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Active filters in HVDC applications

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22F/130/NP	22F/147/RVN

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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][1)]. When the power line consists of cables, this filtering is normally not necessary. The development of power electronics devices and digital computers has made it possible to achieve a 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.

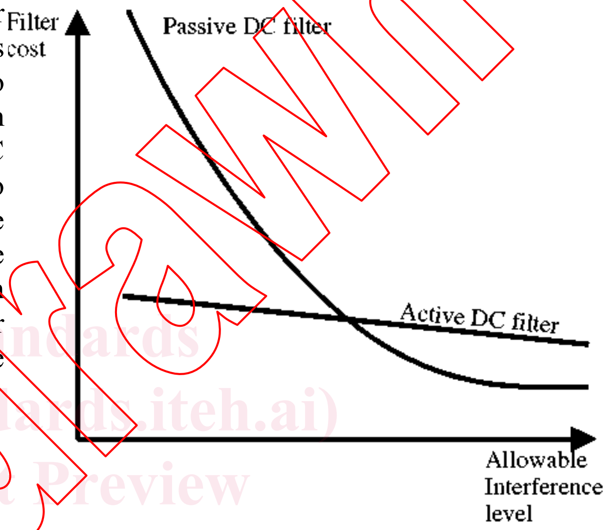

Figure 1.1.1 Conceptual diagram of allowable interference level and DC filter cost

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.

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:

$$U_{ind} = \sqrt{\sum_{n=1}^{50} (2 * \pi * f_n * M * I_n * p_n)^2} \quad . \quad I_{pe} = \frac{1}{p16} * \sqrt{\sum_{n=1}^{50} (k_n * p_n * I_n)^2}$$

where f_n is the frequency of the n-th harmonic, M is the mutual inductance between the telephone line and the power line, $k_n = \frac{f_1 * n}{800}$, I_n is the vectorial sum of the n-th harmonic current flowing in the line conductors (Common mode/earth mode current). p_n is the n-th psophometric weighting factor defined by CCITT Directives 1963 [3] (see also Table 1.2.1) and p_{16} is the 16th psophometric weighting factor. The characteristic harmonics n=12, 24, 36, 48 as well as the non-characteristic harmonics up to n = 50 shall be considered.

Table 1.2.1 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.

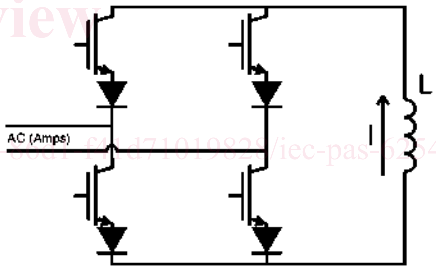

Figure 1.3.1 Simple current source converter

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.

A circuit of simple VSC is shown in Figure 1.3.2.

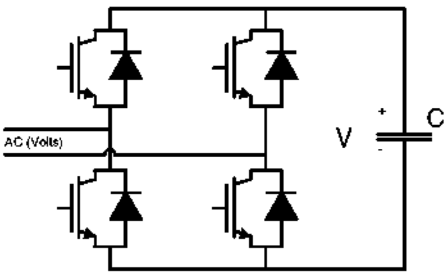

Figure 1.3.2 Simple voltage source converter

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.

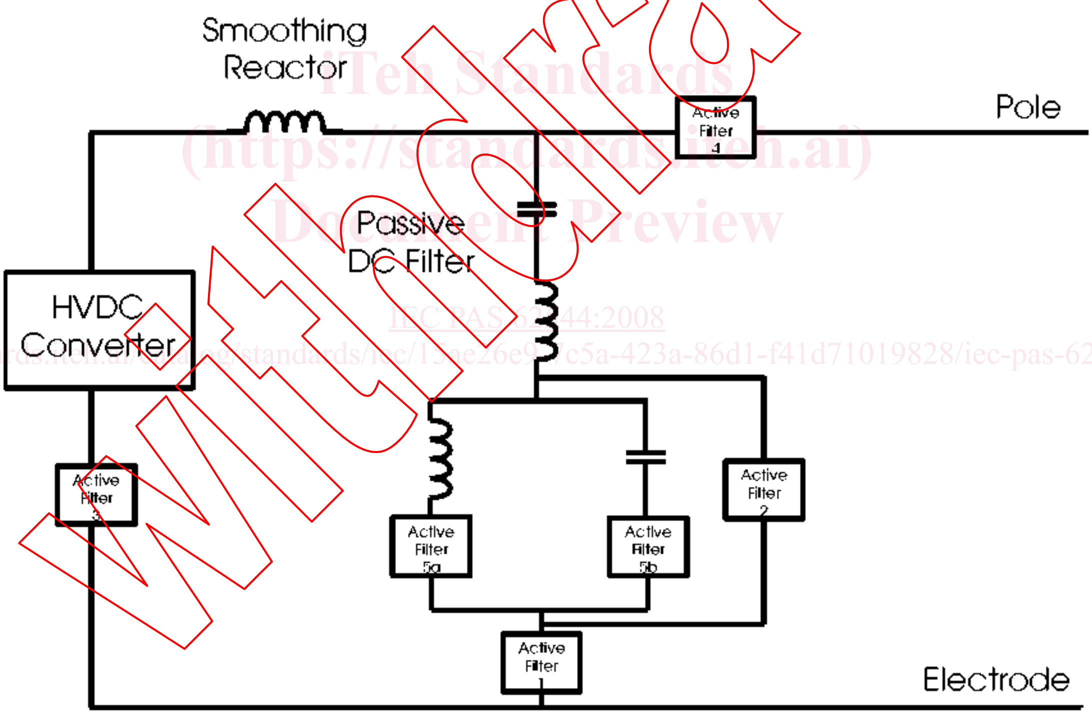

Figure 1.3.3 Possible connections of active DC filters

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 therefor 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 “$(I_{dconv} + I_r)^2*L_r$. The rating of the active filter (converter) is determined by “U_{dr}^2/L_r”. Hence the economical optimisation between the active and passive part of the active filter can be adjusted by increasing “L_r”. The rating of “T_c” will be increased and the rating of the active filter part will be decreased or vice versa.

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

The advantages of this connection are:

- there are no harmonics in the HVDC converter 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.

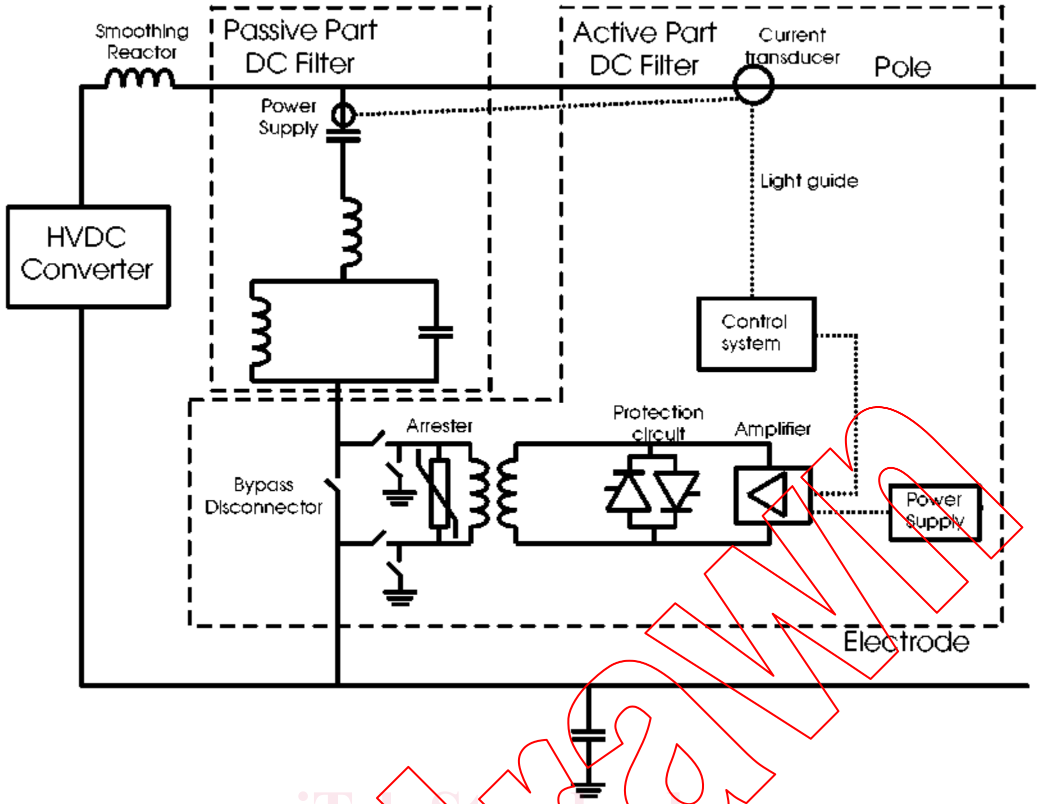

Figure 1.4.1 Filter components in the active filter

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 reator 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 μF. The root sum of squares of a typical measured current spectrum through the smoothing reactor gives 15.7 A_{rms}. The current spectrum is used to calculate the assumed voltage which is required for the active part to compensate the harmonics for the three mentioned filter configurations shown in Figure 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.