UNIT-V
HARMONICS

INTRODUCTION:

Electrical energy transmitted through AC transmission or DC transmission is to be delivered at the consumer's terminals at specified voltage levels of constant magnitude without deviation from the ideal waveform.

An HVDC transmission system generates harmonic currents on the AC side and harmonic voltages on the DC side during operation. The harmonic currents generated at the AC bus of the converter get transmitted to the AC network and then cause the following adverse effects.

- Heating of the equipment connected.
- Instability of converter control.
- Generates telephone and radio interference in adjacent communication lines, thereby inducing harmonic noise.
- Harmonics can lead to generation of overvoltages due to resonance when filter circuits are employed

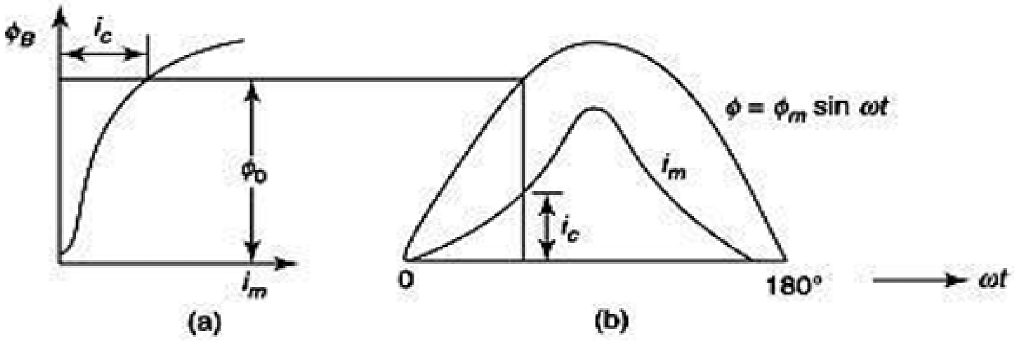
An HVDC transmission system consists of a rectifier and an inverter whose operation generates harmonics on the AC and DC side of the converter. The three distinct sources of harmonics in HVDC systems are

1. Transformer.
2. AC Generator.
3. Converter along with its control devices

Transformer as source of harmonics:

Transformers can be considered as a source of harmonic voltages, which arise from magnetic distortion and magnetic saturation due to the presence of a DC component in its secondary. The magnitude of these harmonics depends upon the operating flux density. Converter transformers are usually operated at high flux densities than conventional 3-phase transformers, and therefore the possibility of generation of harmonics is more.Although the waveform is usually good, an AC generator may be regarded as a source of balanced harmonics because of non-uniform distribution of flux on the armature windings.

The converter which forms the basic unit in HVDC transmission imposes changes of impedances in the current.

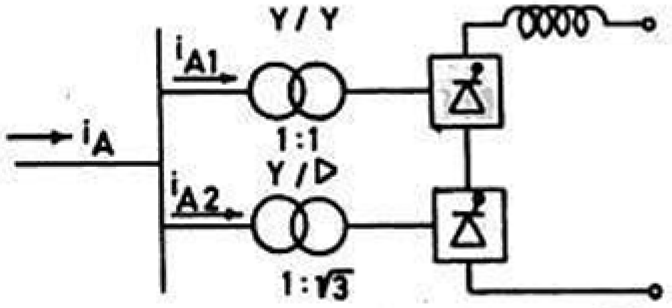


Transformer magnetisation (without hysteresis)
(a) Magnetisation curve (b) Flux and magnetisation current waveforms

When hysteresis effect is considered, then the non-sinusoidal magnetizing current waveform is no longer symmetrical which is mainly caused by triple n harmonics and particularly the third harmonic. Thus, in order to maintain a reasonable sinusoidal voltage supply, it is necessary to supply a path for triple n harmonics which is achieved by the use of delta- connected windings.

Harmonics due to Converters:

A 12-pulse connection consists of two 6-pulse groups. One group having Y-Y connected converter transformer with 1:1 turns ratio and the other group having Y-Δ converter transformer bank with 1:√3 turns ratio.



Schematic Diagram of a 12 Pulse Converter Unit

Generation of Harmonics:

The harmonics which are generated are of two types.

(i) Characteristic harmonics.

(ii) Non- characteristic harmonics.

Characteristic Harmonics:

The characteristic harmonics are harmonics which are always present even under ideal operation. In the converter analysis, the DC current is assumed to be constant. But in AC current the harmonics exist which are of the order of

$$h = np \pm 1$$

and in DC current it is of the order of

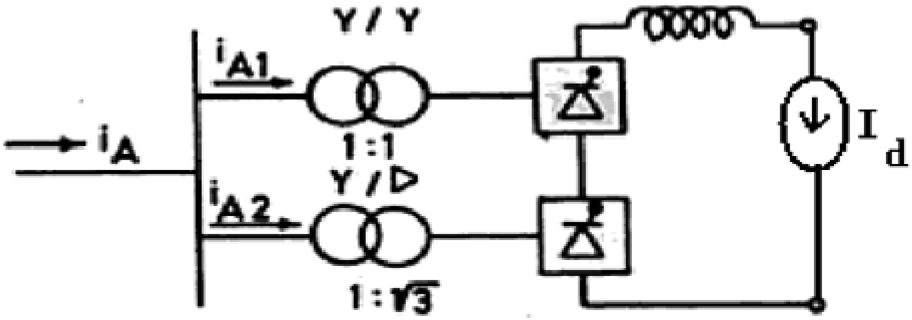
$$h = np$$

where n is any integer and p is pulse number

Neglecting overlap, primary currents of Y-Y and Y-Δ connection of the transformer are considered taking the origin symmetrical where

$$\left.\begin{array}{l} i = I_d \text{ for } -\pi/3 \le \omega t \le \pi/3 \\ = 0 \text{ for } \pi/3 \le \omega t \le 2\pi/3 \text{ and} \\ \qquad -\pi/3 \le \omega t \le -2\pi/3 \end{array}\right\} \text{for Y-Y connection converter transformer}$$

$$= -I_d \text{ for } -2\pi/3 \le \omega t \le -\pi \text{ and } 2\pi/3 \le \omega t \le \pi$$



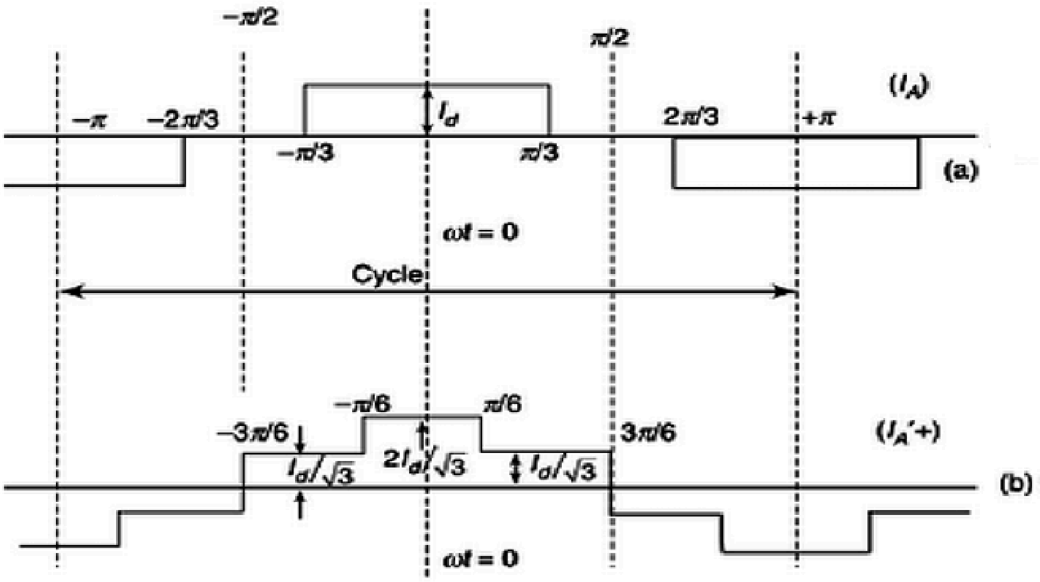


Figure (a): Phase current on primary side of Y-Y connection converter transformer

Figure (b): Phase current on primary side of Y-Δ connection converter transformer

For convenience, the ordinate axis (corresponding to ωt = 0) is chosen such that the waveform has even symmetry. So, generally, by fourier series

$$f(t) = \frac{1}{2}a_0 + \sum_{n=0}^{\infty} a_n \cos n\omega t + \sum_{n=0}^{\infty} b_n \sin n\omega t$$

As positive and negative half cycle cancel each other, so $a_0 = 0$ and as it is (waveform is) even symmetry, so $b_n = 0$ due to which f(t) becomes

$$f(t) = \sum_{n=0}^{\infty} a_n \cos n\omega t (or) \sum_{n} a_n \cos n\omega t$$

$$\text{Therefore, } i_{A_1} = \sum_{n} a_{n_1} \cos n\omega t$$

$$\text{where, } a_{n_1} = \frac{2}{T} \int_{0}^{PeriodOfConduction} f(t)\,dt$$

Here total time period is T = π and period of conduction is π/3

So,

$$a_{n_1} = 2X\frac{2}{\pi}\int_{0}^{\pi/3} I_d \cos n\omega t d(\omega t)$$

$$a_{n_1} = \frac{4I_d}{\pi}\int_0^{\pi/3}\cos n\omega t d(\omega t) = \frac{4I_d}{\pi}\left(\frac{\sin n\omega t}{n}\right)_0^{\pi/3}$$

$$a_{n_1} = \frac{4I_d}{n\pi}\left(\sin n\frac{\pi}{3}\right)$$

For triplen harmonics, $a_{n_1} = 0$

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,

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

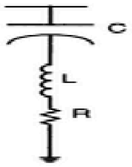
Types of AC Filters

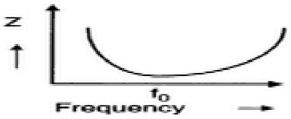
The various types of filters that are used are

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.



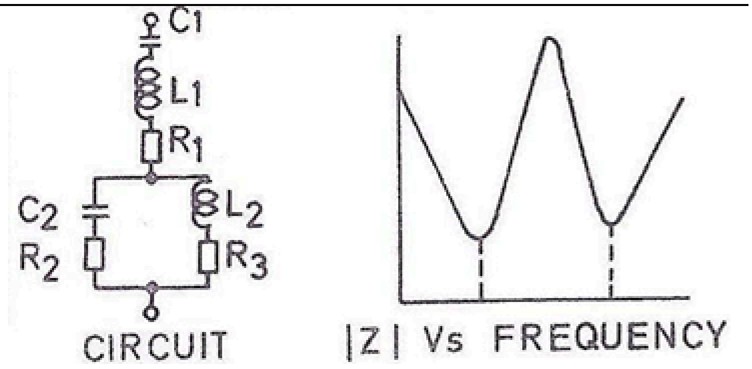


Double Tuned Filter

The Double Tuned Filters are used to filter out two discrete frequencies, instead of using two Single Tuned Filters. Their main disadvantages are

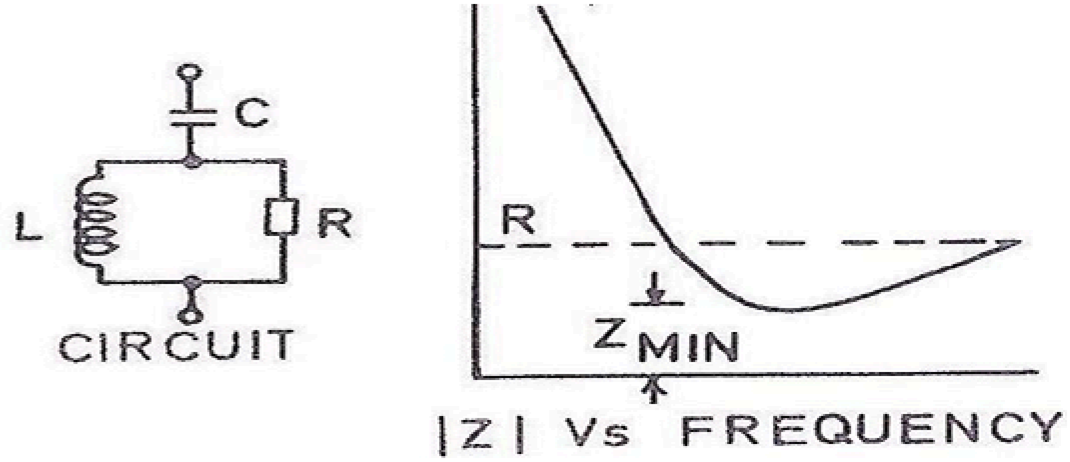
i. only one inductor is subject to full line impulse voltage.

ii. power loss at the fundamental frequency is considerably reduced.



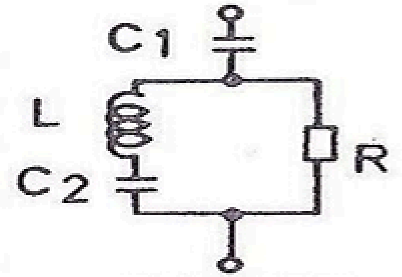
Second Order High Pass Filter

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

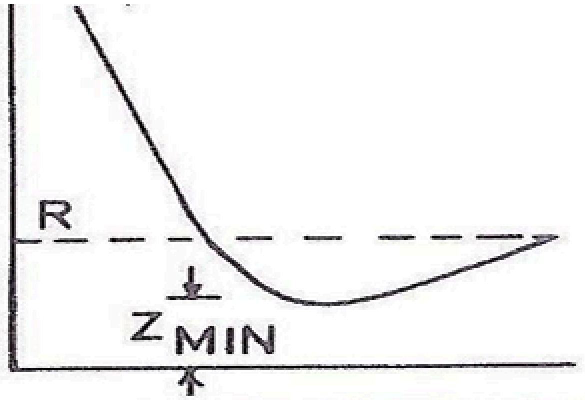


High Pass C Type Filter

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.



CIRCUIT



|Z| Vs FREQUENCY

A converter system with 12 pulse converters has Double Tuned (or two Single Tuned) Filter banks to filter out 11th and 13th 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 3rd 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

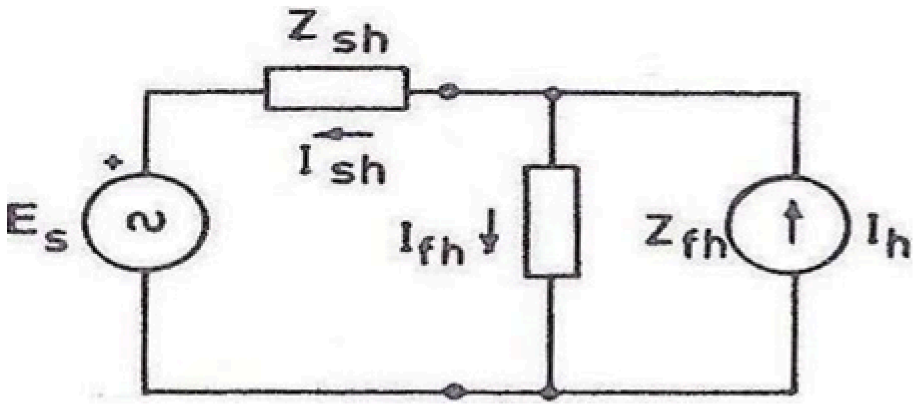
(ii) the variation in C due to the temperature dependence of the dielectric constant.

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

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

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

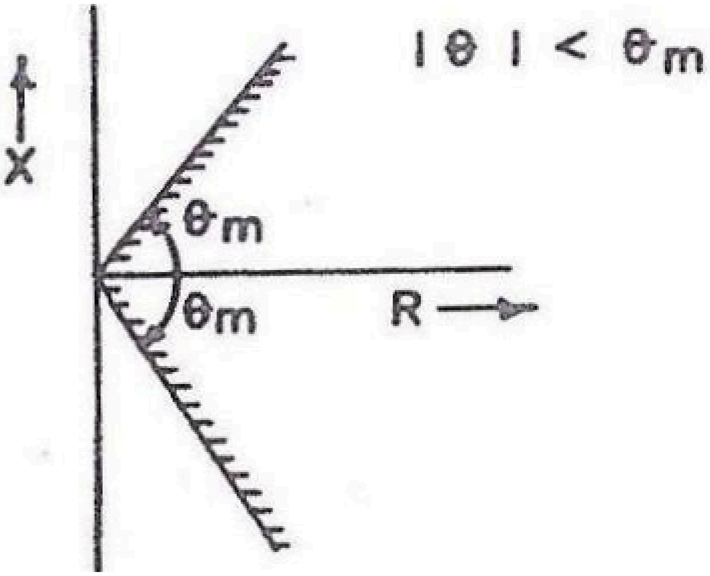


The harmonic voltage at the converter bus is

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

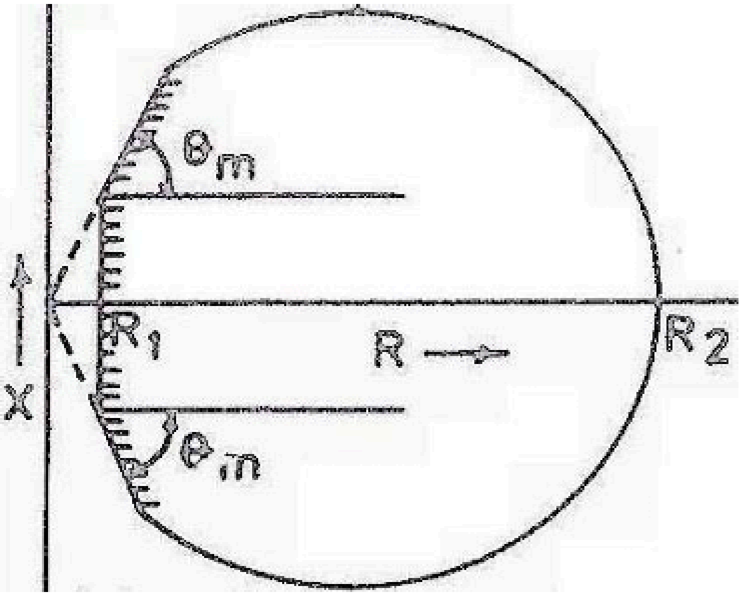
The basic objective in designing the filter is to select the filter admittance Y_{Fh} in order to minimize V_h or satisfy the constraints on V_h . The problem of designing a filter is complicated by the uncertainty about the network admittance (Y_{Sh}). There are two possible representations of system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

(a) impedance angle is limited

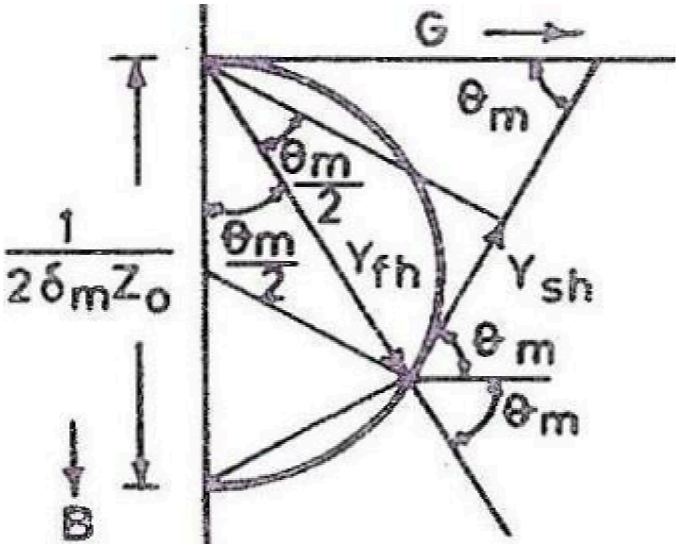


This allows a simplified computation of the optimum value of Q. In computing the optimum value of Q, we need to minimize the maximum value of V_h . The optimum value of Q corresponds to the lowest value of the upper limit on V_h .

(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,