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

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National foreword

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

FOREWORD

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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- withdrawn,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.

A1⟩ 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, IEC 62001 and IEC 62747 terminology have not been defined. ⟨A1

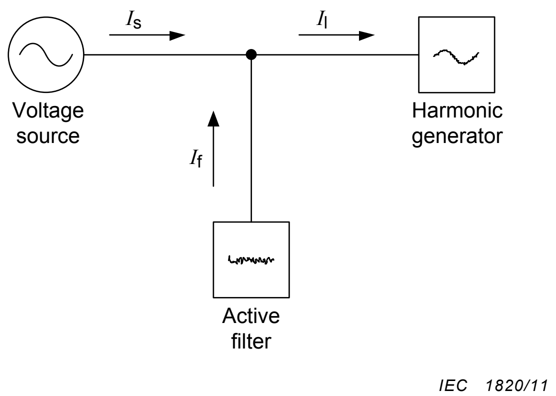

Figure 1 – Shunt connection

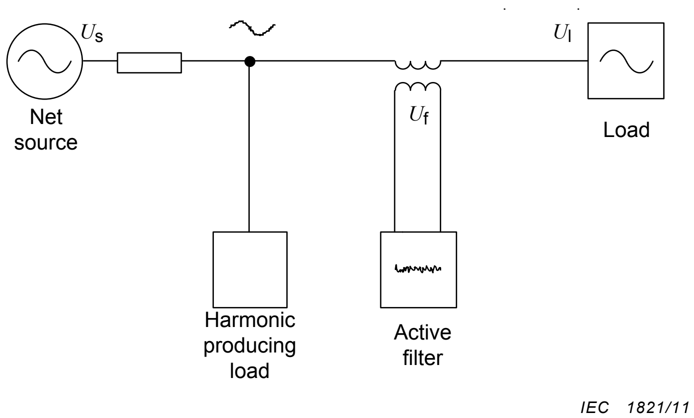

Figure 2 – Series connection

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

A1⟩ *Text deleted* ⟨A1

3.3.1
insulated gate bipolar transistor
IGBT
A1⟩ turn-off semiconductor device with a gate terminal (G) and two load terminals emitter (E) and collector (C) ⟨A1

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

A1⟩ **3.3.4**
turn-off semiconductor device
controllable semiconductor device which may be turned on and off by a control signal

EXAMPLE Insulated gate bipolar transistor (IGBT).

NOTE There are several types of turn-off semiconductor devices which can be used in active filters for HVDC. Currently, the IGBT is the major device used in such converters. The term IGBT is used throughout this Technical Report to refer to the turn-off semiconductor device. However, this Technical Report is equally applicable to other types of devices with turn-off capability in most of the parts. ⟨A1

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
A1⟩ converter in which the voltage between the a.c. terminals of the voltage sourced converter (VSC) unit and the VSC unit midpoint is switched between two discrete d.c. levels ⟨A1

3.4.3
three-level converter
A1⟩ converter in which the voltage between the a.c. terminals of the voltage sourced converter (VSC) unit and the VSC unit midpoint is switched between three discrete d.c. levels ⟨A1

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.

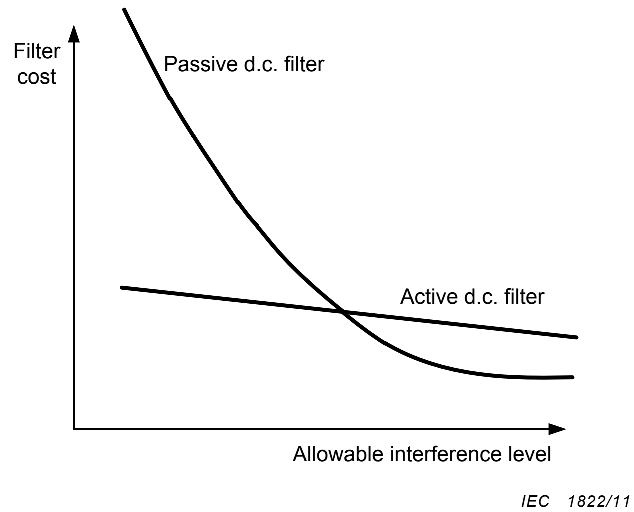

Figure 3 – Conceptual diagram of allowable interference level and d.c. filter cost

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.

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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:

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

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

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 16th 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

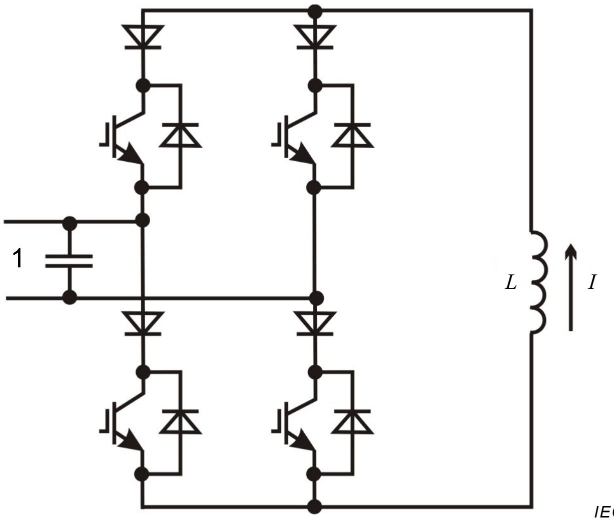
In a current-source converter, the d.c. element is a current source, which normally consists of a d.c. voltage source power supply in series with an inductor. For correct operation, the current should flow continuously in the inductor. Hence if a.c. current is not required current must be by-passed within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

A1

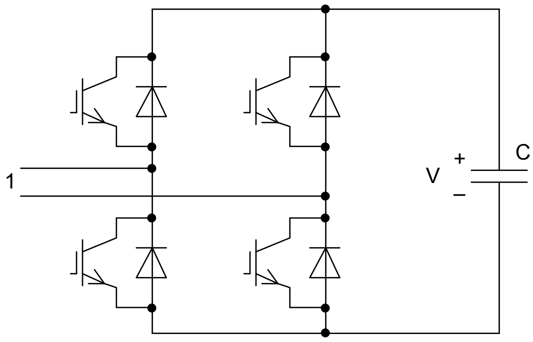


A1

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.

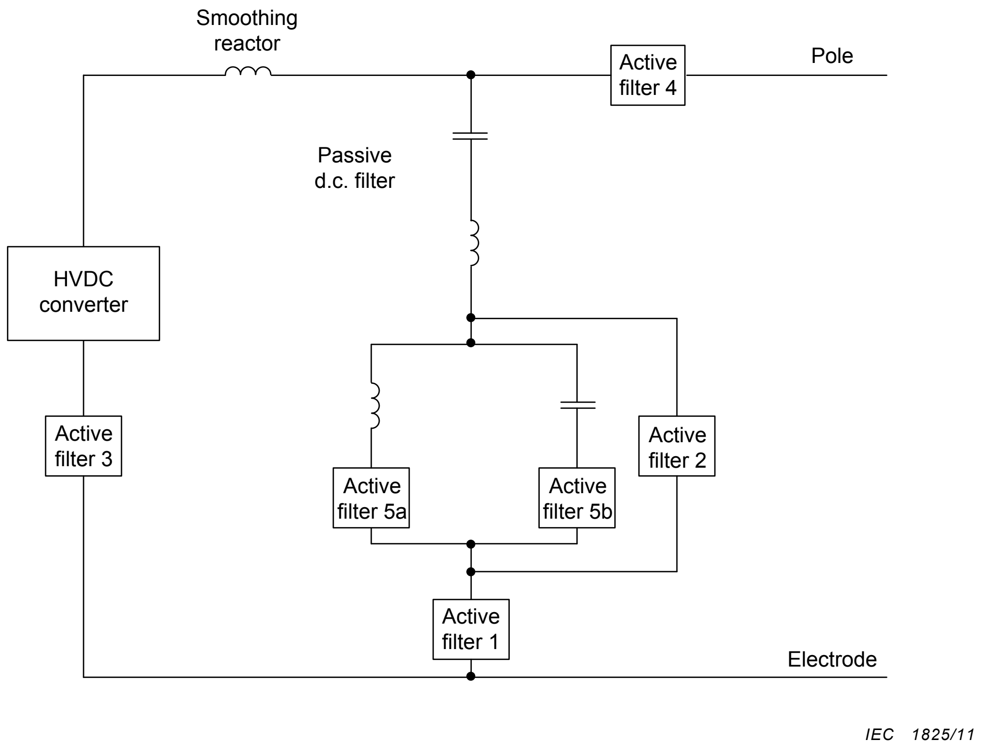


Figure 6 – Possible connections of active d.c. filters

5.2.3.2 "Active filter 1" connection

The active d.c. filter realised in HVDC schemes today is connected as the shunt “Active filter 1” in Figure 6. By connecting the active filter in series with the passive d.c. filter, usually a 12/24th double tuned filter, the active filter rating can be reduced. A VSC is chosen in order to make the smallest influence on the original function of the passive filter, especially on frequencies where the control algorithm is not active.

5.2.3.3 "Active filter 2" connection

The “Active filter 2” in Figure 6 is similar to the shunt “Active filter 1” solution. The power consumption of the tuning circuit in the passive filter will probably reduce the efficiency to inject harmonic currents to counteract the disturbance current and thereby increase the rating of the converter. There may be additional inductance inserted in series with the active part.

5.2.3.4 "Active filter 3" connection

The “Active filter 3” in Figure 6 is a series active filter described in [11], but there is a lack of knowledge of such a system. The active filter converter must be connected to the HVDC system by a coupling transformer T_c. To prevent saturation of the coupling transformer T_c by the direct load current of the HVDC converter I_{dconv}, the core must have an air gap.

In this way, the coupling transformer T_c is a d.c. reactor with a galvanic insulated auxiliary winding to connect the active filter (converter). To achieve no ripple voltage at the point of connection of the passive d.c. filter and therefore no ripple current in the d.c. pole line, the active filter must generate across the main winding T_c a voltage which compensate the ripple voltage U_r of the d.c. side of the HVDC converter.

The a.c. load current I_r of the main winding of T_c is determined by U_r and its inductance value L_r, the converter transformer inductance and the smoothing reactor inductance. The rating of T_c is determined by $(I_{dconv} + I_r)^2 \times L_r$. The rating of the active filter (converter) is determined by U_{dr}^2/L_r. Hence the economical optimisation between the active and passive part of the active filter can be adjusted by increasing L_r. The rating of T_c will be increased and the rating of the active filter part will be decreased or vice versa.

The smoothing reactor (which is already designed for U_{dr}) is eventually an alternative for T_c, although is must be relocated to the neutral side of the HVDC converter valve and provided with an auxiliary winding.

The advantages of this connection are:

- There are no harmonics in the HVDC converter direct current.
- The control algorithm of a series filter will probably be simplified compared to the shunt filter control.

The disadvantages are:

- Even by an optimal design, the rating of T_c and the active filter part will be considerable.
- The T_c side of the HVDC converter has no earth potential, which should be considered in the design of the HVDC converter and the transformer T_c.

5.2.3.5 "Active filter 4" connection

The “Active filter 4” in Figure 6 is a series active filter fundamentally with the same configuration and problems as the “Active filter 3”. The filter is connected at the pole bus on the line side of the d.c. filter capacitor. The major advantage of this arrangement is that the active filter rating (due to the fact that the HVDC converter output ripple voltage is attenuated already by the passive filter) will be considerably less than the “Active filter 3” connection. The disadvantage of this arrangement is that the filter is situated at line potential and that the filter must conduct the whole direct current.

5.2.3.6 "Active filter 5" connection

There has not been any information describing “Active filter 5a and 5b” in Figure 6. The application of such a filter is expected to be limited to either higher frequencies or lower frequencies and not the whole frequency range as the “Active filter 1 and 2”.

5.2.3.7 Conclusion on active filter connections

The advantages and disadvantages of the most possible connections of the active part of the d.c. filter have been described above. The main conclusion is that series connections of active filters on the d.c. side are possible but with the facts available today not recommendable.

The injected power for active filtering can be reduced by choosing the optimum line injection point on the passive circuit or the d.c. line. All active d.c. filter applications implemented today and in the near future will use the “Active filter 1” solution in Figure 6. The remaining of this paper therefore discusses the “Active filter 1” solution.

5.2.4 Characteristics of installed active d.c. filters

The active d.c. filters (Figure 7) are connected in feedback control loop. The line current is measured by a current transducer. The current signal is passed through a light guide into a computer. The computer calculates a signal to feed a VSC, so that the current injected at the pole line is in opposition to the measured line current.

Characteristics of the active d.c. filters:

- frequency range 300 Hz to 3 000 Hz;
- the achieved harmonic current attenuation is high, at least 10 times attenuation in addition to achievements with the passive part alone, at all chosen frequencies in the whole frequency range (see Figure 29);

- adaptable to variations of network frequency;
- compensate detuning effects of the passive d.c. filter;
- comparatively small size. The active part of the active d.c. filter can be fully assembled and tested at the factory and then transported to site;
- significant changes in characteristics of the active d.c. filter can be achieved any time after commissioning within the active filter ratings by software changes without hardware modification.

5.3 Main components in a d.c. active filter

5.3.1 General

The active d.c. filter is a hybrid filter consisting of a passive and an active part. The passive part can usually be defined as a double tuned passive filter which connects the active part with the d.c. line. The active part in the d.c. active filter is shown in Figure 7. All the components in the active part shall ensure proper function of the active filter in steady state conditions and during faults. Testing of active filters during system tests for high-voltage direct-current installations should be carried out in accordance with IEC 61975.

5.3.2 Passive part

The main function of the passive part is to connect the active part with the high voltage d.c. line. The reasons for choosing a double tuned filter are both an optimisation of the VSC cost compared with the double tuned circuit and to ensure a reasonable performance if the active part is not in operation.

The choice of the characteristics for the passive part, together with the size of the smoothing reactor, will influence the rating of the active part. The following example illustrates the rating requirements of the active part with a fixed size smoothing reactor when

- only a capacitor is used;
- a single tuned 12^{th} harmonic filter is used;
- a double tuned $12/24^{th}$ harmonic filter is used.

Table 2 shows a scheme calculated from some typical measured current values from a 600 MW, 400 kV HVDC converter connected to a 400 kV, 50 Hz a.c. grid. The smoothing reactor has 200 mH, the main capacitor has 1 μF. The root sum of squares of a typical measured current spectrum through the smoothing reactor gives 15,7 A_{rms}. The current spectrum is used to calculate the assumed voltage which is required for the active part to compensate the harmonics for the three mentioned filter configurations shown in Figure 8. The attention should be paid to the fact that the calculated case in Table 2 is a simplified case, with a short overhead line connected to a long HVDC cable. The HVDC cable mitigates the influence from the other HVDC converter. The calculated example will only illustrate the impact of rating on the active part with selection of different passive parts. In the “real” rating of the d.c. filter design, the designer has to include various other parameters.

The primary costs in the design of a conventional d.c. filter are the smoothing reactor and the main d.c. filter capacitor connected to the d.c. line. If one disregards the smoothing reactor, which costs the same or more than the main capacitor, the cost of the main capacitor is approximately 90 % of the totals, while the reactors, the low voltage capacitor and resistors have small influence on the total cost.

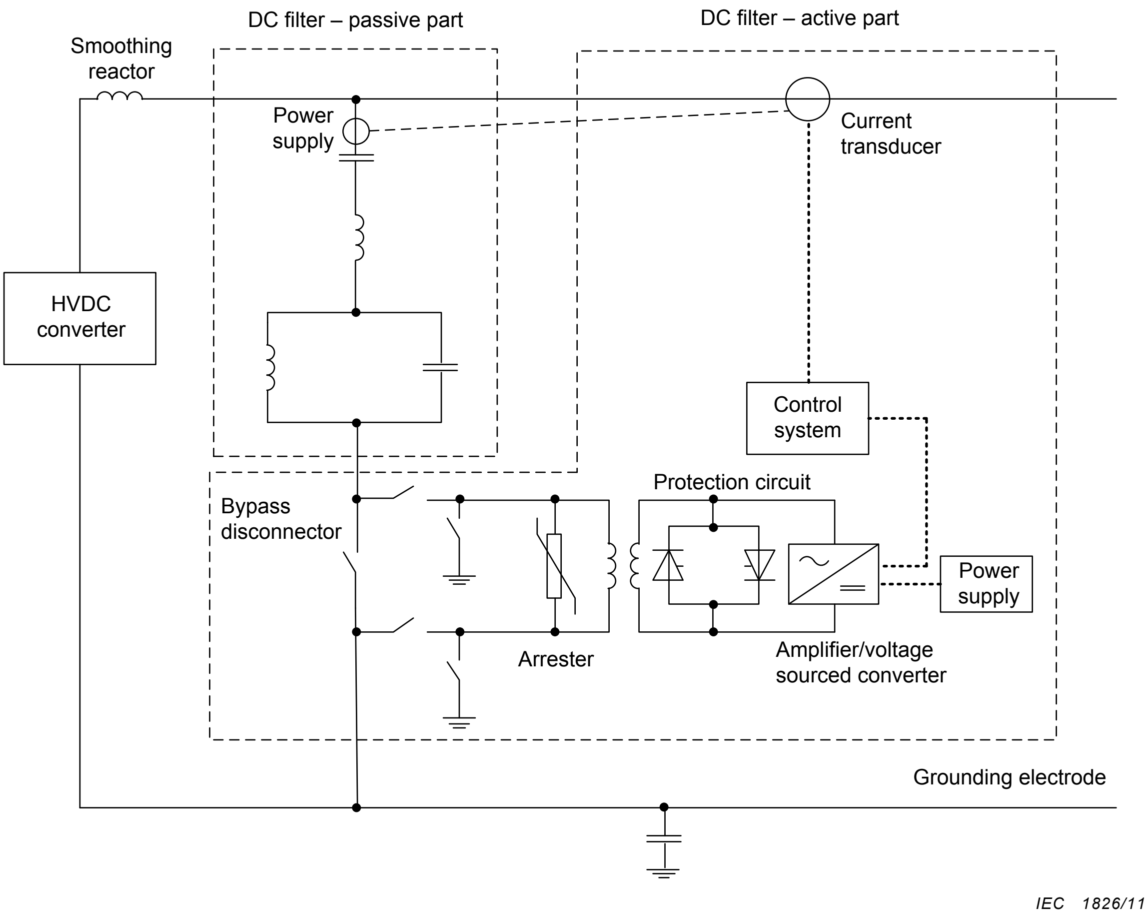


Figure 7 – Filter components in the active filter

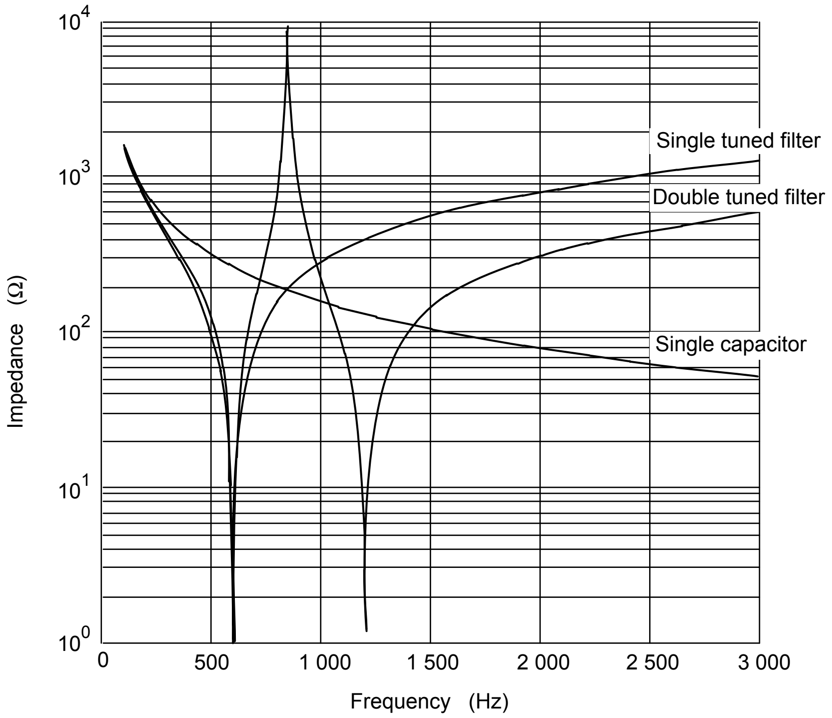


Figure 8 – Impedance characteristics of different passive filters

Table 2 – Voltage to be supplied by the active part with different selections of passive parts

Assumed frequency deviation	Single capacitor	Single tuned filter	Double tuned filter
0,0 Hz	6,7 kV	4,4 kV	2,8 kV
± 0,1 Hz	6,7 kV	4,4 kV	2,8 kV
± 1,0 Hz	6,8 kV	4,6 kV	3,1 kV

The main difference between a conventional passive d.c. filter and the passive part in the active filter is the lack of resistive elements in the filter. The reason is that the control algorithm and VSC are able to compensate the frequency deviation on the a.c. side of the HVDC converter and the component deviation. Hence it is not necessary for the filter designer to optimise the filter in that respect. When an active d.c. filter is used, the frequency deviation will change from a performance issue to a rating question on the VSC. In a recent project with long HVDC lines, resistive elements in the passive part of the d.c. filter have been inserted to reduce the resonance in the overall system.

The d.c. capacitor will always be a part of the active d.c. filter, connecting the active part with high voltage d.c. line. In future active d.c. filters, parts of the resonance circuit or the additional components in the passive filter are expected to be replaced by larger power stages, since the price of the power stages decrease rapidly.

5.3.3 Current transducer

The function of the current transducer is to measure the line current. The Rogowski coil has been chosen as the current transducer in all known projects [7]. To get a correct functioning of the active d.c. filter, it is required to have at least one current transducer at each pole line in the station where the active d.c. filter(s) is/are installed. The current transducer may be connected to the control through a light guide (Figure 7) and is fed from a power supply which utilise the harmonic current flowing in the filter, or by a photocell array at the sensor and a second light guide connected to the control equipment. The following data has to be taken into account when designing the transducer.

- A very high direct current through the current transducer. The direct current makes it difficult to use an iron core transformer.
- The second harmonic current can be of considerable size (more than 10 A_{rms}), where the harmonics at other frequencies is in the size of 10 mA, when the control is active.
- Some current transducers may need a power supply at the high voltage d.c. transmission level. The current transducer can be equipped with an electronic unit to communicate with ground level equipment.
- The current measurement with the analog/digital conversion must be accurate within a large temperature range from minimum ambient temperature with minimum load in the winter to maximum ambient temperature with sun and a maximum load in the summer.
- The current transducer shall be able to measure the current with sufficient bandwidth (typical 1,5 to 2 times the selected active range for the control) to secure a well performing control in the active frequency range (normally in the range 300 Hz to 3 000 Hz).

5.3.4 Control system

An analog/digital (A/D) conversion is necessary before the signal from the current transducer enters the digital signal processors (DSP) and, in some installations, also a digital/analog (D/A) conversion before the calculated signal from the computer enters the VSC. The duration of the control process from measured current on line to injected current on line adds a delay which the control algorithm shall be able to handle. At high frequencies the phase shift will be considerable. The control will be further described in 5.4. To be able to control the VSC at frequencies up to 3 000 Hz, the computer or parts of the computer shall process complex tasks with a sample rate of at least 10 000 Hz. The control sample rate can be less, if the demand to the frequency range to control is reduced.

Although analog control circuits are theoretically possible, preference is given to digital computer assisted controls. The main reasons to choose digital computers are that they can supply the needed flexibility to the complexity of the overall system to control and the easy adaptability to new control algorithms.

5.3.5 Amplifier

The voltage sourced converters in the first installed filters comprised a transformer and MOSFET PWM amplifiers with a switching frequency at 66 kHz and a voltage of 330 V peak. They are able to maintain full power (3 dB limit) in the frequency range 100 Hz up to 3 000 Hz. New water cooled IGBT PWM amplifiers with switching frequencies considerably lower than the MOSFET amplifiers are expected to be used in all future projects. The IGBT PWM amplifiers are expected to have sufficient high switching frequency (at least 10 000 Hz), higher voltage and better power handling with lower losses.

When using switching devices, harmonic distortions in the PLC range (30 kHz to 500 kHz) outside the active control range may be introduced. With the present active d.c. filter design, including a transformer and a passive filter working as a low-pass filter particularly for frequencies in the PLC range, this distortion is normally suppressed.

5.3.6 Transformer

The transformer is used because the existing amplifiers, providing voltages in the range 300 V to 1 000 V, are not able to deliver the necessary voltage above 3 kV. Because the transformer provides not only the necessary voltage, but also the galvanic separation between the main circuit of the HVDC plant and the amplifier, it will be still necessary in the future. The transformer is designed to produce the required voltage and to present a low impedance, making a minimum impact on the original passive filter characteristic.

5.3.7 Protection circuit and arrester

The protection circuit measures the currents and voltages and hence ensures that the amplifier is not stressed. The protection circuit consists of two thyristors able to carry the full fault current coming from the main circuit. The thyristors can be fired from the voltage/current supervision as well as the own supervision of the amplifiers. The arrester limits the voltage across the transformer and amplifier. The insulation coordination should be ensured in accordance with IEC 60071-5.

Adequate protection of the amplifier or power stage is essential for active d.c. filter schemes and has to include a protection circuit to conduct the fault current past the amplifier.

5.3.8 Bypass switch and disconnectors

The bypass switch and disconnectors are installed in all active d.c. filters and enable the operation of the HVDC link without using the active part. This feature makes it possible to work on the active part without taking the HVDC link out of operation.

5.4 Active d.c. filter control

5.4.1 General

The aim of an active d.c. filter control is to mitigate the harmonic currents on the pole line and/or the electrode line current which are originated at the local HVDC converter station, so that the interference on telephone lines, adjacent to the HVDC lines may be brought within allowable limits. The active d.c. filter creates virtually a low impedance path between the pole and electrode lines (or ground, depending on the configuration of the system) at the chosen harmonic frequencies. In this way, the harmonics are guided through the d.c. filter and thereby prevented from entering the HVDC line, so that the disturbance on the line is diminished.

Below are some of the items that meet an important part of the design specification of the active filter control:

- The required distortion level
- The modes of operation of the HVDC transmission
- The type of HVDC transmission
- The number of terminals in the HVDC system
- Single active d.c. filter / multiple active d.c. filters
- The control system must be able to recover from abnormal system conditions.

5.4.2 Active d.c. filter control methods

5.4.2.1 Feedback control

Feedback control forms the core of existing active d.c. filters in HVDC applications [8] – such as shown in Figure 9. This controller is not only able to practically eliminate the harmonic currents, but it also compensates for inaccuracies of both the current measuring device and the control parameters.

The basic feedback control scheme is illustrated as a block diagram in Figure 9. The functionality of the control has been proven, but the compromise between stability and response has to be considered.

The quantity i_l is the measured harmonic current in the transmission line, I_conv is the disturbance current from the HVDC converter and I_filt is the compensation current from the active d.c. filter. The total line current I_line is the sum of I_conv and I_filt. The external process is the transfer function between the output voltage from the active d.c. filter control, u_a, and the current I_filt.

The controller of Figure 9 consists of four blocks. The first block filters the input signal, to limit its frequency contents to within the operational range of the active filter (typically 300 Hz to 3 000 Hz).

The second block identifies each individual harmonic and then refer it to a set of two orthogonal vectors (cos $n \times \omega \times t$, sin $n \times \omega \times t$ - where the integer n is harmonic order, $\omega = 2\pi \times f_0$ and f_0 is the fundamental frequency). The block receives a synchronising signal derived from the converter a.c. voltage to enable the controller to adapt to changes in the network frequency. Notch filters, usually connected in parallel [4], may be used to isolate the individual harmonics.

The third block performs the function of filter and PI controller. The block also compensates the external process at the harmonic frequency $n \times f_0$. An example of a measured transfer function of the external process is shown in Figure 10.

The fourth block combines the output of the previous blocks into a signal with suitable amplitude, phase and harmonic contents to form the compensating signal.

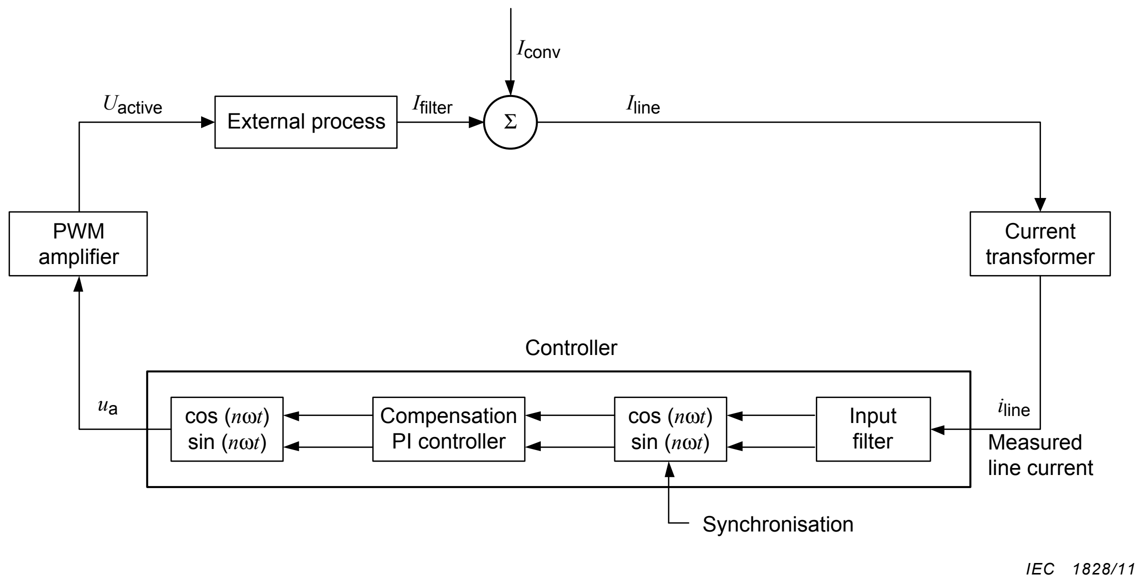
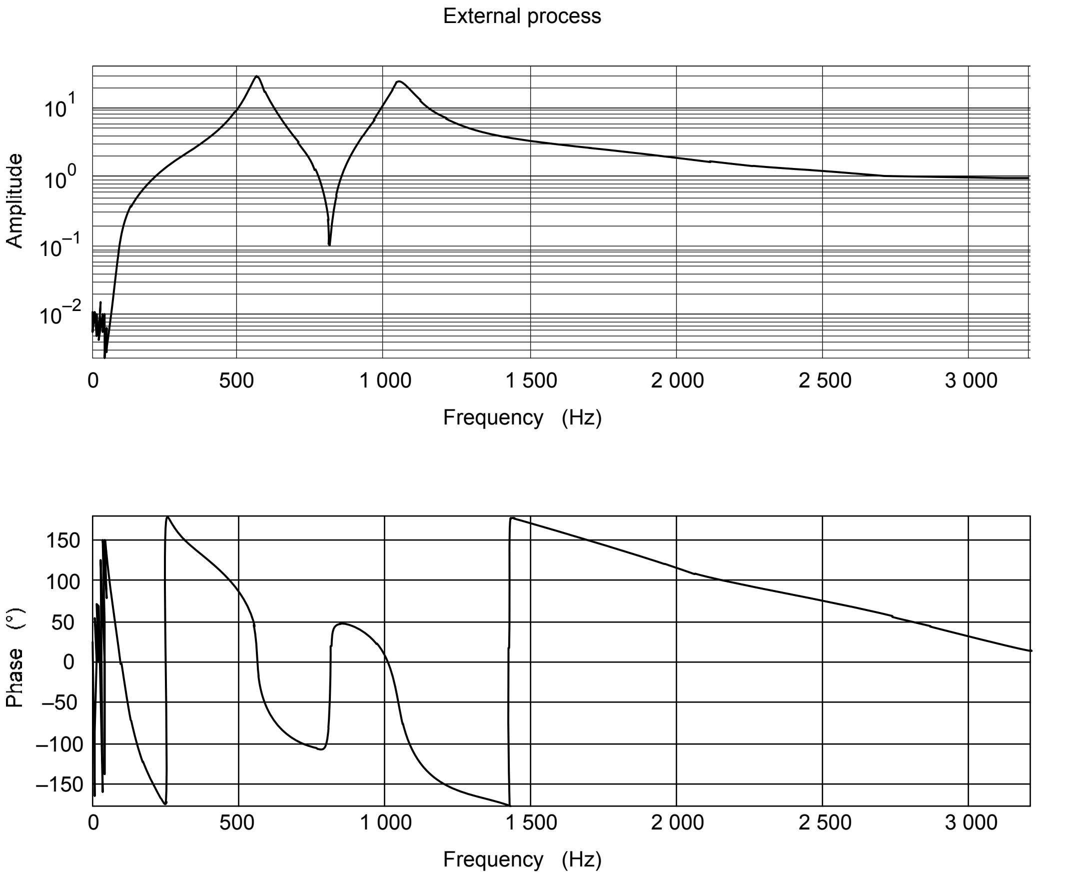


Figure 9 – Basic control loop of an active d.c. filter

5.4.2.2 Feedforward control

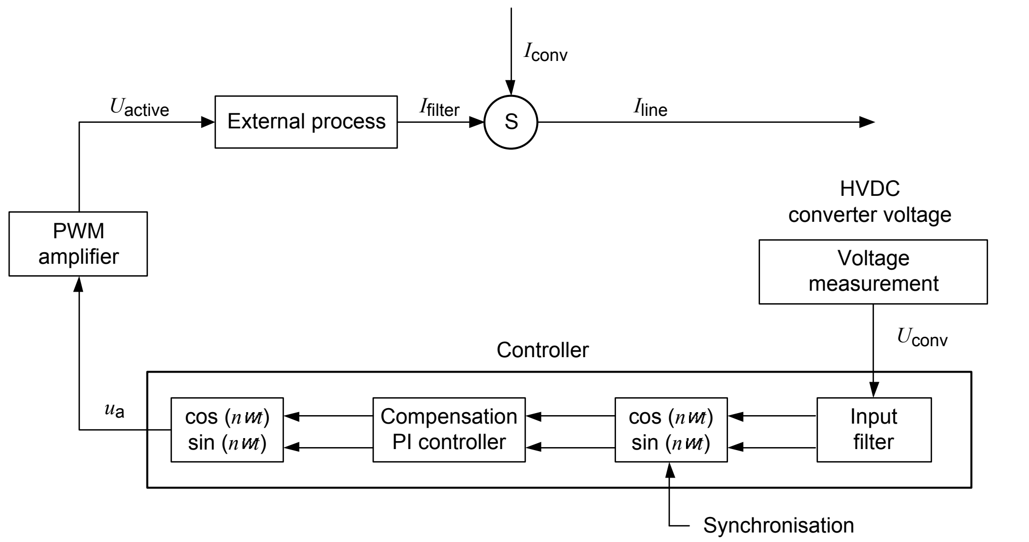
Active filters are designed for the normal stable harmonic load currents and voltages generated in the HVDC power circuit. In case of disturbance (voltage breakdown, a.c. filter switching, transformer energising, overload conditions, etc.) in the HVDC scheme, the load conditions can be too extreme for the active filter; therefore the operation of the active filter has to be adapted or even blocked temporarily. Feedforward information (for example, the d.c. output voltage of the HVDC converter) to correct the active filter control loops during and after the disturbance, is a great help to achieve optimal active filter operation with a minimum of delay.

Contrarily to the feedback control, the feedforward control is an open loop control system and does not require a high gain as the feedback controller (Figure 11). Compared to feedback control, feedforward control results in a quicker corrective action and thus reduces the controller’s response time, but the use of feedforward alone is not sufficient to compensate the disturbances to required level. The feedforward control has not been used in any HVDC systems.



IEC 1829/11

Figure 10 – Measured transfer function of external system, Baltic Cable HVDC link



IEC 1830/11

Figure 11 – Feedforward control for the active d.c. filter

5.4.2.3 Combined control system using feedforward and feedback control

In the combined control system, the major control (feedforward control) mitigates the harmonics. The feedback controller then plays a supporting role by correcting loop errors that result from measurements and changing networks. The stability of the active d.c. filter control, the dynamic specifications of the active filter and the cost and availability of high voltage measurement equipment are some of the factors that will determine whether the combined controller will be used. It should be mentioned that the combined feedback and feedforward control system will be considerably more complex than the conventional feedback control system and has not yet been used in any HVDC systems.

5.4.2.4 Control and supervision for the active d.c. filter

The active filter needs different control and supervision loops to ensure its proper function. The following points consider an outline of a possible controller that consists of two control/supervision loops.

- **Primary controller.** The harmonic contents of the line current are diminished using the injection source. In a HVDC system that has the active d.c. filters, one control algorithm for each pole in each station should be sufficient to mitigate the pole line harmonic currents.
- **Harmonic supervision.** A relevant criterion, for instance the severity of the interference caused by the harmonic, is used to identify the most troublesome harmonics. This is done at an interval of approximately 1 minute. The harmonic supervision verify if the primary control is working satisfactory.

5.4.2.5 Measurement systems

The following quantities can be measured for either control or supervising functions:

- The pole line I_{line} and/or the electrode current I_{elec}, using a Rogowski coil or a d.c. current transformer
- The filter current (I_{filt})
- The HVDC converter current (I_{conv})
- The HVDC converter voltage (U_{conv})
- The active d.c. filter output voltage (U_{active})
- AC side frequencies.

5.5 Example – Performance of the Skagerrak 3 HVDC Intertie active d.c. filter

To illustrate the performance of the active d.c. filter, a pole line current was measured in the Skagerrak 3 HVDC Intertie. Pole 3 was operated as monopole and the transmitted power level was 240 MW. The pole line current with and without the active part is shown in Figure 12. The first current spectrum shows the line current with the active part not in operation and the second spectrum shows the line current with the active part in operation.

As it is shown in 5.1 the psophometric current can be calculated using the following formula:

$$I_{pe} = \frac{1}{p_{16}} \sqrt{\sum_{n=1}^{60} (k_n \cdot p_n \cdot I_n)} \qquad (3)$$

The psophometric current of the current spectra shown in Figure 12, was reduced from 4780 mA to 255 mA. The major harmonic line currents are shown in Table 3.

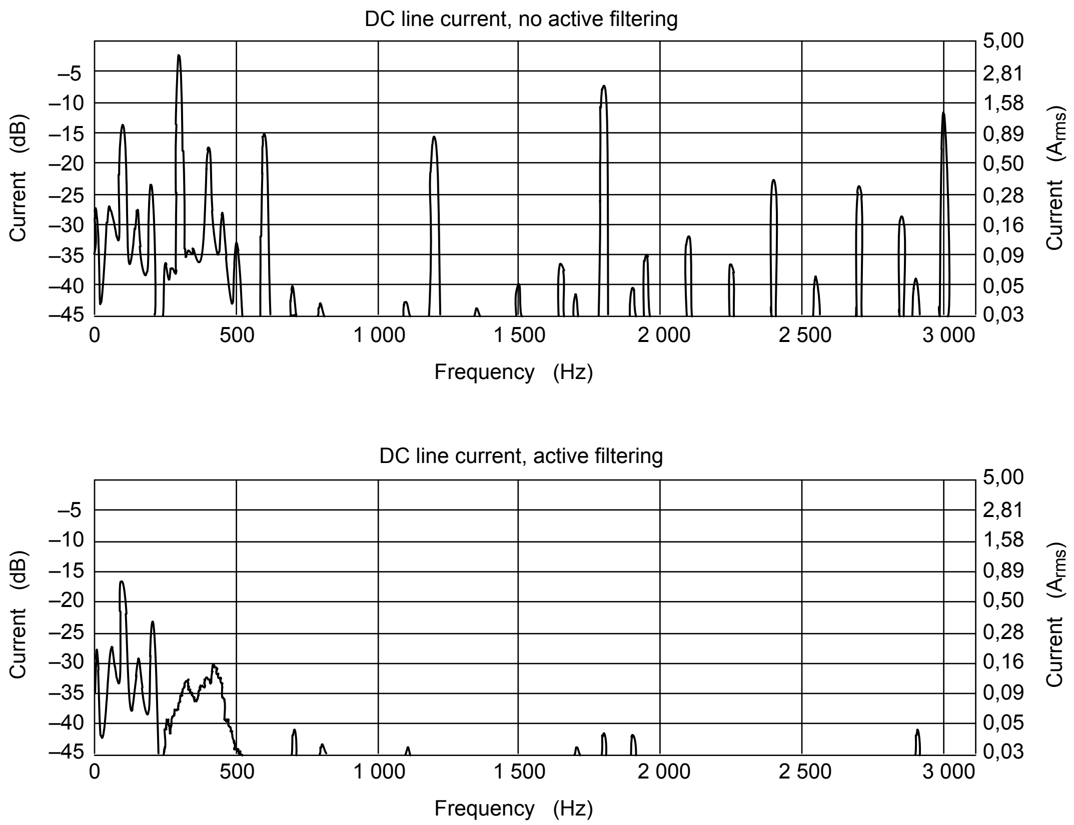


Figure 12 – Measured line current spectra, pole 3 operated as monopole

Table 3 – Major harmonic line currents, pole 3 operated as monopole

Frequency [Hz]	**Weight factor** $P_{n} \times k_{n}$	**No active filtering**		**Active filtering**	
		Current [A_{rms}]	Weighted current [A_{rms}]	Current [A_{rms}]	Weighted current [A_{rms}]
300	0,111	3,668	0,406	0,088 1	0,009 7
600	0,595	0,844	0,503	0,018 0	0,010 7
1 200	1,500	0,836	1,253	0,024 5	0,036 8
1 800	1,710	2,216	3,788	0,043 6	0,074 6
2 400	1,902	0,350	0,675	0,025 3	0,048 8
2 700	1,957	0,338	0,662	0,021 7	0,042 4
3 000	1,969	1,164	2,292	0,024 2	0,047 7

5.6 Conclusions on active d.c. filters

- The need for active d.c. filters is a consequence of stringent demand on telephone systems. Further introduction of digital and optical systems can reduce these requirements.
- Series connections of active filters in the main HVDC circuit are conceivable, but some basic problems have to be solved before the solution becomes recommendable.
- All active d.c. filters implemented today and in the near future will be connected as a hybrid filter, where the passive filter is used to connect the active part with the high voltage d.c. line.

- The type most suited to power stage applications, particularly high power, is the voltage sourced converter.
- The relative high frequencies for active filtering exclude thyristors and GTO. Consequently MOSFET and IGBT are used in voltage sourced converters.
- Although analog control circuit in theory is possible, digital computer assisted controls are preferred.
- All control systems in existing and expected systems with active d.c. filters use feedback control, but feedforward control or a combination might be a future option.
- Adequate protection of the voltage sourced converter is essential for active d.c. filter schemes.

6 Active a.c. filters in HVDC applications

6.1 General

Non-linear loads and sources cause voltage distortion of the sine wave in electrical distribution and transmission networks. The primary sources of electrical energy, synchronous generators or over-synchronous running asynchronous generators, produce nearly undistorted sine waves.

Classical loads such as uncontrolled motors, heaters and incandescent lamps connected to a sinusoidal source will take nearly undistorted currents. This is in contrast to fluorescent lamps, controlled motor drives, computers and TV sets. Most of the distortion in low-voltage (LV) and medium-voltage (MV) distribution networks is caused by such loads, and may even be propagated into HV networks. In particular the 5^{th} harmonic is of great concern for the utilities, particularly during the evening hours. The increasing non-linear loads over the last ten years are topic of many conferences on power quality.

For larger loads such as traction rectifiers, 12 pulse instead of 6 pulse operation shifts the distortion to the 11^{th} and 13^{th} harmonics. Sometimes passive filters in single or double tuned configurations are used. These filters are less effective for distributed loads and non-characteristic harmonics.

HVDC converters feeding into an existing HVAC network are a source of distortion themselves. From the beginning of the HVDC transmission, these problems have been recognised and passive filters for the $11/13^{th}$ and $23/25^{th}$ harmonics are applied in all existing schemes. The filters also contribute to the compensation of the inductive character of the rectifier and inverter.

The interest in active power filters has grown over a number of years due to more stringent requirements and guidelines placed on customers and supply utilities such as the IEEE 519 or IEC 61000 series. These place maximum limits on various current and voltage harmonics generated and drawn at the point of common coupling (PCC). Requirements to develop low-cost and robust active filters with multifunctional control capabilities, such as sag and dip compensation has emerged from industry. The developments in active filters have also motivated their application for HVDC, on the a.c., d.c. or both sides of the HVDC converter [9, 10].

In contrast to passive filters designed to operate at distinct frequencies, active filters can cover a range of frequencies, including non-characteristic harmonics. Active filters for the d.c. side of a HVDC system are already in operation. A1⟩ The power requirements for HV AC side can be considerably higher than for the HV DC side. ⟨A1

6.2 Harmonic disturbances on the a.c. side of a HVDC system

When connecting HVDC converter stations or large loads to the a.c. system, that generate harmonics like industrial rectifiers, large motor drives and electrical arc furnace plants, a.c.

filters are usually installed as a part of these loads or HVDC system in order to ensure that the injection of harmonics into the a.c. system is limited to acceptable levels.

Filtering is required due to the following effects of harmonics:

– Additional stresses

  The waveform distortion causes losses, resulting in additional heating, and stresses in both customer's and utility's equipment.

– Maloperation of electronic equipment

  Also the harmonics may cause maloperation of electronic equipment and protective equipment, e.g. protection relays.

– Telecommunication system disturbance

  In the case of overhead lines with nearby telecommunication lines, the harmonics may the induced voltages in telecommunication and other low voltage system caused by harmonics flowing in the a.c. system may result in voltages higher than the regulations with respect to human safety.

A discussion on the permissible distortion limits is included in IEC 62001:2009, Clause 4, and in [1]. Some typical values are considered in 5.1of the present report.

6.3 Passive filters

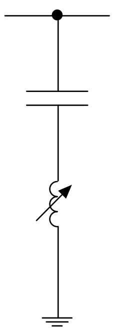
6.3.1 Conventional passive filters

Traditionally, the filters installed in large harmonic generating loads have been of the passive type, usually designed as shunt elements creating a low impedance path for the harmonics to be filtered. The filter is build up as a resonant circuit consisting of capacitor(s) and inductor(s), and in most cases also resistor(s) for giving the filter a more 'soft' damped characteristic.

These filters are discussed in detail in IEC 62001:2009, Clauses 7 and 8, and in reference [1].

6.3.2 Continuously tuned passive filters

Figure 13 shows a continuously tuned filter. A continuously tuned a.c. filter is always tuned to the harmonic frequency (e.g. 11th or 13th) and has a high Q-factor thus giving high performance and low losses. In the continuously tuned filter, the tuning frequency is automatically adjusted to provide perfect tuning irrespective of frequency excursions and component variations. The filters therefore need no additional damping resistor. The perfect tuning is achieved by variations of the inductance of the filter reactor. Just one continuously tuned filter is sufficient to provide the required filtering for a particular harmonic.



IEC 1832/11

Figure 13 – Continuously tuned filter

Continuously tuned filters are mainly used in capacitor commutated converter based HVDC schemes, as well as in controlled series capacitor converter based HVDC schemes.

6.4 Reasons for using active filters in HVDC systems

Unlike passive filters, where the harmonic reduction depends on the combination of filter impedance and network impedance, active filters use power electronics to produce a voltage or a current with the proper waveform to mitigate selected harmonics or harmonics inside a given frequency range.

The active filter output has to present all selected harmonics, each one with the amplitude and phase that are required to counteract the harmonic sources. To get this, voltages and/or currents are measured in the HVDC station and processed by a suitable control equipment using signal processing techniques. An IGBT converter (see 6.7, "Converter configurations") produces the necessary voltages or currents as determined by the control equipment. For HV applications, like HVDC, the active filter will be generally connected to the network through a passive filter, thus building a hybrid filter scheme.

Due to its nature, active filters present the following characteristics:

- High effectiveness. The harmonics can be mitigated effectively, even if the network impedance is very low at the harmonic frequencies.
- One active filter alone can mitigate several harmonics simultaneously. This results in smaller space requirements and simpler filter arrangements in comparison to passive filter solutions.
- In contrast to passive filters, active filters do not introduce any resonance with the network. This results from the fact that active filters reduce each particular harmonic just by injecting a controlled voltage or current with the frequency of that harmonic.
- Active filters do not add reactive power to the network, by the same reason as in the last point.
- Elimination of existing resonance effects. This is achieved through the cancellation of the harmonic voltage on the filter busbar or harmonic current in the lines. Other control method was presented in [22].
- Flexibility for changing frequency characteristics within derated capability. Changes, like for instance selection of harmonics to be filtered, can be made just by settings in the software.
- Self-adaptation to changes in the network frequency.
- Self-adaptation to changes in the network harmonic impedance. Self-tuning control algorithms can extend this characteristic, so that the necessary performance is reached even though the harmonic impedance of the network varies over a wide range.
- The characteristic of the same active filter can be optimised for harmonic voltage (e.g. total harmonic distortion THD, Telephone Harmonic Form Factor THFF, telephone interference factor TIF) or harmonic current (e.g. IT product, equivalent disturbing current), depending on the measured magnitudes and control settings.

The active filter may be connected to the network through a comparatively small passive filter, which can be switched on before starting the HVDC converter and then stay permanently in service. This combination of active and passive filters is called a hybrid filter. The additional demand on reactive power is then covered by capacitor banks and where necessary a small number of passive filters.

The use of hybrid filters in HVDC schemes could be considered due to the above listed reasons. Some cases where these filters should be considered:

- Very small harmonic distortion levels are envisaged.
- The reactive power compensation can be performed with less filters than the amount of passive filters required for harmonic elimination.
- A passive filter solution gets complex due to resonance with the network

- Other harmonic sources in the network have to be regarded and a current-optimised filter solution is preferred (rather than a voltage-optimised solution).
- In the series compensated HVDC schemes (Capacitor Commutated Converter CCC, Controlled Series Capacitor Converter CSCC).
- When an existing filter installation could be up-graded by adding an active part (due to more harmonics, resonance problems, etc.)
- Important advantages of using such hybrid filters are:
- The performance is not reduced neither in case of variation of network frequency nor in case of variations in the associated passive filter due to temperature or failures in capacitor cells (which causes detuning of the passive filter).
- Damping resistors can be avoided at the associated passive filter, as the active filter covers the whole specified frequency range and is not affected by "detuning".
- Smaller amount of filters in comparison to a passive filter solution by the above mentioned reason.

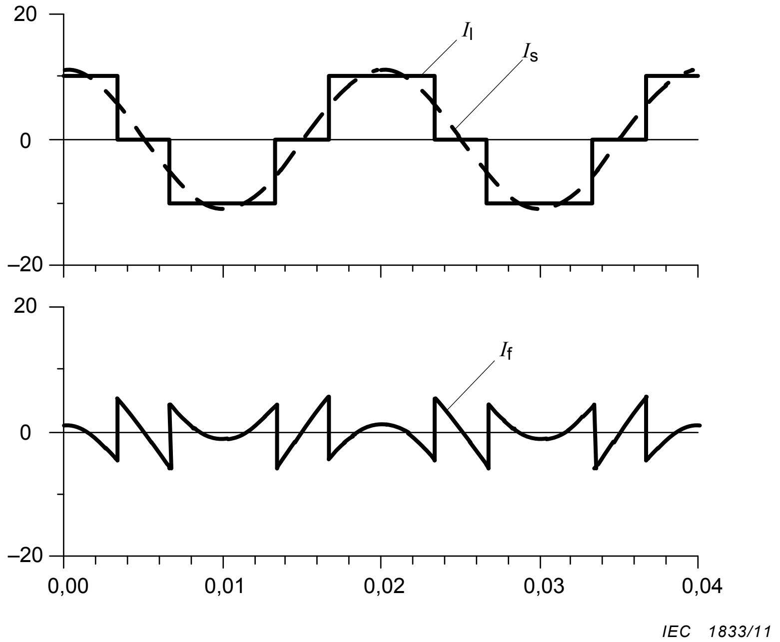
6.5 Operation principles of active filters

6.5.1 Shunt connected active filter

The most common configuration is the shunt connection, where the active filter is connected in parallel with the a.c. network and provided with a current control (see Figure 1).

The active filter constantly injects harmonic currents in opposition to the harmonic currents generated by the load. These harmonic currents are compensating each other and the result is that the current supplied by the power source remains sinusoidal (see Figure 14).

The active filter needs to be sized only for the harmonic currents, generated by the non-linear load and not for the full load current. For higher voltages than the voltage level of the active part, a coupling transformer will be used.



Key

I_l Load current

I_s Resulting source

I_f Compensating filter current

Figure 14 – Example of current waves

6.5.2 Series connected active filter

This type of filter, connected in series with the line, is mainly aimed at reducing the voltage distortion already present on the a.c. system and applied to the load (see Figure 2). It acts as a "harmonic isolator" device. Associated with a passive filter, it can also reduce the harmonic currents generated by the load (see hybrid configurations).

The connection of the active filter to the supply is made through a coupling transformer, which must be sized for the total load current rating and injected series voltage U_f. The current through the active filter should be designed for the transformed load current as well.

6.6 Parallel and series configuration

6.6.1 General

In some cases, the combined features of parallel and series configurations may be needed at one location (see Figure 15).

A d.c. link between the two active filters may be used for transfer of active power between the active filters.

The following table summarises the preferred configurations depending on the origin of the harmonic distortion (load or source side) considering common LV and MV applications.

6.6.2 Hybrid filter schemes

This solution, combining an active filter and a passive filter, may be either of the series or parallel type.

An example of parallel combination, which is feasible for low and medium voltage systems is presented in Figure 16. For high voltage applications, a hybrid filter built up by the combination of a passive and active filter in series is required. Such a hybrid configuration is further discussed in 6.8.3.

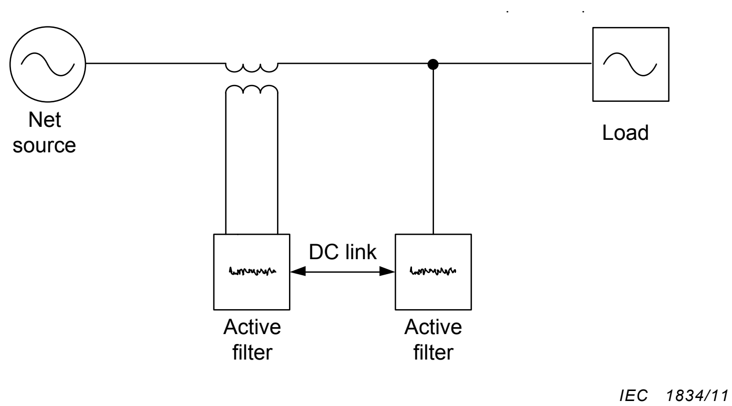


Figure 15 – Series and parallel connection

Table 4 – Preferred topologies for common LV and MV applications

Source	**Load**	
	Non distorting	**Distorting**
Non distorted	-	Shunt
Distorted	Series	Shunt + Series

In the example of Figure 16, the passive filter may carry out basic filtering of the predominant harmonic (generally, the 5th in low and medium voltage systems), while the active filter, due to its limited rating, covers the other harmonics.

This configuration gives better performances than a passive filter alone, at a lower cost than with a purely active filter. This association is a technical and economical compromise solution when high performances are required.

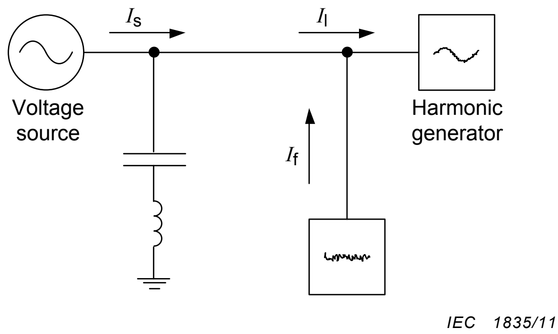


Figure 16 – Hybrid configuration

6.7 Converter configurations

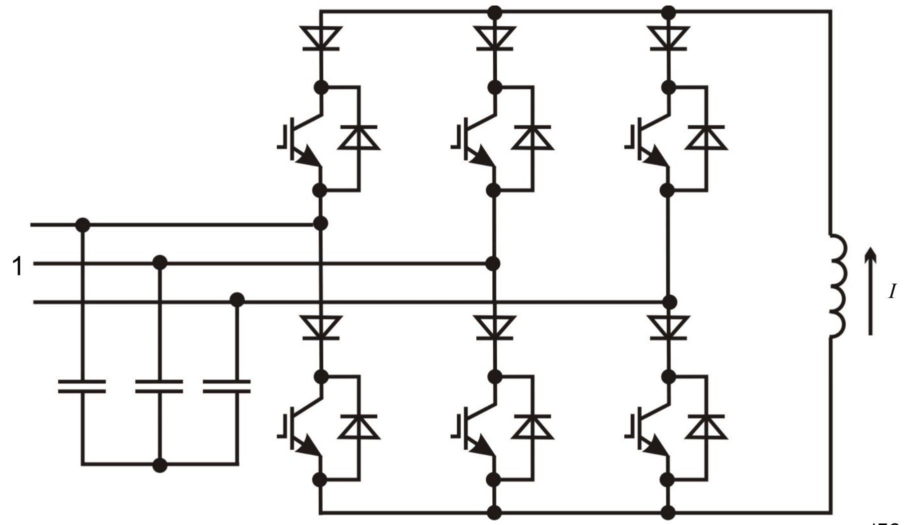
6.7.1 Converters

Basically, two types of converters can be used in active a.c. filters, the voltage-sourced converter and the current-source converter. In both cases, the converter can present a three-phase (three or four wire type) or a single-phase structure.

6.7.1.1 Current-source converter

This kind of converter has an inductor as the energy storage component (see Figure 17). The use of this configuration is limited due to the coil and additional semiconductor losses (see also 5.2.2.2).

A1



A1

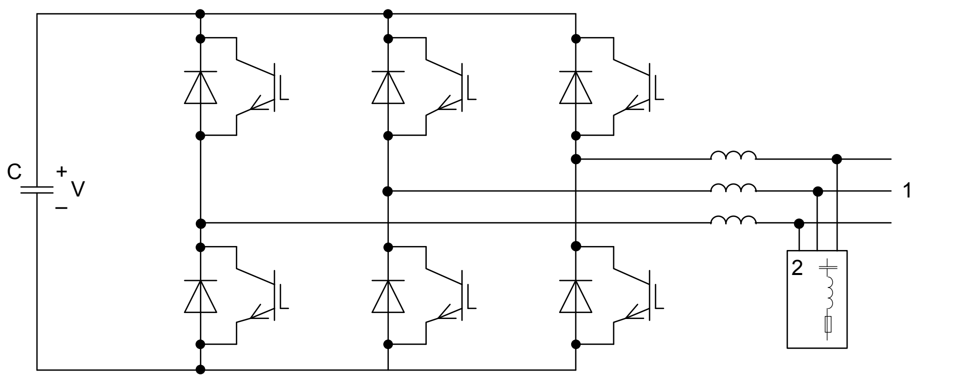
Key

1 AC grid

Figure 17 – Three phase current-source converter

6.7.1.2 Voltage-sourced converter

This is the preferred configuration (see Figure 18), because it is the most cost-effective. Almost all active filters, which have been put into operation, have adopted the voltage-fed PWM inverter structure (see also 5.2.2.3).



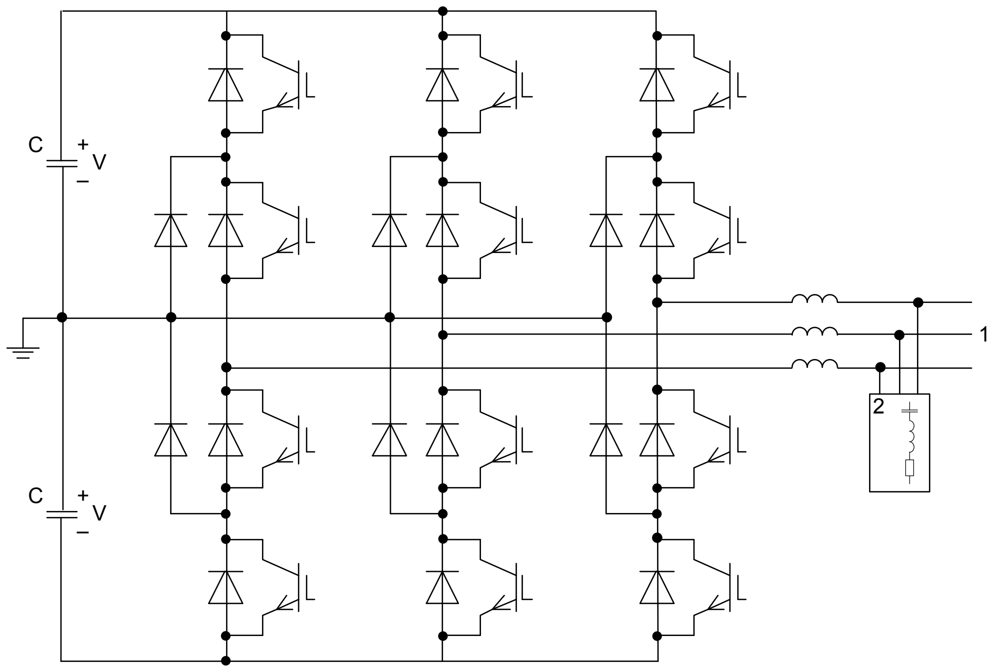
Key

1 AC grid

2 Filter

Figure 18 – Three phase 2 level voltage-sourced converter (three-wire type)

The neutrally clamped 3 level converter (see Figure 19) is used to minimize the losses or to increase power handling capability. This topology can also compensate unbalanced currents.



IEC 1838/11

Key

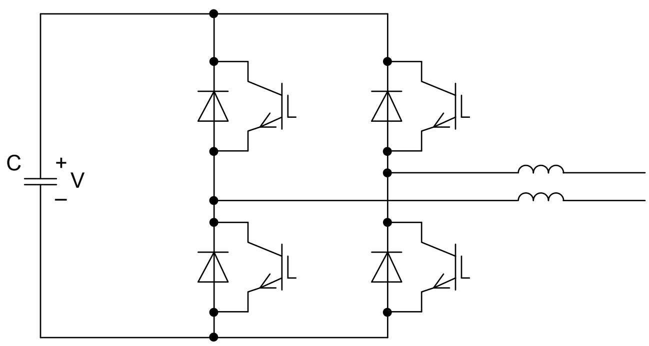
1 AC grid

2 Filter

Figure 19 – Three phase 3 level voltage-sourced converter (three-wire type)

6.7.1.3 Single-phase voltage-sourced converter

Single phase active filters are based on a single phase voltage sourced bridges shown below (see Figure 20). Although three-phase converters have been used for most low and medium voltage applications, three separate single-phase converters can be used in the three phase active filter applications also.



IEC 1839/11

Figure 20 – Single-phase voltage sourced converter

6.8 Active a.c. filter configurations

6.8.1 Active a.c. filters for low voltage application

At the present state of the art, direct connection of the active filter converter to the a.c. bus is only feasible for low voltage systems, due to the voltage capability of the semiconductor devices used in active filters. Moreover, if a voltage-sourced IGBT converter is used like in almost all case, at least an inductor has to be installed between the converter and the network bus. In some examples, transformers have been used for connecting the active filter to the network in order to eliminate zero-sequence components of currents.

6.8.2 Active a.c. filters for medium voltage application

More practical examples are available of active filters connected directly to medium voltage system through, for instance, a dedicated transformer. In most of the existing examples of medium voltage schemes, the active filter is connected in parallel with the load at the low voltage side of the system.

Recent developments in power semiconductors improve the manufacturing of power electronic converters for higher voltages, but these are rather suited for advanced forms of reactive power compensation and voltage regulation. The implementation of harmonic elimination features with these installations is conceivable, at least for low order harmonics.

6.8.3 Active a.c. filters for HVDC applications

An active filter may be connected to the high voltage a.c. bus via a coupling capacitor. The size of the capacitor will influence the capacity of the active filter. If elements are added to the capacitor to perform a tuned passive filter, and the active part is connected via this filter, a low impedance path to the a.c. bus is obtained at tuned frequencies.

The technique of hybrid filters, where an active filter is combined in series with a passive one, has been applied at the a.c. side and at the d.c. sides of HVDC converter stations, the latter already in several projects.

A possible hybrid filter scheme is illustrated in Figure 21. In this scheme, the hybrid filter comprises an active filter connected in series with a single tuned passive filter. This arrangement is efficient to mitigate harmonics around the tuned frequency of the passive filter.

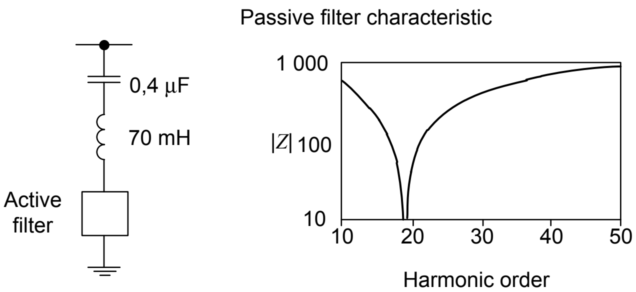


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Figure 21 – Active filter connected to the HV system through a single-tuned passive filter

A filter with the components shown in Figure 23 would contribute to only 20 Mvar (three phase) at a 400 kV, 50 Hz system. The fundamental component of the current in the converter should be limited because it would result into larger component ratings and contribute to additional losses. The 50 Hz current component in the present example is around 30 A, which is a good compromise.

For frequencies far from the tuned frequency, the impedance of the passive filter in the example of Figure 21 increases significantly, so that higher active filter voltages would be required. The efficiency of the scheme is thus low for these harmonics. A possible solution to extend the application of the filter is shown in Figure 22. In this example, the passive filter is a double tuned filter, presenting minimum impedance at the 19^{th} and 37^{th} harmonics. In this case, the active filter can mitigate a wide range of harmonics. The reactive power and the fundamental frequency current in the filter are nearly the same as in the previous case. Therefore, this scheme offers a better cost-benefit ratio compared to the previous one.

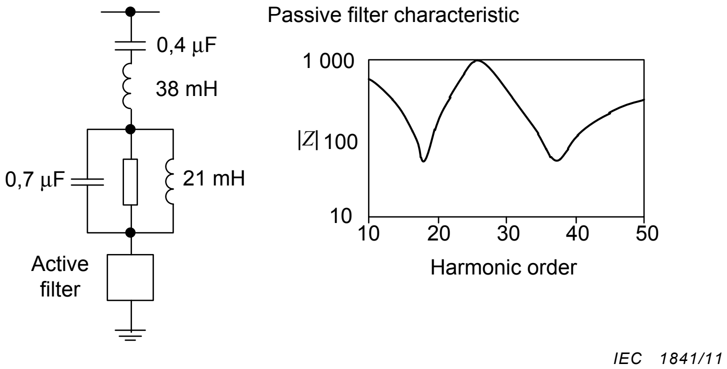


Figure 22 – Active filter connected to the HV system through a double-tuned passive filter

In some HVDC applications, larger reactive power may be desirable at the active filter branch. Or an active filter may be installed in series with an existing passive filter, to improve an scheme already in operation. In both cases, the fundamental current in the filter will be considerable, which should be disadvantageous compared with the previous examples, as the fundamental current flows through the active part of the filter as well. Figure 23 shows a solution that can be used in this case to prevent the fundamental current from flowing in the active filter. In this figure, an LC circuit tuned at the fundamental frequency was introduced in parallel with the active part. The LC path takes over the fundamental component of the current, while the harmonics flow in the active part.

During network disturbances or filter switching, high transient currents will flow in the active filter. To cope with this, the active filter should be equipped with a fast by-passing device, like a thyristor switch. The by-pass should be initiated if overcurrent is detected and be removed after the overcurrent has disappeared, with a delay of some hundred milliseconds to match the network typical disturbance times [47].

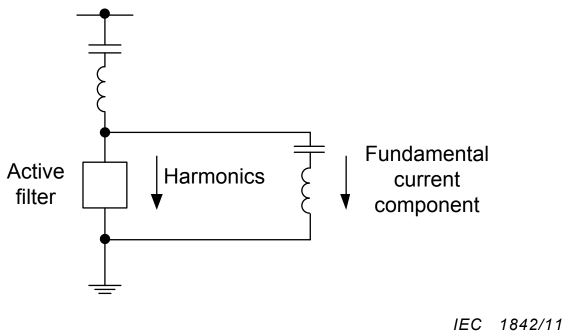


Figure 23 – Using an LC circuit to divert the fundamental current component

6.9 Series connected active filters

This solution is feasible if the current in the insertion point is low. However, in most cases, at least some hundreds of amperes flow in the line, which makes this arrangement costly with respect to installation and losses. In addition the equipment must be located at line potential, which increase the cost as well. Due to these reasons, this solution is not recommended for transmission systems, however it could be feasible for applications close to end-users in the distribution systems to improve voltage quality.

6.10 Control system

6.10.1 General

Various control algorithms exist that are applied to active power filtering. It is not the aim of this report to discuss the various advantages and disadvantages of each but rather to provide a holistic idea of the most well known techniques. Some of these algorithms were evaluated in reference [11].

Some of the most common algorithms that can be used are described below.

6.10.2 Description of a generic active power filter controller

A non-linear load generates fundamental frequency and harmonic currents i_l, as described in the preceding paragraphs. A per phase representation of an active power filter is shown in Figure 24. The active power filter injects a filter current i_f at the point of common coupling to compensate the non-linear load current i_l.

The controller normally has as input the supply voltage u_s, and the line current i_l. The active filter controller consists normally of a digital outer-loop and analogue or digital inner loop (PWM) controller, imbedded into digital signal processors and gate arrays. The input to the PWM inner loop controller is the injected current i_f and the d.c. link voltage u_{dc}. Based on the generated reference current i_{ref}, the converter generates a current. This current is filtered with a low-pass filter with at least 1 kHz to 2 kHz cut-off frequency. Normally a step-up transformer is provided. In order to have a bandwidth of for instance 1 kHz to 2 kHz, the required switching frequency of the active filter should be at least 3 kHz to 5 kHz.

The injected current i_f, of an idealised active filter is such that the instantaneous sum of this injected current and the distorted load current i_l is equal to the active current i_a. In practice the active current is an ideal sinusoid with the amplitude proportional to the load conductance G at fundamental frequency, as discussed in the following equation (assuming u_s as the fundamental frequency component of the supply voltage) [12]:

$$i_f(t) = i_l(t) - i_a(t) = i_l(t) - G \cdot u_s(t) \quad (4)$$

External inputs to the active filter controller may also be included to input the set references for maximum harmonic levels, THD, individual harmonic limits, reactive power demands, etc.

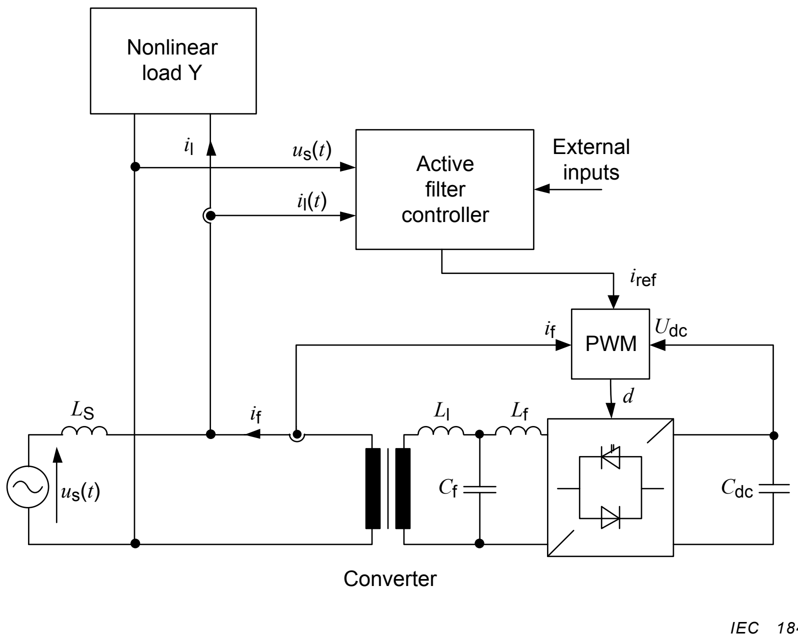


Figure 24 – Per-phase schematic diagram of active filter and controller

6.10.3 Calculation of reference current

As indicated in Figure 24, the reference current i_{ref} is an instantaneous current to be generated from the measured supply voltage u_s(t), the load current i_l(t) and external inputs. Different control algorithms may be used to generate this reference current i_{ref}. These algorithms are generated from time-domain and frequency domain approaches.

To calculate fictitious power in the time domain the apparent power was sub-divided into two orthogonal components namely active power and fictitious power. Active power is based on the rate of energy transferred per time unit and is only available after some time. This means that it is not possible to compensate for fictitious power components in real-time. Several time-domain implementations of active filter control have been used in the past [12],[13] to [17].

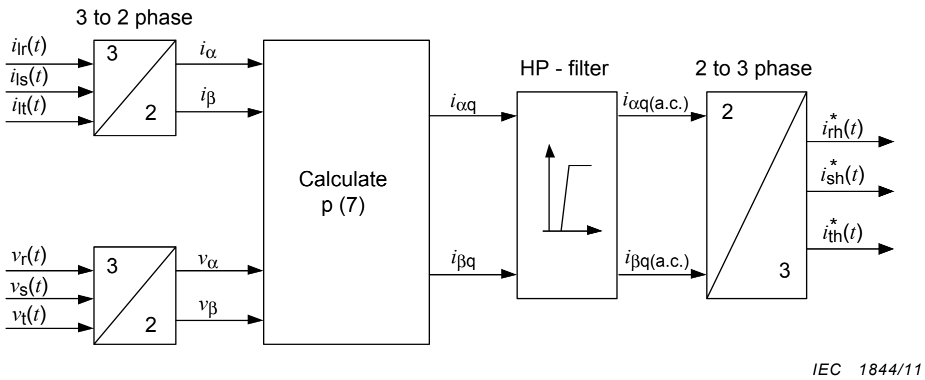


Figure 25 – Block diagram of IRPT

One of the most successfully commercialised algorithms for active filter controllers is based on the Instantaneous Reactive Power Theory (IRPT) [14] depicted in Figure 25. This theory defines a new electrical quantity, the instantaneous reactive power (q) as a unique value determined by using the instantaneous values of the three phase voltages and load currents. The related equations are the following:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_r \\ i_s \\ i_t \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} i_{rh}^{*} \\ i_{sh}^{*} \\ i_{th}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_0 \\ p_{ac} \\ q_{ac} \end{bmatrix} \quad (8)$$

The measured three phase voltages and currents are converted into α-β coordinates using (5) and (6). The instantaneous power is defined as the vector sum of the dot products of the α-β coordinates and reactive power as the vector product of the α-β coordinates as shown in (7). The fundamental of the source current is transformed by these calculations to d.c. components of the instantaneous active and reactive power and harmonic values. A high-pass filter and the conversion back to three phases with (8) can extract the harmonic components. The theory is also extended to include zero-phase sequence components and instantaneous active power (p). It was implemented in various three-phase topologies [13], [14].

6.10.4 Synchronous reference frame (SRF)

The Synchronous Reference Frame (SRF) technique [15] to be used as a control algorithm in a compensator as shown in Figure 26.

The corresponding equations are:

$$\begin{bmatrix} i_q^e \\ i_d^e \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} i_q^s \\ i_d^s \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} i_{qdc}^s \\ i_{ddc}^s \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} i_{qdc}^e \\ i_{ddc}^e \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} i_{ar} \\ i_{as} \\ i_{at} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{qdc}^s \\ i_{ddc}^s \end{bmatrix} \quad (11)$$

The three phase currents are converted into the two phase α-β co-ordinates in a similar way as in Equation (6), excluding the zero-phase sequence components. By using (9), these two stationary reference frame quantities (i^{s}) are then converted into two synchronous rotating reference frame quantities (i^{e}). The fundamental frequency components are now transformed into a d.c. quantity and the harmonics to a.c. components which are separated using a low pass filter. A PI controller ensures zero steady state control error. The resulting d.c. components are then converted back to the stationary reference frame with (10). The three active current components of the load current are calculated by using (11).

6.10.5 Other control approaches

There is another method [17] to control an active filter based on the synchronous reference frame technique [15] extended into the flux domain by integrating the voltage. Several other approaches are developed which differs somewhat form these original approaches. Some implementations estimators, used Neural Networks and Kalman filters, in electrical networks with highly dynamic characteristics, with varied success. In some cases the harmonic current reference is provided in an open loop or feed forward way and injected without any line current feed-back.

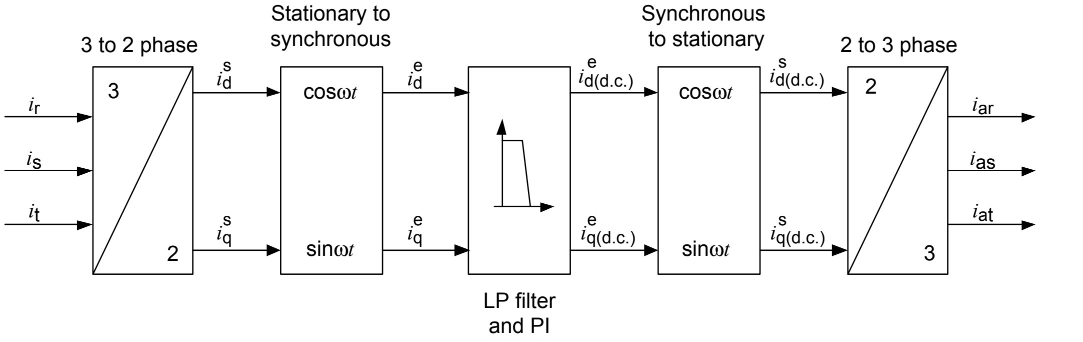


Figure 26 – Block diagram of SRF

6.10.6 HVDC a.c. active filter control approach

An example of an active a.c. filter in the HV a.c. network in operation at the HVDC converter station of Tjele (Energinet) in Denmark. is presented in the next subclause. In this case selected harmonics are split into *d-q* components similar to the SRF. There is such a controller for each selected harmonic and these operate simultaneously.

6.11 Existing active a.c. filter applications

6.11.1 Low and medium voltage

Several low and medium voltage active power filters exist in industry [18].

6.11.2 High voltage applications

6.11.2.1 General

Active filters for the HVDC side are already in operation and have been studied [10], [19]. The power requirements for HV a.c. side are considerable higher. Furthermore, while the configuration of a d.c. side connection practically do not change during operation, the a.c. network changes frequently. This is the case when lines are energised or de-energised or when capacitor banks are switched. Due to these facts, additional features, like automatic adaptation to changes in the network impedance, had to be added to the active filter technology.

6.11.2.2 Performance of the active a.c. filter in service

The graphics in Figure 27 show the results of site measurements at the HVDC substation Tjele (Energinet), Denmark.

The figure shows plots from a measurements of the 400 kV busbar voltage at Energinet's Tjele substation, Denmark without (top) and with (bottom) active filter control. It can be seen that the active filter causes a strong reduction of the selected harmonics. A reduction of more than 30 dBV is shown (Figure 27) for the 23rd harmonic in this case.

The measurement was performed using a frequency analyser connected to the input of the active filter control equipment through D/A converter with optical input.

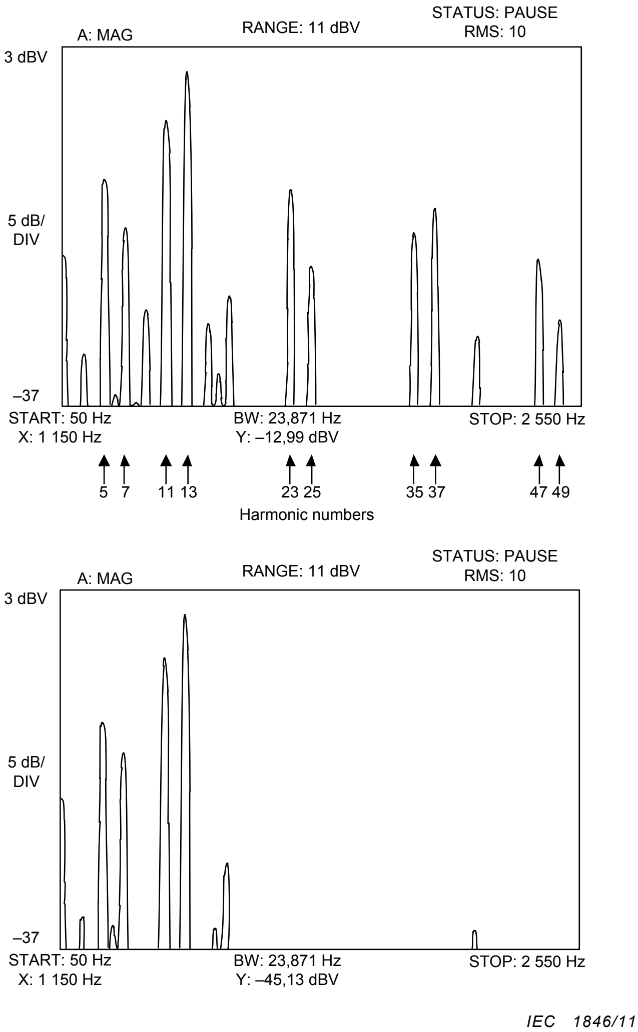
Measurements were also performed for the currents in the parallel filters of the station. These measurements show that when the active filter is in operation, eliminating the voltage on the 400 kV bus for the selected harmonics, no current of these harmonics flow in the parallel filters. This result is interesting, because it means that no other filters are required at the station for the harmonics controlled by the active filter.

6.12 Overview on filter solutions for HVDC systems

6.12.1 Solution with conventional passive filters

In IEC 62001:2009, passive a.c. filters for HVDC systems are described and discussed in detail. For a typical HVDC converter station, a reactive power installation of 50 % to 60 % of the active power rating is required in order to obtain reactive power balance with the a.c. system. The reactive power installation will be divided into shunt capacitor banks, and a part of these banks will be designed as filters. In this way the demands of fundamental frequency reactive power and harmonic distortion will be achieved. The a.c. filters, including their switchyard equipment can occupy over half the total land required by a typical converter station. Where the land is expensive, this could lead to a considerable cost. The cost for the filter equipment is a significant part of the total station cost, in the order of 10 %.

With high demand to filter efficiency it may be difficult to maintain the reactive power balance with the a.c. system and at the same time meet the filtering requirements, requiring more sophisticated solutions.



Key

Top figure: without active filter control

Bottom figure: with active filter control

Figure 27 – Plots from site measurements

6.12.2 Solution with continuously tuned passive filters

6.12.2.1 Solution for conventional HVDC substations

The filter solution for conventional HVDC converter substations can comprise the continuously tuned filters tuned to the dominant characteristic (11^{th} and 13^{th}) harmonics and conventional high pass filters (for example HP24 and HP36). Such a solution has the following main advantages:

- De-couples filtering and reactive power requirement. The filters are assigned a small portion of the total reactive power requirement of the station and the balance reactive power is provided by simple shunt capacitors. All the filters are switched at the converter de-block and remain connected throughout the load. The intervening switchings are only that of the shunt capacitors so as to fulfil the reactive power exchange requirement.
- Gives high performance and low losses.
- Avoids frequent switching of filters thus reducing wear and maintenance requirement on the switchgear.

6.12.2.2 Solution for series compensated HVDC substations

For series compensated HVDC substations, a small portion of the total reactive power compensation can be assigned to the filters that consist of continuously tuned and conventional high pass filters. The balance reactive power compensation is provided by the series capacitors. This solution has the following main advantages:

- Needs small size filters that facilitate fulfilment of voltage change on switching in a weak a.c. network.
- Avoids the use of shunt reactors at minimum load, particularly in a weak a.c. network.
- Gives high performance and low losses.
- Avoids frequent switching of filters thus reducing wear and maintenance requirement on the switchgear.

6.12.3 Solution with active filters

6.12.3.1 Solution for conventional HVDC substations

The filter solution for conventional HVDC converter substations may comprise an active filter for the 23^{th} to the 49^{th} harmonics forming a hybrid series scheme with, for instance, a double-tuned DT12/24, which will be switched at the converter starting and remains connected regardless the converter load, conventional passive filters for the 11^{th} and 13^{th} harmonics and capacitor banks. Such a solution has the following main advantages:

- De-couples filtering and reactive power requirement, as the filters are assigned just to a portion of the total reactive power requirement.
- Presents high performance and low losses (see 5.3).
- Avoids frequent switching of filters.
- Coverage of non-characteristic harmonics without additional filter hardware.

6.12.3.2 Solution for series compensated HVDC substations

For series compensated HVDC substations, a small portion of the total reactive power compensation can be assigned to the filters that consist of active (hybrid) filters. The balance reactive power compensation is provided by the series capacitors. This solution has the following main advantages:

- Needs small size filters that facilitate fulfilment of voltage change on switching in a weak a.c. network.
- Avoids the use of shunt reactors or static Var compensators (SVC) at minimum load, particularly in a weak a.c. network.

- Gives high performance (see 5.3) and low losses.
- Avoids frequent switching of filters thus reducing wear and maintenance requirement on the switchgear.

6.12.4 Solution with continuously tuned passive filters and active filters

This solution may comprise active a.c. filters with moderate amplifier rating and continuously tuned passive filters, providing high efficiency with both series compensated and conventional HVDC converter stations. In this solution continuously tuned 11th and 13th filters can be combined with an active filter for higher harmonics (for example, 23rd to 49th).

6.12.5 Study cases with the CIGRÉ HVDC model

This subclause presents results obtained using three a.c. filter solutions for the CIGRÉ HVDC model. The model is a 1 000 MW, 500 kV monopolar HVDC transmission system with a d.c. cable.

AC system frequency range of 50 ± 0,5 Hz was considered.

The three filter configurations that satisfy the specified performance are:

a) Conventional 11/13th, 24/36th and high pass third harmonic tuned filters (HP3 filters).
b) Continuously tuned 11th and 13th filters, with conventional HP24, HP36 and HP3 passive filters.
c) Continuously tuned 11th and 13th filters, a conventional HP3 passive filter for the 3rd harmonic and an active (hybrid) filter for higher order harmonics supplying 75 Mvar reactive power.

The performance requirements are defined in terms of the parameters shown in Table 5. The used filter configuration and system impedance data are presented in Figure 28.

Table 5 – Performance Requirements

Parameter	Limit
Individual harmonic distortion, Dn	1,0 % for all odd harmonics 0,5 % for all even harmonics
THD	1,5 %
THFF	1,0 %

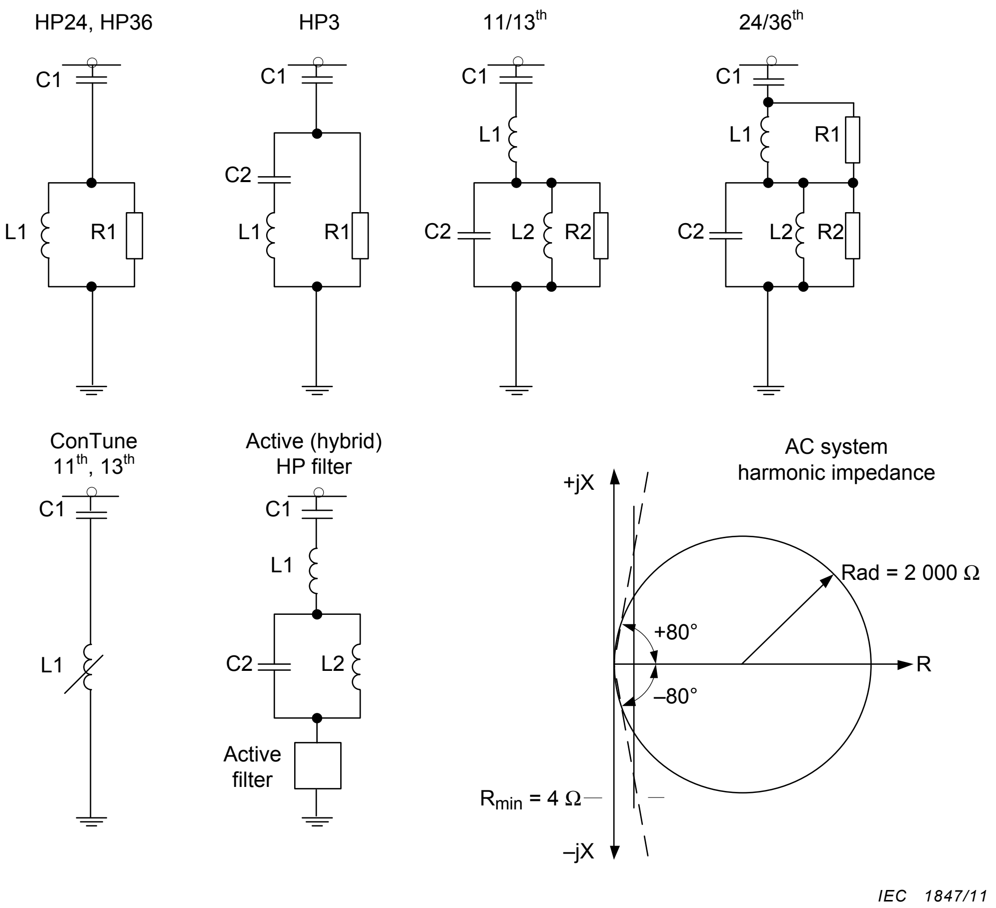


Figure 28 – Filter configuration and a.c. system harmonic impedance data

Parameters of filters installed at a.c. substations A (375 kV) and B (230 kV) are shown in Tables 6 and 7.

Table 6 – Parameters of filters at a.c. substation A (375 kV)

Filter Type →	11th	13th	HP3	HP36	11/13th
3-phase reactive power at nominal a.c. voltage, MVAr	43,8	31,2	60	37,5	90
C1, µF	1,16	0,84	1,61	1,00	2,39
L1, mH	72,17	72,17	789,31	7,80	29,65
C2, µF	-	-	12,84	-	85,44
L2, mH	-	-	-	-	0,83
R1, Ω	-	-	1 800	350	-
R2, Ω	-	-	-	-	65

Table 7 – Parameters of filters at a.c. substation B (230 kV)

Filter Type →	11th	13th	HP3	HP36	11/13th
3-phase reactive power at nominal a.c. voltage, MVAr	43,8	31,2	60	37,5	90
C1, μF	2,61	1,87	3,61	2,26	5,378
L1, mH	32,07	32,07	350,8	3,47	13,18
C2, μF	-	-	28,88	-	192,25
L2, mH	-	-	-	-	0,37
R1, Ω	-	-	850	170	-
R2, Ω	-	-	-	-	30

The highest values of each of the performance parameters at rated (1 000 MW) power are shown in Table 8.

Table 8 – Performance results of filters

Filter configuration	Performance parameter value		
	Dn/n (%)	THD (%)	THFF (%)
1	0,90/5	1,41	0,97
2	0,91/5	1,34	0,83
3	0,91/5	1,28	0,64

The configurations with the continuously tuned filter and active filters (configuration 3) give better performance as compared to that with the conventional passive filters.

These results cannot be generalised. For drawing conclusions for specific projects, the calculations need to consider realistic input data regarding a.c. system, e.g. harmonic impedance and reactive compensation requirements. Also filter detuning (important for passive filters) has to be considered.

6.13 ACfilters for HVDC installations using VSC

The application of voltage sourced converters (VSC) for d.c. interconnections has recently begun and will rise in the future. The features of HVDC systems with VSC are described in IEC 62543. By this reason less requirements for external reactive power demand and low frequency harmonic distortion compensation would be required in the future. In such a case at large power ratings, passive or small active filters may be included to compensate non-characteristics harmonics at higher frequencies than the PWM switching frequency of the main VSC. By this method of operation, the VSC can compensate lower order harmonics internally.

6.14 Conclusions on active a.c. filters

- For HVDC solutions a hybrid active power filter would be required in order to minimize the power rating of the active power filter and maximize the performance of the full filter.
- For retrofitting existing HVDC links with increased power quality problems in networks, it is expected that active filter configurations will be added to existing passive filter solutions.
- For series compensated converter HVDC systems, hybrid active power filters or tuneable passive solutions may be more cost effective than a pure passive solution.
- Active filters using multi-level topologies may be connected directly to the MV and LV networks without the use of transformers.

- It may be advantageous to connect active filters for HV networks via an existing or special coupling transformer. In such a case the current regulating reactor may be included into the design of the series impedance of the transformer. For protection purposes it is unlikely to connect the active filter on HV networks directly onto the supply voltage.
- In the future voltage sourced converter d.c. links may combine the harmonic filter and reactive power demand into a single power solution for HV networks.

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