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TECHNICAL REPORT

RAPPORT TECHNIQUE

Performance of high-voltage direct current (HVDC) systems with line-commutated converters –
Part 2: Faults and switching

Fonctionnement des systèmes à courant continu haute tension (CCHT) munis de convertisseurs commutés par le réseau –
Partie 2: Défauts et manœuvres

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

PERFORMANCE OF HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS WITH LINE-COMMUTATED CONVERTERS –

Part 2: Faults and switching

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IEC 60919-2, which is a technical report, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

This second edition cancels and replaces the first edition, published in 1991, and constitutes a technical revision.

This edition includes the following main changes with respect to the previous edition:

a) this report concerns only line-commutated converters;
b) significant changes have been made to the control system technology;

c) some environmental constraints, for example audible noise limits, have been added;

d) the capacitor coupled converters (CCC) and controlled series capacitor converters (CSCC) have been included.

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

Enquiry draft	Report on voting
22F/160/DTR	22F/165/RVC

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

A list of all parts of the IEC 60919 series, under the general title: *Performance of high-voltage direct current (HVDC) systems with line-commutated converters*, can be found on the IEC website.

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

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- withdrawn,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

PERFORMANCE OF HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS WITH LINE-COMMUTATED CONVERTERS –

Part 2: Faults and switching

1 Scope

This part of IEC 60919 which is a technical report provides guidance on the transient performance and fault protection requirements of high voltage direct current (HVDC) systems. It concerns the transient performance related to faults and switching for two-terminal HVDC systems utilizing 12-pulse converter units comprised of three-phase bridge (double way) connections but it does not cover multi-terminal HVDC transmission systems. However, certain aspects of parallel converters and parallel lines, if part of a two-terminal system， are discussed. The converters are assumed to use thyristor valves as the bridge arms, with gapless metal oxide arresters for insulation co-ordination and to have power flow capability in both directions. Diode valves are not considered in this report.

Only line-commutated converters are covered in this report, which includes capacitor commutated converter circuit configurations. General requirements for semiconductor line-commutated converters are given in IEC 60146-1-1, IEC 60146-1-2 and IEC 60146-1-3. Voltage-sourced converters are not considered.

The report is comprised of three parts. IEC 60919-2, which covers transient performance, will be accompanied by companion documents, IEC 60919-1 for steady-state performance and IEC 60919-3 for dynamic performance. An effort has been made to avoid duplication in the three parts. Consequently users of this report are urged to consider all three parts when preparing a specification for purchase of a two-terminal HVDC system.

Readers are cautioned to be aware of the difference between system performance specifications and equipment design specifications for individual components of a system. While equipment specifications and testing requirements are not defined herein, attention is drawn to those which could affect performance specifications for a system. Note that detailed seismic performance requirements are excluded from this technical report. In addition, because of the many possible variations between different HVDC systems, these are not considered in detail. Consequently this report should not be used directly as a specification for a specific project, but rather to provide the basis for an appropriate specification tailored to fit actual system requirements for a particular electric power transmission scheme. This report does not intend to discriminate the responsibility of users and manufacturers for the work specified.

Terms and definitions for high-voltage direct current (HVDC) transmission used in this report are given in IEC 60633.

Since the equipment items are usually separately specified and purchased, the HVDC transmission line, earth electrode line and earth electrode are included only because of their influence on the HVDC system performance.

For the purpose of this report, an HVDC substation is assumed to consist of one or more converter units installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring, protective, measuring and auxiliary equipment. While there is no discussion of a.c. switching substations in this report, a.c. filters and reactive power sources are included, although they may be connected to an a.c. bus separate from the HVDC substation.

2 Normative references

The following referenced documents are indispensable for the application 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 60146-1-1, *Semiconductor converters – General requirements and line commutated converters – Part 1-1: Specifications of basic requirements*
Amendment 1 (1996)

IEC 60146-1-2, *Semiconductor converters – General requirements and line commutated converters – Part 1-2: Application guide*

IEC 60146-1-3, *Semiconductor converters – General requirements and line commutated converters – Part 1-3: Transformers and reactors*

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

IEC 60071-1, *Insulation co-ordination – Part 1: Terms, definitions, principles and rules*

IEC 60700-1, *Thyristor valves for high-voltage direct current (HVDC) power transmission – Part 1: Electrical testing*

IEC/TR 60919-1:2005, *Performance of high-voltage direct current (HVDC) systems with line-commutated converters – Part 1: Steady-state conditions*

IEC 60919-3, *Performance of high-voltage direct current (HVDC) systems with line-commutated converters – Part 3: Dynamic conditions*

3 Outline of HVDC transient performance specifications

3.1 Transient performance specifications

A complete performance specification related to transient performance of an HVDC system during faults and switching should also include fault protection requirements.

These concepts are introduced at the appropriate locations in the following transient performance and related clauses:

– Clause 4 – Switching transients without faults
– Clause 5 – AC system faults
– Clause 6 – AC filter, reactive power equipment and a.c. bus faults
– Clause 7 – Converter unit faults
– Clause 8 – DC reactor, d.c. filter and other d.c. equipment faults
– Clause 9 – DC line faults
– Clause 10 – Earth electrode line faults
– Clause 11 – Metallic return conductor faults
– Clause 12 – Insulation co-ordination - HVDC systems
– Clause 13 – Telecommunication requirements
– Clause 14 – Auxiliary systems

Discussion in the following clauses on the d.c. line, earth electrode line and earth electrode is limited to the relationships between these and either the transient performance or protection of HVDC converter stations.

3.2 General comment

In general, control strategies can be used to minimize the effect of disturbances, but when the safety of equipment depends on their correct performance, this should be identified.

4 Switching transients without faults

4.1 General

This clause deals with the transient behaviour of the HVDC system during and after switching operations both on the a.c. and the d.c. sides of converter substations, and is not related to equipment or line faults which are treated in the following clauses of this report.

Switching operations without faults can be classified as follows:

a) energization and de-energization of a.c. side equipment such as converter transformers, a.c. filters, shunt reactors, capacitor banks, a.c. lines, static var compensators (SVC), and synchronous compensators;
b) load rejection;
c) starting and removal from service of converter units;
d) operation of d.c. breakers and d.c. switches for paralleling of poles and lines; connection or disconnection of d.c. lines (poles), earth electrode lines, metallic return paths, d.c. filters, etc.

4.2 Energization and de-energization of a.c. side equipment

During the operating life of an HVDC transmission system, energization and de-energization of converter transformers, a.c. filters, shunt reactors, capacitor banks, SVCs, and other equipment may occur many times. Depending on the characteristics of the a.c. system and the equipment being switched, resulting current and voltage stresses will be imposed on equipment being switched and generally impinge as well on part of the overall a.c. system.

The overvoltages and overcurrents which are critical for plant design are usually due to faults (Clauses 5 to 9), and not to normal switching operations. Nevertheless, they are discussed here for completeness. They are relevant in consideration of disturbances to a.c. system voltages.

Filter switching will also result in transient distortion of the bus voltage. This could disturb the commutation process and in a weak system could lead to commutation failure.

Thus equipment switching should be investigated to:

– determine critical a.c. network and equipment conditions which may contribute to such abnormal stresses and actions which may be taken to mitigate them;
– design the equipment;
– verify arrester duties.

Transients occur routinely when filters and capacitor banks are switched as necessary to control harmonic interference and steady-state terminal voltages.

Because of the frequency of occurrence of switching overvoltages it is generally desirable that the overvoltage protective devices do not absorb appreciable energy during such operations. For example the amplitudes of overvoltages arising from routine switching operations can be minimized by the use of suitable resistors incorporated in the circuit-breakers associated with filters and capacitor banks or by synchronizing the closing of the circuit-breakers. This can also reduce the possibility of inverter commutation failures. The HVDC control system can also be used effectively to damp certain overvoltages.

Restrike-free switching devices should be used for capacitor switching to avoid onerous overvoltages from restriking which otherwise could occur when disconnecting filters or capacitor banks.

Transformer energization inrush currents can cause an undesirable interaction in the a.c. and d.c. systems. When disconnecting a converter transformer from the ac network, the transformer should be disconnected maintaining the ac filters connected in parallel if possible, instead of disconnecting the transformer alone. In that way, residual saturation will be decreased, and inrush currents would be reduced. After some hundreds of milliseconds the filters could be disconnected from the transformer.

To reduce inrush currents, typical control measures include circuit-breaker pre-insertion resistors, using the synchronized circuit-breaker, or setting of the transformer on-load tap changers at their highest tap changer positions. Highest tap changer position refers to the tap changer position with highest number of winding turns. Synchronization requires switching at an optimum instant in each phase, i.e. breaker closing 90 degrees after voltage zero crossing. This implies that the three poles of a circuit-breaker cannot switch simultaneously. For breakers with one-pole operating mechanisms (and thus a separate synchronizing unit), this is not a problem. The synchronizing unit is simply programmed to give switching orders suitably separated in time to the poles. Some breakers with three-pole operating mechanism can also be used for synchronized switching if the operating mechanism can be arranged to give a mechanical time delay. However it should also be noted that saturation of already energized converter transformers can arise from energization of another transformer in the converter station or from switching of an SVC.

Also the application of low order harmonic filters can be helpful in reducing the problems with inrush currents. The effectiveness of such measures depends largely on the system and pertinent equipment characteristics. In addition, the response of the a.c. system can be sensitive to the number of converter transformers already energized, especially if they are not yet loaded as for series connections of multiple converter units.

Energization of capacitor and filter banks changes the system impedance characteristic. In case of system with relatively small short circuit capacity, adding capacitive component shifts high impedance peak of frequency-impedance curve to lower frequency side. If the high impedance peak becomes closer to second harmonic, severe overvoltages could be presumed during faults. To mitigate such situation, damping resister could be added to capacitors.

The energization of capacitor and filter banks produces oscillations between these elements and the rest of the network. Again, depending on the size of the banks and the network characteristics, switching overvoltages can appear along with overcurrents in the already energized a.c. system components.

Attention should be paid to the possibility of damage to the capacitors during re-energization of capacitors because of trapped charges in the capacitors from a preceding opening operation. Measures may be necessary for discharging them before reclosing if their internal discharge resistors are not sufficiently effective within the desired switching time. Alternatively, a longer switching time may be necessary.

Energization of filters excites the frequencies to which they, in combination with the a.c. network, are tuned. Also switching out of filter and capacitor banks can cause the a.c. system voltage to oscillate.

SVCs can be provided to stabilize the voltage and control temporary overvoltages. Energization of SVCs should be such as to produce a light or even no transient in the system voltage. Most of them have an active control which can be used to accomplish this objective.

Connection or disconnection of shunt reactors and capacitors produces change in a.c. voltage. Size and operation of this equipment should be specified so as to limit switching-caused voltage changes to acceptable levels.

Energization and de-energization of a.c. transmission lines connected to HVDC sub-stations generate voltage transients as well, which should be taken into account. These operations change the a.c. harmonic impedances which also influence the transient harmonic effects.

Synchronous compensators can produce voltage transients when started and operated as induction motors, drawing reactive power and reducing the system voltage. This aspect of their performance should be carefully examined.

A table of acceptable levels of temporary or transient overvoltages and overcurrents during switching operations of the various system components or preferably a diagram of the expected transient overvoltage and overcurrent levels versus time should be developed for the specifications.

Related to the foregoing, information about the electrical characteristics of the a.c. system and its future development as complete as possible should also be supplied in the specifications. Relevant operating criteria along with existing and expected a.c. overvoltage levels should also be shown.

The desired performance of the HVDC substations under the transient conditions described in the foregoing subclauses should be stated for both switching in and out of the various components.

Overvoltage performance for the HVDC link should be co-ordinated with the actual performance characteristics of the existing a.c. network with which it is to be integrated.

4.3 Load rejection

Sudden reductions of transmitted power over the HVDC link without occurrence of faults could take place:

– due to unintentional tripping of the a.c. circuit-breakers at either terminal;
– due to blocking and bypass of converter units as a consequence of control system action;
– due to loss of generation and for a multitude of other possible causes.

Voltage levels on the a.c. system would rise primarily because of the consequent excess of reactive power compensation at the HVDC substation. Resonant conditions can be reached due to saturation of the power transformers and resonances between transformers, filters and the a.c. network. These overvoltage effects can be accentuated by frequency deviations in the a.c. system.

Special care shall be taken for the case that the inverter becomes isolated from the a.c. system with only the filters and shunt capacitor banks connected to it.

For this contingency, the inverter shall be blocked and bypassed to prevent overvoltage-caused damage to the filter components or the a.c. side arresters or the valve arresters. Opening of the remote end circuit-breakers, for a system with a single or only a few lines connecting the inverter to the a.c. system shall be taken into account in the design of the protective scheme.

Load rejection transients following system faults are discussed in 5.3.5.

Acceptable load rejection-caused overvoltages, in terms of amplitudes and durations should be specified particularly if the resulting stresses are expected to be greater than those discussed in 4.2.

Suitable operating strategies to return to normal operating conditions should be developed. Among the procedures for achieving this are controlling the converter units still in service to regulate the system voltage or switching in reactors or by removal of capacitor or filter banks. If capacitor or filter banks are to be switched under overvoltage conditions this shall be taken into account when fixing the associated circuit-breaker ratings and capabilities. In cases when an existing circuit-breaker of inadequate capacity could be called on to perform this duty, its operation should be inhibited and other means used to reduce overvoltages.

When converters are to be used for voltage control, consideration should be given to the design and manufacture of the valves for operation at large delay angles.

The extent to which converter measures can be used for reducing a.c. system overvoltage will depend on the requirements for continuity of supplied power to satisfy the a.c. system dynamic performance.

Other means, such as switched capacitors or reactors, synchronous compensators, SVCs, special metal oxide (MO) temporary overvoltage absorbers (TOV), etc. may need to be used to limit overvoltages to acceptable levels and to achieve the desired converter performance.

As in most system design decisions, economics will play a major role. However, trade-offs may be necessary between cost and system performance.

4.4 Start-up and shut-down of converter units

Normal operator-initiated start-up and shut-down procedures for an HVDC pole should be established.

Start-up and shut-down of series-connected converter units is performed by the control system sometimes in conjunction with the operation of switching devices in parallel with the converter units. For this purpose normally an automatic sequence is followed in which a valve bypass path within the bridge is activated before the opening or closing of the bypass switch.

For this procedure any special requirements or constraints such as the maximum allowable a.c. bus voltage variation, special interlock requirements or maximum variation in transmitted power, etc., should be specified.

Whether the system is to be operated with a smaller number of converters than in the ultimate configuration, particularly during the development stages of the project, should be noted.

4.5 Operation of d.c. breakers and d.c. switches

Switching devices have been used on the d.c. side of HVDC transmission systems for several functions as follows:

- by-pass and disconnect converter units;
- connect or disconnect the substation pole to the earth electrode line in bipolar links;
- connect poles or bipoles in parallel, including polarity reversal;
- switch the neutral bus-bar;
- connect or disconnect the d.c. line;
- connect or disconnect d.c. filters;
- connect d.c. filters in parallel during monopolar operation.