IEC TR 63065

Edition 1.0 2017-09

TECHNICAL REPORT

Guidelines for operation and maintenance of line commutated converter (LCC) HVDC converter station

IEC TR 63065:2017-09(en)

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Guidelines for operation and maintenance of line commutated converter (LCC) HVDC converter station

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.200; 29.240.01

ISBN 978-2-8322-4802-7

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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GUIDELINES FOR OPERATION AND MAINTENANCE OF LINE COMMUTATED CONVERTER (LCC) HVDC CONVERTER STATION

FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC TR 63065, which is a technical report, has been prepared by IEC technical committee 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
115/153/DTR	115/163/RVDTR

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

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

GUIDELINES FOR OPERATION AND MAINTENANCE OF LINE COMMUTATED CONVERTER (LCC) HVDC CONVERTER STATION

1 Scope

This Technical Report provides general guidance on basic principles and general proposals for the safe and economic operation and maintenance of an LCC converter station.

These guidelines are based on the operation and maintenance practices that have been used successfully during the last decades at HVDC converter stations all over the world, and can be referred to by new HVDC users to optimize operation and maintenance policy and assist in performing the operation and maintenance work.

This document focuses only on the operation and maintenance of the equipment inside an LCC converter station, including back-to-back HVDC systems. The operation and maintenance of HVDC overhead transmission lines, HVDC cables and voltage sourced converter (VSC) are not covered by this document.

NOTE Usually the agreement between the purchaser and the suppliers of the HVDC converter station includes specific requirements regarding contractual requirements of particular systems. Such specific requirements will supersede the general/typical description mentioned in this document and all functions mentioned in this document are not necessarily applicable for all systems.

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 60633, *Terminology for high-voltage direct current (HVDC) transmission*

IEC 60919 (all parts), *Performance of high-voltage direct current (HVDC) systems with line-commutated converters*

IEC 61975, *System tests for High-voltage direct current (HVDC) installations*

IEC TS 62672-1, *Reliability and availability evaluation of HVDC systems – Part 1: HVDC systems with line commutated converters*

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60633 and the following apply.

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

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

3.1.1
manned station
MS
HVDC converter station that is operated locally by several operators, 24 h a day

Note 1 to entry: In some systems the manned station controls and observes not only its own converter station but also the opposite unmanned station.

3.1.2
unmanned station
US
HVDC converter station that is operated remotely with no operator on site

3.1.3
time based maintenance
TBM
maintenance carried out in accordance with a specified time schedule, in most cases annually

3.1.4
condition-based maintenance
CBM
necessary maintenance performed based on the equipment's condition, sometimes combined with TBM

3.1.5
reliability centred maintenance
RCM
necessary maintenance performed after analyzing the performance of the equipment

3.1.6
operator
person operating the converter station

3.1.7
asset manager
person that manages the plant/asset for the overall planning, operation, maintenance and performance in accordance with a set of criteria as assigned by the asset owner

3.2 Abbreviated terms

BOD	break over diode
BPS	by-pass switch
CBM	condition-based maintenance
CT	current transformer
DGA	dissolved gas analysis
GIS	gas insulated switchgear
GRTS	ground return transfer switch
HMI	human-machine interface
LCC	line commuted converter
MCB	micro circuit breaker
MRTB	metallic return transfer breaker
MV	medium voltage
NBS	neutral bus switch
OEM	original equipment manufacturer

OLT	open line test
OLTC	on line tap changer
OTDR	optical time domain reflectometer
RCM	reliability-centred maintenance
RPC	reactive power control
SCADA	supervisory control and data acquisition
SER	sequence of event records
TBM	time-based maintenance
TFR	transient fault record

4 Operation

4.1 Operation policy

4.1.1 Target reliability and availability

Generally, an availability of 97 % is requested as the minimum value in the design specification of a new HVDC project. This is based on a forced unavailability of less than 1 % and a scheduled unavailability of about 2 %. With good quality control applied in the design, manufacture, installation and testing stages, as well as appropriate operating and careful maintenance during operation, this requirement can be met in most modern HVDC systems.

According to the survey conducted by CIGRE B4 AG4 ([2] to [6][1]) for the period 2003 to 2014, typical target performance indicators for an HVDC system can be:

a) forced unavailability < 1 %;

b) availability > 97 %.

Scheduled unavailability varies from system to system depending on which operation and maintenance policy is taken. This can be seen from the performance reports of CIGRE B4 AG4. For example, some systems perform maintenance using 24 h shifts, whereas others work only 8 h a day and leave the system out of service for 16 h each day and on weekends. In other systems, maintenance is performed when the generator is not available (thermal unit out for maintenance or low water conditions, etc.). That is why the typical scheduled unavailability and overall unavailability is not given above.

The number of forced outages, including sudden interruption of power transmission both by protections and by manual emergency shutdown, is an important parameter for reliability. Usually, for a bipolar LCC HVDC scheme, the number of monopole trips is designed to be four times or fewer a year and the number of bipolar trips below once every ten years. According to the operation practice of modern HVDC systems, the number of monopole trips can be even limited to once a year. In systems with more than one converter in series per pole, the converters' trips can be limited to two trips per converter per station.

Outage hours, a parameter that indicates not only the health of the equipment but also the ability of maintenance, also affect the reliability and availability considerably. The outage hours would be longer due to severe damage of the equipment, complex fault analyzing and troubleshooting, or long waiting times for tools or spare parts. Every effort should be made to put the HVDC system back into full operation as soon as possible.

Refer to IEC TS 62672-1 for the main performance indicators.

1 Numbers in square brackets refer to the Bibliography.

4.1.2 Operation cost

The operation cost covers the following aspects:

a) human resources (salary for the operation and maintenance staff),
b) consumables,
c) maintenance and tests,
d) auxiliary power and cooling waters,
e) spare parts,
f) improvements and upgrade, and
g) other costs.

There are a number of variables that will impact the operational cost of an HVDC station. The human resources cost for an unmanned station is much less than for a manned station. The maintenance cost for an RCM station is much less than for a TBM station. The spare parts cost for an old station is usually higher than for a new station.

Due to the above reasons, it is hard to give an average cost for running an HVDC converter station for one year. The costs can be reduced if optimal operation, maintenance and spare part policies are considered.

4.1.3 Manned or unmanned

Traditionally, an LCC HVDC converter station is a manned station, where several operators monitor the status of the HVDC link and the equipment 24 h a day. Even for a manned station, the power flow on the HVDC system may be dispatched remotely. As development in automation increases, as well as the improvement of HVDC equipment, unmanned stations or less-manned stations (e.g. manned only during office hours) are more common. Many stations in Europe (like FennoSkan, SwePol) are unmanned. An unmanned converter station is operated remotely from an operation centre or even a dispatch centre, and manned only when something has failed.

Some important HVDC converter stations, such as Itaipu (Brazil), Nelson River (Canada) and Fulong (China),which are responsible for transmitting 70 % of the power generated by nearby hydro plants, are still manned stations. Equipment failure can be fixed faster at a manned station. This in turn contributes to the reliability and availability of the HVDC link.

Whether a station is manned or unmanned can be evaluated technically and economically. If it takes more than two hours to drive from a nearby city to the station, if the equipment failure rate of the station is still high, or if the converter station is critical to the grid, it may be better to man the station.

NOTE Some parts of the text in this document are applicable for manned stations only and are not applicable for unmanned stations, as there is no operator in the station.

4.2 Operation condition and limits

Before entering commercial operation of an HVDC converter station, the following conditions are normally required to be fulfilled:

a) the system test (IEC 61975) and the trial operation have been completed successfully;
b) the operating and maintenance staff is available and has been trained;
c) the communication between the dispatch centre and the converter station has been set up;
d) the standard operating procedure for operation and maintenance of the HVDC station has been established; and
e) spare parts are available.

Keeping and preserving the life of an HVDC converter station/link is the most important aspect to manage. Generally, HVDC systems are planned, designed and expected to have a lifetime of 30 years or more. To meet this requirement, operation limits should be clearly defined and faithfully followed by the operating and maintenance staff. They at least include:

1) the current, voltage and temperature of the main equipment are within the limits defined by HVDC suppliers;
2) the temperature, humidity and cleanliness of the valve hall, valve cooling system, relay buildings and control rooms can meet the requirements of normal operation of related equipment or devices;
3) the maximum acceptable current for electrodes and station grounds is such that it will not affect nearby industry pipes or the environment;
4) environment (oil, water, PCB, etc.) management systems and procedures are in place and the staff regularly reviews these procedures.

4.3 Operations of an HVDC system

4.3.1 General

Subclause 4.3 gives a generic guidance as to how to operate an HVDC system. Note that the suppliers' documentation for the given HVDC system shall always be consulted for the particular HVDC system.

4.3.2 Typical operation configuration

4.3.2.1 General

Availability, reliability, and flexibility for operation and maintenance are closely related to the operational configuration of HVDC systems. The general configuration and performance of high voltage direct current (HVDC) system are given in IEC 60919.

4.3.2.2 Point-to-point HVDC system

A point-to-point HVDC system is mainly for bulk transmission. It usually consists of two separate poles, which can be operated individually or together in a bipolar arrangement. This kind of system can be operated in three operating configurations.

a) Bipolar ground return with bipolar power control

   This is the normal operation mode for a bipolar HVDC system. Active power order is shared between each pole and the current of both poles is balanced so that the earth current is kept to a low value, typically less than 10 A. Furthermore, if one pole is tripped, part of its power can be taken up by the healthy pole so that less power will be lost. The above benefits make this the most commonly used operation modes in a bipolar HVDC system.

   During bipolar operation, the bipole neutral bus can be connected to either the electrode or the station ground. This allows the electrode or electrode lines maintenance job to be done without interruption of normal power transmission. However, it may be noted that when the station ground is used, in the event of a trip of a pole, another pole will also be tripped as a consequence of increased station ground current. Attention should also be paid to a possible station ground potential change at pole ground fault.

   Under contaminated conditions, which are often a combination of rain or fog in an HVDC station or along the corridor of its DC lines, the affected pole can continue the power transmission by running at reduced voltage, for instance 70 % or 80 % of rated DC voltage.The current of each pole is balanced by the control system and the earth current is still limited to a low value. The HVDC system can resume the rated voltage when the weather conditions improve.

   In the case where the DC equipment of one pole develops a fault such that the power or current needs to be limited to a certain level, the defective pole can be set to pole power control or pole current control.

b) Monopole metallic return

This is an optional operation mode for a bipolar system. If one pole for a bipolar HVDC system is not available, and if long-term flow of high earth current is not allowable and the DC line of the other pole is still available, the remaining pole can be connected to both DC lines and earthed at one predefined station. The equipment belonging to the outage pole can be checked or repaired and put into operation again. Compared to monopole ground return, the power loss on the DC line will be doubled, so once the faulty pole is available again, the operating pole can be transferred back first from metallic return to ground return and then to bipolar ground return.

c) Monopole ground return

This is also an optional operation mode for a bipolar HVDC system. If one pole is not available, for example when it is under construction, maintenance, or it is tripped by protections, and if long-term flow of earth current is acceptable, the remaining pole is connected to the electrode via the MRTB and can go on operating. The equipment belonging to the faulty pole, as well as its DC line, can be checked or repaired and put into operation again.

4.3.2.3 Back-to-back HVDC system

A back-to-back HVDC system is mainly used for asynchronous connections. In this arrangement, there are no DC transmission lines or DC filters, and both converters are located at one station. The valves for both the rectifier and the inverter are typically located in one valve hall.

There is only one operating configuration for a back-to-back system. The 12-pulse converters of both the rectifier and the inverter are connected directly through busbars. Some back-to-back systems are comprised of several units so that the loss of a converter will not lead to a total loss of power transmission or network islanding.

4.3.2.4 Two 12-pulse converters per pole

If the DC voltage or DC current of the converter reach their limits, two 12-pulse converters are connected in series or in parallel for higher voltage or higher current. This configuration is applied to Nelson River, Itaipu, and the UHVDC systems in China and India.

The operational configuration of 12-pulse converters per pole is the same as for bipolar systems except that the system can still be operated in bipole mode when one converter is out of service (forced or scheduled). In this case, the pole will operate at half the normal voltage or half the DC current capability.

4.3.2.5 Set up the operation configuration

Operators should evaluate the state of main circuit equipment including:

a) AC configuration and minimum availability of AC filter;
b) availability of HVDC equipment of each pole;
c) allowed ground return current;
d) connectivity of DC lines;
e) ensuring all major or critical alarms have already been acknowledged and reset.

The operational configuration can then be set up by connecting both poles or a single pole, in ground return or metallic return, and the DC lines of each pole or of both poles.

4.3.3 Set up the control mode

4.3.3.1 General

A combination of different DC voltage settings, power direction, power control methods, power control modes, reactive power control methods and reactive power control modes gives a large combination of options.

Bipolar power control ensures that the total power of the DC bipolar transmission remains at the ordered value and that the current is equally distributed between the two poles, thus minimizing the earth current. This is the main mode of operation, and to fully synchronize the two stations, telecommunication has to be in service.

Pole power control keeps the transmitted DC power equal to the power order given by the operator. To keep the power constant, the DC voltage variation is compensated by adjusting the DC current accordingly. The current order I_o is obtained by dividing the total power order by the DC voltage of the converter.

Pole current control keeps DC current equal to the current order given by the operator.

4.3.3.2 Basic control mode

Before starting the power transmission of an HVDC system, the operators should set up the following control modes:

a) reference DC voltage of each pole;
b) power transmission direction of each pole;
c) select control method and control mode of active power control;
d) enable joint control as long as telecommunication is available;
e) select control method and control mode of reactive power control;
f) enable or disable the supplementary control function such as frequency control, damping control.

4.3.3.3 Additional control functions

The inherent high-speed power control capability of the HVDC transmission system may be used for different objectives such as frequency control, power modulation, and power oscillation damping.

Frequency control modifies the DC power transfer to assist the connected AC systems in recovering from severe contingencies by limiting AC system frequency deviation above and below the nominal frequency. The characteristics and dead bands of the frequency controls are determined during the design studies.

Contingencies involving loss of generation in the inverter AC system and loss of load in the rectifier AC system may require that the power on the DC system be rapidly increased to improve the performance of the AC systems. Contingencies involving a loss of generation in the rectifier AC system or a loss of load in the inverter AC system may require an automatic reduction in DC power transfer. Power modulation functions are available both in bipolar and monopolar operation.

Some HVDC systems of which both ends are connected to the same synchronized AC system apply power modulation that can dampen the power oscillations that may be caused either by a large disturbance or specific system conditions. The power flow of the HVDC system is quickly controlled to repress power oscillation.

Therefore, before starting the power transmission of an HVDC system, operators should also set up the following additional controls.

a) Enable or disable automatic frequency control and set up its parameters. Automatic frequency control should be enabled if the HVDC link is connected to a weak AC system or an islanded system.

b) Enable or disable power modulation and set up its parameters. Power modulation is commonly used for network stability control. After loss of AC lines, DC transmission power can be ramped down if needed. After tripping of DC link, the generators connected to the rectifier and the loads connected to the inverter can be turned off.

c) Enable or disable oscillation damping and set up its parameters. Oscillation damping is mainly used for the rectifier that is fed from thermal power generators and is weakly connected to a power grid. To avoid subsynchronous oscillation, the power at special frequencies is measured and modulated.

4.3.4 Operation procedure

4.3.4.1 Control position and control authority

Control orders to the HVDC system, either in digital or analogue, can be given from the dispatch centre, SCADA, or from backup or local control locations. By default orders from SCADA are accepted by the control system, unless the dispatch centre takes over the control rights or when backup control is enabled.

Only the master station can control the power transmission of an HVDC link. If the slave station needs to control the power, it needs to first take master control from the other station first.

To increase the security of the HVDC system, only authorized operators should control the equipment in corresponding areas such as the DC yard, AC yard, AC filters, and auxiliary power system.

Operators shall log onto the human-machine interface (HMI) before performing any operation.

4.3.4.2 OLT

The open line test (OLT) is a test that is used by the operators to energize the pole DC side with direct voltage for the purpose of testing the insulation on the DC side, as well as the converter. The OLT can be performed either in manual or automatic mode.

The OLT is performed in one station at a time because the DC line will be energized up to the pole disconnector of the other station. When one pole is in open line test the other pole may, depending on the system design and operation permission, be operated independently.

The OLT is usually part of the commissioning of the HVDC scheme, in some cases it is also carried out after annual maintenance or a DC line fault. But it is not necessary to carry out an OLT every time before deblocking a pole. Some HVDC systems have never been subjected to an OLT in the last thirty years, even after pole maintenance.

4.3.4.3 Deblock

Once the main circuit and the control mode are chosen, i.e. an operating mode is set up, the HVDC system can be deblocked for power transmission. Before deblock, the status of the main circuit equipment, control and protections and auxiliary systems should be confirmed to ensure that the HVDC system is ready for operation. If any of the systems indicates a severe alarm, maintenance staff should investigate its cause and should take steps to restore the system to normal condition.

The inverter is always deblocked first to build up DC voltage, and then the rectifier is deblocked to build up the DC current. The control of the two stations is synchronised via telecommunication. In the event of a telecommunication failure, operators of the two stations shall cooperate by telephone to manually deblock the HVDC link.

4.3.4.4 Power ramp

During the change of power generation and load consumption, the power reference of an HVDC link should also be adjusted dynamically. Operators receive the power orders or a daily power curve from the dispatch centre and execute power ramps accordingly.

To ramp up or down the transmission power, the operator should:

a) set up the power ramp speed;
b) set up the power reference at the give time;
c) hold the existing ramp rate or set a new reference if needed.

Corresponding events will be generated after starting the power ramp and when the ramp completes.

To simplify the above operations, an automatic bipolar power curve is used for some systems. In this option, the bipolar power order is controlled automatically in response to a pre-programmed power transfer curve, which will define the power transfer over the daily, weekly or monthly load cycles.

4.3.4.5 Changing the operation mode

Even though it is safer and more economical to have a DC line running in bipolar ground return mode with rated DC voltage, normal power direction and bipolar power control, sometimes it is necessary to change to another operation mode due to the unavailability of HVDC equipment, HVDC line or other reasons..

a) Change to monopole ground return or metallic return mode.

   If one pole of a bipolar HVDC system is not available, for example when it is tripped by protections, and if long-term flow of high earth current is acceptable, the remaining pole can go into operation with the ground return until the other pole is available again and the HVDC system can revert back to bipolar ground return mode. However, if long-term flow of high earth current is undesirable while the DC line of the defective pole is still available, the remaining pole can be transferred from ground return to metallic return by starting the corresponding sequence. Once the other pole is available again, the operating pole can be transferred back first from metallic return to ground return and then to bipolar ground return mode.

b) Change to reduced voltage mode

   If continuous electro-discharging is observed under contaminated conditions, often caused by a combination with rain or fog in the converter station or along the corridor of DC lines, the defective pole can continue the power transmission by running at reduced voltage, for instance 80 % of rated DC voltage.

   When operating in the reduced voltage mode, the taps of converter transformers are lowered to the position resulting in minimum voltage, and the thyristor valve might operate at a relatively higher firing angle so that the snubber circuits are subjected to additional stresses. Additionally, more reactive power is consumed in this mode.

   The HVDC system can be returned to rated voltage when the weather conditions improve.

c) Change to pole power/current control mode

   When the DC equipment of one pole develops a problem so that its power or current needs to be limited, this defective pole can be set to pole power control or pole current control. In both cases, the pole in bipolar control mode will try to balance the current of each pole so that the earth current can be still limited to a low value.

d) Overloaded

   After one pole is blocked by protections, the remaining pole might be overloaded. Futhermore, if the thyristor valve or converter transformer loses its redundant cooling, it might also be overloaded.

In this case, the current order of the corresponding pole will be limited automatically by the HVDC control system according to the continuous and short time overload capability of the equipment. When the limitation ceases, the current order will return to a preset value and the power regulation will be enabled again.

e) Power reversal

Typically, it is often required to change the power transmission direction. Once the operator orders a power reversal, the HVDC control system will ramp down to minimum power and block both poles. After the discharging time of the transformer bushings and DC cable (if applicable), the control system will deblock the HVDC link again in the reverse direction at minimum power. Sometimes, a manual power reversal might be required by the dispatch centre to give enough time to adjust the AC network on both sides.

f) Switch in/out a converter (for two serially connected converters only)

For the HVDC system with two serially connected converters for each pole, the entry or exit of another converter can be done without interrupting the operation of the deblocked converter of the related pole. In these systems, there is a by-pass switch (BPS) across the converters to provide a current path when a converter is blocked.

Two deblocking sequences are used for deblocking a series converter. In the first sequence, the converter is deblocked at 90° with the BPS in the closed position. When the current in the BPS decreases to zero, the BPS is opened and the converter firing angle is ramped to normal values.

In the second sequence, the series converter is deblocked by giving a command to the BPS to open with pole current flowing through the BPS. A short time after the BPS contacts start arcing, the converter is deblocked at 70° (at both inverter and rectifier). This forces the current to commutate from the BPS to the valves. The firing angles are then ramped to normal values within 100 ms.

To switch out a converter, the firing angle of the converter is ramped to 90°, then its BPS is closed and the converter is blocked so that the DC current shifts from the converter to its BPS. The converter is isolated.

4.3.4.6 Stopping

An HVDC link can be stopped either manually by control or automatically by protections. For a scheduled outage, which is either planned or which can be deferred until a suitable time, operators can stop the link by setting its power reference to zero. In this case, it is recommended to ensure that the bipole power order is such that the other pole will pick up the power when one pole is blocked. For a forced outage, the HVDC link is stopped by protections automatically and the operators are not involved.

Usually, the rectifier is blocked first and then the inverter is blocked and bypassed, depending on the type of fault and the blocking sequence. The control of the two stations is synchronised via telecommunication. In the event of a telecommunication failure, the operators of the two stations shall cooperate by telephone to manually block the HVDC system.

Making the decision to initiate an emergency stop can be difficult for the station operators. However, when there is an emergency condition occurring, it is important for the operators to make a quick decision and to stop the HVDC link before the fault develops further and causes major damage. An emergency stop should be ordered in the following cases:

a) smoke or fire is detected by the firefighting system and confirmed by operators, especially in the valve hall or in the converter transformer area;
b) heavy discharging is found on the main circuit equipment, especially on DC voltage dividers, pole bushing, converter transformer bushing, etc.;
c) overheating is observed on the thyristor valve, DC yard switchgear, and on the converter transformer;
d) leakage from the valve cooling system, especially a leakage of the cooling pipes in the valve modules.

4.4 Operations of HVDC equipment

4.4.1 Converter valves

4.4.1.1 Operating

a) Earthed

The valve can be earthed by closing the valve hall grounding switches.

b) Unearthed

The valve can be unearthed by opening the valve hall grounding switches.

c) Energizing

converter valves are energized by the closure of the AC breakers before the converter transformer

d) Deblock

Deblock the valve by starting the deblock sequence, which will build up the minimum DC current within several hundred milliseconds. The converter can also be deblocked by setting a power order.

e) Block

The valve can be blocked manually by starting the block sequence or by setting the power order to zero or below the minimum power limit.

4.4.1.2 Monitoring from human-machine interface (HMI)

Besides checking if the firing angle/extinguish angle, DC voltage, current, power, etc., are within the defined region, the following events should also be monitored.

a) Events before energizing

Before putting the converter valves into operation, operators should check the state of the AC and DC yard, and pay attention to events relating to:

- unearthed valves;
- OK/faulty valve control;
- OK/faulty valve cooling system;
- readiness for energization.

The fulfilment of certain events is normally built into the controls to inhibit inaccurate initiation of the deblock sequence. If any of the conditions is not satisfactory, the operator would have to investigate the reason for the inhibition.

b) Events after energizing

Once the converter transformers are energized, operators should check for events ralating to:

- faulty thyristor position;
- interface fault between valve control and HVDC control system;
- non-readiness for operation.

If any of the conditions is not satisfactory, the operator would then have to investigate the reason for the deblock inhibit.

c) Events after deblock

After deblock, operators should pay attention to the following type of events from the valves:

- faulty thyristor position and loss of thyristor redundancy;
- protective firing;
- valve leakage alarms both from valve monitoring or valve cooling system;

- valve control-related faults;
- commutation failure;
- alarms from converter protections, such as valve stress protection, valve misfire protection, valve DC differential protection, valve short-circuit protection.

d) Events after block

- pole isolated
- valve earthed

4.4.1.3 Site inspection

a) Check before energizing

Before putting the converter valves into operation, operators should confirm the following:

- all permits to work have been signed off;
- no test equipment and no personnel are left in the valve hall;
- main door and emergency door have been shut and locked where necessary;
- valve hall earthing switches have been opened;
- valve hall ventilation and air conditioning are operating normally and the temperature and humidity in the valve hall are within the specification;
- valve cooling system is operating within normal operating level;
- valve controls are operating normally and ensure no any alarm in active mode;
- smoke/fire detection system is working properly;
- the valve hall closed circuit television (CCTV) is working normally.

All these conditions are monitored by the controls and interlocking, and the operator needs to investigate only if an inhibit is applied.

b) Check after energizing

Once the converter valves are energized, operators should check the following:

- if there is any arcing, sparking, abnormal noise or smell.

c) Check after deblock

After deblock, the valve should be inspected regularly, for example once a week, to see if:

- there is abnormal noise or smell;
- there is any hot spot or flashing; if so, inspect with an infrared camera;
- there are any leaks;
- the temperature and humidity in the valve hall is OK;
- the indication LEDs on the valve control are correct.

d) Check after the converter is blocked

- check whether the valve is isolated and all valve hall grounding switches are closed before working inside the valve hall;
- replace the faulty valve component if needed;
- check the cooling pipes if needed.

4.4.1.4 Typical fault/alarm handling

a) Thyristor failure

Once a thyristor is short-circuited, the operator's work station will present an emergency alarm that indicates the faulty thyristor position, and, in some cases, the total number of faulty thyristos in a single valve. If the number of faulty thyristors is close to the number of redundant thyristor levels, it is recommended to apply for an outage to fix the problem, otherwise the converter valve can stay in operation safely.

b) Protective fire alarm (or BOD, break over diode)

A major alarm will be present in this case, indicating the position of the protectively fired thyristor. Protective firing can be a consequence of the failure of the normal firing circuit.

The fault could be with the thyristor firing circuit; in this case, the protective firing function of the board can work for a long period of time so the valve can stay in operation.

Alternatively, it could also be a fault in the damping capacitor or damping resistor, which affects the voltage across the thyristor. In this case, it is better to confirm if there is any evidence of smoke or fire at the faulty thyristor position. If there is, the operator should press the emergency stop to trip the converter as soon as possible.

Operators can try to reset the protective fire alarm to see if it is real or not.

It is recommended to apply for an outage if many thyristors in one valve are protectively fired continuously. This could be an indication of failed thyristor level elements.

c) Valve leakage alarm

An alarm from the leakage detector at the bottom of the valve (if installed) may not trip the converter depending on the severity of the leak. Operators could check if it is a real alarm or not. If it is real, the operator should apply for an outage to find the position of the leak and fix it. For a major leakage, the converter should trip automatically.

d) Valve element overheat

If overheating is observed on a valve component such as a reactor, thyristor, damping capacitor or resistor, the temperature could be compared with a component in the same position in other valves. If the temperature is greater than similar components, it is recommended to apply for a runback or outage to allow further investigation. In some HVDC systems usually temperatures of valve elements are not monitored.

e) Valve control faulty or valve control interface faulty

Valve control faults such as failure of a main processor board or failure of the communication between the valve control and the HVDC control system can be detected by the Valve control itself and cause an automatic switch to the redundant system. The HVDC system can stay in operation with the healthy valve control. The faulty valve control can be turned off for troubleshooting.

Valve control faults, such as the failure of a light-emitting board or light-receiving board, affect normal operation of both redundant valve control systems and might lead to a trip. In this case, operators can apply for an outage to fix the problem.

f) Valve hall fire alarm

Even though many measures have been taken during the design and manufacturing stage, the risk of a thyristor valve fire still exists, especially for new systems with newly designed valve components and for old systems with degraded valve components. Cooling water leaks or blockages, overheating of valve components, discharging on the surface of fibres, for example, could lead to a fire. It is important that the fire can be detected as early as possible, and the valve can be tripped and isolated as soon as possible in this case.

g) Commutation failure

If the commutation failure is due to an inverter AC voltage drop or distortion, it will recover after the AC fault is cleared. If it is due to misfiring, the control should switch automatically to a redundant system without operator action. Operators can then check the cause of the misfiring by checking the valve control, HVDC control and their interface.

h) Trip by converter valve protections

Following a trip by the convertor protection, the sequence of events records (SER) and the transient fault records (TFR) should be analysed, and the converter valve should be checked locally to determine the reason. If there is no real fault in the converter and the trip is just due to an AC system fault, an attempt can be made to energize the transformer and deblock the converter again. If it is due to a valve control failure, measurement failure, or control and protection failure, fix the related device and try to restart. If it is due to a real fault in the converter, for example many failed thyristors, faulty thyristor firing circuit board, broken fibres or broken pipes, try to locate the fault position according to the SER and the TFR, and check, test and replace the faulty components.

4.4.1.5 Special operation condition

a) Loss of redundant cooling

If one cooling tower is out of operation, the related thyristor valve will lose its redundant cooling ability. In this case, the over load ability of the HVDC system will be limited to a predefined level.

b) Converter valve high firing angle operation

If the HVDC system is designed for higher firing angles during a designated operation mode such as reduced voltage operation, a decreased tap changer order or a trip order will be given to avoid the excessive stresses to damping circuits and arresters.

4.4.2 Converter transformers and oil immersed smoothing reactors

4.4.2.1 Operating

a) Energize

Before energizing the transformer, it is important to ensure that the transformer tap is at a start position that will produce minimum no load direct voltage. In most systems, the controls will automatically move the taps to the required position as soon as the transformer is de-energized. In other systems, the operator will be required to ensure that the taps are at the required position before energization.

Energize the converter transformer by starting the energization sequence, which will close the AC breakers for the converter transformer. The tap changers of all related converter transformers will move to their rated position.

b) Operation after deblock

- Check the valve side voltage or firing angle is regulated to its rated value by the tap changer control.
- Set the converter transformer tap changer control to automatic or manual mode if needed.
- Manually synchronize the converter transformer's tap changer position if needed.
- Disable or enable gas relay protections if needed, for example before replenishing oil.

c) De-energizing

De-energize the converter transformer by starting the de-energization sequence, which will open the AC breakers connecting the converter transformer and the taps of converter transformers will move to their minimal positions.

4.4.2.2 Monitoring from human-machine interface (HMI)

Besides checking the oil temperature, oil level and tap changer position of the converter transformers, the following events should be monitored.

a) Events before energizing

Before putting a converter transformer into operation, operators should confirm both the AC/DC layout to ensure:

- unearthing of equipment;
- pole is connected;
- ready-for-energizing conditions are present.

b) Events after energizing

Once the converter transformers are energized, operators should check for events relating to:

- tap changer not synchronized;
- alarm or trip by transformer neutral shift protection;
- alarm or trip from converter transformer protections, including oil/gas-activated relays.

c) Events after deblock

Check the AC side and valve side voltage and current, oil and winding temperature after getting the following alarms:

- tap changer not synchronized;
- alarm from oil/winding temperature indicators, pressure relays, buchholz relays, oil level indicators, bushing SF6 density relays;
- alarm from converter transformer protections;
- failure alarm from the coolers, tap changers.

4.4.2.3 Site inspection

Most modern transformers are equipped with online monitoring systems. The majority of abnormal conditions will be reported by these systems but not all. In order to locate and resolve an abnormal condition before it leads to further damage or a forced outage, local inspection is always recommended.

a) Check before energizing

This is required to be done only once after a major maintenance outage. For some systems, it is required to be done before every energization.

Check the following before energizing a converter transformer:

- all valves on the converter transformers are at correct position;
- the oil level in the oil conservator;
- the permittivity of the transformer oil is in accordance with the specification;
- the oil temperature is above its lowest permitted value;
- the silica gel and oil level inside the dehydrating breather;
- online oil filters for tap changer are working normally;
- the power supply for all the coolers are OK and all the coolers can work smoothly;
- the tap changer is at its start position;
- gas relays are de-aired and no trip order by the gas relays;
- transformer protections have been correctly set up and are working normally;
- fire-fighting system (water spray) is enabled and working properly;
- connections to lines, busbars and earth are effectively made;
- the test tap of the valve-side bushing is appropriately earthed;
- the iron core and clamping unit are earthed;
- the bushings are not earthed.

b) Check after energizing:

- at least one cooler is started;
- the oil and winding temperature is not abnormal;
- no abnormal sound from the transformer;
- the measured valve side bushing voltage is correct.

c) Check after deblock

Analyzing oil samples regularly, monthly for example, at approved laboratories, maintaining a historical record of the condition of the transformer and analyzing the trend of gases over a period, is an effective and cost-efficient way of detecting the onset of any deterioration or sub-standard condition arsing in a transformer. If there is any evidence or probability of a potential problem, operators could initiate investigations and take the corresponding remedial actions.

In addition to oil analysis, the following online monitoring should be done regularly, for instance weekly, either by operators or by an online monitoring system:

- checking oil temperature, winding temperature and bushing temperature;
- checking oil level, oil flow, oil leakage;
- checking bushing oil level or SF6 pressure, and its temperature;
- sound (acoustic detection and location of partial discharges);
- checking if the number of coolers is consistent with the transformer load current and ambient temperature;
- checking tap changer position;
- checking the data collected by online oil monitors;
- checking the control cabinet for its humidity, temperature; checking the components in the cabinet are working normally, i.e. no alarm indications.

It is suggested to inspect more frequently in bad weather (for example, high temperature, fog, rain, snow, etc.), or during heavy loading, or if a transformer is already known to be defective but still in service for fault analyzing purposes.

d) Check after de-energizing

Check the following after a transformer fault or during a maintenance outage:

- oil gas content and constituent gases;
- measure winding resistance if needed.

4.4.2.4 Typical fault/alarm handling

a) Overheating, flashover, leakage at bushings

Once a hot spot, a flashover or a gas leakage is observed at a converter transformer bushing, operators can apply for an outage to check or replace the bushing. If it is due to a design problem, the information should be forwarded to the supplier for analysis and improvement solution.

b) Tap changer not synchronized or out of step

Put the tap changer control in manual and local mode and try to adjust the failed tap changer manually or locally. If it doesn’t work, try to synchronize the tap changer by adjusting the tap changer of the other transformers. The lack of synchronization might be due to a bad connection of the mechanical driving devices or a faulty indication of the tap changer position.

If the tap changer position of a group of transformers differs by more than three steps, the transformers might be tripped by their zero sequence current protection. Therefore operators could apply for an outage if the problem cannot be solved during operation.

c) Oil leakage

If it is a small leakage, the transformer may stay in operation and the leak can be fixed during the next outage. It is assumed that suitable procedures are in place to manage the oil leak until an outage can be arranged. If a serious leak is observed and the oil level has dropped below the lowest position of the oil level indicator, an emergency outage should be requested.

d) Abnormal gas content

If the gas content is abnormal, the trend of the gas content should be monitored carefully. If it continues to increase, apply for an outage and check the transformer internally.

e) Abnormal sound from a transformer

When an abnormal sound is heard from a transformer, a diagnostic gas analysis should be carried out to see if there is any fault inside the transformer. If there is, an emergency outage of the transformer should be requested.

Abnormal sound can also be heard when the transformer is saturated due to a high DC earth current, for instance when operating in monopole configuration at high power. In this case, a runback can be requested to decrease the earth's DC current. Converter transformer saturation can also be related to unsymmetrical firing of converter valves. Operators can try to switch the control system to see if there any improvement.

f) High oil or winding temperature

If high oil or winding temperature is observed at normal load, check if the cooling fan and pumps are working. If not, try to start the cooler manually. Otherwise, apply for a runback. If the temperature goes on increasing, apply for an outage.

g) Smoke or fire on the transformer

Stop the converter immediately. Stop the cooling pumps. Start the water spray pumps as soon as possible and drain the transformer oil if possible.

h) Tripped by the transformer protections, including gas oil activated relay

Check the SER and the TFR, check the transformer locally, analyse if there is any internal fault and report to the dispatch centre. If it is not an internal fault, verify it by gas analysis result and try to energize the transformer again. Otherwise, further investigation should be performed.

4.4.2.5 Special operation condition

a) Loss of coolers

A converter transformer can continue to operate for some predefined time at its rated load after lost of all coolers. If the coolers cannot be fixed within the time, the operator could apply for a runback or an outage for the related converter. An over-temperature trip will likely occur unless the converter is blocked.

b) Overload

A converter transformer can run within its overload limit, for example, 1,05 per unit or 1,1 per unit, for a long period of time, as long as the required amount of cooling is available.

4.4.3 AC/DC breakers and switchgear

4.4.3.1 General

Interlocking prevents operators from carrying out unwanted operations, thereby protecting both operators and the equipment. Interlocking for the AC switch yard and the DC switch yard is valid anytime, and operators are not allowed to disable or bypass any interlocking. This is also applicable to unmanned stations.

4.4.3.2 Operating

a) Open an AC breaker

Control the AC breaker from the HMI and check the breaker indication signals both from HMI and locally at the mechanism. If the breaker needs to be isolated, open the two disconnectors on either side of the breaker. If the breaker needs to be earthed, close the appropriate earthing switchers.

b) Close an AC breaker

Before closing an AC breaker, make sure its earth switchers are opened, both from HMI and from local. Then close the disconnectors beside it. After confirming the disconnectors have been closed, close the AC breaker.

In order to operate pole and neutral side devices, some preconditions need to be be met. These preconditions vary from one system to another. For items c) to f), it is assumed that those preconditions are met.

c) Connect a pole

Close the NBS so that the pole is connected to the electrode line via the MRTB or connected to the DC line of the other pole via the GRTS. Close the pole bus disconnector to the connected the DC line.

d) Isolate a pole

Open the pole bus disconnector after confirming the DC line current is lower than the permissible value. Open the NBS after the disconnector has been opened.

e) Transfer from ground return to metallic return

Isolate the other pole. Connect the pole neutral bus to the DC line of the other pole via the GRTS. Open the MRTB when ground current is partly shared by the GRTS. The transfer function is designed to be automatically controlled step by step. This can be done at full power without interrupting power transmission.

f) Transfer from metallic return to ground return

Isolate the other pole. Close the MRTB, open the GRTS when the current is partly shared by the MRTB. The transferring is designed to be automatically controlled step by step. This can be done at full power without interrupting power transmission.

4.4.3.3 Monitoring from human-machine interface (HMI)

Check for the correct open/close indication of the AC/DC breakers, disconnectors and earthing switches. Compare the current and voltage measurements between three phases or between poles. Monitor events relating to:

a) alarms from AC breakers:
   - SF6 low pressure;
   - spring not charged;
   - discrepancy alarm;
   - breaker reclosing event;
b) alarms from DC breakers:
   - SF6 low pressure;
   - spring not charged;
   - charging device failure;
   - breaker reclosing event;
   - alarm from breaker failure protection.

4.4.3.4 Inspecting locally

Check the following when needed:

- oil level of the hydraulic mechanism;
- SF6 pressure;
- main contact temperature;
- no abnormal sound;
- humidity inside the junction box;
- if the relays, contacts, and other component in the junction box are connected correctly;
- if there is any crack or corrosion on the pull rods or connecting rods;
- if there is any damage on the base or support insulators.

4.4.3.5 Typical fault/alarm handling

a) Disconnector main contact overheat

The contact temperature should be checked with an infrared camera at high loading before the maintenance outage and immediately after the maintenance outage under high loading. Overheating might be observed at the main contact of the disconnector, especially when the HVDC system is running at rated power. The contact can be greased or polished or clamped if the current density through the contact is satisfied with the relative standard, otherwise the contact should be redesigned.

b) SF6 pressure low alarm

If the pressure is decreasing slowly, the breaker can be opened before the open operation is disabled by low pressure. Then the breaker can be isolated for further checks and maintenance.

c) Spring not charged

The breaker should be disabled and isolated before attempting to solve the problem. Close the MCB for the motor power supply if it is open. Check the motor control circuit. If the breaker is closed, it can be opened once.

d) Block of open operation

The motor power supply should be turned off. The breaker should be isolated from the power system by opening the breakers on either side to avoid the unsuccessful opening of the breaker. Once the breaker is isolated, the operating mechanism should be checked.

e) GIS discharging

Discharging inside a GIS might lead to an earth fault trip. The fault position can be located by checking the protection information and by performing gas analysis. The responsible part of the GIS can be opened for further check and repair.

f) Wrong open/closed indication

Open and closed indications are input to the control and protection system for interlocking and ascertaining the AC/DC side configuration. Incorrect indication could lead to a malfunction of the control and protection.This should be considered at the design stage.

Check the auxiliary contacts locally. If the contact is at the right position, then check the signal.

4.4.4 AC/DC filters

4.4.4.1 Operating

a) Energizing an AC filter bank

Close the breaker to charge the filter bus when all the filter sub-banks that connect to the bus are unearthed and isolated.

b) De-energizing an AC filter bank

Open the breaker to de-energize the filter bus. To limit the current extinguished by the breaker, it is recommended to open the breaker after its all sub-banks have been disconnected.

c) Setting up the reactive power control parameters

Reactive power control (RPC) can be set to manual or automatic. It should be set to automatic before deblocking the HVDC system, with the following control parameters set up on the HMI:

- status (off/on, manual/automatic, usually set to 'automatic');
- control mode (Q control /U control, typically set to 'Q control');
- limit of reactive power exchange with AC network, and its margin (typically set to '0' and 70 % of the filter sub-bank capacity);
- limit of bus voltage, both maximal and minimal.

d) Closing the disconnector or switch of an AC filter sub-bank

After closing the disconnector with the filter bus being energized, the filter sub-bank is available and can be switched in and out automatically by the RPC.

e) Opening the disconnector or switch of an AC filter sub-bank

Once the disconnector or switch is opened, the filter sub-bank is not available to RPC. It can be earthed after a predetermined time delay to allow discharge of the filter capacitors.

f) Manually switching in an AC filter sub-bank

If human intervention is needed, the operator can set the RPC to manual mode and switch in a filter sub-bank by closing the filter breaker. It is recommended to switch in a filter sub-bank a few minutes after it has been disconnected so that the filter will not withstand additional stress.

g) Manually switching out an AC filter sub-bank

If human intervention is needed, the operator can turn the RPC to manual mode and switch out a filter sub-bank by giving an open order to the filter breaker. It is recommended to switch in a corresponding sub-bank before switching out another one and to ensure that the two filter sub-banks are of same type.

h) Connecting DC filters

The DC filters are connected automatically by the start the sequence 'connect DC filters'. DC filters will be unearthed and connected between the pole bus and the pole neutral bus. A DC filter can be switched in manually without stopping the power transmission.

i) Disconnecting a DC filter

A faulty DC filter can be disconnected manually when the related pole is operating. If the current through the DC filter is less than the allowed current of the filter disconnector, only the filter is isolated. Otherwise, the pole has to be blocked.

4.4.4.2 Monitoring from human-machine interface (HMI)

Besides checking AC voltage, active power, and exchanged reactive power, the following type of events should be monitored:

a) events before deblock:

before deblock, check the layout of the AC yard and the related events to make sure that

- AC filter protections are working properly,
- all available filter buses are energized,
- enough filter sub-banks are available, both in type and amount,
- the bus voltage signal fed to the RPC is correct, and
- RPC parameters are correct and RPC is on and automatic.

b) events after deblock:

once the converter is deblocked, operators should pay attention to the following type of events:

- the minimum number of AC filters are energized, otherwise the filter components could be damaged due to harmonic overload;
- AC overvoltage;
- breaker discrepancy;
- failure of filter protections;
- AC filter hunting (i.e. where filters keep being connected/disconnected due to specific operating levels occurring).

4.4.4.3 Site inspection

Check the grounding switches, disconnectors and breakers are in correct closed/open position. Check if the SF6 pressure is normal.

Check if there is any abnormal sound, smell, or overheating parts. Check if there are any distorted or leaking capacitor units.

Check the AC filter protections are working correctly. Check the unbalance current of the high voltage capacitor bank is less than 50 % of its alarm settings.

4.4.4.4 Typical fault/alarm handling

a) Reactive power control turn from automatic to manual mode

Check if the pole communications are healthy. Check that the two AC yard main buses are connected or split. Check if the filter is hunting or not. Set the RPC back to automatic mode after fixing the corresponding problem.

b) Filter sub-bank tripped by high voltage capacitor unbalance protection

Once a filter sub-bank is tripped due to capacitor unbalance protection, isolate and then earth the filter sub-bank. Measure the capacitance of the the capacitor units, locate the faulty capacitor and replace it. Unearth the filter sub-bank and put it to available mode.

c) Filter sub-bank tripped by overload protection

If harmonics higher than the definition of the system design is injected from the AC network, the filters could get overloaded. Additionally if insufficient filters, both in type and amount, are switched in, the filters may also get overloaded. Both of these cases could lead to a bipolar trip if all available filters are disconnected or become unavailable.

Before taking any further action, operators could check the reason for filter tripping/overload, and connect filters and disconnect shunt capacitors manually if there are filters available according to the operating manual. Otherwise operators should try to run back the power to an acceptable level.

d) ABSmin or min filter is not fulfilled

Operators should have operating guidelines (provided by the system studies), which should prevent getting into this situation unless the condition is created as result of filter tripping.

If ABSmin filter is not fulfilled and to avoid damaging the filter, the RPC will try to energize the filter sub-banks first. If this does not work, the RPC will then try to run back to a lower power level. If this does not work either, the RPC will trip both poles. It is important therefore to keep enough filter sub-banks available, especially during equipment maintenance.

If min filter is not fulfilled, more harmonics will be fed into the AC network, but this will not lead to filter component damage and the HVDC system can continue operating for a long period of time. Operators should switch in one or two filter sub-banks if they are available.

e) Alarm of detuning

Detuning can occur due to degradation of the reactors or capacitors at the low voltage end of the filter. Measure the reactors and capacitors after the filter is earthed.

f) AC bus overvoltage

AC bus overvoltage may occur due to the trip of one pole while all the filters needed for both poles are still connected to the AC bus. Manually switch out the unwanted filters as per operating guidelines if the RPC is too slow.

g) Protection trip of DC filters

If the current through the DC filter is less than the allowed current of the filter disconnector, only the filter is isolated. Otherwise, the pole is blocked (the sequence of isolating the DC filters may vary between suppliers).

During a DC line fault, large transient currents will flow through the DC filters. The current might lead to a malfunction of the DC filter differential protection if the time delay of the DC filter differential protection is too short.

h) Fire or smoke is observed on AC/DC filter

Switch in a spare filter if there is any. Isolate the faulty filter. Check if it is the capacitor or inductor which has caught fire. Put out the fire as per station procedures. Replace the broken filter components.

4.4.4.5 Special operation condition

a) Only one DC filter group is connected to a pole

Usually the DC filter groups of both stations are connected to each pole. If the DC filter in one station is isolated, the pole can continue in operation. If the DC filter in the other station is isolated also, the pole will be blocked (This may not be the case for all DC systems and will be dictated by the individual system design and operating guidelines). How to handle those cases is completely system dependent.

b) Closing the AC filter sub-bank breaker at voltage peak

A filter bank should be switched in near to the zero crossing moment of the AC voltage. Due to the failure of the breaker synchronizing device, or due to a mechanical problem of the breaker itself, the filter sub-bank may be switched in at the peak voltage of the AC voltage. This may lead to a sudden voltage disturbance to the network. In this case, the breaker can be isolated and checked when it is convenient.

4.4.5 Control and protections

4.4.5.1 Operating

a) Put a control or protection into operation

After making sure there is no hardware or software fault that affects the performance of control and protections, and there is no protection trip, the control or protection device can be switched from test mode into service mode and the device will then go to standby or be active automatically within a few seconds.

b) Put a control or protection into test

After making sure the redundant control or protection is available and operating normally, the control or protection device can be switched from standby into test mode. Further maintenance or troubleshooting work can be carried out on this device.

c) Set up control mode and control parameters

Set up control mode and control parameters before deblocking the HVDC system:

- join /separate,
- master /slave,
- ground return/metallic return,
- normal /reverse direction,
- normal /reduced voltage,
- bipolar power control/pole power control /pole current control,
- power reference,
- power ramp speed.

Or change some of the above parameters to adjust the operation mode.

d) Switch between redundant control and protection

One set of control or protections can be switched from active to standby for test purposes or for maintenance. The other set of control or protections will switch from standby to active automatically.

e) Debug

Modern HVDC control and protection systems integrate debug tools such as event handler, transient fault recorder, and online debugging of the control and protection logic. These tools can be helpful for operators to carry out fault analysis.

4.4.5.2 Monitoring from human-machine interface (HMI)

Operators should monitor the status of the control and protections as well as their alarms. If one computer gets a fault or becomes unavailable, the operator shall try to find the reason and try to fix it as soon as possible, otherwise a fault in the redundant system will cause a trip.

Operators should also monitor alarms such as protection disabled, protection activated, control mode changed, and make sure whether it is due to the HVDC system, or main circuit equipment, or measurement system, or control and protection themselves. The following events should be monitored:

- alarms generated by supervision, including CPU failure, I/O board failure and communication failure;
- alarms generated by protections, such as 'electrode line overload';
- alarms generated by control functions, such as 'control mode shift ';
- events about control orders or control modes, such as 'power ramp completed ';
- events generated by transient fault recorder, such as 'TFR triggered'.

4.4.5.3 Site inspection

a) Before putting a control or protection computer into service

Check the software version is correct. Make sure no additional setting is made by debug tools, otherwise restart the computer. Check that the output relays, if any, are properly connected. Check that no severe or emergency fault, no protection trip order, is generated by the computer.

b) During the normal operation of the HVDC system

Check the temperature, humidity and cleanliness of the control room or relay building where the control and protection computers are located. Check the LED indications of the control/protection computers, I/O racks, and protection relays. Check if there are any abnormal sounds, smells, overheating, and dust inside the cubicles. Check if there are any loose connections in the cubicle. Check if there is any local event or report.

Check the temperature, humidity, and cleanliness of the outdoor junction box.

4.4.5.4 Typical fault/alarm handling

a) CPU board failure, I/O board failure and communication failure

Switch the device to test mode. Check with the debug to get more information about the fault and try to locate the fault position. Turn off the device and replace the faulty board with a spare one. If needed, set up the board by adjusting jumpers, loading programs, set up reference and so on. Turn on the device and check if it is working normally.

Remember to make sure there is no trip or alarm from the device before putting it back into operation.

b) Protection alarm from one protection system

If only a protection A system generates an alarm or a trip order while the other protection system does not generate a similar alarm or order, this is most likely due to a board failure or measurement failure of the A system. In this case, the HVDC system can go on operating and the protection A system can be switched to test mode for troubleshooting.

Remember to make sure there is no trip or alarm from a protection A system before putting it back to operation.

4.4.5.5 Special operation condition

a) Loss of redundant system

The control and protection system is designed to be redundant for better availability and reliability. If one system is already not available, the risk of a forced outage increases so the faulty control and protection system should be repaired as soon as possible.

b) Loss of control or protection

If both control computers are not available, or all the protection computers are not available, the related area controlled or protected by the computer will be tripped. For example, a converter will be blocked after converter control computers or protection computers are lost.

c) Loss of SCADA

If there is something wrong with the SCADA LAN or SCADA servers, the operator has to monitor and operate the HVDC system via the backup control or local control unit before the SCADA problem is solved.

d) Loss of telecommunication

In case of a telecommunication failure, the backup synchronous control will automatically be selected to manage the synchronization of the two stations. Some restrictions in operating the DC link without telecommunication are as follows:

- for operation of the HVDC, the operators shall coordinate their actions via telephone; for example, they have to deblock the inverter before the rectifier;
- supplementary control functions are blocked with telecommunication out of service;
- the on-line power reversal sequence is blocked;
- the DC power rate of change may be limited by the maximum speed of the power tracking function at the inverter;
- the DC line fault recovery sequence is not initiated in cases where the DC fault is not detected at the rectifier;
- the line differential protection function in the DC protection system will be blocked.

4.4.6 DC measurement instruments

4.4.6.1 Operating

There are no operating instructions for the measurement instruments.

4.4.6.2 Monitoring from human-machine interface (HMI)

Check and compare the measurements between the redundant measurement instruments at the same position. Monitor the operational parameters from the instruments, as well as events relating to:

a) alarms from zero flux current transformer:
   - power supply faulty;
   - saturation;

b) alarms from optical current transformer:
   - parity check error;
   - channel shutdown;

c) alarms from voltage divider:
   - measurement board failure;
   - low SF6 gas presser.

4.4.6.3 Site inspection

Check if there are any signs of overheating or discharging on the device. A measurement device should be taken out of service when leakage, abnormal sound or overheating is observed.

Check if there is any leakage if the measurement device is filled with oil or SF6. Check if it is earthed properly. Check if the junction box is sealed properly and if the interface cubicle is working properly.

4.4.6.4 Typical fault/alarm handling

Measurement device failure leads to a malfunction of protections and even forced outage of the HVDC system. So the configuration of the measurement shall be considered during the design stage. Usually two or three independent measurement instruments are installed at the same position and their measurements are fed to separate or redundant protections based on the two-out-of-three or two-out-of-two logic. In this case, a DC measurement instrument fault can be fixed without an outage.

a) Power supply faulty alarm from zero flux current transformer

   The measurement output of the zero flux CT becomes erratic if the power supply of the electronic unit fails. Put the related control or protection into test mode and switch off the electronic unit's power supply before checking and replacing the electronic unit.

b) Parity check error alarm from optical current transformer

   Parity check error means a data transmission error. In most cases it is due to a degradation of optical fibres. It can also be due to degradation of the optical transmitter or receiver. Therefore, check the fibres and the related PCB boards and replace the faulty one with a spare one.

c) Channel shutdown alarm from optical current transformer

   If the laser power goes too high, the emitter diode could be damaged or stop working. Check or replace the optical transmitter board in this case.

d) Board failure alarm from voltage divider

   If one DC voltage measurement board fails, the whole DC voltage measurement will be affected because the ratio of the voltage divider can change. In this case, an outage should be taken to replace the faulty board and calibrate the measurement.

e) The CVT measurement goes to zero

   Check the low voltage side capacitor. Check the small arrester is connected parallel with the capacitor. Check if the MCB is open. Check the humidity in the junction box to see if the contacts are short-circuited.

f) DC voltage divider measurement fault

   It is observed that a DC voltage measurement fault can be related to external insulation flashing over or internal discharging of the DC voltage divider. If it is a flash, a big disturbance can be observed on the DC current measurement too. If it is a small discharge, there may be no obvious change in the curve of the DC current.

   For the former, operators can try to run the HVDC link with reduced voltage and clean the divider during the next outage. For the latter, gas analysis may be helpful for fault tracing.

4.4.7 Valve cooling system

4.4.7.1 Operating

a) Start/stop the cooling pump from HMI

   The valve cooling pump can be started or stopped from the HMI. To stop a pump manually, try to start the redundant pump first and then stop the pump after the flow has reached its rating.

   If a small leak is observed on a cooling pump, operators can start the healthy pump and stop and isolate the leaking pump manually for further maintenance.

b) Enable/disable the leakage protection from HMI

   The leakage protection can be disabled during replenishment of water and be enabled again afterwards.

4.4.7.2 Monitoring from human-machine interface (HMI)

Supervise the supply/return water temperature, expansion vessel water level, main flow, supply/return water pressure, cooling water conductivity, and water level of buffer tank. Compare the above signals between the redundant transducers. Pay attention to events relating to:

a) alarms from main pump:
   - pump not ok;

- pump leakage;

b) alarms from transducers:

- transducer failure (measurement out of range);
- transducer alarm (the difference between two redundant measurements is greater than the allowable error);

c) alarms from valve cooling system protections:

- supply water overtemperature protection;
- derivative leakage protection;
- run back from return water overheat protection;
- low flow protection;
- conductivity protection;

d) alarms from valve cooling system surpervision:

- CPU or I/O board failure;
- communication failure between cooling control and pole control;
- events about system switching;
- loss of one cooling control and protection system;
- loss of both two cooling control and protection systems;
- loss of redundant cooling.

4.4.7.3 Site inspection

a) Before starting the cooling pump:

- make sure all valves, including the valves of the cooling tower, are in the right position;
- make sure the power supply of pumps, valves, fans is switched on;
- confirm all transducers are working normally;
- confirm the redundant valve cooling control and protection systems are both working with correct settings;
- check if there is any leakage, especially the main pumps, the pipe joints and valves;
- check the water level in the expansion vessel, buffer tank. Refill water if necessary;
- check the water temperature;
- check if the water conductivity is within the acceptable range, start the pump for a while and check again, until the conductivity is acceptable.

b) After deblocking of the converter:

- check the main pump oil level and shaft leakage;
- check to see if there is any leakage, overheating, abnormal sound and vibration in the main pumps;
- check the temperature, flow, pressure, level and conductivity transducers locally;
- confirm the redundant valve cooling control is working properly;
- check the water level of the buffer tank.

c) After blocking of the converter:

- it is not necessary to stop the main pump after blocking the related converter, unless leakage protection has operated;
- in some systems the cooling pumps are switched off automatically after a predetermined time delay after the converter is blocked; in that case, the operator shall verify that the pumps have restarted immediately after deblock;

- if the converter valve is blocked for a long period (more than 2 weeks), remember to run the cooling pump every week for at least 30 min; if the converter stops for more than 6 months, remember to eject all the water inside the valve cooling system, together with the silica gel in the ion exchanger;
- for systems located in very cold climates where the ambient temperature can fall below freezing (−5 °C to −40 °C), the temperature of the valve cooling system shall be monitored continuously and shall not be allowed to fall below 15 °C.

4.4.7.4 Typical fault/alarm handling

a) Transducer failure

A transducer failure can be detected when its measurement value is out of range or very different from the measurement of the redundant transducer or related transducer. Some of the transducers can be replaced during operation.

b) Low flow alarm

Check if the main pump is running. Check supply pump pressure to see if it is due to the flow transducer being faulty. Check the voltage recorded by the TFR to see if it is due to disturbance from the auxiliary power system. Switch to another pump to see if the flow recovers. Otherwise check if there is any leakage along the pipes or blockage in the filters.

c) High supply water temperature alarm

If the temperature measurement transducers are OK, check if there are enough cooling towers working or not. If not, manually start more cooling towers. The reason for cooling towers not working should be investigated. Otherwise apply for a runback.

d) Leakage alarm

Check if there is any leakage on the valve hall floor or bottom shield of the valve tower. If not, check if it is due to a decrease of ambient temperature or increase of the transmitted power. If the leak is on a pump, switch to another pump and isolate the faulty pump. If the leak is in a converter valve, apply for an emergency outage, stop the main pump and check further. If the leakage is somewhere along the main cooling pipe, try to seal it and apply for an outage if needed. Monitor the water level if the converter is in operation.

e) Expansion vessel low pressure alarm

This can be due to the failure of the nitrogen pressurizing system. Check if the over-pressure valve is set correctly, the nitrogen bottle is not empty, and the pressure adjustment valve is not broken. Check if there is a nitrogen leak.

f) Main pump failure

If the main pump is tripped by over-current protection, open its power supply breaker and safety breaker, turn off its supply and return water, and check the pump. It is noticed that most of main pump failures are related to faulty shaft seals. So remember to grease the shaft periodically.

g) Buffer tank low level alarm (if applicable)

The treated water collected in the buffer tank is fed to the evaporative cooling tower by spray pumps. If the water level is too low, the spray pumps may stop working and hence the temperature of the cooling water will increase to the trip level. So check and refill the buffer tank as soon as possible after getting this alarm.

h) Frequency controller failure alarm

Frequency controllers are commonly used in valve cooling systems to drive the motors for the main pump or cooling fans. Check the fault code of the frequency controller and try to solve the problem accordingly. Reset the fault and put the frequency controller into operation.

4.4.7.5 Special operation condition

a) Loss of one valve cooling control system

The converter can go on working with the loss of one valve cooling control system either due to control board failure or by transducer failure. However, if the other valve cooling system fails as well, the converter will be tripped. The faulty system should be repaired and put back to operation as soon as possible.

b) Loss of one main pump

Two main pumps should be designed for redundancy purposes. Once one main pump fails, close attention shall be paid to the healthy pump and the auxiliary power system, to avoid loss of both pumps, which will lead to a trip.

c) Loss of one cooling tower

An HVDC link should be designed so that it can still operate at rated power when one cooling tower is out of service even when temperature reaches its maximum value. However the actual temperature near the cooling tower, if located beside the hot transformers, can be even higher than the maximum value. So, in this case, monitor the cooling water temperature and apply for a runback if needed.

4.4.8 Auxiliary power system

4.4.8.1 Operating

a) Enable or disable the auto-switching function

The auto-switching function for local auxiliary supply buses can be set to manual or automatic mode. When a low voltage is detected, the power supply connected to the bus will automatically transfer to another separate power supply, hence increasing the reliability of the auxiliary power system.

b) Set up the voltage regulation function of the local auxiliary supply buses

The voltage regulation of the local auxiliary supply buses can be done manually or automatically by adjusting the tap changer of the auxiliary power input transformers to maintain the bus voltage within a certain range.

4.4.8.2 Monitoring from human-machine interface (HMI)

Check the voltage of local auxiliary supply buses. Check the current through the auxiliary power transformers. If there is an alarm from auto-switching or protection, check the layout of the auxiliary power system to make sure that the configuration is correct and try to restore the normal configuration as soon as possible.

4.4.8.3 Inspecting locally

Check the sound and temperature of the auxiliary power transformers. Check the protections are working correctly.

4.4.8.4 Typical fault/alarm handling

Faults in the auxiliary power supply or auxiliary power equipment are isolated by protections and auto-switching function automatically.

a) Loss of one or two auxiliary power supplies

The design depends on the customer specification and may be different. Usually, multiple power supplies are fed to the three medium voltage buses respectively. After losing one or more of the auxiliary power supplies, the auto-switching function will isolate the faulty power supplies and close the bus tie breakers so that all low-voltage buses still have a good power supply. In this case, it is essential to restore the failed power supply to avoid loss of all three power supplies and hence a bipolar trip.

b) Protection trip of a medium voltage load breaker

Check the protection events and the TFR. Check if the breaker and its nearby equipment are OK or not. Try to reclose the breaker once if the equipment has no indication of faults. If the breaker is tripped again, check the cable and the load itself.

c) Low voltage auxiliary power transformer tripped by protection

If the transformer is tripped as soon as it is energized, check the excitation current, which can lead to a malfunction of the differential protection or over-current protection. If so, correct the protection settings. Otherwise, check the gas content of the transformer's oil to see if there is a real fault inside the transformer.

d) DC battery system grounding alarm

Only one earth fault at the positive or negative bus of the DC battery system will not affect too much, but the fault has to be located and fixed in a timely manner. Otherwise it might develop into faults such as an earth fault between a positive or negative bus, or an earth fault between a DC and AC power supply, which might lead to malfunction of control and protections.

4.4.8.5 Special operation condition

a) Loss of one or two auxiliary power supplies

Usually, multiple power supplies are fed to the MV buses. After losing one or more of the auxiliary power supplies, the auto-switching function will isolate the faulty power supplies and close the bus tie breakers so that all MV buses still have a good power supply. In this case, it is essential to restore the failed power supply to avoid loss of all three power supplies and hence a bipolar trip.

b) Temporary overvoltage or low voltage

Temporary overvoltage or low voltage can occur during an AC line fault or even a commutation failure, thus the motors, fans and pumps connected to the auxiliary power system could trip owing to their protections. Consideration should be given at the design stage to avoid this situation.

5 Maintenance

5.1 Maintenance policy

5.1.1 General

Traditionally, an annual maintenance outage of one or two weeks is scheduled for an HVDC system. To meet the requirements for improved availability, the length of the maintenance outage is decreasing. However, the requirements for improved availability are increasing. In order to meet availability targets and perform prudent and effective maintenance activities, a maintenance philosophy and programme should be developed.

Different maintenance philosophies are employed by operators of HVDC stations and interconnections. It is up to the individual owner/operator to decide which philosophy best fits their needs and provides the best solution.

The performance of HVDC systems around the world, as well as the failure statistics on individual HVDC components, is presented by CIGRE every alternate year (www.cigre.org). The report provides a good starting point for a utility to set up its own maintenance policy.

5.1.2 Corrective maintenance

Corrective maintenance is a reactionary maintenance policy that waits for equipment to fail before being repaired. It is inefficient and not good utility practice.

5.1.3 Time-based maintenance (TBM)

Traditionally an annual outage of one or two weeks is arranged for an HVDC system. During the outage, detailed inspections and predictive tests for converter transformers, converter valves, AC/DC switchgears and arrestors are carried out, together with routine maintenance such as cleaning of the insulators.

Time-based maintenance is sometimes considered to be less efficient because too much time and money is spent in testing all HVDC equipment. It can lead to unnecessary maintenance activities being performed. However, some HVDC systems that are fed by hydroelectric plants still use this maintenance philosophy to perform maintenance when the generating station is either partly shutdown for maintenance or operating at low capacity (e.g. low water conditions for a hydro plant).

5.1.4 Condition-based maintenance (CBM)

CBM is a kind of routine maintenance activity based on asset conditions. With a good condition monitoring system, condition-based maintenance can not only decrease the outage time but also improve system reliability. It is lower cost and more efficient than TBM.

The disadvantages of CBM are:

- high installation costs;
- unpredictable maintenance periods cause costs to be divided unequally;
- increased number of parts (the CBM installation itself) that need maintenance and checking.

Due to its costs, CBM is only used for important parts of the HVDC equipment. The examples of successful application of CBM in an HVDC station are:

- tan delta measurements to monitor the insulation strength of electrical equipment such as capacitors and bushings;
- dissolved gas analysis (DGA) used to monitor whether any defects such as partial discharges and overheating appear in transformer tank;
- continuous on-line gas monitoring used to monitor the condition of converter transformers; this type of system can provide advance warning of potential serious failure;
- infrared scanning used to monitor the condition of disconnectors, transformer coolers, bus work, heating in motor contactors, hot spots in thyristor valves and hot spots on filter capacitor cans.

5.1.5 Reliability-centred maintenance (RCM)

RCM is a process to ensure that assets continue to do what their users require in their present operating context. The RCM technique has been introduced to some HVDC converter stations and has resulted in high availability, lower cost and less manpower.

RCM eliminates the need to perform maintenance every year. This results in increased availability of the system as planned outages are reduced. In addition, the maintenance costs are reduced as the amount of maintenance carried out every year is reduced. The challenge, however, is to determine the appropriate maintenance interval. It is therefore essential to continuously monitor the effectiveness of the maintenance programme and make adjustments over time if necessary.

Reference [1] provides step by step details of application of the RCM process to the system. It is important to note that each HVDC system is unique and the information provided in the reference should be used only as a guide.

5.1.6 Maintenance programme

The planned maintenance time for an HVDC system has changed from two weeks every year in the last decade to one week a year or even one week every four years recently. To make the best use of the limited time, a maintenance plan shall be carefully prepared.

The maintenance programme should be developed based on the recommendations from the HVDC supplier, and its sub-suppliers, as well as the asset owners' own procedures and other national or regulatory requirements.

A maintenance programme for LCC converter stations should be established to ensure the safe, reliable and cost-effective operation of the facility and interconnection. The maintenance programme should include all station equipment and should be based on risk, criticality and include coordinated scheduling. It will require determining which test will be performed on each asset and developing detailed testing procedures.

The plan should cover the work to be done, the needed human resources and test equipment, and of course a feasible time schedule. Generally, the following three kinds of maintenance work should be carried out on HVDC equipment.

a) Diagnostic inspection is the maintenance work to be done during outage to visually inspect the appearance of a piece of equipment and its mechanical parts, for example checking the motor drive mechanism of a breaker.
b) Routine maintenance is the maintenance work to be done on a regular interval to prevent equipment failure, for example greasing the bearing of motors and pumps.
c) Preventive maintenance is the maintenance work to be done on a regular interval or when an impending equipment failure is detected by monitoring the equipment's working condition, for example the ratio, resistance, and insulation test on windings.

The plan should also consider the operation mode for maintenance work. Maintenance work can be done firstly pole by pole with monopole ground return or monopole metallic return. Then the maintenance work at the bipolar area can be done with a bipolar outage. In this way, the availability of an HVDC system can be minimally affected by planned outages.

5.2 Maintenance during operation

5.2.1 Routine maintenance for converter transformers

During normal operation, the following work needs to be carried out on converter transformers:

a) infrared detection once a month during full power transmission;
b) oil dissolved gas analysis every three months or when needed;
c) replace or regenerate the gel when ¾ of the silica gel has changed colour to light brown;
d) vibration test twice a year.

5.2.2 Maintenance for control and protections

To achieve high availability for the HVDC transmission system, the HVDC control and protections are usually duplicated or even triplicated. Therefore, a single failure will not interrupt the operation of the HVDC system. Based on the alarms by the internal supervision functions, maintenance engineers can easily trace and locate the fault, and fix the problem, in most cases by replacing a failed printed circuit board.

It is important to follow the following principles for faulty clearing of control and protections:

a) recover the faulty system as soon as possible, otherwise the HVDC system could be blocked if the other system also develops a fault;
b) before putting the system into service, double check if there are any alarms or trips on the system, otherwise the HVDC system might be tripped when the system becomes active.

Sometimes the control and protection software needs to be upgraded. It is not necessary to apply for an outage to do this work. The new software can be loaded one by one.

5.2.3 Maintenance for DC measurements

DC measurements are usually also duplicated or even triplicated. Therefore, a DC measurement failure will not interrupt the operation of an HVDC system. In most cases, the failure is due to a degraded board or a broken fibre, and can be solved by a replacement part.

It is important to follow the following principles to clear a fault on the DC measurement:

a) put all the control and protection cubicles that the faulty DC measurement feeds to into test mode to prevent a trip order being sent out;
b) make sure that work is carried out only on the faulty measurement system and that the operation of the redundant DC measurement system is not disturbed;
c) before putting the related control and protection devices into service, double check if there are any alarms or trips standing.

If there is a fault on the DC voltage measurement board, it is recommended to replace the board after the related pole is blocked because the DC voltage divider ratio can change when replacing the board and hence can lead to a forced outage.

5.2.4 Routine maintenance for valve cooling system

The valve cooling system is normally operated in automatic mode. All faults are alarmed. To prevent a severe fault, the valve cooling system should be checked every month regarding the following points:

a) check oil level, noise, leakage, and vibration of the main cooling pumps, lubricate the pump motor if needed;
b) de-aeration of the ion exchange vessel;
c) measure the oxygen content and gas level in the nitrogen bottles;
d) check for leakage in the cooling system;
e) check nozzles and spray pumps of the cooling tower spray system;
f) check the other motors, both for fine water and raw water.

5.3 Maintenance under outage

5.3.1 Converter valves

5.3.1.1 General

To work on the converter valves, the following safety instruction and guideline shall be strictly observed:

a) any person working on the modules of the valve towers has to wear a safety harness;
b) the thyristor valve towers shall be earthed before any work commences in the valve hall;
c) the maintenance lift or platform driver shall have a valid license.

5.3.1.2 Visual check

It is necessary to climb up the valve tower to check for signs of overheating, discharging or loose connections.

5.3.1.3 Routine maintenance

- Replace any faulty thyristor.
- Replace any faulty thyristor firing and monitoring boards.
- Replace degraded damping capacitors or resistors.
- Replace the broken fibres to or from the thyristor.

- Clean the valve tower if needed.

5.3.1.4 Preventive maintenance

- Check if there are any loose cooling pipes. Tighten the loose cooling pipes to the correct torque. Pressure test the valve cooling system.
- Check if there are any loose connections between valve components. Tighten the loose bolts and nuts and the loose electrical terminals to the correct torque.
- Thyristor level test such as firing test, protective firing test, damping capacitor and resistor measurement. Replace the valve components that exceed the criteria.
- Valve arrester test if needed.

5.3.2 Converter transformers

5.3.2.1 Visual check

During an outage, it is recommended to check if the silica-gel breather, the oil level indicators, the gas relays, the control cabinet, and other auxiliary devices of the transformer are in good condition.

5.3.2.2 Routine maintenance

- Clean the bushings if needed.
- Check the tap changer drive mechanism. Manoeuvre from the lowest position to the highest position to make sure the tap changer works smoothly.
- Clean the cooler heat exchanger by high-pressure washing.
- Grease the cooler fan motor, change the motor bearing in the event of jarring sounds from the motor.
- Fix any oil leakage.

5.3.2.3 Preventive test

Depending on the maintenance policy, all or part of the following tests are performed every year or when necessary:

- measurement of winding insulation and absorption ratio;
- measurement of winding resistance to see if there is any inter short-circuit;
- measurement of voltage ratio to see if there is any inter short-circuit;
- measurement of bushing capacitance and tan δ;
- hydrophobicity check of the bushings;
- analysis of insulation oil;
- functional tests of auxiliary equipment.

If a converter transformer is considered to be defective following the above tests, further checks and tests should be carried out.

5.3.2.4 Detective test

Once it is noticed that a converter transformer could have a problem, the following tests can be carried out for further fault analysis:

- measurement of no-load loss and current to see if there is something wrong with the iron core;
- measurement of short-circuit impedance and load loss to see if there is something wrong with the winding;

- induced AC voltage withstand test with PD measurement to check the insulation of AC side windings;
- frequency response analysis to see if there is any distortion with the winding;
- AC/DC applied voltage withstand test with a PD measurement to check the insulation of valve side windings;
- insulation oil test;
- internal inspection.

5.3.2.5 Replace a converter transformer

A faulty converter transformer, either with abnormal insulation oil content or with abnormal temperature rise, should be replaced with a spare converter transformer. Typically, it takes two or three days to do the following:

- disconnect the cables to other main circuit equipment and control and protections;
- remove the valve hall sealing materials, as well as the fire-fighting detectors and pipes;
- remove the faulty transformer from its position with a cart;
- move the spare transformer smoothly to its service position and fix it;
- seal the valve hall, reinstall the fire-fighting detectors and pipes;
- connect the cables to other main circuit equipment and control and protections;
- check and test the function of the OLTC protection relays;
- transformer preventive test;
- enable the transformer energizing protection and energize the transformer;
- check the polarity of current measurement and phase sequence at low load; disable the transformer energizing protections if they are correct;
- insulation oil analysis on the 1^{st}, 4^{th}, and 10^{th} day after the spare transformer starts operation, combined with infrared measurement.

5.3.3 AC/DC breakers and switchgear

5.3.3.1 Visual check

Check for cleanliness, corrosion, heater function, gas pressure, ventilations of the breakers and other switchgear. Look for loose bolts and nuts and oil leaks in breakers and switchgear operating mechanisms.

5.3.3.2 Routine maintenance

The following service should be done every 3 to 6 years or after 2 000 close-open operations:

- greasing of the worn gear in the operating mechanism;
- check the contact of disconnectors and earthing switches, clean and apply molykote paste if needed, replace contacts that show damage or are badly eroded owing to mechanical load, arcing etc.;
- cleaning the operating mechanism when necessary using a vacuum cleaner;
- check the bolts, nuts, washers and terminal connectors are in place and in good condition; replace items showing excessive wear or corrosion;
- check rust protections for the parts in the operating mechanism; rust stains shall be polished off and new rust inhibitor brushed or sprayed on;
- trial operation in combination with measurement of the operation times of breakers.

5.3.3.3 Preventive test

Depending on the maintenance policy, the following tests can be carried out every year or when necessary:

- SF6 content, pressure and leakage test;
- insulators' hydrophobicity measurement; spray and rub insulators clean if needed;
- operating characteristics' measurements, measuring opening time, closing time, phase discrepancy;
- measurement of minimum operating voltage of the open coils and closed coils;
- test the control and protection functions such as block, mechanical interlocking, trip at discrepancy;
- measure the capacitance and inductance of the oscillating circuits (for DC breakers only).

5.3.4 AC/DC filters

5.3.4.1 Visual check

The voltage stress of the AC/DC filters is withstood mainly by the capacitors on the high voltage side of the filters. So maintenance of the AC/DC filters is mainly maintenance of its high-voltage capacitors.

Once the AC/DC filters are earthed for about 10 min, it is safe to climb up the capacitor stacks to check the capacitor units. Capacitors with oil leakage or distortion should be discovered and be replaced.

Check the oil level of current transformers.

5.3.4.2 Routine maintenance

No service work is needed for the AC/DC filters.

5.3.4.3 Preventive test

Depending on the maintenance policy, all or part of the following tests are performed every year or when necessary:

- measure the capacitance of each capacitor bridge to see if they are balanced;
- measure the capacitance of each capacitor unit if the capacitor bridge is not balanced;
- check the hydrophobicity of support insulators; clean insulators if needed;
- measure the resistance of the resistor and the reactor;
- measure the tuning frequency of the filter.

5.3.5 DC measurements

5.3.5.1 Visual check

Check if there are any marks or cracks on the surface of the DC voltage divider insulators. Check that all the connections are tight. Check if there is any oil leakage or SF6 leak.

5.3.5.2 Routine maintenance

Clean the insulators of the DC voltage divider with clean and clear water every year.

5.3.5.3 Preventive test

For the DC voltage divider, the following test can be carried out:

- SF6 analysis, including trace water analysis;
- resistance and capacitance measurement.

For the zero flux DC current transformer, the following test can be carried out:

– insulation resistance measurement;
– dielectric loss and capacitance measurement;
– DC accuracy test.

5.3.6 Valve cooling system

5.3.6.1 Visual check

After one year of continuous operation, it is recommended to carry out the following checks on the valve cooling system:

- check for any leakage on the cooling pipes;
- check for any loose valves;
- check if the quality of the cooling water meets the requirement;
- check if the measurement accuracy of the sensors meets the requirement.

5.3.6.2 Routine maintenance

Annual servicing is necessary for the valve cooling system and the following work should be carried out every year:

- check threaded parts and couplings, mechanical sealing, alignment of the main pump;
- check all flanged joints for tightness;
- exchange of ion exchange resin when water conductivity reaches minimum allowable level recommended by the OEM (clean the inside of the ion exchange vessel if needed);
- cleaning of strainers and change of filters;
- check, clean and calibrate sensors;
- check functions of all the valves, check their position indicators while operating a valve;
- check the safety valve opening pressure;
- clean the buffer tank (RO-water tank) by high pressure washing;
- check the make-up pump, drainage pump.

5.3.6.3 Preventive test

Depending on the maintenance policy, the following tests can be carried out every year or when necessary:

- pressure test;
- pump vibration measurement;
- pump shaft concentricity;
- pump motor current measurement.

5.3.7 AC/DC arresters

5.3.7.1 Visual check

Check if there are any marks or cracks on the insulator. Check the connections to the ground. Check the counters.