

TECHNICAL REPORT



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



THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2024 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

IEC Secretariat
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, ...). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch

Discover our powerful search engine and read freely all the publications previews, graphical symbols and the glossary. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org

The world's leading online dictionary on electrotechnology, containing more than 22 500 terminological entries in English and French, with equivalent terms in 25 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

TECHNICAL REPORT



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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.240.99

ISBN 978-2-8322-9712-4

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD.....	4
INTRODUCTION.....	6
1 Scope.....	7
2 Normative references	7
3 Terms and definitions	7
3.1 Terms and definitions.....	7
3.2 Abbreviated terms.....	7
4 Test environment.....	8
4.1 General.....	8
4.2 Real-time simulator	8
4.2.1 General	8
4.2.2 Simulation interface devices	8
4.2.3 Simulation model	9
4.3 HVDC control and protection devices	11
4.3.1 Control devices.....	11
4.3.2 Protection devices	11
4.3.3 Measurement devices	12
4.3.4 Monitoring devices.....	12
4.3.5 Fault recording devices.....	12
4.3.6 Valve base control devices	12
5 Steady state control tests	12
5.1 General.....	12
5.2 DC switching sequence tests	13
5.3 Energization of reactive power components	13
5.4 Energization of converter transformers.....	13
5.5 Open line test of HVDC control system	13
5.6 Deblock-block performance tests	13
5.7 Operator control mode transfer tests	14
5.8 Operation status tests	14
5.9 Tap changer control tests.....	14
5.10 Reactive power control tests	14
5.10.1 Reactive power component switching function tests.....	14
5.10.2 Reactive power curve tests	14
5.11 Power ramping tests	15
5.12 Overload tests	15
5.13 Metallic and ground return configuration and transfer tests	15
5.14 Reduced voltage operation tests	15
5.15 Tests of static characteristic curves of converters	15
5.16 PQ diagram tests of VSC-HVDC converters	15
6 Dynamic control tests	16
6.1 General.....	16
6.2 Power step test.....	16
6.3 Current step test.....	16
6.4 Voltage step test.....	16
6.5 Gamma step test.....	17
6.6 AC system related tests	17

6.6.1	AC disturbance tests	17
6.6.2	AC/DC interaction tests	17
6.7	Stability control function tests	18
6.8	Power system restoration test	18
6.9	Grid code tests	18
7	Protection tests	19
7.1	General.....	19
7.2	Trip signal logic tests	19
7.3	Converter unit area protection tests	19
7.4	DC bus area protection tests.....	19
7.5	DC filter area protection tests	20
7.6	DC line area protection tests.....	20
7.7	Switch protection tests	20
7.8	Other protection tests	20
8	Redundancy and reliability of control and protection system tests.....	21
8.1	General.....	21
8.2	Redundant system failure tests	21
8.3	System monitoring and switching tests.....	21
8.4	Electromagnetic interference tests (optional)	22
8.5	IT security.....	22
9	Special tests for VSC.....	23
9.1	General.....	23
9.2	Control system delay (optional).....	23
9.3	Valve control and protection function tests	23
9.3.1	Valve control function test	23
9.3.2	Valve protection function tests	24
9.4	STATCOM tests	24
10	Test report.....	24
Annex A (informative)	Examples of protection areas and faults	25
Annex B (informative)	A typical test method for control system delay	28
Bibliography.....		30
Figure 1 – Relationship between clauses and test phases.....		6
Figure A.1 – Typical faults in a LCC HVDC substation (IEC/TR 60919-2:2008/AMD1:2015, Figure 7).....		26
Figure A.2 – Typical faults in a VSC HVDC substation (example – symmetrical monopole shown in single phase)		27
Figure B.1 – Composition of control system delay		28
Figure B.2 – The real-time simulation test scheme for control system delay		29

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at <https://patents.iec.ch>. IEC shall not be held responsible for identifying any or all such patent rights.

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:

Draft	Report on voting
22F/763/DTR	22F/787/RVDTR

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.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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.

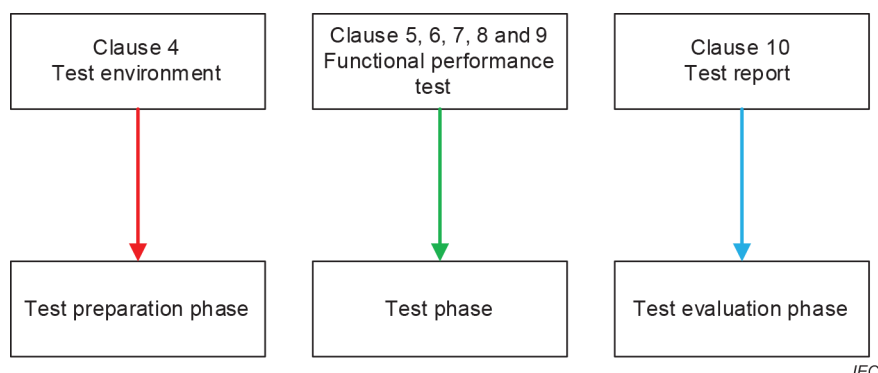
Clause 7 introduces the test practices and test methods of DC protection, whose main concerns are DC protection logic and threshold values.

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.



IEC

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 μ s. 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.