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TECHNICAL REPORT

colour inside

Unified power flow controller (UPFC) installations – System tests

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UNIFIED POWER FLOW CONTROLLER (UPFC) INSTALLATIONS – SYSTEM TESTS

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

Draft	Report on voting
22F/781/DTR	22F/795/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

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INTRODUCTION

IEC TR 63262:2019 introduces the importance of the system tests of unified power flow controller (UPFC) installations and gives the test items of the system tests. However, the details of the system tests of UPFC installations, including test methods and test procedures, are not given. For the commercial use of UPFC installations, this document provides the details of the system tests of UPFC installations for reference. The system tests are to verify the quality of UPFC after on-site installation and integration, the coordination between a UPFC installation and the grid, the fault ride-through performance of the UPFC installation and so on, which make the commercial operation of the UPFC installation more efficient and safer.

This document summarizes the system test experience of the existing UPFC projects, and the content has been verified by several years of stable operation of the UPFC projects.

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UNIFIED POWER FLOW CONTROLLER (UPFC) INSTALLATIONS – SYSTEM TESTS

1 Scope

This document provides the general information, items, conditions, and evaluation of test results for on-site system tests of unified power flow controller (UPFC) installations based on modular multi-level converter (MMC) technology. For special functions or performances that are claimed by specific projects, some extra test items not included in this document can be added according to the technical specification.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TR 63262:2019, *Performance of unified power flow controller (UPFC) in electric power systems*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TR 63262 and the following 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
unified power flow controller
UPFC
equipment which has two (or more) voltage sourced converters (VSCs) sharing common DC bus connected to the transmission system in parallel and in series, and can control the line impedance, voltage amplitude and phase angle at the same time

[SOURCE: IEC TR 63262:2019, 3.1.1]

3.2
system test
test verifying functions and performances of UPFC installations as a whole as well as the interaction with adjacent AC systems

[SOURCE: IEC 61975:2010 and IEC 61975:2010/AMD1:2016, 3.1.2, modified – The words "HVDC system" have been changed to "UPFC installations".]

3.3
converter unit test
test verifying functions and performances of converter units, including the shunt unit and series unit

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3.4
subsystem test
test verifying functions and performances of subsystems, such as converter system, water cooling system, relay protection system

3.5
thyristor bypass switch
TBS
power electronic switch with anti-parallel connected thyristors between the converter and the series transformer valve-side winding

[SOURCE: IEC TR 63262:2019, 3.1.6]

3.6
mechanical bypass switch
MBS
mechanical switch between the grid-side winding terminals of the series transformer

4 Objectives of system tests

4.1 Purpose

The system tests complete the commissioning of a UPFC installation. For the user, the completion of the system tests marks the beginning of the commercial operation of the UPFC installation. For the supplier, the system tests verify the suitability of the installed UPFC equipment and the functional completeness of the UPFC system. Moreover, adjustments and optimizations of the UPFC installation are made according to the results of system tests.

The system tests are to demonstrate that the requirements and stipulations in the contract are met.

The system tests consist of five major aspects:

a) UPFC installation equipment;
b) UPFC installation control and protection equipment and their settings;
c) environmental considerations;
d) interaction between the parallel unit and series unit;
e) system performance when the UPFC installation jointly operated with connected AC systems.

4.2 Basic principles

The basic principles for the system tests of the UPFC installation are as follows.

a) For the safety of the UPFC installation, the system tests are conducted until the completion of equipment factory tests, equipment on-site tests and on-site subsystem tests;
b) All designed functions and performances are tested to confirm that all technical requirements are satisfied;
c) The system test plan is agreed between the supplier and the user.

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4.3 Items of system tests

A typical structure of the UPFC installation is illustrated in Figure 1, consisting of the main circuit (shunt unit and series unit) and a control and protection system. The main circuit consists of two VSCs connected back-to-back by the DC bus, and the AC terminals are connected to the AC grid via two transformers: the shunt converter is connected to the transmission line in parallel via shunt transformer, and the series converter is connected to the transmission line serially via series transformer. The shunt converter and shunt transformer are the main components of the shunt unit. The series converter, TBS, MBS and series transformer are the main components of the series unit. The TBS is connected between the series converter and the series transformer.

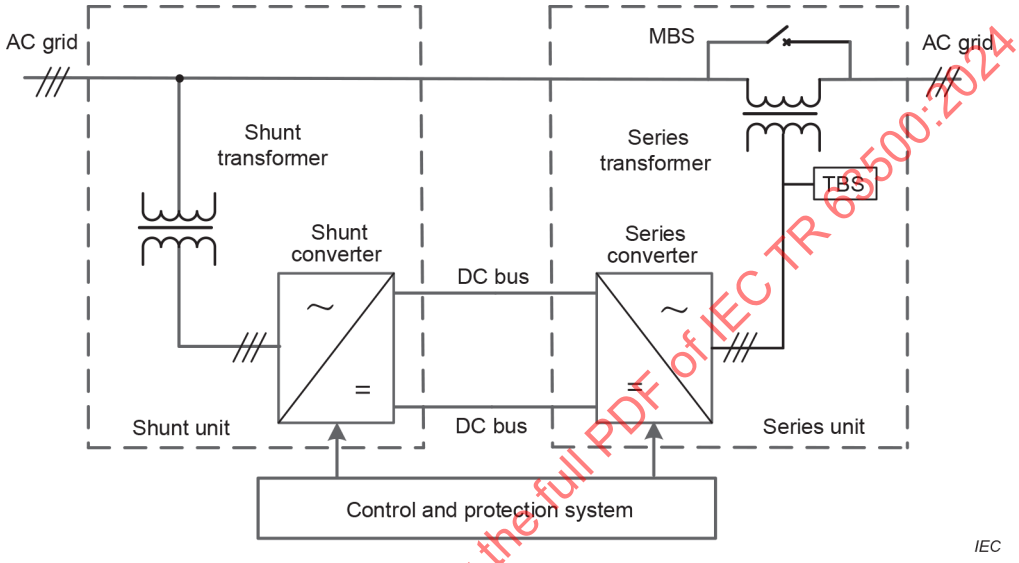

Figure 1 – Structure diagram of the UPFC installation

The typical control structure of the UPFC installation generally includes a system control, a converter control, and a valve control. The converter control and valve control are equipped independently for the series converter and shunt converter.

a) System control

Coordinates the control objects and targets of different converters, and mainly achieves the coordination control among substations and among different converters.

The system control functions include the following:

– power coordination control of power grid;
– power control of transmission interface;
– emergency power control and emergency voltage control of power grid;
– power oscillation damping control, etc.

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b) Converter control

Mainly accomplishes the multiple basic control functions of converters.

The shunt converter control includes the following:

– DC voltage control;
– AC voltage control or reactive power control;
– overload limitation control (if applicable).

The series converter control includes the following:

– active power control;
– reactive power control;
– emergency current control;
– impedance control (if applicable);
– overload limitation control of transmission line (if applicable).

c) Valve control

Direct control and monitoring of valves.

The system test items of the UPFC installation are listed in Table 1. For some special functions or performances required by the user, the system test items can be modified accordingly.

The system tests of the UPFC installation are divided into three stages: stage I involves testing the converter unit in the UPFC installation, stage II involves testing the system function and performance of the UPFC installation, and stage III involves trial operation of the UPFC installation.

The system tests follow the structure of the UPFC installation, starting from the smallest device, usually a transformer, then the least complex operational unit, usually a converter, and ending with the entire system in operation. Table 1 illustrates the test objects related to each test item.

Table 1 – Test stage, item and configuration of system tests

Stage	No.	Test item	Configuration
Stage I	1	Trip test	The control and protection systems
	2	Energizing test of the shunt transformer	See Figure 2.
	3	Energizing test of the series transformer	See Figure 3.
	4	Energizing test of the shunt converter	See Figure 4.
	5	Energizing test of the series converter	See Figure 5.
	6	Output phase sequence verification test of the shunt converter	See Figure 6.
	7	Output phase sequence verification test of the series converter	See Figure 7.

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Stage	No.	Test item	Configuration
Stage II	8	Initial operation tests	See Figure 8.
	9	Steady-state performance tests	
	10	Dynamic performance tests	
	11	Fault switching tests of control system	
	12	Transfer tests of auxiliary system	
	13	Grid control function tests (optional)	
	14	Heavy load and overload tests	
	15	Artificial short circuit test on AC grid (optional)	
	16	Other operation mode tests	See Figure 9. a) STATCOM mode See Figure 10. b) SSSC mode
Stage III	17	Trial operation	See Figure 11.

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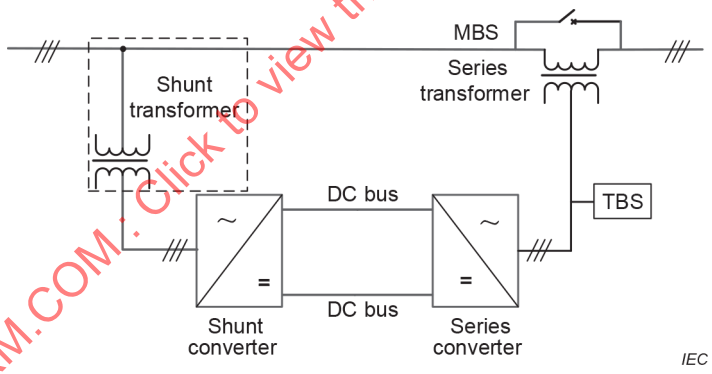

Figure 2 – Energizing test of the shunt transformer

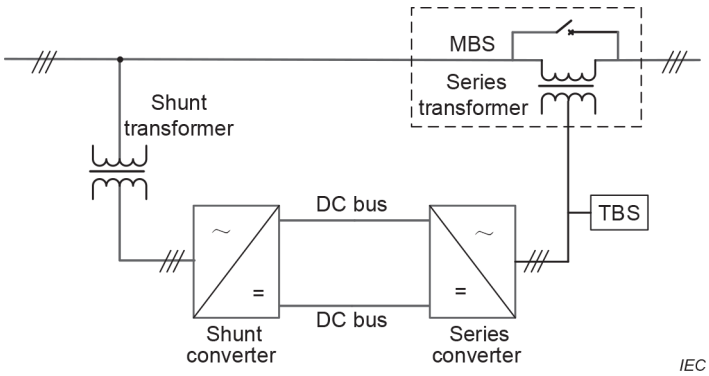

Figure 3 – Energizing test of the series transformer

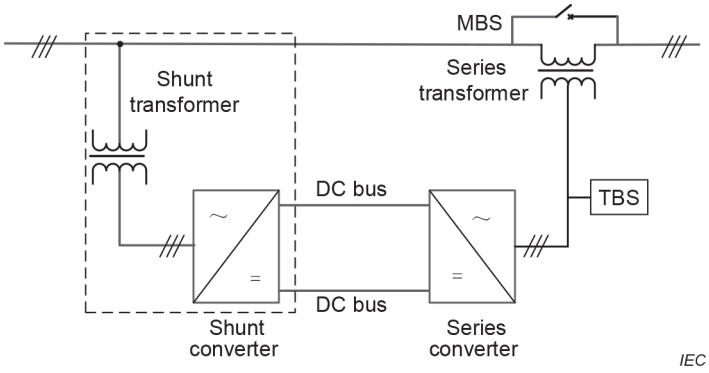

Figure 4 – Energizing test of the shunt converter

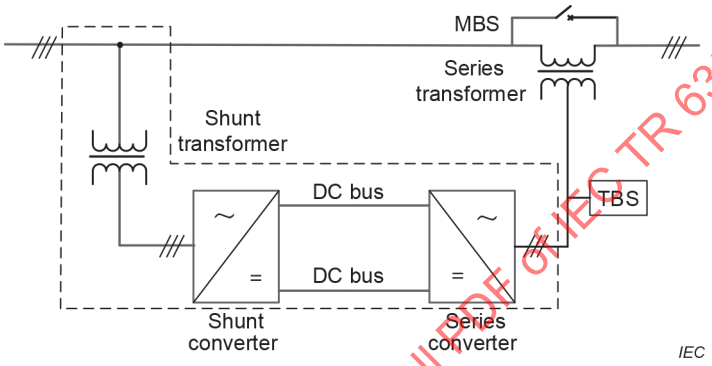

Figure 5 – Energizing test of the series converter

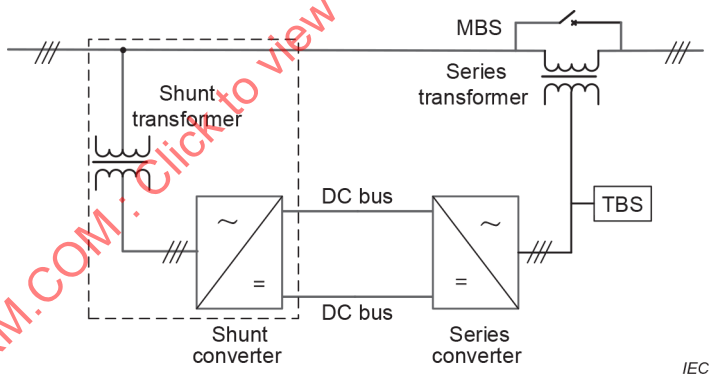

Figure 6 – Output phase sequence verification test of the shunt converter

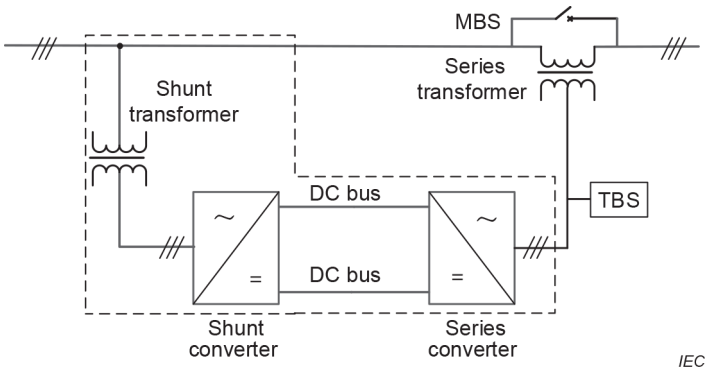

Figure 7 – Output phase sequence verification test of the series converter

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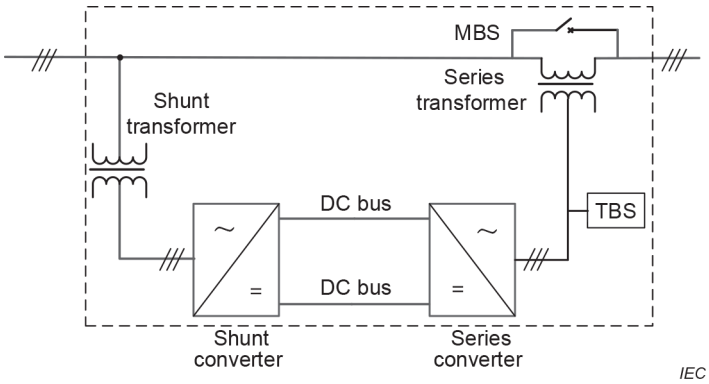

Figure 8 – System function and performance tests of UPFC

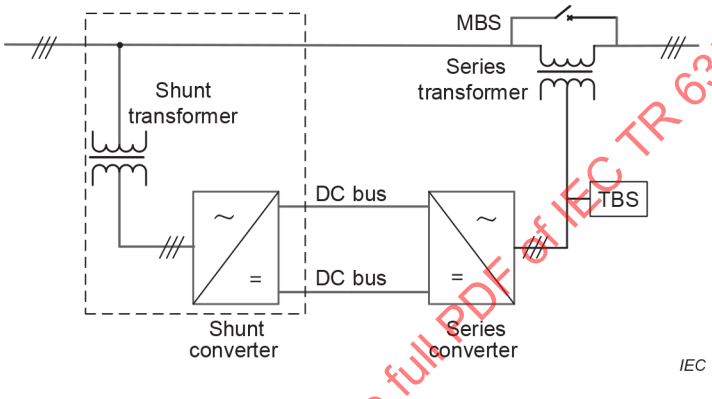

Figure 9 – Other operation mode tests – STATCOM mode

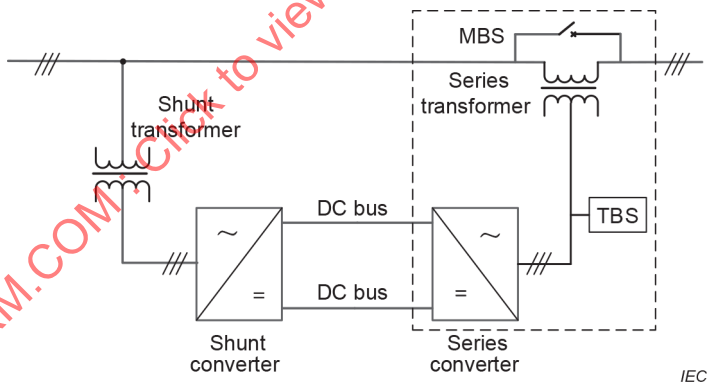

Figure 10 – Other operation mode tests – SSSC mode

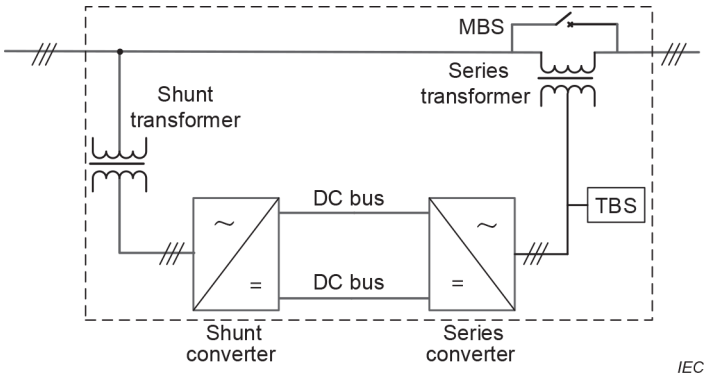

Figure 11 – Trial operation

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5 Preconditions of system tests

5.1 Basic conditions

The commissioning of a UPFC installation involves all the contract parties. The complexity and diversified aspects regarding the system tests require thorough planning and scheduling, the cooperation of all involved parties, and complete and structured documentation.

a) Operators are sufficiently trained.

b) Permission for each test procedure is available by the substation manager.

c) Safety and security instructions are made available to all personnel.

d) The system test program is approved.

e) Power profiles for each test are determined by both the supplier and user through negotiation.

f) Communications between operators and test personnel are established.

g) All necessary testing equipment is calibrated and operational.

5.2 Preconditions of system tests for the UPFC installation

The basic preconditions for the system tests regarding the UPFC installation are listed below, and other important preconditions are listed in each test.

a) The subsystem tests of the UPFC installation are completed, and all results are satisfied. The main equipment is ready for operation. The water cooling system of the converter valves is in service.

b) The temporary ground connection for the on-site high voltage test is removed. Any temporary structure in the UPFC installation is removed, and the testing sections are isolated from other sections.

c) All auxiliary systems, including the auxiliary power system, fire prevention system, heating, ventilation and air conditioning (HVA/C) system as well as lighting, are installed and operational.

d) Preliminary off-site tests of the control and protection system are conducted before delivery to verify the functionality of the UPFC control and protection system.

e) The UPFC monitoring and its communication, control and protection system are set correctly and operational.

5.3 Preconditions of system tests for the AC grid

The basic preconditions for the system tests regarding the AC grid are listed below, and other important preconditions are listed in each test.

a) The AC grid configuration and power profiles are adjusted according to the system test program.

b) The transmission lines connected to the UPFC installation in series and their relevant protections are operational.

c) The relevant safety devices in the grid are set correctly and operational.

d) In order to formulate the system test plan, relevant simulations are conducted to satisfy the safety and stability requirements for the equipment and system before the system tests, with an emphasis on power flow, stability and overvoltage.

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6 Converter unit tests

6.1 Trip test

6.1.1 Purpose of test

The test is to verify protection action (especially the functionality of the protective trip circuits of the equipment in the converter unit) and examine the records of the control system.

6.1.2 Test preconditions

The test preconditions are the following.

a) All the electric equipment in the UPFC installation is disconnected from the AC grid.

b) All control and protection systems (main and backup) associated with high voltage equipment are operational and their functionality and performance are verified.

c) All alarm and monitoring (including recording sequence of events) systems are verified and in service.

d) All safety procedures, including a visual inspection of high voltage equipment, are carried out before the test.

6.1.3 Test procedure

6.1.3.1 General

Trip signals are initiated from different devices, including but not limited to the tests listed in 6.1.3.2 to 6.1.3.7.

6.1.3.2 Protection trip test of converters

Initiate a trip signal from the protection trip terminal of the converter; the AC circuit breaker in grid side trips in this case.

6.1.3.3 Protection trip test of transformers

Initiate a trip signal from the protection trip terminal of the transformer; the AC circuit breaker in grid side trips in this case.

6.1.3.4 Protection trip test of the series unit

Initiate a trip signal from the protection trip terminal of the series unit; the TBS and bypass switch close in this case.

6.1.3.5 Protection trip test of the transmission line

Initiate a trip signal from the protection trip terminal of the transmission line; the line protection trips. In addition, the TBS and MBS close in this case.

6.1.3.6 Protection trip test of the water cooling system

Initiate a trip signal from the protection trip terminal of the water cooling system; the AC circuit breaker in grid side trips in this case.

6.1.3.7 Trip test of the emergency switch-off button

Press the emergency switch-off button in the control room; the AC circuit breaker in grid side trips in this case.

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6.1.4 Evaluation of test results

The evaluation of test results includes the following.

a) When activated by either position protection or manually by the emergency switch-off button, the AC circuit breaker in grid side trips without any fault.

b) No abnormal alarm occurs.

6.2 Energizing test of the shunt transformer

6.2.1 Purpose of test

This test is to verify the insulation strength of the shunt transformer satisfies the designed requirements and the electrical phasing of the shunt transformer is correct.

6.2.2 Test preconditions

The test preconditions are the following.

a) The on-site test of the shunt transformer is completed.

b) The trip test is completed before high voltage energizing (see 6.1).

c) The position of the voltage tap of the shunt transformer is correct.

d) The cooling system of the shunt transformer is in normal operation.

e) The shunt transformer is disconnected from the AC grid and the shunt converter.

f) The arrestor counter numbers are recorded.

6.2.3 Test procedure

The test procedure is the following.

a) Energize the shunt transformer for a certain time to complete the operational inspection and live detection, for example in some UPFC projects, no less than 30 min.

b) Record the inrush current and overvoltage.

c) Visually inspect all devices.

d) Pay special attention to abnormal sounds, corona discharge and ferro-resonance during the test.

e) Test the voltage tap control function using the manual mode and automatic mode separately.

f) Perform chromatographic analysis of the shunt transformer oil after the test.

g) Deenergize the shunt transformer.

6.2.4 Evaluation of test result

The evaluation of test results includes the following.

a) No protection function is activated during the test.

b) The voltage phasing of shunt transformer is correct.

c) No abnormal sound or corona discharge or ferro-resonance occurs.

d) Measurements, such as the noise, overvoltage and inrush current, meet the requirements.

6.3 Energizing test of the series transformer

6.3.1 Purpose of test

This test is to verify the insulation strength of the series transformer satisfies the designed requirements and the electrical phasing of the shunt transformer is correct.

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6.3.2 Test preconditions

The test preconditions are the following.

a) The on-site test of the series transformer is completed.
b) The trip test is completed before high voltage energizing (see 6.1).
c) The cooling system of the series transformer is in normal operation.
d) The series transformer is disconnected from the AC grid and the series converter.
e) The windings of the series transformer on both the grid side and valve side are bypassed
f) The arrestor counter numbers are recorded.

6.3.3 Test procedure

There are two methods to conduct this test according to the structure of UPFC installation.

Based on the UPFC structure in Figure 12 a), the test procedure of the first method is the following.

a) Energize the series transformer through closing the AC circuit breaker in grid side for a certain time as shown in step 1 to complete the operational inspection and live detection, for example in some UPFC projects, no less than 30 min.
b) Open the MBS after energizing the series transformer to insert the series transformer to the transmission line as shown in step 2.
c) Record the inrush current and overvoltage.
d) Close the MBS to bypass the series transformer as shown in step 3.
e) Visually inspect all devices.
f) Pay special attention to abnormal sounds, corona discharge and ferro-resonance during the test.
g) Deenergize the series transformer.
h) Perform chromatographic analysis of the series transformer oil after the test.

Based on the UPFC structure in Figure 12 b), the test procedure of the second method is the following.

1) Energize the series transformer through closing the AC circuit breaker in series transformer side for a certain time as shown in steps 1, 2 and 3 to complete the operational inspection and live detection, for example in some UPFC projects, no less than 30 min.
2) Open the MBS after energizing the series transformer to insert the series transformer to the transmission line as shown in step 4.
3) Record the inrush current and overvoltage.
4) Close the MBS to bypass the series transformer.
5) Visually inspect all devices.
6) Pay special attention to abnormal sounds, corona discharge and ferro-resonance during the test.
7) Deenergize the series transformer.
8) Perform chromatographic analysis of the series transformer oil after the test.

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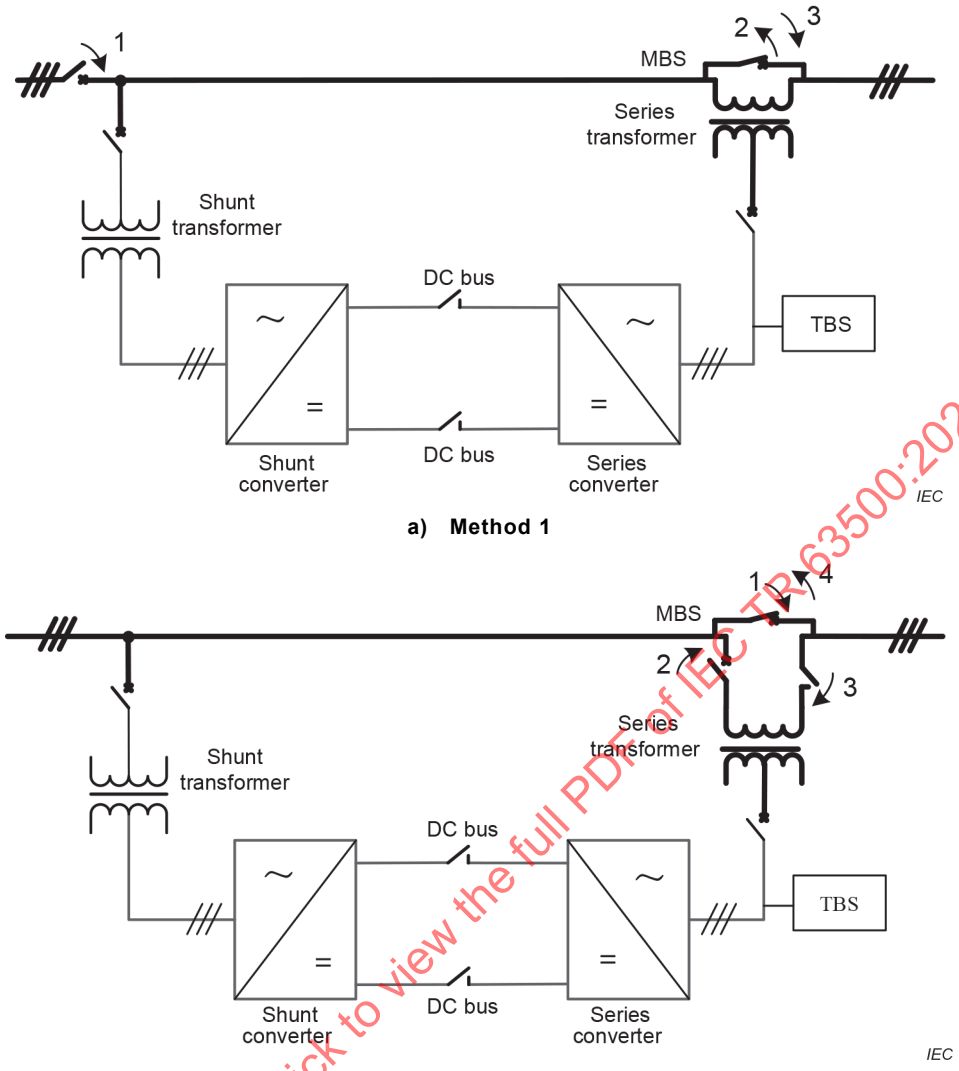

Figure 12 – Test procedure diagram of series transformer energizing test

6.3.4 Evaluation of test results

The evaluation of test results includes the following.

a) No protection function is activated during the test.
b) The voltage phasing of series transformer is correct.
c) No abnormal sound or corona discharge or ferro-resonance occurs.
d) Measurements, such as the noise, overvoltage and inrush current, meet the requirements.

6.4 Energizing test of the shunt converter

6.4.1 Purpose of test

This test is to verify that the shunt converter is energized safely and the function of phase locked loop is correct.

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6.4.2 Test preconditions

The test preconditions are the following.

a) The on-site test of the shunt converter is completed.
b) The trip test is completed before high voltage energizing (see 6.1).
c) The energizing test of shunt transformer is completed (see 6.2).
d) The converter water cooling system is in normal operation.
e) The shunt converter is disconnected from the shunt transformer.
f) The shunt converter is disconnected from the series converter.
g) The converter control and protection system is in service.
h) The shunt transformer is in normal operation.

6.4.3 Test procedure

The test procedure is the following.

a) Energize the shunt converter by connecting the shunt transformer (a charging resistance can be connected in series with the shunt transformer to limit charging current; after the energization is completed, the charging resistance is bypassed).
b) The energization of the shunt converter lasts for a certain time to complete the operational inspection and live detection, for example in some UPFC projects, no less than 30 min.
c) Check the voltage phase of the shunt converter valve and the state signals of submodules in the converter.
d) Deenergize the shunt converter.

6.4.4 Evaluation of test results

The evaluation of test results includes the following.

a) No protection function is activated during the test.
b) The shunt converter control system functions correctly.
c) No abnormal sound or corona discharge or ferro-resonance occurs.
d) Measurements, such as the valve temperature, meet the requirements.
e) The voltage waveforms of the shunt converter meet the requirements.
f) The results of state signals of submodules in the shunt converter meet the requirements.

6.5 Energizing test of the series converter

6.5.1 Purpose of test

This test is to verify that the series converter is energized safely through the DC bus and the function of phase locked loop is correct.

6.5.2 Test preconditions

The test preconditions are the following.

a) The on-site test of the series converter is completed.
b) The trip test is completed before high voltage energizing (see 6.1).
c) The energizing tests of shunt transformer and series transformer are completed (see 6.2 and 6.3).
d) The energizing test of shunt converter is completed (see 6.4).
e) The time interval between the shunt converter energizing test and the series converter energizing test is sufficient to allow the full discharge of the capacitors in the converters.

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f) The converter water cooling system is in normal operation.

g) The shunt converter is disconnected from the shunt transformer.

h) The series converter is disconnected from the series transformer.

i) The shunt converter is connected to the series converter.

j) The converter control and protection system is in service.

k) The shunt transformer is in normal operation.

6.5.3 Test procedure

The test procedure is the following

a) Energize the series converter through the DC bus by closing the AC circuit breaker on grid side of the shunt converter.

b) The energization of the series converter lasts for a certain time to complete the operational inspection and live detection, for example in some UPFC projects, no less than 30 min.

c) Check the voltage phase of the series converter valve and the state signals of submodules in the converter.

d) Record the polarity and amplitude of DC bus voltage.

e) Deenergize the series converter and shunt converter.

6.5.4 Evaluation of test results

The evaluation of test results includes the following.

a) No protection function is activated during the test.

b) The converter control system functions correctly.

c) No abnormal sound or corona discharge or ferro-resonance occurs.

d) Measurements, such as the valve temperature, meet the requirements.

e) The voltage waveforms of the DC bus and the converter meet the requirements.

f) The results of state signals of submodules in the series converter meet the requirements.

6.6 Output phase sequence verification test of the shunt converter

6.6.1 Purpose of test

This test is to verify that the shunt converter operates safely under no load conditions and the deblocking mechanism of the shunt converter functions normally for the first deblocking.

6.6.2 Test preconditions

The test preconditions are the following.

a) The energizing test of shunt converter is completed (see 6.4).

b) The converter water cooling system is in normal operation.

c) The shunt converter is connected to the shunt transformer.

d) The shunt converter is disconnected from the series converter.

e) The converter control and protection system is in service.

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6.6.3 Test procedure

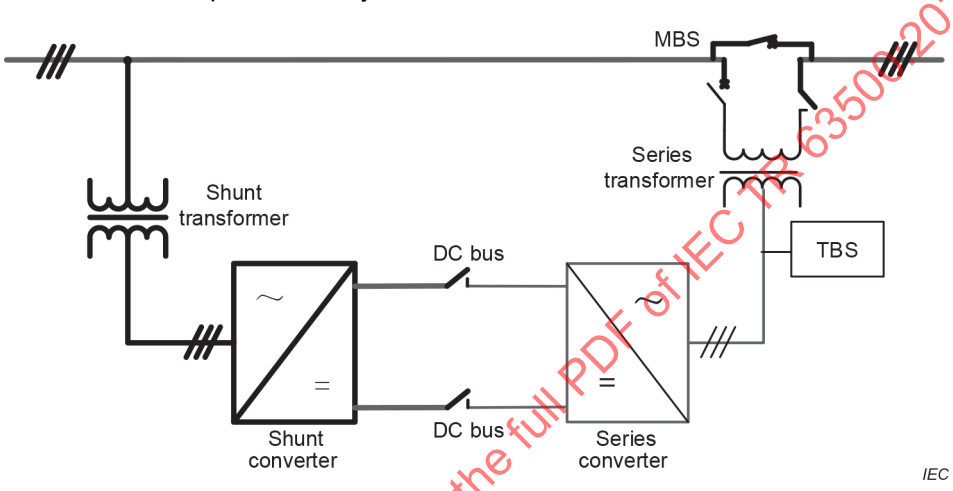
After energizing the shunt converter, disconnect it from the AC grid, deblock it with a given modulation voltage, and check the output results with no load. The test procedure is the following.

a) Energize the shunt converter as shown in Figure 13 a).

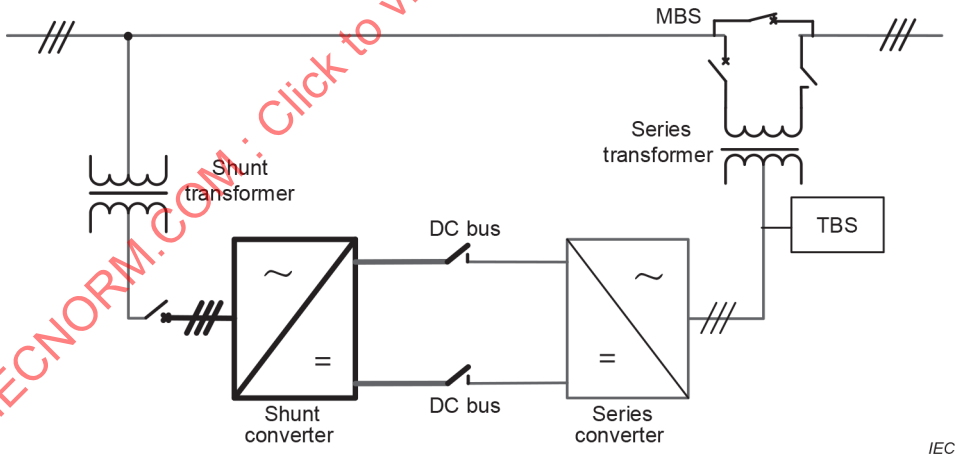
b) Once the energizing of the shunt converter is completed, isolate the shunt converter from the AC grid and then deblock the shunt converter based on the remaining charge on the valve capacitor with a given reference voltage waveform as shown in Figure 13 b).

c) After a certain period, compare the AC voltage of the shunt converter with the AC grid voltage, and then block the shunt converter.

d) Check the control and protection system.



a) Energize the shunt converter



b) Isolate the shunt converter from the AC grid

Figure 13 – Test procedure diagram of output phase sequence verification test of the shunt converter

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6.6.4 Evaluation of test results

The evaluation of test results includes the following.

a) No protection function is activated during the test.
b) The converter control system functions correctly.
c) No abnormal sound or corona discharge or ferro-resonance occurs.
d) The AC voltage waveforms of the shunt converter, including the phase sequence, phase angle difference and amplitude, meet the requirements.
e) The functions of deblock, block, phase locked loop are correct.
f) The delay of the control system meets the design requirements.

6.7 Output phase sequence verification test of the series converter

6.7.1 Purpose of test

This test is to verify that the series converter operates safely under no load conditions and the deblocking mechanism of the series converter functions normally for the first deblocking.

6.7.2 Test preconditions

The test preconditions are the following.

a) The energizing tests of shunt converter and series converter are completed (see 6.4 and 6.5).
b) The output phase sequence verification test of the shunt converter is complete (see 6.6).
c) The converter water cooling system is in normal operation.
d) The shunt converter is connected to the shunt transformer.
e) The shunt converter is connected to the series converter.
f) The series converter or the series transformer is disconnected from the AC grid.
g) The converter control and protection system is in service.

6.7.3 Test procedure

After energizing the series converter through the DC bus, disconnect it from the AC grid in shunt side, deblock it with a given modulation voltage, and check the output results of the series converter with no load. The test procedure is the following.

a) Energize the series converter as shown in Figure 14 a).
b) Once the energizing of the series converter is completed, isolate the series converter from the AC grid in shunt side and then deblock the series converter based on the remaining charge on the valve capacitor with a given reference voltage waveform as shown in Figure 14 b).
c) After a certain period, for example in some UPFC projects, 6 cycles, compare the AC voltage of the series converter before blocking with the AC grid voltage in series side. and then block the series converter and the shunt converter.
d) Check the control and protection system.

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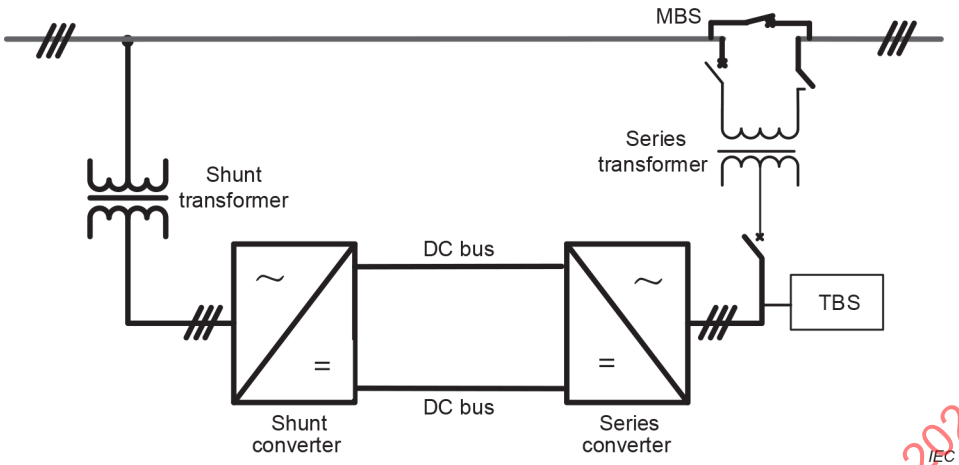
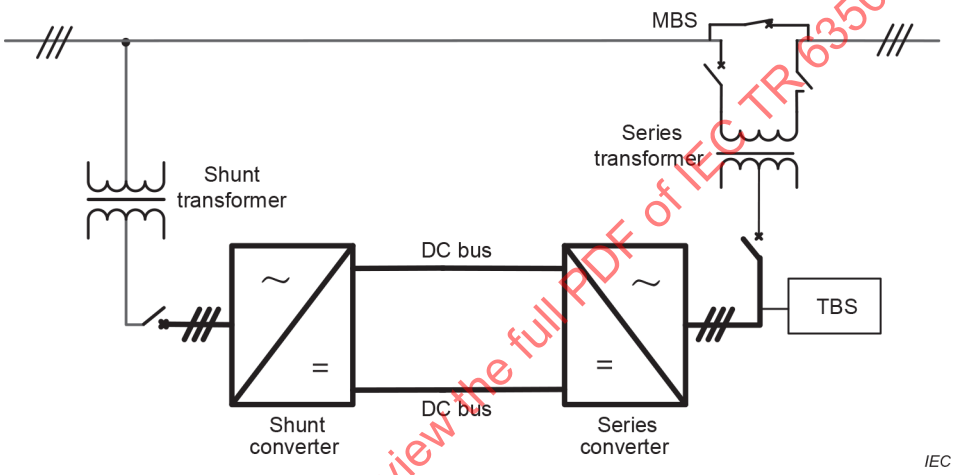


a) Energize the series converter



b) Isolate the shunt converter from the AC grid

Figure 14 – Test procedure diagram of output phase sequence verification test of the series converter

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6.7.4 Evaluation of test results

The evaluation of test results includes the following.

a) No protection function is activated during the test.
b) The converter control system functions correctly.
c) No abnormal sound or corona discharge or ferro-resonance occurs.
d) The AC voltage waveforms of the series converter, including the phase sequence, phase angle difference and amplitude, meet the requirements.
e) The functions of deblock, block and phase locked loop are correct.
f) The delay of the control system meets the design requirements.

7 System function and performance tests

7.1 Initial operation tests

7.1.1 Purpose of test

This test is to verify that the UPFC installation deblocks and blocks properly and the functions of start, stop, emergency shutdown, and control transfer under UPFC mode perform correctly.

7.1.2 Test preconditions

The test preconditions are the following.

a) The off-site tests of the control and protection system are completed.
b) The converter unit tests are completed (see Clause 6).
c) The shunt converter and shunt transformer are connected to the AC grid.
d) The shunt converter is connected to the series converter.
e) The series converter and series transformer are connected to the AC grid.
f) The converter control and protection system is in service.
g) The UPFC installation operates in UPFC mode.

7.1.3 Test procedure

7.1.3.1 Short-term deblocking test

The test procedure is the following.

a) After the shunt converter completed charging, deblock the shunt converter and wait until the DC bus voltage reaches the rated value.
b) The series converter is charged through the DC bus.
c) After the series converter completed charging, deblock the series converter at least twice. The first deblocking time is set to a very short time, for example in some UPFC projects, half of a cycle, and the last deblocking time is set to a few seconds but not exceeding 10 s.
d) Block the series converter and the shunt converter.

The following is checked.

1) The DC bus voltage rises smoothly to the rated value.
2) The deblocking and blocking sequences are performed in the right order.
3) The voltage waveforms of the series converter meet the design requirements.

7.1.3.2 Start and stop test

The start and stop test is conducted from the operation panel. The test procedure is the following.

a) Charge the shunt converter, deblock it and check the voltage waveforms of the shunt converter and DC bus;
b) Once the series converter is ready, deblock it and the bypass switch (MBS and TBS) opens automatically;
c) Set the UPFC mode to control the line power and operate for a certain time, for example 15 min;
d) Block the series converter and check it. The bypass switch closes automatically;
e) Block the shunt converter and check it. The DC voltage declines smoothly to the energization level.

The following is checked.

1) The start and stop sequence is performed in the correct order.
2) After blocking the series converter, the power of AC transmission line is reduced to the natural power level.
3) During the deblocking period, check the control and protection signals. The errors of the voltage and current of the converter and signals in the control and protection system meet the design requirements.

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7.1.3.3 Emergency switch-off test

When the UPFC installation operates at the state of zero power in shunt side and zero voltage in series side, press the emergency switch-off button and then check the test results and trip sequence.

The following is checked.

a) The series converter and shunt converter block normally.

b) The AC circuit breaker in shunt side is tripped out, and the bypass switch in series side is closed automatically.

c) The protection operates correctly.

7.1.3.4 Transfer test of control system

The transfer test of the control system is conducted at a low power level. The test procedure is the following.

a) Transfer the control system from the main control system to the backup control system and check the control functions.

b) Start and stop the UPFC installation from the backup control system and check the control functions.

7.1.3.5 Transfer test of control location

The transfer test of the control location is conducted at a low power level. The test procedure is the following.

a) Transfer the control location from the substation control system to the local control system and check the control functions.

b) Start and stop the UPFC installation from the local control system and verify the control functions.

7.1.4 Evaluation of test results

The evaluation of test results includes the following.

a) No protection function is activated during the test;

b) The converter control and protection system functions correctly.

c) No abnormal sound or corona discharge occurs.

d) The output electrical waveforms, including the current, voltage and power, meet the requirements.

e) The delay of the control system meets the design requirements.

f) Transfer between different systems and different locations does not cause any disturbance to the DC and AC networks.

7.2 Steady-state performance tests

7.2.1 Purpose of test

This test is to verify that the UPFC installation operates stably and that the steady-state performance of the UPFC installation meets the design requirements.

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7.2.2 Test preconditions

The test preconditions are the following.

a) The off-site tests of the control and protection system are completed.
b) The converter unit tests and the initial operation tests are completed (see Clause 6 and 7.1).
c) The shunt converter and shunt transformer are connected to the AC grid.
d) The shunt converter is connected to the series converter.
e) The series converter and series transformer are connected to the AC grid.
f) The converter control and protection system is in service.
g) The UPFC installation operates in UPFC mode.

7.2.3 Test procedure

7.2.3.1 Transfer tests of control functions

Under the UPFC mode and operating in the deblock condition, transfer the control functions of the shunt unit and the series unit separately. The test procedure is the following.

a) Transfer test of shunt unit control function
   1) Transfer the voltage control function and the reactive power control function in the shunt unit and verify the steady-state performance of the UPFC installation.
   2) If the shunt unit has both manual and automatic control functions, verify the transfer between both of them.
b) Transfer test of series unit control function
   1) Transfer the reactive power control function and the power factor control function (if any) in the series unit and verify the steady-state performance of the UPFC installation.
   2) Transfer the power control function and the power flow following control function (if any) in the series unit and verify the steady-state performance of the UPFC installation.

7.2.3.2 Line active power control tests

Under the power control mode of the series unit, the ramping test of the line active power is conducted. The test procedure is the following.

a) Adopt the fixed active power control function in the series unit. Set the reference values of the line active power to several typical values.
b) Start the UPFC installation and ramp the line active power up from the minimum power to the set values until the power reaches a stable status.
c) Ramp the line active power down to the set values and then down to the minimum active power.
d) Stop the UPFC installation and check the following.
   1) The line active power ramps smoothly and reaches the reference value stably.
   2) The ramping of the line active power does not disturb the DC and AC networks.
   3) Monitor the power quality of the AC grid.

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7.2.3.3 Line reactive power control tests

Under the power control mode of the series unit, the ramping test of the line reactive power is conducted. The test procedure is the following.

a) Adopt the control function of fixed reactive power in the series unit. Set the reference values of the line reactive power to several typical values.

b) Start the UPFC installation and ramp the line reactive power up from the minimum power to the set values until the power reaches a stable status.

c) Ramp the line reactive power down to the set values and then down to the minimum reactive power.

d) Stop the UPFC installation and check the following.

   1) The line reactive power ramps smoothly and reaches the reference value stably.

   2) The ramping of the line reactive power does not disturb the DC and AC networks.

   3) Monitor the power quality of the AC grid.

7.2.3.4 Additional control tests (optional)

Other control functions of the line power include the power factor control function and the suspend control function. The test procedure is the following.

a) Power factor control test: Adopt the fixed active power control function and the fixed power factor control function in the series unit and set the reference values of the line active power. Start the UPFC installation and ramp up the line active power from the minimum power to the set values until the power reaches a stable status. Verify the line power factor remains almost the same during the ramping process.

b) Suspend control test: During the ramping process of active or reactive power, press the "pause" function and verify that the active or reactive power maintains at the "pause" moment.

7.2.4 Evaluation of test results

The evaluation of test results includes the following.

a) No abnormal alarm or event occurs.

b) The control and protection system functions correctly.

c) The output electrical waveforms, including the current, voltage and power, meet the requirements.

d) The steady-state performance meets the design requirements.

7.3 Dynamic performance tests

7.3.1 Purpose of test

This test is to verify that the dynamic performance of the UPFC installation by the step response tests. These tests include the step response tests of the line active power, line reactive power, shunt unit reactive power and shunt unit AC voltage.

7.3.2 Test preconditions

The test preconditions are the following.

a) The off-site tests of the control and protection system are completed.

b) The converter unit tests are completed (see Clause 6).

c) The initial operation tests and the steady-state performance tests are completed (see 7.1 and 7.2).

d) The shunt converter and shunt transformer are connected to the AC grid.

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e) The shunt converter is connected to the series converter.

f) The series converter and series transformer are connected to the AC grid.

g) The converter control and protection system is in service.

h) The UPFC installation operates in UPFC mode.

7.3.3 Test procedure

7.3.3.1 General procedure

The test general procedure is the following.

a) The step response tests are conducted in the directions of both increasing and decreasing reference.

b) The step response tests of the shunt unit and the series unit are conducted separately.

c) The controller parameters are optimized based on the structure and parameter of the AC grid to meet the requirements of dynamic response.

7.3.3.2 Step response test of line active power

The step response test of the line active power is conducted by changing the reference value of the line active power. The test procedure is the following.

a) Apply a step change in the power order.

b) Verify the dynamic performance, including the step response time, overshoot, and stabilization time.

7.3.3.3 Step response test of line reactive power

The step response test of the line reactive power is conducted by changing the reference value of the line reactive power. The test procedure is the following.

a) Apply a step change in the power order.

b) Verify the dynamic performance, including the step response time, overshoot, and stabilization time. For example in some UPFC projects, the step response time is not exceeding 80 ms, the overshoot is less than 30 % of the step, and the stabilization time is less than 120 ms.

7.3.3.4 Step response test of shunt unit AC voltage

The voltage control function is adopted by the shunt unit. The step response test of AC voltage of shunt unit is conducted by changing the AC voltage reference value. The test procedure is the following.

a) Apply a step change in the AC voltage order of shunt unit.

b) Verify the dynamic performance, including the step response time, overshoot, and stabilization time.

7.3.3.5 Step response test of shunt unit reactive power

The reactive power control function is adopted by the shunt unit. The step response test of reactive power of the shunt unit is conducted by changing the reactive power reference value. The test procedure is the following.

a) Apply a step change in the reactive power order of shunt unit.

b) Verify the dynamic performance, including the step response time, overshoot, and stabilization time.

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7.3.4 Evaluation of test results

The evaluation of test results includes the following.

a) No abnormal alarm or event occurs.
b) The control and protection system functions correctly.
c) No instability occurs during the step response tests.
d) The output electrical waveforms, including the current, voltage, power and so on, meet the requirements.
e) The dynamic performance meets the design requirements.

7.4 Fault switching tests of control system

7.4.1 Purpose of test

This test is to verify the control system switches automatically when a fault of the control system occurs.

7.4.2 Test preconditions

The test preconditions are the following.

a) The converter unit tests are completed (see Clause 6).
b) The initial operation tests, steady-state performance tests and dynamic performance tests are completed (see 7.1, 7.2 and 7.3).
c) The shunt converter and shunt transformer are connected to the AC grid.
d) The shunt converter is connected to the series converter.
e) The series converter and series transformer are connected to the AC grid.
f) The converter control and protection system is in service.
g) The UPFC installation operates in UPFC mode.
h) The UPFC installation operates at a minimum power.

7.4.3 Test procedure

7.4.3.1 General procedure

The fault switching tests of the control system are conducted by simulating various faults, including the crash of main control system, the power supply fault of control system, the fault of field bus, the fault of control bus, the fault of control LAN network, the interruption of voltage secondary circuit, and the communication failure of valve control system.

7.4.3.2 Crash test of main control system

When simulating the crash of the main control system, the backup control system switches automatically to the main control state. The transmission power, DC voltage and AC voltage of the UPFC installation are checked during the test process.

7.4.3.3 Power supply fault test of control system

When disconnecting the power supply of the main control system, the backup control system switches automatically to the main control state. The transmission power, DC voltage and AC voltage of the UPFC installation are checked during the test.

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7.4.3.4 Fault test of field bus

When disconnecting one field bus of the main control system, the backup control system switches automatically to the main control state. The transmission power, DC voltage and AC voltage of the UPFC installation are checked during the test.

7.4.3.5 Fault test of control bus

When disconnecting one control bus of the main control system, the backup control system switches automatically to the main control state. The transmission power, DC voltage and AC voltage of the UPFC installation are checked during the test.

7.4.3.6 Fault test of control LAN network

When disconnecting the LAN network fibre of the main control system, the backup control system switches automatically to the main control state. The transmission power, DC voltage and AC voltage of the UPFC installation are checked during the test.

7.4.3.7 Interruption test of AC voltage secondary circuit

When simulating the interruption of single-phase and three-phase of valve voltage secondary circuits, respectively, the backup control system switches automatically to the main control state. The transmission power, DC voltage and AC voltage of the UPFC installation are checked during the test.

7.4.3.8 Communication failure test of valve control system

In case of disconnecting the communication between the converter control system and the valve control system, when simulating the communication failure of the valve control system, such as the loss of the deblock signal, the trip signal and so on, the backup converter control system switches automatically to the main control state. The transmission power, DC voltage and AC voltage of the UPFC installation are checked during the test.

7.4.4 Evaluation of test results

The evaluation of test results includes the following.

a) No abnormal alarm or event occurs.
b) The control and protection system functions correctly.
c) The monitoring system functions correctly.
d) The switching sequence is correct.
e) Switching between the main system and backup system does not disturb the DC and AC networks.

7.5 Transfer tests of auxiliary system

7.5.1 Purpose of test

This test is to verify the transfer functions of substation power and water cooling system in the UPFC installation.

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7.5.2 Test preconditions

The test preconditions are the following.

a) The converter unit tests are completed (see Clause 6).
b) The initial operation tests, steady-state performance tests and dynamic performance tests are completed (see 7.1, 7.2 and 7.3).
c) The shunt converter and shunt transformer are connected to the AC grid.
d) The shunt converter is connected to the series converter.
e) The series converter and series transformer are connected to the AC grid.
f) The converter control and protection system is in service.
g) The UPFC installation operates in UPFC mode.
h) The UPFC installation operates at a minimum power.

7.5.3 Test procedure

7.5.3.1 Transfer test of AC power supply

Under the steady-state operation of the UPFC installation, disconnect the AC power supply to trigger switching to the backup AC power supply automatically, and verify the self-switched to backup power function.

7.5.3.2 Transfer test of DC power supply

Under the steady-state operation of the UPFC installation, disconnect the DC power supply to trigger switching to the backup DC power supply automatically, and verify the self-switched to backup power function.

7.5.3.3 Transfer test of water pump of water cooling system

Initiate a transfer of the backup water pump by placing the command from the control system, or doing a manual switch, or simulating a fault in the control and protection system, and then verify the transfer function.

7.5.4 Evaluation of test results

The evaluation of test results includes the following.

a) No abnormal alarm or event occurs.
b) The control and protection system functions correctly.
c) The transfer sequence is correct.
d) The transfer process does not disturb the DC and AC networks.

7.6 Grid control function tests (optional)

7.6.1 Purpose of test

This test is to verify the grid control functions of the UPFC installation, such as voltage control, automatic voltage control (AVC), emergency power control, and transmission section power control.

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7.6.2 Test preconditions

The test preconditions are the following.

a) The converter unit tests are completed (see Clause 6).
b) The initial operation tests, steady-state performance tests and dynamic performance tests are completed (see 7.1, 7.2 and 7.3).
c) The shunt converter and shunt transformer are connected to the AC grid.
d) The shunt converter is connected to the series converter.
e) The series converter and series transformer are connected to the AC grid.
f) The converter control and protection system is in service.
g) The UPFC installation operates in UPFC mode.

7.6.3 Test procedure

7.6.3.1 General procedure

The grid control function tests are conducted based on the actual configuration of the UPFC installation and the AC grid. It generally includes but is not limited to: AC voltage control test, automatic voltage control (AVC) interface test, emergency power control test, transmission section power control test, and automatic power curve control test.

7.6.3.2 AC voltage control test

Simulate a condition of the AC system voltage being higher or lower than the preset abnormal voltage action value and verify the UPFC installation adjusts the system voltage to the set normal voltage automatically within its regulation capacity.

7.6.3.3 AVC interface test

If the shunt unit participates in the AVC, verify the AVC function is activated by the external signal and executed according to the requirements.

7.6.3.4 Emergency power control test

Simulate a condition of the line current or power exceeding the limit value, verify the UPFC installation controls the line power according to the established strategy, and automatically adjusts the line current or power to the limit value within its regulation capacity.

7.6.3.5 Transmission section power control test

The test procedure is the following.

a) Power control test of the transmission section: Simulate the power transmission section regulation, power transmission section limit and other basic control functions, and verify that the control results meet the design and technical specifications.
b) Emergency control function test of the transmission section: Simulate a controlled transmission section overload and verify that the UPFC installation eliminates the section overload by controlling power flow.

7.6.3.6 Automatic power curve control test

Set the line power curve and activate the automatic power curve control function in the series unit, verify the line power follows the power curve and changes smoothly.

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7.6.4 Evaluation of test results

The evaluation of test results includes the following.

a) No abnormal alarm or event occurs.

b) The control and protection system functions correctly.

c) The output electrical waveforms, including the current, voltage, power and so on, meet the requirements.

d) The dynamic and steady-state performance meets the design requirements.

7.7 Other operation mode tests

7.7.1 General

The system tests of UPFC mode are not equivalent to the system tests of STATCOM mode as well as SSSC mode, where the electrical structure, control strategy and logic are different. Therefore, the UPFC mode system tests cannot verify the function and performance of STATCOM mode and SSSC mode, and separate tests are needed. The system tests of STATCOM mode and SSSC mode are scheduled either before or after the system test of UPFC mode. For easy implementation, the test sequence is generally: first STATCOM mode system tests, then UPFC mode system tests, last SSSC mode system tests.

7.7.2 STATCOM mode tests

7.7.2.1 Purpose of test

The purposes of the test are as follows.

a) Verification of the function of STATCOM mode.

b) Verification of the performance of STATCOM mode.

7.7.2.2 Test preconditions

The test preconditions are the following.

a) The off-site tests of the control and protection system are completed.

b) The converter unit tests are completed (see Clause 6).

c) The shunt converter and shunt transformer are connected to the AC grid.

d) The shunt converter is disconnected from the series converter.

e) The converter control and protection system is in service.

f) The UPFC installation operates in STATCOM mode.

7.7.2.3 Test procedure

7.7.2.3.1 Reactive power control test

The shunt converter is set to reactive power control function with the inductive and capacitive reactive power reference values, including the speed and target values. The test procedure is the following.

a) Deblock the shunt converter.

b) Ramp the reactive power up to the rated value and checking the measuring circuit.

c) Record the operating parameters, including AC voltage, AC current, reactive power, shunt transformer tap, arm current, DC voltage, and modulation ratio.

d) Measure the equipment temperatures and hot spots.

e) Verify the steady-state performance of the shunt converter.

f) Block the shunt converter.

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7.7.2.3.2 Voltage control test

The shunt converter is set to AC voltage control function with a voltage reference value. The test procedure is the following.

a) Deblock the shunt converter.
b) Ramp the AC voltage up to the rate value and checking the measuring circuit.
c) Record the operating parameters, including AC voltage, AC current, reactive power, shunt transformer tap, arm current, DC voltage, and modulation ratio.
d) Monitor the power quality index of the converter access point.
e) Block the shunt converter.

7.7.2.3.3 Step response test of dynamic reactive power

The step response test of reactive power is conducted by changing the reference value of the reactive power of the shunt unit. The test procedure is the following.

a) Apply a step change in the reactive power order.
b) Verify the dynamic performance, including the step response time, overshoot, and stabilization time.

7.7.2.3.4 Evaluation of test results

The evaluation of test results includes the following.

a) No abnormal alarm or event occurs.
b) The control and protection system functions correctly.
c) No instability occurs during the tests.
d) The output electrical waveforms, including the current, voltage, power and so on, meet the requirements.
e) The measurements, including the temperature, meet the requirements.

7.7.3 SSSC mode tests

7.7.3.1 Purpose of test

The purposes of the test are as follows.

a) Verification of the function of SSSC mode.
b) Verification of the performance of SSSC mode.

7.7.3.2 Test preconditions

The test preconditions are the following.

a) The off-site tests of the control system are completed.
b) The converter unit tests are completed (see Clause 6).
c) The series converter and series transformer are connected to the AC grid.
d) The series converter is disconnected from the shunt converter.
e) The converter control and protection system is in service.
f) The UPFC installation operates in SSSC mode.

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7.7.3.3 Test procedure

7.7.3.3.1 Line active power control test

The reference value of the line active power is set to several typical values lower or higher than the initial active power. The test procedure is the following.

a) Deblock the series unit and ramp the line active power up from the minimum power to the set values until the power reaches a stable status.

b) Ramp the line active power down to the set values and then down to the minimum active power.

c) Block the series unit and check the following.

   1) The line active power ramps smoothly and reaches the reference value stably.

   2) The ramping of line active power does not disturb the DC and AC networks.

   3) Monitor the power quality of the AC grid.

7.7.3.3.2 Control system transfer test

The control system transfer test is conducted at a low power level. The test procedure is the following.

a) Transfer the control system from the main control system to the backup control system and check the control functions.

b) Deblock and block the series unit from the backup control system separately and check the control functions.

7.7.3.3.3 Evaluation of test results

The evaluation of test results includes the following.

a) No abnormal alarm or event occurs.

b) The control and protection system functions correctly.

c) No instability occurs during the tests.

d) The output electrical waveforms, including the current, voltage, power and so on, meet the requirements.

e) The measurements, including the temperature, meet the requirements.

7.8 Heavy load and overload tests

7.8.1 Purpose of test

This test is to verify the operation capacity of the UPFC installation, including the equipment such as VSCs and transformers, and check the temperature, AC harmonics, radio interference, electromagnetic field strength, and audible noise.

7.8.2 Test preconditions

The test preconditions are the following.

a) The converter unit tests are completed (see Clause 6).

b) The initial operation tests, steady-state performance tests and dynamic performance tests are completed (see 7.1, 7.2 and 7.3).

c) The shunt converter and shunt transformer are connected to the AC grid.

d) The shunt converter is connected to the series converter.

e) The series converter and series transformer are connected to the AC grid.

f) The converter control and protection system is in service.

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