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TECHNICAL REPORT

Control and protection systems for high-voltage direct current (HVDC) power transmission systems – Off-site real-time simulation testing

colour inside

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Control and protection systems for high-voltage direct current (HVDC) power transmission systems – Off-site real-time simulation testing

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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CONTROL AND PROTECTION SYSTEMS FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION SYSTEMS – OFF-SITE REAL-TIME SIMULATION TESTING

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IEC TR 63368 has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment. It is a Technical Report.

The text of this Technical Report is based on the following documents:

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Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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- revised.

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INTRODUCTION

It has been the mainstream practice of HVDC transmission system engineering to build a real-time simulation test system with actual control and protection (C&P) devices to test the functionality of various functions of the HVDC C&P system.

In order to provide practical guidance for the functional tests of HVDC transmission systems, this document covers the real-time test environment, functional performance tests, and the test report.

In order to construct the test system in the test preparation phase, Clause 4 introduces the off-site real-time simulation test environment of the functional performance tests (FPT), including the real-time simulator, the C&P system for test purposes, the interface devices and their connection relationships, and the simulation models.

Clause 5 introduces the test practices and test methods of HVDC steady state control functions.

Clause 6 introduces the test practices and test methods of HVDC dynamic control functions, whose main concerns are dynamic responses of DC voltage, DC current and DC power.

Clause 7 introduces the test practices and test methods of DC protection, whose main concerns are DC protection logic and threshold values.

Clause 8 introduces the reliability tests of C&P systems, including redundancy tests and related system switching tests, with the test practices and test methods described in detail.

Clause 9 introduces the special test practices and test methods for VSC-HVDC. In order to thoroughly test the unique functions of VSC-HVDC, it can be necessary to add some specific tests to be decided case by case.

Clause 10 introduces test reports. It includes mainly the contents of a test report.

The above clauses introduce various possible functionalities which do not apply to every HVDC project mandatorily as a whole. It is the purchaser's task to select the appropriate project-specific combination of functionalities. This document describes various possibilities; however, it is important that project-specific needs be clearly defined by the purchaser. The relationship between clauses and test phases is shown in Figure 1.

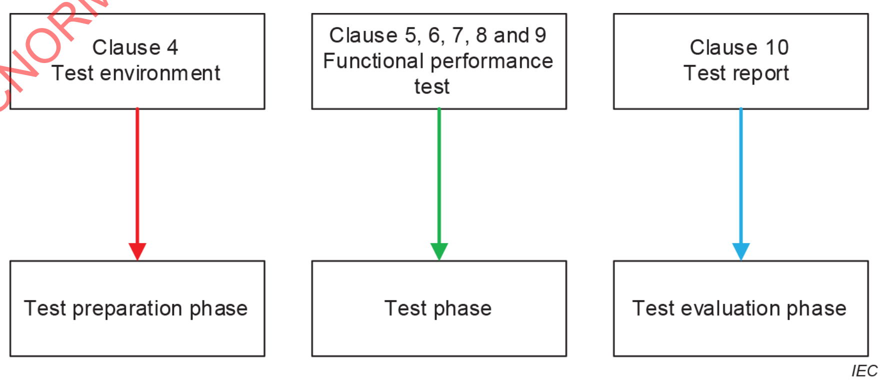

Figure 1 – Relationship between clauses and test phases

CONTROL AND PROTECTION SYSTEMS FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) POWER TRANSMISSION SYSTEMS – OFF-SITE REAL-TIME SIMULATION TESTING

1 Scope

This document provides guidance on off-site real-time simulation tests of control and protection (C&P) systems for HVDC power transmission systems. The off-site real-time simulation tests are carried out after the testing of C&P devices and prior to on-site system tests.

This document covers point-to-point, back-to-back, and multi-terminal HVDC systems of line commutated converters (LCC), voltage-sourced converters (VSC) and hybrid HVDC technologies.

In order to provide practical guidance for the functional performance tests of HVDC power transmission systems, this document covers the test environment, the contents and methods of functional performance tests, and the test report.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1 Terms and definitions

3.1.1
control system delay
total time delay of the control link, including sampling delays, transmission delays and signal processing time of all control devices

3.2 Abbreviated terms

C&P	Control and protection
EHV	Extra high voltage
EMT	Electromagnetic transient
FPGA	Field-programmable gate array
FPT	Functional performance test
GRTS	Ground return transfer switch
HIL	Hardware in loop
HMI	Human machine interface
HVDC	High-voltage direct current

IGBT	Insulated-gate bipolar transistor
I/O	Input / output
LCC	Line-commutated converter
MMC	Modular multilevel converter
MRTB	Metallic return transfer breaker
MTDC	Multi-terminal HVDC transmission system
RTS	Real-time simulator/simulation
SCADA	Supervisory control and data acquisition
SER	Sequence of event recording / Sequence of event recorder
SM	Sub-module
STATCOM	Static synchronous compensator
SVC	Static var compensator
TCSC	Thyristor controlled series compensation
VDCOL	Voltage dependent current order limitation
VSC	Voltage-sourced converter

4 Test environment

4.1 General

The test environment is used for providing various power system conditions. The system conditions are based on real-time simulation for testing the functionality including dynamic behavior of an HVDC C&P system. It commonly includes RTS with models and delivered C&P devices of a specific HVDC project.

4.2 Real-time simulator

4.2.1 General

RTS refers to real-time digital simulators based on electro-magnetic transient (EMT) algorithm. RTS is used to model HVDC main circuits, adjacent AC system(s), and adjacent HVDC system(s) as required by the purpose of the test, to connect actual C&P devices with simulation interfaces. It runs models with sufficient simulation cycle time, stably and continuously, strictly in real-time in every simulation time step.

4.2.2 Simulation interface devices

4.2.2.1 General

Simulation interface devices are used to connect C&P devices, with RTS for establishing closed-loop HIL simulation systems. The protocols used for the communication among RTS, the C&P devices and the simulation interface devices are dependent on the actual project and type of simulator in use.

4.2.2.2 I/O interface devices

Simulation interface devices are used for establishing the I/O communications with RTS. Generally, there are two types of interface techniques used for commercial RTS nowadays: analog interface and digital interface.

1) Analog interface: the interface connections are performed through wires connected to the I/O interface cards of RTS.
2) Digital interface: the interface connections are performed through digital system buses, and in most of the applications, physically established via optical fibers.

4.2.2.3 Other special interfaces for RTS tests

1) Power amplifiers can be used to amplify RTS analog output signals to ensure the interface adaptation to the C&P devices designed for the actual interfaces on site. It is optional and dependent on the measurement input design of the C&P devices.
2) Disconnectors and earthing switches with slow operating time are usually not represented in RTS. Instead, they are simulated in other suitable ways such as by AC and DC switch simulator in the form of relay or digital system.

4.2.2.4 Valve interfaces for MMC-HVDC

In order to test the functions of the MMC valve base control device, appropriate interface devices could be provided for RTS. These devices are optional, and if needed, used for translating the packets of MMC sub-module on/off commands from the MMC valve base control device into a specific form adapting to the MMC models in RTS.

4.2.3 Simulation model

4.2.3.1 General

The simulator model must be adapted for the specific project and for the planned testing. Generally, the detailed characteristics of equipment in the model match the testing purposes. The simulation model is generally composed of one or more of the following in 4.2.3.2.

4.2.3.2 Model of HVDC main circuit

4.2.3.2.1 LCC converter and transformer

The LCC converter and transformer are generally integrated with one component or two individual models according to the test requirement.

The component simulates the key characteristics of the converter and transformer, including compensation algorithm, firing angle, and extinction angle measurement.

4.2.3.2.2 MMC converter and transformer

The large number of sub-modules creates an excessive computational burden for the EMT simulation of MMC-HVDC systems, especially in real-time environments. For the HIL test, the exchange of large numbers of capacitor voltages and individual firing pulses presents a communication challenge for the simulation model and the external physical control devices. In order to meet the requirements of MMC-HVDC simulation and testing, various types of models based on both processors and FPGAs have been developed using vast parallel computation techniques, which can model the MMC converter with up to thousands of sub-modules.

The time step of the MMC converter model on FPGA is usually less than 10 μs. In this case, the transformer can be modelled as an interface model for decoupling the MMC converter in small time step from the main network in large time step.

If the MMC converter model and the main network use the same time step, a traditional transformer model can be used to connect the MMC converter model and the main network.

4.2.3.2.3 HVDC transmission line and electrode line or metallic return conductor

Generally, the distributed parameter frequency-dependent model is used in RTS for HVDC overhead lines, HVDC cables, and the electrode line or metallic return conductor. The model parameters are in accordance with the actual project. For stability and accuracy purposes, the phase domain frequency dependent line model can be utilized to model DC lines and cables.

4.2.3.2.4 Reactive power components

Reactive power components in an LCC-HVDC converter station can be modelled as integrated components or individual equipment branches. Integrated components are recommended for high efficiency in resources.

The breakers of reactive power components are modelled individually in accordance with HVDC reactive power control.

4.2.3.2.5 DC filter

The DC filter and its current measurements are modelled in detail in RTS if DC filter protection is to be tested.

4.2.3.2.6 Pre-insertion resistor

If used in the actual project, the pre-insertion resistor and its resistor bypass breaker are modelled to perform a converter energization test.

4.2.3.3 Model of interconnecting AC system(s)

4.2.3.3.1 General

The connected AC system can be modelled as a simplified static voltage source or as a dynamic equivalent model in accordance with the need for specific tests.

4.2.3.3.2 AC system: Simplified static voltage source model

Simplified static voltage source models are used to simulate the connected AC system. In this model, the short circuit impedance of the connected AC system is configured. The dynamic behavior of the AC system is not considered and simulated in this model, e.g., angular stability. However, a harmonic current path must be provided in the source model to ensure the numerical stability of the simulation.

4.2.3.3.3 AC system: Dynamic equivalent model of AC systems

To simulate the dynamic and transient interactions between the DC system and the connected AC system or between the new DC system and other existing DC systems, a dynamic equivalent model of the AC system is required. It is noteworthy that these interaction studies are optional in RTS and can be done in offline simulation. The advantage of the interaction study on RTS is the high fidelity brought by the real control devices in the loop. This type of AC system model depends on the project requirements.

For example, a dynamic equivalent model preserves the essential transmission network, including AC transmission lines, transformers, and large-scale generators at a high voltage level. Other parts of the AC system can be reasonably simplified.

As part of the dynamic equivalent model of the AC system, real-time simulation models of adjacent HVDC C&P systems could be included to verify the interaction with existing HVDC transmission systems, such as multi-HVDC infeed systems.

4.2.3.4 Adjacent HVDC systems

It is noteworthy to consider the requirement of modeling adjacent (in the context of electrical distance) HVDC systems and power electronic equipment if the necessity is demonstrated and a detailed model or a replica is available.

The interactions between an HVDC system being tested and other adjacent HVDC transmission systems (especially when they are part of a multi-HVDC infeed system) are typically investigated by means of EMT offline studies. Alternatively, they can be verified or performed in a real-time test environment, provided the resources on the RTS are adequate.

4.2.3.5 Model validation

4.2.3.5.1 General

The goal of model validation is to evaluate whether the model and its parameters can be simulated with the necessary precision for the tests to be performed.

4.2.3.5.2 Validating main circuit equipment models

The main circuit equipment models based on the design specifications, including LCC and VSC converters, DC lines/cables, high speed switches, and AC/DC filters, can be verified by comparison with the results of offline software simulation.

4.2.3.5.3 Validating short-circuit ratio (SCR) and dynamic equivalent model

When equivalent AC voltage sources are used to simulate the adjacent AC power grids connected with the HVDC system, SCR can be compared with the pre-calculated values.

While the static equivalents focus on representing the exact steady state performances of the actual AC power systems, the dynamic equivalents aim at representing both the exact steady state and dynamic performances of the actual AC system, from the perspective of HVDC converter stations.

4.2.3.5.4 Validating HVDC control and protection system model

If the C&P models of adjacent C&P systems mentioned in 4.2.3.4 are included in the real-time simulation, it is necessary to validate these HVDC C&P models.

The HVDC C&P models can be software providing basic C&P functions such as closed-loop power control, closed-loop current control, and valve control. The software models are usually simplified from the actual control and protection system functions and do not include all the details.

The validation of the offline software models can be started from the individual closed-loop control functions. In order to validate the algorithms, it can be ensured that the logic and control response is consistent with the offline models, the control replicas or the software programs.

After this validation is successful, the dynamic performances of the offline software models are validated by normal operation tests and system disturbance tests. The important system parameters and control device outputs are compared in detail, such as the AC/DC voltages, currents, active power, and reactive power.

4.3 HVDC control and protection devices

4.3.1 Control devices

Based on the requirements of tests, the control system devices to be tested are consistent with the requirements of the actual project configuration and design. However, in case of optional dynamic control tests, system redundancy is not necessarily required.

4.3.2 Protection devices

The protection devices to be tested, including the pole protection, the valve group protection, the DC line protection, and the optional DC filter protection, are consistent with the actual project configuration and design.

4.3.3 Measurement devices

The measurement devices to be tested are used to collect signals for the C&P system. These devices are optional in the RTS C&P test system. If FPT needs to test related functions, the necessary measurement devices are included.

4.3.4 Monitoring devices

The monitoring system to be tested includes the monitoring system servers, the monitoring network interface device, the operator workstations, and the synchronous clock system.

4.3.5 Fault recording devices

The fault recording system to be tested includes the delivered fault recorder equipment of a specific HVDC project. Generally, the fault recording system is used for analysis and verification. Meanwhile, the capability of the fault recording system can be checked during the RTS test.

The test of the fault recording system is optional. The specific fault recording system delivered to an HVDC project can be tested along with the control/protection devices by the real-time simulator if necessary.

4.3.6 Valve base control devices

There are two kinds of valve base control devices: the LCC valve base control device and the VSC valve base control device.

The LCC valve base control device is optional in RTS. Normally the thyristors in the same arm are assumed to switch simultaneously, therefore, the valve base control device is not needed in the simulation and testing. If FPT needs to test related functions, the valve base control device can be represented by the special valve control functions provided by the manufacturers for the actual project, using either the equivalent devices or the equivalent function model in RTS.

The VSC valve base control devices switch every sub-module inside the RTS model individually. Therefore, the VSC valve base control device provided for the actual project is used in RTS for the test.

5 Steady state control tests

5.1 General

The steady state control functions include DC switching sequences, reactive power components energizing, the converter transformer energizing, the open line test, deblock/blocking, control mode switching, reactive power control, steady state performance, power ramping, stability control function, overloading, metallic and ground return configuration and switching, and voltage reduction operation, as applicable.

Please note that it is possible that not all functions will be applicable for every project. The objective of the functional performance tests for steady state control is to verify whether these applicable functions meet the design specifications.

All of the functions described in 5.2 to 5.16 can be verified in the real-time simulation test system while some of them can also alternatively be verified on-site or in a non-real-time simulation environment. The test items performed in the real-time simulation test are selected based on mutual agreement between the project owner and the manufacturer.

5.2 DC switching sequence tests

The sequential control operations by manual and automatic orders can smoothly switch the HVDC system into the different operating states that are required. Meanwhile, the test verifies whether the interlocks for different operation switching meet the designed specification. The sequential operations triggered by the orders include all required HVDC system operation modes (monopolar metallic return, monopolar ground return, or open line test) and DC filter connection/isolation, as/if applicable.

5.3 Energization of reactive power components

The functional performance tests for energization of reactive power components are to:

1) Verify whether the energization and dis-connection of the reactive power components are correct.
2) Verify whether the influence on the AC systems during the energization/dis-connection is acceptable.

These tests are carried out in manual mode. The operator issues a manual command to switch on or off the reactive power component to verify whether the corresponding component is switched on/off correctly.

5.4 Energization of converter transformers

The tests of energization of converter transformers are to:

1) Evaluate the magnitude of inrush current.
2) Verify the impact on HVDC devices already in operation in the same station.

5.5 Open line test of HVDC control system

The open line test (OLT) function confirmation in the real-time simulation verifies that this control function is implemented as designed and verifies the protection functions in case of a DC line being short circuited to ground. If the OLT function does not exist in a specific project, this test is not applicable.

5.6 Deblock-block performance tests

The deblock-block performance tests are to:

1) Verify that the HVDC system can deblock smoothly without any unexpected disturbance under different power control modes with a single pole (or multiple poles).
2) Verify that the single pole (or multiple poles) of the HVDC system can be blocked stably without any unexpected disturbance at different power control modes.
3) Verify the stable and undisturbed deblocking of the blocked valve groups when other valve groups are in operation, and smooth DC power transfer after the successful deblock.
4) Verify that a certain operating valve group can achieve stable and undisturbed blocking when several valve groups are in operation, and that DC power can be transferred smoothly after the successful block.
5) Verify a converter station being put into or out of operation as designed while the others remain in operation for a MTDC system.
6) Verify the deblock-block performance when inter-station communication is lost, if required.

5.7 Operator control mode transfer tests

The operator control mode transfer tests are to:

1) Verify that the interlocking and selection of master control, slave control, and different control locations of converter stations are correct in different operations, as applicable and designed.
2) Verify that the toggle of control modes of reactive power components at the rectifier or inverter has no influence on the steady-state operation.
3) Verify that the transitions between different power control modes are smooth and as expected.

5.8 Operation status tests

Operation status tests are to verify whether the HVDC steady operating points are compliant with the results of system design studies, such as the main circuit parameter report.

5.9 Tap changer control tests

The tap changer control tests are to:

1) Verify whether HVDC control could perform the tap-changer control functions correctly over the entire designed operating range.
2) Verify whether the tap-changers of single-phase transformers are operated synchronously in different control modes and from different control locations.
3) Verify whether the tap-changer control could avoid unexpected false trips in case of un-synchronized tap-changer positions during operation.

5.10 Reactive power control tests

5.10.1 Reactive power component switching function tests

The reactive power control tests in LCC-HVDC are to:

1) Verify the reactive power component switching coinciding with the designed reactive power control under U_{ac} mode and Q mode in the process of power ramp up/down.
2) Verify another reactive power component with the same type being switched on automatically while the one in service becomes unavailable, when expected so.
3) Verify the low-load reactive power optimization function, if specified, is the same as designed.

5.10.2 Reactive power curve tests

This Subclause 5.10.2 applies to VSC-HVDC.

The reactive power curve tests are carried out for the VSC-HVDC converter stations. The reactive power control of VSC-HVDC have several modes, e.g., the Q mode and the U_{ac} mode. These modes are designed according to the specification and system study report in the form of corresponding reactive power curves, which represent the relationships between I_q and U_{ac}. I_q is the amplitude of the current in the q-axis of the d-q coordinate system.

In Q mode, the control target is the exchange of reactive power of the converter with the connected AC system at the defined point of control. In U_{ac} mode, the control target is the voltage of the AC bus at the defined point of control.

The reactive power curve tests are to verify that the control system is working correctly with the designed strategies at different AC voltages.

5.11 Power ramping tests

The power ramping tests are to:

1) Verify whether the DC power can be manually ramped up or down in different operation modes.
2) Verify the DC power ramping function based on the automatic power curves under different power control modes, when so designed.
3) Verify that the reaction of power ramping pause, control mode switching and communication fault between converter stations during the process of power ramping meets the designed specifications.

5.12 Overload tests

For HVDC projects with overload capabilities considered, the overload tests are performed.

Generally, the overload tests are to verify whether the HVDC system overload functions are correct in the conversion processes of different operation modes, the changes of DC power, DC voltage, and firing angle.

5.13 Metallic and ground return configuration and transfer tests

This Subclause 5.13 applies to the projects in which the function is specified by design.

The metallic-ground return configuration and transfer tests are to verify whether the metallic and ground return configurations of the DC system can correctly be transferred from one to the other and vice-versa within the designed limits of MRTB and GRTS components.

5.14 Reduced voltage operation tests

This Subclause 5.14 applies to the projects in which the function is specified by design.

The reduced voltage operation tests are to:

1) Verify that the DC voltage controller works as required during the reduced voltage operation.
2) Verify that the transfer is smooth for different reduced voltage levels.

5.15 Tests of static characteristic curves of converters

This Subclause 5.15 applies to LCC-HVDC.

By adjusting the tap-changer positions of converter transformers and configuring relative control parameters or by the equivalent tests set up in the RTS models, the HVDC control system can operate stably in different control modes. Based on the data recorded in these control modes, the static characteristic curves of converters can be obtained to confirm that the external characteristics of converters meet the requirements of project design.

5.16 PQ diagram tests of VSC-HVDC converters

This Subclause 5.16 applies to VSC-HVDC.

The steady-state operation ranges of the VSC-HVDC converters are defined by the ranges of active power and reactive power exchanged with AC systems. The steady-state operation ranges are shown as the PQ diagrams and are highly related with the conditions of the AC systems connected.

The RTS test is to verify that the converter stations are operating stably and continuously within the steady-state operation ranges, as designed and expected.

6 Dynamic control tests

6.1 General

The dynamic function tests include power step response tests, current step response tests, voltage step response tests, and AC/DC system interaction tests. These tests are optional to perform in the real-time simulation test. It is noteworthy that the main dynamic behavior investigation is covered by offline simulations and studies in the early period of the HVDC project. The main dynamic behavior can also be performed in RTS to verify that the pretested software shows similar results on the target hardware including all hardware-specific communication delays.

Normally, power system restoration is an individual and optional test item, depending on whether it is specified for the project under test.

In general, the purpose of the step response tests is to verify that dynamic behavior of the control system is stable and as expected. When dynamic performance requirements are not verified in separate detailed offline simulation studies, e.g. EMT, the same requirements are simulated in RTS environment.

The purpose of the AC/DC system interaction tests is to verify that DC system control strategies do not cause large fluctuations to the frequency and voltage of AC systems connected.

6.2 Power step test

Before a power step change is applied, it is necessary to ensure that the system is operating in the power control mode and all system parameters are at pre-defined values before starting to verify the response characteristics of the power controller.

In addition, for LCC-HVDC, the power needs to be adjusted so that the DC system has constant current control characteristics during transient disturbances in the AC system (this disturbance duration is typically less than 10 s). Further, as per customers' requirements, the power control mode would be used for VSC as well.

The power step change tests are to verify that the system dynamic response meets expectations as designed, with respect to:

1) the maximum of power variation,
2) the duration from initiation of step change until the target value has been automatically regulated.

6.3 Current step test

The current step tests are performed in the current control mode.

The permitted communication delay is not included in the calculation of the response time.

The current step test is to verify that the response of the step increase or the step decrease meets expected behavior.

6.4 Voltage step test

The DC voltage step test is to apply a voltage step change command (step increase or step decrease) on the voltage control side of the control system, to observe the response of the DC system. This test is to verify that the DC voltage controller's performance is stable and satisfactory.

6.5 Gamma step test

This Subclause 6.5 applies to LCC-HVDC.

The gamma step test is to apply a step change on the extinction angle (i.e. gamma) to verify if the response of gamma and the HVDC system are correct, when the inverter station of LCC-HVDC is in the control mode with fixed gamma. This test is to verify that the DC gamma controller's performance is stable and satisfactory.

6.6 AC system related tests

6.6.1 AC disturbance tests

The dynamic performance of the HVDC C&P system is tested to see whether it can maintain stability in accordance with the design for the embedded AC system during an instant of AC system disturbance.

AC disturbance includes several types and can be located on both rectifier and inverter sides, e.g., single phase to ground, two-phases, two phases to ground, and three-phase faults at different locations with different fault impedances (residual voltages) and fault clearance time (for main, back-up, and remote back-up protection) as applicable and possible, or as simulated in the setup.

6.6.2 AC/DC interaction tests

The strength of the AC systems connected with the HVDC rectifier and inverter stations and the characteristics of AC equipment adjacent to the converter stations can cause complex AC-DC interaction problems. In addition, there is strong coupling between VDCOL or other system-level coordination control strategies (such as reactive power and voltage coordination control) of the HVDC transmission systems and of the AC systems. These interaction issues are generally investigated and presented in a corresponding AC-DC interaction study report before the RTS test.

The AC/DC interaction tests contain three components:

1) Verification of the coordination between an HVDC system and generator units of an adjacent islanded AC system (optional)

   Under the islanded operation mode of an HVDC terminal, the effective short circuit ratio of the islanded AC system connected with the HVDC terminal is very low and thus may cause serious instability problems such as frequency instability, voltage instability, over-voltage, ultra-low frequency oscillation, and sub-synchronous oscillation.

   Generally, the procedure of simulating AC faults, DC faults and islanded interconnection conversion is used to verify whether the islanded system is stable and meets the project requirements.

2) Verification of sub-synchronous damping control for HVDC system (optional)

   The most economical and feasible measure to suppress the sub-synchronous oscillation related to an HVDC system is to add an additional control function to its control system and to use the fast response characteristic of the HVDC system to provide positive electrical damping to the generator set threatened by the sub-synchronous oscillation. Thus, the purpose of suppressing sub-synchronous oscillation can be achieved. The real-time simulation is used to verify the correctness and effectiveness of the sub-synchronous damping control of the HVDC system.

   For the verification of the sub-synchronous damping control function, it needs to simulate the AC system with certain details. If there is no sub-synchronous oscillation or the sub-synchronous oscillation is suppressed after the pre-defined disturbances, the function is considered to be correctly implemented.

3) Interaction between HVDC and FACTS systems (optional)

At present, FACTS devices used in AC/DC power grids mainly include TCSC, STATCOM, and SVC. These devices can be directly connected to the AC power networks through isolation elements (such as transformers). Different FACTS devices accessing HVDC systems (especially at the DC power receiving ends) will bring new control variables, which make these AC/DC hybrid systems more flexible to operate. The operation control characteristics of the large current power grids are more sophisticated. Especially when the receiving end of the HVDC system is connected to a weak AC system, the interaction between the FACTS devices and the HVDC system will be more likely to cause significant impacts on the power grid. When HVDC transmission systems and various FACTS devices are close to each other or are connected to a weak AC system, problems related with voltage stability, coordinated control, harmonic resonance, etc. can arise.

During the tests, a system model is built containing FACTS equipment and necessary control functions and then the FACTS equipment is operated to observe the response of the AC/DC hybrid power system.

It is preferable to investigate the interaction between the DC system and existing FACTS, as described above, via offline simulation. The investigation requires detailed technical data including the control principles of FACTS. Nevertheless, the real-time HIL simulation environment can also be used to verify the interaction with the high fidelity of replica controllers. Hence, this Subclause 6.6.2 is marked as optional.

For this, it is necessary that complete data and models of such FACTS devices are made available to the supplier by the owner/purchaser.

6.7 Stability control function tests

The stability control function tests are to:

1) Verify whether all the stability control functions meet the requirements of project design in different conditions of the DC system.
2) Verify whether the power limit functions can correctly regulate the total DC power to the set values.

6.8 Power system restoration test

This Subclause 6.8 applies to VSC-HVDC.

The power system restoration, also known as black-start, is an optional control functionality for VSC-HVDC systems. Such functionality can be tested in steps with a generic AC system representation suited to the components available in the specific AC grid. It is not the intention of FPT to determine the correct sequence of components to be energized during the restoration of a black-outed grid. The focus is more on showing that the HVDC is capable of restoring the AC system.

6.9 Grid code tests

More and more utilities worldwide provide their own grid codes. Tests of grid codes are generally required to be performed on-site and verified at the connection point of HVDC system and AC grid to get the final permission of the utility to operate the HVDC system. Such dynamic tests are selected frequency and load change response tests. Since the grid codes are country/region specific, this document does not cover any detailed requirement.

The RTS test can incorporate such specific tests prior to the commissioning on site, when specified and considered necessary.

7 Protection tests

7.1 General

This Clause 7 is to verify the fault protections for HVDC systems. The protections designed for an HVDC project are tested to ensure they work correctly during a fault in their protective zones and co-ordinate well with others, even with the AC system protection. Generally, the HVDC protections are designed according to the fault area, such as the converter unit area, DC filter area, DC line area, neutral area and so on. The protection areas are specifically defined project by project. If one or more of the above-mentioned protection areas do not exist for a specific project, the related tests are adjusted.

The protection requirements and implementations are different among projects. Besides, not all protections are tested in the RTS environment. However, protections can be verified via unit tests, such as pure AC protections like busbar and converter transformer protection systems. Hence, the vendor usually incorporates the corresponding protection tests into the list for RTS tests and makes an agreement with the customer.

This Subclause 7.1 describes the RTS test for the general HVDC protection areas. All the applicable tests are carried out based on the pre-defined fault points in the simulation model, as referenced in Annex A and as applicable for the project. In all the performed tests, the protection system needs to correctly respond in accordance with the design specifications.

7.2 Trip signal logic tests

The test objective is to verify the correctness of the trip signal logic within the HVDC C&P system. The complete trip circuit needs to be tested on site.

The trip signal circuit tests are to:

1) Verify the correctness of the tripping logic of DC protection devices and control devices under block state.
2) Verify the correctness of monopole/bipole trip functions with normal communication.
3) Verify the correctness of monopole/bipole trip functions with communication failure.
4) Verify whether the actions of the C&P system are correct after a power failure of the entire redundant pole control, valve group control or DC station control systems, as applicable.

7.3 Converter unit area protection tests

This Subclause 7.3 discusses the tests for the protections for the converter unit faults, i.e., those which take place between the valve side of the converter transformers and DC bus area.

The converter unit area protection tests are to:

1) Verify the correctness of protection behavior under different system conditions, at different power levels, and with different fault types in different regions.
2) Verify that the protection correctly detects the faults in the corresponding area and can operate according to the design specifications.

7.4 DC bus area protection tests

This Subclause 7.4 discusses the tests for the protections for faults on the DC pole bus, neutral bus and the bipolar area. If one or more of the protection areas in 7.4 do not exist for a specific project, the related tests are not applicable.

The DC bus area protection tests are to:

1) Verify the correctness of protection behavior under different system conditions, at different power levels, and with different fault types in different regions.
2) Verify that the protection correctly detects the faults in the corresponding area and can operate according to the design specifications.

7.5 DC filter area protection tests

This Subclause 7.5 discusses the tests for the protections of DC filters. Sometime this area may be covered in other protection zones. The DC filter area protection tests are to:

1) Verify whether the DC filter protection works correctly when a short circuit fault occurs.
2) Verify whether the DC filter protection behaves correctly (no mis-operation for example) with external faults outside the DC filter area.

7.6 DC line area protection tests

This Subclause 7.6 discusses the tests for the protections for DC line or cable faults, including the electrode line fault or the metallic return line fault in the project with electrode or dedicated metallic return. In an MTDC system with junction busbar areas, the protections for junction busbar area faults are also tested.

The DC line area protection tests are to:

1) Verify with faults at different locations along the DC line(s), whether the DC line protection can initiate the HVDC system restart correctly according to the set values and whether the voltage recovery time and the steady-state characteristics meet the design specification.
2) Verify that the DC pole line and electrode line protection functions are independent of DC power and DC voltage levels and operate correctly in accordance with the design specifications.
3) Verify that the DC line protections are able to determine on which segment of the DC lines a fault occurred accurately, and act to isolate the fault reliably in an MTDC system, as designed.

7.7 Switch protection tests

This Subclause 7.7 discusses the tests for the protections for the switch faults, like bypass switch, metallic return transfer breaker and ground return transfer switch. If these switches or breakers are used for the project, the protections are tested.

The switch protection tests are to:

1) Verify that the switch protection is working correctly with different faults including switch malfunctions during operation modes changes of the HVDC system.
2) Verify that the switch protection is responding correctly to the faults in the corresponding protection areas as required in the design specification.

7.8 Other protection tests

This Subclause 7.8 discusses the tests for the protections coordinated with the AC system, like commutation failure protection, harmonic protection and others. These protection requirements depend on the project specifications. They are tested if applicable.

8 Redundancy and reliability of control and protection system tests

8.1 General

The hierarchical structure of the HVDC control system is defined in IEC 60633 for LCC systems or IEC 62747 for VSC systems. The control system is provided with complete redundancy and the redundant control systems operate independently to ensure safe isolation and shutdown of faulty control and protection equipment/system. Breakdown of a single control or protection equipment will not affect the normal operation of the entire HVDC system. Corresponding to the severity, the system faults are typically classified into different categories, such as minor warning, serious fault and emergency stop, to define the status of the HVDC control and protection system. If a fault is detected, control system changeover will take place based on pre-defined principles.

In order to verify the redundancy and reliability of the control and protection system, the FPT tests for redundancy and reliability of the control and protection system are designed and carried out with the RTS, which includes redundant system failure tests, system monitoring and switching tests, and IT security, with details given in the list below.

Generally, the pre-conditions for the tests include:

1) The basic functional performance tests have been completed with the requirements fulfilled.
2) The system parameters are set properly based on the defined operating configurations.
3) The whole control and protection system works under normal condition without any fault and the simulated HVDC system operates under steady-state condition.

8.2 Redundant system failure tests

The redundant system failure tests aim to verify the reliability of the C&P system.

Generally, the C&P system is redundantly configured and the operational status is defined into different categories, such as warning, minor fault, serious fault, and emergency fault. The control system with better status will operate as the active system while the other redundant system(s) operate as the standby system(s). The standby system is switched to active level when the original active system fails or operates at a suboptimal level.

The protection functionalities will be active conforming to the designed principle. For example, the protection works in the principle of two-out-of-three with a triplicated system. If one of the three systems quits, the protection will take effect by either of the remaining two systems. While in some other C&P systems, there are two redundant protection systems A & B, and active system directly acts.

The redundant system failure tests are to verify HVDC system can be in service in the event that one of the redundant C&P system fails.

Tests of some functions, valve water-cooling system tests, station power tests, low voltage AC system tests, low voltage DC system tests, for example, are mainly performed in on-site commissioning. They could also be included in FPT, if required, by the specification of the project.

8.3 System monitoring and switching tests

The system monitoring and switching tests are to:

1) Verify whether the faults of various communication networks (all kinds of buses and LAN networks) and virtual circuits can be correctly detected, and whether the switching and blocking strategies of the control system are correct.

2) Verify whether the loss of power and other kinds of power failures of host board cards (or main boards) can be correctly detected, whether the system switching and blocking behavior is correct, and whether the HVDC system runs without any unexpected disturbance during the system switching process.
3) Verify whether the functions and behavior of the C&P system still fulfill the requirements of the HVDC system operation after the power failure of one of the redundant systems.
4) Verify whether the HVDC system can maintain stable operation according to the design specification and/or be blocked correctly after a complete power loss of both redundant control systems of the converter station, as designed.
5) Verify whether system faults can be correctly detected and used for generating corresponding event alarms (alarm) and verify that the HVDC system runs without any unexpected disturbance as designed.
6) Verify whether the action logic of the redundant protection systems can automatically adapt to the actual operating status of the entire protection system. For example, if there are three sets of redundant protection systems in a specific HVDC protection, typically trip commands will be recognized as effective in the control system when those from at least two protection systems are received.
7) Verify whether the control system can correctly determine the action logic of the redundant protection systems when one or more than one set of protection systems have emergency failure, and when the systems recover from the failure.
8) Verify whether the control systems can correctly switchover when the valve control system fails.
9) Verify that the online replacement of a minimum replaceable unit under defined conditions (for example a circuit board), if required and if permitted, does not affect the functions of the host system it belongs to.
10) Verify whether the control systems can correctly switchover during DC power ramping and sequences.
11) Verify whether system can switch back to an active or standby configuration if there is no failure in one system.

8.4 Electromagnetic interference tests (optional)

The real-time simulator test is the first occasion where the core components of HVDC C&P devices are placed and interconnected as at its final destination.

The electromagnetic interference tests on the interconnected C&P devices are to verify that there is no influence on the active and reactive power transmission of the HVDC by WLAN, cellular phones and portable receivers in the frequency range and field strength as specified for the HVDC project. This test is deemed to be optional if not specified in the HVDC project. They could also be included in FPT, if required, by the specification of the project.

8.5 IT security

Owing to the increasing number of cyber-attacks worldwide, the topic of security measures for critical infrastructure, including within the energy business, is receiving more and more attention. Various national and international regulations have been released in recent years (e.g. Regulation on Security Protection of Critical Information Infrastructure (CII) in CN, Network and Information Systems Directive (NIS) in the EU or North American Electric Reliability Corporation Critical Infrastructure Protection (NERC CIP) in the US). The IEC 62443 regulation framework has evolved as the de facto standard for IT security in the energy solution business and can be mapped to different national standards.

All these regulations have in common the aim of identifying and managing cyber, as well as general security risks introduced by third parties. The regulations help to perform a risk and vulnerability assessment on the C&P devices.

Mandatory tests include regular patch management, system hardening, malware protection, and the verification of user management and logging. The solution must also be tested against open port scans, cryptography scans, and compliance scans. In addition, a penetration test by professional hackers to identify intrusion possibilities to the C&P systems is performed.

In the end, the supplied C&P devices must be proven to be in line with the project-specific applicable security regulations and standards.

Since the requirements are country- and region-specific, this document cannot describe any detailed requirements.

9 Special tests for VSC

9.1 General

The MMC based VSC-HVDC is much more complicated than the traditional LCC-HVDC, and results in some special FPT tests for VSC functions. The tests specify higher requirements for the accuracy of the simulation system. Generally, FPGA based sub-module level electromagnetic transient models are used. Engineering practice has shown that the tests are relatively economical and very effective. Therefore, RTS can be used to verify the reliability and performance of the VSC-HVDC C&P system via the tests.

When the tests are carried out, the major test items are the test of control system delay, valve control function tests and STATCOM tests.

The control system delay of VSC-HVDC is one of the key parameters that affects the performance of the VSC-HVDC system and the harmonic resonance occurring between the VSC-HVDC system and an AC system connected with it.

The valve control system is typically equipped with functions such as circulation suppression, sub-module trigger control, defective module detection, and fast over-current protection. If one or more of the above-mentioned protections do not exist for a specific project, the related tests are not applicable.

MMC has become the mainstream of VSC-HVDC due to its extensive application in the industry. The examples presented in this Clause 9 are based on MMC.

9.2 Control system delay (optional)

The VSC-HVDC control system delay refers to the time difference between a given input or disturbance of the control system and its response output. The control system delay is one of the key parameters that affect the VSC-HVDC dynamic performance and the harmonic resonance between VSC-HVDC and AC power grids connected with it. Generally, the control system developer would optimize this control delay, as well as other parameters and make them verified in the harmonic tests. Considering the control system delay is helpful to VSC-HVDC harmonic analysis even during the operational phase, the test is optional to be performed in RTS. A typical test method for the total control system delay is introduced in Annex B.

9.3 Valve control and protection function tests

9.3.1 Valve control function test

The valve control system, responsible for controlling the conducting of valves and monitoring the operating status, is an important part of VSC-HVDC control system. The functionality depends on the topology of the voltage-sourced converter, such as MMC, two-level converter and three-level converters. Hence, it is tested according to project specifications.

The valve control function tests are to:

1) Verify that the valve can correctly conduct and turn off under the valve control and meet the specification.
2) Verify that the valve control can correctly detect the operating status of the valve and take corresponding actions according to preset strategy.

For example, MMC-HVDC is one type of VSC-HVDC. For MMC-HVDC, a series of critical control functions, such as charging control and sub-module capacitor voltages balancing, are typically included in valve control and need to be verified.

In addition, for different VSC-HVDC projects, there are different valve control functions to improve the performance of valves, such as circulation suppression and switching frequency reduction. For example, circulation suppression could reduce the power loss and the fluctuation of the sub-module capacitor voltage of MMC-HVDC. It is necessary to verify the effect of circulation suppression and that the harmonic level is meeting the requirement of design specification under this function.

9.3.2 Valve protection function tests

As an important part of the C&P system of VSC-HVDC, valve protections, such as arm over-current protection and over-voltage protection, are responsible for protecting the power electronic devices.

For different VSC-HVDC projects, valve protection functions can vary within a large range due to the differences in technical routes, application requirements, etc. Therefore, the tests for valve protections are taken according to the project specification, supplier's technical solution, and testing conditions.

Take MMC-HVDC for example, the valve protection function tests are to:

1) Verify that the bridge arm overcurrent protection correctly operates under the condition of short circuit fault and overcurrent.
2) Verify that the bridge arm current rise rate protection correctly operates under the condition of short circuit fault and overcurrent rise rate.
3) Verify that the under-voltage protection correctly operates.
4) Verify that the over-voltage protection correctly operates.

If one or more of the above-mentioned protections do not exist for a specific project, the related tests are not applicable.

9.4 STATCOM tests

The STATCOM tests are to verify that the VSC-HVDC converter can operate correctly in STATCOM mode. The tests include but are not limited to charging control test, deblock-block performance test, control mode switching test, steady state test, and AC disturbance test.

10 Test report

The test report is issued in accordance with general guidelines of the laboratory/manufacturer describing the test performed and results obtained.

Annex A
(informative)

Examples of protection areas and faults

The faults of the LCC converters are set in accordance with the general guidelines as given in IEC TR 60919-2.

The faults listed in Figure A.1 and Figure A.2 are just for fully testing the protection functions.

These faults could be adjusted based on the RTS environment.