CHAPTER TWO

HARMONIC AND PASSIVE FILTER

2-1 Introduction

Power system harmonics is an area that is receiving a great deal of attention recently. This is primarily due to the fact that non-linear or (harmonic producing) loads are comprising an ever-increasing portion of the total load for a typical industrial plant. The increase in proportion of non-linear load has prompted more stringent recommendations in IEEE Std. 519 and stricter limits imposed by utilities. Incidence of harmonic related problems is low, but awareness of harmonic issues can help to increase plant power system reliability. On the rare occasions that harmonics are a problem, it is either due to the magnitude of the harmonics produced or a power system resonance.

Until the 1960s the main harmonic sources in the power system were arc furnace and a very few converter loads. With the thyristor's and static power supplies many variable speed drives were introduced in all industries in the 1970s. With the increase in the converter load in the power system, several new problems became noticeable such as:

- Flow of harmonic currents from the converter to the ac system.
- Poor power factor on the ac side.
- Poor voltage regulation on the ac side due to low power factor.
- Excessive interference induced into the telecommunication equipment due to mutual coupling.
- Distortion of ac supply voltages that affect the performance of computer equipment and numerical control devices.
- Error in the metering.
- Continuous neutral currents in the neutral conductors of the four wire systems.

Therefore, there is a need to understand the behavior of the industrial power systems with the converter/inverter equipment. With the introduction of the new filtering devices, the need to improve the power factor and control the harmonics together in the utilities can encounter new system problems. In this Chapter, the sources of harmonics, the system response, modeling of the system for harmonic analysis, acceptable harmonic limits and the approach for the harmonic analysis are presented [4].

2-2 Harmonic Definition

The typical definition for a harmonic is “a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency.”

Some references refer to “clean” or “pure” power as those without any harmonics. But such clean waveforms typically only exist in a laboratory.

Electrical generators try to produce electric power where the voltage waveform has only one frequency associated with it, the fundamental frequency. In the North America, this frequency is 60 Hz, or cycles per second. In European countries and other parts of the world, this frequency is usually 50 Hz. Aircraft often uses 400 Hz as the fundamental frequency. At 60 Hz, this means that sixty times a second, the voltage waveform increases to a maximum positive value, then decreases to zero, further decreasing to a maximum negative value, and then back to zero. The rate at which these changes occur is the trigo-metric function called a sine wave, as shown in Figure 2.1. This function occurs in many natural phenomena, such as the speed of a pendulum as it swings back and forth, or the way a string on a violin vibrates when plucked.

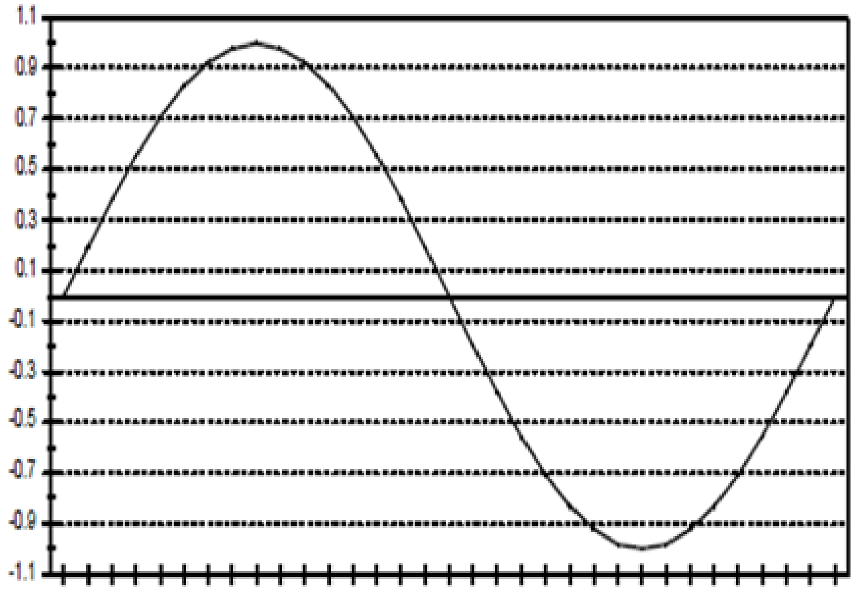

Figure2.1: Sine wave

The frequencies of the harmonics are different, depending on the fundamental frequency. For example, the 2nd harmonic on a 60 Hz system is 2*60 or 120 Hz. At 50Hz, the second harmonic is 2* 50 or 100Hz, 300Hz is the 5th harmonic in a 60 Hz system, or the 6th harmonic in a 50 Hz system.

Figure 2.2 shows how a signal with two harmonics would appear on an oscilloscope-type display, which some power quality analyzers provide.

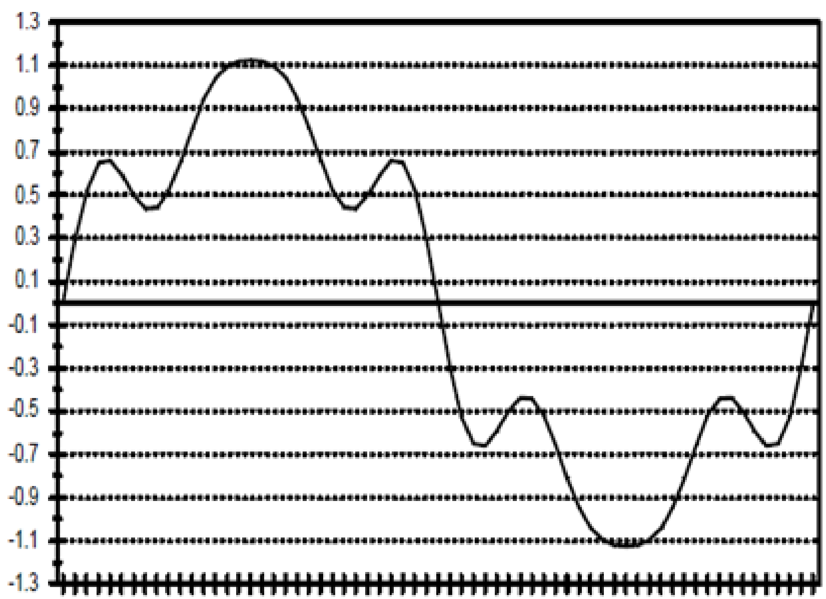

Figure 2.2: Fundamental Harmonics

In order to be able to analyze complex signals that have many different frequencies present, a number of mathematical methods were developed. One of the more popular is called the Fourier Transform. However, duplicating the mathematical steps required in a microprocessor or computer-based instrument is quite difficult. So more compatible processes, called the FFT for Fast Fourier Transform or DFT for Discrete Fourier Transform are used. These methods only work properly if the signal is composed of only the fundamental and harmonic frequencies in a certain frequency range (called the NY Quist frequency, which is one-half of the sampling frequency). The frequency values must not change during the measurement period. Failure of these rules to be maintained can result in misinformation.

For example, if a voltage waveform is comprised of 60 Hz and 200 Hz signals, the FFT cannot directly see the 200 Hz. It only knows 60, 120, 180, 240, etc. which are often called “bins”. The result would be that the energy of the 200 Hz signal would appear partially in the 180Hz bin, and partially in the 240 Hz bin. An FFT-based processer could show a voltage value of 115V at 60 Hz, 18 V at the 3rd harmonic, and 12 V at the 4th harmonic, when it really should have been 30 V at 200 Hz.

These in-between frequencies are called “inter-harmonics”. There is also a special category of inter-harmonics, which are frequency values less than the fundamental frequency value, called sub-harmonics. For example, the process of melting metal in an electric arc furnace can result large currents that are comprised of the fundamental, inter-harmonic, and sub-harmonic frequencies being drawn from the electric power grid.

These levels can be quite high during the melt-down phase, and usually effect the voltage waveform [2].

2-3 Harmonics indices

Harmonics are a mathematical way of describing distortion to a voltage or current waveform. The term harmonic refers to a component of a waveform that occurs at an integer multiple of the fundamental frequency.

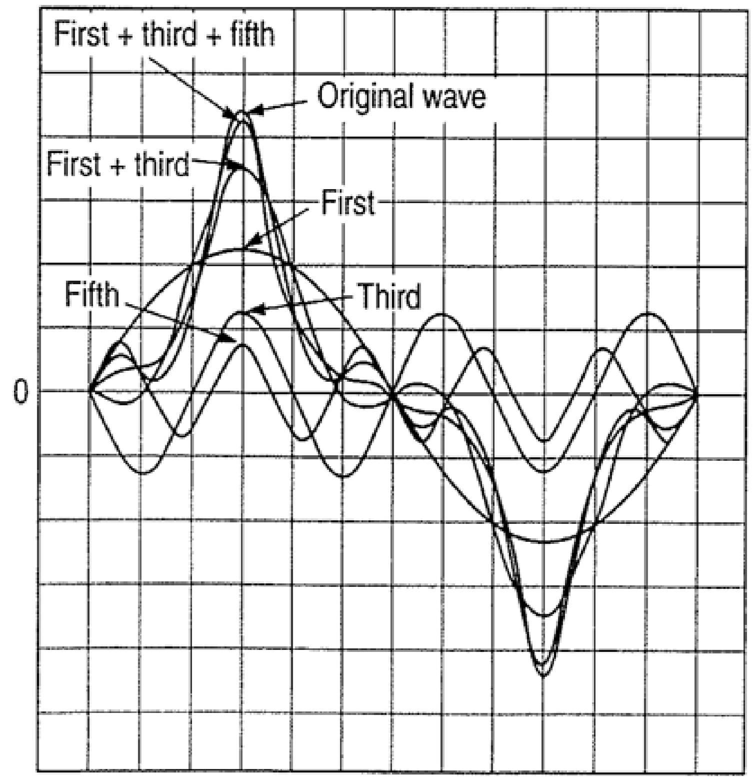

Figure 2.3: Harmonic analysis of peaked no-load currents

Fourier theory tells us that any repetitive waveform can be defined in terms of summing sinusoidal waveforms which are integer multiples or (harmonics) of the fundamental frequency. For the purpose of a steady state waveform with equal positive and negative half-cycles, the Fourier series can be expressed as follows:

$$F(t) = \sum_{n=1}^{\infty}\left(A_n . \sin\left(\frac{n\pi t}{T}\right)\right) \tag{2.1}$$

Where F(t) is the time domain function n is the harmonic number (only odd values of n are required), A_n is the amplitude of the n^{th} harmonic component and T is the length of one cycle in seconds.

The simplified Fourier expression states:

$$v(t) = v_0 + v_1 \sin(\omega t) + v_2 \sin(2\omega t) + \cdots v_n \sin(n\omega t) \quad (2.2)$$

The analyzed waveform composes of:

1- A direct current (DC) component v_o.

2- Fundamental component at nominal frequency (50 HZ).

3- Sinusoidal harmonics having frequencies that are multiples of the fundamental frequency [3].

2-4 Total Harmonic Distortion

A common term that is used in relation to harmonics is THD or Total Harmonic Distortion. THD can be used to describe voltage or current distortion and is calculated as follows:

$$\mathrm{THD}(\%) = \sqrt{(\mathrm{ID}_1^2 + \mathrm{ID}_2^2 + \cdots \mathrm{ID}_n^2)} \quad (2.3)$$

Where ID_n is the magnitude of the n^{th} harmonic as a percentage of the fundamental (individual distortion). Another closely related term is Distortion Factor (DF) which is essentially the same as THD [3].

2-5 Power Factor In the Presence of Harmonics

There are two different types of power factor that must be considered when voltage and current waveforms are not perfectly sinusoidal. The first type of power factor is the Input Displacement Factor (IDF) which refers to the cosine of the angle between the 60 Hz voltage and current waveforms. The second type is Distortion Factor (DF) is defined as follows:

$$\mathrm{DF} = \frac{1}{\sqrt{1 + \mathrm{THD}^2}} \quad (2.4)$$

The Distortion Factor will decrease as the harmonic content goes up. The Distortion Factor will be lower for voltage source type drives at reduced speed and load. Total Power Factor (PF) is the product of the Input Displacement Factor and the distortion factor as follows:

$$PF = IDF \times DF \tag{2.5}$$

In order to make a valid comparison of power factor between drives of different topologies, it is essential to look at Distortion Factor. The Displacement Power Factor may look attractive for certain types of drives, but the actual power factor may be somewhat lower when the effect of harmonics is taken into account [1].

2-6 Effects of Harmonics in power system

The power industry has recognized the problem of power system harmonics since 1920s when distorted voltage and current waveforms were observed on power lines. However, the levels of harmonics on distribution system have generally been insignificant in the past. Today, it is obvious that the levels of harmonic voltages and currents on distribution systems are becoming a serious problem. Some of the most important power system operational problems caused by harmonics have been reported to include the flowing:

1. Capacitor bank failure from dielectric breakdown or reactive power overload
2. Interference with ripple control and power-line carrier system, causing miss-operation of system which a ccomplish remote switching, load control and metering.
3. Excessive losses in and heating of induction and synchronous machines.
4. Overvoltage and excessive currents on the system from resonance to harmonic voltages or current on the network.
5. Dielectric instability of insulated cables resulting from harmonic over voltages on the system.
6. Inductive interference with telecommunication system.
7. Errors in induction watt-hour meters.

8. Signals interference and really malfunction, particularly in solid-state and microprocessor-controlled system.
9. Interference with large motor controllers and power plant excitation systems (reported to cause motor problems as well as no uniform output).

Also, harmonics increase the load current which than effect the operation of as following equipment's:

- Overloading of neutrals
- Overheating of transformers
- Nuisance tripping of circuit breakers
- Over-stressing of power factor correction capacitors

Also, the harmonics affect system voltage which produces the following results:

- Voltage distortion & zero-crossing noise
- Overheating of induction motors (oscillating torques).

In balanced three phase systems the fundamental current cancels, but triple-N harmonics add arithmetically! Non triple-N harmonics cancel in the neutral. Neutral currents can easily approach twice the phase currents - sometimes in a half-sized conductor.

IEEE 1100-1992 recommends that neutral bus-bars feeding non-linear loads should have a cross-sectional area not less than 173% that of the phase bars.

Neutral cables should have a cross-sectional area that is 200% that of the phases, e.g. by using twin single core cables [2,4].

2.7 Effect of harmonics on transformers

Harmonics are also largely produced by transformers in power systems distribution. A transformer is usually designed to make optimum use of magnetic core materials, resulting in a peak magnetic flux density in its steady state. Transformers supplying harmonic loads must be appropriately de-rated

Harmonic currents, being of higher frequency, because increased magnetic losses in the core and increased eddy current and skin effect losses in the windings.
Triple-n harmonic currents circulate in delta windings, they do not propagate back onto the supply network, but the transformer must be specified and rated to cope with the additional losses. (K)Rating of Transformers:

$$K = \sum_{h=1}^{h=h_{max}} I_h^2 h^2 \tag{2.6}$$

Where h is the harmonic order and I_h is the RMS current at h in per unit of rated load current, The K factor describes the increase in eddy current losses, not total losses [3].

2.8 Effect of harmonics in Skin effect

Alternating current tends to flow on the outer surface of a conductor - skin effect - and is more pronounced at high frequencies. At the seventh harmonic and above, skin effect will become significant, causing additional loss and heating. Where harmonic currents are present, cables should be de-rated accordingly. Multiple cable cores or laminated bus-bars can be used [3].

2.9 Effect of harmonics in Circuit breakers

Nuisance tripping can occur in the presence of harmonics for two reasons:

1. Residual current circuit breakers are electromechanical devices. They may not sum higher frequency components correctly and therefore trip erroneously.
2. The current flowing in the circuit will be higher than expected due to the presence of harmonic currents. Most portable measuring instruments do not read true RMS values [3].

2.10 Effects on rotating machines

Power system harmonics introduce losses in rotating machines. These losses occur in their stator windings, rotor circuits, and stator and rotor cores. Actually, the effects mainly are contributed by low order harmonics with large magnitudes. Due to eddy currents and skin effect, the losses in the conductors of stators and rotors with harmonics re much greater than those without harmonics. The leakage fields set up by the harmonic currents in stator and rotor end windings produce extra losses. Large harmonic contents in induction machines can reduce their output torques at rated speeds and cause vibration. The harmonic currents have little effects on the average torque; however, they produce significant torque pulsation, which causes the shaft vibration of the machine [5].

2-11 Harmonic Sources

These effects depend, of course, on the harmonics sources, its location on the power system, and the network characteristics that promote propagation of harmonics. These are numerous sources of harmonics. In general, the harmonics sources can be classified as, previously known harmonics sources and new harmonics sources.

The previously known harmonics sources include:

1. Tooth or ripples in the voltage waveform of rotating machines.
2. Variations in air-gap reluctance over synchronous machines pole pitch.
3. The flux distortion in the synchronous machine from sudden load changes.
4. No sinusoidal distribution of the flux in the air-gap of synchronous machines.
5. Transformers magnetizing currents.
6. Network nonlinearities from loads such as rectifiers, inventers, welders, arc furnaces, voltage controllers, frequency converters, etc.

While the establishment sources of harmonics are still present on the system, the power network is also subjected to new harmonics sources:

1. Energy conservation measures, such as those for improved motor efficiency and load matching which employ power semiconductor devices and switching for their operation. These devices often produce irregular voltage and current waveforms that are rich in harmonics.
2. Motor control devices such as speed controllers for traction.
3. High-voltage DC power transmission.
4. Interconnection of wind and solar power converters with distribution systems.
5. Static-var compensators which have largely replaced synchronous condensers as continuously variable-var sources [4].

2-12 Causes of Harmonic

Harmonics are caused by non-linear loads that are loads that draw a non-sinusoidal current from a sinusoidal voltage source. Some examples of harmonic producing loads are electric arc furnaces, static VAR compensators, inverters, DC converters, switch-mode power supplies, and AC or DC motor drives. In the case of a motor drive, the AC current at the input to the rectifier looks more like a square wave than a sine wave.

Non-linear loads generally do not cause reactive power to flow at the fundamental line frequency. They can, however, draw higher RMS currents and hence add to distribution system losses for a given load. The non-linear nature of these loads then draws non-pure sine wave currents thus causing harmonics of the fundamental current to be present. Since harmonic distortion is caused by non-linear elements connected to the power system, any devices has non-linear characteristics will cause harmonic distortion. Examples of common sources of powers system harmonics, some of which never cause serious problems are:

1. Transformers saturation and inrush.

2. Transformers neutral connections.

3. MMF distribution in AC rotating machines.

4. Electrical arc furnaces.

5. Fluorescent lighting.

6. Computers switch mode power supplies.

7. Battery charges.

8. Imperfect AC sources.

9. Variable frequency motor drives (VFD).

10. Inverters.

11. Television power supplies [1,2].

2-13 Passive Filter

Passive (or passive-tunes) filters are relatively inexpensive but they have potential for adverse interaction with the power system. They are used either to shunt the harmonic currents off the line or to block their flow between parts of the system by tuning the elements to create a resonance at a selected harmonic frequency. As shown in Figure 2.4 passive filters are made up of inductance, capacitance and resistance elements. A single-tuned "notch" filters is the most common type of filter since it is often sufficient for the application and inexpensive.

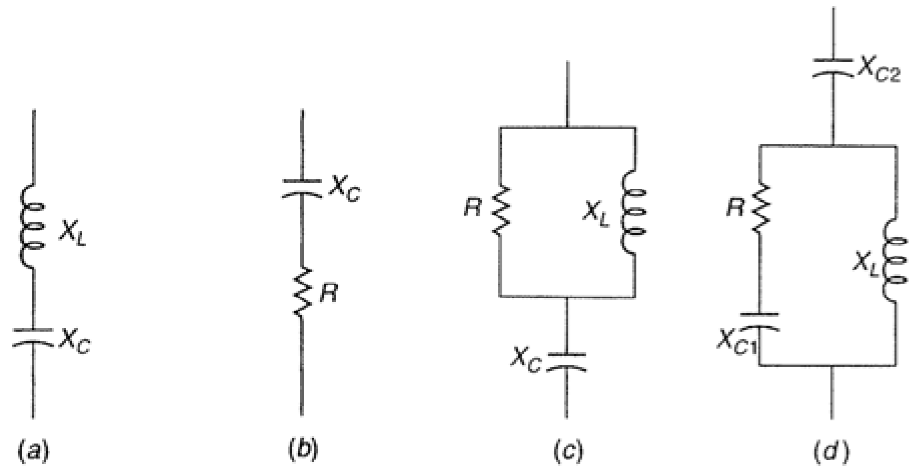

Figure 2.4: Passive Filters Elements

Figure 2.5 shows typical 480-V single-tuned wye or delta-connected filters. Such notch filter is serious-tuned to present low impedance to a specific harmonic current and is connected shunt with power system. As a result, harmonic currents are diverted from their normal flow path on the line into filter.

Notch filters provide PF correction in addition to harmonic suppression. As shown in the figure, a typical delta-connected low-voltage capacitor bank is converted into a filter by adding an inductance (reactor) in series. The tuned frequency for such combination is selected somewhere below the fifth harmonic to prevent parallel resonance at any characteristics harmonic. This is in order to provide a margin of safety in case there is some change in system parameters later. This point represents the notch harmonic, h_{notch} and is related to the fundamental frequency reactance X_1 by

$$h_{notch} = \sqrt{\frac{X_c}{3X_1}} \quad (2.7)$$

Here X_C is the reactance of one leg of the delta rather than the equivalent line-to neutral capacitive reactance. If the line-to-line voltage and three-phase capacitive reactive power is used to calculate X_C then it should not be divided by three in Equation 2.7.

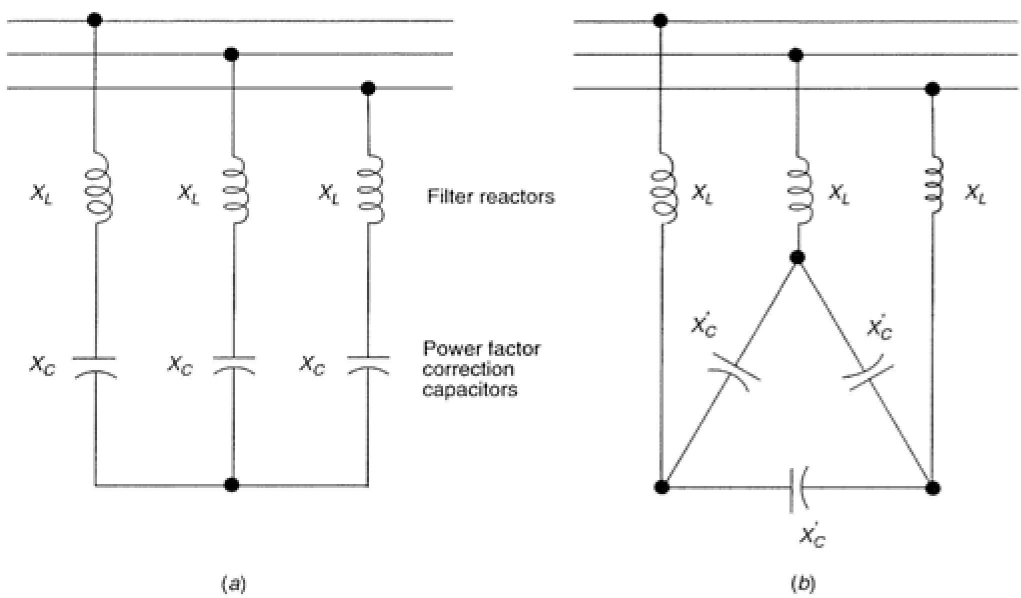

Figure 2.5: Typical 480-V single-tuned wye- or delta-connected filter configuration

Note that if such filter were tuned exactly to the harmonic, changes in inductance or capacitance with failure or due to change in temperature might push the parallel resonance higher into the harmonic. As a result, the situation becomes much worse than having no filter.

Also, it is usually a good idea to use capacitor with a higher voltage rating in filter applications because of the voltage rise across the reactor at the fundamental frequency and due to the harmonic loading .In this case 600V capacitor are used for a 480V application.

In general, capacitors on utility distribution system are connected in wye. It provides a path for the zero-sequence triple harmonics by changing the neutral connection. In addition, placing a reactor in the neutral of a capacitor is a common way to force the bank to filter only zero-sequence harmonics. It is often used to get rid of telephone interference. Usually, a tapped reactor is inserted into the neutral, and the tap is adjusted according to the harmonic causing the interference to minimize the problem.

Passive filters should always be placed on a bus where X_{scis} constant. The parallel resonance will be much lower with standby generation than utility system. Because of this, filter is often removed for standby operation. Furthermore, filters should be designed according to the bus capacitor not only for the load.

Note that tuned capacitor banks act as a harmonic filter for the fifth harmonic. They will have to absorb some percentage of the fifth harmonic current from loads within the facility and also will have absorb fifth harmonic current due to fifth harmonic voltage distortion on the utility supply system . IEEE 519-1992 allows the voltage distortion on the supply system to be as high as 3% at an individual harmonic on medium voltages systems. Thus, this level of fifth harmonic distortion should be assumed for filter design purposes.

The general methodology for applying filters is explained in the following steps:

1. Only a single –tuned shunt filter designed for the lowest produced frequency is applied first.

2. The voltage distortion level at the low-voltage bus is determined.

3. The effectiveness of the filter design is checked by changing the elements of the filter in conformity with the special tolerance.

4. It is assured that the resulting parallel resonance is not close to a harmonic frequency by reviewing the frequency response characteristic.

5. The requirement for having several filters, for example, fifth and seventh, or third, fifth, and seventh, is considered in the application.

Consider the single-tuned 480V notch filter shown Figure 2.5. Such filter should be tuned slightly below the harmonic frequency of concern. This permits for tolerances in the filter components and prevents the filter from acting as a short circuit for the offending harmonic current. It causes the tuning frequently to shift slightly higher.

The actual fundamental frequency compensation provided by rated capacitor bank is found from

$$\mathrm{Q_{actual}} = \mathrm{Q_{rated}} \left(\frac{\mathrm{V_{actual}}}{\mathrm{V_{rated}}}\right)^2 \tag{2.7}$$

The fundamental frequency current of the capacitor bank is

$$\mathrm{I_{c(FL)}} = \frac{Q_{actual}}{\sqrt{3}V_{actual}} \tag{2.8}$$

The equivalent single-phase reactance of the capacitor bank is:

$$X_{c(wye)} = \frac{V^2}{Q_c} \tag{2.9}$$

The reactance of the filter reactor is found from

$$\mathrm{X_L} = \mathrm{X_{reactor}} = \frac{X_c}{\mathrm{h_{tuned}^2}} \tag{2.10}$$

Where, h_1 is the tuned harmonic. The fundamental frequency current of the filter becomes

$$\mathrm{I_{filter(FL)}} = \frac{V_{bus}}{\sqrt{3}(\mathrm{X_c} + \mathrm{X_{reactor}})} \tag{2.11}$$

Since the filter draws more fundamental current than the capacitor alone the supplied var compensation is larger than the capacitor rating and is found from:

$$Q_{supplied} = \sqrt{3}V_{bus}I_{(FL)} \tag{2.12}$$

The tuning characteristic of this filter is defined by its quality factor, Q. it is the measure of sharpness of tuning. For such series filter, it is given by

$$Q = \frac{X_n}{R} = \frac{X_L}{R} = \frac{h \times X_{reactor}}{R} \qquad (2.13)$$

Where h is the tuned harmonic, $X_L = X_{reactor}$ is the reactance of the filter reactor at fundamental frequency, and R is the series resistance of the filter. Usually, the value R is only the resistance of the inductor which results in a very large value of Q and a very strong filtering. Normally, this satisfaction for a typical single – filter usage. It is a very economical filter operation due to its small energy consumption.

However, occasionally it might be required to have some losses to be able to dampen the system response. To achieve this, a resistor is added in parallel with the reactor to create a high-pass filter. In such a case, the quality factor is given by

$$Q = \frac{R}{h \times X_l} \qquad (2.14)$$

Here the larger the Q, the sharper the tuning. It is not economical to operate such filters at the fifth and seventh harmonics because of the amount of losses. However, they are used at the eleventh and thirteenth or higher order of harmonics.

In special cases where tuned capacitor banks are not sufficient to control harmonic current levels, a more complicated filter design may be required. Figure 2.6 gives the general procedure for designing these filters.

Significant de-rating of the filters may be required to handle harmonics from the power system. Including the contribution from the power is part of the process of selecting a minimum size.

Filter at each tuned frequency. The filter size must be large enough to absorb the power system harmonics [4].

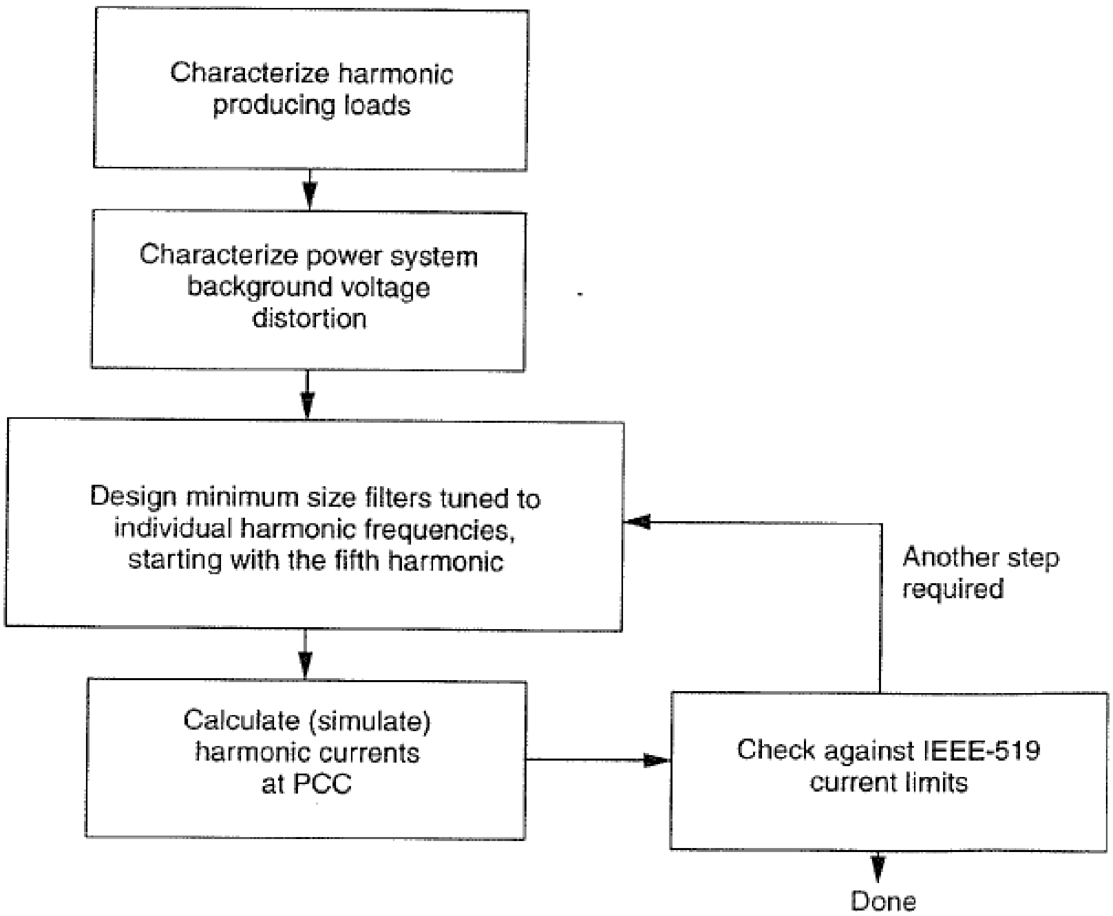

Figure 2.6: General procedures for designing individually tuned filter steps for harmonic control