20) (a) Describe the method of compensation of reactive power in HVDC substation.

(b) Draw simple single line schematics for each.

21) What is a Static VAR system? How many types of SVS schemes are present and what are they?

22) (a) Discuss about alternate converter control strategies for reactive power control.

(b) Discuss how shunt capacitors can be used to meet reactive power requirement of a converter.

23) (a) Why Reactive power control is required for HVDC stations? Discuss about conventional control strategies for Reactive power control in HVDC link.

(b) Discuss how reactive power requirement is met using synchronous condensers.

25) Write a note on the following sources of reactive power

(a) Synchronous condensers

(b) Static VAR system

Design of AC Filters

1. Harmonic Distortion:

Harmonic Distortion is given by,

$$D = \frac{\sum_{n=2}^{m} I_n Z_n}{E_1} \times 100$$

where,

I_n – harmonic current injected

Z_n – harmonic impedance of the system

E_1 – fundamental component of line to neutral voltage

m – highest harmonic considered

Harmonic Distortion is also given by,

$$D_{RSS} = \frac{\left[\sum_{n=2}^{m} (I_n Z_n)^2\right]^{1/2}}{E_1} \times 100$$

2. Telephone Influence Factor (TIF):

An index of possible telephone interference and is given by,

$$TIF = \frac{\left[\sum_{n=2}^{m} (I_n Z_n F_n)^2\right]^{1/2}}{E_1}$$

where,

$F_n = 5\ n\ f_1\ p_n$

P_n is the c message weighting used by Bell Telephone Systems (BTS) and Edison Electric Institute (EEI) in USA. This weighting reflects the frequency dependent sensitivity of the human ear and has a maximum value at the frequency of 1000Hz.

3. Telephone Harmonic Form Factor (THFF):

It is similar to TIF and is given by,

$$F_n = (n\ f_1 / 800)\ W_n$$

where,

W_n – weight at the harmonic order n, defined by the Consultative Commission on Telephone and Telegraph Systems (CCITT).

TIF is used in USA.

THFF is popular in Europe.

4. IT Product:

In BTS-EEI system, there is another index called IT product and is defined by,

$$IT = \left[\sum_{n=2}^{m} (I_n F_n)^2 \right]^{1/2}$$

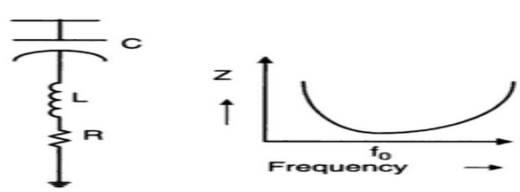
Types of AC Filters

The various types of filters that are used are

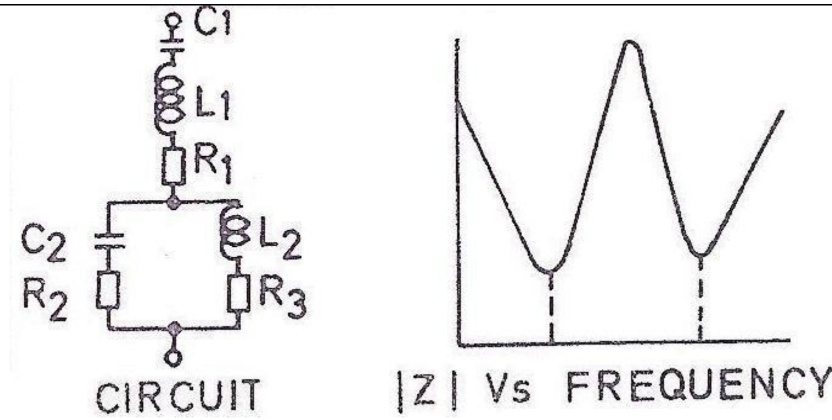
1. Single Tuned Filter
2. Double Tuned Filter
3. High Pass Filter
   a) Second Order Filter
   b) C Type Filter

Single Tuned Filter

Single Tuned Filters are designed to filter out characteristic harmonics of single frequency.

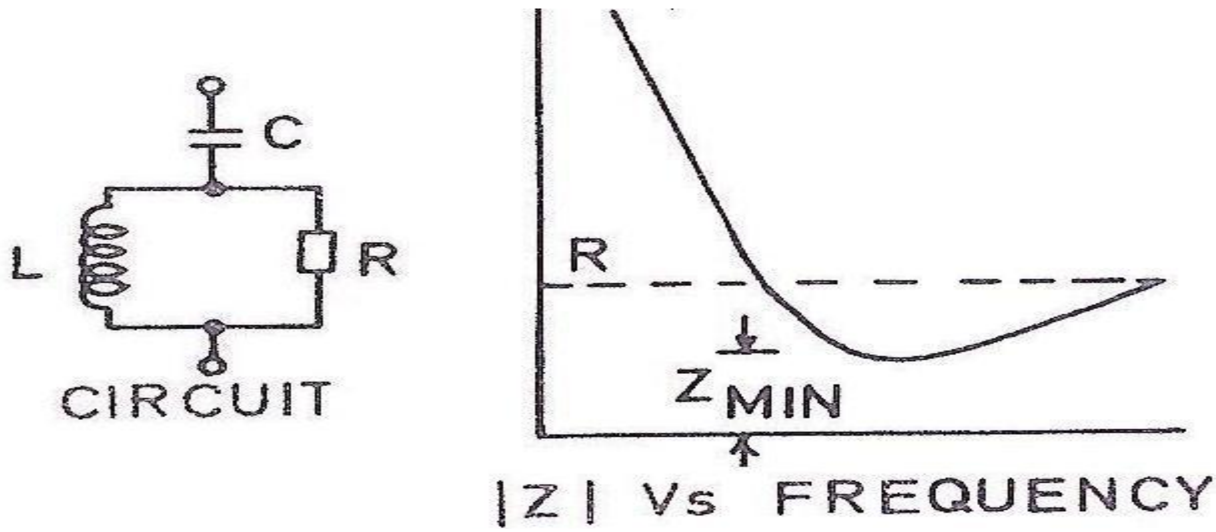


Double Tuned Filter

The Double Tuned Filters are used to filter out two discrete frequencies, instead of using two Single Tuned Filters. Their main disadvantages are i. only one inductor is subject to full line impulse voltage. ii. power loss at the fundamental frequency is considerably reduced.	

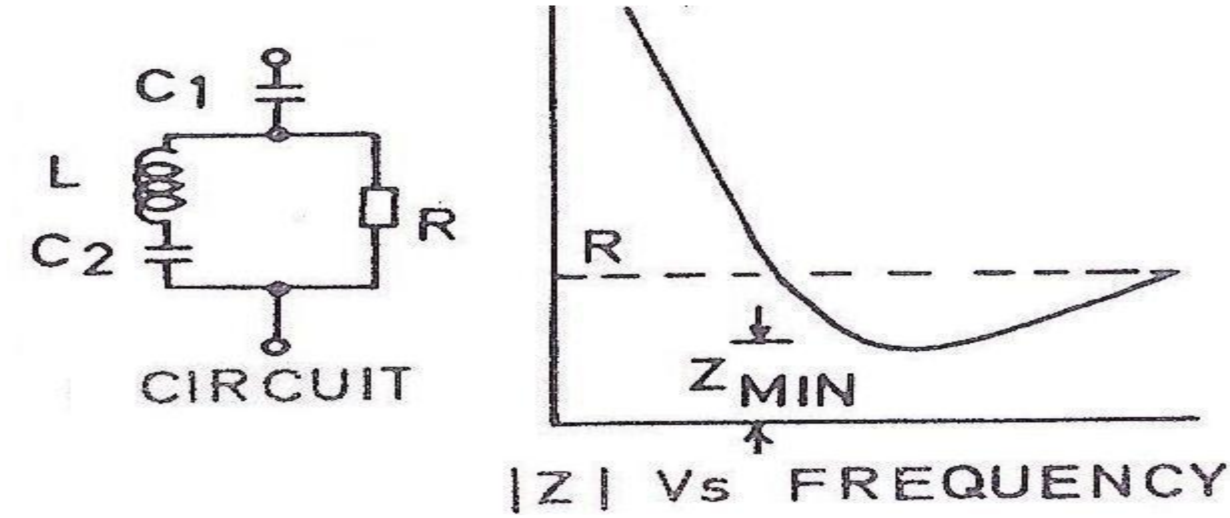
Second Order High Pass Filter

The Second Order High Pass Filters are designed to filter out higher harmonics.



High Pass C Type Filter

The losses at the fundamental frequency can be reduced by using a C Type Filter where capacitor C_2 is in series with inductor L, which provides a low impedance path to the fundamental component of current.



A converter system with 12 pulse converters has Double Tuned (or two Single Tuned) Filter banks to filter out 11^{th} and 13^{th} harmonics and a High Pass Filter bank to filter the rest of harmonics. Sometimes a third harmonic filter may be used to filter the non-characteristic harmonics of the 3^{rd} order particularly with weak AC systems where some voltage unbalance is expected.

All filter branches appear capacitive at fundamental frequency and supply reactive power.

Design of Single Tuned Filter

The impedance Z_{Fh} of the single tuned filter at the harmonic order 'h' is given by

$$Z_{Fh} = R + j\left(h\omega L - \frac{1}{h\omega C}\right)$$

where ω is the fundamental frequency which can vary with the power system operating conditions.

A tuned filter is designed to filter a single harmonic of order h_r . If $h_r\omega=\omega_r$, then $Z_{Fh}=R=\frac{X_0}{Q}$ and is minimum.

Since ω is variable and there could be errors in the tuning($\omega_r \neq h_r\ \omega_n$ where ω_n is the nominal (rated) frequency), it is necessary to compute the impedance of the tuned filter as a function of the detuning parameter (δ) defined by

$$\delta = \frac{h_r\omega - \omega_r}{h_r\omega_n} = \frac{\omega}{\omega_n} - \frac{\omega_r}{h_r\omega_n}$$

Considering variations in the frequency (f), inductance (L) and capacitance (C),

$$\delta = 1 + \frac{\Delta f}{f_n} - \left[\left(1 + \frac{\Delta L}{L_n}\right)\left(1 + \frac{\Delta C}{C_n}\right)\right]^{1/2}$$

$$\delta = \frac{\Delta f}{f_n} + \frac{1}{2}\frac{\Delta L}{L_n} + \frac{1}{2}\frac{\Delta C}{C_n}$$

where L_n and C_n are the nominal values of L and C such that $h_r\omega_n=(L_nC_n)^{-1/2}$

The variation in C can be due to

(i) error in the initial setting of C

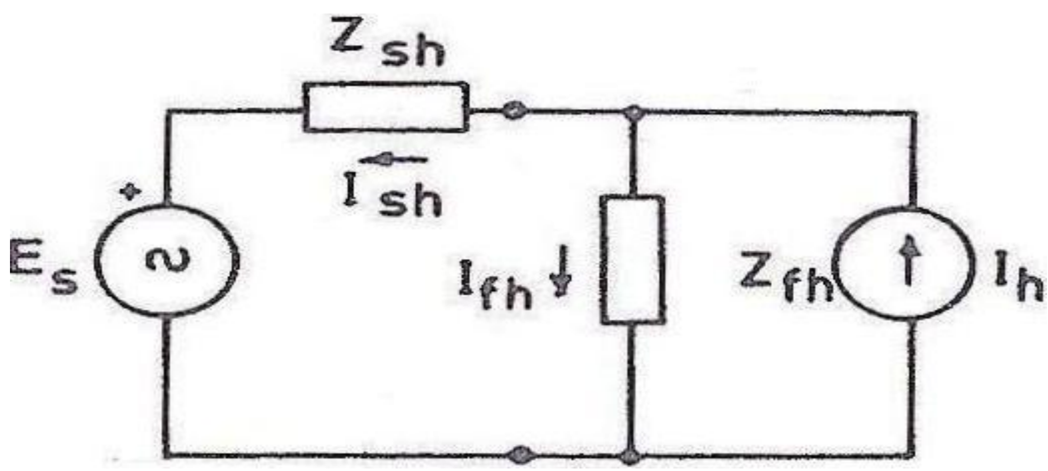
(ii) the variation in C due to the temperature dependence of the dielectric constant.

$$Z_{Fh} = R + jX_0\left(\frac{\omega}{\omega_n}\frac{L}{L_n} - \frac{\omega_n}{\omega}\frac{C_n}{C}\right)$$

where $$X_0 = h_r\omega_n L_n = \frac{1}{h_r\omega_n C_n}$$

The single tuned filters are designed to filter out characteristic harmonics of single frequency. The harmonic current in the filter is given by

$$I_{Fh} = \frac{I_h|Z_{Sh}|}{|Z_{Sh} + Z_{Fh}|}$$

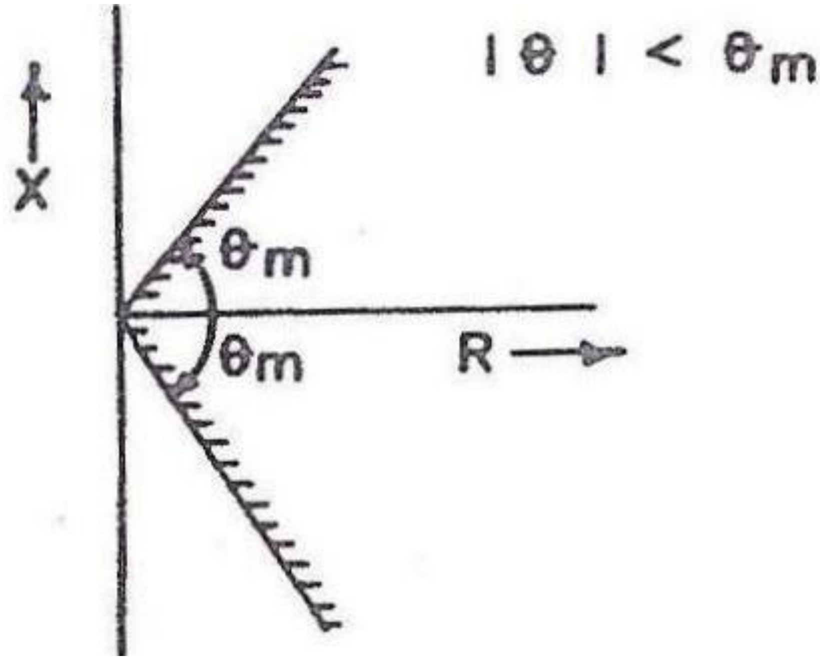


The harmonic voltage at the converter bus is

$$V_h = I_{Fh}|Z_{Fh}| = \frac{I_h}{|Y_{Fh} + Y_{Sh}|} = \frac{I_h}{|Y_h|}$$

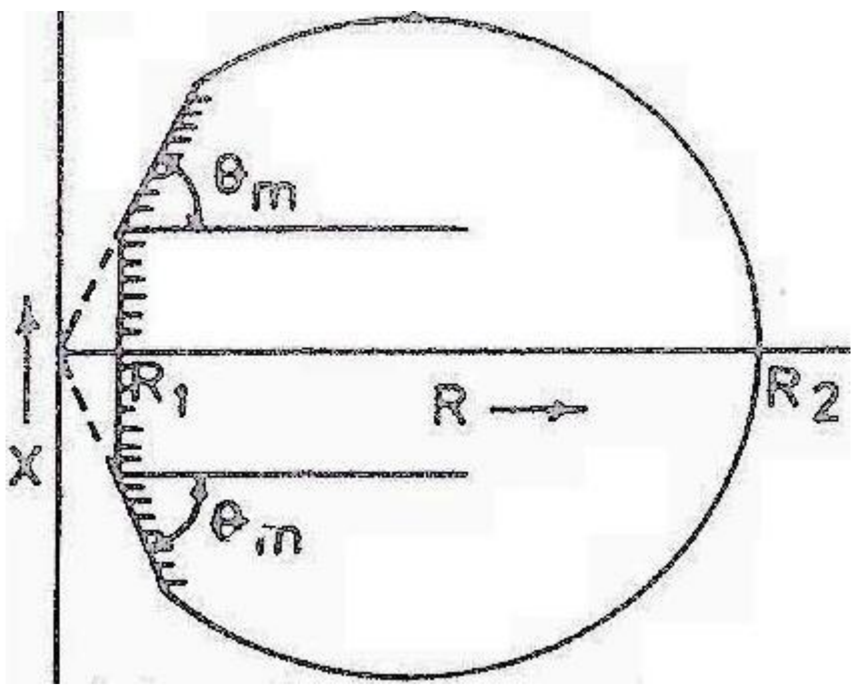
The basic objective in designing the filter is to select the filter admittance Y_{Fh} in order to minimize V_h or satisfy the constraints on V_h . The problem of designing a filter is complicated by the uncertainty about the network admittance (Y_{Sh}). There are two possible representations of system impedance in the complex plane where

(a) impedance angle is limited

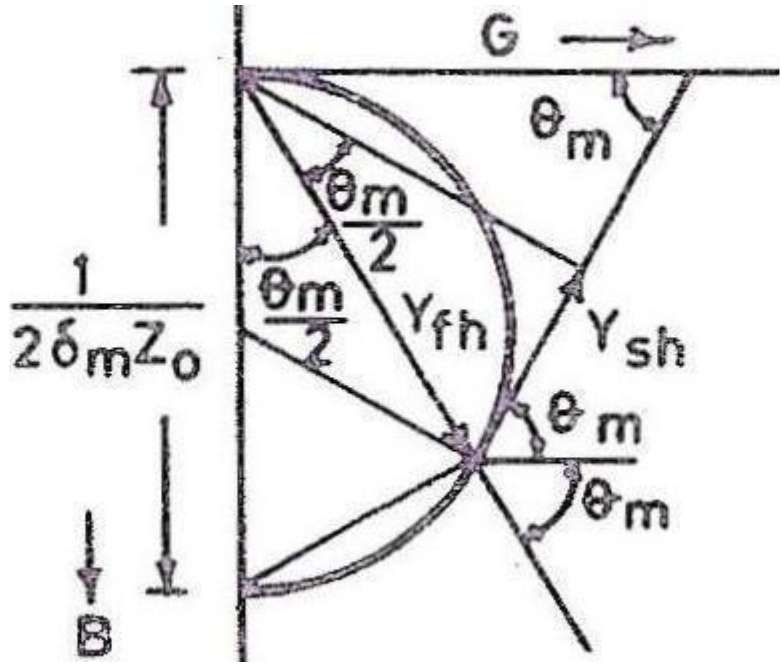


This allows a simplified computation of the optimum value of Q. In computing the optimum value of Q, we need to minimize the maximum value of V_h . The optimum value of Q corresponds to the lowest value of the upper limit on V_h .

(b) the impedance is limited both in angle and impedance



The value of Y_h is reduced if the detuning parameter δ is maximum = δ_m . For a specified value δ_m and X_0 , the locus of the filter impedance as Q is varied is a semicircle in the 4th quadrant of the G-B plane as shown below.



The optimum value of Q can be obtained from game-theoretic analysis. If one selects Y_{Fh} arbitrarily (the tip of Y_{Fh} lying along the semicircle), the network can select Y_{Sh} such that the vector Y_h is perpendicular to the vector Y_{Sh} and ensure Y_h is minimum. To maximize the minimum magnitude of Y_h , it is necessary to have Y_{Sh} tangential to the circle. Thus, we select Y_{Fh} to maximize Y_h when the network tries to minimize it.

Design of High Pass Filter

For harmonic frequencies of order equal to or higher than 17, a common second order high pass filter is provided. By defining the following parameters

$$h_0\omega_1 = 1/\sqrt{LC}, Z_0 = \sqrt{L/C}, \sigma = R/Z_0$$

The following values can be chosen

$$0.5 < \sigma < 2$$

$$h_0 \le \sqrt{2}\, h_{min}$$

where h_{min} is the smallest value of h to be handled by the filter. The choice of h_0 given above implies that the filter impedance at h_{min} has decreased approximately to the value of R.

The filter impedance is given by

$$Z_f = \frac{Z_0[\sigma + j(h_0/h).(\sigma^2 - 1 - (\sigma h_0/h)^2)]}{1 + (\sigma h_0/h)^2}$$

The reactive power supplied by the filter is

$$Q_f = (h_0 / (h_0^2 - 1)) . (V_1^2 / Z_0)$$

The filtering is improved if Q_f is increased and higher value of h_0 can be chosen. Hence, it is advantageous in designing high pass filter to exclude six pulse operation.

Protection of Filters

The filter is exposed to overvoltage during switching in and the magnitude of this overvoltage is a function of the short-circuit ratio (higher with low values of SCR) and the saturation characteristics of the converter transformer.

During switching in, the filter current (at filter frequencies) can have magnitudes ranging from 20 to 100 times the harmonic current in normal (steady-state) operation. The lower values for tuned filters and higher values are applicable to high pass filters. These overcurrents are taken into consideration in the mechanical design of reactor coils.

When filters are disconnected, their capacitors remain charged to the voltage at the instant of switching. The residual direct voltages can also occur on bus bars. To avoid, the capacitors may be discharged by short-circuiting devices or through converter transformers or by voltage transformers loaded with resistors.

If the network frequency deviates from the nominal value, higher currents and losses will result in AC filters. If they exceed the limits,