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TECHNICAL REPORT

RAPPORT TECHNIQUE

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

Fonctionnement des systèmes à courant continu haute tension (CCHT) munis de convertisseurs commutés par le réseau – Partie 3: Conditions dynamiques

IEC/TR 60919-3:2009

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

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Tél.: +41 22 919 02 11
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

Part 3: Dynamic conditions

FOREWORD

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IEC 60919-3, 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, which was issued as a technical specification in 1999. It constitutes a technical revision.

This edition includes the following significant technical 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/183/DTR	22F/192/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- withdrawn,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 3: Dynamic conditions

1 Scope

This Technical Report provides general guidance on the dynamic performance of high-voltage direct current (HVDC) systems. Dynamic performance, as used in this specification, is meant to include those events and phenomena whose characteristic frequencies or time domain cover the range between transient conditions and steady state. It is concerned with the dynamic performance due to interactions between two-terminal HVDC systems and related a.c. systems or their elements such as power plants, a.c. lines and buses, reactive power sources, etc. at steady-state or transient conditions. The two-terminal HVDC systems are assumed to utilize 12-pulse converter units comprised of three-phase bridge (double way) connections. The converters are assumed to use thyristor valves as bridge arms, with gapless metal oxide arresters for insulation coordination and to have power flow capability in both directions. Diode valves are not considered in this specification. While multi-terminal HVDC transmission systems are not expressly considered, much of the information in this specification is equally applicable to such systems.

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.

This report (IEC 60919-3) which covers dynamic performance, is accompanied by publications for steady-state (IEC 60919-1) and transient (IEC 60919-2) performance. All three aspects should be considered when preparing two-terminal HVDC system specifications.

A difference exists 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 would affect performance specifications for a system. There are many possible variations between different HVDC systems, therefore these are not considered in detail. 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 between the responsibility of users and manufacturers for the work specified.

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: Specification of basic requirements*

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

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

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

IEC/TR 60919-2:2008, *Performance of high-voltage direct current (HVDC) systems with line-commutated converters – Part 2: Faults and switching*

3 Outline of HVDC dynamic performance specifications

3.1 Dynamic performance specification

A complete dynamic performance specification for an HVDC system should consider the following clauses:

– a.c. system power flow and frequency control (see Clause 4);
– a.c. dynamic voltage control and interaction with reactive power sources (see Clause 5);
– a.c. system transient and steady-state stability (see Clause 6);
– dynamics of the HVDC system at higher frequencies (see Clause 7);
– subsynchronous oscillations (see Clause 8);
– power plant interaction (see Clause 9).

Clause 4 deals with using active power control of the HVDC system to affect power flow and/or frequency of related a.c. systems in order to improve the performance of such a.c. systems. The following aspects should be considered at the design of HVDC active power control modes:

a) to minimize the a.c. power system losses under steady-state operation;

b) to prevent a.c. line overload under steady-state operation and under a disturbance;

c) to coordinate with the a.c. generator governor control;

d) to suppress a.c. system frequency deviations under steady-state operation and under a disturbance.

In Clause 5, the voltage and reactive power characteristics of the HVDC substation and other reactive power sources (a.c. filters, capacitor banks, shunt reactors, SVC (static var compensator), synchronous compensators) as well as interaction between them during control of the a.c. bus voltage are considered.

In Clause 6, a discussion is provided concerning methods of controlling active and reactive power of an HVDC link to improve the steady-state and/or transient stability of the interconnected a.c. system by counteracting electromechanical oscillations.

Clause 7 deals with dynamic performance of an HVDC system in the range of half fundamental frequency and above due to both characteristic and non-characteristic harmonics generated by converters. Means for preventing instabilities are also discussed.

In Clause 8, the phenomenon of amplification of torsional, mechanical oscillations in turbine-generators of a thermal power plant at their natural frequencies, due to interaction with an HVDC control system (constant power and current regulation modes), is considered. Specifications for subsynchronous damping control are defined.

The interaction between a power plant and an HVDC system located electrically near to it is considered in Clause 9, taking into account some special features of the nuclear power plant and requirements for the reliability of the HVDC system.

3.2 General comments

Any design requirements for future HVDC systems being specified should fall within the design limits covered in publications on steady-state (IEC 60919-1) and transient (IEC 60919-2) performance. It is recommended that during preparation of the dynamic HVDC system performance specification, the proper HVDC system control strategy should be identified based on detailed power system studies. The priorities of control signal inputs and the way they are processed should be specified.

4 AC system power flow and frequency control

4.1 General

Active power control of an HVDC system can be used to control the power flow and/or frequency in related a.c. systems in order to improve the performance of a.c. systems in steady-state operation and under disturbance.

In this clause, the HVDC active power operation modes, which are used to improve the a.c. system performance for the following purposes, will be covered:

– HVDC power control to minimize the total power system losses under steady-state operation;

– HVDC power control for prevention of a.c. line overload under a disturbance as well as steady state;

– coordinated HVDC power control with an a.c. system generator governor control;

– HVDC power control for suppression of an a.c. system frequency deviation under a disturbance as well as steady state.

HVDC active and/or reactive power modes used to improve a.c. system dynamic and transient stability or improve a.c. voltage control is discussed in Clauses 5 and 6.

4.2 Power flow control

4.2.1 Steady-state power control requirements

The power of an HVDC system is sometimes controlled to minimize overall power system losses, to prevent a.c. line overloading, and to coordinate with the governor control of a.c. system generators. Such power control requirements differ from time to time according to the role of HVDC systems in the overall power system.

When an HVDC system is used to transmit power from remote generating stations, the HVDC transmission power control is coordinated with the governor control of the power station generators. In this case, the generator voltage, frequency or the rotor speed may be used as a reference to the HVDC power control system.

When two a.c. power systems are connected by an HVDC link, the HVDC power is controlled to a pre-determined pattern under normal circumstances, but an additional function can be incorporated to this HVDC power control so that the frequency of either or both a.c. power systems is controlled. When one of the a.c. systems is an isolated system, such as one supplying a separate island, frequency control of this isolated a.c. system may have to be realized by the HVDC system.

The a.c. system frequency control by an HVDC system is discussed in 4.3.

When two a.c. systems are interconnected by more than one d.c. link or d.c. and a.c. links, or when a d.c. system exists within an a.c. system, HVDC power may be controlled in order to minimize the total transmission losses of the interconnected systems.

In some cases of a.c./d.c. system configurations described above, the HVDC power change control can be used to prevent overloading of one or more transmission lines in the power system.

In certain special HVDC control schemes, such as the one designed to improve a.c. system performance by increasing the d.c. power during and after a disturbance, the steady-state d.c. transmission power may have to be set at a restricted value so that the d.c. power does not exceed the d.c. rated power, including overload capability, when the control is initiated. It is important to consider also the additional reactive power supply required both by the HVDC converters and the a.c. systems in such a situation.

The following items a) to g) need to be considered in the specification of steady-state control requirements. Note that at the time of preparing the specification, the complete steady-state control requirements may not have been determined or designed, but allowance for possible future inputs is necessary.

a) When a power flow control system is designed to have more than one function, including the a.c. system frequency control, the HVDC control system should be so designed that priorities are set between each control function.

b) Under steady-state conditions, the control for prevention of a.c. line overloading is usually given higher priority over other power flow controls. The control for minimization of power system losses is implemented either by setting the d.c. power to a pattern which has been pre-determined by the power system data, or in response to an on-line computation which is conducted in the central load dispatching office. Usually, its control response is relatively slow, being several seconds or several minutes, even in the latter case.

c) In isolated systems or systems with a relatively large d.c. infeed, frequency is often maintained by the HVDC power. In such a case, HVDC frequency control could have a priority over system loss minimization, but may be limited by overload protection.

d) The change in reactive power demand accompanying the power changes may result in frequent switching of reactive power equipment. In such a case, it is necessary to figure out particular a.c. voltage control measures such as reactive power control by converter units, or to set limits of the magnitude of HVDC power change.

e) The need for special power order adjustment signals unique to the power system should be identified, studied, and specified. The signals cannot be permitted to cause d.c. current or power, or a.c. voltage to deviate beyond equipment and system ratings and limits. The priority of two or more input signals having simultaneous demand on d.c. link power should be established and coordinated.

f) Bipolar d.c. links normally require that d.c. power and current be effectively shared between poles. For loss of one pole, an overload strategy for the remaining pole could be developed to minimize disruption to a.c. system power flow, voltage and frequency.

g) Disruption of the telecommunication link between the sending and receiving system of the d.c. link should not cause disruption to the a.c. power system. A minimum specification requirement is that power transmission is maintained at the same power level which existed before the telecommunication failure. If additional functions such as frequency control are required during temporary outage of the telecommunication link, these should be specified.

4.2.2 Step change power requirement

Under certain power system conditions, it may be required to change the HVDC power in steps in order to improve the performance of a.c. systems during and after power system disturbances. Under certain circumstances, the step change may involve d.c. power reversal.

A step change of d.c. power is realized by changing the set value of d.c. power order or by changing the power range in response to an input signal. The rate of change of power and limit to the magnitude of the d.c. power change demanded by the step change should be adjustable within specified limits according to a.c. system requirements. For example, different ramp rates may be required for different events. Special considerations may be required when the step change would include power reversal.

Power system disturbances to be considered in specifying d.c. power step changes may include: a.c. line trip, loss of large power supply source or large drop in a.c. system frequency and sudden increase or decrease of power system load with its corresponding large frequency deviation.

In some of the above cases of power system disturbances, the a.c. systems will also be supported by the a.c. frequency control provided by the d.c. system.

In specifying and designing HVDC control functions, the effects of the step change power functions should be surveyed in detail for various power system conditions. It is best to specify limits and ranges for power changes and ramp rates rather than specific settings. Setting adjustment can be made with the d.c. system in operation.

The signals for initiation of HVDC step power changes include overload relay signals or trip signals of particular transmission lines which are transmitted to the HVDC substation, or a.c. system frequency which is detected at the HVDC substation or at some point in a.c. systems.

The time delay involved in a telecommunication system which transmits these initiation signals may affect the a.c. or d.c. system performance. Therefore, in some cases, a high speed telecommunication system may be required. When the transmission delay time is large, this effect should be taken into account.

There are some cases in which signals are sent to both HVDC substations, or more than one signal is received by an HVDC substation. In these cases, it is necessary to set priorities of control functions.

The magnitude of d.c. power step change may be limited by a.c. and d.c. system conditions, and it may be required under certain circumstances to detect the changes in system conditions to update the values of such limits.

In particular, when there is a large step change in d.c. power, the a.c. voltage may change substantially. For this reason, it may be required to study the allowable range of a.c. voltage fluctuation to determine the limits on step power changes, or introduce special a.c. voltage control measures.

The allowable limits of a.c. voltage deviation can be different for steady-state operation and transient conditions and should be specified.

When an HVDC system is connected to a high impedance and/or low inertia a.c. system, the step change in d.c. power may have adverse effects on the voltage stability, transient stability, and frequency of the a.c. system. In such cases, the magnitude and rate of change of power may have to be limited, or other special measures may have to be provided, to prevent deterioration of the a.c. system dynamic performance. When an HVDC system interconnects two a.c. systems, the effect of d.c. power step change must be evaluated in detail not only for the a.c. system in which a disturbance occurs, but also for the other a.c. system in which a fault does not occur.

When the d.c. step change of power causes the d.c. current to fall below the minimum allowable operational current of the HVDC system, which is usually 5 % to 10 % of the rated current, the converter operation should be set to the positive minimum current. Otherwise the converter should be blocked after the allowable period of low current operation, or be specified to operate down to zero current. One possible measure to overcome minimum allowable operational current is to set the power flows of two poles in opposite direction and let the power flow of two poles cancel each other when the HVDC system configuration is bipolar. The difference in the power flows of each pole is the actual operating power flow of the overall HVDC system.

Because of inverter control limitations and possible risks to a.c. system operation, it is not advisable to request a current order step change larger than the current margin unless special control actions are taken upon loss of telecommunications.

Certain considerations may be required when an HVDC system is to be started up from a no load stand-by state in response to a step change power order (see Clause 7 of IEC 60919-1).

4.3 Frequency control

The a.c. system frequency control by the HVDC system can be applied for the following purposes:

a) frequency control of the receiving and/or sending end a.c. system for a d.c. transmission from remote power sources;
b) frequency control of an a.c. system in an isolated island or a small a.c. system when it is interconnected to a large a.c. system through a d.c. system;
c) frequency control of either of the a.c. systems interconnected by an HVDC system, also taking the frequency of the other system into account.

The a.c. system frequency control is executed either as a continuous function of frequency under steady-state conditions, or when the frequency deviation of the a.c. system exceeds certain limits. It may only be activated under certain circumstances such as when the local a.c. system connected to the HVDC substation is disconnected (islanded) from the main a.c. system. Accordingly, the specification should state the duties and performance requirements of the frequency control function.

If the frequency at the receiving end is controlled by varying or modulating the power transmitted by the d.c. link, there must be coordination of the d.c. link frequency control with any governor control on associated a.c. generators. It may be possible to use transient frequency deviation capability of an asynchronous sending end system for support of the receiving end, provided the a.c. generating equipment is designed accordingly.

When an HVDC substation is electrically far from the centre of the a.c. system, the phase angle of a.c. voltage at the HVDC substation changes substantially with power changes. In such circumstances, the speed of response of the frequency signal can be reduced. To avoid this lower speed of response, the frequency signal can be detected at the centre of the a.c. system and transmitted to the HVDC substation.

In frequency control it may be required to provide limits of power change and rate of power change which maintains the a.c. system voltage fluctuation within an allowable range, or utilize special voltage regulation measures such as reactive power control by converters or SVC. The allowable limits of voltage fluctuation during steady state frequency control should be specified.

When the d.c. contribution to a.c. system frequency control is implemented, it is possible that generator frequency control is degraded unless the controls are properly coordinated. When two different power systems are interconnected, it may be required to provide appropriate dead band or to select suitable gain in the frequency control by the HVDC system so that only large or fast frequency fluctuations are compensated by the d.c. power control, and small or slow frequency fluctuations are controlled by the power stations belonging to the individual a.c. systems.

The frequency control designed to correct for severe disturbances, such as those caused by the tripping of large generation units, may be realized more effectively if the generator unit trip signal is transmitted to the HVDC substation to initiate the control action.

Fast and large magnitude of d.c. power change for frequency control may produce overvoltage or voltage dip in the a.c. systems. Such a situation may be relieved by limiting the rate of power change or by fast reactive power compensations. The allowable overvoltage or voltage dip, and the allowable duration time should be specified.

One possible measure for continuous and smooth operation of frequency control is to set the power flows of two poles in opposite direction and let the power flow of two poles cancel each other when the HVDC system configuration is bipolar. This special operation mode is called "Frequency control with zero power setting." However, note that there is additional system loss and accompanying polarity reversals, which happen when crossing the border of minimum current.

It is sometimes difficult to set optimal parameters of frequency control since the power system configuration often changes due to outages of transmission lines and/or substations for maintenance. This could be accounted for by adopting multi variable frequency control.

When d.c. power control is performed for the purpose of frequency control, it is usually necessary to provide high speed telecommunication channels, such as a microwave channels or fiber optic channels, between two HVDC substations. In case of loss of telecommunication between the two substations, frequency control is usually limited to the network connected to the current controlling substation.

When the frequency detection point is located far from the HVDC substation control terminal, or when it is intended to initiate the frequency control action by special signals issued from the a.c. system, telecommunication channels are required.

In any case, the effect of telecommunication time delay should be taken into account.

For a discussion of telecommunication channels, refer to Clause 13 of IEC 60919-1.

5 AC dynamic voltage control and interaction with reactive power sources

5.1 General

Change in reactive power flow due to load change, switching operations or faults produce voltage fluctuations in the a.c. network. In high impedance a.c. systems, i.e. in systems with low short-circuit capacity, larger voltage fluctuation can be expected and the need for voltage control is more pronounced.

Sudden voltage changes in the network should be limited e.g. to less than 3 % if occurring frequently and to less than 10 % if happening seldom. Appropriate values should be specified.

High temporary overvoltages in excess of the normal operating range due to large load changes and load rejection in networks with low short-circuit capacity could risk endangering station equipment. High temporary overvoltages can be limited by tripping of reactive power sources. The acceptable limit and duration for temporary overvoltages should be specified.

5.2 Voltage and reactive power characteristics of an HVDC substation and other reactive power sources

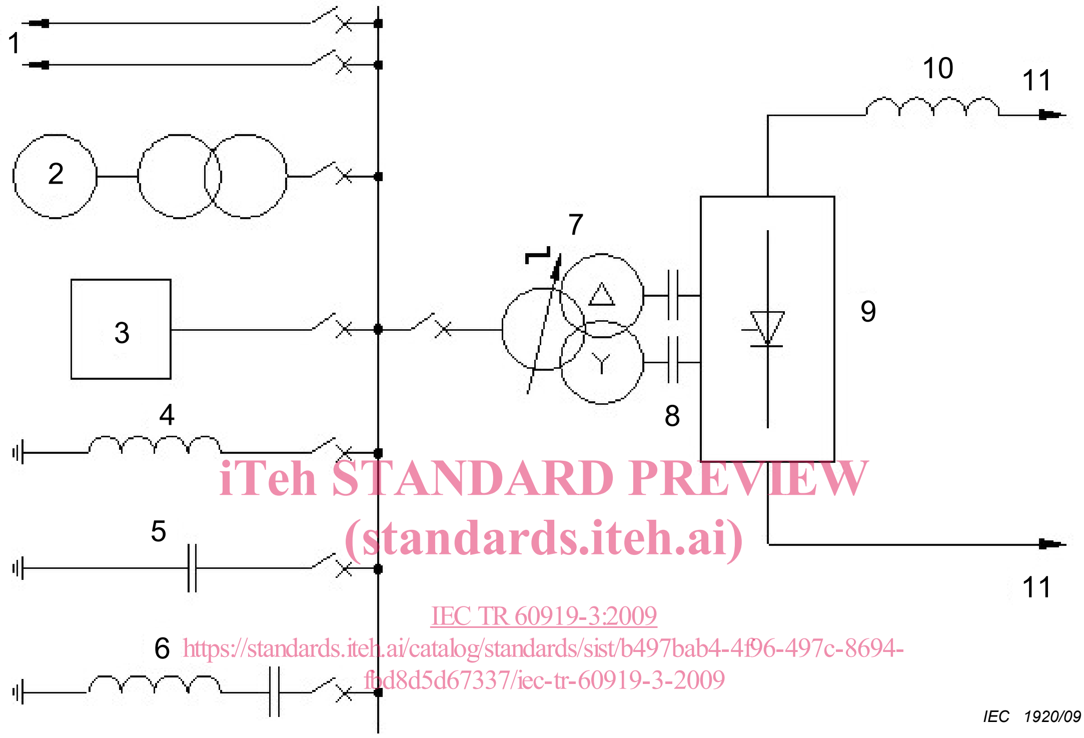
5.2.1 General

Dynamic reactive power and voltage control on the a.c. bus of an HVDC substation can be obtained by using different equipment. Figure 1 shows schematically an HVDC substation with elements for reactive power compensation. Which of the depicted elements is used depends on the a.c. network characteristics and requirements on the data of the HVDC substation concerned, as well as on the economic evaluation of the different possible solutions.

5.2.2 Converter as active/reactive power source

The active/reactive power of an HVDC converter depends on the following factors:

– commutation impedance (including commutation capacitance, if applicable);
– commutation voltage;
– delay angle α at the rectifier or extinction angle γ at the inverter;
– d.c. current.



Key

1 a.c. network
2 synchronous compensator
3 static var compensator
4 a.c. reactor
5 capacitor
6 a.c. filter
7 converter transformer
8 commutation capacitors
9 converter
10 d.c. reactor
11 d.c. terminal

Figure 1 – Elements for reactive power compensation at an HVDC substation

Converter operating time constants are the composite of control system, measurement systems, and d.c. transmission line constants. With typical control systems, time constants are in the range of a few milliseconds, and this provides the control of delay angle or extinction angle in the range of less than 20 ms. The response time of the total d.c. system is normally in the range of 50 ms to 150 ms.

The tap changer control can be active in addition to the converter firing control. However, each tap changer step has a time delay of a few seconds. Therefore, this control is not used for fast active/reactive power control, but only for adjustments to the optimum operation conditions at the new operating point.