AC-DC Harmonic Filters for Three Gorges-Changzhou ± 500 kV HVDC Project

Bernt Bergdahl, ABB Power Systems, Sweden, and Rebati Dass, ABB Limited, India

***Abstract*-- Three Gorges-Changzhou ±500 kV, 3000 MW transmission system being built in China is the 2nd largest single bipole long distance bulk power HVDC transmission link of the world. Harmonic filters have been provided on both AC and DC sides of the associated converter stations. The purpose of the AC side harmonic filters is to suppress the flow of harmonic currents into the connected AC networks. The DC side harmonic filters are to restrict the flow of harmonic currents in the DC pole and electrode lines thereby avoiding telephone interference.**

The AC-DC filters have been robustly designed in accordance with the customer's technical specification. This paper summarises the specification requirements, design aspects, filter configuration and special features.

***Index Terms*—AC-DC Harmonic Filters - HVDC - Background Harmonics - Reactive Power-Performance - Rating.**

I. INTRODUCTION

The converter stations associated with the Three Gorges-Changzhou ±500 kV HVDC bipole project are Longquan, in the Yichang County of Hubei Province, and Zhengping, in the Changzhou City of Jiangsu Province. The length of the overhead transmission line is 890 km. The salient specification requirements and design features of the project have been presented in [1].

The AC and DC side harmonics are to be suppressed, to the levels specified in the technical specification, by installing filters. This paper deals with detailed design aspects, specification requirements, filter configuration and special features of AC and DC filters associated with the project.

II. AC HARMONIC FILTERS

The basic purpose of AC harmonic filters is to restrict the flow of harmonic currents that are generated by the HVDC converters. The extent to which the harmonic currents are restricted is measured in terms of a number of indices or performance quantities. Most commonly specified indices are related to voltage harmonic distortion at the point of common coupling (PCC). AC harmonic filters serve the dual purpose of suppressing the converter generated harmonics and supplying reactive power to the HVDC converters at fundamental frequency.

A. Model for Performance

The 12-pulse HVDC converter generates characteristic harmonic currents of order 12n±1 on AC side under ideal conditions. Due to unbalances in the AC system voltage and unbalances in the converter, small amounts of harmonics at orders other than 12n±1 will be generated. On the AC side the converter can be represented as a source of harmonic currents. The harmonic currents enter the connected AC network and the filters. Fig. 1 shows the model for calculation of performance indices at PCC. The correct representation of the filter and AC network impedance at harmonic frequencies is paramount as it governs the flow of harmonic currents and their amplification due to parallel resonance, thereby the harmonic voltage distortion at PCC.

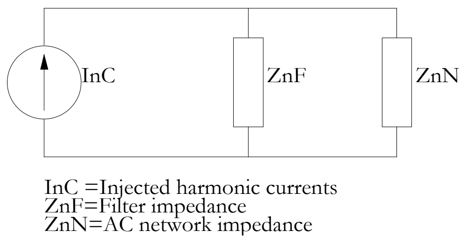

Fig. 1. Model for calculation of performance and filter component stresses

B. Model for Steady State Rating

The same model, as shown in Fig. 1, with modified harmonic currents and impedances is used also for determining steady state and temporary (short time) harmonic stresses on filter components caused by converter generated harmonic currents. In this project, the effects of harmonics existing in the network (background harmonics) are also taken into account. These are modelled in terms of harmonic voltages behind impedance. Fig. 2 shows the model that was used for determining the component stresses due to the background harmonics, U_{bn}.

The AC network harmonic impedance Z_{nN} is defined as any value within an envelope in the complex plane. In the model for converter generated harmonics, the value within the envelope is selected, which results in the worst case parallel resonance with the filter impedance Z_{nF}. In the model used for determining stresses due to background harmonics, Z_{nN} is chosen such that it results into worst case of series resonance

Bernt Bergdahl is with ABB Power Systems, Box 703, S-771 80 Ludvika, Sweden, Phone: +46 (0)240 782585, Fax: +46 (0)240 782177, E-mail: bernt.bergdahl@se.abb.com

Rebati Dass is with Asea Brown Boveri Limited, Chandiwala Estate , Maa Anand Mai Ashram Marg , Kalkaji , New Delhi–110019, India, Phone: +91-11-6826505, E-mail: rebati.dass@in.abb.com

condition with the impedance of filters and thus resulting in maximisation of the filter current. The filter component stresses obtained from these two models are than added to achieve the filter component ratings.

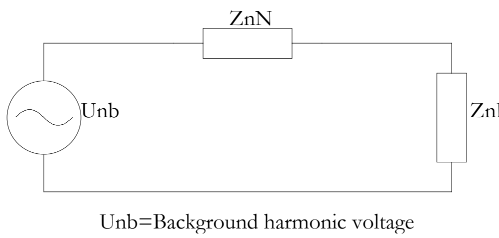

Fig. 2. Model for calculation of AC filter component stresses due to background harmonic voltages

C. Model for Transient Rating

The transient rating calculations comprise the selection of the suitable arresters, transient current and insulation levels of the filter components. The arresters inside the filters are used for protecting filter components, mainly reactors and resistors, against lighting and switching type surges. The calculation model includes proper representation of filter components, arresters and associated busworks. The worst transient stresses on both the filter components and the arresters protecting them are determined by taking close-in as well as remote faults. The arrester protective levels are chosen such that the arresters will not conduct for normal switching of the filters. Fig. 3 presents a transient model for a double tuned filter.

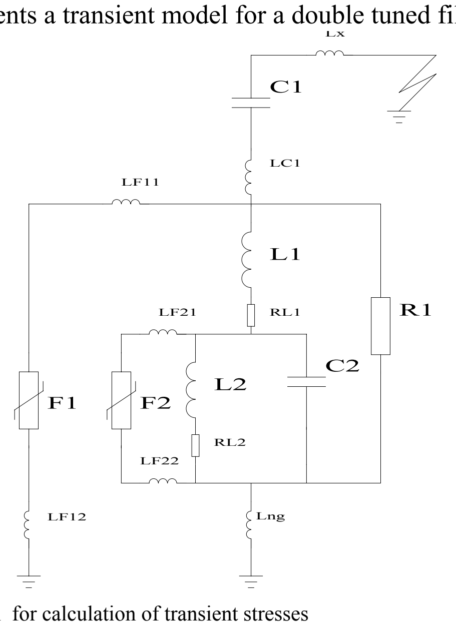

Fig. 3. Model for calculation of transient stresses

D. Specification Requirements

The performance is defined in terms of individual harmonic distortion (D_n), total RMS harmonic distortion (D_{eff}), and telephone harmonic form factor (T.H.F.F.). These quantities are defined as follows:

The individual harmonic voltage distortion is defined as:

$$D_n = \frac{E_n}{E_{ph}} \cdot 100\% \qquad (1)$$

The total harmonic voltage distortion is defined as:

$$D_{eff} = \sqrt{\sum_2^{50} \left(\frac{E_n}{E_{ph}} \right)^2} \cdot 100\% \qquad (2)$$

The telephone harmonic form factor (T.H.F.F. in the C.C.I.T.T. system) is defined as:

$$T.H.F.F. = \sqrt{\sum_1^{50} \left(\frac{E_n}{E_{ph}} \cdot K_n \cdot P_n \right)^2} \cdot 100\% \qquad (3)$$

Where:

E_n is the component of phase-to-ground RMS voltage at harmonic "n" due to harmonic currents generated by the converters.

E_{ph} is phase-to-ground RMS fundamental frequency voltage

n is harmonic number

and:

$$K_n = \frac{n \cdot 50}{800} \qquad (4)$$

$$P_n = \frac{\text{Psophometric weighting of harmonic n}}{100} \qquad (5)$$

The requirements on the limits of the above performance quantities are summarised in TABLE I.

TABLE I
LIMITS OF PERFORMANCE QUANTITIES

Quantity	Limit
D_n	1.25% for 3rd and 5th harmonics 1.0 % for all other odd harmonics 0.5 % for even harmonics
D_{eff}	1.75 %
THFF	1.0 %

The reactive power compensation equipment, i.e. AC filters and shunt capacitors, are required to be dimensioned to meet the converters consumption with:

- the maximum permitted support of 800 Mvar and 0 Mvar from the AC networks at Longquan and Zhengping respectively,
- the outage of the largest AC filter or shunt capacitor sub-bank.

The maximum permitted size of sub-banks at Longquan and Zhengping is 140 Mvar and 220 Mvar respectively. At both the converter stations, 3 banks are required to be supplied to meet the specified reactive compensation and voltage control requirements.

The technical specification requires that one sub-bank of each type is redundant, i.e. any one sub-bank can be out of service up to 100% HVDC transmission power and still meeting the performance requirements. For rating, even more numbers of sub-banks are considered unavailable.

The background harmonic voltages are to be considered for rating of the filters. Their impact on the ratings of the filter components is significant due to the assumed series resonance condition between the filters and AC network impedance.

E. Filter Configuration

The AC filter and shunt capacitor configuration for the converter stations consist of switchable sub-banks and banks as shown in Fig. 4. TABLE II and TABLE III give details on the sub-banks for Longquan and Zhengping respectively. The Mvar rating of the sub-banks is defined at nominal AC network voltage of 525 kV and 500 kV for Longquan and Zhengping respectively.

At Zhengping, there are 4 shunt capacitor sub-banks which are required to fulfil the reactive power compensation requirement. Damping reactors are connected to the shunt capacitors to limit the inrush current during back-to-back charging of the shunt capacitors.

TABLE II
FILTER COMPONENT VALUES FOR LONGQUAN

Components	Filter Sub-bank Type		
	HP11/13	HP24/36	HP3
C1 , μF	1.6	1.6	1.4
L1, mH	43.8	7.2	929.4
C2 , μF	57.8	9.7	10.9
L2, mH	1.2	1.2	-
R1, Ω	2000	500	1800
Tuning freq., Hz	550/650	1200/1800	150

The AC filter scheme at Zhengping is simple and robust with only one type of HP12/24 filter branch plus shunt capacitor banks, while the filter scheme at Longquan is somewhat more complicated with HP11/13, HP24/36 and HP3 branches. The different filter solutions are necessitated due to different a.c. system conditions at the two ends:

- At Longquan the converter station is connected close to the Three Gorges Hydro Power Plant. This means low resistance in the harmonic impedance of the AC network and a 3^{rd} harmonic filter is required for damping of low order harmonic resonance. Full reactive compensation of the converters is not required since reactive power can be supplied by the generators. This led to a limited amount of Mvars available for filtering of the characteristic harmonics, therefore, efficient filters tuned to several frequencies are required to meet the performance criteria.
- At Zhengping the AC network is strong and well damped, and low order harmonic filter branches are not required. There is also full reactive compensation of the converters which gives plenty of Mvars available for filtering of the characteristic harmonics, and thus a simple filtering scheme can be used.

The selected filter configurations meet all the specified performance requirements.

TABLE III
FILTER COMPONENT VALUES FOR ZHENGPING

Components	Filter Sub-bank Type	
	HP12/24	SC
C1 , μF	2.8	2.4
L1, mH	13.0	2.0
C2 , μF	5.1	-
L2, mH	7.1	-
R1, Ω	300	-
Tuning freq., Hz	583/1200	-

F. Special Features

There are a number of special features, some of them, such as the effect of background harmonics, are discussed above. Other interesting features are briefly described as follows:

- Fundamental frequency and harmonic voltages have been added arithmetically to determine the rated voltage of the filter capacitors.
- Filter arresters' reference voltage is chosen sufficiently high with due consideration to the harmonic content and a deviation from ideal point-on-wave switching. This will ensure that the arresters do not operate at normal switching, thus avoiding temperature rise and aging effects during switching.

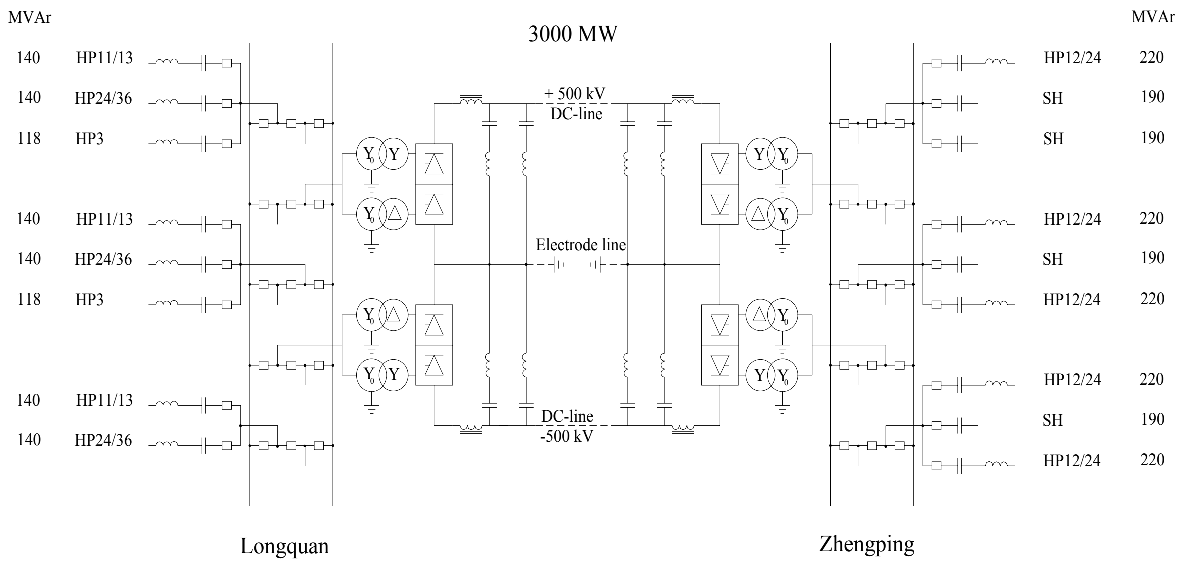

Fig. 4. Power circuit arrangement of the transmission scheme

III. DC Harmonic Filters

An HVDC converter generates harmonic voltages on DC side [2] and these voltages drive currents through the DC circuit. The flow of harmonic currents in the pole and electrode lines can cause interference due to electro-magnetic induction on the open-wire telecommunication lines in the vicinity of the pole and electrode lines.

DC harmonic filters together with the smoothing reactors are required to limit the flow of harmonic currents into the pole and electrode lines. The smoothing reactors, also serve other purposes than impeding the flow of harmonic currents. The DC side filters serve the sole purpose of filtering.

A. Model for Performance and Rating

Seen from the DC side, the HVDC converter can be considered as a harmonic voltage source and be represented by the 3-pulse model described in [3]. Under ideal conditions the voltages will result in a set of characteristic 12-pulse harmonics, i.e. harmonics of order $12n$. Due to unbalance in the AC system voltage, stray capacitances and unsymmetries in the converter bridge, small amounts of other non-characteristic harmonics are also generated.

The harmonic content on the AC side generates harmonic voltages on DC side and this was considered in the performance and rating calculations. It was done by a translation of AC side harmonic voltages to the equivalent DC side harmonics, corresponding to the modulation effect of the converter switching at fundamental frequency. The frequency and magnitude of the DC side harmonics are calculated from the frequency, phase sequence and magnitude of the AC side harmonics.

Fig. 5 and Fig. 6 show the models that have been used for performance and rating calculations. In rating calculations wider range, as compared to performance, of AC network parameters and tolerances on filter component and converter parameters is considered. In contrast to the AC side where the network impedance is more or less unknown, the circuit on the DC side is well known and can be modelled in detail.

The DC circuit model includes three parts, namely the converter, the transmission line and the filter. Each 12-pulse converter is represented by 3-pulse harmonic voltage sources in series as shown in Fig. 5 and 6. The stray capacitances-to-ground in the converter transformers and bushings are also included in the model as well as converter transformer reactance.

The DC transmission line and the electrode lines are modelled by taking into account line geometry, ground resistivity and all aspects of conductor construction. The harmonic currents induced in the shield wires are calculated explicitly and are added vectorially to the currents in the pole lines to give the total residual harmonic current at any point in the transmission corridor.

The filter components are modelled by taking into account the effect of ambient temperature and manufacturing tolerances in the worst manner.

The methodology similar to the one for AC filters is used for transient rating calculations of the DC filter components. The transient model of Fig. 4 will include the representation of the relevant neutral equipment.

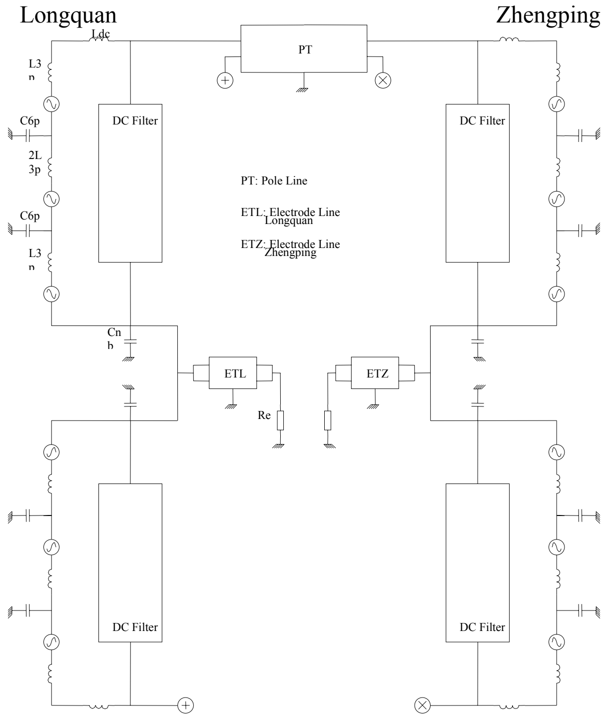

Fig. 5. Calculation model for bipolar operation

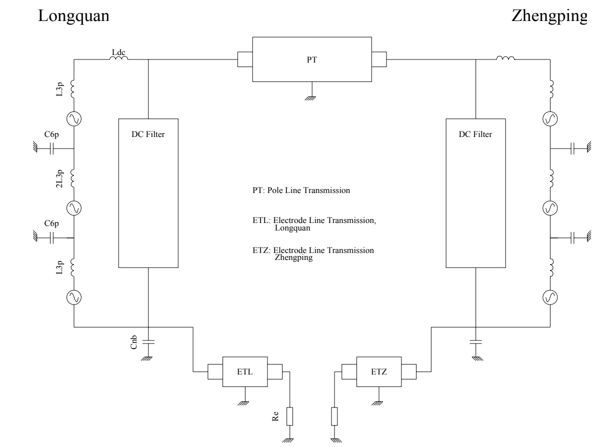

Fig. 6. Calculation model for monopolar operation

B. Technical Specification Requirements

The performance criterion is based on the maximum permissible limit of the psophometric weighted equivalent disturbing current I_{eq} along the DC transmission pole and electrode lines. The equivalent disturbing current is defined as:

$$I_{eq}(x) = \sqrt{I_e(x)_L^{\,2} + I_e(x)_Z^{\,2}} \quad \text{(in mAp)} \qquad (7)$$

Where;

$I_{eq}(x)$ is the 800 Hz equivalent disturbing current in milli-amps psophometrically weighted (mAp) at any point along the transmission corridor.

$I_e(x)_L$ is the magnitude of the RSS equivalent disturbing current due to harmonic voltage sources at Longquan (mAp)

$I_e(x)_Z$ is the magnitude of the RSS equivalent disturbing current component due to harmonic voltage sources at Zhengping (mAp)

x denotes the relative location along the transmission corridors.

The maximum acceptable equivalent disturbing currents, $I_{eq}(x)$, at any location along the DC line corridor or electrode line corridors are:

Bipolar operation 500 mAp
Monopolar mode with metallic or ground return 1000 mAp

For the rating of the DC filter components it is to be assumed that any one DC filter arm can be out of service in any converter pole.

C. Filter Configuration

The DC filters at Longquan and Zhengping are identical. In each pole there are two double tuned filter branches tuned to 12/24th and 12/36th harmonics. Since both branches are tuned to the 12th harmonic, which is the dominating harmonic on the DC side, it is possible to operate with one filter branch disconnected. The filter branch configurations are as shown in Fig. 3 except for resistors, and the component values are given in TABLE IV. The chosen filters give the performance well within the specified limits.

TABLE IV
FILTER COMPONENT VALUES FOR LONGQUAN

Components	Filter Type	
	12/24	12/36
Tuning frequency, Hz	600/1200	600/1800
C1 , μF	2	2
L1, mH	11.7	6.46
C2 , μF	9.0	3.8
L2, mH	5.8	11.4

D. Special Features

There are a number of special features of DC filters design for the project. Some of which, such as the effect of ambient (or background) harmonics, have been mentioned in the preceding sections of the paper. Other interesting features are:

- The DC smoothing reactor and DC filter components are selected to avoid resonance at the fundamental and the 2nd harmonic frequencies.
- A DC filter branch can be disconnected when the DC transmission is in operation, and continued operation is possible with one filter branch out.
- The DC filter capacitors are rated by taking arithmetic sum of harmonic and increased DC voltage as follows:

$$\sqrt{2}\sum_{n=1}^{50} U_n + kU_{DC} \tag{9}$$

where the factor k is 1.3

IV. CONCLUSION

Conventional passive filters of well proven design are used both on the AC and DC sides. The filters are designed to operate satisfactorily even during outage conditions. Reactive Power balance requirements are also met at filter outage. The filter components have been designed with generous design margins, with due considerations also to background harmonics in the network. These factors give a robust filtering scheme contributing to a high reliability and availability of the HVDC transmission.

V. REFERENCES

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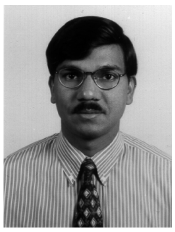
VI. BIOGRAPHIES



Rebati Dass was born in Mainpuri, India, on July 28, 1962. He received his degree in Electrical Engineering from the University of Roorkee, Roorkee, India, in 1983.

His employment experience includes the service with National Thermal Power Corporation (NTPC), a power utility owned by government of India, and ABB Limited, a multinational company. His special fields of interest include power quality and AC-DC filters.

In NTPC, he was involved with power system analysis, transmission system planning and design of HVDC converter stations. He is a recipient of 1994 Young Engineer award from CBIP, a national autonomous body, for his significant contribution in Indian power systems. He joined ABB Limited in 1995, since then has been involved in the design of HVDC systems, particularly, AC-DC filters. He is a member of CIGRE and has been a contributing member on a number of CIGRE SC-14 working groups.

Bernt Bergdahl was born in Forshaga, Sweden on January 3, 1950. He received his M.S. degree in engineering from the University of Linköping in 1974.

He joined ASEA in 1974, where he has worked in different topics of HVDC system design, such as controls, filter design and development of methods for HVDC system design. In 1980 he joined the ASEA-Promon consortium in Rio de Janeiro where he was responsible for the filter design studies. In 1982 he returned to Sweden and ASEA/ABB for continued work in HVDC system design and as technical coordinator for several HVDC projects and proposals. Between 1994 and 1999 he was manager of the Filter design department of the HVDC division of ABB Power Systems. Since 1999 he has been working as Senior Specialist in HVDC Filter- and System Design.