6

Harmonic Elimination

6.1 Introduction

When planning the installation of large nonlinear plant components the decision has to be made between designing the nonlinear devices for low levels of waveform distortion or installing harmonic compensation equipment at the terminals. The first solution is often possible by phase-shifting of the transformers and/or the control of converter bridges or by the use of switching devices with turn-off capability. These alternatives have been discussed under harmonic sources (Chapter 3). External harmonic compensation, on the other hand, is achieved by means of filters. In each case the decision will depend on factors like the power and voltage rating of the equipment to be installed and the effect of the local (internal) waveform distortion on the rest of the plant.

When the sole purpose is to prevent a particular frequency from entering selected plant components or parts of the power system (e.g. in the case of ripple control signals) it is possible to use a series filter consisting of a parallel inductor and capacitor which presents a large impedance to the relevant frequency. Such a solution, however, can not be extended to prevent the harmonics from arising at the source, because the production of harmonics by nonlinear plant components (like transformers and static converters) is essential to their normal operation.

In the case of static converters, the harmonic currents are normally prevented from entering the rest of the system by providing a shunt path of low impedance to the harmonic frequencies.

Although this chapter is mainly concerned with passive filters, a section is devoted to active filtering due to the increasing interest in this alternative.

6.2 Passive Filter Definitions

A shunt filter is said to be tuned to the frequency that makes its inductive and capacitive reactances equal.

The quality of a filter (Q) determines the sharpness of tuning and in this respect filters may be either of a high or a low Q type. The former is sharply tuned to one of the lower harmonic frequencies (e.g. the fifth) and a typical value is between 30

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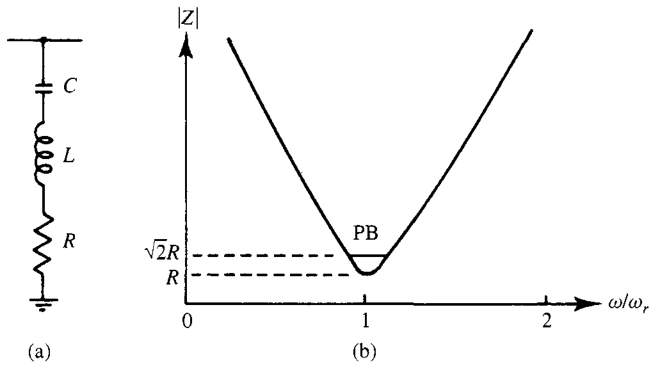


Figure 6.1 (a) Single-tuned shunt filter circuit; (b) single-tuned shunt filter impedance versus frequency

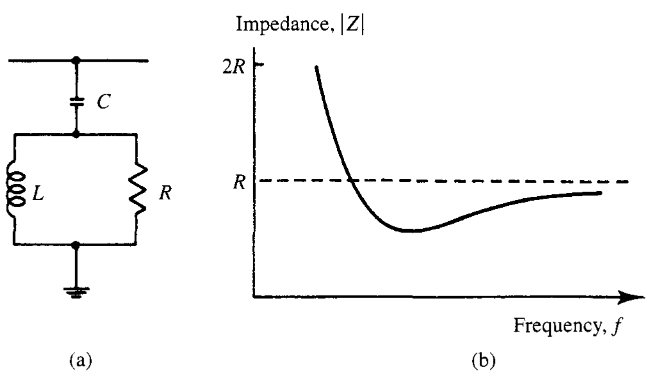


Figure 6.2 (a) Second-order damped shunt filter; (b) second-order damped shunt filter impedance versus frequency

and 60. The low Q filter, typically in the region of 0.5–5, has a low impedance over a wide range of frequency. When used to eliminate the higher-order harmonics (e.g. 17th up wards) it is also referred to as a high-pass filter. Typical examples of high and low Q filter circuits and their impedance variation with frequency are illustrated in Figures 6.1 and 6.2.

In the case of a tuned filter Q is defined as the ratio of the inductance (or the capacitance) to resistance at the resonant frequency, i.e.

$$Q = X_0/R \tag{6.1}$$

As shown in Figure 6.1(b), the filter pass band (PB) is defined as being bounded by the frequencies at which the filter reactance equals its resistance, i.e. the impedance angle is 45° and the impedance module $\sqrt{2}R$. The quality factor and pass band are related by the expression

$$Q = \omega_n/\mathrm{PB} \tag{6.2}$$

where ω_n is the tuned angular frequency in radians per second. The sharpness of tuning in high-pass damped filters is the reciprocal of that of tuned filters, i.e. $Q = R/X$.

The extent of filter detuning from the nominal tuned frequency is represented by a factor δ. This factor includes various effects: (i) variations in the fundamental (supply) frequency; (ii) variations in the filter capacitance and inductance caused by ageing and temperature; and (iii) initial off-tuning caused by manufacturing tolerances and finite size of tuning steps.

The overall detuning, in per unit of the nominal tuned frequency, is

$$\delta = (\omega - \omega_n)/\omega_n \tag{6.3}$$

Moreover, a change of L or C of say 2% causes the same detuning as a change of system frequency of 1%. Therefore δ is often expressed as

$$\delta = \frac{\Delta f}{f_n} + \frac{1}{2}\left(\frac{\Delta L}{L_n} + \frac{\Delta C}{C_n}\right) \tag{6.4}$$

6.3 Filter Design Criteria

6.3.1 Conventional Criteria

The size of a filter is defined as the reactive power that the filter supplies at fundamental frequency. It is substantially equal to the fundamental reactive power supplied by the capacitors. The total size of all the branches of a filter is determined by the reactive power requirements of the harmonic source and by how much this requirement can be supplied by the a.c. network.

The ideal criterion of filter design is the elimination of all detrimental effects caused by waveform distortion, including telephone interference, which is the most difficult effect to eliminate completely. However, the ideal criterion is unrealistic for technical and economic reasons. From the technical point of view, it is very difficult to estimate in advance the distribution of harmonics throughout the a.c. network. On the economic side, the reduction of telephone interference can normally be achieved more economically by taking some of the preventive measures in the telephone system and others in the power system.

A more practical approach is to try to reduce the problem to an acceptable level at the point of common coupling with other consumers, the problem being expressed in terms of harmonic current, harmonic voltage, or both. A criterion based on harmonic voltage is more convenient for filter design, because it is easier to guarantee staying within a reasonable voltage limit than to limit the current level as the a.c. network impedance changes.

The voltage THD index is more representative than the arithmetic sum, because it corresponds to the power of the harmonics and is therefore more closely related to the severity of the disturbance. The recommended criteria for HVd.c. converter filters [1] is the maximum level of any single harmonic and the THD. In general it will be sufficient to include all harmonics up to the 25th order. The maximum values of individual harmonics generally occur for different conditions. It is therefore necessary

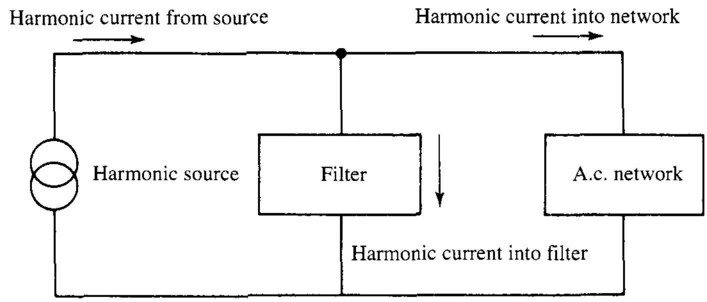


Figure 6.3 Circuit for the computation of voltage harmonic distortion

to clarify whether the THD should use those values of individual harmonics which are simultaneously present, or the non-coincident maximum values of each harmonic. Regarding telephone interference, although used in a number of projects, the IT index into a node of a meshed transmission system has little meaning. However, in cases when earth resistivity is high there is justification to limit the magnitudes of harmonic currents flowing in particular transmission lines which run close to telephone lines; this is normally achieved with the use of the 'equivalent disturbing current' concept.

To comply with the required harmonic limitations, the design of filters involves the following steps:

(1) The harmonic current spectrum produced by the nonlinear load is injected into a circuit consisting of filters in parallel with the a.c. system (Figure 6.3) and the harmonic voltages are calculated.
(2) The results of (1) are used to determine the specific parameters, i.e. the THD, TIF and IT factors.
(3) The stresses in the filter components, i.e. capacitors, inductors and resistors, are then calculated and with them their ratings and losses.

Three components require detailed consideration in filter design: the current source and the filter and system admittances.

The current source content should be varied through the range of load and (in the case of static converters) firing angle conditions. This subject has been discussed in Chapter 3. As far as system and filter admittances are concerned, it is essential to calculate the minimum total equivalent admittance at each harmonic frequency, which will result in maximum voltage distortion.

The obvious filter design is a single broad band-pass configuration capable of attenuating the whole spectrum of injected harmonics (e.g. from the fifth up in the case of a six-pulse converter). However, the capacitance required to meet such a target is too large, and it is usually more economical to attenuate the lower harmonics by means of single arm tuned filters.

6.3.2 Advanced Filter Design Criteria

The conventional criteria described above provide adequate filter designs for most applications. However, in cases where the nonlinear plant has a very large power rating, such as an HVd.c. converter, these criteria can lead to inadequate solutions and even harmonic instabilities. The reason is that the conventional approach ignores the interaction that exists between the nonlinear device and the rest of the power system. Such interaction affects the harmonic current injections as well as the overall system harmonic impedances (which should include the effective contribution of the nonlinear device), and thus requires an iterative solution, rather than the direct solution of the conventional approach.

The derivation of advanced models of nonlinear plant, taking into account their harmonic interaction with the rest of the system, is described in Chapter 8.

6.4 Network Impedance for Performance Calculations

The network harmonic impedances change with system configuration and load conditions. Although these can be determined from measurements, it is difficult to monitor all possible network conditions; in particular, future changes can not be captured by measurements.

The use of computer programs provides greater flexibility. If the derived impedances are too pessimistic (i.e. unreasonably large and/or the damping too low), which is normally the case due to lack of accuracy in the parameters used for the calculation, the filter will be more expensive than necessary. Thus the correct modelling of the variation of component/branch resistance with frequency, particularly for transformers and loads, is important to determine accurately the damping of the network.

6.4.1 Size of System Representation

As the system harmonic impedances vary with the network configuration and load patterns, large amounts of data are generated. Considering the large number of studies involved in filter design, it is prohibitive to represent the whole system with the same degree of detail for every possible operating condition. The detail of component representation depends on their relative position to the harmonic source, as well as their size in comparison with that of the harmonic source. Any local plant components such as synchronous compensators, static capacitors and inductors, etc., will need to be explicitly represented.

As the high voltage transmission system has relatively low losses, it is also necessary to consider the effect of plant components with large (electrical) separation from the harmonic source. It would thus be appropriate to model accurately at least all of the primary transmission network. Moreover, due to the standing wave effect on lines and cables, a very small load connected via a line or cable can have a dramatic influence on the system response at harmonic frequencies.

It is recommended to consider the loads on the secondary transmission network in order to decide whether these should be modelled explicitly or as an equivalent circuit. If these loads are placed directly on the secondary side of the transformer, their damping can be overestimated when using simple equivalents.

Increasing network complexity results in a greater number of resonance frequencies. By way of illustration [2], Figure 6.4 shows the harmonic impedance at a converter

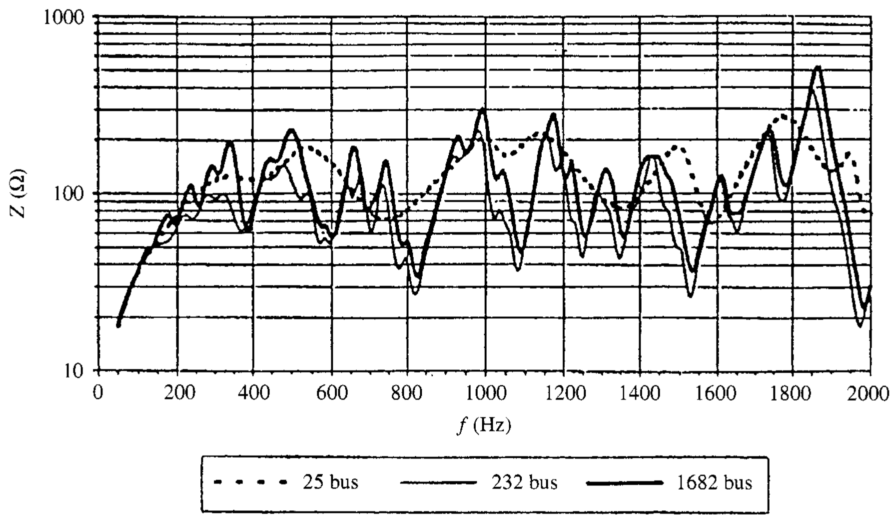


Figure 6.4 Effect of size of system representation [2]

bus of a primary (400 kV) system with either 25, 232 or 1682 buses included; the 25-bus case includes the nearest 400 kV lines terminated by equivalent circuits plus the transformers and large generators in this area. The continuous thick line shows the same information when the network consists of 1682 buses, which include the complete 400 kV, 220 kV and 110 kV networks plus the generators down to the 1 MVA size; however, it must be emphasised that the number of buses is not the only relevant criterion for increased accuracy. The considerable differences observed are due to the 'hand-made' formation of the small network while the large network is produced automatically from the network database. Because modern computers can handle the larger network in reasonable times, the larger representation must be recommended as it gives accurate results at any point in the network and only one model for the whole network has to be maintained.

Radial parts of the system or neighbouring interconnected systems that remain invariant when performing multiple case studies can be replaced by frequency-dependent circuits, or by their harmonic admittances at the point of connection.

6.4.2 Effect of A.C. Network Resistance at Low Frequencies [1]

When considering classical resonant filters, taking into account the damping of the a.c. network generally allows the use of smaller sized filters when a target of maximum harmonic voltage has been specified. This size reduction is a function of the maximum phase angle ($\phi_{h\,\max}$) of the network impedance at harmonic frequency h and is expressed by

$$1/(1 + \cos\phi_{h\,\max})$$

The filtering performance of damped filters (Section 6.6) for high frequencies does not depend much on the converter power rating or on the network impedance, the latter being generally higher than that of the filters.

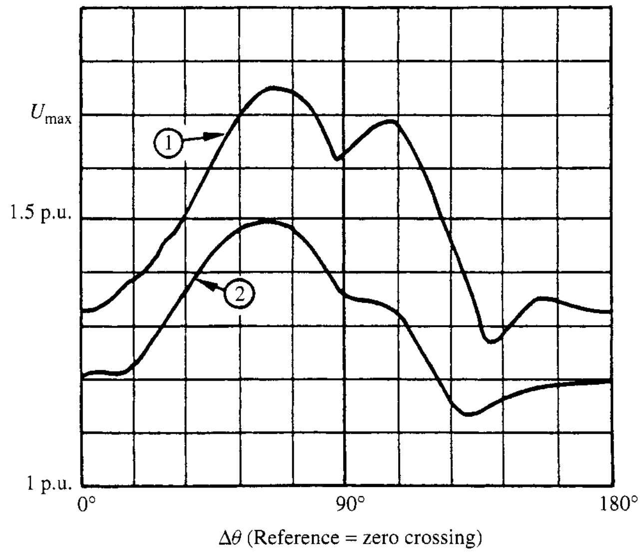


Figure 6.5 Influence of system damping on the maximum overvoltage during the energisation of a 150 MVAr filter bank. (1), Purely inductive system; (2), the real system (400 kV/4 GVA/50 Hz)

On the other hand, when designing a damped filter for stronger damping of a low-order harmonic voltage, it is essential to know accurately the network impedance at low frequencies. It is necessary to ensure that connecting the filter in parallel with the network impedance has a positive effect on the harmonic voltage and avoids excessive amplification of harmonic voltages of other orders, especially those which are close. These requirements must be fulfilled while keeping an acceptable level of losses.

The simulation of the transient overvoltages resulting from the energisation of the converter transformers and of compensation equipment also depend on the damping of the a.c. network at low frequencies. Figure 6.5 illustrates the calculated overvoltages due to switching of a second-order high-pass filter bank for different switching instants; these results show the influence of the damping representation of the network. Such analysis requires the determination of the network impedance locus for its various configurations and, especially, for the resonant frequencies between the a.c. network and the filters.

6.4.3 Impedance Envelope Diagrams

The results of the computer studies can be presented in the form of tables or, more effectively, as envelope diagrams, such as sector, polygon or circle diagrams. In the latter case an X/R area in the complex impedance diagram is defined for a certain frequency range. The locus of the a.c. system impedance for varying system conditions and at different harmonic frequencies is defined to be within the envelope of these areas. Envelope diagrams permit a systematic search for the worst-case impedance.

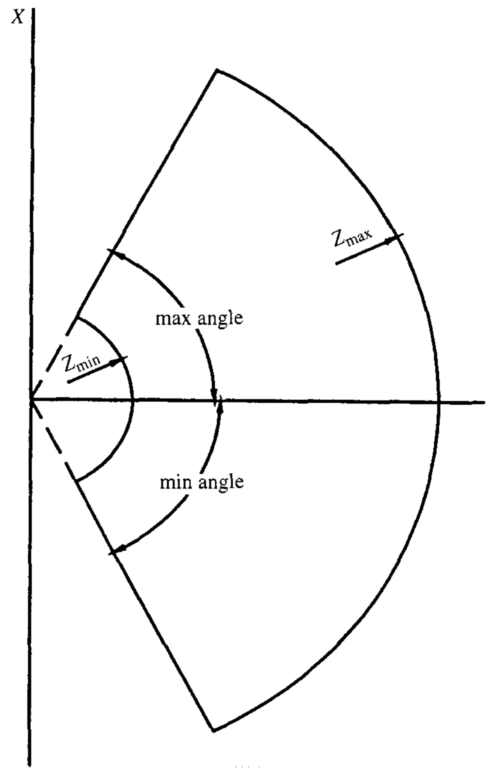


Figure 6.6 A.c. system impedance general sector diagram. CIGRE © copyright

Sector Diagrams The sector diagram restricts the area encompassing the loci of a particular harmonic impedance to a circular sector limited by maximum and minimum radii and angles, as shown in Figure 6.6. As the lower limit of the impedance, either the minimum impedance or the minimum resistance is given.

This diagram is very simple to define when little information about the network is available. The disadvantages of this representation are:

- Where the maximum R in a harmonic range is set by a system parallel resonance, this will define the maximum Z, and will produce corresponding reactance limits which often exceed their actual value.
- The maximum and minimum angles will normally be lower than those in the diagram for the higher reactance values.
- The relationship between the minimum limits of Z and R is unlikely to correspond to reality and yet it is an important factor in filter design.

Circle Diagram As Figure 6.7 illustrates, in this representation the locus of the system impedances is a circle with a radius selected to encompass the maximum impedance to be considered. In addition to the radius, the maximum and minimum angle and minimum resistance should be specified.

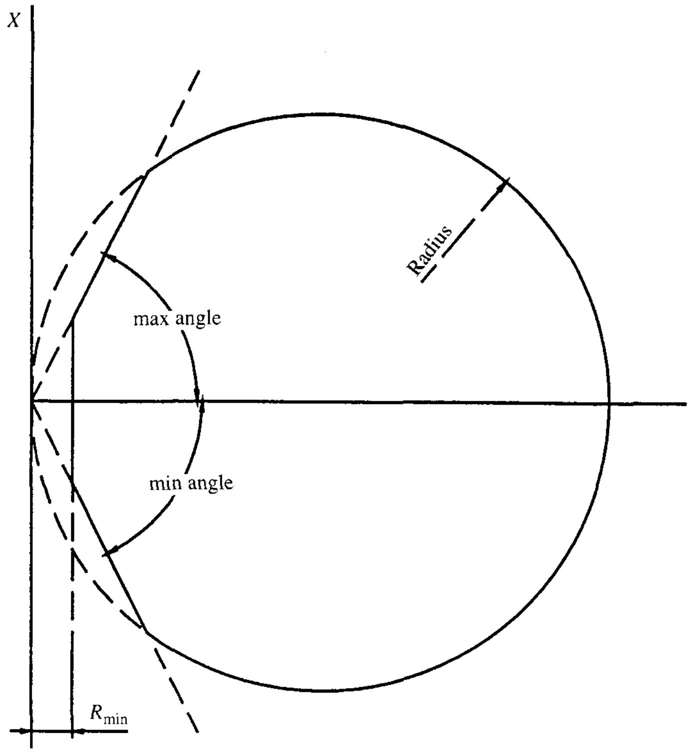


Figure 6.7 A.c. system impedance general circle diagram, with minimum resistance. CIGRE © copyright

This diagram provides a better fitting envelope for the real values than the sector diagram and a more realistic approximation for the characteristic harmonics. However, the radius is determined by the largest value of the impedance range, generally fixed by a parallel resonance which may apply over a more limited frequency range than that of the complete diagram (or there may be a set of resonances at different frequencies for different system conditions). Hence this approach could result in the inclusion of an even larger non-applicable area than the sector diagram, particularly in the capacitive reactance sector for the lower harmonic range.

Discrete Polygons For a more accurate representation of the network impedance, it is necessary to use different diagrams for different frequency ranges, as the system impedance is frequency dependent. In this way relatively limited impedance sectors can be defined for each harmonic, thus permitting a more exact matching of the a.c. filter design to the actual network conditions. This solution avoids filter over-designs of the low-order and 11th and 13th characteristic harmonics.

Care should be taken in specifying impedances for the low-order harmonics, particularly the second, third and fifth. If the values specified are too large the calculations may lead to filters tuned at these frequencies. Thus, it may be advisable to specify separate diagrams for these frequencies.

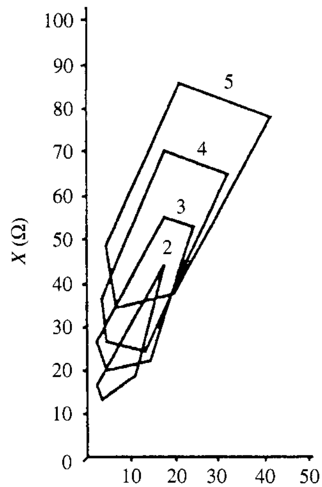


Figure 6.8 Discrete polygons for the 2nd to 5th harmonic impedances

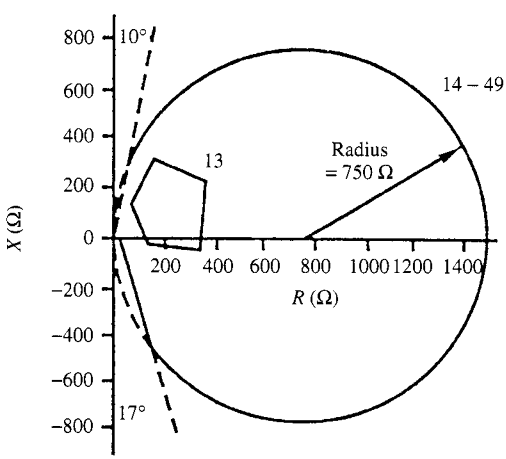


Figure 6.9 Harmonic impedance loci for the 13th and envelope of harmonic impedance loci for orders 14 to 49. Reproduced by permission of CIGRE

Figure 6.8 shows these polygons for the harmonic orders 2 to 5. In practice the polygons encompassing the impedances at high frequencies become rather large and it is more practical to use a circle diagram for these frequencies without introducing too much pessimism in the filter designs. A combination of polygons (up to the 13th harmonic) and circle diagram for the orders higher than the 13th is illustrated in Figure 6.9.

6.5 Tuned Filters

A single tuned filter is a series *RLC* circuit (as shown in Figure 6.1) tuned to the frequency of one harmonic (generally a lower characteristic harmonic). Its impedance is given by

$$Z_1 = R + j\left(\omega L - \frac{1}{\omega C}\right) \tag{6.5}$$

which at the resonant frequency (f_n) reduces to R. There are two basic design parameters to be considered prior to the selection of R, L and C. These are the quality factor (Q), and the relative frequency deviation (δ), already defined.

In order to express the filter impedance in terms of Q and δ, the following relationships apply:

$$\omega = \omega_n(1 + \delta) \tag{6.6}$$

where

$$\omega_n = \frac{1}{\sqrt{LC}} \tag{6.7}$$

The reactance of inductor or capacitor in ohms at the tuned frequency is

$$X_0 = \omega_n L = \frac{1}{\omega_n C} = \sqrt{\frac{L}{C}} \tag{6.8}$$

$$Q = \frac{X_0}{R} \tag{6.9}$$

$$C = \frac{1}{\omega_n X_0} = \frac{1}{\omega_n R Q} \tag{6.10}$$

$$L = \frac{X_0}{\omega_n} = \frac{RQ}{\omega_n} \tag{6.11}$$

Substituting equations (6.6), (6.10) and (6.11) in equation (6.5) yields

$$Z_f = R\left(1 + jQ\delta\left(\frac{2+\delta}{1+\delta}\right)\right) \tag{6.12}$$

or, considering that δ is relatively small as compared with unity,

$$Z_f \approx R(1 + j2\delta Q) = X_0(Q^{-1} + j2\delta) \tag{6.13}$$

and

$$|Z_f| \approx R(1 + 4\delta^2 Q^2)^{1/2} \tag{6.14}$$

It is generally more convenient to deal with admittances rather than impedances in filter design, i.e.

$$Y_f \approx \frac{1}{R(1 + j2\delta Q)} = G_f + jB_f \tag{6.15}$$

where

$$G_f = \frac{Q}{X_0(1 + 4\delta^2 Q^2)} \tag{6.16}$$

$$B_f = -\frac{2\delta Q^2}{X(1 + 4\delta^2 Q^2)} \tag{6.17}$$

The harmonic voltage at the filter busbar is

$$V_n = \frac{I_n}{Y_{nf} + Y_{sn}} = \frac{I_n}{Y_n} \tag{6.18}$$

and therefore to minimise the voltage distortion it is necessary to increase the overall admittance of the filter in parallel with the a.c. system.

For a prediction of the largest V_n, the variables that are not accurately known have to be chosen pessimistically; these are the frequency deviation δ and the network admittance Y_{sn}. Since the harmonic voltage increases with δ, the largest expected deviation δ_m must be used in the analysis. Again, the worst realistic system condition (the lowest admittance) must be represented.

With certain limits the designer can decide on the values of Q and filter size (VA rating at the fundamental frequency).

In terms of Q and δ, equation (6.18) can be written as follows:

$$|V_n| = I_n \left\{ \left[G_{sn} + \frac{1}{R(1+4Q^2\delta^2)} \right]^2 + \left[B_{sn} - \frac{2Q\delta}{R(1+4Q^2\delta^2)} \right]^2 \right\}^{-1/2} \tag{6.19}$$

The case of a purely inductive a.c. network admittance, often used in filter design, is unduly pessimistic.

The impedance loci indicate that generally the harmonic impedances can be circumscribed in a region of R, jX determined by two straight lines and a circle passing through the origin (see Figure 6.7). The maximum phase angle of the network impedance can thus be limited to below 90° and generally decreases with increasing frequency (except in cable networks for high harmonic orders). The highest harmonic voltage is then obtained by using ϕ_{sn} with a sign opposite to that of δ.

Then equation (6.19) becomes

$$|V_n| = I_n\{(|Y_{sn}|\cos\phi_{sn} + G_f)^2 + (-|Y_{sn}|\sin\phi_{sn} + B_f)^2\}^{-1/2} \tag{6.20}$$

taking ϕ_{sn} positive and δ negative.

If $|Y_{sn}|$ is left unrestricted, the admittance giving maximum $|V_n|$ is

$$|Y_{sn}| = \frac{\cos\phi_{sn}(2Q\delta\tan\phi_{sn} - 1)}{R(1+4Q^2\delta^2)} \tag{6.21}$$

giving

$$|V_n| = I_n\omega_n L \left[\frac{1+4Q^2\delta^2}{Q(\sin\phi_{sn} + 2Q\delta\cos\phi_{sn})} \right] \tag{6.22}$$

There is an optimum Q which results in the lowest harmonic voltage, i.e.

$$Q = \frac{1+\cos\phi_{sn}}{2\delta\sin\phi_{sn}} \tag{6.23}$$

for which

$$|V_n| = I_n \delta\omega_n L \left[\frac{4}{(1+\cos\phi_{sn})} \right] = \frac{2I_n R}{\sin\phi_{sn}} \tag{6.24}$$

Nevertheless, it should be noted that filters are not usually designed to give minimum harmonic voltage under these conditions. Normally a higher Q is selected in order to reduce losses.

A condition that also has to be considered in the design of filters, and which can restrict the operation of the converters, is an outage of one or more filter branches. The remaining filter branches may then be over-stressed as they have to take the total harmonic current generated by the converter.

6.5.1 Graphic Approach

A graphic explanation is given by Kimbark [3] which helps to understand the selection of optimum Q, i.e. the value that maximises Y_n.

For a given maximum value of the frequency deviation factor δ_m, and using a fixed reactance X_0 and variable resistance R, the locus of the filter admittance, i.e.

$$Y_f = \frac{1}{R(1+j2\delta Q)}$$

is a semicircle of diameter $1/(2\delta_m X_0)$ tangent to the G-axis at the origin, as shown by the dashed line in Figure 6.10. The same figure displays (shaded area) the system

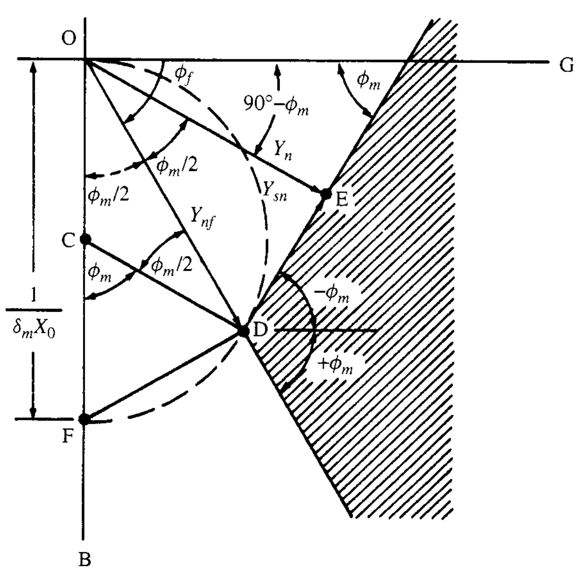


Figure 6.10 Construction for finding optimum Q and worst network admittance Y_{sn}, drawn for $\phi_m = 60°$. From [3]. Copyright 1971, John Wiley and Sons, Inc

admittance domain (Y_{sn}), obtained by inverting the impedance locus, and the minimum admittance for each frequency lies on the boundary of the shaded area.

For a given Y_{nf}, the shortest vector Y_n is perpendicular to and ends on the boundary. The vector diagram of Figure 6.10 drawn for a positive δ_m and negative $\phi = \phi_m$ produces the highest harmonic voltage. Moreover, the optimum value of Y_{nf} is that which terminates on the semicircle at a point where the boundary at angle $+\phi_m$ is the tangent to the semicircle. This optimum case is illustrated in Figure 6.10, where at point D, Y_{nf} maximises V_n and Y_{sn} minimises it.

For such conditions the filter admittance can be shown to be

$$|Y_{nf}| = \frac{\cos(\phi_m/2)}{2\delta_m X_0} \tag{6.25}$$

and

$$|Y_n| = |Y_{nf}|\cos(\phi_m/2) = \frac{1+\cos\phi_m}{4\delta_m X_0} \tag{6.26}$$

The quality factor of the chosen Y_{nf} is

$$Q = \frac{X_0}{R} = \frac{X_0}{X_f/(\tan\phi_f)} \tag{6.27}$$

but (from equation (6.13)

$$X_f = 2\delta_m X_0 \tag{6.28}$$

and (from Figure 6.10)

$$\tan\phi_f = \cot(\phi_m/2) \tag{6.29}$$

Therefore

$$Q = \frac{\cot(\phi_m/2)}{2\delta_m} = \frac{\cos\phi_m + 1}{2\delta_m \sin\phi_m} \tag{6.30}$$

After the individually tuned filter Qs values have been determined, the entire filter configuration must be used to determine the network admittance Y_n that yields the minimum total admittance Y at each harmonic frequency.

In practice, the minimal possible system admittances are also limited by a minimum conductance, thus resulting in the admittance domain shown shaded in Figure 6.11.

At any harmonic frequency the equivalent admittance of the filter configuration consists of a vector that ends at point O and starts in one of three regions of the admittance plane as shown in Figure 6.11.

At frequencies for which tuned filters are provided, the origin of the filter admittance is likely to lie in region 3, i.e. the total filter admittance is relatively large. At other frequencies, however, the filter admittance origin may lie in region 1 or 2.

The most pessimistic values of the network admittance are those which result in the lowest total admittance. These are clearly defined in the graph: (i) in region 1 the resultant admittance vector Y_n ends on the vertical (i.e. minimum conductance) part of the boundary; (ii) in region 2, Y_n ends on the corner of the boundary; and (iii) in region 3, Y_n is perpendicular to the nearer angular limit.

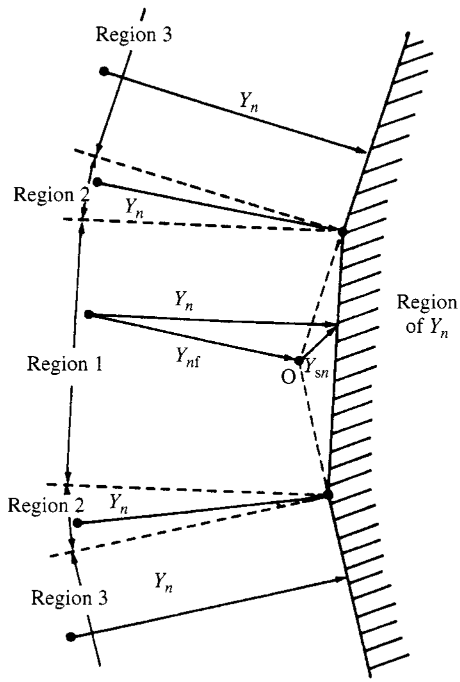


Figure 6.11 Determination of network admittance Y_{sn}, for minimum resultant admittance Y_n corresponding to filter admittances Y_f lying in different regions. From [3]. Copyright 1971, John Wiley & Sons, Inc

6.5.2 Double-Tuned Filters [4]

The equivalent impedances of two single-tuned filters (Figure 6.12(a)) near their resonance frequencies are practically the same as those of a double-tuned filter configuration, illustrated in Figure 6.12(b), subject to the following relationships between their components

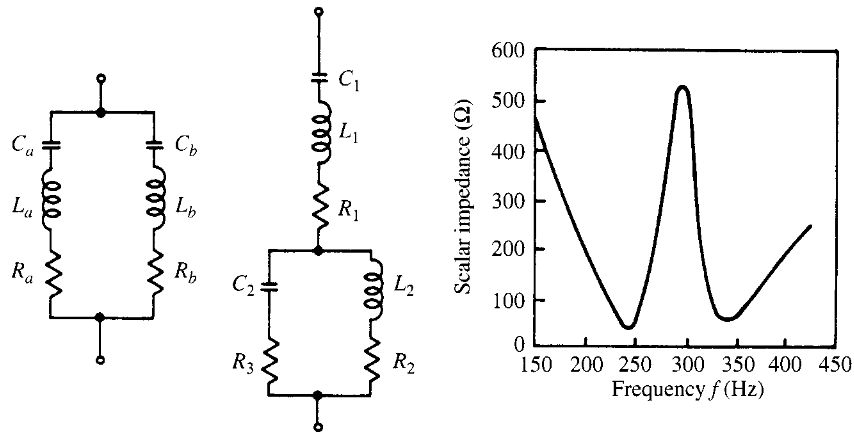
$$C_1 = C_a + C_b \tag{6.31}$$

$$C_2 = \frac{C_a C_b (C_a + C_b)(L_a + L_b)^2}{(L_a C_a - L_b C_b)^2} \tag{6.32}$$

$$L_1 = \frac{L_a L_b}{L_a + L_b} \tag{6.33}$$

$$L_2 = \frac{(L_a C_a - L_b C_b)^2}{(C_a + C_b)^2 (L_a + L_b)} \tag{6.34}$$

$$R_2 = R_a \left[\frac{a^2(1-x^2)}{(1+ax^2)^2(1+x^2)}\right] + R_b \left[\frac{1-x^2}{(1+ax^2)^2(1+x^2)}\right] + R_1 \left[\frac{(1-x^2)(1-ax^2)}{(1+x^2)(1+ax^2)}\right] \tag{6.35}$$



(a) (b) (c)

Figure 6.12 Transformation from (a) two single-tuned filters to (b) double-tuned filters. (c) The impedance versus frequency of filter double-tuned for 5th and 7th

where

$$a = \frac{C_a}{C_b} \text{ and } x = \sqrt{\frac{L_b C_b}{L_a C_a}}$$

The above practical approximation is carried out by omitting resistor R_1, which is therefore determined by the minimum resistances of the inductor L_1. This has the advantage of reducing the power loss at fundamental frequency as compared with the single-tuned filter configurations. The main advantage of the double-tuned filter is in high-voltage applications, because of the reduction in the number of inductors to be subjected to full line impulse voltages. Typical equivalent impedances of a double-tuned filter are illustrated in Figure 6.12.

A common design of double-tuned filter configurations is that of the Vindhyachal HVd.c. converter plant [1], shown in Figure 6.13. The scheme consists of three sets of double-tuned filters for 11/13, 3/27 and 5/24 harmonic orders. A filter for the third harmonic is needed to eliminate resonances with the a.c. network and the fifth harmonic filter is required to limit the individual harmonic distortion.

Triple- and quadruple-tuned filters can also be designed but these are rarely justified because of the difficulty of adjustment.

6.5.3 Automatically Tuned Filters

In tuned filter design it is advantageous to reduce the maximum frequency deviation. This can be achieved by making the filters tunable by either automatically switching the capacitance or by varying the inductance. A range of ±5% is usually considered adequate. A control system, which measures the harmonic frequency reactive power in the filter (both its sign and magnitude) and uses the information to alter the value of

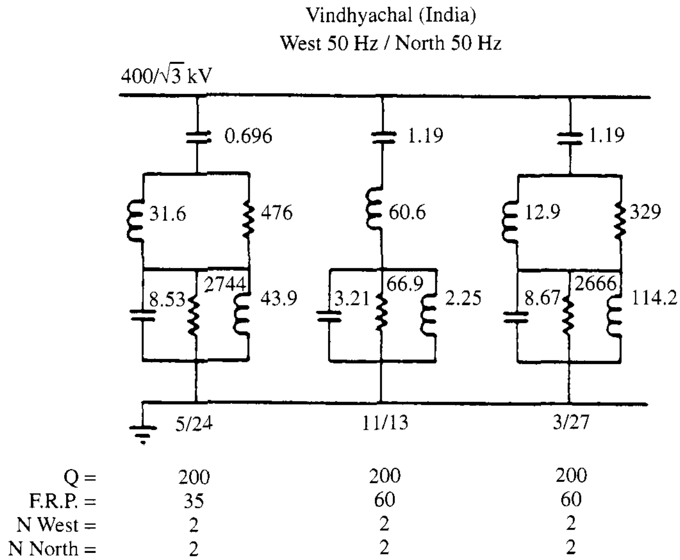


Figure 6.13 Filter configuration of the Vindhyachal HVd.c. scheme. CIGRE © copyright

the L or the C, has been used in HVd.c. converter filters. Automatically tuned filters offer the following advantages over fixed filters:

(1) The capacitor rating is lower.

(2) The capacitor used can combine a high temperature coefficient of capacitance and a high reactive power rating per unit of volume and per unit of cost.

(3) Because of the higher Q, the power loss is smaller.

Advantages (1) and (2) reduce the cost of the capacitor, which is the most expensive component of the filter. Advantage (3) reduces the cost of the resistor and the cost of the system losses.

6.6 Damped Filters

The damped filter offers several advantages:

(1) Its performance and loading are less sensitive to temperature variation, frequency deviation, component manufacturing tolerances, loss of capacitor elements, etc.

(2) It provides a low impedance for a wide spectrum of harmonics without the need for subdivision of parallel branches, which increases switching and maintenance problems.

(3) The use of tuned filters often results in parallel resonance between the filter and system admittances at a harmonic order below the lower tuned filter frequency, or in between tuned filter frequencies. In such cases the use of one or more damped filters is a more acceptable alternative.

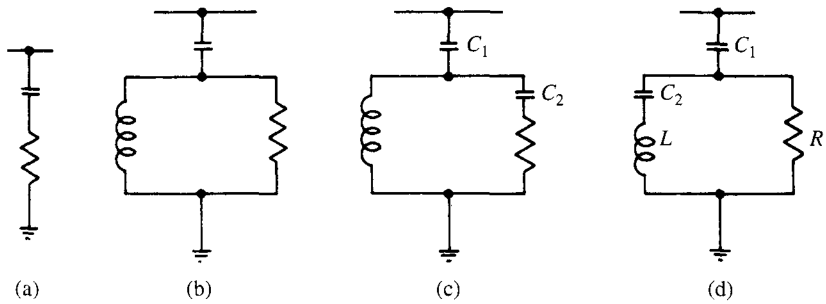


Figure 6.14 High-pass damped filters: (a) first order; (b) second order; (c) third order; (d) C-type

The main disadvantages of the damped filter are as follows:

(4) To achieve a similar level of filtering performance the damped filter needs to be designed for higher fundamental VA ratings, though in most cases a good performance can be met within the limits required for power factor correction.

(5) The losses in the resistor and reactor are generally higher.

6.6.1 Types of Damped Filters

Four types of damped filters are shown in Figure 6.14, first-order, second-order, third-order and C-type.

(1) The first-order filter is not normally used, as it requires a large capacitor and has excessive loss at the fundamental frequency.

(2) The second-order type provides the best filtering performance, but has higher fundamental frequency losses as compared with the third-order filters.

(3) The main advantage of the third-order type over the second-order type is a substantial loss reduction at the fundamental frequency, owing to the increased impedance at that frequency caused by the presence of the capacitor C_2. Moreover, the rating of C_2 is very small compared with C_1.

(4) The filtering performance of the C-type [5] filter lies in between those of the second- and third-order types. Its main advantage is a considerable reduction in fundamental frequency loss, since C_2 and L are series tuned at that frequency. However, this filter is more susceptible to fundamental frequency deviations and component value drifts.

6.6.2 Design of Damped Filters

When designing a damped filter the Q is chosen to give the best characteristic over the required frequency band and there is no optimal Q as with tuned filters.

The behaviour of damped filters has been described by Ainsworth [4] with the help of two parameters

$$f_0 = \frac{1}{2\pi CR} \tag{6.36}$$

$$m = \frac{L}{R^2C} \tag{6.37}$$

Typical values of m are between 0.5 and 2. For a given capacitance these parameters (and hence L and R) are decided to achieve an appropriately high admittance over the required frequency range.

The conductance and susceptance terms of a second-order damped filter admittance are

$$G_f = \frac{m^2x^4}{R_1[(1-mx^2)^2 + m^2x^2]} \tag{6.38}$$

$$B_f = \frac{x}{R_1}\left[\frac{1-mx^2+m^2x^2}{(1-mx^2)^2+m^2x^2}\right] \tag{6.39}$$

where $x = f/f_0$.

The minimum total admittance (i.e. the filter Y_F plus the a.c. system Y_{sn}) can be shown to be

$$Y = B_f \cos\phi_m + G_f \sin\phi_m \tag{6.40}$$

with both terms in equation (6.40) being positive and x being less than the value that gives

$$|\cot\phi_f| = |G_f/B_f| = |\tan\phi_m| \tag{6.41}$$

For greater values of x the minimum total admittance is that of the filter (i.e. with $Y_{sn} = 0$).

Figure 6.15 illustrates typical minimal admittances for a second-order damped filter in parallel with a lossless system (i.e. $\phi_m = \pm 90°$). For comparison the conductance component G_f of a third-order damped filter, for the case of equal capacitors, is shown in Figure 6.16. These figures show that the third-order filter peaks are much sharper than those of the second order.

6.7 Conventional Filter Configurations

6.7.1 Six-Pulse Design

Static converters of large ratings are normally designed for at least 12-pulse operation. In many schemes, however, to cope with maintenance and other partial temporary outages, six-pulse operation is permitted. Under such conditions they produce considerable 5th and 7th harmonics as well as the characteristic 12-pulse-related orders. These are conventionally filtered by using a hybrid combination of tuned branches for the low

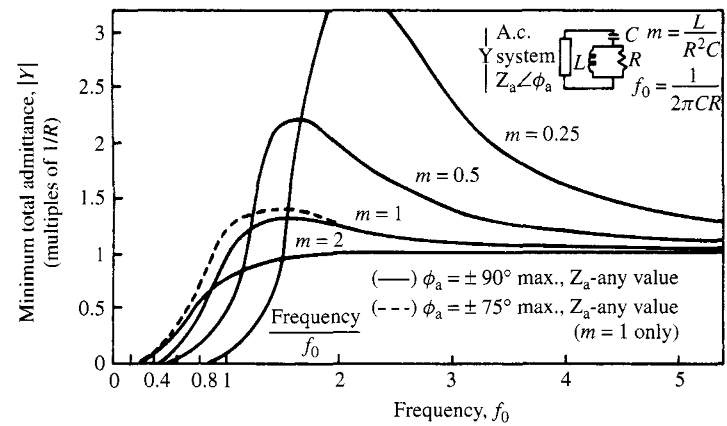


Figure 6.15 Admittance of second-order low-pass filter

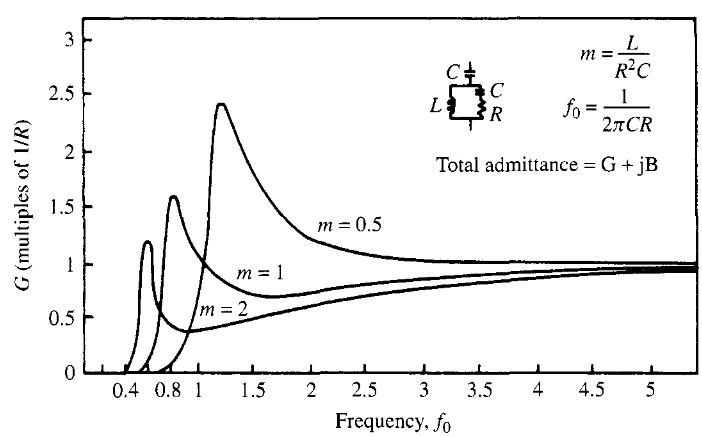


Figure 6.16 Conductance component for third-order low-pass filter

orders, i.e. 5th, 7th, 11th and 13th, and a high-pass damped filter for the 17th and higher orders.

The conventional design is best illustrated with some examples.

(i) Strong a.c. System Connection [4] A six-pulse converter bridge is rated at 100 kV, 100 MW d.c., operating at $\alpha = 15°$. The bridge is connected to a 275 kV, 50 Hz a.c. system via a 275/83 kV converter transformer with 15% leakage reactance. The secondary fundamental current is 780 A and that of the primary 236 A. The filters, to be connected to the primary side, consist of resonant arms for the 5th, 7th, 11th and 13th harmonics, and a second-order high-pass arm.

For a total filter size of 50 MVAr, and assuming that the capacitance is to be equally divided among the filter branches, each branch requires 0.421 μF. If the capacitor temperature coefficient is 0.05% per degree Celsius, the inductor temperature coefficient 0.01% per degree Celsius, ambient temperature ±20°C and frequency tolerance ±1%, then from equation (6.4),

$$\delta = (1/100)[1 + 0.5(0.05 \times 20 + 0.01 \times 20)] = 0.016$$

Let the a.c. system impedance be of any magnitude but its phase angle restricted to $\phi_a < 75^\circ$ at any frequency. The optimum Q (giving the lowest harmonic voltage) is then obtained from equation (6.30), i.e.

$$Q = \frac{1 + \cos 75^\circ}{2(0.016)\sin 75^\circ} = 40.7.$$

With Q and C known, the values of L and R of the resonant arms can then be determined.

The damped arm components are found from equations (6.36) and (6.37) by choosing $m = 1$ and $f_0 = 17 \times 50 = 850$ Hz. Since C has been fixed above (i.e. 0.421 μF), the resulting values of inductor and resistor are 0.083 H and 444.9 Ω, respectively.

The complete circuit design is then as shown in Figure 6.17.

(ii) Weak a.c. System Connection Let us now consider the possible connection of the converter of the test system described above to a 110 kV instead of 275 kV network and assess whether the filters are effective at third harmonic. Let us further assume that the system third harmonic impedance may lie between 70 and 100 Ω, while the phase angle remains at 75°.

The total filter capacitance is now

$$C = \frac{\text{MVAr}}{(2\pi 50)(110)^2} = 13.15\ \mu\text{F}$$

and that of the individual filter branches $C/5 = 2.631$ μF

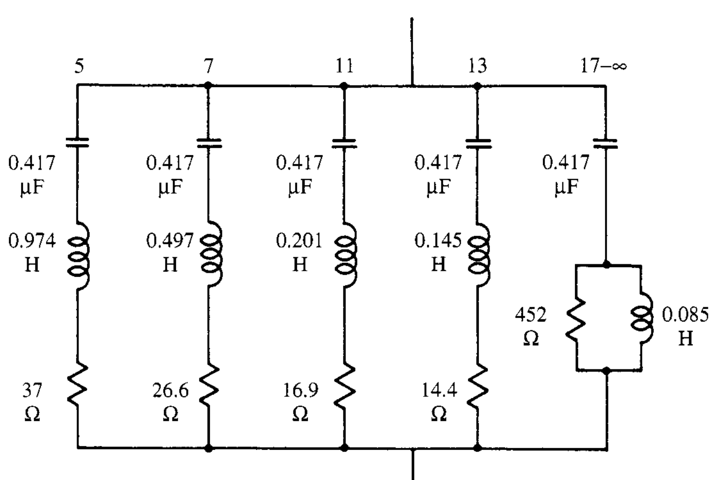


Figure 6.17 Example of a.c. filter design

Following the same reasoning as in case (i), equations (6.36) and (6.37) give the new values of the damped filter branch parameters, i.e.

$$R = 71.2\ \Omega \text{ and } L = 0.0133\ \text{H}$$

Similarly, equations (6.10) and (6.11) provide the following values for the remaining branches:

5th-tuned branch :	$R = 5.94\ \Omega$	$L = 0.1541$ H
7th-tuned branch :	$R = 4.24\ \Omega$	$L = 0.0786$ H
11th-tuned branch :	$R = 2.70\ \Omega$	$L = 0.0318$ H
13th-tuned branch :	$R = 2.29\ \Omega$	$L = 0.0228$ H

The filter branch impedances at the third harmonic are obtained by substituting $\omega_3 = 150$ Hz in the tuned and damped branch impedance equations. These are then inverted and added together to produce the total filter admittance, i.e.

$$Y_3^F = 0.00016 - j(0.01469)$$

The system harmonic impedance that yields the largest parallel impedance with the filter at 150 Hz has been found to be $Z_3 = 71\angle 75^\circ$, i.e.

$$Z_3^F = 71\ (\cos(75^\circ) - j\sin(75^\circ)) = 18.38 - j68.58$$

and

$$Y_3^F = 0.00365 - j0.01360$$

Thus, the parallel system and filter admittance is

$$Y_3^T = Y_3^F + Y_3^S = 0.00381 + j(0.00108)$$

The third harmonic voltage distortion is

$$V_3 = (I_3)/(Y_3^T)$$

where I_3 is the maximum expected level of injected third harmonic current. This is a difficult parameter to calculate, as it results from a number of different sources, among them the presence of some background third harmonic in the supply voltage, the presence of negative sequence, some unbalance in the commutation reactance and firing angle unbalance. Unbalance in the commutation reactances is the most likely cause of third harmonic generation, which can be typically up to 0.7% of the fundamental current (as shown in Table 3.7).

The fundamental frequency current for the 275 kV connection is 236 A and assuming that the new current is inversely proportional to the voltage, the 110 kV current will be

$$I_1 = 236 \times (275)/(110) = 588.5\ \text{A}$$

Therefore

$$I_3 = (0.7 \times I_1)/100 = 4.12 \text{ A}$$

and

$$V_3 = 4.12/(\sqrt{0.00381^2 + 0.00108^2}) = 1040.61 \text{ V or } 1.64\%$$

Although this value is within the 2% limit of the IEC standard (61000-3-6), it is very close to it, considering that only one of the possible third harmonic sources has been included in the calculation. A reduction of the filter capacity is introduced in the following case to further illustrate the problem.

(iii) Reduced Filter Capacitance Case (ii) is now repeated with a total filter capacity of 40 instead of 50 MVAr, with the capacitance still equally divided between the various filter branches.

At 110 kV the total capacitance required to supply 40 MVAr is 10.523 μF, or 2.105 μF per filter branch. Following the same process as for case (ii), the following values of R and L are obtained:

5th-tuned branch	$R = 7.428\ \Omega$	$L = 0.1926$ H
7th-tuned branch	$R = 5.306\ \Omega$	$L = 0.0983$ H
11th-tuned branch	$R = 3.376\ \Omega$	$L = 0.0398$ H
13th-tuned branch	$R = 2.857\ \Omega$	$L = 0.0285$ H

The new damped filter branch parameters are:

$$R = 88.97\ \Omega \text{ and } L = 0.0167 \text{ H}$$

The corresponding total filter admittance at 150 Hz is:

$$Y_3^F = 0.000131 + j(0.011748)$$

The third harmonic impedance for the system under consideration will typically lie within a sector limited by 70 Ω and 100 Ω radii and 75° and 80° phase angle. Within this range the impedance which in parallel with the filters produces the largest impedance value has been found to be $Z_3^S = 87\angle 80° = 15.1074 + j85.6783$.

The corresponding system admittance is thus

$$Y_3^S = 0.0020 - j(0.01132)$$

The combined system/filter admittance becomes:

$$Y_3^T = Y_3^F + Y_3^S = 0.00213 + j(0.00043)$$

The uncorrected (i.e. before the filters) power factor of the converter load is approximately

$$\cos\phi = (1/2)(\cos\alpha + \cos(\alpha + \mu))$$

where $\cos(\alpha + \mu)$ is derived from the commutation equation (3.37) using the information of the test system (case (i) above), i.e. $V_l = 83$ kV, $I_{dc} = 1000$ A, $\alpha = 15$ and $X = 15\%$; the resulting value of $\cos\phi$ is 0.878.

When corrected by the addition of the filters (40 MVAr), the power factor becomes 0.990 and the primary side fundamental current is:

$$I_1 = 1000\frac{\sqrt{6}}{\pi}\left(\frac{83}{110}\right) = 588.5 \text{ A}$$

Again, using the firing unbalance criterion of Table 3.7, the third harmonic current injection will be

$$I_3 = 588.5(0.7)/(100) = 4.12 \text{ A}$$

and

$$V_3 = \frac{4.12}{\sqrt{0.00213^2 + 0.00043^2}} = 1896.0022 \text{ V}$$

or

$$\frac{1896.0022}{(110/\sqrt{3}) \times 10^3} \times 100 = 2.99\%$$

which is well above the limit recommended by the IEC.

6.7.2 Twelve-Pulse Configuration

Whenever a reasonable twelve-pulse operation can be guaranteed under all operating conditions the fifth and seventh harmonic filters can be eliminated. An example of the configuration used in a high-voltage d.c. converter and its corresponding impedance locus are shown in Figure 6.18. The locus exhibits resonant points at the 11th, 13th and 27th harmonics, and reasonably low impedances to the fifth and seventh, which will cope with the levels expected under slight unbalanced power distribution between the individual bridges.

6.8 Band-Pass Filtering for Twelve-Pulse Converters

The conventional filter design for static converters, based on the use of separate tuned filters of the resonant type for the 11th and 13th harmonics and a high-pass filter for the higher orders, will usually provide a more effective reduction than required. This is because the minimum size of the filters is usually determined by the available economic size of the capacitor units and the minimum amount of reactive power generation required by the converters.

Therefore the filter design can be simplified, either by replacing the 11th and 13th tuned filters by a single filter of the damped type, or replacing all filters by a single damped filter. In the first case, the damped filter replacing the two tuned filters should be tuned to about the 12th harmonic and a fairly high Q can be selected (20–50),

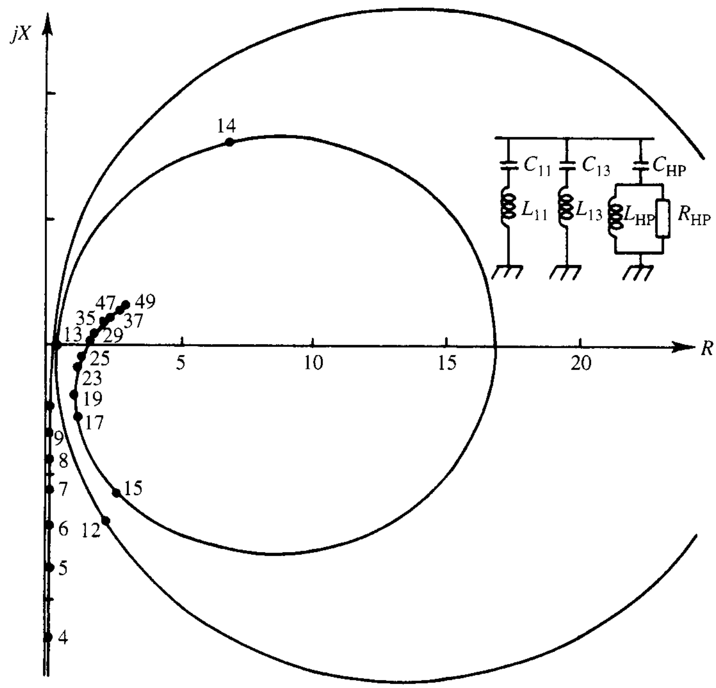


Figure 6.18 Filter configuration for 12-pulse operation and typical impedance locus

while the damped filter for the higher harmonics has a much smaller Q (2–4). In the second case, the single damped filter is also tuned to about the 12th harmonic but at a fairly low Q (2–6) to get a sufficiently low impedance at high harmonics.

Moreover, the hybrid design discussed in the last section (Figure 6.18) exhibits increasing impedance at the lower harmonic frequencies.

With the large ratings of some HVd.c. projects there is an increased probability of low-order non-characteristic harmonic resonance between the system impedance and the filter capacitance. This condition is more likely when the network includes cables or long a.c. overhead lines which provide substantial capacitive generation. The damping of a network tends to increase with increasing frequency; for low-order harmonics the limiting impedance angle can be high and severe resonances can occur. Moreover, in order to control the voltage profile of the a.c. network the tendency is to compensate totally, by local means, the reactive power absorbed by the converters. The high capacity of the filters or shunt capacitor banks decreases the resonant frequency with the network. A parallel resonance can amplify considerably several harmonics at different times, i.e. the critical frequency varies as a function of the a.c. system and of the configuration and number of capacitors in operation; in general, therefore, remedies can not be adopted only for one specific harmonic, but must avoid unacceptable amplification for a number of frequencies.

A very common condition resulting from system unbalance is the production of a significant third harmonic current by the converter (as explained in Section 3.6.9); this third harmonic is of positive sequence and will not be blocked by the transformer connection.

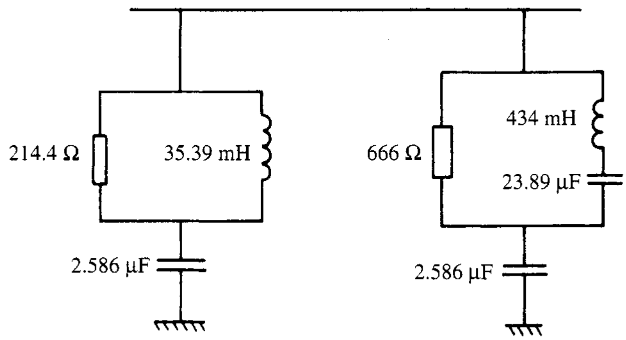


Figure 6.19 Combined second-order and C-type damped filters

An alternative filter design consisting of a C-type and a second-order damped filter (shown in Figure 6.19) can be used to eliminate the low-order resonance [5].

It is unduly pessimistic to consider the possibility of a number of harmonics in near resonance simultaneously. In the filter design of the 2000 MW cross-channel HVd.c. link the following combination of system impedances has been used:

(1) The harmonic order that produces the highest voltage distortion is assumed to be at or near resonance with the system.
(2) Other harmonics in the range 2–25 are selected from tables containing information about the system impedances under all likely system and planned outage conditions.
(3) The remaining harmonics in the range 25–49 are assumed to lie within a wide radius of 750 Ω, centred at $R = 750$ Ω, limited by impedance angles of 73° (capacitive) and 85° (inductive).

The filter configuration for this scheme (at the Sellindge end) is shown in Figure 6.20.

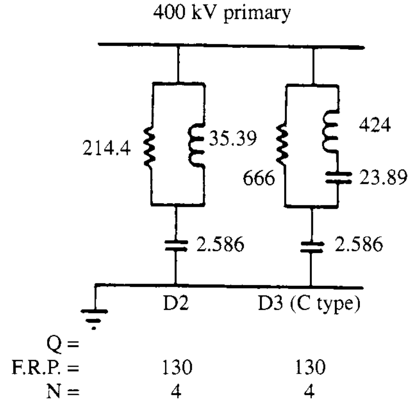


Figure 6.20 Filter configuration of the cross-channel scheme. CIGRE © copyright

Table 6.1 Derivation of the maximum r.m.s. distortion for the filter configuration of four second-order plus four C-type filters at 2000 MW d.c. load

Harmonic order	2	3	5	7	11
Pre-existing distortion on the a.c. system (%)	0.39	0.34	0.22	0.12	0.01
Distortion due to converter harmonic current (%)	0.13	0.42	0.56	0.29	0.43
Distortion from converter third harmonic current due to negative sequence on the a.c. system (%)	–	0.19	–	–	–
Distortion due to VAR compensator harmonic current (%)	–	0.03	0.03	0.02	0.01
Distortion due to compensator third harmonic current due to a.c. system unbalance (%)	–	0.17	–	–	–
Total contribution due to each harmonic (%)	0.41	1.16	0.60	0.31	0.43

Four of the 130 MVAr filter banks are second-order high-pass filters to absorb the characteristic harmonic currents. Large magnification factors for several system conditions are possible, particularly at the third harmonic, and therefore the remaining four filter banks are arranged as third-order C-type damped filters and have their minimum impedance at around 150 Hz.

The predicted performance characteristics are illustrated in Table 6.1. Since in this case the highest distortion is caused by the third harmonic, this harmonic is taken as the arithmetic sum of the contents produced by the various sources listed.

6.9 Distribution System Filter Planning [6]

The increasing levels of voltage distortion in some distribution systems can best be contained by the application of harmonic filters at strategic locations. In this respect, radial distribution systems have special characteristics that make filter planning and design different to those of industrial system plant. Among these are the differing X/R ratios and larger electrical distances, a wider variation in load with limited information on load characteristics, the use of capacitors for voltage control and power factor correction and the dispersed nature of the harmonic injections.

Dispersed distribution loads generate smaller currents at the higher harmonics and the phase angles of these currents are widely distributed [7, 8], resulting in a high degree of cancellation. At the lower frequencies, particularly the third, fifth and seventh harmonics, there is less cancellation and the resulting harmonic currents are higher.

Radial distribution systems with primary capacitor banks generally have resonances in the vicinity of the fifth and seventh harmonic frequencies involving the entire group of distributed capacitors. These resonances are much broader than the higher frequency resonances, which involve only one or two capacitor banks.

The trend in distribution planning is to consider simultaneously the optimised use of capacitances for the fundamental and harmonic frequencies. Although this can be achieved very effectively by genetic algorithms, this solution is extremely demanding in computational requirements. Thus, generally, the locations and sizes of the reactive compensation in distribution systems are made on fundamental frequency considerations. Then the choice of capacitor banks to be tuned for filtering purposes is carried out based on harmonic flow considerations. Such tuning is first made to reduce the fifth harmonic content.

The effect of fifth harmonic tuning on the seventh harmonic voltage varies depending on the system configuration. In general, replacing a capacitor bank with a fifth harmonic filter tends to shift the resonance points above the fifth harmonic to a higher frequency, and the resulting voltages at the seventh harmonic will depend on the location and strength of these resonances.

On systems where a fifth harmonic filter also reduces the seventh harmonic voltage near the filter location, a choice exists as to the frequency of additional filters. Any further filtering investigation should include a comparison of both fifth and seventh harmonic filters, as the best choice is not necessarily at one or the other frequency.

On systems where a fifth harmonic filter increases the seventh harmonic voltages the frequencies must be treated separately. While additional filters at one frequency may raise voltage at the other, this is generally a second-order effect and the filter placement can be done independently.

6.10 Filter Component Properties

From knowledge of the fundamental and harmonic voltages at the relevant busbars the current and voltage ratings of the capacitors, inductors and resistors can be calculated, and with them the active and reactive powers and losses.

To prevent damage of these components their ratings must be based on the most severe conditions expected. These should include the highest fundamental voltage, the highest effective frequency deviation, and the harmonic currents from other sources and from possible resonances between the filter and a.c. system.

6.10.1 Capacitors

Capacitors are composed of standard units connected in series and/or parallel in order to achieve the desired overall voltage and kVA rating. The main factors involved in their design are [9]: temperature coefficient of capacitance, reactive power per unit volume, power loss, reliability and cost.

A very low temperature coefficient of capacitance is desirable for tuned filters in order to avoid detuning caused by change of capacitance with ambient temperature or with capacitor self-heating; this property, however, is unimportant for damped filters or power capacitors.

Capacitors obtain their high reactive power per unit volume by having low losses and by operating at very high voltage stresses. For this reason, prolonged operation at moderate over-voltage must be avoided to prevent thermal destruction of the dielectric; at higher over-voltages even brief periods of operation can produce destructive ionisation of the dielectrics.

The required reactive power rating of the capacitor is the sum of the reactive powers at each of the frequencies to which it is subjected.

6.10.2 Inductors

Inductors used in filter circuits need to be designed bearing in mind the high frequencies involved, i.e. skin effect and hysteresis losses must be included in the power loss calculation. Also, the effect of the flux level in the iron, i.e. the detuning caused by magnetic nonlinearity, must therefore be taken into account. This normally leads to the use of low flux densities when using iron cores. Alternatively, filter inductors are better designed with non-magnetic cores.

The Q at the predominant harmonic frequency may be selected for lowest cost and is usually between 50 and 150. However, lower Q values are normally required and these are derived by using a series resistor.

Inductor ratings depend mainly on the maximum r.m.s. current and on the insulation level required to withstand switching surges. Normally the R and L form the ground side of a tuned filter.

6.11 Filter Costs

An effective filter adequately suppresses harmonics at the least cost and supplies some reactive power, but perhaps not all that is required. The cost of losses incurred in the filters may be charged to reactive power supply and some to filtering, although there is no logical basis for the division.

The following assumptions are usually made in the cost analysis of filter components:

(1) In a typical installation, a capacitor bank consists of a ‘matrix’ of capacitor units, each having a nominal rating at the prescribed operating voltage and protected by an external fuse.

The cost of a capacitor bank is thus approximately constant up to the rating of the minimum matrix containing full units. For higher ratings, one or more units are added to each series group as required and a reasonably accurate cost per MVAr or SIZE can be arrived at. The situation is complicated further by the availability of standard units with different nominal ratings, e.g. 50, 100, 150 kVAr etc., and the incremental cost varies for different bands of capacitor bank SIZES. Although such factors would have to be included in the development of an accurate cost equation, here we are assuming that the capacitors’ cost is proportional to their ratings.

(2) Although the cost of filter inductors depends greatly on the method of construction (e.g. oil insulated/cooled units, natural air-cooled reactors of open construction, etc.), their cost does not vary greatly for units of different rating. The cost approximation used in the analysis, therefore, is of the form

$$\text{Inductor cost} = U_K + U_L \times (\text{total MVAr rating})$$

where U_K is a constant cost component and U_L is the inductor incremental cost per MVAr rating.

(3) The power rating of the resistor necessary for Q-adjustment in each filter branch will affect the cost to some extent. However, the nominal resistance of the unit is difficult to predict in a general analysis, because it depends on the natural Q factor of the inductor. For this reason, and also because the cost of an air-cooled resistor is small compared with that of the other components, a constant cost per resistor is allocated in the analysis. If an air-cooled unit is used, the cost would be more significant but it would, in fact become virtually independent of power rating.

(4) Finally, it is assumed that the resistance of the inductor, for the purposes of power loss estimation, is constant at all frequencies.

6.11.1 Single-Tuned Filter

In a high-Q circuit it may be assumed that

$$V_c = V_L + V_s \tag{6.42}$$

where V_c, V_L and V_s represent the capacitor, inductor and supply voltages, respectively.

The filter SIZE is expressed as

$$S = \frac{V_s^2}{X_c - X_L} \tag{6.43}$$

where X_c and X_L are the fundamental frequency reactances of the capacitor and inductor.

But for a filter tuned to harmonic n,

$$X_0 = nX_L = X_c/n$$

i.e.

$$X_L = X_c/n^2 \text{ and } V_L = V_c/n^2$$

Therefore

$$S = V_s^2/[X_c(1 - 1/n^2)] = (V_s^2/X_c)[n^2/(n^2 - 1)] \text{ MVAr} \tag{6.44}$$

Also

$$V_c - V_L = V_c(1 - 1/n^2) = V_s$$

i.e.

$$V_c = [n^2/(n^2 - 1)]V_s \text{ kV} \tag{6.45}$$

The loadings for each filter component are determined for cost evaluation as follows:

Capacitor

Fundamental loading:

$$\begin{aligned} V_c^2/X_c &= (V_s^2/X_c)[n^2/(n^2-1)]^2 \\ &= S[n^2/(n^2-1)] \text{ MVAr} \end{aligned} \tag{6.46}$$

Harmonic loading:

$$I_n^2(X_c/n) = [(I_n^2.V_s^2)/(S.n)][n^2/(n^2-1)] \quad \text{MVAr} \tag{6.47}$$

Power loss:

$$K_{CL} \cdot (\text{total loading}) = K_{CL}[S + (I_n^2 \cdot V_s^2)/(S \cdot n)][n^2/(n^2-1)] \quad \text{kW} \tag{6.48}$$

where K_{CL} is the loss factor of the capacitors (in kW/MVAr).

Inductor

Fundamental loading:

$$\begin{aligned} V_L^2/X_L &= (V_c/n^2)^2 \cdot (n^2/X_c) = V_c^2/n^2X_c \\ &= (S/n^2)[n^2/(n^2-1)] \quad \text{MVAr} \end{aligned} \tag{6.49}$$

Harmonic loading is the same as for the capacitor since the reactances are equal at harmonic frequency.

For cost purposes, it is convenient to consider the losses in the total effective resistance R, where

$$R = X_0/Q = X_c/nQ$$

The fundamental current is

$$I_1 = S/V_s \text{ kA}$$

and the total power loss

$$\begin{aligned} (I_1^2 + I_n^2)R &= (S^2/V_s^2)X_c/nQ + I_n^2X_c/nQ \\ &= [S^2/nQ](1/S)[n^2/(n^2-1)] + [I_n^2V_s^2/nSQ][n^2/(n^2-1)] \\ &= [S/nQ + I_n^2V_s^2/nSQ][n^2/(n^2-1)] \times 10^3 \text{ kW} \end{aligned} \tag{6.50}$$

For comparison purposes, the cost of energy losses is expressed in terms of equivalent capital cost by use of a present value factor:

$$P_v = [(1+i)^N - 1]/[i(1+i)^N] \tag{6.51}$$

where i is the interest rate and N is the budgeted filter life.

Thus the present value cost of energy losses is

$$P_v U_u F_u \times 365 \times 24 \times \text{(total power loss)}$$
$$= 8760 P_v U_u F_u \times \text{(total power loss)} \tag{6.52}$$

where U_u is the cost of energy loss per kilowatt-hour and F_u is the filter utilisation factor. The complete expression for the total cost is

$$\text{TCOST} = U_T + [n^2/(n^2-1)]\left\{U_c\left(S + \frac{V_s^2 I_n^2}{nS}\right) + U_L\left(\frac{S}{n^2} + \frac{V_s^2 I_n^2}{nS}\right) + 8760 P_v U_u F_u\left[K_{CL}\left(S + \frac{V_s^2 I_n^2}{nS}\right) + 10^3\left(\frac{S}{nQ} + \frac{I_n^2 V_s^2}{nSQ}\right)\right]\right\}$$

i.e.

$$\text{TCOST} = U_T + AS + \frac{B}{S} \tag{6.53}$$

where U_T is the total constant cost of the filter branch, U_c is the capacitor incremental cost per MVAr, U_L is the inductor incremental cost per MVAr,

$$A = [n^2/(n^2-1)]\left[U_c + \frac{U_L}{n^2} + 8760 P_v U_u F_u\left(K_{CL} + \frac{10^3}{nQ}\right)\right] \tag{6.54}$$

and

$$B = [n^2/(n^2-1)][V_s^2 I_n^2/n]\left[U_c + U_L + 8760 P_v U_u F_u\left(K_{CL} + \frac{10^3}{Q}\right)\right] \tag{6.55}$$

As SIZE S is varied, the minimum total cost occurs when

$$\mathrm{d(TCOST)}/\mathrm{d}S = 0$$

i.e. when

$$S_{\text{MIN}} = \sqrt{\frac{B}{A}} \quad \text{MVAr} \tag{6.56}$$

6.11.2 Band-Pass Filter

The component loadings at fundamental and all harmonic frequencies may be determined as for the single-tuned filter, i.e.

$$S = (V_s^2/X_c)[n_0^2/(n_0^2-1)] \quad \text{MVAr} \tag{6.57}$$

where n_0 is the ratio of the tuned frequency to the supply frequency.

Capacitor rating

The fundamental loading is

$$S[n_0^2/(n_0^2 - 1)] \quad \text{MVAr} \tag{6.58}$$

The loading at harmonic n is

$$I_n^2(X_c/n) \tag{6.59}$$

and using equation (6.57) this becomes

$$\frac{1}{S}(I_n^2/n)V_s^2 n_0^2/(n_0^2 - 1) \tag{6.60}$$

Thus the total harmonic loading is

$$\left[\frac{1}{S}(V_s^2 n_0^2)/(n_0^2 - 1)\right] \sum_{n=n_{\min}}^{n_{\max}} (I_n^2/n) \quad \text{MVAr} \tag{6.61}$$

Inductor rating

Referring to Figure 6.2(a), for a Q value of 1.5, say,

$$R = 1.5X_0 = 1.5n_0X_L$$

Thus if the filter is tuned to a frequency close to the 17th harmonic

$$R \approx 25X_L$$

Since $I_c = I_L + jI_R$ it follows that, at fundamental frequency,

$$I_c \approx I_L$$

and the fundamental loading is

$$\begin{aligned} I_L^2X_L &= I_c^2X_c/n_0^2 \\ &= (S/V_s)^2[V_s^2/n_0^2S][n_0^2/(n_0^2 - 1)] \\ &= (S/n_0^2)[n_0^2/(2 - 1)] \quad \text{MVAr} \end{aligned} \tag{6.62}$$

At harmonic n,

$$(I_L)_n = I_nR/(R + jX_L) = I_nQ/[Q + (jn/n_0)] \tag{6.63}$$

and

$$|(I_L)_n| = I_nQ/[Q^2 + (n/n_0)^2]^{1/2} \tag{6.64}$$

The inductive reactance at harmonic n is

$$\begin{aligned}(X_L)_n &= X_0(n/n_0) = (n/n_0)(X_c/n_0)\\ &= (n/n_0^2)(V_s^2/S)[n_0^2/(n_0^2-1)]\end{aligned}$$

Thus the loading at harmonic n is

$$(I_L)_n^2(X_L)_n = \frac{1}{S}Q^2V_s^2[n_0^2/(n_0^2-1)][nI_n^2/(Q^2n_0^2+n^2)] \quad \text{MVAr} \tag{6.65}$$

and the total harmonic loading is

$$\frac{1}{S}Q^2V_s^2[n_0^2/(n_0^2-1)]\sum_{n=n_{\min}}^{n_{\max}}\left[\frac{nI_n^2}{Q^2n_0^2+n^2}\right] \quad \text{MVAr} \tag{6.66}$$

Power losses

(1) The power loss in the capacitor is

$$K_{CL} \times \text{(total rating in kilowatts)} \tag{6.67}$$

(2) The inductor series resistance at fundamental frequency is

$$R_L = X_0/Q_L = (n_0/Q_L)X_L \tag{6.68}$$

where Q_L is the quality factor of the inductor, and the corresponding power loss is

$$\begin{aligned}I_L^2R_L &= (n_0/Q_L)\ \text{(MVAr loading)}\\ &= [S/(n_0Q_L)][n_0^2/(n_0^2-1)] \quad \text{MW}\end{aligned} \tag{6.69}$$

Similarly, the harmonic power loss is

$$\sum (I_L)_n^2(R_L)_n = \frac{1}{S}(Q^2V_s^2n_0/Q_L)[n_0^2/(n_0^2-1)]\sum_{n=n_{\min}}^{n_{\max}}\frac{I_n^2}{Q^2n_0^2+n^2} \quad \text{MW} \tag{6.70}$$

(3) The power loss in the shunt resistor R may also be expressed as a fraction of the inductor loading. At the fundamental frequency,

$$R = QX_0 = Qn_0X_L, \quad |I_R| = \frac{|I_L|X_L}{R} = \frac{I_LX_L}{Qn_0X_L} = \frac{I_L}{Qn_0} \tag{6.71}$$

and the power loss is

$$\begin{aligned}I_R^2R &= (1/Qn_0)I_L^2X_L\\ &= (1/Qn_0)\ \text{(MVAr loading)}\\ &= [S/(Qn_0^3)][n_0^2/(n_0^2-1)] \times 10^3\ \text{kW}\end{aligned} \tag{6.72}$$

At harmonic n,

$$|(I_R)_n| = |(I_L)_n|(X_L/R) \tag{6.73}$$

and the power loss is

$$\sum (I_R)_n^2(R)_n = \frac{1}{S}(QV_s^2/n_0)[n_0^2/(n_0^2-1)] \sum_{n=n_{\min}}^{n_{\max}} \left[\frac{n^2 I_n^2}{Q^2 n_0^2 + n^2}\right] \times 10^3 \text{ kW} \tag{6.74}$$

Total cost

Applying the present-value factor to energy costs and collecting terms in S and in $1/S$ as for the single-tuned filter, it can be shown that once again the total cost is given by

$$\text{TCOST} = U_T + AS + \frac{B}{S} \tag{6.75}$$

where

$$A = \left[U_c + \frac{U_L}{n_0^2} + 8760 P_v U_u F_u \left(K_{CL} + \frac{10^3}{Q_L n_0} + \frac{10^3}{Q n_0^3}\right)\right](n_0^2/(n_0^2-1)) \tag{6.76}$$

and

$$B = [n_0^2/(n_0^2-1)]V_s^2 \sum_{n=n_{\min}}^{n_{\max}} I_n^2 \left[\frac{U_c}{n} + \frac{Q^2 U_L n}{Q^2 n_0^2 + n^2}\right.$$
$$\left. + 8760 P_v U_u F_u \left(\frac{K_{CL}}{n} + \frac{Q^2 n_0 \times 10^3}{Q_L(Q^2 n_0^2 + n^2)} + \frac{Q n^2 \times 10^3}{n_0(Q^2 n_0^2 + n^2)}\right)\right] \tag{6.77}$$

As before, TCOST is a minimum when

$$S = S_{\text{MIN}} = \sqrt{\frac{B}{A}} \quad \text{MVAr} \tag{6.78}$$

6.12 D.C. Side Filters

Although the d.c. side voltage ripple of static converters generates harmonic currents, these are rarely filtered out because they do not have a direct effect on other processes or consumers.

High-voltage d.c. transmission is a special case, where overhead lines are used, because of communications interference. The amplitudes of the harmonic currents, discussed in Chapter 3, depend on the delay, extinction and commutation overlap angles as well as the various impedances of the d.c. circuit (i.e. smoothing reactors, damping circuits, surge capacitors and the line itself). The inclusion of the stray capacitances in a three-pulse model of the converter produces a standing wave pattern of the total

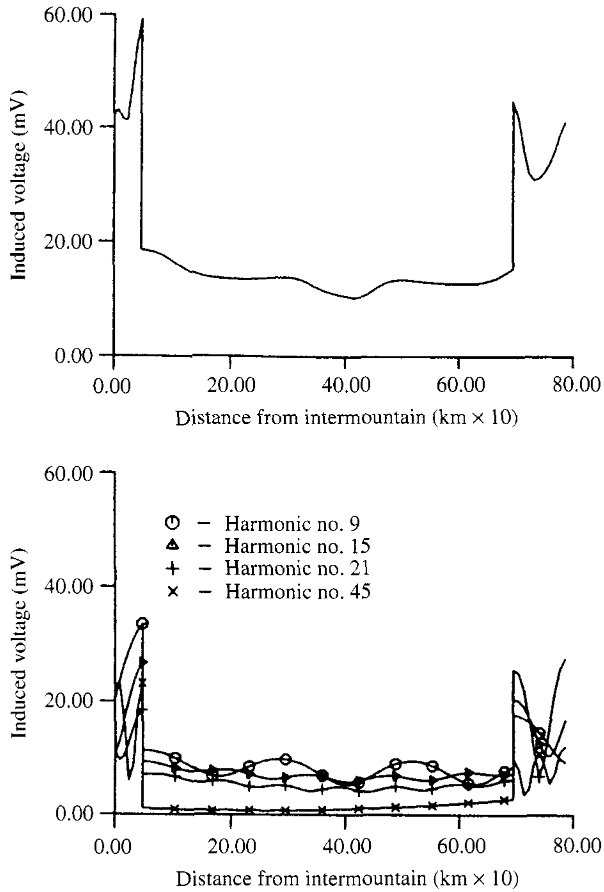


Figure 6.21 Example of induced voltage versus distance. Copyright © 2003 IEEE

earth mode equivalent disturbing current along the line distance, or alternatively the total induced voltage on an open circuit test line at a specified distance from the d.c. line (typically 1 km). An example of such calculation is shown in Figure 6.21, where the discontinuities are caused by parallel sections of electrode line at the ends of the d.c. line.

Other criteria used to define the performance of the d.c. filters in d.c. transmission schemes are the maximum voltage TIF on the high-voltage bus and the maximum permissible noise to ground in telephone lines close to the high voltage d.c. line.

Typical types and location of d.c. filters used in existing schemes are illustrated in Figure 6.22, and the subject is discussed thoroughly in [10].

Component ratings are considerably different to those for an a.c. filter, since the harmonic current is reduced to a relatively small value by the large d.c. smoothing reactor; consequently the capacitor cost is almost entirely dependent on its capacitance and the d.c. voltage level. The capacitor has the greatest cost and is chosen first; the inductor is then fixed for a given frequency. The selection of the quality factors is made as for an a.c. filter (e.g. by using equation (6.29)).

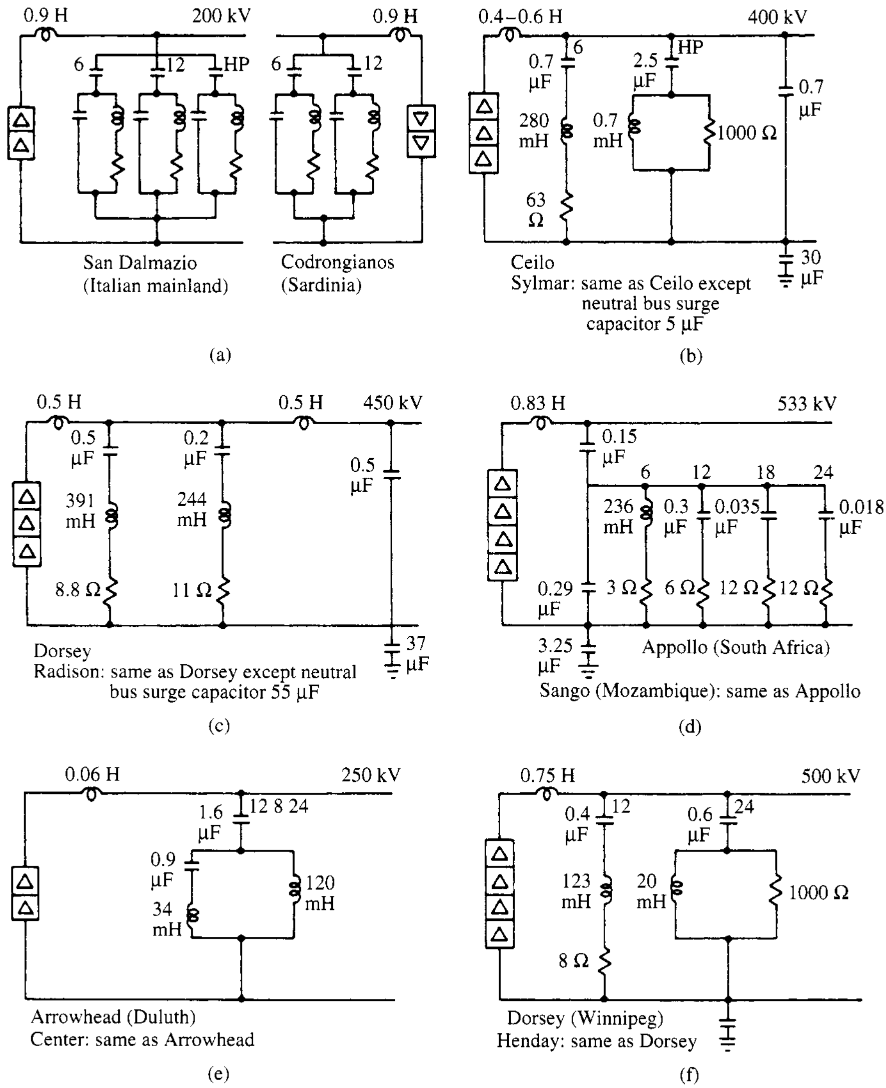


Figure 6.22 D.c. filter circuits of various HVd.c. schemes [10]

If the conventional stringent telephone interference criteria is imposed on HVd.c. lines the result is expensive filtering arrangements. However, the propagation of harmonics can be predicted with much greater accuracy in HVd.c. lines (as compared with a.c. lines) and it is possible to make more realistic cost comparisons with alternative changes in the telecommunications system.

6.13 Active Filters

The design complexity and high cost of losses of the conventional passive filters, as well as their restricted capability to eliminate inter-harmonics and non-characteristic

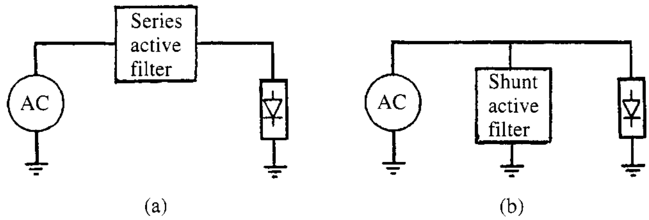


Figure 6.23 Active filters: (a) series; (b) shunt

harmonics, has encouraged the development of harmonic compensation by means of power electronic devices, commonly referred to as active filters.

According to their connection to the network, active filters can be of the series type, as shown in Figure 6.23(a), to prevent the transfer of harmonic current, or of the shunt type, shown in Figure 6.23(b), to reduce the harmonic content in the network.

The operating characteristics and limitations of the two types of active filter are discussed in the following sections.

6.13.1 Series Connection of Active Filters

As the generation of harmonic content is an inherent part of the operation of the nonlinear components, a path must be provided for them to flow. Therefore the use of series-connected filters in isolation is not normally viable and they have to be combined with some type of passive filtering. The latter absorb the current harmonics generated by the nonlinear plant, while the active filters blocks the transfer of harmonics in either direction. This combination isolates the passive filters from the a.c. system impedance, improving their response and reducing possible overloads.

Figure 6.24 shows a single phase diagram of the series active and shunt passive filtering combination. The harmonics are represented by a current source i_L and the network and passive filter by the impedances Z_S and Z_F, respectively. The active filter is represented by a voltage source V_C in series.

The controlled voltage source offers no impedance to the flow of the fundamental component but introduces a very large resistance between the network and the nonlinear

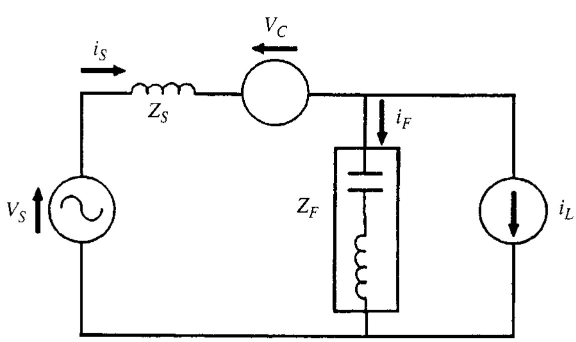


Figure 6.24 Single-phase circuit of a series active filter

plant for the harmonic frequencies. In practice, due to the limitation of the active filter bandwidth, there is a maximum level for that resistance.

In the ideal case, the nonlinear plant current harmonic content is forced to circulate via the passive filter, and the active filter voltage is the sum of the supply and passive filter voltages. The power rating of the series active filter is of the order of 2–5% of the nonlinear plant nominal power (in VA) [11].

The main limitation of the active/passive filter configuration is that it is restricted to a fixed fundamental frequency.

6.13.2 Shunt Connection of Active Filters

An early proposal for the shunt active filter connection was made in 1971 [12] for the elimination of the converter current harmonics via magnetic compensation, as shown in Figure 6.25.

In this configuration a current transformer captures information about the total converter current. The fundamental current is then eliminated by means of a series resonant circuit. The remaining content of the current is amplified to the appropriate level by means of a linear amplifier, the output of which is fed back via a tertiary winding in the converter transformer.

More recently there has been considerable research in this field, especially in the derivation and processing of the signal representing the current harmonic components in order to derive the appropriate compensation current [13–15].

Besides harmonic elimination, the active compensation systems can be designed to improve the power factor. Figure 6.26 shows a circuit based on the use of a signal processor unit (SPU) for the compensation of a load harmonic current and the displacement angle of the current fundamental frequency. In this unit the sampled harmonic current content is transmitted to the SPU. The SPU synthesises a sinusoidal wave in phase with the fundamental component of the load current (for the purpose of harmonic elimination) or with the terminal voltage (for the combined compensation of harmonics and displacement factor improvement). The synthesised sinusoidal current is then subtracted from the signal representing the load current to obtain the required compensating current; this signal is fed to an amplifier and then combined, via a reinjection transformer (or by direct connection using an inductor), with the load current in order to form an almost sinusoidal system current.

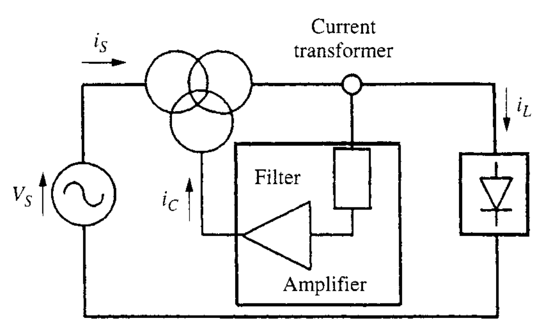


Figure 6.25 Magnetic compensation of converter harmonics

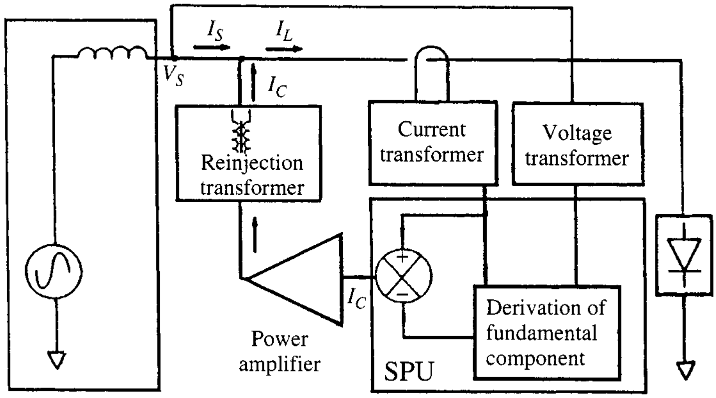


Figure 6.26 Active system for the compensation of the harmonic distortion

The main characteristic of this processing system is that the SPU operates in the time domain and thus avoids the need for complex processing to extract the harmonic components. Therefore the shunt-connected active filter is not tied to a specific fundamental frequency and thus the compensation achieved is effective at any source frequency within the limits imposed by the design.

Although the shunt active filter has definite advantages over passive filtering, its use in real industrial applications has so far been limited. This is because the cost of the inverter is still higher than the passive filter solution. A recent contribution [16] has proposed the connection of a shunt active filter in series with a passive filter. In this case the rating of the active filter is reduced and improves the performance of the passive filter.

The compensating effect of an active filter prototype [17] is illustrated in Figure 6.27. Figure 6.27(a) shows the current waveform absorbed by a single-phase bridge rectifier feeding a resistive load, and Figure 6.27(b) illustrates the compensating effect achieved by the active filter.

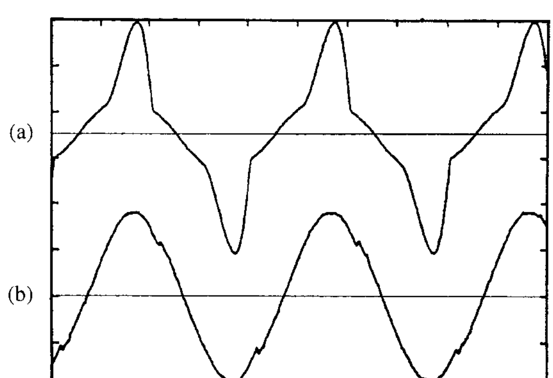


Figure 6.27 Typical magnitudes of an active filter: (a) load current; (b) compensated supply current

6.14 Discussion

The decision on the magnitude and type of harmonic reduction to be used is always made by economic considerations. Filters of whatever type are always expensive and thus, if at all possible, must be avoided. One of the problems in this respect is the difficulty in determining the extent of liability by the different parties involved. The installation of passive harmonic filters at a point in the system normally has a positive effect on the system as a whole. However, often the cost of providing such general welfare is rarely shared between the parties benefiting from it. On the negative side, the parallel combination of the filters and system impedances produces resonances (normally at non-characteristic harmonics) and, thus increases substantially the distortion at those frequencies.

Active filters, on the other hand, can be designed to compensate the harmonic content of the particular nonlinear load consideration, without providing an attractive path for the harmonics of neighbouring plant. Looking at it from the supplier viewpoint, though, too much active elimination can have a negative effect on the rest of the system, because active filters do not provide damping for existing harmonics. With the increasing use of highly controllable power electronic devices, especially in distributed generation with active waveform control, the lack of system damping is going to be a growing problem in the future.

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