Verification of the CCC concept in a high power test plant

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The paper presents the first high power verification of ABB’s Capacitor Commutated Converter (CCC) concept. The high power tests were performed in a 6-pulse back-to-back test plant.

The purpose of the CCC-tests was to gather experience of the concept with the plant run at high power and with components manufactured in the same manner as for commercial plants. The test results presented include steady state operation, valve short circuit and AC ground faults. The CCC tests in the high power test circuit have also verified the results obtained from calculations and computer simulations.

The high power tests have confirmed that the CCC is a safe and robust converter alternative.

Summary

Main Circuit Configuration

The main circuit consists of two 6-pulse converter bridges connected as a back-to-back converter with a smoothing reactor. Both bridges are connected to a generator through separate transformers and commutation capacitors. On the generator side there are passive filters for the 5th, 7th and higher order harmonics.

The valve bridges are supplied with a total of four extra valve functions and six disconnectors in order to enable valve short-circuit testing. The disconnectors and the valve functions are individually controlled to perform the correct selection of the valve that is to be included in the short-circuit test.

A single-line diagram of the main circuit is presented in Fig. 1.

Key terms

Valve-test-plant, Valve-short-circuit, Capacitor-commutated-converter, CCC

The Valve Test Plant

The Valve Test Plant (VTP) is a test facility where HVDC thyristor modules are type and sample tested. The thyristors and their associated components are tested with the same stresses as in the real plant and the rating of the valve components is therefore accurately and thoroughly verified.
For the CCC test set-up the following main circuit parameters were selected:

- Nominal DC power = 12 MW
- Nominal DC voltage = 8 kV
- Nominal DC current = 1500A
- Nominal generator voltage = 3.7 kV
- Nominal no-load ideal voltage = 8 kV
- AC filter reactive power = 12 Mvar
- Commutation capacitance
  - Converter 1: 2415 µF, \( d_{ic} = 0.236 \)
  - Converter 2: 3460 µF, \( d_{ic} = 0.163 \)
- Transformer connection
  - TK1 ratio: \( \Delta/Y \), \( d_{il} = 0.0682 \)
  - TK2 ratio: \( \Delta/\Delta \), \( d_{il} = 0.0465 \)

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**Control and Protection**

The converter firing controls and the protection equipment are of the latest generation of hardware and software, MACH1. The entire converter control and protection package are designed with user-friendly and efficient software handling features. In addition to the ordinary control and protection functions the software is adjusted to enhance the unique test sequences designed for thyristor module testing according to international standards and internal requirements.

The converter firing control includes the current control regulator, commutation margin control and the firing pulse generator. As the converter transformers are not equipped with tap-changers, the inverter or rectifier operating conditions are achieved by changing the firing angles.

The converter protections installed to protect the equipment are the following:

- Valve short-circuit protection
- Overcurrent & thyristor thermal overload protection
- Commutation failure protection
- DC harmonic protection
- Ground fault protection
- Commutation capacitor unbalance protection
- Valve cooling system protection
- Thyristor monitoring

Control and protection settings for specific projects can be quickly changed without any need for re-programming of computers. A user-friendly project setting page on the Station Control and Monitoring system (SCM) can be adjusted to set the appropriate settings for the specific projects.

**Recording Facilities**

Test results are recorded by a Transient Fault Recorder (TFR) which is integrated as part of the control and protection system in the MACH1 design. The TFR is automatically initiated by the test sequences upon execution of the test procedures. The sampling rate of the TFR can be individually set for each test, but is normally set at 4 kHz.

In addition to the TFR, another PC-based recording system, TEAMPRO, is used to record signals where the sampling rate needs to be set in the MHz range.
Station Control and Monitoring System (SCM)

Operator interface and alarm & supervision of the plant are performed through the SCM system. This system is built into a standard PC solution and integrated with MACH1 control and protection equipment in the same way as in our recently completed HVDC projects. This system enables the operator to control the plant via selectable menus for switching of main circuit apparatus, current order setting, selection of ramping time, AC voltage control, firing angle setting and selection of test to be performed.

Test Features

A large number of tests can be easily performed in the test circuit without tedious main circuit reconnections. The majority of tests are already prepared for, and all that need be done is to select the type of test via the operator’s interface. The test preconditions are set by the operator and also manually started. From the moment a test is started the test sequence is automatically performed and recorded.

The following tests can be performed:

- Valve short circuit, with and without subsequent blocking voltage *
- Commutation failure.
- DC side faults (both inside and outside the smoothing reactor)
- α-90 operation
- Minimum AC voltage operation
- Intermittent current operation
- Impulse test during thyristor recovery period *

*) All twelve valves can be individually selected. Short circuits can be performed with one current pulse with blocking voltage or one to nine pulses without blocking voltage.

The settings for each test enable the operator to select the following parameters:

- Time duration of the fault
- The fault time delay in degrees (el.) from valve voltage zero crossing
- The number of pulses (short-circuit tests only)

Each test can be preceded by a power profile where up to five different power levels or ramping profiles can be set. In each profile the following operating parameters are individually set:

- DC current level/ramp
- Time duration for ramp or current level
- Control angle (alpha or gamma)
- Generator voltage (AC voltage)

The converter power profile after each test is also set prior to the activation of the test.

In addition to the automatically set and performed tests, all types of AC fault can be performed by external fault sequence controls. AC fault tests can be performed with a variable AC network impedance and phase angle. By having the network de-energized, the AC network inductance and resistance can be adjusted.

In the case of DC fault simulation, the converter retard and restart behavior is set identical to that of the commercially supplied control system. The dynamic behavior of the converter is therefore also realistic and results in stresses that are comparable to those in a commercial installation.

CCC high power tests

Over the last five years great efforts have been made to develop the concept of Capacitor Commutated Converters (CCCs) for HVDC, i.e., conventional line commutated converters with commutation capacitors in series with the valves. The concept has been studied by means of detailed computer simulations and simulations in HVDC simulators. The purpose of the studies performed was to investigate the dynamic properties and to develop a strategy for reliable control of a CCC transmission. Another very important task was to define the design stresses of the various main circuit components of a CCC station.

As a complement, and for verification, a study has now been carried out in a high power thyristor valve test plant. The rating and configuration of the test circuit are described in the first section of this paper. The purpose of the CCC study in the valve test plant was to gain experience of the concept, with the plant run at high power and with components manufactured in the same manner as for commercial plants. Of special interest are detailed records of the response and stresses of the main circuit components.

Fig. 2. Commutation capacitors in the 12 MW CCC high-power test circuit.
In parallel with the high power tests EMTDC simulations of the same test cases have been performed. The EMTDC set-up is a very close replica of the real test circuit. Included in the EMTDC set-up are:

- Converters equipped with valve arresters
- Commutation capacitors with varistor units and discharge resistors.
- Converter transformers
- AC filters
- A generator, represented by an infinite voltage source and an impedance corresponding to the subtransient impedance of the machine.
- Converter controls, based on the same software as used in the test circuit.

**Test results**

In this section the results from some selected test cases are presented.

The complete CCC test program included:

- Steady state operation
- Harmonic measurements of the AC currents and DC voltage
- Measurement of valve stresses, such as commutation overshoots, valve current derivatives, and valve snubber stresses during steady state operation
- Ramps and step response
- Unbalance in the commutation capacitor
- Valve short circuit
- DC line fault
- Three -phase faults
- Phase-to-phase faults

**Steady-state operation**

During steady-state operation in various operating conditions the main parameters of the converter were recorded.

The measured capacitor voltages at nominal current, 1500 A, are shown in Fig. 3 for the inverter.

**AC harmonic measurements**

The single line diagram of the test circuit is shown in Fig. 1. The $\Delta/Y$ bridge was operated as rectifier and the $\Delta/\Delta$ bridge as inverter. Consequently, the AC harmonic currents are dominated by the 5th and 7th harmonics.

In Fig. 4 the measured harmonic currents for the rectifier operating at 1500 A and $\alpha=0$ deg are presented together with the calculated values (x marks).

**Capacitor can failure**

A capacitor can in one phase in the inverter was disconnected to give a static unbalance in the commutation capacitance. When the converter was then started, the Capacitor Unbalance Protection detected the fault and ordered a block of the converter. In order to register records of steady-state operation during a capacitor can failure the Capacitor Unbalance Protection was disabled.

As a result of disconnection of one can out of all seven cans in a phase capacitor unit the current in each of the remaining cans increases by 17%. The test records show that the converter operates without any disturbances due to the capacitor failure. In the direct voltage a second harmonic component is found as a result of the capacitor voltage asymmetry. As expected the unbalance also results in non-characteristic harmonics in the AC currents. The measured capacitor voltages and currents for operation at 1500 A with a
capacitor can failure in the inverter are shown in Fig. 5 and 6.

![Fig. 5. Inverter capacitor voltages at a capacitor can failure at 1500 A.](image1)

Fig. 7 and 8 show the results for a valve short circuit across valve 5 with continuous firing of valve 1, which is stressed by the fault current. This represents a worst case fault corresponding to the stressed valve failing to block after the first current pulse, which results in three fault current pulses until the converter breaker trips.

![Fig. 7. Valve short circuit, capacitor voltages.](image2)

In the capacitor voltage traces can be seen how the commutation capacitors are charged by the fault current, resulting in a counter-voltage which reduces the fault current compared to what happens in a classic converter.

![Fig. 8. Valve short circuit, transformer valve side currents.](image3)

In Fig. 8 the three consecutive short-circuit current pulses are shown, the last two, however, with a considerably reduced amplitude due to the counter-

Valve short circuit
One of the decisive fault cases for the rating of the capacitor varistors is a valve short circuit. In the test circuit this fault is created by firing of a special short-circuit valve connected, with reversed polarity as shown in Fig. 1, in parallel with valve 5 in the 6-pulse bridge. This will result in valve 1 being exposed to the short-circuit current.

The test sequence starts by blocking all valves at an instant just before valve 1 is fired. Then a delay of one cycle is introduced before firing of valve 1 together with the short-circuit valve across valve 5. During the remaining part of the test sequence continuous firing pulses are maintained, resulting in three short-circuit current pulses before the converter is tripped after three cycles.

![Fig. 6. Inverter AC currents at a capacitor can failure at 1500A.](image4)
voltage built up across the commutation capacitors during the first current pulse.

Fig. 9 shows the same fault case from EMTDC, but with the short circuit applied to valve 1, resulting in short-circuit current in valve 3.

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**Fig. 9. EMTDC results, valve short circuit.**

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**Fig. 10. 3-phase inverter side AC fault.**

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**Fig. 11. 3-phase inverter side AC fault, inverter capacitor voltages.**

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**Fig. 12. 3-phase inverter side AC fault, inverter currents.**

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**Three-phase fault, inverter**

Using a circuit breaker connected between the reactor (item 2 in Fig. 1) and the converter transformer, TK1, the response to AC faults has been verified. Since the generator of the test circuit is high-impedance-grounded, the tests have been limited to phase-to-phase faults and three-phase faults. The reason for application of the fault between the reactor and the transformer is to reduce the fault current stress on the generator and also to avoid reducing the AC voltage of converter 2, which is operating as rectifier, to zero. The fault is cleared after 90 ms, resulting in restart of the converters and resumption of normal operation.

Results from the test circuit for the inverter three phase fault is shown in Fig. 10, 11 and 12.
In Fig. 13 the result from EMTDC for the same fault is shown.

During the fault, commutation voltage is provided by the commutation capacitors, which results in continuous commutation throughout the fault without commutation failure.

Conclusions

The Valve Test Plant, VTP, is, by virtue of its features, a useful and efficient tool for the testing of valve components and new HVDC concepts such as the CCC converter.

The CCC tests in the high-power test circuit have verified the results obtained from calculations and computer simulations. The recorded component stresses from the tests match closely those obtained from computer calculations. Further, the dynamic behavior of the capacitor commutated converter recorded in the tests verifies the computer simulation results.

The high-power tests have confirmed that the CCC is a safe and robust alternative to classic HVDC converters.

Fig. 13. EMTDC results, 3-phase fault inverter.