

# PUBLICLY AVAILABLE SPECIFICATION PRE-STANDARD

Active filters in HVDC applications

IECNORM.COM : Click to view the full PDF of IEC PAS 62544:2008

WithNorm



## THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2008 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester.

If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

IEC Central Office  
3, rue de Varembe  
CH-1211 Geneva 20  
Switzerland  
Email: [inmail@iec.ch](mailto:inmail@iec.ch)  
Web: [www.iec.ch](http://www.iec.ch)

### About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

### About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

- Catalogue of IEC publications: [www.iec.ch/searchpub](http://www.iec.ch/searchpub)

The IEC on-line Catalogue enables you to search by a variety of criteria (reference number, text, technical committee,...). It also gives information on projects, withdrawn and replaced publications.

- IEC Just Published: [www.iec.ch/online\\_news/justpub](http://www.iec.ch/online_news/justpub)

Stay up to date on all new IEC publications. Just Published details twice a month all new publications released. Available on-line and also by email.

- Electropedia: [www.electropedia.org](http://www.electropedia.org)

The world's leading online dictionary of electronic and electrical terms containing more than 20 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary online.

- Customer Service Centre: [www.iec.ch/webstore/custserv](http://www.iec.ch/webstore/custserv)

If you wish to give us your feedback on this publication or need further assistance, please visit the Customer Service Centre FAQ or contact us:

Email: [csc@iec.ch](mailto:csc@iec.ch)  
Tel.: +41 22 919 02 11  
Fax: +41 22 919 03 00

IECNORM.COM: Click to view the full IEC PAS 62544:2008



IEC/PAS 62544

Edition 1.0 2008-02

# PUBLICLY AVAILABLE SPECIFICATION PRE-STANDARD

---

Active filters in HVDC applications

INTERNATIONAL  
ELECTROTECHNICAL  
COMMISSION

PRICE CODE **XA**

ICS 29.240.99

ISBN 2-8318-9595-2

## CONTENTS

<b>FOREWORD</b> .....	<b>4</b>
0.1 INTRODUCTION .....	5
0.2 SCOPE .....	5
<b>1 ACTIVE DC FILTERS IN HVDC APPLICATIONS</b> .....	<b>6</b>
1.1 INTRODUCING ACTIVE DC FILTERS .....	6
1.2 TECHNICAL DEMANDS TO DISTURBANCES ON THE DC SIDE .....	7
1.3 DESCRIPTION OF ACTIVE DC FILTERS .....	7
1.3.1 Semiconductors available for a power stage .....	8
1.3.2 Types of converters available .....	8
1.3.3 Connections of the active DC filter .....	9
1.3.4 Characteristics of installed active DC filters .....	11
1.4 MAIN COMPONENTS IN AN ACTIVE DC FILTER .....	11
1.4.1 The Passive Part .....	12
1.4.2 The current transducer .....	13
1.4.3 The control system .....	14
1.4.4 The amplifier .....	14
1.4.5 The Transformer .....	14
1.4.6 Protection circuit and arrester .....	14
1.4.7 Bypass switch and disconnectors .....	15
1.5 ACTIVE DC FILTER CONTROL .....	15
1.5.1 Active DC Filter Control methods .....	15
1.6 PROJECT DESCRIPTIONS AND DC FILTER SOLUTIONS .....	18
1.6.1 Skagerrak 3 HVDC Intertie .....	18
1.6.2 Baltic Cable HVDC Link .....	19
1.6.3 Chandrapur-Padghe HVDC power transmission project .....	20
1.6.4 Tian - Guang long distance HVDC project .....	21
1.6.5 EGAT-TNB (Thailand-Malaysia) HVDC Interconnection .....	21
1.7 PERFORMANCE OF THE SKAGERRAK 3 HVDC INTERTIE ACTIVE DC FILTER .....	22
1.8 CONCLUSIONS ON ACTIVE DC FILTERS .....	24
<b>2 ACTIVE AC FILTERS IN HVDC APPLICATIONS</b> .....	<b>25</b>
2.1 INTRODUCING ACTIVE AC FILTERS .....	25
2.2 TECHNICAL DEMANDS TO HARMONIC DISTURBANCES ON THE AC SIDE ....	25
2.3 PASSIVE FILTERS .....	26
2.3.1 Conventional passive filters .....	26
2.3.2 Continuously tuned passive filters .....	27

2.4	REASONS FOR USING ACTIVE FILTERS IN HVDC SCHEMES .....	28
2.5	OPERATION PRINCIPLES OF ACTIVE FILTERS .....	29
2.5.1	Shunt connected active filter .....	29
2.5.2	Series connected active filter .....	30
2.6	PARALLEL AND SERIES CONFIGURATION .....	31
2.6.1	Hybrid filter schemes .....	32
2.7	CONVERTER CONFIGURATIONS .....	33
2.7.1	Converters .....	33
2.7.2	STATCOM .....	35
2.8	ACTIVE AC FILTER CONFIGURATIONS .....	37
2.8.1	Active ac filters for low voltage application .....	37
2.8.2	Active ac filters for medium voltage application .....	37
2.8.3	Active ac filters for HVDC applications .....	37
2.9	SERIES CONNECTED ACTIVE FILTERS .....	38
2.10	CONTROL SYSTEM .....	39
2.10.1	Introduction .....	39
2.10.2	Description of a Generic Active Power Filter Controller .....	39
2.10.3	Calculation of Reference Current .....	40
2.10.4	Synchronous Reference Frame (SRF) .....	41
2.10.5	Other Control Approaches .....	42
2.10.6	HVDC AC Active Filter Control Approach .....	43
2.11	EXISTING ACTIVE AC FILTER APPLICATIONS .....	43
2.11.1	Low and medium voltage .....	43
2.11.2	High voltage applications .....	43
2.12	OVERVIEW ON FILTER SOLUTIONS FOR HVDC SYSTEMS .....	46
2.12.1	Solution with conventional passive filters .....	46
2.12.2	Solution with continuously tuned passive filters .....	47
2.12.3	Solution with active filters .....	47
2.12.4	Solution with continuously tuned passive filters and active filters .....	48
2.12.5	Study cases with the Cigré HVDC model .....	48
2.13	FUTURE TECHNOLOGIES .....	50
2.14	CONCLUSIONS ON ACTIVE AC FILTERS .....	50
<b>3</b>	<b>BIBLIOGRAPHY .....</b>	<b>51</b>

INTERNATIONAL ELECTROTECHNICAL COMMISSION

**ACTIVE FILTERS IN HVDC APPLICATIONS**

FOREWORD

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

A PAS is a technical specification not fulfilling the requirements for a standard, but made available to the public and established in an organization operating under given procedures.

IEC-PAS 62544 was submitted by the CIGRÉ (International Council on Large Electric Systems) and has been processed by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

The text of this PAS is based on the following document:

This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document

Draft PAS	Report on voting
22F/130/NP	22F/147/RVN

Following publication of this PAS, which is a pre-standard publication, the technical committee or subcommittee concerned will transform it into an International Standard.

An IEC-PAS licence of copyright and assignment of copyright has been signed by the IEC and CIGRÉ and is recorded at the Central Office.

This PAS shall remain valid for an initial maximum period of three years starting from the publication date. The validity may be extended for a single three-year period, following which it shall be revised to become another type of normative document or shall be withdrawn.

# ACTIVE FILTERS IN HVDC APPLICATIONS

By Cigré Working Group 14.28

## 0.1 INTRODUCTION

Fourteen active DC filters and one active AC filter exist already in HVDC converter stations. The interest in active filters for HVDC systems is mainly due the fact that a single active filter is able to mitigate effectively diverse harmonics simultaneously, which otherwise would require several passive filters to achieve a comparable result. They can also contribute to reducing the size of the smoothing reactors used at the DC side and to reducing losses. They are also able to cope with harmonic resonance problems and to adapt themselves to changes in the harmonic impedance of the system, which are important characteristics, especially for the connection to the AC side.

## 0.2 SCOPE

This report prepared by Working Group 14.28 presents both DC and AC active filters, including the existing installations. The items of the report are basically arranged in two consecutive parts, the first one treating the DC application, and the second covering the AC filters. As active DC and AC filters share many concepts, the reader interested in such a subject is encouraged to search for it in both parts.

# 1 ACTIVE DC FILTERS IN HVDC APPLICATIONS

## 1.1 INTRODUCING ACTIVE DC FILTERS

The conversion process in an HVDC transmission system introduces harmonic currents into the DC transmission lines and the AC grid connected to the HVDC converters. These harmonic currents may cause interference in the adjacent systems, such as telecommunication equipment. The conventional solution to reduce the harmonics has been to install passive filters in HVDC converter stations [1]<sup>1)</sup>. 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 powerful new way for further reduction of harmonic levels, namely, active filters.

The active filters can be divided into two groups, active AC and DC filters. Active DC filter installations are in operation in several HVDC links and have been economically competitive due to increased demand on telephone interference levels on the DC overhead lines (Figure 1.1.1). An active AC filter is already in operation as well. In addition to the active DC filter function of mitigating the harmonic currents on the DC overhead lines, the active AC filters may be part of several solutions in the HVDC scheme to improve reactive power exchange with the AC grid and to improve the dynamic stability.

Already in the 1960s there were attempts to develop and install an active filter in a HVDC converter station in Sweden, but the project turned out unsuccessfully. In the middle of the 1980s the technological development of the presently installed active filters was initiated. Mainly two reasons make the projects successful. Primarily, the prices on semiconductors have decreased dramatically and secondly, digital computers are getting more powerful.

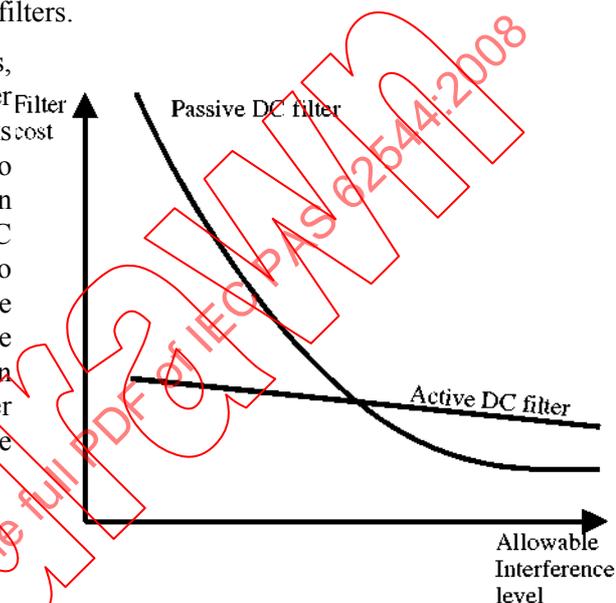


Figure 1.1.1 Conceptual diagram of allowable interference level and DC filter cost

The reasons to develop first the active DC Filter and subsequently the active AC filter, were:

- Active AC and DC 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 AC filter is used to supply the HVDC converter demand of reactive power and thereby loaded with the fundamental current, the required rating of the DC filter active part is lower than that of the AC filter active part.
- The control philosophy for the active DC filter is less complex than for the AC one.
- The present HVDC applications where active AC filters are feasible will be limited, due to the fact that AC filters are also required to supply the HVDC converter demand of reactive power. The filter size is therefore often well above the filtering demand.

In future HVDC projects a new converter technology may be applied, implying that the reactive power can be separated from the AC filters and thereby make the active AC filter more feasible. The most promising technologies are the Capacitor Commutated Converters (CCC) and the Controlled Series Capacitor Converter (CSCC), but GTO controlled converters are also able to keep the reactive power balance from the converter within a minimum.

1) Figures in square brackets refer to the Bibliography.

## 1.2 TECHNICAL DEMANDS TO DISTURBANCES ON THE DC SIDE

The main reason for specifying demands on the DC 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 DC line or as an induced voltage “ $U_{ind}$ ” in a fictive telephone line. The reader should keep in mind that the harmonic demand, the specific HVDC system and surroundings (earth resistivity, telephone system etc.) all together define the DC filter solution.

The specified demand:

- The induced voltage “ $U_{ind}$ ” in a theoretically 1 km telephone line situated 1 km from the DC 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 DC pole overhead line shall be below 400 mA.

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

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

where  $f_n$  is the frequency of the n-th harmonic.  $M$  is the mutual inductance between the telephone line and the power line,  $k_n = \frac{f_n}{80} * n$ ,  $I_n$  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 1.2.1) and  $p_{16}$  is the 16<sup>th</sup> 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 1.2.1 The psophometric weighting factor at selected frequencies.

Frequency/Hz	50	100	300	600	800	1000	1200	1800	2400	3000
n	1	2	6	12	16	20	24	36	48	60
$p_n$ Factor	0.0007	0.009	0.295	0.794	1.000	1.122	1.000	0.760	0.634	0.525
$p_n * k_n$	0.00004	0.001	0.111	0.595	1.000	1.403	1.500	1.710	1.902	1.969

## 1.3 DESCRIPTION OF ACTIVE DC FILTER

Active DC filters use a controllable converter to introduce currents in the network, presenting a waveform which counteracts the harmonics. This clause describes types of power stages, converters to be

used in active filters and the possible connections in HVDC schemes.

### 1.3.1 Semiconductors available for a power stage

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

- The MosFET
- The IGBT
- The GTO

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 DC filter range, is inferior to the MosFET. However the IGBT power handling is significantly higher than the MosFET.

The GTO has the highest power handling capacity, but with a relatively limited switching speed far below the required frequency range for active DC filter. The use of GTO will probably be limited to handling frequencies below a few hundred of Hertz.

The relatively high frequency band for active DC 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 to the use of IGBT in future power stages.

### 1.3.2 Types of converters available

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

In a CSC the DC element is a current source, which normally consists of a DC voltage source power supply in series with an inductor. For correct operation the current should flow continuously in the inductor. Hence, if AC current is not required, current must be by-passed within the converter. This fact restricts the switching actions. A simple CSC is shown in Figure 1.3.1.

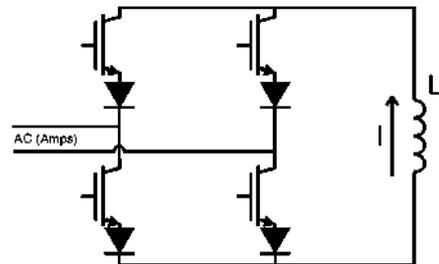


Figure 1.3.1 Simple current source converter

#### 1.3.2.2 Voltages source converters (VSC)

In the VSC the DC element is a voltage source. This may be a DC power supply or, in the case of an active DC filter application, an energy storage unit. In practice, the voltage source for an active DC 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 AC output appears as a voltage source.

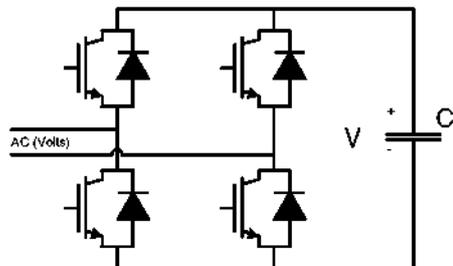


Figure 1.3.2 Simple voltage source converter

A circuit of simple VSC is shown in Figure 1.3.2.

### 1.3.2.3 Comparison between current and voltage source converters

The CSC 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 that can be employed, while the CSC is restricted as described above. The necessity for continuous current in the CSC, combined with the fact that (neglecting superconductivity) an inductor has higher losses than a capacitor, ensures that the losses in the CSC are higher than those in the VSC. Another parameter influencing losses is that a CSC needs switching devices which can block reverse voltage. Most of the operating 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 CSC 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.

### 1.3.3 Connections of the active DC filter

Advantages and disadvantage of connecting the active filters at locations shown in Figure 1.3.3 have been discussed in several papers [4,5,6,7,8,9,10]. The active filters can be connected either as shunt active filters or as series active filters.

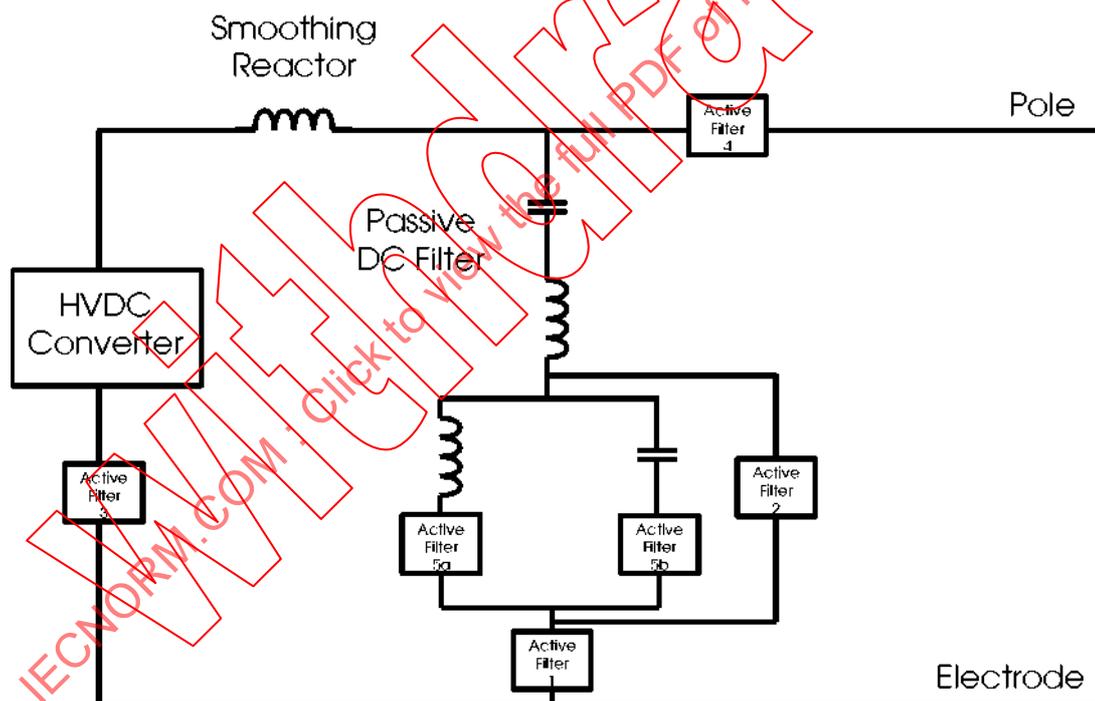


Figure 1.3.3 Possible connections of active DC filters

#### 1.3.3.1 The "active filter 1" connection

The active DC filter realised in HVDC schemes today is connected as the shunt "active filter 1" in Figure 1.3.3. By connecting the active filter in series with the passive DC 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.

### 1.3.3.2 The "active filter 2" connection

The "active filter 2" in Figure 1.3.3 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 for injecting harmonic currents to counteract the disturbance current and thereby increase the rating of the converter. There may be an additional inductance inserted in series with the active part.

### 1.3.3.3 The "active filter 3" connection

The "active filter 3" in Figure 1.3.3 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 DC 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 DC 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 DC filter and therefore no ripple current in the DC pole line, the active filter must generate across the main winding " $T_c$ " a voltage which compensates the ripple voltage " $U_r$ " of the DC side of the HVDC converter.

The AC 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 " $(I_{dconv} + I_r)^2 \cdot L_r$ ". 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 it 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 DC 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 " $T_c$ ".

### 1.3.3.4 The "active filter 4" connection

The "active filter 4" in Figure 1.3.3 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 DC 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 DC current.

### 1.3.3.5 The "active filter 5" connection

There has not been any article describing "active filter 5a and 5b" in Figure 1.3.3. 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".

### 1.3.3.6 Conclusion on active filter connections

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

The injected power for active filtering can be reduced by choosing the optimum line injection point on the passive circuit or the DC line. All active DC filter applications implemented today and in the near future will use the "active filter 1" solution in Figure 1.3.3. The remaining part of this document therefore discusses the "active filter 1" solution.

## 1.3.4 Characteristics of installed active DC filters

The active DC filters today (Figure 1.4.1), 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 DC filters:

- frequency range 300 Hz -3000 Hz;
- the achieved harmonic current attenuation is high, at least 10 times more attenuation than that achievements with the passive part alone, at all chosen frequencies in the whole frequency range (Figure 1.7.1);
- adaptable to variations of network frequency;
- compensate detuning effects of the passive DC filter;
- comparatively small size. the active part of the active DC filter can be fully assembled and tested at the factory and then transported to site;
- significant changes in characteristics of the active DC filter can be achieved any time after commissioning within the active filter ratings by software changes without hardware modification.

## 1.4 MAIN COMPONENTS IN AN ACTIVE DC FILTER

The active DC 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 DC line. The active part in the DC filter is defined as the components within the box shown in Figure 1.4.1. All the components in the active part shall ensure proper function of the active filter in steady state conditions and during faults.

Figure 1.4.1 shows the active filter components in the filters today.

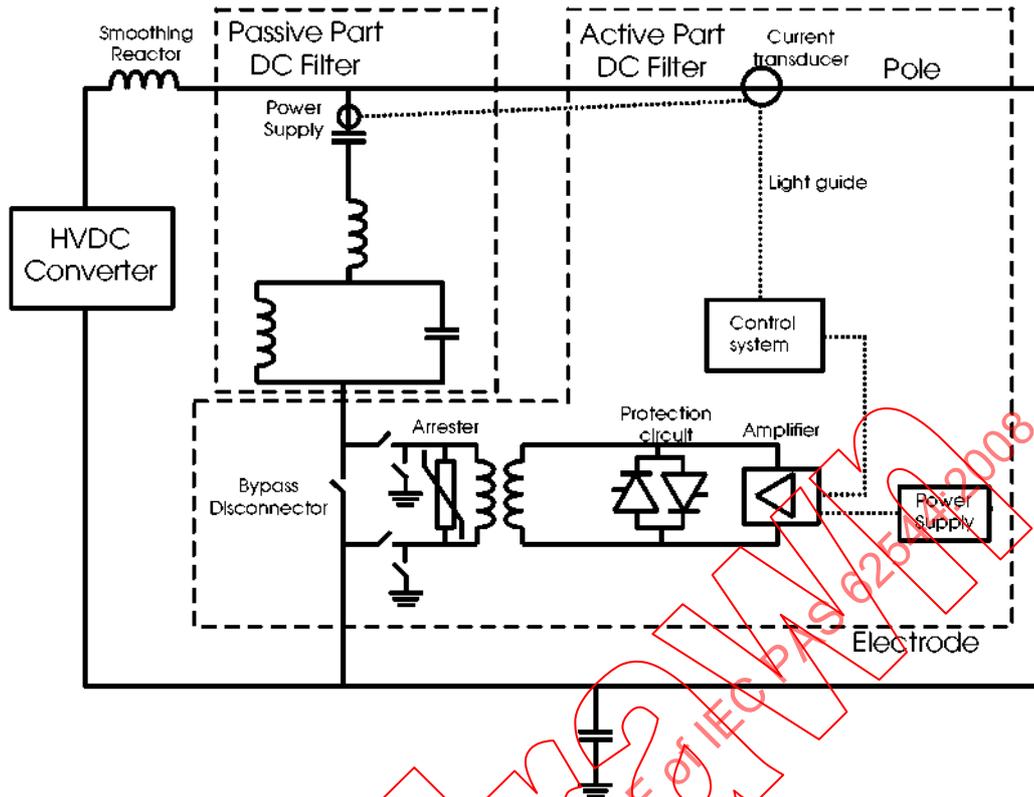


Figure 1.4.1 Filter components in the active filter

### 1.4.1 The Passive Part

The main function of the passive part is to connect the active part with the high voltage DC 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 harmonic filter is used;
- a double tuned 12/24 harmonic filter is used.

Table 1.4.1 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 AC grid. The smoothing reactor has 200 mH, the main capacitor has 1  $\mu$ F. The root sum of squares of a typical measured current spectrum through the smoothing reactor gives 15.7 A<sub>rms</sub>. 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 1.4.2.

The reader should pay attention to the fact that the calculated case in Table 1.4.1 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 DC filter design, the designer has to include various other parameters.

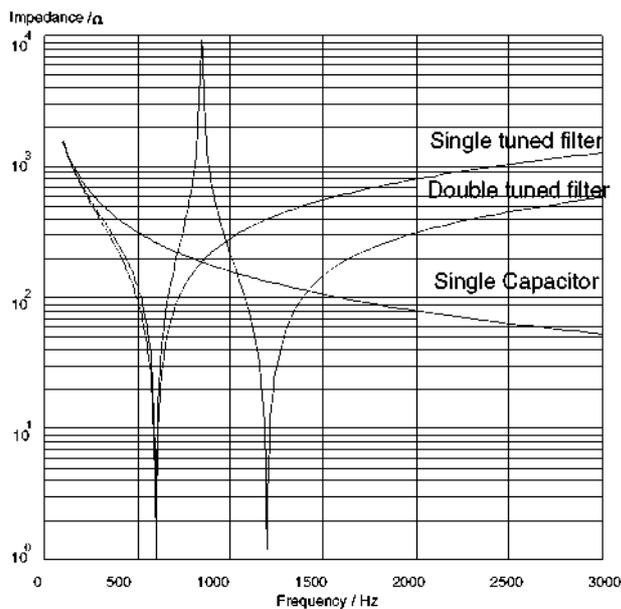


Figure 1.4.2 Impedance Characteristic of different passive filters

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

Table 1.4.1 Voltage to be supplied by the active part with different selections of passive parts

### 1.4.2 The 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 [12],[13]. To get a correct functioning of the active DC filter, it is required to have at least one current transducer at each pole line in the station where the active DC filter(s) is/are installed. The current transducer may be connected to the control through a light guide (Figure 1.4.1) and is fed from a power supply which utilizes 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 DC current through the current transducer. The DC current makes it difficult to use an iron core transformer.
- The second harmonic current can be of considerable size (more than  $10 A_{\text{rms}}$ ), 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 DC transmission level. The current transducer can be equipped with an electronic unit to communicate with ground level equipment.

The primary costs in the design of a conventional DC filter are the smoothing reactor and the main DC filter capacitor connected to the DC 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.

The main difference between a conventional passive DC 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 AC 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 DC 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 DC filter were inserted to reduce the resonance in the overall system.

The DC capacitor will always be a part of the active DC filter, connecting the active part with high voltage DC line. In future active DC 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.

- The current measurement with the analogue/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 (typically 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).

### 1.4.3 The control system

An A/D conversion is necessary before the signal from the current transducer enters the digital signal processors (DSP) and, in some installations, also a 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 clause 1.5. To be able to control the VSC at frequencies up to 3,0 kHz, the computer or parts of the computer shall process complex tasks with a sample rate of at least 10 kHz. 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 of control and easy adaptability to new control algorithms.

### 1.4.4 The amplifier

The voltage source 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 kHz. 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 kHz), higher voltage and better power handling with lower losses.

When using switching devices, harmonic distortions in the PLC range (30 kHz – 500 kHz) outside the active control range may be introduced. With the present active DC 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.

### 1.4.5 The 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, 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.

### 1.4.6 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.

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

### 1.4.7 Bypass switch and disconnectors

The bypass switch and disconnectors are installed in all active DC 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.

## 1.5 ACTIVE DC FILTER CONTROL

The aim of an active DC 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 DC 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 DC 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 DC filter / multiple active DC filters;
- the control system must be able to recover from abnormal system conditions.

### 1.5.1 Active DC Filter Control methods

Three basic different control principles are discussed in this section, namely, feedback control, feedforward control or a combination of the two methods.

#### 1.5.1.1 Feedback control

Feedback control forms the core of existing active DC filters in HVDC applications [14, 15] - such as shown in Figure 1.5.1. 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 1.5.1. 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  $I_{fil}$  is the compensation current from the active DC filter. The total line current  $I_{ine}$  is the sum of  $I_{conv}$  and  $I_{fil}$ . The external process is the transfer function between the output voltage from the active DC filter control,  $u_a$ , and the current  $I_{fil}$ .

The controller of Figure 1.5.1 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 – 3 000 Hz).

The second block identifies each individual harmonic and then refers it to a set of two orthogonal vectors ( $\cos n \cdot \omega_0 \cdot t$ ,  $\sin n \cdot \omega_0 \cdot t$  - where the integer  $n$  corresponds to the harmonic order and  $\omega_0$  to  $2\pi f_0$ , and  $f_0$  represents the fundamental frequency). The block receives a synchronising signal derived from the converter AC 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.

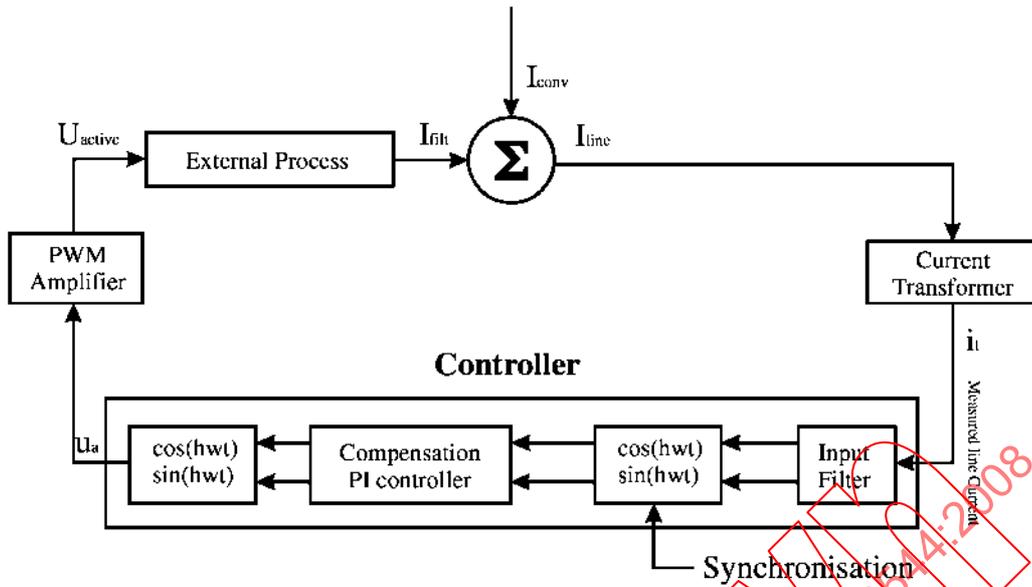


Figure 1.5.1 Basic control loop of an active DC filter

The third block performs the function of filter and PI controller. The block also compensates the external process at the harmonic frequency  $n \cdot f_0$ . An example of a measured transfer function of the external process is shown in Figure 1.5.2.

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.

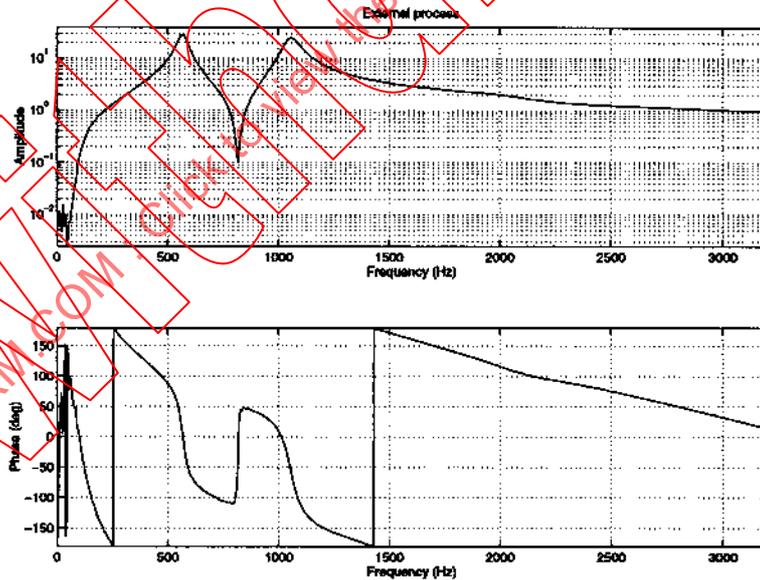


Figure 1.5.2 Measured transfer function of external system, Baltic Cable HVDC link

### 1.5.1.2 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, AC 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 DC 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.

Contrary 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 1.5.3). 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.

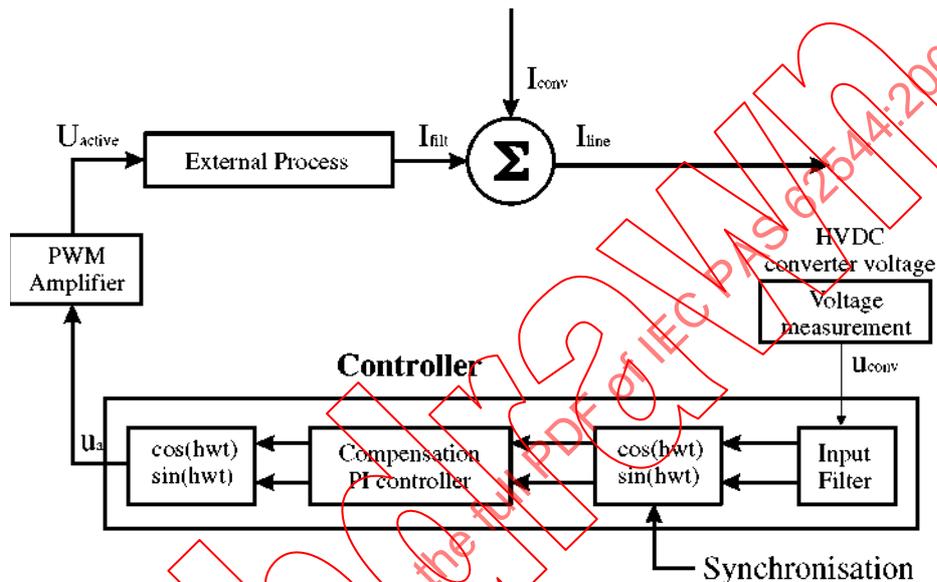


Figure 1.5.3 Feed Forward Control for the active DC filter

### 1.5.1.3 The 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 DC filter control, the dynamic specifications of the active filter and the cost/availability of high bandwidth 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.

### 1.5.1.4 Control and supervision for the active DC 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 DC 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 min. The harmonic supervision verifies if the primary control is working satisfactory.

### 1.5.1.5 Measurement systems

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

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

## 1.6 PROJECT DESCRIPTIONS AND DC FILTER SOLUTIONS

Several active DC filters are in operation in HVDC schemes today. All of the installed active DC filters for HVDC applications have been manufactured by ABB Power Systems AB and by Siemens AG. This clause will describe the background of the installed active filters.

In 1991 a test installation of an active DC filter was in operation at the Lindome Converter Station [16]. The first commercial active DC filter was installed at the Tjele Converter Station in the Skagerrak 3 HVDC Intertie commissioned in 1993, the second active DC filter was installed at the Baltic Cable HVDC Link commissioned in 1994. In the Chandrapur-Padghe HVDC Bipole Project two active DC filters in each station were commissioned in 2001. In the Tian-Guang long distance HVDC project two active filters plus one spare active filter in each station were installed in 2001. One active filter each at both the Thailand and Malaysia sides of the EGAT-TNB HVDC Interconnector project were also commissioned in 2001.

### 1.6.1 Skagerrak 3 HVDC Intertie

The new pole 3 has approximately the capacity of the two existing poles. The design was not a single pole solution. To minimise the losses and the electrode current, the current on one of the existing poles was reversed and the link with the three poles was operated as a hybrid bipole (Figure 1.6.1).

The Pole 1 and Pole 2 DC filters have been extended from just a capacitor to tuned filters to meet the changes in the old poles and to be able to fulfil the demands in the specification. Active DC filter on Pole 3 is a passive double tuned 12/36 filter with an active part. The passive filter has two functions: To couple the VSC to the 350 kV pole line and to work as a passive filter when the active part is not in operation. The pole 3 DC filter is coupled between the pole line and neutral bus.

The overall control strategy is to minimise the earth mode current, thus three current transducers are installed, one at each pole. Consequently the harmonic current on the pole 3 line shall only be zero when pole 3 is operated as a monopole.

The control algorithm of the active DC filter will work on whole multiples of the fundamental frequency in the frequency domain 300 Hz – 3 000 Hz. The reason not to control lower frequencies is that the rating of the VSC will increase manifold times. Furthermore when considering the psophometric weighting factor in the overall disturbance, the contribution from lower harmonics is negligible.

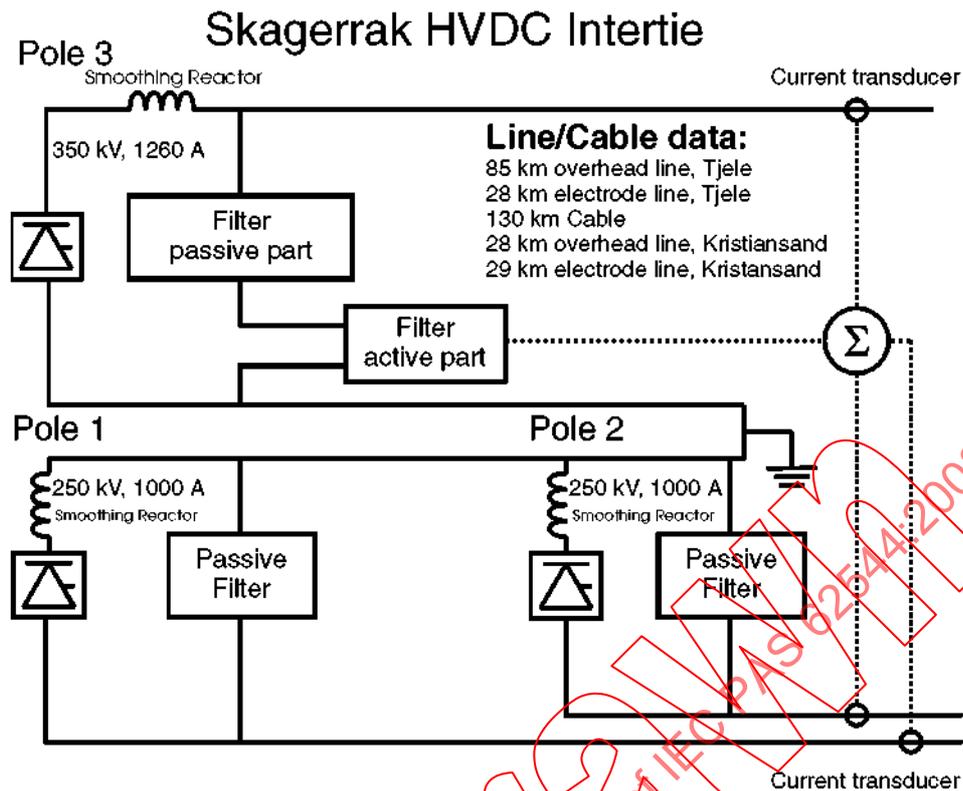


Figure 1.6.1 Simplified diagram, showing active filter connection

The active DC filter in Skagerrak replaces one additional passive filter branch compared to a purely passive solution.

### 1.6.2 Baltic Cable HVDC Link

The active DC filter is a passive double tuned 12/24 filter with an active part, located at the Kruseberg station at the Swedish side. Since no overhead line is present at the German side, no DC filter was installed in Germany. The passive filter couples the active part to the 450 kV DC pole line. The tuning of the passive filter is chosen to minimise the rating of the active part. The active DC filter is coupled from the pole line to earth (Figure 1.6.2).

The control strategy is to minimise the DC pole line current harmonics coming from Kruseberg (the Swedish station) and from Herrenwyck (the German station). The control algorithm of the active DC filter works on whole multiples of the fundamental frequency in the frequency domain 300 Hz – 3 000 Hz. Since no DC filter is installed in Herrenwyck, the harmonics 600 Hz and 1 200 Hz currents coming through the cable are especially significant, therefore the controller has to mitigate these currents as well.

The active filter solution in Baltic cable replaces one additional passive filter branch and one smoothing reactor placed on the line side of the passive filter branches in Kruseberg. If only shunt filters were used, filters in both stations had to be installed. Due to the low impedance of the DC line and cable seen from Kruseberg the number of filter branches would be impractical and definitely not economical.

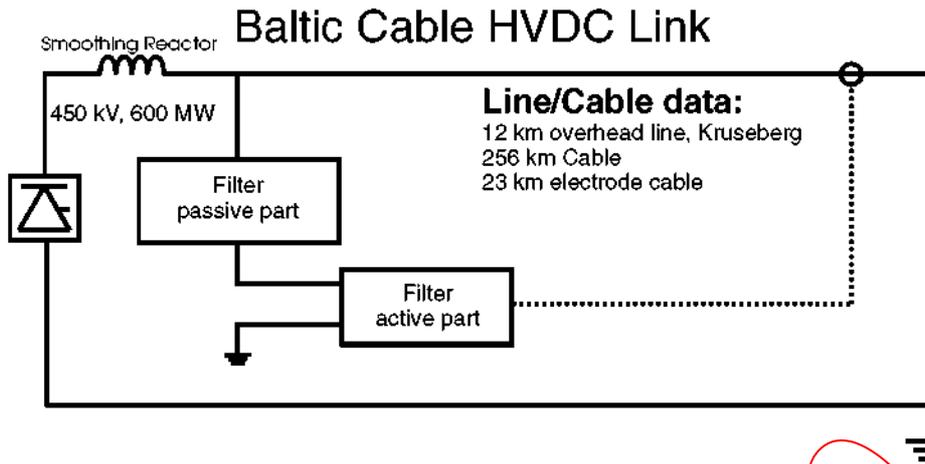


Figure 1.6.2 Simplified diagram, showing active filter connection

### 1.6.3 Chandrapur-Padghe HVDC power transmission project

The DC filter is a passive double tuned 2/6 filter and passive double tuned high-pass 12/24 filter with an active part. The 2/6 filter is necessary due to resonance with the DC line. Four active filters will be installed and each active DC filter is connected from the pole line to neutral bus (Figure 1.6.3).

The control strategy is to minimise earth mode current. The active DC filters works on whole multiples of the fundamental frequency in the frequency range 350 Hz – 2 500 Hz. The project was the first project with four active filters co-operating in one transmission.

The active filter solution in Chandrapur-Padghe replaces one additional passive filter branch in each pole and station compared to a purely passive solution.

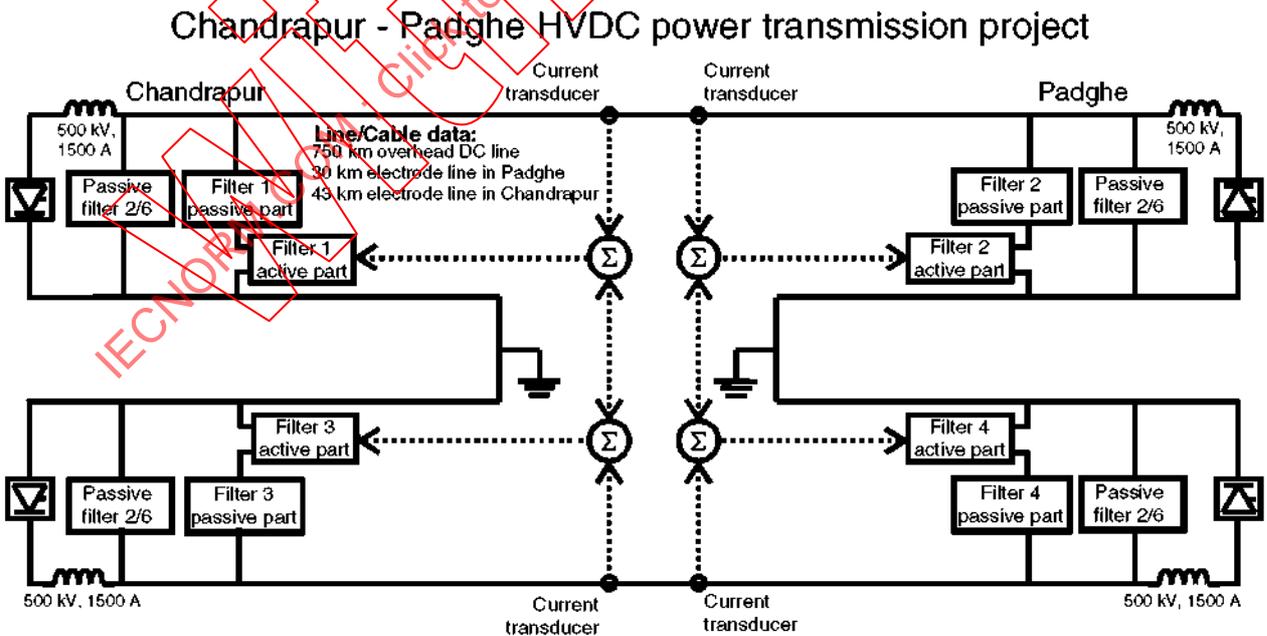


Figure 1.6.3 Simplified diagram, showing active filter connection

### 1.6.4 Tian - Guang long distance HVDC project

Each terminal station is provided with a DC filter scheme as shown in Figure 1.6.4. The DC filter consists of a passive part with a double tuned 12/24 filter with damping resistor and an active part. At each station a spare DC filter is installed, able by means of disconnectors to replace the DC filter at either pole. Six active filters are thus installed with four DC filter in continuous operation.

The control objective is to mitigate the harmonics in both lines.

The current transducers are Rogowski coils, but contrary to the previous current transducers, the electronics are powered by light guides directly from the control equipment.

The active filter solution in the Tian - Guang HVDC project replaces one additional passive filter branch in each pole and station and reduces the size of the smoothing reactor compared to a purely passive solution.

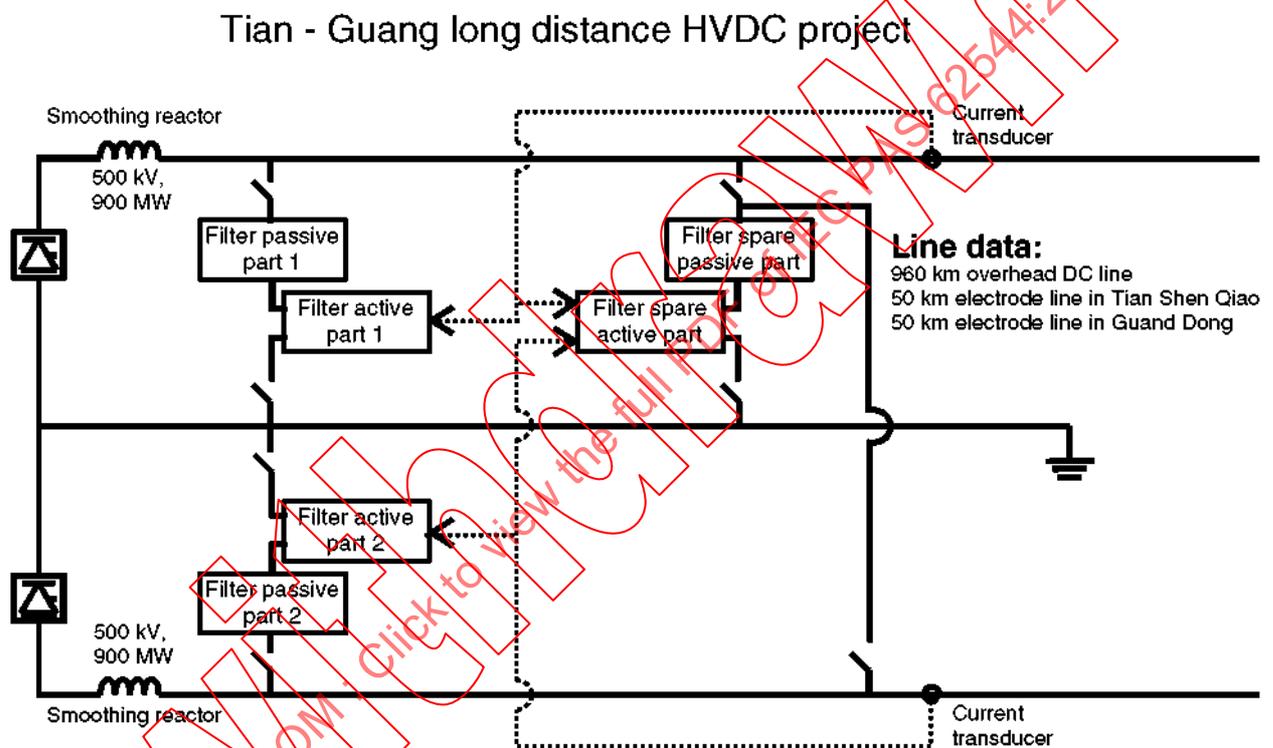


Figure 1.6.4 Simplified diagram, showing active filter connection

### 1.6.5 EGAT-TNB (Thailand-Malaysia) HVDC Interconnection

Each terminal station is provided with a DC filter scheme as shown in Figure 1.6.5. The DC filter consists of a passive part with a double tuned 12/24 filter without damping resistors and an active part. The control objective is to mitigate the harmonics in the line conductor connected to the smoothing reactor.

At its first stage, the interconnection operates as a monopolar metallic return scheme, where either line pole 1 or 2 can be used as an HV conductor. The current transducers are Rogowski coils with light guide powered electronics. The proper current signal is automatically selected according to the operation mode of the line.

The active filter solution in the EGAT-TNB HVDC Interconnection replaces one additional passive filter branch in each station and reduces the size of the smoothing reactor compared to a purely passive solution.

### TNB - EGAT HVDC Interconnection (1<sup>st</sup> stage)

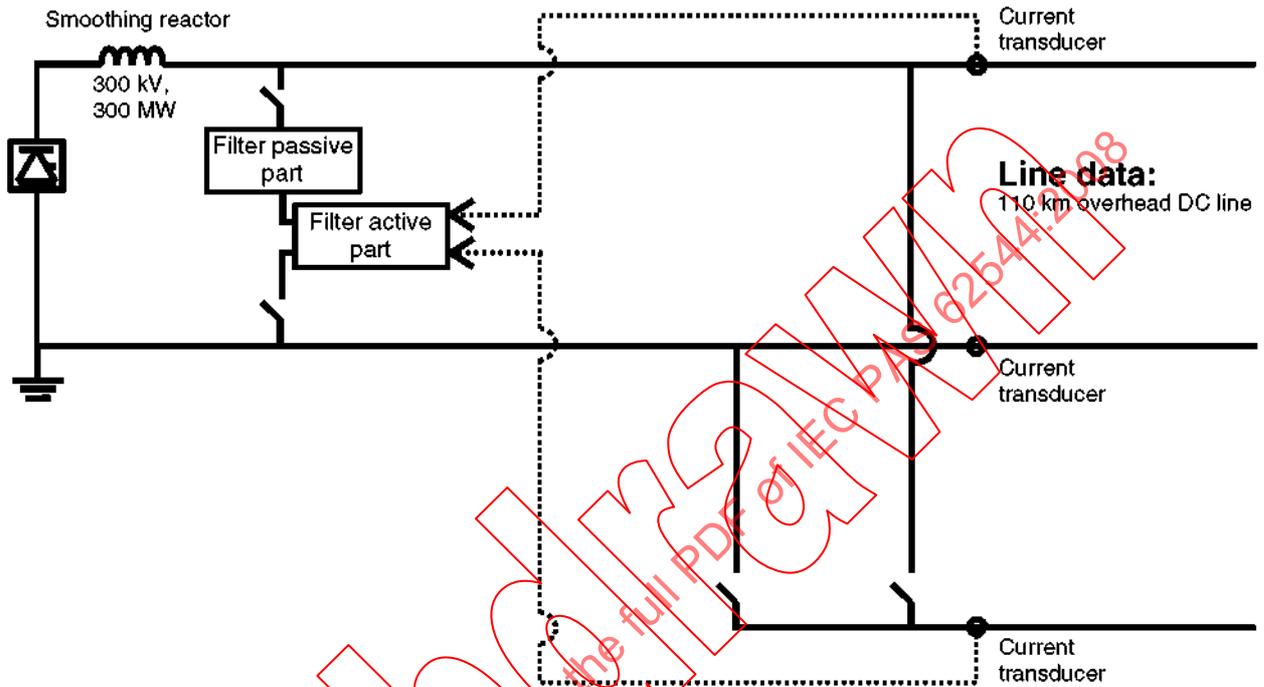


Figure 1.6.5 Simplified diagram, showing active filter connection

### 1.7 PERFORMANCE OF THE SKAGERRAK 3 HVDC INTERTIE ACTIVE DC FILTER

To illustrate the performance of the active DC 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 1.7.1. 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.

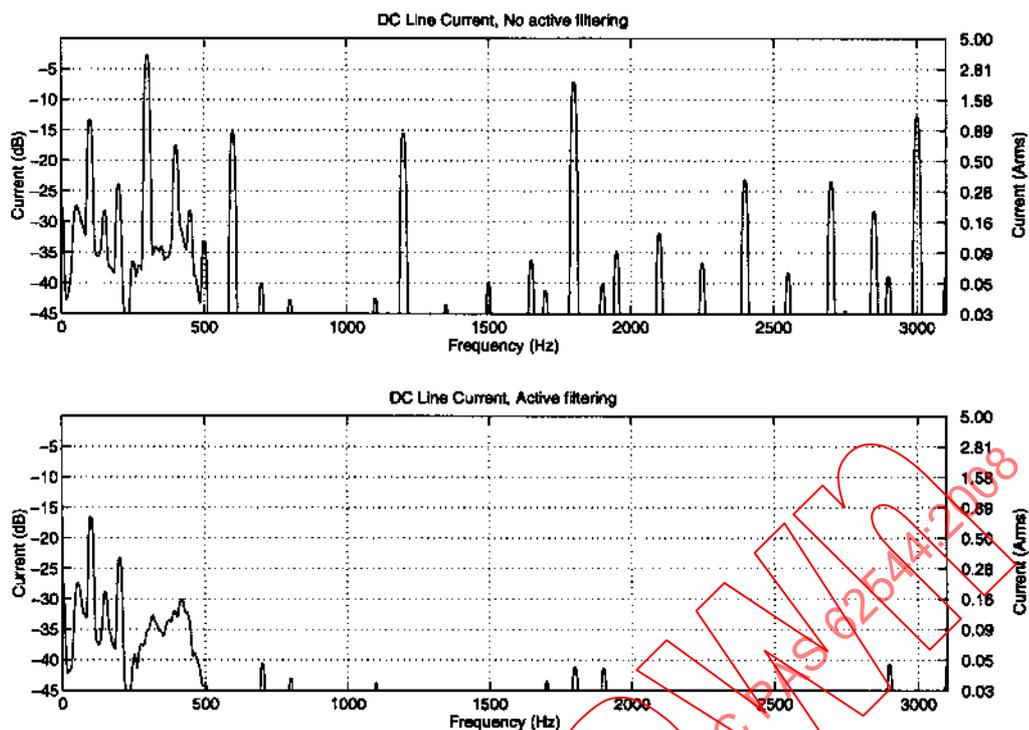


Figure 1.7.1 Measured line current spectra, pole 3 operated as monopole.

The psophometric current (see Clause 2)

Figure 1.7.1, was reduced from 4780 mA to 255 mA. The major harmonic line currents are shown in Table 1.7.1.

Table 1.7.1 Major harmonic line currents, pole 3 operated as monopole

Frequency [Hz]	Weight factor $p_n * K_n$	No active filtering		Active filtering	
		Current [A <sub>rms</sub> ]	Weighted Current [A <sub>rms</sub> ]	Current [A <sub>rms</sub> ]	Weighted Current [A <sub>rms</sub> ]
300	0.111	3.668	0.406	0.0881	0.0097
600	0.595	0.844	0.503	0.0180	0.0107
1200	1.500	0.836	1.253	0.0245	0.0368
1800	1.710	2.216	3.788	0.0436	0.0746
2400	1.902	0.350	0.675	0.0253	0.0488
2700	1.957	0.338	0.662	0.0217	0.0424
3000	1.969	1.164	2.292	0.0242	0.0477

## 1.8 CONCLUSIONS ON ACTIVE DC FILTERS

- The need for active DC 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 DC 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 DC line.
- The type most suited to power stage applications, particularly high power, is the voltage source converter.
- The relative high frequencies for active filtering exclude thyristors and GTO. Consequently MosFET and IGBT are used in voltage source 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 DC filters use feedback control, but feedforward control or a combination might be a future option.
- Adequate protection of the voltage source converter is essential for active DC filter schemes.

IECNORM.COM : Click to view the full PDF of IEC PAS 62544:2008

Withdorm

## 2 ACTIVE AC FILTERS IN HVDC APPLICATIONS

### 2.1 INTRODUCING ACTIVE AC FILTERS

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 LV and MV distribution networks is caused by such loads, and may even be propagated into HV networks. In particular the 5<sup>th</sup> 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<sup>th</sup> and 13<sup>th</sup> 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<sup>th</sup> and 23/25<sup>th</sup> 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 power filters have also motivated their application for HVDC, on the AC, DC or both sides of the HVDC converter [20],[21],[22],[23].

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 HVDC side are already in operation and have been studied by our WG recently [24]. The power requirements for the HVAC side may be considerably higher. Only one plant is under operation at the AC side of an HVDC converter station, as a pilot project, and it is also described in this report.

For tutorial reasons, LV and MV applications of active filters with different control schemes are also discussed briefly.

### 2.2 TECHNICAL DEMANDS TO HARMONIC DISTURBANCES ON THE AC SIDE

Many loads produce harmonics at low and medium voltage networks. Fluorescent tubes and lamps as well as computers and other electronic devices generate harmonics. For the low and medium voltage, the grid owner may need to install filters at the distribution bus if the voltage distortion caused by all small harmonic sources in the system, is unacceptable. When connecting HVDC converter stations or large loads to the AC system that generate harmonics, such as industrial rectifiers, large motor drives and electrical arc furnace plants, AC filters are usually installed as a part of these loads or the HVDC system in order to ensure that the injection of harmonics into the AC 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 the customer's and the 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 interfere with the telecommunication via inductive couplings between the two systems. Even the induced voltages in telecommunication and other low voltage system caused by harmonics flowing in the AC system may result in voltages higher than the regulations permit with respect to human safety.

A discussion on the permissible distortion limits is included in the report "Guide to the Specification and Design Evaluation of AC Filters for HVDC Systems" by the WG 14.30 [25]. Some typical values are considered in the item 1.12.5 of the present report.

## 2.3 PASSIVE FILTERS

### 2.3.1 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. Usually the passive filters are tuned to one frequency only (single-tuned filter), to two frequencies (double-tuned filter) or even to three frequencies (triple-tuned filter). Variations in frequency and temperature, causing impedance variation of the filters (detuning), in most cases result in the need for damping resistors in the filter in order to make the characteristics more 'soft'. The introduction of the damping resistor makes the filtering performance at tuning frequency less effective, however a wider frequency range can be filtered and hence the frequency variations are coped with.

The reduced filtering efficiency caused by the resistor may lead to a need for larger filters or installation of more parallel filter banks. The design of passive filters is highly dependent on the connected harmonic impedance of the network. It is vital that critical resonances between network and filter are avoided. In order to obtain an adequate passive filter design, detailed studies are required to be performed.

A typical double-tuned filter is shown in Figure 1.3.1.

In Cigré technical brochure no. 139 [25], passive AC filters for HVDC systems are described and discussed in detail.

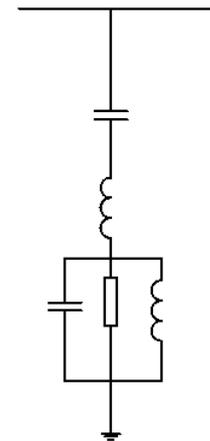


Figure 1.3.1: Conventional double tuned passive filter with damping resistor

With high demand on filter efficiency, it may be difficult to maintain the reactive power balance with the AC system and at the same time meet the filtering requirements. In this case more sophisticated solutions should be applied, such as continuously tuned filters, active filters or hybrid filters.

## 2.3.2 Continuously tuned passive filters

### 2.3.2.1 Introduction

As mentioned above, conventional bandpass filters (for example, 11<sup>th</sup> and 13<sup>th</sup>) have to be equipped with damping resistors for giving a broad band characteristic to allow them to cope with the frequency variations of the AC network and the variations in component values due to temperature changes. Consequently, filtering at high harmonic levels may require a number of large harmonic filter banks.

Figure 1.3.2 shows a continuously tuned filter. A continuously tuned AC filter is always tuned to the harmonic frequency (e.g. 11<sup>th</sup> or 13<sup>th</sup>) 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.

### 2.3.2.2 Filter reactor with variable inductance

No physically moving parts are needed for changing the inductance. An iron core is placed in the centre of the reactor. Around the iron core there is a control winding, see Figure 1.3.4. By feeding direct current into the control winding, the total magnetic flux in the reactor is influenced, thereby changing the inductance. The linearity of the rate of change of inductance with respect to the control current is high, which simplifies designing to avoid instability in tuning control.

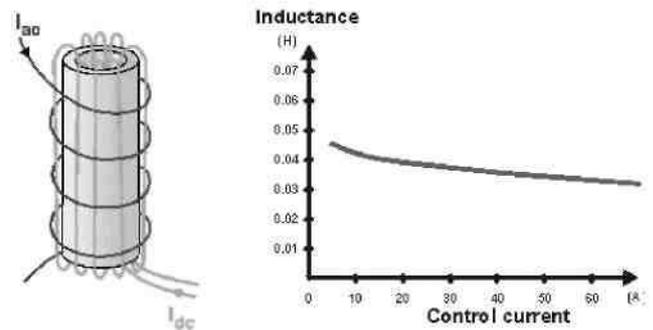


Figure 1.3.4:  
Principal overview of a filter reactor  
with variable

### 2.3.2.3 Automatic tuning control

The schematic overview of the continuously tuned filter is shown in Figure 1.3.3.

The AC bus harmonic voltage and the filter harmonic current are measured and the phase angle  $\alpha$ ,

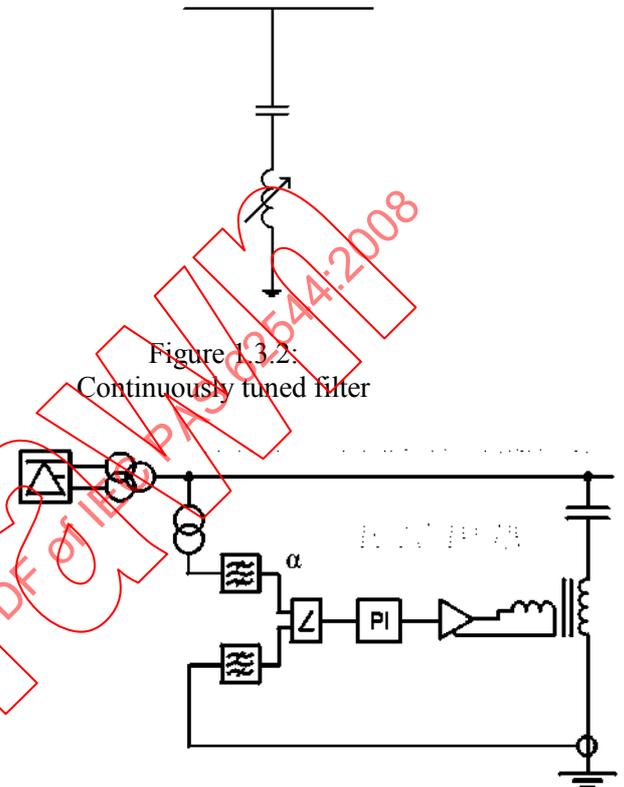


Figure 1.3.3:  
Schematic overview of continuously tuned filter

calculated. The direct control current fed through the control winding is then adjusted to achieve zero phase shift between the voltage and current of the particular harmonic. This is the criterion for perfect tuning of the filter.

### 2.3.2.4 Existing continuously tuned filter installations

A prototype 11<sup>th</sup> harmonic ConTune AC filter (ConTune: is a trade mark for ABB's continuously tuned filter) has been in operation at the Lindome station of the Konti-Skan HVDC link since December 1993. The operation experience from this has been very good.

A commercial 11<sup>th</sup> filter is in operation at Celilo station of the Pacific Intertie HVDC transmission.

A filter scheme consisting of 11<sup>th</sup> and 13<sup>th</sup> ConTune and 24<sup>th</sup> and 36<sup>th</sup> conventional high-pass filters is installed for the 600 MW SwePol cable transmission with conventional HVDC converters (see also 1.12.2.1). Capacitor banks provide the reactive power balance.

A filter scheme with 11<sup>th</sup> and 13<sup>th</sup> ConTune and 24<sup>th</sup> and 36<sup>th</sup> conventional high pass filters is installed for 2x550 MW Brazil-Argentina Interconnection (Garabi back-to-back station) – see also 1.12.2.2. The reactive power balance is provided by series capacitors.

## 2.4 REASONS FOR USING ACTIVE FILTERS IN HVDC SCHEMES

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 1.7, "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 place 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. Another control method was presented in [22].
- Flexibility for changing frequency characteristics within derated capability.  
Changes, such as 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 between active and passive filters is called a hybrid filter. The additional demand on reactive power is than covered by capacitor banks and eventually few 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 either in case of variation of network frequency or 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.

## **2.5 OPERATION PRINCIPLES OF ACTIVE FILTERS**

### **2.5.1 Shunt connected active filter**

The most common configuration is the shunt connection, where the active filter is connected in parallel with the AC network and provided with a current control.

The active filter constantly injects harmonic currents in opposition to the harmonic currents generated by the load. These harmonic currents compensate each other and the result is that the current supplied by the power source remains sinusoidal.

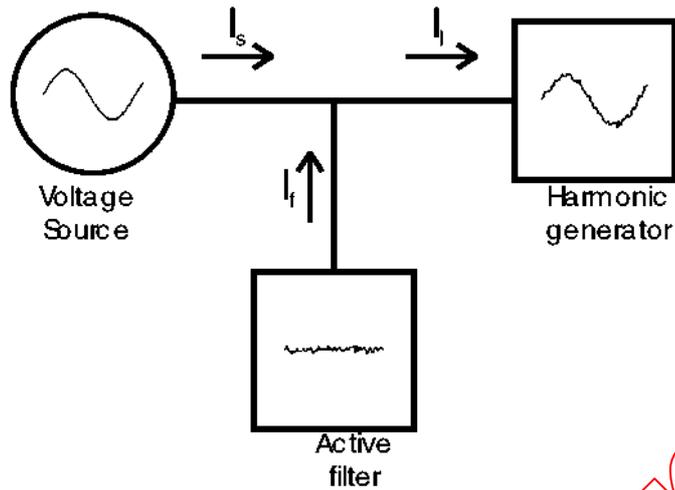


Figure 1.5.1: Shunt connection

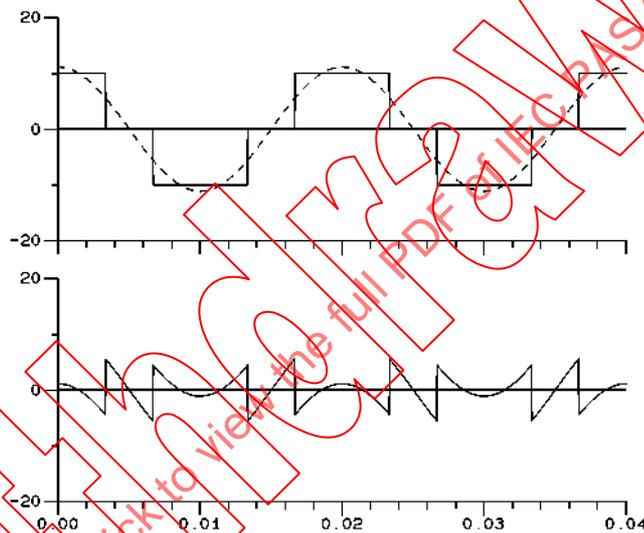


Figure 1.5.2: Example of current waves

- top, solid line: Load current current  $I_l$
- top, dotted line: resulting source current  $I_s$
- bottom: compensating filter current  $I_f$

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.

### 2.5.2 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 AC system and applied to the load. 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.

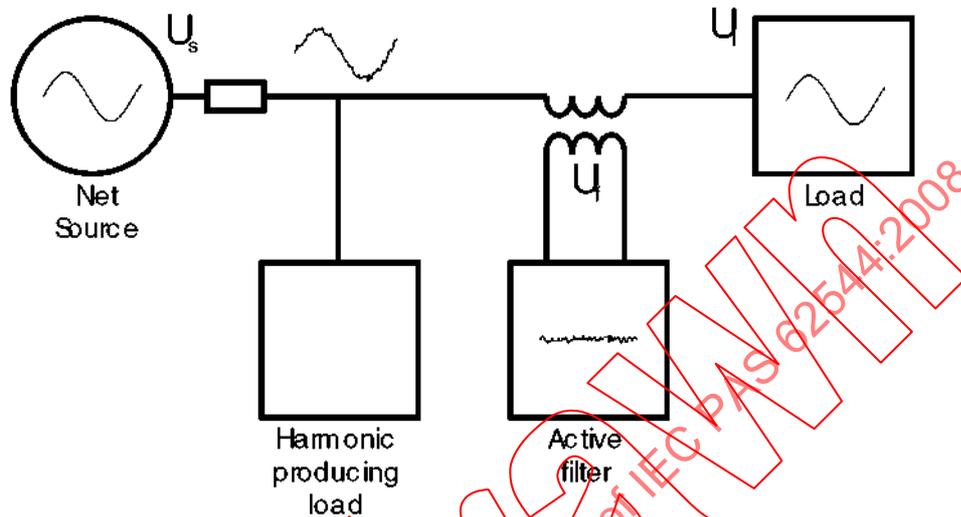


Figure 1.5.3: Series connection

## 2.6 PARALLEL AND SERIES CONFIGURATION

In some cases, the combined features of parallel and series configurations may be needed at one location.

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

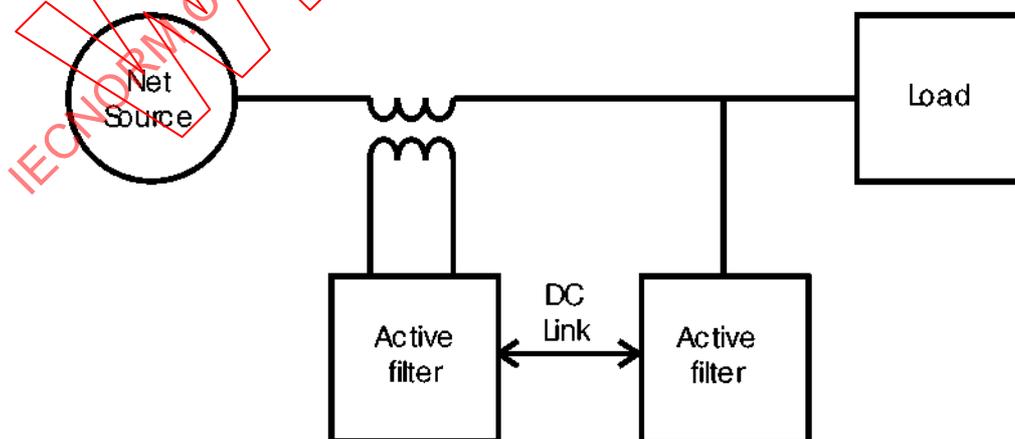


Figure 1.6.1: Series and parallel connection

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.

Table 1.6.1: Preferred topologies for common LV and MV applications

Source	Load	
	Non-distorting	Distorting
Non-distorted	-	<b>Shunt</b>
Distorted	<b>Series</b>	<b>Shunt + Series</b>

### 2.6.1 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 1.6.2. For high voltage applications, a hybrid filter built up by the combination of a passive and an active filter in series is required. Such a hybrid configuration is further discussed in 1.8.3.

In the example of Figure 1.6.2, the passive filter may carry out basic filtering of the predominant harmonic (generally, the 5<sup>th</sup> 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.

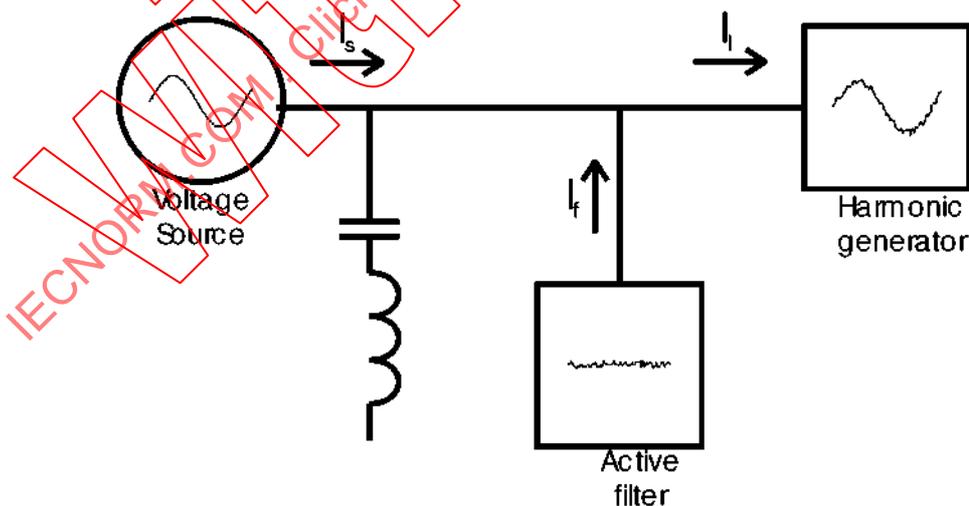


Figure 1.6.2: Hybrid configuration

## 2.7 CONVERTER CONFIGURATIONS

### 2.7.1 Converters

Basically, two types of converters can be used in active AC filters, the voltage-source 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.

#### 2.7.1.1 Current-source converter

This kind of converter has an inductor as the energy storage component. The use of this configuration is limited due to the coil and additional semiconductor losses.

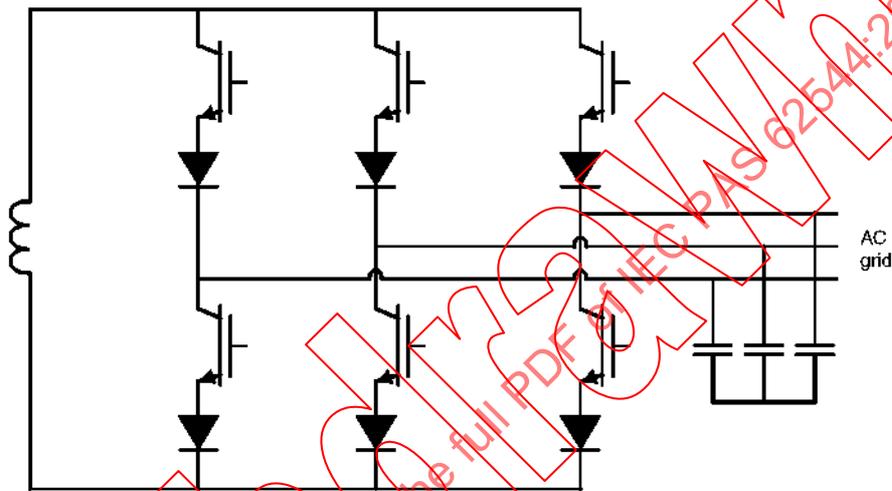


Figure 1.7.1: Three-phase current-source converter

#### 2.7.1.2 Voltage-source converter

This is the preferred configuration, 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.

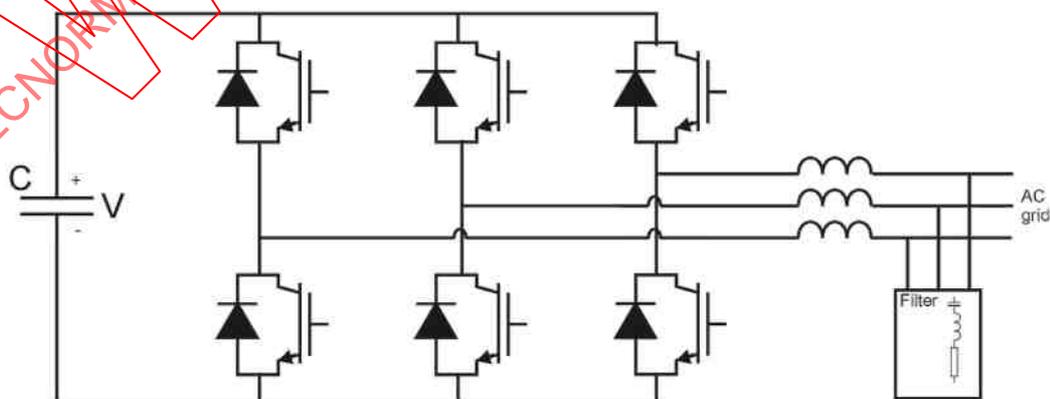


Figure 1.7.2: Three-phase 2-level voltage-source converter (three-wire type).

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

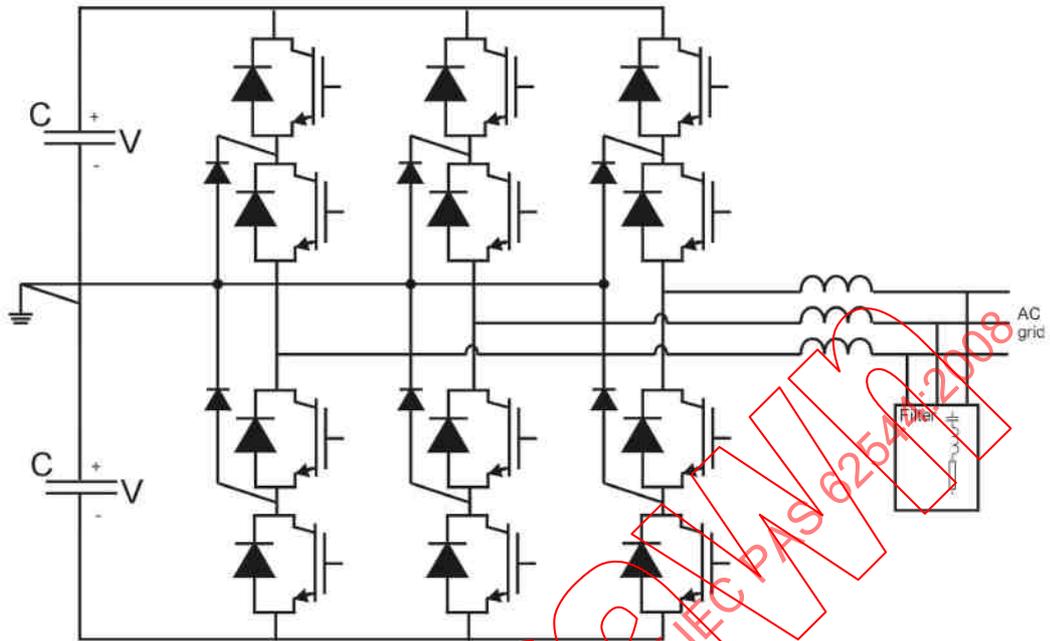


Figure 1.7.3: Three-phase 3-level voltage-source converter (three-wire type).

### 2.7.1.3 Single-phase voltage-source converter

Single phase active filters are based on a single phase voltage source bridges shown below. 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.

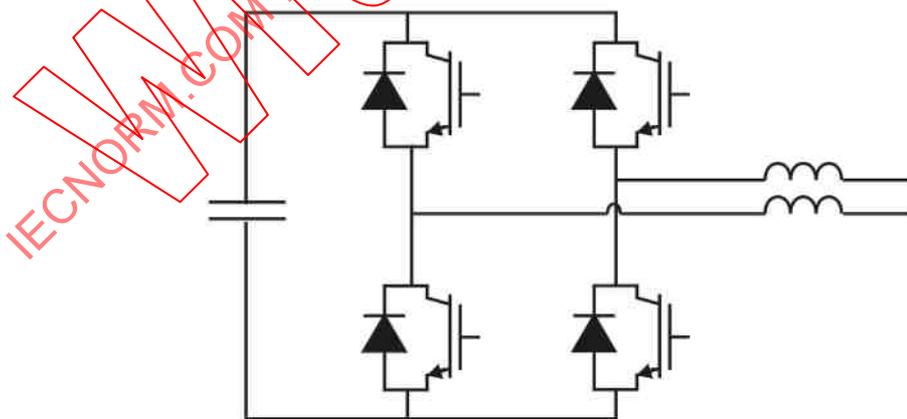


Figure 1.7.4: Single-phase voltage source converter

## 2.7.2 STATCOM

The term STATCOM (Static Synchronous Compensator) stands for a device using GTOs, IGCT (Integrated Gate Commutated Thyristor) or IGBT to produce reactive power at the network frequency. WG14-19 has prepared a full document on STATCOM principles and applications [26].

This section presents basic principles of the STATCOM and explains how it can be conceived to incorporate active filter features. The STATCOM can also be used as active filter, if the device is fast enough (either a high switching frequency or multi-levels or a combination).

### 2.7.2.1 STATCOM principles

The principle behind the operation of a STATCOM is very simple; it depends on the idea of two generators connected together by an inductor. For the case in question one generator is the power system, while the other is the STATCOM. The operation can be divided into five sections:

- 1 - The system and the STATCOM have the same amplitude and phase, so under this condition no current flows in the inductor and the STATCOM is operating at "float".
- 2 - The system voltage is higher than the STATCOM voltage, but the phase shift is still zero. A voltage now appears across the inductor, in phase with the system voltage. Since current in an inductor lags the voltage by  $90^\circ$  a lagging current is seen by the system and only inductive reactive power is transferred.
- 3 - The system voltage is lower than the STATCOM voltage, but the phase shift is again zero. A voltage appears across the inductor that is in anti-phase with the system, hence the inductor will pass a leading current when viewed from the system and only capacitive reactive power is transferred.
- 4 - When the system and STATCOM voltages are the same, but the phase of the STATCOM lags by a small amount, a voltage appears across the inductor which leads by  $90^\circ$  and a current will flow which is in phase with the system voltage, i.e. active power is delivered to the STATCOM.
- 5 - The last case is when the system and STATCOM voltages are the same amplitude and the STATCOM leads the system by a small amount. The inductor voltage now lags the system by  $90^\circ$  and the current is in anti-phase with the system voltage and active power is returned from the STATCOM to the system.
- 6 - All operating modes can be performed simultaneously.

In practice, sections n°4 and n°5 are limited to controlling the DC voltage of the STATCOM. For other applications, large energy storage elements are required.

The conditions above are not exclusive, and accordingly combinations of real and reactive current can be made to flow.

### 2.7.2.2 The practical STATCOM

In a practical STATCOM the generator is provided by a Voltage-Source Converter (VSC). In general the voltage source is a capacitor and this is of sufficient size to give a substantially constant voltage over the time of a mains frequency cycle. Since, as described in points 4 and 5 above, it is possible to cause real power (either positive or negative) to flow into the inverter, the capacitor can be either charged or discharged at will. The output voltage of the inverter is directly proportional to the capacitor voltage, thus by changing the capacitor voltage the reactive current is also changed and can vary between leading and lagging.

Although a simple inverter can act as a STATCOM it suffers from two main difficulties. The first is that

for most applications a simple inverter will not provide enough power. The second results from the quasi-square wave shape of the simple inverter, which generates considerable distortion and hence a high harmonic content. Using some form of multi-level inverter can largely solve both of these problems. Two examples are shown in Figure 1.7.5.

These types of inverter produce a number of quasi-square pulses superimposed upon each other. The outcome is a "staircase" waveform, in which the switching time of every level can be separately determined. As the number of levels increases, the power rating of the inverter increases at the same rate.

The two examples shown will both result in a waveform of five levels (two positive, two negative and one zero). The power capability will be four times the rating for a simple inverter. When the number of levels has been increased to obtain a suitable power rating, the output waveform contains sufficient steps to very closely approximate to the ideal sinusoid.

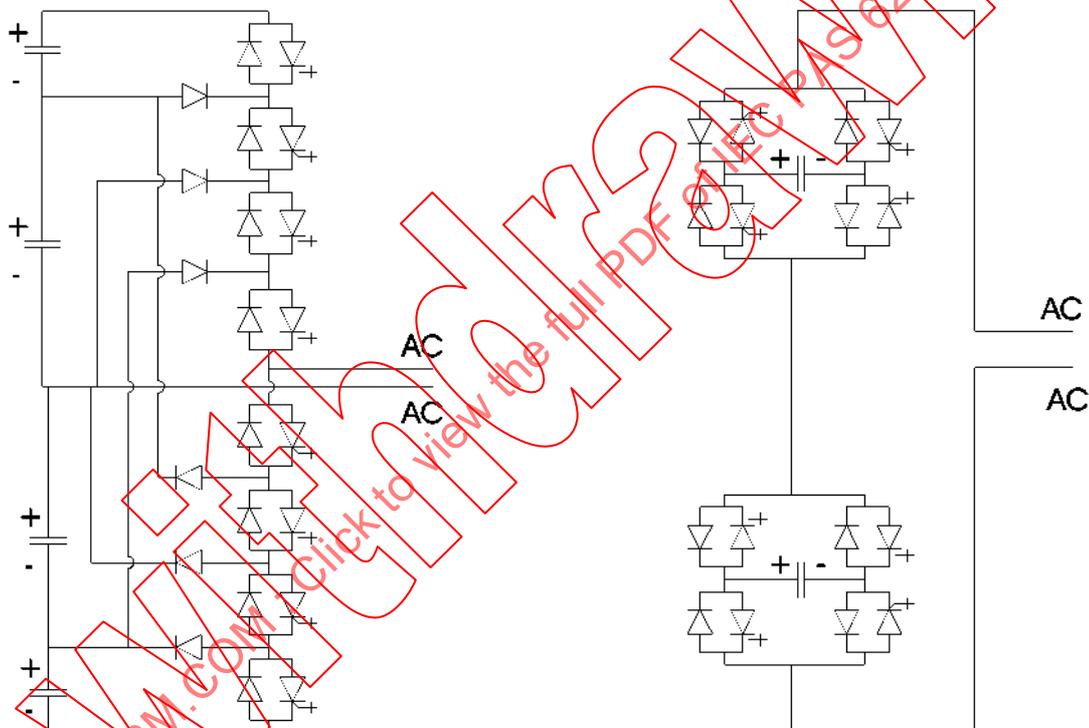


Figure 1.7.5: Two STATCOM converter approaches with GTO

### 2.7.2.3 Deviations from ideal

In a real system, the actual system voltage may not be a pure sinusoid. In this case to enable the STATCOM to draw a sinusoid of current, the inverter must generate an output voltage which contains an identical spectrum of harmonics as the system. Since the switching time of each level is individually adjustable, a close approximation to this condition is possible.

### 2.7.2.4 STATCOM as active AC filter

As described above it is possible to generate a STATCOM output waveform containing harmonics. When acting as a STATCOM, harmonics to oppose those on the system are adequate, but this is not the

limit. If the statcom is in a part of the system where the flow of harmonic currents is disturbing the system voltage, for example at the input to an HVDC scheme, a suitably distorted inverter wave shape can cause those currents to be diverted into the statcom. The order of harmonics which can be accurately controlled will depend upon the number of adjustable switching times (number of levels) available or by increasing the switching frequency. Thus a low power statcom based on GTO can only deal with low order harmonics, but for high power statcoms the range of controllable harmonics can be very wide. With the use of IGCT and IGBT even low power statcom can handle a wide range of harmonics.

## 2.8 ACTIVE AC FILTER CONFIGURATIONS

### 2.8.1 Active ac filters for low voltage application

At the present state of the art, direct connection of the active filter converter to the AC 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-source 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.

### 2.8.2 Active ac 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 pure 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 (see 1.7.2.4).

### 2.8.3 Active ac filters for HVDC applications

An active filter may be connected to the high voltage AC 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 AC bus is obtained at tuned frequencies.

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

A possible hybrid filter scheme is illustrated in Figure 1.8.1. 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.

A filter with the components shown in Figure 1.8.1 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 in 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 1.8.1 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 1.8.2. In this example, the passive filter is a double tuned filter, presenting minimum

impedance at the 19<sup>th</sup> and 37<sup>th</sup> 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.

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 a 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 1.8.3 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. This solution is used in the active AC filter installed at the Tjele station (Eltra), in Denmark.

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.

### 2.9 SERIES CONNECTED ACTIVE FILTERS

This solution is feasible if the current in the insertion point is low. However, in most cases, at least several hundred 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 increases 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.

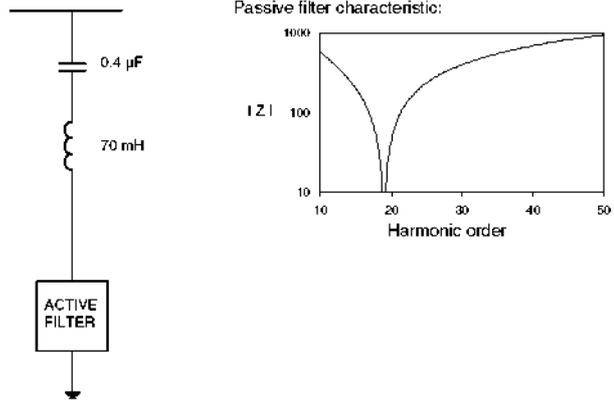


Figure 1.8.1: Active filter connected to the HV system through a single-tuned passive filter

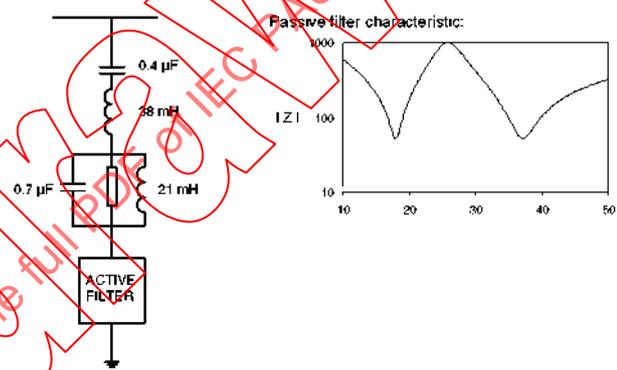


Figure 1.8.2: Active filter connected to the HV system through a double-tuned passive filter

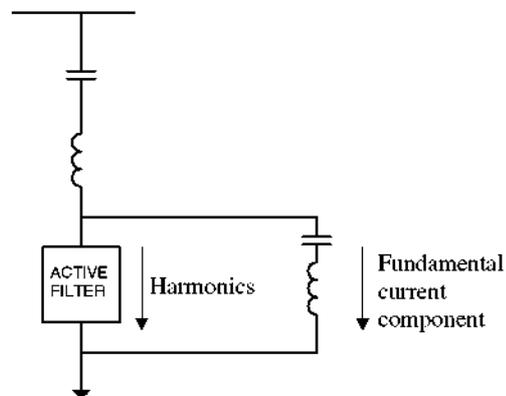


Figure 1.8.3: Using an LC circuit to deviate the fundamental current component

## 2.10 CONTROL SYSTEM

### 2.10.1 Introduction

Various control algorithms exist that are applied to active power filtering. It is not the aim of this document 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 [27].

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

### 2.10.2 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 1.10.1. 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 DC-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 – 2 kHz cut-off frequency. Normally a step-up transformer is provided. In order to have a bandwidth of for instance 1 kHz – 2 kHz, the required switching frequency of the active filter should be at least 3 kHz – 5 kHz.

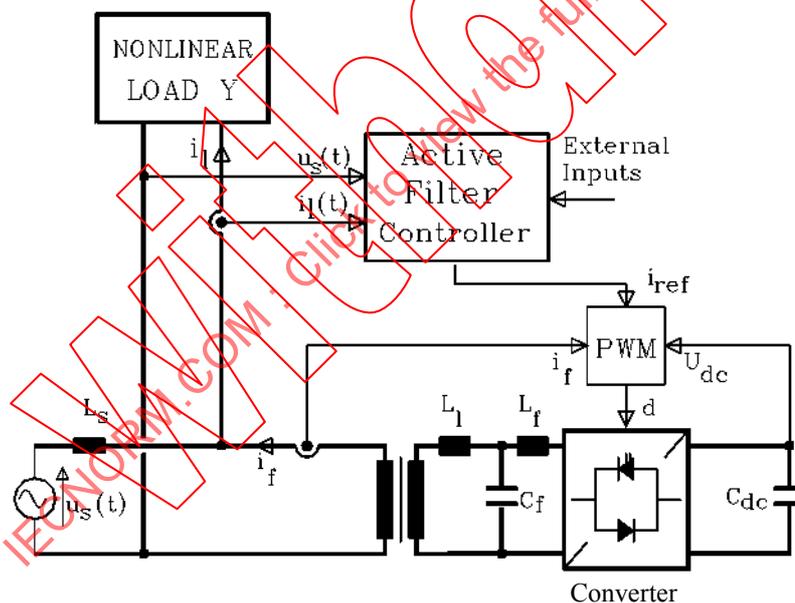


Figure 1.10.1: Per-phase Schematic Diagram of Active Filter and Controller

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 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) [28],[29]:

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

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.

### 2.10.3 Calculation of Reference Current

As indicated in Figure 1.10.1, 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. Instantaneous Reactive Power Theory (IRPT)

Fryze [29] is accredited as being the first to calculate fictitious power in the time domain in 1932. He subdivided the apparent power 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. This approach is recommended by the International Electrotechnical Commission (IEC). Several time-domain implementations of active filter control have been used in the past [28],[30],[31],[32],[33],[34], [35], [36].

One of the most successfully commercialised algorithms for active filter controllers is based on the Instantaneous Reactive Power Theory (IRPT). Akagi [31] introduced the IRPT, depicted in Figure 2.2. He defined 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 also

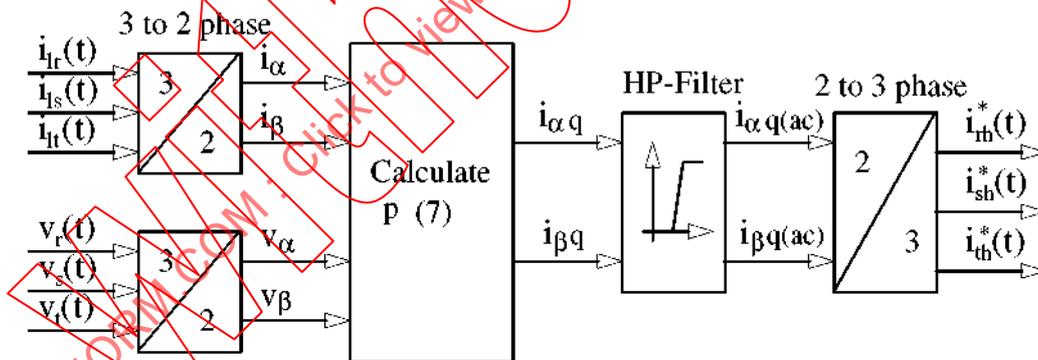


Figure 2.2. Block Diagram of IRPT.

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

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

$$\begin{bmatrix} p_o \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_o & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (7)$$

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

The measured three-phase voltages and currents are converted into **a-(3)** co-ordinates using (5) and (6). The instantaneous power is defined as the vector sum of the dot products of the **a-(3)** co-ordinates and reactive power as the vector product of the **a-(3)** co-ordinates as shown in (7). The fundamental of the source current is transformed by these calculations to DC 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 [30],[31].

#### 2.10.4 Synchronous Reference Frame (SRF)

Divan [32] implemented the Synchronous Reference Frame (SRF) technique to be used as a control algorithm in a compensator as shown in Figure 1.10.3.

The corresponding equations are:

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

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

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

The three-phase currents are converted into the two-phase a-b 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 DC quantity and the harmonics to AC components which are separated using a low pass filter. A PI controller ensures zero steady state control error. The resulting DC 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).

### 2.10.5 Other Control Approaches

Bhattacharya [36] introduced a method to control an active filter based on the synchronous reference frame technique [32] extended into the flux domain by integrating the voltage. Several other approaches are developed which differs somewhat from these original approaches. Some implementations estimators used Neural Networks and Kalman filters in electrical networks with highly dynamic characteristics, with varied success [34]. 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.

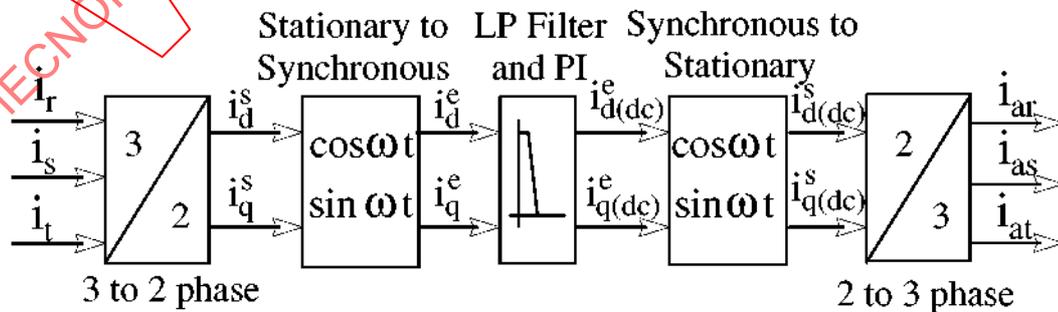


Figure 1.10.3 :Block Diagram of SRF.

### 2.10.6 HVDC AC Active Filter Control Approach

The installed AC active filter for HVDC at Tjele are presented in a later paragraph. 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.

## 2.11 EXISTING ACTIVE AC FILTER APPLICATIONS

### 2.11.1 Low and medium voltage

Several low and medium voltage active power filters exist in industry [21][40][41].

### 2.11.2 High voltage applications

Active filters for the HVDC side are already in operation and have been studied by our WG recently [24]. The power requirements for the HVAC side are considerable higher. Furthermore, while the configuration of a HVDC connection practically does not change during operation, the AC 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.

The only active AC filter at the HVAC network to date is in operation at the HVDC converter station of Tjele (Eltra) in Denmark.

#### 2.11.2.1 Active AC filter at Tjele (Eltra), Denmark - introduction

The active AC filter at the HVDC converter station of Tjele, Denmark, was manufactured and installed by SIEMENS at the end of 1998 as a joint demonstration project with the Danish utility ELTRA. All components of the active filter are assembled inside an 8 m long and 4 m wide housing of container type, which can be transported as a single piece. The container has two compartments provided with air conditioning, one for the medium voltage equipment and another for the control, the IGBT converters and the remaining low voltage components.

The active filter is connected to the network through one of the four existing passive filters, thus implementing a hybrid filter scheme. The ground connection of each phase of the passive filter was sectioned and brought into the container by an underground cable. The rated voltage at the connection point to the passive filter is 10 kV.

Rather than a three-phase block, the active filter comprises three single-phase units with common control equipment. The main components for each phase are shown in Figure 1.11.1. It includes a voltage source type converter (1) with IGBT-diode pairs controlled by PWM with a pulse frequency of 10 kHz. Each converter is rated for a crest voltage of 750 V and has nominal output of 200 kW. The transformer (4) matches the voltage specifications at the converter side and the passive filter side. Together with the LP filter (5) and the inductor (2) in series with the converter, the transformer has also the function to block high frequency voltages that result from the PWM process.

Because the passive filter is also used to compensate reactive power demanded by the HVDC converter, the biggest component of the current flowing in the filter is the 50 Hz one. An "adaptation impedance" (9) consisting of a LC series circuit allows this current component to flow directly to the grounding point instead of flowing through the converter. In case of transients in the network, the

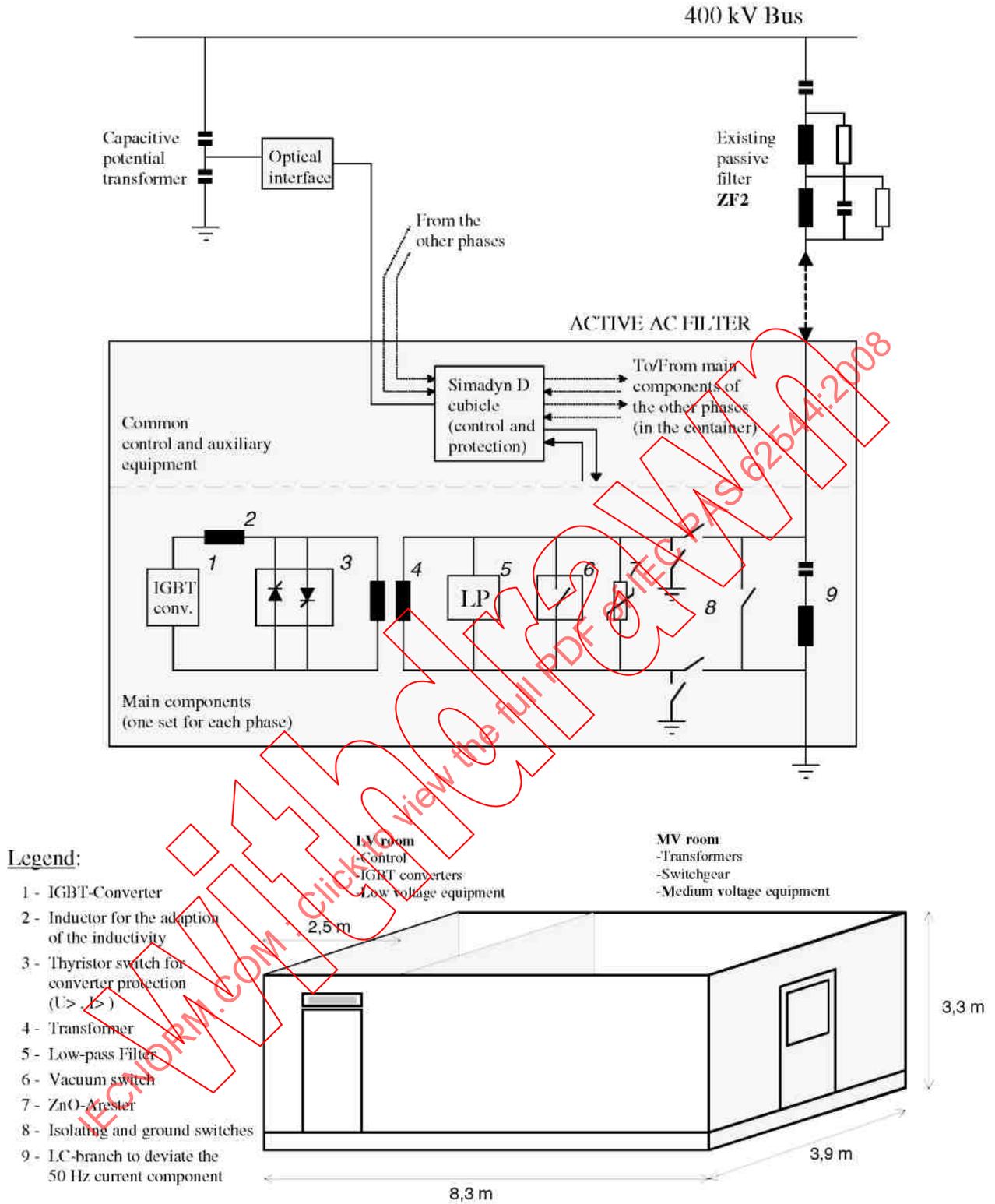


Figure 1.11.1: Structure of the active AC filter at the HVDC station of Tjele (ELTRA), Denmark