

This is a preview - click here to buy the full publication



IEC TR 60919-3

Edition 2.1 2016-03  
CONSOLIDATED VERSION

# TECHNICAL REPORT



---

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

INTERNATIONAL  
ELECTROTECHNICAL  
COMMISSION

---

ICS 29.200; 29.240.99

ISBN 978-2-8322-3241-5

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

## REDLINE VERSION



---

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



## CONTENTS

FOREWORD.....	5
1 Scope .....	7
2 Normative references .....	7
3 Outline of HVDC dynamic performance specifications.....	8
3.1 Dynamic performance specification .....	8
3.2 General comments .....	9
4 AC system power flow and frequency control .....	9
4.1 General.....	9
4.2 Power flow control .....	9
4.2.1 Steady-state power control requirements .....	9
4.2.2 Step change power requirement .....	10
4.3 Frequency control.....	12
5 AC dynamic voltage control and interaction with reactive power sources.....	13
5.1 General.....	13
5.2 Voltage and reactive power characteristics of an HVDC substation and other reactive power sources .....	13
5.2.1 General .....	13
5.2.2 Converter as active/reactive power source.....	14
5.2.3 Voltage characteristics of a.c. networks depending on the power loading at the busbar of the HVDC substation.....	16
5.2.4 Voltage characteristics of a.c. filters, capacitor banks and shunt reactors for power compensation at the HVDC substation .....	18
5.2.5 Voltage characteristics of static var compensator (SVC) .....	18
5.2.6 Voltage characteristics of synchronous compensator (SC) .....	19
5.2.7 Voltage characteristics of static synchronous compensator (STATCOM).....	19
5.3 Voltage deviations on the busbar of an HVDC substation.....	19
5.4 Voltage and reactive power interaction of the substation and other reactive power sources .....	20
5.4.1 HVDC converters, switchable a.c. filters, capacitor banks and shunt reactors .....	20
5.4.2 HVDC converters, switchable reactive power sources, SVC .....	21
5.4.3 HVDC converters, switchable reactive power sources and synchronous compensators .....	21
5.4.4 HVDC converters, switchable reactive power sources, STATCOM.....	22
6 AC system transient and steady-state stability.....	23
6.1 General.....	23
6.2 Characteristics of active and reactive power modulation .....	23
6.2.1 General .....	23
6.2.2 Large signal modulation .....	24
6.2.3 Small signal modulation .....	25
6.2.4 Reactive power modulation .....	25
6.3 Classification of network situations .....	26
6.4 AC network in parallel with the HVDC link .....	26
6.5 Improvement of the stability within one of the connected a.c. networks .....	30
6.6 Determination of the damping control characteristics .....	30

6.7	Implementation of the damping controller and telecommunication requirements .....	31
7	Dynamics of the HVDC system at higher frequencies .....	31
7.1	General .....	31
7.2	Types of instability .....	32
7.2.1	Loop instability (harmonic instability) .....	32
7.2.2	Current loop instability .....	32
7.2.3	Core saturation instability .....	32
7.2.4	Harmonic interactions .....	32
7.3	Information required for design purposes .....	33
7.4	Means available for preventing instabilities .....	34
7.5	Damping of low order harmonics by control action .....	34
7.6	Demonstration of satisfactory performance at higher frequencies .....	34
8	Subsynchronous oscillations .....	35
8.1	General .....	35
8.2	Criteria for subsynchronous torsional interaction with an HVDC system .....	36
8.3	Screening criteria for identifying generator units susceptible to torsional interactions .....	37
8.4	Performance considerations for utilizing subsynchronous damping <del>controls</del> <b>controllers (SSDCs)</b> .....	38
8.5	Performance testing .....	38
8.6	Turbine generator protection .....	38
9	Power plant interaction .....	39
9.1	General .....	39
9.2	Specific interactions .....	39
9.2.1	General .....	39
9.2.2	Frequency variation effects .....	39
9.2.3	Frequency controls interactions .....	40
9.2.4	Overvoltage effects .....	40
9.2.5	Harmonics .....	40
9.2.6	Subsynchronous and shaft impact effects .....	40
9.2.7	Resonance .....	41
9.2.8	Overvoltages .....	41
9.2.9	Stresses in a.c. switching equipment .....	41
9.2.10	Under-frequency .....	41
9.2.11	Starting procedure for an HVDC converter .....	41
9.3	Special considerations for a nuclear plant .....	41
	Bibliography .....	42
	Figure 1 – Elements for reactive power compensation at an HVDC substation .....	14
	Figure 2 – <i>P/Q</i> diagram of a converter .....	15
	Figure 3 – Reactive power requirements of a weak a.c. system depending on the active power loading for various constant voltage characteristics at the a.c. bus of an HVDC substation .....	17
	Figure 4 – Representation of the a.c. network .....	17
	Figure 5 – Example of voltage – current characteristic showing possible current modulation range in the absence of telecommunication between rectifier and inverter .....	25
	Figure 6 – Reactive power modulation in an HVDC transmission operating at minimum extinction angle $\gamma_{\min}$ .....	27

Figure 7 – Reactive power modulation in an HVDC transmission operating at extinction angle $\gamma > \gamma_{\min}$ .....	28
Figure 8 – Stability improvement of an a.c. link or network.....	29
Figure 9 – Principle arrangements of a damping controller.....	29

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

**Part 3: Dynamic conditions**

FOREWORD

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

**This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.**

**IEC TR 60919-3 edition 2.1 contains the second edition (2009-10) [documents 22F/183/DTR and 22F/192/RVC] and its amendment 1 (2016-03) [documents 22F/376/DTR and 22F/382A/RVC].**

**In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.**

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 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 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.

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 the base publication and its amendment will remain unchanged until the stability 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.

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

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

## 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 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 TR 60919-1:~~2005~~ 2010, *Performance of high-voltage direct current (HVDC) systems with line-commutated converters – Part 1: Steady-state conditions*

[IEC TR 60919-1:2010/AMD1:2013](#)

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

[IEC TR 60919-2:2008/AMD1:2015](#)

## FINAL VERSION

---

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



## CONTENTS

FOREWORD.....	5
1 Scope .....	7
2 Normative references .....	7
3 Outline of HVDC dynamic performance specifications.....	8
3.1 Dynamic performance specification .....	8
3.2 General comments .....	9
4 AC system power flow and frequency control .....	9
4.1 General.....	9
4.2 Power flow control .....	9
4.2.1 Steady-state power control requirements .....	9
4.2.2 Step change power requirement .....	10
4.3 Frequency control.....	12
5 AC dynamic voltage control and interaction with reactive power sources.....	13
5.1 General.....	13
5.2 Voltage and reactive power characteristics of an HVDC substation and other reactive power sources .....	13
5.2.1 General .....	13
5.2.2 Converter as active/reactive power source.....	14
5.2.3 Voltage characteristics of a.c. networks depending on the power loading at the busbar of the HVDC substation.....	16
5.2.4 Voltage characteristics of a.c. filters, capacitor banks and shunt reactors for power compensation at the HVDC substation .....	18
5.2.5 Voltage characteristics of static var compensator (SVC) .....	18
5.2.6 Voltage characteristics of synchronous compensator (SC) .....	18
5.2.7 Voltage characteristics of static synchronous compensator (STATCOM).....	19
5.3 Voltage deviations on the busbar of an HVDC substation.....	19
5.4 Voltage and reactive power interaction of the substation and other reactive power sources .....	20
5.4.1 HVDC converters, switchable a.c. filters, capacitor banks and shunt reactors .....	20
5.4.2 HVDC converters, switchable reactive power sources, SVC .....	21
5.4.3 HVDC converters, switchable reactive power sources and synchronous compensators .....	21
5.4.4 HVDC converters, switchable reactive power sources, STATCOM.....	22
6 AC system transient and steady-state stability.....	22
6.1 General.....	22
6.2 Characteristics of active and reactive power modulation .....	23
6.2.1 General .....	23
6.2.2 Large signal modulation .....	23
6.2.3 Small signal modulation .....	25
6.2.4 Reactive power modulation .....	25
6.3 Classification of network situations .....	26
6.4 AC network in parallel with the HVDC link .....	26
6.5 Improvement of the stability within one of the connected a.c. networks .....	30
6.6 Determination of the damping control characteristics .....	30

6.7	Implementation of the damping controller and telecommunication requirements .....	31
7	Dynamics of the HVDC system at higher frequencies .....	31
7.1	General .....	31
7.2	Types of instability .....	32
7.2.1	Loop instability (harmonic instability) .....	32
7.2.2	Current loop instability .....	32
7.2.3	Core saturation instability .....	32
7.2.4	Harmonic interactions .....	32
7.3	Information required for design purposes .....	33
7.4	Means available for preventing instabilities .....	34
7.5	Damping of low order harmonics by control action .....	34
7.6	Demonstration of satisfactory performance at higher frequencies .....	34
8	Subsynchronous oscillations .....	35
8.1	General .....	35
8.2	Criteria for subsynchronous torsional interaction with an HVDC system .....	36
8.3	Screening criteria for identifying generator units susceptible to torsional interactions .....	37
8.4	Performance considerations for utilizing subsynchronous damping controllers (SSDCs) .....	38
8.5	Performance testing .....	38
8.6	Turbine generator protection .....	38
9	Power plant interaction .....	39
9.1	General .....	39
9.2	Specific interactions .....	39
9.2.1	General .....	39
9.2.2	Frequency variation effects .....	39
9.2.3	Frequency controls interactions .....	39
9.2.4	Overvoltage effects .....	40
9.2.5	Harmonics .....	40
9.2.6	Subsynchronous and shaft impact effects .....	40
9.2.7	Resonance .....	41
9.2.8	Overvoltages .....	41
9.2.9	Stresses in a.c. switching equipment .....	41
9.2.10	Under-frequency .....	41
9.2.11	Starting procedure for an HVDC converter .....	41
9.3	Special considerations for a nuclear plant .....	41
	Bibliography .....	42
	Figure 1 – Elements for reactive power compensation at an HVDC substation .....	14
	Figure 2 – $P/Q$ diagram of a converter .....	15
	Figure 3 – Reactive power requirements of a weak a.c. system depending on the active power loading for various constant voltage characteristics at the a.c. bus of an HVDC substation .....	17
	Figure 4 – Representation of the a.c. network .....	17
	Figure 5 – Example of voltage – current characteristic showing possible current modulation range in the absence of telecommunication between rectifier and inverter .....	25
	Figure 6 – Reactive power modulation in an HVDC transmission operating at minimum extinction angle $\gamma_{\min}$ .....	27

Figure 7 – Reactive power modulation in an HVDC transmission operating at extinction angle $\gamma > \gamma_{\min}$ .....	28
Figure 8 – Stability improvement of an a.c. link or network.....	29
Figure 9 – Principle arrangements of a damping controller.....	29

INTERNATIONAL ELECTROTECHNICAL COMMISSION

---

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

**Part 3: Dynamic conditions**

FOREWORD

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

**This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.**

**IEC TR 60919-3 edition 2.1 contains the second edition (2009-10) [documents 22F/183/DTR and 22F/192/RVC] and its amendment 1 (2016-03) [documents 22F/376/DTR and 22F/382A/RVC].**

**This Final version does not show where the technical content is modified by amendment 1. A separate Redline version with all changes highlighted is available in this publication.**

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 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 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.

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 the base publication and its amendment will remain unchanged until the stability 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.

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

## 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 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 TR 60919-1:2010, *Performance of high-voltage direct current (HVDC) systems with line-commutated converters – Part 1: Steady-state conditions*  
IEC TR 60919-1:2010/AMD1:2013

IEC TR 60919-2:2008, *Performance of high-voltage direct current (HVDC) systems with line-commutated converters – Part 2: Faults and switching*  
IEC TR 60919-2:2008/AMD1:2015