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High-voltage direct current (HVDC) systems – Application of active filters

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High-voltage direct current (HVDC) systems – Application of active filters

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HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS – APPLICATION OF ACTIVE FILTERS

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This Technical Report cancels and replaces IEC/PAS 62544 published in 2011. This first edition constitutes a technical revision.

IEC/TR 62544, 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 electronics.

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

Enquiry draft	Report on voting
22F/242/DTR	22F/250/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.

The committee has decided that the contents of this publication 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- withdrawn,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.

HIGH-VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS – APPLICATION OF ACTIVE FILTERS

1 Scope

This technical report gives general guidance on the subject of active filters for use in high-voltage direct current (HVDC) power transmission. It describes systems where active devices are used primarily to achieve a reduction in harmonics in the d.c. or a.c. systems. This excludes the use of automatically retuned components.

The various types of circuit that can be used for active filters are described in the report, along with their principal operational characteristics and typical applications. The overall aim is to provide guidance for purchasers to assist with the task of specifying active filters as part of HVDC converters.

Passive filters are specifically excluded from this report.

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/TS 60071-5, *Insulation co-ordination – Part 5: Procedures for high-voltage direct current (HVDC) converter stations*

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

IEC 61000 (all parts), *Electromagnetic compatibility (EMC)*

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

IEC/TR 62001:2009, *High-voltage direct current (HVDC) systems – Guidebook to the specification and design evaluation of A.C. filters*

IEC/TR 62543, *High-voltage direct current (HVDC) power transmission using voltage sourced converters (VSC)*

IEEE 519, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*

3 Terms and definitions

For the purposes of this technical report, the terms and definitions given in IEC 60633 and IEC 62001:2009 for passive a.c. filters, as well as the following apply.

NOTE Only terms which are specific to active filters for HVDC are defined in this clause. Those terms that are either identical to or obvious extensions of IEC 60633 or IEC 62001:2009 terminology have not been defined.

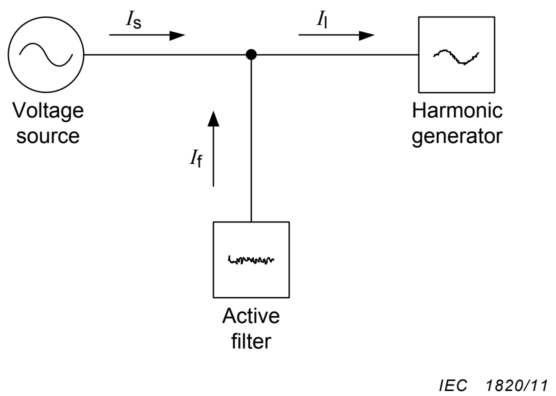


Figure 1 – Shunt connection

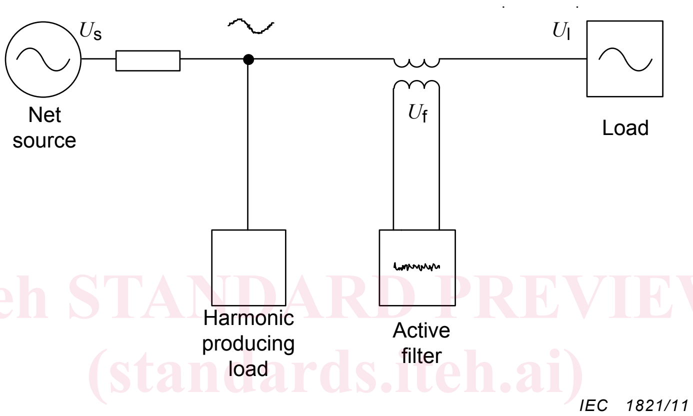


Figure 2 – Series connection

3.1 Active and passive filters

3.1.1
active filter
a filter whose response to harmonics is either wholly or partially governed by a controlled converter

3.1.2
passive filter
a filter whose response to harmonics is governed by the impedance of its components

3.2 Active filter topologies

3.2.1
shunt active filter
an active filter connected high-voltage (HV) to low-voltage (LV) or HV to ground such that it experiences the full a.c. or d.c. voltage of the HVDC system or its a.c. connection (see Figure 1)

3.2.2
series active filter
an active filter connected between the HVDC converter and the a.c. or d.c. supplies such that it must withstand the full HVDC system current, either a.c. or d.c. (see Figure 2)

3.2.3
shunt and series active filter
an active filter containing both series and shunt elements as defined above

3.3 Power semiconductor terms

NOTE There are several types of power semiconductor devices which can be used in active filters for HVDC and currently the IGBT is the major device used in such converters. The term IGBT is used throughout this report to refer to the switched valve device. However, the report is equally applicable to other types of devices with turn-off capability in most of the parts.

3.3.1
insulated gate bipolar transistor
IGBT
a controllable switch with the capability to turn-on and turn-off a load current

NOTE 1 An IGBT has three terminals: a gate terminal (G) and two load terminals - emitter (E) and collector (C).

NOTE 2 By applying appropriate gate to emitter voltages, current in one direction can be controlled, i.e. turned on and turned off.

3.3.2
free-wheeling diode
FWD
power semiconductor device with diode characteristic.

NOTE 1 A FWD has two terminals: an anode (A) and a cathode (K). The current through the FWDs is in opposite direction to the IGBT current.

NOTE 2 FWDs are characterized by the capability to cope with high rates of decrease of current caused by the switching behaviour of the IGBT.

3.3.3
IGBT-diode pair
arrangement of IGBT and FWD connected in inverse parallel

3.4 Converter topologies

3.4.1
pulse width modulation
PWM
a converter operation technique using high frequency switching with modulation to produce a particular waveform when smoothed

3.4.2
two-level converter
a converter in which the voltage at the a.c. terminals of the VSC unit is switched between two discrete d.c. voltage levels

3.4.3
three-level converter
a converter in which the voltage at the a.c. terminals of the VSC unit is switched between three discrete d.c. voltage levels

3.4.4
multi-level converter
a converter in which the voltage at the a.c. terminals of the VSC unit is switched between more than three discrete d.c. voltage level.

4 Active filters in HVDC applications

4.1 General

The conversion process in an HVDC transmission system introduces harmonic currents into the d.c. transmission lines and the a.c. grid connected to the HVDC converters. These harmonic currents may cause interference in the adjacent systems, like telecommunication equipment. The conventional solution to reduce the harmonics has been to install passive filters in HVDC converter stations [1][1]. When the power line consists of cables, this filtering is normally not necessary. The development of power electronics devices and digital computers has made it possible to achieve a new powerful way for a further reduction of harmonic levels, namely, active filters.

The active filters can be divided into two groups, active a.c. and d.c. filters. Active d.c. filter installations are in operation in several HVDC links and have been economically competitive due to more onerous requirements for telephone interference levels on the d.c. overhead lines (Figure 3). An active a.c. filter is already in operation as well. In addition to the active d.c. filter function of mitigating the harmonic currents on the d.c. overhead lines, the active a.c. filters may be part of several solutions in the HVDC scheme to improve reactive power exchange with the a.c. grid and to improve dynamic stability.

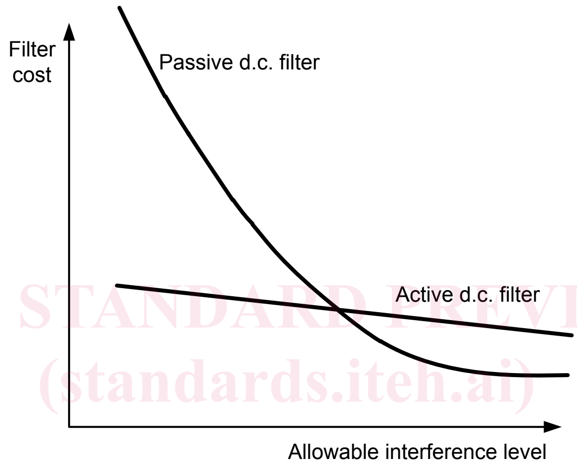


Figure 3 – Conceptual diagram of allowable interference level and d.c. filter cost

The features of active filters are the following:

- Active a.c. and d.c. filters consist of two parts, a passive part and a corresponding active part which are loaded with the same currents. Due to the fact that the passive a.c. filter is used to supply the HVDC converter demand of reactive power and thereby loaded with the fundamental current, the required rating of the d.c. filter active part is lower than the one of the a.c. filter active part.
- The control philosophy for the active d.c. filter is less complex than for the a.c. one.
- The present HVDC applications where active a.c. filters are feasible will be limited, due to the fact that a.c. filters are also required to supply the HVDC converter demand of reactive power. The filter size is therefore often well above the filtering demand.

Many recent and future HVDC projects use new converter technologies which allow the reactive compensation to be separated from the a.c. filters and thereby make the active a.c. filter more feasible. For line-commutated converters, capacitor commutated converters (CCC) and the controlled series capacitor converter (CSCC) allow reduced reactive power absorption. Moreover, self-commutated converters (which include most voltage sourced converters) are able to control active and reactive power independently, avoiding the need for separate reactive power compensation altogether.

1 Figures in square brackets refer to the Bibliography.

4.2 Semiconductor devices available for active filters

Three types of power semiconductor devices, suitable for use in an active filter, are available at present:

- metal-oxide-semiconductor field-effect transistor (MOSFET);
- insulated gate bipolar transistor (IGBT);
- gate turn-off thyristor (GTO) and other thyristor-derived devices such as the gate commutated thyristor (GCT) and integrated gate commutated thyristor (IGCT).

The MOSFET is an excellent switching device capable of switching at very high frequencies with relatively low losses, but with limited power handling capability.

The IGBT has a switching frequency capability which, although very good and sufficient to handle the frequencies within the active d.c. filter range, is inferior to the MOSFET. However the IGBT power handling is significantly higher than the MOSFET.

The GTO-type devices has the highest power handling capacity, but with a relatively limited switching speed far below the required frequency range for active d.c. filter. The use of GTO-type devices will probably be limited to handle frequencies below a few hundred of hertz.

The relatively high frequency band for active d.c. filtering excludes the use of thyristors and GTO. Even though the MOSFET and IGBT are suited as switching elements in a power stage, the limited power handling capacity on MOSFET and the installed cost evaluations tend to point on the use of IGBT in future power stages.

5 Active d.c. filters

5.1 Harmonic disturbances on the d.c. side

The main reason for specifying demands on the d.c. circuit is to keep disturbances in nearby telephone lines within an acceptable limit, which will vary depending on whether the telephone system consists of overhead lines or underground cables which are generally shielded and therefore have a better immunity [2]. A summary is given below to illustrate the demands which made it feasible to install the active filters. As described, the demand on disturbances can appear as an harmonic current on the d.c. line or as an induced voltage U_{ind} in a fictive telephone line. It should be kept in mind that the harmonic demand, the specific HVDC system and surroundings (earth resistivity, telephone system, etc.) all together define the d.c. filter solution.

The specified requirements:

- The induced voltage U_{ind} in a theoretically 1 km telephone line situated 1 km from the d.c. overhead line shall be below 10 mV for monopolar operation.
- A one minute mean value of the equivalent psophometric current I_{pe} fed into the d.c. pole overhead line shall be below 400 mA.

The mentioned induced voltage and the equivalent psophometric current are defined as:

$$U_{ind} = \sqrt{\sum_{n=1}^{50} (2\pi \cdot f_n \cdot M \cdot I_n \cdot p_n)^2} \tag{1}$$

$$I_{pe} = \frac{1}{p_{16}} \sqrt{\sum_{n=1}^{50} (k_n \cdot p_n \cdot I_n)} \tag{2}$$

where

f_n is the frequency of the n^{th} harmonic,

M is the mutual inductance between the telephone line and the power line,

k_n $= f_1 \times n/800$,

I_n is the vectorial sum of the n^{th} harmonic current flowing in the line conductors (common mode/earth mode current),

p_n is the n^{th} psophometric weighting factor defined by CCITT Directives 1963 [3] (see also Table 1),

p_{16} is the 16^{th} psophometric weighting factor.

The characteristic harmonics n = 12, 24, 36, 48 as well as the non-characteristic harmonics up to n = 50 shall be considered.

Table 1 – The psophometric weighting factor at selected frequencies

Frequency, Hz	50	100	300	600	800	1 000	1 200	1 800	2 400	3 000
n	1	2	6	12	16	20	24	36	48	60
p_n factor	0,0007	0,009	0,295	0,794	1,0	1,122	1,0	0,76	0,634	0,525
$P_n \times k_n$	0,00004	0,001	0,111	0,595	1,0	1,403	1,5	1,71	1,902	1,969

5.2 Description of active d.c. filters

5.2.1 General

Active d.c. filters use a controllable converter to introduce currents in the network, presenting a waveform which counteracts the harmonics. This subclause describes types of power stages, converters to be used in active filters and the possible connections in HVDC schemes.

5.2.2 Types of converters available

5.2.2.1 General

Two basic types of switching converters are possible in an active d.c. filter; the current-source converter using inductive energy storage and the voltage-sourced converter (VSC) using capacitive energy storage.

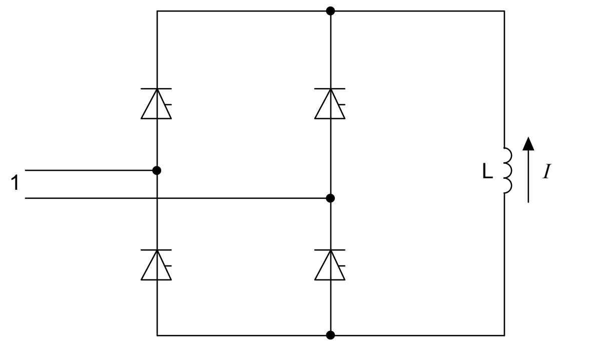
5.2.2.2 Current source converters

In a current-source converter, the d.c. element is a current source, which normally consists of a d.c. voltage source power supply in series with an inductor. For correct operation, the current should flow continuously in the inductor. Hence if a.c. current is not required current must be by-passed within the converter. This fact restricts the switching actions. A simple current-source converter is shown in Figure 4.

5.2.2.3 Voltage sourced converters (VSC)

In the VSC, the d.c. element is a voltage source. This may be a d.c. power supply or, in the case of an active d.c. filter application, an energy storage unit. In practice, the voltage source for an active d.c. filter power stage is usually a capacitor with a small power supply to offset the power stage losses. A VSC also has the property that its a.c. output appears as a voltage source.

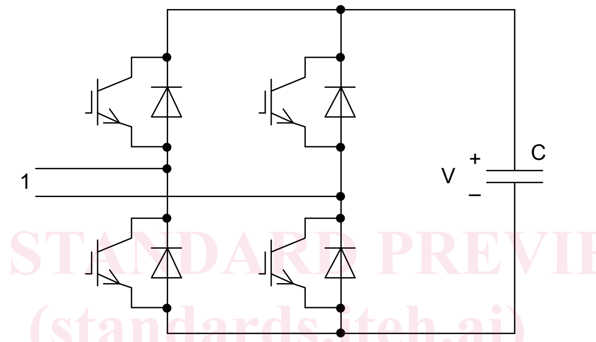
A circuit of simple VSC is shown in Figure 5.



Key

1 AC current

Figure 4 – Simple current source converter



Key

1 AC voltage

Figure 5 – Simple voltage sourced converter

5.2.2.4 Comparison between current and voltage sourced converters

The current-source converter has a high internal impedance for currents through the converter, while the VSC has a low impedance. The VSC has no constraints on the switching pattern which can be employed, while the current-source converter is restricted as described above. The necessity for continuous current in the current-source converter, combined with the fact that (neglecting superconductivity) an inductor has higher losses than a capacitor, ensures that the losses in the current-source converter are higher than in the VSC. Another parameter influencing losses is that a current-source converter needs switching devices which can block reverse voltage. Most of the available semiconductors do not fulfil this requirement. In this case an extra diode in series with each device is necessary and this again increases the losses. Some GTOs are able to support reverse voltage, but these are less common than the GTOs which do not support reverse voltage. The former have higher losses than the more common devices.

Conclusion: Considering the above properties of current-source converter and VSC, the type most suited for power stage applications, particularly high power, is the VSC. The VSC has been preferred in all HVDC projects applicable today.

5.2.3 Connections of the active d.c. filter

5.2.3.1 General

Advantages and disadvantage of connecting the active filters at locations shown in Figure 6 have been discussed in several papers [4], [5], [6]. The active filters can either be connected as shunt active filters or as series active filters.