ACTIVE FILTERS IN HVDC TRANSMISSIONS

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In 1991 the world's first active dc filter of an HVDC Transmission was demonstrated by a test installation at the Lindome station of the Konti-Skan HVDC link. The first commercial active dc filter was installed in 1993 at the Skagerrak 3 HVDC Intertie, followed by Baltic Cable HVDC Link (commissioned 1994) and Chandrapur-Padghe HVDC Power Transmission (commissioned 1998).

This paper aims to give a description of active filters, with a brief discussion on topologies, main components and control principles followed by a review on achieved performance and operational experience in the above projects. Finally, the paper concludes with future expectations for active dc filters. In addition the paper gives a brief discussion on active ac filters and continuously tuned filters for HVDC schemes.

1 INTRODUCTION

An HVDC converter station always requires ac filters, the purpose of which is to mitigate voltage distortion and reduce telephone interference in the connected ac network. In addition the ac filters also play a vital part in reactive power support. In almost all HVDC projects the primary decisive factor for the ac filter design is the requirement on telephone interference.

If the converter station is connected to a dc transmission with overhead lines the scheme will also contain dc filter with the sole purpose of reducing interference with telephone subscriber wires or similar in the close vicinity of the dc line along its route.

For an in-depth discussion on filter design, specification of filters and definitions on performance criteria it is referred to [1] and [2], [3] for ac and dc filters respectively.

Both ac and dc side requirements on telephone interference consist of frequency weighted measures. Typically the parameters TIF or THFF are used for ac filters; both give a rms value of the weighted ac bus voltage distortion. For the dc side an equivalent (residual) weighted current is specified, either as fed into the line or along the line. There are several reasons why the ac and dc sides are treated differently, both historical, and through accepted praxis. From a strict technical point of view any telephone interference level limit should (theoretically) be set based on the result of an inductive coordination study. For a two terminal dc system the routing of the line(s) is known, as are nearby telephone subscriber wires and the task of defining a permissible level of interfering current in the dc line is achievable with a reasonable effort. For the ac side, which is by nature more complex and also changing over time, with different load and line configurations, it is a significantly more difficult and laborious task to undertake, which is why levels of TIF or THFF are most often selected based on earlier experience.

Frequently used levels of THFF or TIF for HVDC stations is in the range of about 1 % or 30 to 40 respectively. More details are given in [1], [4] and [5].

As already noted dc filter performance levels should be selected following an inductive coordination and there are no appropriate typical levels. Historically levels of equivalent weighted current have been specified within the range of 0.1A up to 2 A; a comprehensive reference list is provided in [3]. Frequently specified levels in recent bipolar schemes are in the range of 0.5 A in balanced bipolar operation and with a relaxation up to 1 A in monopolar operation.

In the late 1980's, with recent dc filtering requirements in the range of 0.1 A, and a concern regarding more complex and costly dc filter designs as background, the development of high power pulse width modulated (PWM) amplifiers and improved digital signal processors (DSP), enabling signal processing at a high rate, made active dc filters achievable and attractive from both a technical and a economical point of view.

In 1991 the world's first active dc filter of an HVDC Transmission was demonstrated by a test installation at the Lindome station of the Konti-Skan HVDC link [7], [8]. The test installation was successful and was followed by commercial installations of active dc filters in several projects. Discussed in clause 3 of this paper are:

- Skagerrak 3 HVDC Intertie, commissioned -93 [9],
- Baltic Cable HVDC Link, commissioned –94 [10] and
- ± 500 kV Chandrapur-Padghe HVDC Bipole Project, commissioned -98 [11].

Active dc filters are also installed at "Tiang–Guang Long Distance HVDC Project", commissioned 2000, and at the "EGAT-TNB HVDC Interconnection", commissioned 2001, [6].

2 ACTIVE FILTERS FOR HVDC APPLICATIONS

Reference [6] give a detailed discussion on active filter topologies, main components and control principles. Provided below is a brief summary.

2.1 Main Components and Topology

There are several possible configurations (topologies) of active filters. They can be connected in series with the load or parallel, directly or through a coupling connection etc. Common for all present schemes in HVDC are that they are hybrid filters. That is, the active part (amplifier) is connected to the high voltage bus through a passive part (a conventional shunt filter). Figure 1 gives a typical topology of an active dc filter.

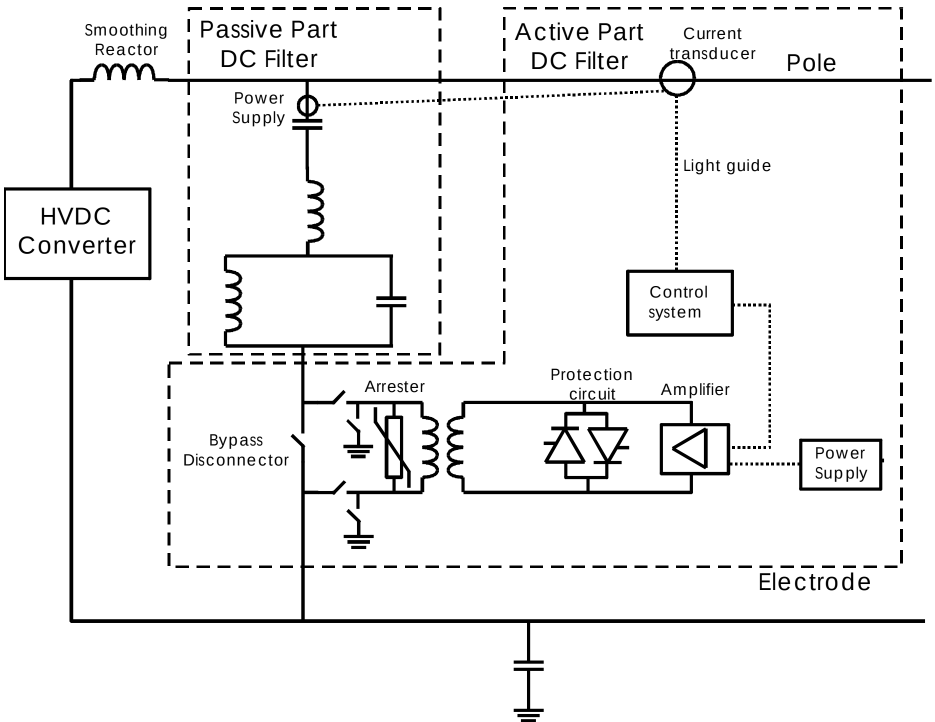

Figure 1 Topology of an active dc filter

In **Figure 1** the main components of a hybrid active filter are indicated. The passive part, through which the active part connects to the HV bus is a conventional filter. On the dc side the expected tuning frequencies would be 12th and 24th (if a double-tuned filter). On the ac side the passive part would probably be high pass or double tuned branch tuned above 11th and 13th harmonics, eg a HP24 branch. In addition the active part would be bypassed with a LC branch tuned to the fundamental, all of which measures are designed to reduce the required rating of the amplifier.

The active part can be divided into the measuring system, the control system, the amplifier, the transformer, protective devices and bypass disconnectors, each of which is discussed in detail in [6], and a survey is given below.

The measuring system is crucial, as its resolution will define the limit of the dynamics of the system. That is, no active filter can be better than its measuring system permits. For a current measuring system, e.g. as on the dc side **Figure 1**, the comparatively huge series direct current has to be taken into account, as has the required active filter bandwidth (about 0.3 to 3 kHz) etc. For the active dc filters a Rogowski coil is used and communication to the control is made through a fibre optic link.

The control system is a discrete control, built with DSPs operating at a high sample rate. The control system is complex, as it does not only need to convert measured levels to appropriate amplifier input signals, it also needs to handle changes in the main circuit, e.g. going from bipolar operation to monopolar, recovery from abnormal system conditions (eg during and following fault contingencies) etc. A brief discussion on control principles is added below.

The amplifier in all existing active filter schemes is a pulse width modulated (PWM) voltage source converter (VSC). The first amplifiers were built using MOSFET technology (Metal Oxide Silicon Field Effect Transistor), but later designs are built using an IGBT technology (Insulated Gate Bipolar Transistor). The trade-off between MOSFET and IGBT is a reduction in switching frequency but a gain in higher voltage and lower losses.

The transformer provides a galvanic separation between the amplifier and the HVDC plant, as well as raising the amplifier output voltage to a suitable system level, in the range from 0.3 to 1.0 kV to above 3 kV. The protection circuit protects the amplifier from external over-voltages and currents. The bypass disconnectors enable the active part of the filter to be disconnected while the HVDC link remains in service.

2.2 Control Principles

The dc circuit in a monopolar HVDC system can be simplified into that of **Figure 2 a)**, where E_c represent the converter harmonic EMF, L_s the smoothing reactor, C_f and L_f the dc filter with harmonic impedance, and Z_f and Z_l the line harmonic impedance. Further, I_s, I_f and I_l denote the current through the smoothing reactor, the filter and that fed into the line.

For each harmonic frequency the line current can be written as $I'_l = I_s \frac{Z_f}{Z_f + Z_l}$, that is, for the harmonics at which Z_f is small relative to Z_l (i.e. at the tuning frequencies of the filter) the line current will be small, at other harmonics the impact of the passive filter branch is less.

In **Figure 2 b)** an active filter is represented as a voltage source, E_f, in the bottom of the filter branch. The line current generated by the active filter will be $I''_l = G \times E_f$ where G is the transfer function between E_f and I''_l. The transfer function G is determined by the impedance characteristics of both the passive dc filter and the remaining dc circuit (predominantly the line impedance). That is, G is a physical measurable quantity. Given G, the active filter source voltage can be controlled such that I''_l adds to I'_l in opposite phase and both, theoretically, cancel each other out as illustrated by **Figure 2 c)**. In practice a complete cancellation will never occur; at best, cancellation down to the dynamic of control and measuring system resolution is obtainable, however, these levels are more than sufficient for any practical purpose.

The transfer function G is continuous function with frequency, as illustrated by **Figure 3**. A basic control concept of a active dc filter operates on selected, discrete harmonics using a single frequency control (SFC) for each individual harmonic. **Figure 4** give a principle layout of a dc filter control and its process. Here each SFC controller contains two initial “Fourier filters” synchronised to the ac side fundamental frequency, Ω_1. The signal is then forwarded into a PI controller that also compensates the external process.

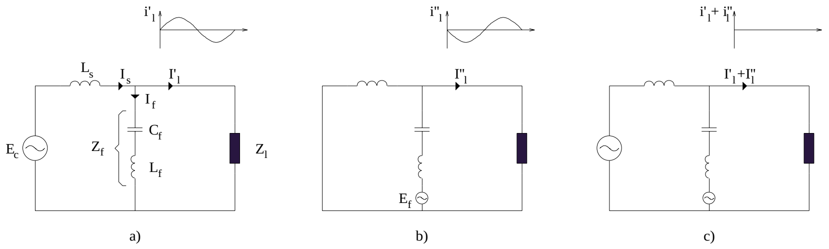

Figure 2 Simplified dc side of a monopolar HVDC system

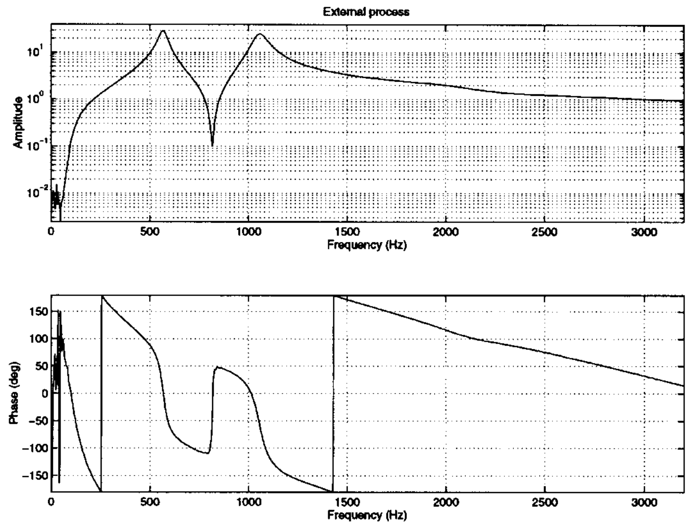

Figure 3 Example of transfer function, G

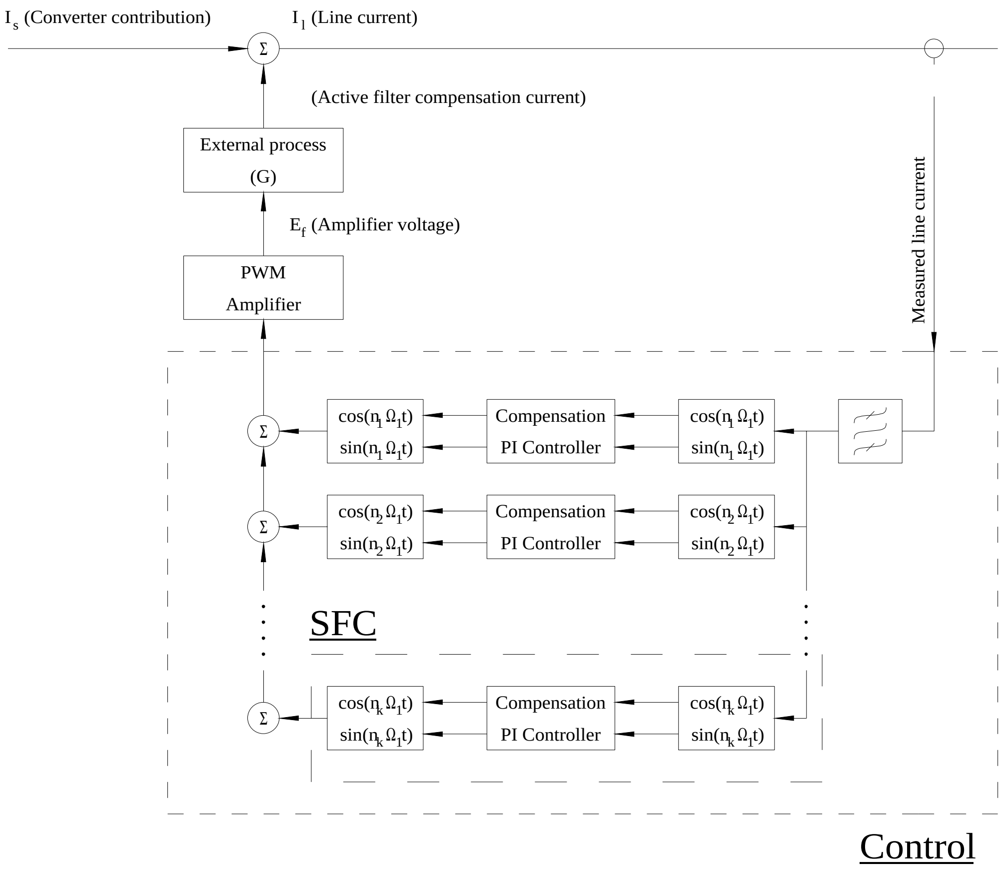

Figure 4 Principle control scheme for active dc filter

3 GAINED PERFORMANCE AND OPERATIONAL EXPERIENCE

3.1 Skagerrak (1)

The first commercial active dc filter was installed at the Tjele converter station in the Skagerrak 3 HVDC Intertie. The active filter was commissioned in 1993.

The additional pole 3 has approximately the capacity of the two previously existing poles. To minimise losses and electrode current, the current on one of the existing poles was reversed and the three-pole link can be operated as a bipole, see Figure 5.

The dc filters in pole 1 and pole 2 have been extended from simple capacitors to tuned filters in order to fulfil the demands in the specification of the three-pole link. The dc filter on the third pole consists of a passive double tuned 12/36 filter with an active part. The passive filter has two functions: to couple the active part to the 350 kV pole line and to work as a passive filter when the active part is not in operation. The dc filter of the third pole is coupled between the pole line and the neutral bus.

One advantage of installing an active filter in the third pole is the possibility of minimising the earth mode current when two or more poles are running. Current transducers are therefore installed in all three poles. When the third pole is operated as a monopole the harmonic current on the pole line is reduced to zero.

The control algorithm of the active dc filter functions on whole multiples of the fundamental frequency in the frequency domain 300-3000 Hz. The reason to not control lower frequencies is that the rating of the VSC PWM amplifier would increase many times. Furthermore, when considering the psophometric weighting factor in the overall disturbance, the contribution from the lower harmonics is negligible.

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

To illustrate the performance of the active dc filter, a pole line current was measured in Skagerrak 3 HVDC Intertie. The third pole was operated as monopole and the transmitted power was 240 MW. The pole line current was measured and the spectra are shown in Figure 6. The first spectrum shows the line current without the active part and the second spectrum shows the line current with the active part in operation.

The psophometric weighted current, $I_{pe} = \frac{1}{p16} \cdot \sqrt{\sum_{n=1}^{60} (k_n \cdot p_n \cdot I_n)^2}$, of the current spectrum was reduced from 4780 mA to 255 mA. The major harmonic line currents are shown in Table 1.

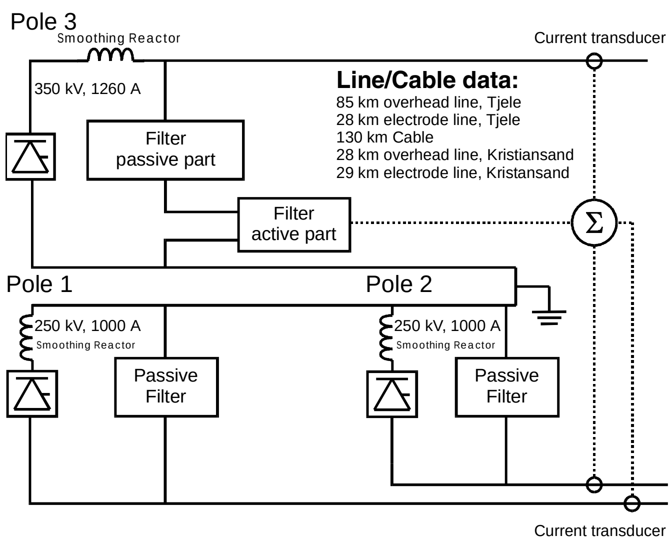

Figure 5 Simplified diagram of Skagerrak HVDC Intertie, showing active connection

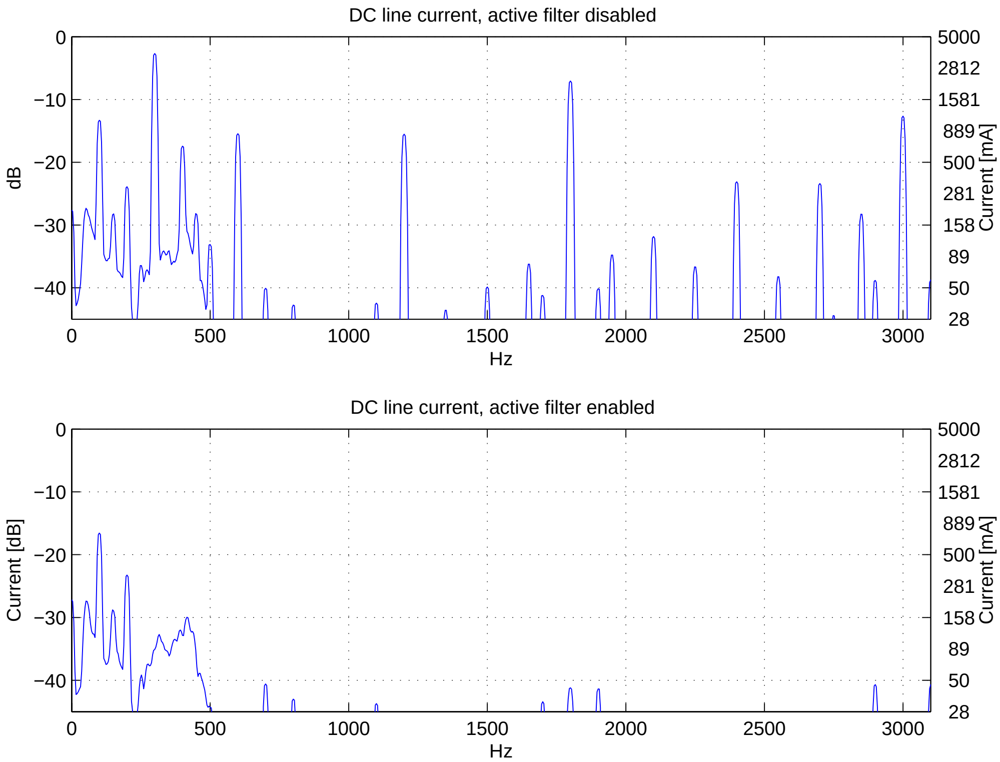

Figure 6 Measured line current spectra, third pole operated as monopole

Frequency [Hz]	Weight factor P_n*k_n	No active filtering		Active filtering	
		Current [A_{rms}]	Weighted Current [A_{rms}]	Current [A_{rms}]	Weighted Current [A_{rms}]
300	0.111	3.668	0.406	0.0881	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

Table 1 Major harmonic line current, third pole operated as monopole

Figure 7 Active filter cubicle in front of dc filter at Tjele, Skagerrak 3

3.2 Baltic Cable

The active dc filter is a passive doubled tuned 12/24 filter with an active part, located at the Kruseberg station at the Swedish side, where a section of overhead line connects the converter station to the undersea cable. Since no dc overhead line is present on the German side, no dc filter was installed at this end. The passive filter couples the active part to the 450 kV dc pole line. The tuning of the passive part is chosen to minimise the rating of the active part. The dc filter is coupled from the pole line to earth, see **Figure 8**.

The control strategy is to minimise the dc pole line harmonic current emanating from both Kruseberg (Swedish station) and Herrenwyk (German station). The control algorithm of the active dc filter works on whole multiples of the fundamental frequency in the frequency domain 350-3000 Hz. Since no dc filter is installed in Herrenwyk, harmonic currents are transferred through the cable to the Swedish side, especially the harmonic current at 600 Hz and the 1200 Hz . The active dc filter control also mitigates these currents.

The active filter solution in Baltic Cable eliminates the need for 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 would have had to be installed. Due to the low impedance of the dc line and cable as seen from Kruseberg, the number of filter branches would be impractical and not economical.

To illustrate the performance of the active dc filter, the pole line current was measured in Kruseberg. The transmitted power was 180 MW. The pole line current was measured and the spectra are shown in **Figure 9**. The first spectrum shows the line current without the active part and the second spectrum shows the line current with the active part in operation.

The psophometric weighted current, $I_{pe} = \frac{1}{p16} \cdot \sqrt{\sum_{n=1}^{60} (k_n \cdot p_n \cdot I_n)^2}$, of the current spectrum was reduced from 5075 mA to 320 mA. The major harmonic line currents are shown in **Table 2**.

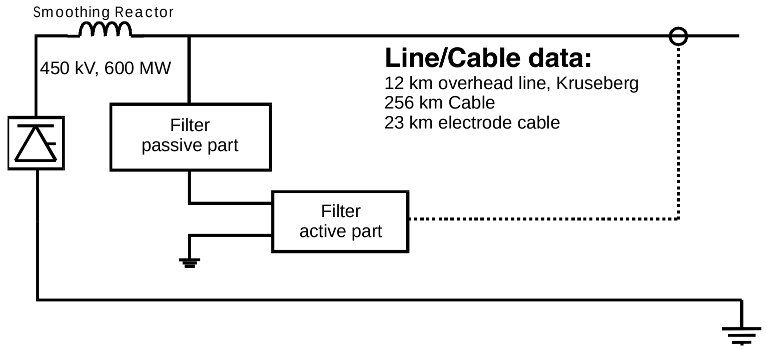

Figure 8 Simplified diagram of Baltic Cable HVDC Link, showing active filter connection

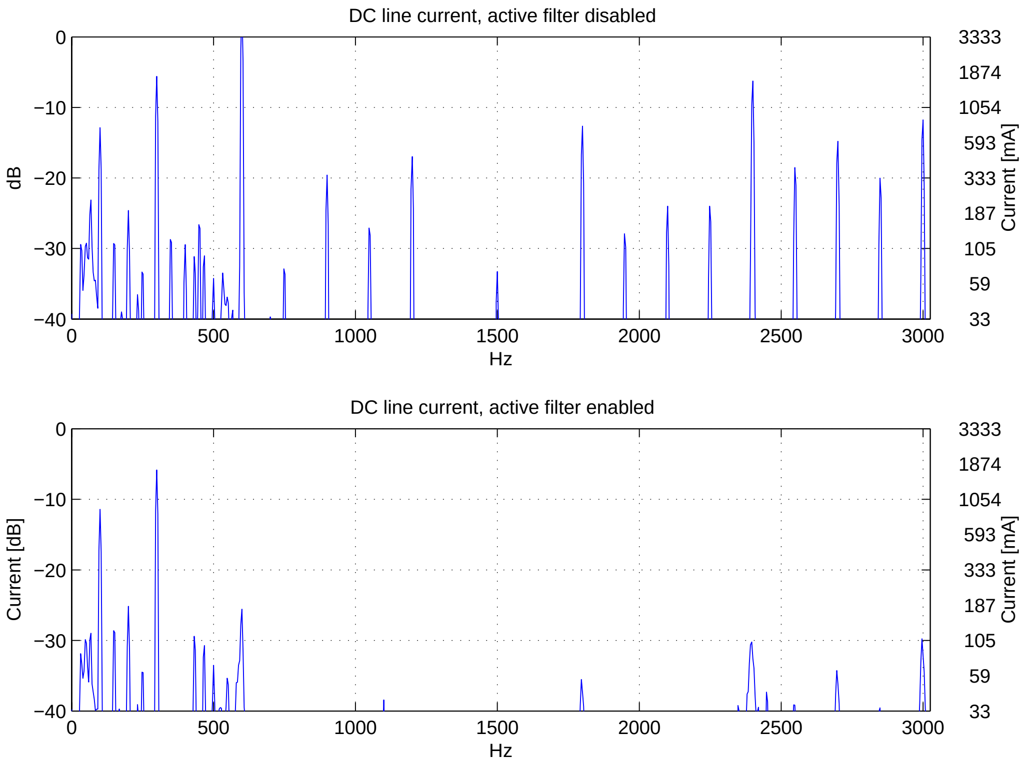

Figure 9 Measured line current spectra

Frequency [Hz]	Weight factor P_n*k_n	No active filtering		Active filtering	
		Current $[A_{rms}]$	Weighted Current $[A_{rms}]$	Current $[A_{rms}]$	Weighted Current $[A_{rms}]$
600	0.595	4.95	2.96	0.176	0.105
1200	1.500	0.473	0.710	0.022	0.033
1800	1.710	0.776	1.33	0.045	0.077
2400	1.902	1.62	3.08	0.079	0.150
2700	1.957	0.606	1.19	0.052	0.102
3000	1.969	0.860	1.69	0.082	0.161

Table 2 Major harmonic line current

Figure 10 Active filter cubicle and dc filter in front of valve hall at Kruseberg, Baltic Cable

3.3 Chandrapur-Padghe

The dc filter consists of a passive double tuned 2/6 filter and a passive doubled 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 are installed and each active filter is connected from the pole line to the neutral bus, see **Figure 11**.

The control strategy is to minimise the earth mode current. The active dc filters works on whole multiples of the fundamental frequency in the frequency range 350-2500 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.

The residual or earth mode current was measured by measuring the two pole line currents and then adding them. The spectrum is shown in **Figure 12**. The transmitted power was 1500 MW in bipolar operation. The equivalent psophometric current along the dc line was calculated, using the measured earth mode current, to 170 mA.

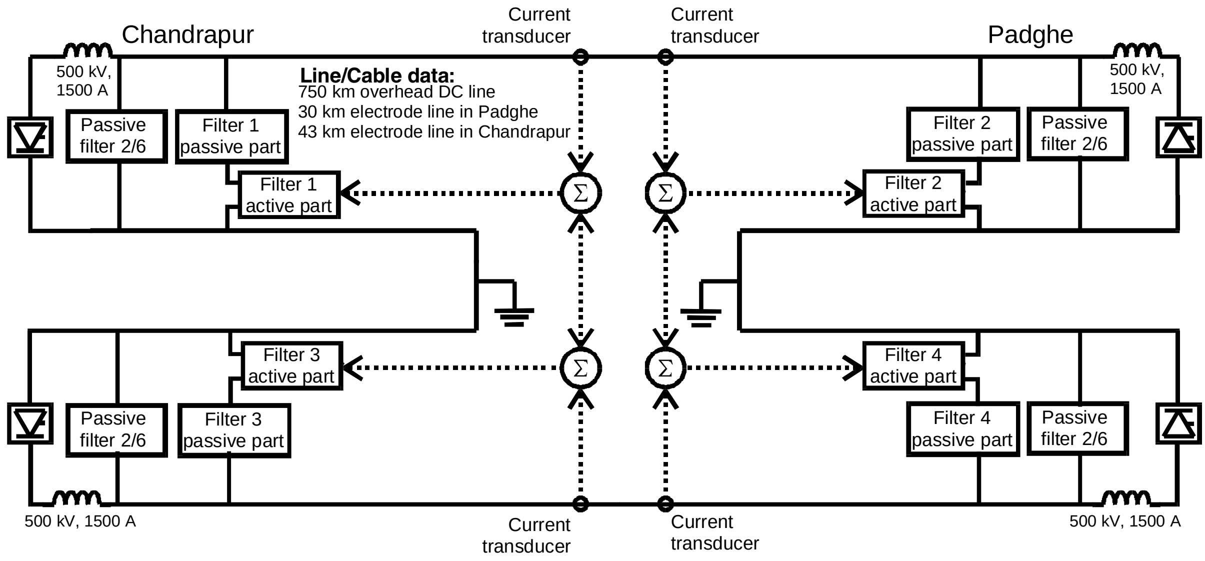

Figure 11 Simplified diagram of Chandrapur-Padghe HVDC transmission project, showing active filter connection

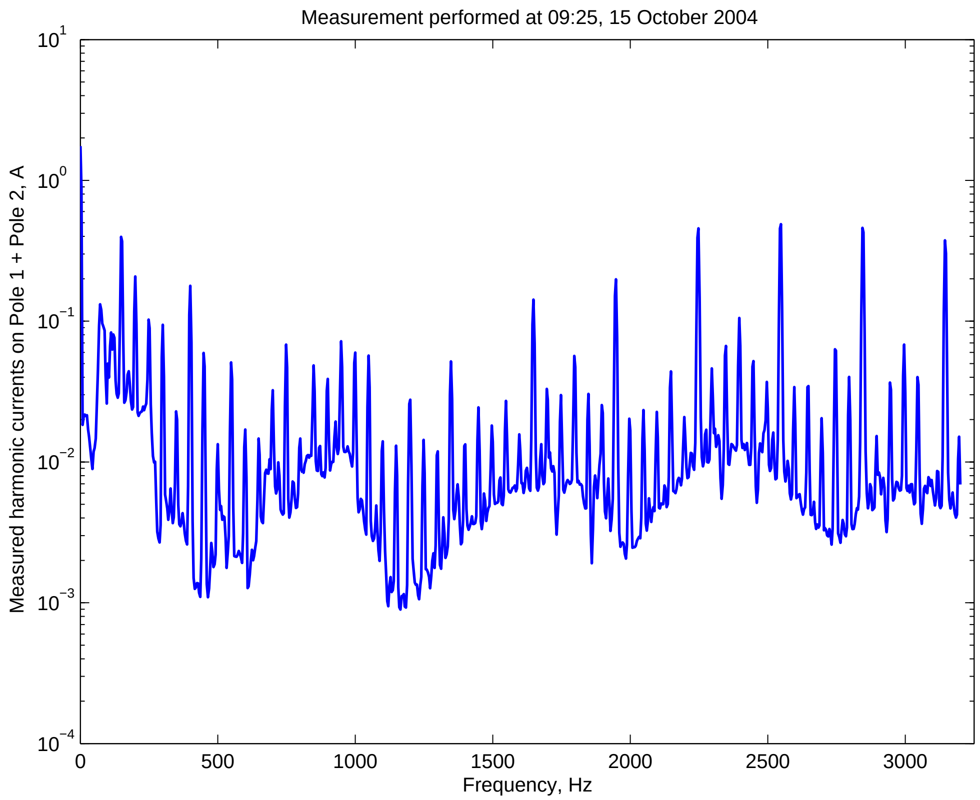

Figure 12 Measured earth mode current spectrum

4 AC SIDE ACTIVE FILTERS

The only known active ac filter used in HVDC is the one presented in [4]. The filter was installed at Tjele converter station and commissioned in 1998.

As of the present date there is no known HVDC project with requirements on ac side filtering that explicitly would require an active ac filter. There is certainly more than one project with strict requirements, but designs with conventional passive or continuously tuned filter branches have still shown to provide the most technical and economical beneficial solution.

There are several different reasons for this. The most evident is that line commutated HVDC converters have a Mvar deficit in the range of 50 % of transmitted power. Thus the need of supporting reactive power will provide sufficient filtering in most HVDC schemes.

For other line commutated HVDC converter configurations, such as the Capacitor Commutated Converter with a lower reactive power deficit, continuously tuned filters or conventional passive filters have been used, as described in [12], [14] and [15].

For HVDC schemes with pulse width modulated voltage-source converters the characteristics are radically different, for example reactive power can be controlled (within limits) independently of power. Further, by the selection of PWM technique the harmonic properties of the converter can be controlled in a way that is impossible for a line commutated converter and at present the need of a separate active ac filter is not predicted. The flexibility of a PWM converter can also allow it to counteract external low order harmonic influence through control measures, see [16] and [17].

5 CONTINUOUSLY TUNED FILTERS

Continuously tuned filters are on the borderline between passive and active filters. They are passive in the sense that they use passive components, but on the other hand their tuning frequency is supervised and controlled actively. Through the years different designs have been proposed and used; in more recent HVDC projects a design using a static reactor with variable inductance has been used. The reactor has two main components, an outer main coil winding and an inner magnetic core. The main coil inductance is governed by controlling the permeability of the core. This is achieved by surrounding the core with a toroidally wound control winding, which is fed by a dc current, and thereby creating a permeability-controlling field perpendicular to the main coil flux direction, [18].

A simplified control scheme is given in **Figure 13**. At resonance frequency the phase shift between the voltage across the branch and current through the filter branch is zero, and the control strives to minimise the phase angle between the two by adjusting the inductance and thereby compensating for both component variations as well as system frequency excursions. This type of continuously tuned filter was first commissioned as a test installation at Lindome converter station of Konti-Skan 2 HVDC Link and has since also been used at:

- Pacific Intertie HVDC Transmission An 11th harmonic ConTune filter was added at Celilo Converter station, commissioned 1999.
- Swe-Pol Link, 600 MW. Both converter terminals have a single 95 Mvar filter bank containing four branches, 11th and 13th ConTune and two conventional HP24 and HP36 filters. To satisfy reactive power demands additional shunt banks are added. Commissioned 2000, [13].
- Garabi I and II, 4×550 MW Capacitor Commutated Converter back-to-back scheme. Each block has a single bank with 11th and 13th ConTune and two conventional HP24 and HP36 filter branches on both sides. Two blocks commissioned in 1999 and two blocks in 2002, [14].

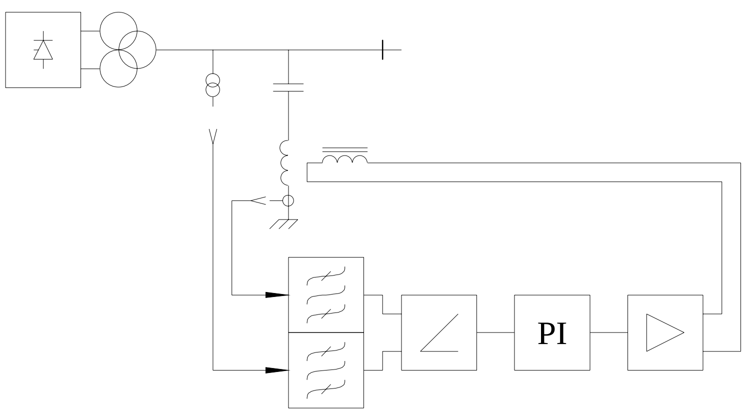

Figure 13 Simplified control scheme

6 FUTURE EXPECTATIONS

Considering the development within the telecommunications field during the last decade or two, it could be that active filters, ac as well as dc, will have played out their role as means of telephone interference mitigation within the 20 years or so to come. The reason is not only the increase in public cellular systems but also in the services they provide and services that will be requested by subscribers independent of communication media, by wire or wireless; services that will require digital systems on a high frequency carrier.

If the above assumption is correct it will be an important task of bodies such as CIGRÉ to ensure that guidelines and recommendations are revised to reflect these expected changes.

At present however there still are situations were active filters can be an alternative to a passive filter design. A few examples related to the dc side are

- In refurbishment of an existing dc filter scheme, which has unsatisfactory performance.
- In a project where the dc side configuration is changed or rebuilt, eg a new pole is added, such as Skagerrak 3.
- In a project where the dc transmission has a relatively short overhead line followed by a cable, as in Baltic Cable.
- In projects with very stringent performance requirements and/ or where switchyard area is critical.

The above are only a few possible situations. The need of a dc filter is determined by the possibility of causing telephone interference, and this in turn is unique for each different project and dependent on the overhead dc line route and if telephone subscriber or other signalling wires are present in the vicinity. Therefore, every project should be evaluated uniquely, both in terms of specifying requirements as well as in making the design adhering to those requirements.

For the ac side it is not expected that active filters as a means for mitigating telephone interference will be required. The design praxis and corresponding limits have proven valid over a long period of years for many HVDC schemes. Active ac filters can of course be used for other reasons than for mitigation of telephone interference, but such needs have to be evaluated on an individual project basis.

7 CONCLUSIONS

The paper has presented active dc filters provided for 3 different HVDC projects, with in total six active filters giving a sum of about 50 unit-years of operational service. The availability and overall experience is good.

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