to rated conditions (I\textsubscript{dc}=1.6 kA). There is, however, a small deviation at larger currents, but the curves demonstrate a very similar trend. This indicates that the derived steady-state CCC-equations and the iteration algorithm have been correctly implemented in the computer program.

The primary point to be recognised is that the CCC-option, based on steady-state analysis, demonstrates a more robust operation against a sudden increase in current.

**Fig. 2. Steady-state comparison between the CCC and the conventional inverter.**

**TRANSPORT PERFORMANCE**

The analytical formulation is based on steady-state equations at fundamental frequency. In order to make a more thorough comparison between the two converter types, a study using electromagnetic transient simulation is necessary. Such a study will also take into account the transient nature (gains, time-constants, limits, etc.) of the
Modelling

The suitability of the CCC-inverter is investigated in a 600 km long cable 12-pulse HVDC-scheme of 1200 MW (500 kV, 2.4 kA) power rating, as shown in the Appendix. The conventional rectifier is connected to a very strong sending end, whereas the inverter is connected to a relatively weak receiving ac-network (SCR=2.05). At the CCC-inverter's ac-bus, there are bandpass filters to eliminate harmonic components of 11th, 13th, 23rd and 25th order, as well as a highpass filter for removal of higher order harmonics. The total reactive power installation in the ac-filters and the shunt capacitors at the conventional inverter bus is 55 % of its rated dc-power. The ac-filters at the CCC-inverter bus have a reactive power installation of only 14.5 % of the rated dc-power, because this converter type consumes significantly less reactive power. The ac-network on the inverter side is represented by an RRL-type equivalent with a SCR equal to 2.05 and a damping angle of 85 degrees at fundamental frequency. The selection of the series-capacitor impedance represents a trade-off between a good power factor and a sufficient margin to commutation failure versus low voltage stress on the thyristor valves. The 144 µF value selected in this design is based on 10 % additional voltage stress on the valves compared to the conventional converter. The overvoltages across the series-capacitors are limited to 3 pu by surge arresters. Smoothing inductors of 0.4 H are located at both the rectifier and inverter side of the dc-connection. The dc-cable is modelled as simple π-equivalent. The rectifier operates in voltage control and the inverter operates in current control during normal operation in both types of HVDC-schemes. Additional control details are described in (3).

Results

The transient performance of the CCC and the conventional HVDC scheme was investigated when various faults were applied in the inverter ac-network and when setpoint changes were made in the controls.

Inverter load rejection overvoltage. A sudden change in dc-power transmitted, for instance caused by an inverter load rejection, results in an immediate surplus of reactive power. This will temporarily raise the inverter bus voltage particularly if the ac-network is weak. The steady-state overvoltage resulting from the load rejection of the CCC-inverter is recorded to 350.5 kV (i.e. 1.17 pu). This is significantly smaller than the 448.5 kV (i.e. 1.50 pu) overvoltage generated by load rejection of the conventional inverter.

The CCC is able to operate at significantly lower extinction angles than the conventional option. The lower load rejection overvoltage for the CCC is simply due to the smaller amount of reactive power installed in ac-filters and shunt capacitors at its inverter bus.

Robustness against remote ac-fault. The robustness against two types of remote faults is investigated for both HVDC-schemes. A remote fault is, in this context, defined as a fault occurring electrically distant from the inverter bus. The remote fault is simulated by connecting a shunt reactor (due to the inductive impedance of transmission lines) to the inverter bus. The minimum value of fault inductance under which the system remains operating without suffering commutation failure, is identified by trial and error. Any fault with more severity (lower inductance) than this limiting value causes commutation failure. Because a low inductance corresponds to a more severe fault, the lower the limiting inductance, the more robust is the scheme. The results are obtained with a fault clearance time of 200 ms.

First, the inverters' robustness against a single-phase-to-ground remote fault is investigated. This is the most typical type of fault that occurs in overhead lines and is by Thio et al (4) considered more severe than a three-phase-fault in terms of commutation failure. The reason for this is due to the fact that the single-phase faults result, contrary to the balanced three-phase fault, in phase-shifts in the zero-crossings of the commutation voltages. These phase-shifts decrease the commutation margin for some of the thyristor valves and increase it for other valves.

The results do not support this theory since both inverter types demonstrate a larger degree of robustness against single-phase faults in comparison to three-phase faults. The reason could be the presence of the large cable capacitance, since the single-phase fault results in a smaller lowering of the dc-voltage and thus also a smaller discharge current from the cable. The results for the single-phase remote fault show that the conventional inverter is able to withstand a more severe fault (0.75 H) in comparison to the CCC (1.04 H).

The steady-state impact of a three-phase-to-ground remote fault is first investigated theoretically. It is evident that the fault causes the inverter ac-voltage to drop in magnitude and its phase to move in the leading direction. Both these effects bring the inverter closer to commutation failure. They happen immediately and occur at both inverter types, but to a larger extent for the conventional inverter than for the CCC. The theoretical results therefore indicate that the CCC is the most robust option against this type of remote fault.

Let us consider the immediate impact caused by the remote fault prior to any response from the controls. The drop in inverter ac-voltage magnitude clearly increases the overlap angle and hence increases the likelihood of commutation failure. The positive phase shift in the ac-voltage takes place instantaneously, whereas the phase-lock-loop (PLL) based firing scheme needs, due to its time constants, a certain time to lock on to the ac-voltage again. The ac-voltage leads its PLL-signal during this period of time, which means that the firing angle is transiently larger than the ordered firing angle. A larger
firing angle at the inverter results in a smaller commutation margin since the valves becomes forward biased sooner before they cease conducting. Both the above-mentioned effects are thus bad from the commutation point of view, but they have opposite impact on the inverter dc-voltage. The drop in magnitude permanently reduces the dc-voltage, whereas the positive phase-shift temporary increases the dc-voltage. It is evident from the results that the dominant effect is due to the drop in magnitude, since the response from the controls is to compensate for the reduction in dc-voltage by increasing the firing angle. The results for the three-phase remote fault show that the CCC inverter is able to withstand a more severe fault (1.16 H) in comparison to the conventional inverter (1.22 H).

The results therefore show that the CCC is more robust against a three-phase remote fault, but less robust against a single-phase fault than the conventional inverter.

**Recovery from close-in ac-faults.** Commutation failure and succeeding discharge of the cable into the inverter ac-network is often unavoidable if the ac-fault takes place electrically close to the inverter bus. Recovery of HVDC-schemes is usually more difficult and slower for weak ac-networks than for strong networks. Fast recovery is, however, more critical for weak networks in order to maintain stability, because they are less capable of withstanding the temporary deficit of power.

The recovery performance is investigated when a 50 ms single-phase and a three-phase to ground fault are applied at the ac inverter bus. The clearance time is mainly determined by the relay detection time and the breaker switching time. The latter obviously depends on the type of breaker used. The selected fault clearance (50 ms) requires state-of-the-art equipment both for relays and breakers. 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.

The single-phase to ground fault is, in general, considered to be less severe than three-phase faults in terms of power system stability. This type of unbalanced fault can, however, be particularly critical for the CCC since it may generate imbalance in the series capacitor voltages resulting in performance deterioration during transients. The surge arresters will however limit any imbalances from reaching extreme values.

**Figure 3.** Single-phase to ground fault applied at the inverter bus.

![Fig. 3.](image)

Figure 3 shows the recovery performance following the single-phase fault of both the conventional (dashed) and the CCC (solid-drawn) inverter based scheme. The results show that the CCC has a slower recovery (240 ms) than the conventional type (145 ms). The surge of current into the ac-network, given by the inverter dc-current, is close to identical (18 kA, i.e. 7.5 pu) for the two options. The negative power during recovery is a
consequence of the voltage being negative. With a sustained line-to-line short circuit as happens during commutation failure, the ac-voltage gets applied to the dc-side resulting in this negative value.

The recovery performance following the three-phase fault show that the conventional alternative has a much higher temporary overvoltage after fault clearance in comparison to the CCC-alternative. The surge of current into the ac-network, given by the inverter dc-current, is reduced from 18.1 kA (i.e. 7.5 pu) in the conventional option to 10.6 kA (i.e. 4.4 pu) in the CCC-option. This is favourable since it reduces the current stress on the valves. The CCC-alternative demonstrates a quicker recovery (90 ms) than the conventional alternative (145 ms). This rapid recovery is quite remarkable, particularly in the view of the weak inverter ac-network. The dc-voltage, and thus the dc-power, becomes negative during recovery in the conventional option.

Both schemes demonstrate a recovery time that falls within 300 ms both for unbalanced and balanced faults. This is considered acceptable since most HVDC-schemes recover within 100 to 300 ms. The transient peak in the rectifier dc-current is lower in the CCC-option for both types of faults.

Set-point changes in the dc-controllers. A step-change is made to the dc-current order at rated conditions to evaluate the robustness of the schemes to set-point changes in the controls. This essentially means a step-change in the ordered dc-power. A generally accepted performance level is that the HVDC-schemes should follow an instantaneous ±10% change in order. Both alternatives meet this specification, albeit with different margin. The maximum step-change that could be made without causing commutation failure is significantly larger (24 %) for the CCC than the conventional inverter (16 %). Both inverter options allow a 99 % reduction in the dc-current from rated conditions. The results are highly dependent on the settings in the controls, particularly the maximum allowable change in the Voltage Dependent Current Order Limit (VDCOL). With the settings selected here, it is evident that the CCC demonstrates better performance than the conventional scheme.

CONCLUSIONS
An analytical formulation was developed in order to investigate the steady-state behaviour of the Capacitor Commutated Converter and conventional HVDC converters. The validity of the formulation was confirmed by electromagnetic transient simulation. The steady-state results obtained by the formulation, show that the CCC is superior to the conventional converter in its voltage regulation, ability to work into depressed voltage systems, stability margin and ability to avoid commutation failure when operated in power control.

The transient analysis shows that the CCC does not demonstrate an uniformly favourable performance in a long cable HVDC transmission scheme when compared to the conventional converter type. It is true that the load rejection over-voltages are smaller for the CCC and its performance under balanced remote- and close-in faults is superior. The CCC also allows larger set-point changes in the controls. However, with unbalanced disturbances such as single-phase to ground faults, the conventional converter demonstrates the better performance.

The likely reason for this behaviour is the additional dynamics due to the energy storage in the CCC’s series-capacitors. For unbalanced disturbances, each of the series-capacitor voltages impacts the system to differing degrees.

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REFERENCES
APPENDIX

The analytical steady-state formulation for the CCC consists of 18 variables and 14 equations.

\( V_d, I_d \) - Dc voltage and current.
\( \alpha, \gamma, \mu \) - Firing-, apparent extinction- and overlap angle.
\( \Delta v_1, \Delta v_2 \) - Change in series capacitor voltage for incoming and outgoing valve during overlap interval.
\( B \) - Constant resulting from the solution of the overlap differential equations
\( n \) - Transformer turns ratio (primary/valve side)
\( V_p \) - Transformer primary side ac-voltage
\( I_p, \phi \) - Magnitude and phase of ac-current in transformer.
\( I_s, \phi \) - Magnitude and phase of the current in ac-network.
\( V_s, \delta \) - Ac-network source voltage magnitude and phase.

Symbols:
\( L, C \) - Transformer leakage inductance, series capacitor.
\( Z_s, Z_f \) - Ac-network- and filter impedance.
\( \omega \) - Ac-network angular frequency.
\( \omega_0 \) - Angular frequency for comm. circuit \((=1/\sqrt{LC})\). 

The first six equations of the 14 required are obtained by applying Ohm’s Law on the ac-side of the transformer:

\[
\begin{align*}
V_p - V_s &= \sqrt{3} Z_s I_s \quad (1.2) \\
I_{ap} &= I_d + I_s \quad (3.4) \\
V_p &= I_0 \sqrt{3} Z_f \quad (5.6)
\end{align*}
\]

Each of these three equations in complex form is divided into two equations based on their real and imaginary part.

The other eight equations are related to the converter:

\[
\begin{align*}
\Delta v_2 &= \frac{V_{lp} I_0}{n \sqrt{2(\omega_0^2 - \omega^2) L} \sin \alpha - \frac{\pi L_0 (\omega_0^2 - \omega^2) L}{3\omega} = B} \quad (7) \\
\Delta v_1 + \Delta v_2 &= \frac{I_d \mu}{\omega C} \quad (8) \\
\frac{n L_0}{\pi} &= \frac{\sqrt{3}}{\pi} I_d \quad (9) \\
\cos \phi_0 + \frac{\cos \alpha + \cos(\alpha + \mu)}{2} &= 0 \quad (10) \\
\alpha + \mu + \gamma_{app} &= \pi \quad (11)
\end{align*}
\]

The apparent extinction angle \( \gamma_{app} \) is a measure of the inverter’s power factor since it is related to the positive zero-crossing of the inverter bus voltage. The real extinction angle \( \gamma_{real} \) is related to the commutation voltage, and is hence a measure of margin to commutation failure. Based on the solution of the analytical formulation, \( \gamma_{real} \) is calculated by solving the following equation by an iterative technique.

\[
\frac{\sqrt{2} V_{lp}}{n} \sin(\alpha + \mu + \gamma_{real}) + \frac{2 \pi L_d}{3 \omega C} - \Delta v_1 - \frac{I_d \gamma_{real}}{\omega C} = 0 
\]  

(15)

Figure 4 presents the CCC-inverter-based 1200 MW HVDC-scheme used for the electromagnetic transient simulation studies. Both transformers (YY and YΔ) have a turns ratio of 185/300 kV and a leakage reactance of 0.15 pu. The conventional HVDC scheme is similar in its design, but differs in transformer turns ratio, reactive compensation and control parameter settings.

**Fig. 4. The 1200 MW HVDC-scheme employing CCC-type inverters.**