# 1 Introduction

## 1.1 General

Since last three to four decades, aim of electrical power system is to supply uninterrupted power to the end users maintaining voltage and frequency at the terminals of electrical equipments within tolerable limits. Hence, the most of the research work was carried out to achieve first task. Very less attention is paid on quality of power supply. In early 1980s, power quality became an important issue. Since then, it is a burning issue and gaining an attention to electricity consumers at all levels of usage.

The present power distribution system is usually configured as a three-phase three-wire or four-wire structure featuring a power-limit voltage source with significant source impedance, and an aggregation of various types of loads. Ideally, the system should provide a balanced and pure sinusoidal three-phase voltage of constant amplitude to the loads; and the loads should draw a current from the line with unity power factor, zero harmonics, and balanced phases. To four-wire systems, no excessive neutral current should exist. As a result, the maximum power capacity and efficiency of the energy delivery are achieved, minimum perturbation to other appliances is ensured, and safe operation is warranted. However, with a fast increasing number of applications of industry electronics connected to the distribution systems today, including nonlinear, switching, reactive, single-phase and unbalanced three-phase loads, a complex problem of power quality evolved characterized by the voltage and current harmonics, voltage flickers, unbalances, low power factor. Power electronics has three faces in power distribution: one that introduces valuable, industrial and domestic equipment; second that creates problems; and finally, a third one that helps to solve those problems. The technology based on power electronic devices has considerably improved the quality of modern life allowing the introduction of sophisticated energy-efficient controllable equipment to industry and home. On other hand, those same sensitive technologies are conflicting with each other and increasingly challenging the maintenance of power quality in electric energy delivery, while at the same time costing billions of dollars in lost customer productivity. The term power quality was introduced in 1968 [1]-[2].

In recent years active methods for power quality control have become more attractive compared with passive ones due to their fast response, smaller size, and higher performance. Increased use of these modern power electronics equipments leads to pollution of power distribution systems. This pollution appears in the form of harmonic contamination, unbalance and distortion in the system voltages. On the other hand, the power electronics equipments are highly sensitive to these very irregulations of the supply [3]-[4]. Therefore, maintaining quality of power has emerged as one of the most prominent challenges for the utilities, fixed compensation and resonance with the supply system, which are normally overcome by active filters [5]-[6]. Active filters have been explored in shunt, series and combination of shunt-series configurations to compensate distortions in current and voltage [7]-[10].

But, the main drawback of active filter is that its rating is sometimes very close to load (up to 80%) in some typical applications and thus it becomes a costly option for power quality improvement in a number of situations. In response to these factors, hybrid/composite filters are considered as one of the best options owing to reduced cost, simple design, better control and high reliability compared to other options of power quality improvement [11]-[13].

Utilities encounter harmonic related problems such as higher transformer and line losses, reactive power, required de-rating of distribution equipment, harmonic interactions between customers or between the utility and the load, reduced system stability and reduced safe operating margins. Standard regulation and recommendations of IEEE-519 enforce the limit on the aforementioned power quality problems [14].

## 1.2 Power Quality issues in Power Network

### 1.2.1 Distortion in power networks

As shown in Figure 1.1 the different sources of distortion in power networks can be divided into three classes according to the power level of the equipment and frequency range

[14]: (a) sub-cycle distortion give rise to “flicker” and occur generally at higher power level. They are caused by dynamic loads, such as arc furnaces, mill drives, mine winders, (b) intra-cycle distortion which covers a very wide range of power, and results from the power processing techniques. The distortion generated by these last sources is usually termed as “harmonics”, and (c) high frequency distortion is caused by modern power electronics equipment, due to high rate of current and voltage, which is termed as “interference”.

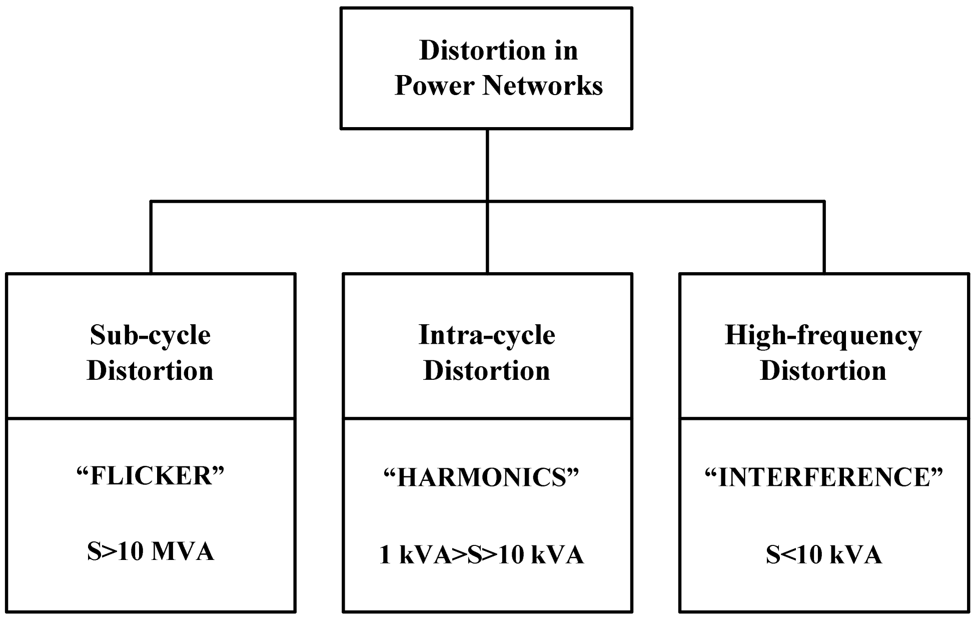


**Figure 1.1 Classification of distortion in power networks**

### 1.2.2 Power Quality issues

The PQ issue is defined as “any occurrence manifested in voltage, current, or frequency deviations that results in equipment overheating, damage devices, EMI related problems etc.” Almost all PQ issues are closely related with power electronics in almost every aspect of commercial, domestic, and industrial application. Equipment using power electronic devise are (a) residential appliances like TVs, PCs etc., business and office equipment like copiers, printers etc., (b) industrial application like electric arc furnaces (EAFs), programmable logic controllers (PLCs), adjustable speed drives (ASDs), rectifiers, inverters, CNC tools and so on. The PQ problem can be detected from one of the following several symptoms depending on the type of issue involved [15]-[16]:

- Lamp flicker
- Unpredictable behavior of installed protection system and nuisance tripping of sensitive loads
- Degradation of meter accuracy
- Failure of capacitors, insulation and fuses due to harmonic resonance
- Overheating of transformers and system components
- Over loaded neutrals
- Increased reactive power demand
- Increased power losses
- Telephone interference
- Frequent blackouts

Power quality issues are commonly classified as [14], [17]:

- Harmonics: Power systems are designed to operate at frequency 50 Hz. However non-linear loads produce currents and voltages with frequencies that are integer multiples of the 50 Hz fundamental frequency. Those higher frequencies are a form of electrical pollution known as power system harmonics. By definition, harmonics are voltage and currents whose frequencies are multiples of the 50 Hz wave form.
- Voltage flicker: Voltage flicker is rapidly occurring voltage sags caused by sudden and large increases in load current. Voltage flicker is most commonly caused by rapidly varying loads that require a large amount of reactive power such as welders, rock-crushers, sawmills, wood chippers, metal shredders, amusement rides, and electric arc furnaces. It can cause visible flicker in lights and cause other processes to shut down or malfunction.
- Voltage sags: Voltage sags are a short-term reduction in voltage (that are 80-85% of normal voltage), and can cause interruptions to sensitive equipment such as adjustable-speed drives, relays, and robots. Sags are most often caused by fuse or breaker operation, motor starting, or capacitor switching. Voltage sags typically are non-repetitive, or repeat only a few times due to re-closer operation. Sags can occur on multiple phases or on a single phase and can be accompanied by voltage swells on other phases.

- Power interruptions: Power interruptions are zero-voltage events that can be caused by weather, equipment malfunction, re-closer operations, or transmission outages. Interruptions can occur on one or more phases and are typically short duration events, the vast majority of power interruptions are less than 30 seconds.
- Power Surges: A power surge takes place when the voltage is 110% or more above normal. The most common cause is heavy electrical equipment being turned off. Under these conditions, computer systems and other high tech equipment can experience flickering lights, equipment shutoff, errors or memory loss.
- Switching transients: Switching transients are extremely rapid voltage peak of up to 20,000 volts with duration of 10 microseconds to 100 microseconds. Switching transients take place in such a short duration that they often do not show up on normal electrical test equipment. They are commonly caused by machinery starting and stopping, arcing faults and static discharge.
- Electrical line noise: Electrical line noise is defined as Radio Frequency Interference (RFI) and Electromagnetic Interference (EMI) and causes unwanted effects in the circuits of computer systems. Sources of the problems include motors, relays, motor control devices, broadcast transmissions, microwave radiation, and distant electrical storms. RFI, EMI and other frequency problems can cause equipment to lock-up, and data error or loss.

## 1.3 Harmonic Standards and Recommended Practices

Different standards that are followed are listed below:

- IEEE 519: Harmonic control Electrical Power Systems.
- IEEE Harmonic‘s working group.
- IEC Norm 555-3, prepared by the International Electrical Commission.
- IEC Power quality standards- numbering system (61000-1-X - Definitions and methodology; 61000-2-X - Environment (e.g. 61000-2-4 is compatibility levels in industrial plants); 61000-3-X - Limits (e.g. 61000-3-4 is limits on harmonics emissions); 61000-4-X - Tests and measurements (e.g. 61000-4-30 is power quality measurements); 61000-5-X - Installation and mitigation; 61000-6-X - Generic

immunity & emissions standards; IEC SC77A: Low frequency EMC Phenomena -- essentially equivalent of "power quality" in American terminology).

- US Military Power Quality Standards (MIL-STD-1399, MIL-STD-704E).
- EN 50 006, —The limitation of disturbances in electricity supply networks caused by domestic and similar appliances equipped with electronic devices, European standard prepared by CENELEC.
- West German Standards VDE 0838 for household appliances, VDE 0160 for converters, and VDE 0712 for fluorescent lamp ballasts.

The institute of Electrical and Electronics Engineers (IEEE) sets limits to the permitted voltage distortion and current distortion at PCC of the utility-plant interface in IEEE 519 [18]. The PCC refers to the location in the network where other customers may be connected. This distinction is important where a distorted load is fed from a dedicated line and the substation represents the lower distortion point of the network where other customers may be connected. In the thesis IEEE 519-1992 standards is taken for comparison with the obtained results from simulation.

The harmonic compensation reduces load outages and susceptibility to harmonic related problems. The standards also set a basis for defining responsibility for correction if a new load is to be connected which could have adverse effects.

Let us define $V_n$ to be the per unit voltage (with respect to the fundamental) of the $n^{th}$ harmonic. Then the individual harmonic components and the THD at the PCC are given in Table 1.1.

**Table 1.1 IEEE 519-1992: Voltage distortion limits**

| **Bus voltage at PCC** | **Individual $V_n$ (per unit)** | **Voltage THD (%)** |
|---|---|---|
| Less than 69 kV | 3.0 | 5.0 |
| Between 69 kV and 161 kV | 1.5 | 2.5 |
| Above 161 kV | 1.0 | 1.5 |

The current distortion limit at the PCC is given in Table 1.2. The current limits are given for odd harmonics. The even harmonics are limited to 25% of the odd harmonics limits.

**Table 1.2 IEEE 519-1992: Current distortion limits (120 V-69 kV)**

| $\frac{I_{SC}}{I_L}$ | $I_{SC}/I_L\ (\%)$ | | | | | $THD\ (\%)$ |
|---|---|---|---|---|---|---|
| | n < 11 | 11 ≤ n < 17 | 17 ≤ n < 23 | 23 ≤ n < 35 | 35 ≤ n | |
| <20 | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20-50 | 7.0 | 2.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50-100 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| 100-1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| >1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |

For all power generation equipment, distortion limits are those with $I_{SC}/I_L$ < 20. Power compensating devices should be designed in such a way that load balancing, reactive power compensation etc. are achieved along with harmonic mitigation as per IEEE-519 standard.

## 1.4 Harmonic Mitigation Techniques

The term electric power quality is defined as any occurrence manifested in voltage, current, or frequency deviations that result in damage, upset, failure, or mal-operation of end-use equipment. In addition, the energy supply to a customer must be continuous and reliable. The quality of the voltage waveform at the entry point of a consumer's premises depends upon the type of loads within those premises, especially in weak ac connection. These loads may be linear and/or non-linear (harmonic producing) in nature. For linear loads, any distortion in the voltage waveform should be the responsibility of the supply authority. On the contrary, for non-linear loads, any deviation from no load to full load voltage waveform is the responsibility of the consumer. The main aim of surveys conducted by various utilities is to find out causes and consequences of power disturbance. The Electrical Power Research Institute (EPRI) is also developing advanced technology which will be useful to utilities in order to improve overall distribution system reliability and also to solve power quality problems [19].

### 1.4.1 Passive Filter

In order to solve the current harmonic related problems, passive filters consisting of capacitors, inductors and damping resistors have been used for a long time. They are used as either to inject a series high impedance to block the harmonic currents, or to create a shunt low impedance path to divert the harmonic currents path. So, passive filters are installed either in shunt connection or series connection. Passive filters in power systems are usually shunt connected, the accepted practice being to connect a number of separate shunt branches across the terminals of the load or the plant. Each of these branches is tuned to one of the dominant harmonics; with a low pas branch added that exhibits low impedance for the remaining higher order harmonics [20]. While shunt connected passive filters carry only a fraction of line current, series filters are subjected to full line current [21]. Moreover, the reactive power compensation capability of shunt connected passive filters and the lower installation cost of shunt filters make series passive filters non preferable. The shunt connected passive filters are classified as band-pass, high pass and C-type filters.

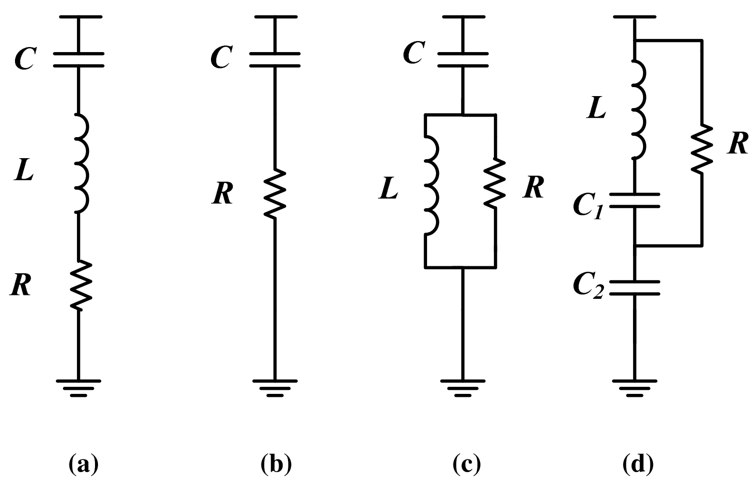


**Figure 1.2 Shunt passive filters (a) single tuned filter (b) first order high-pass filter (c) second order high-pass filter (d) C-type filter**

Among these types, low pass and high pass filters are the most common types due to their design simplicity and low cost [22]. In Figure 1.2 most common types of shunt passive filters and their circuit configuration is represented. One of the most commonly filter type used in industry for harmonic suppression is band-pass filters. Although sufficiently low impedance is obtained at a specific frequency, characteristics of the filter may considerably change with system parameters. A parallel resonance occurs at frequencies lower than the tuned frequency. As a result, undesirable harmonic currents can be magnified which decreases the performance of the overall system [23]. The impedance of a single tuned filter represented in Figure 1.2 is calculated as follows:

$$Z_F = R + j\left[\omega L - \frac{1}{\omega C}\right] \tag{1.1}$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{1.2}$$

$$X_c = \frac{V^2}{kVAr\ Filter} \tag{1.3}$$

Another parameter included in the filter design is the quality factor ($Q_L$) which defines the sharpness of the filter [24]. The mathematical representation of quality factor given in (1.4) shows that the resistance value of the filter is based on $Q_L$ value.

$$Q_L = \frac{\sqrt{L \cdot C}}{R} \tag{1.4}$$

Generally quality factor term is not adjusted to change the filtering characteristic because of the considerable increase in losses [25]. As a result, resistance value is chosen to be the internal resistance value of the filter reactor. Finally, the parallel resonance frequency which occurs lower than the tuning frequency is given by (1.5) where $L_s$ is the corresponding inductance of the source.

$$f_o = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{1}{(L_s + L) \cdot C}} \tag{1.5}$$

Another most commonly used filter type for harmonic suppression is high pass filters. They provide low impedance above a corner frequency. However, the impedance obtained with a high pass filter in its pass-band cannot be as low as an impedance value obtained by a single tuned filter at its tuned frequency. The harmonics of a system can be reduced with a definite percentage above the corner frequency but large rating of the filter results in high losses at fundamental frequency. First order high pass filters represented in Figure 1.2 shows higher losses at fundamental frequency, so first order type high pass filters are rarely used. In opposite to this, second order high pass filters show less losses at fundamental frequency when compared with the first order types.

There exist also C-type filter which is a variation of high pass filter, where the inductance $L$ is replaced with a series $LC$ circuit tuned at fundamental frequency as shown in Figure 1.2. So, the resonant $LC_1$ circuit bypasses the resistance at fundamental frequency thus reduces the losses. C-type filters are generally applied for compensating arc furnaces and cyclo-converters.

Although passive filters have been used for harmonic related problems due to their installation simplicity, low cost and efficiency, there are some limitations, restrictions and undesirable effects on the overall system performance as stated below [26]:

- The system performance is greatly dependent on the supply impedance. Once passive filters are installed, it is not so easy to change their corner frequency or size in the vicinity of change in system conditions.
- Resonance may occur between the source impedance and the filter impedance which results in amplification of harmonics.
- Passive filters have fixed compensation characteristics.
- Aging, deterioration and temperature effects may change the tolerances of the filter components. Therefore, passive filters may result in detuning problem.

As a result, the preceding disadvantages of passive filters have increased theattention on active power filter solutions.

### 1.4.2 Active Filters

The first attempts to reduce harmonies without the use of conventional passive filters, were made by B. Bird at al. [27] and H. Sasaki et al. [28] in late 1970s. Their design proposed changing the waveform of the current drawn by the load by injecting a third harmonic current, displaced in phase, into the converter itself. With this method however it is impossible to fully eliminate more than one harmonic.

In 1982, an 800 kVA current source inverter based active power filter was implemented by using GTO thyristors for the first time in the world [29]. For the proceeding 20 years, the control strategies of active power filters have been developed [30].

It was Arnetani's idea to expand the current injection method by proposing a technique to eliminate multiple harmonics [31]-[32]. According to this theory, an active control circuit could be used to precisely shape the injected current. Ideally, this current would contain harmonic components of opposing phase, thus the harmonics would be neutralized, and only the fundamental component would remain. Despite the promising theoretical concept, Arnetani was not successful in producing a practical circuit capable of creating a precise current. The total harmonic distortion was reduced, but single harmonics were not completely eliminated.

Over the last ten to fifteen years remarkable progress in capacity and switching performance of devices such as bipolar transistors (BJT), gate turn-off thyristors (GTO) and insulated gate bipolar transistors (IGBT), has spurred in the study of active power filters for harmonic compensation. There exist several active power filter types in the literature in accordance with their converter types, circuit topologies and number of phases [10].

### 1.4.3 Classification of active filters

Active power filters are divided into two groups according to their converter types used in the development of the power circuit, as Current Source Converter (CSC) and Voltage Source Converter (VSC) type active power filters. The main difference between these two topologies is the energy storage element at the DC link side of the converter.

In CSC type APF, the power circuit acts as a non-sinusoidal current source with a DC link inductor ($L_{dc}$) as an energy storage element as shown in Figure 1.3 (a). The converter is formed by six controllable semiconductor switches and series diodes to each switch, in order to obtain reverse voltage blocking capability. The connection of APF to the AC mains side is made by a second order low pass filter formed by $L_f$ and $C_f$. The second order filter suppresses the high frequency switching ripples formed by APF. However, it amplifies the harmonic contents around the resonance frequency of the filter. In order to damp the amplification due to the second order low pass filter, an appropriate current control method or damping resistors are used for CSC based APFs [33].

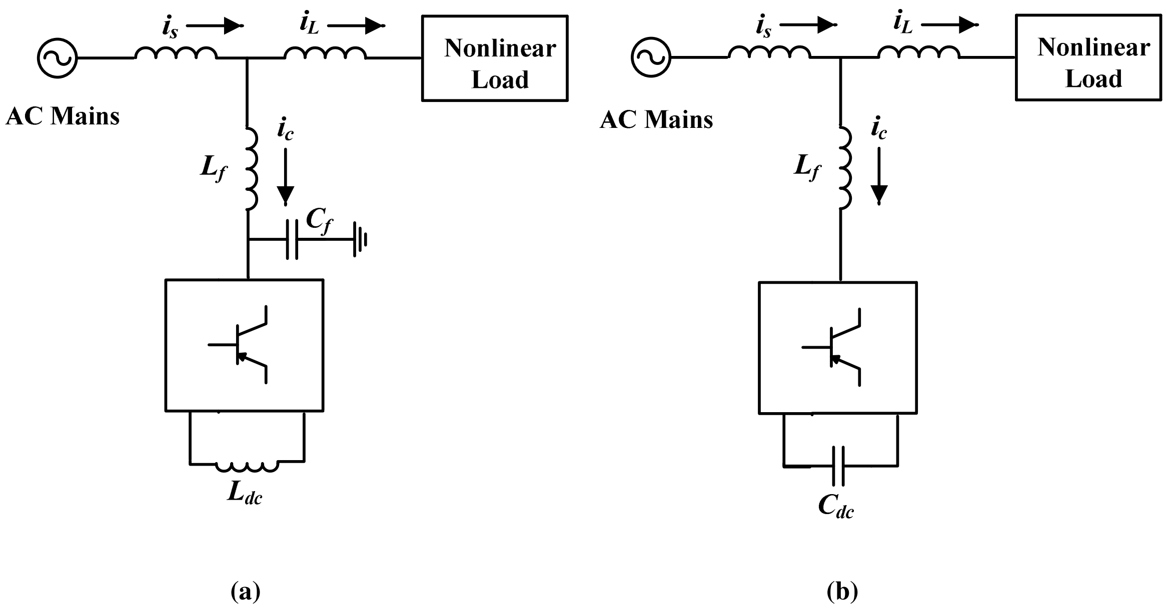


**Figure 1.3 APF converter classification (a) current source converter type (b) voltage source converter type**

In VSC type APF, the power circuit has a DC link capacitor ($C_{dc}$) as an energy storage element as shown in Figure 1.3 (b). The inverter consists of six controllable semiconductor switches each of which should support the maximum filter current injected to the mains side. The APF is connected to the mains side through $L_f$ to provide the controllability of active power filter current. The filter inductor also acts as a first order passive filter to suppress high frequency ripples generated by the converter.

For both type of APFs, the practical solution for the controllable semiconductor device selection is, choosing an IGBT which is superior to GTOs if the allowable switching frequency, conduction/switching losses and power ranges of these devices are considered together. However, available IGBT modules, which are always fabricated with their antiparallel diodes in the market, are more convenient for voltage source type active power filters [34]. Therefore, for current source converter topology additional series diodes are required to obtain a reverse voltage blocking capability which increases the cost, size and design level of the CSC type APFs. Moreover, using a reactor as a storage element at the DC link side, results in higher losses compared to voltage source converter type APFs [35]. Although CSC type active power filters present direct current control capability, high reliability and fast response, voltage source type active power filters have become more popular and preferable in industrial applications due to their small size, lower initial cost and higher efficiencies.

Active power filters are also classified as shunt (parallel) APF, series APF, unified power quality conditioners (UPQC) and hybrid filters according to their topologies [36]. Shunt APFs are widely used for eliminating load current harmonics and reactive power compensation. Both of the filters represented in Figure 1.4 are shunt active power filters.

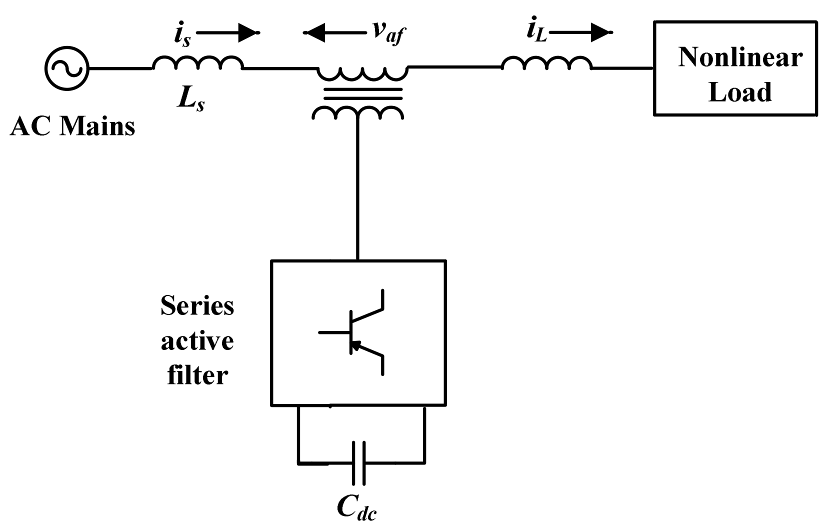


**Figure 1.4 Series active power filter**

Figure 1.4 shows the connection of a series APF which is usually used for eliminating voltage harmonics and regulating voltage at the load or line terminal [37]. Moreover, in many cases series active power filters are combined with shunt passive filters in order to decrease the rated power of the APF [38].

Another type of APF which combine the series and shunt active filters is developed as an UPQC.

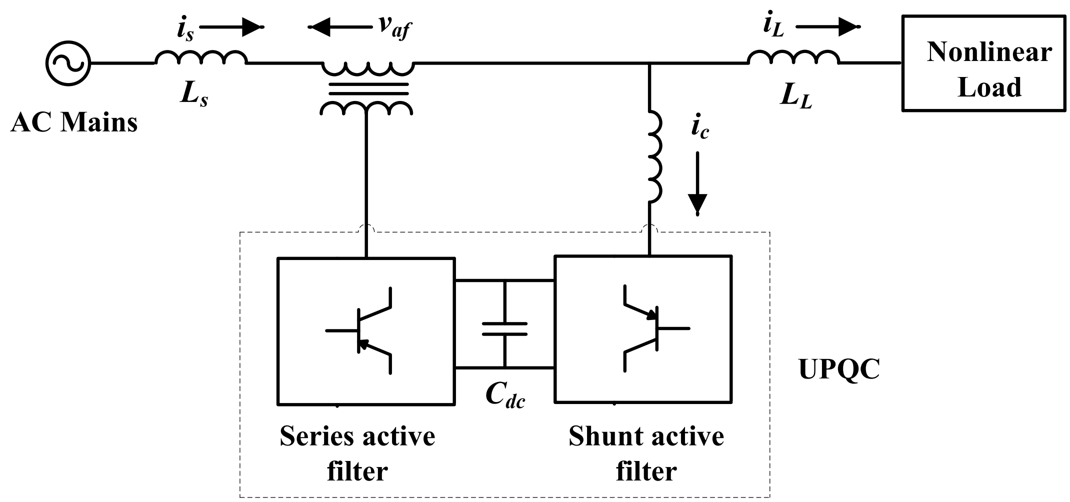


**Figure 1.5 Unified power quality conditioner**

As indicated in Figure 1.5, the shunt connected part is located at the load side and the series part is located at the source side. Since the topology is the combination of a series APF and shunt APF with a common DC link, it can perform voltage harmonic filtering, voltage regulation as well as current harmonic filtering and reactive power compensation. Although UPQC is an ideal solution for most of the power quality problems, the complexity of their control strategies and the higher cost of their power stages confines their applications.

### 1.4.4 Hybrid/composite filter

Although an increased attention has been paid to the active power filters, some problems about APFs have also been discovered as the active power filters are put into practical usage. For large power applications, it is difficult to implement a low loss and a low cost PWM converter. Moreover, currents injected by APF may be absorbed by passive filters which are previously installed into the AC system. As a result, various hybrid filter topologies which combine the traditional harmonic filtering method of passive filters, and active power filters have been developed.

In 1988, a series active filter connected via a matching transformer was combined with a shunt connected passive filters as shown in Figure 1.6 [39]-[40].

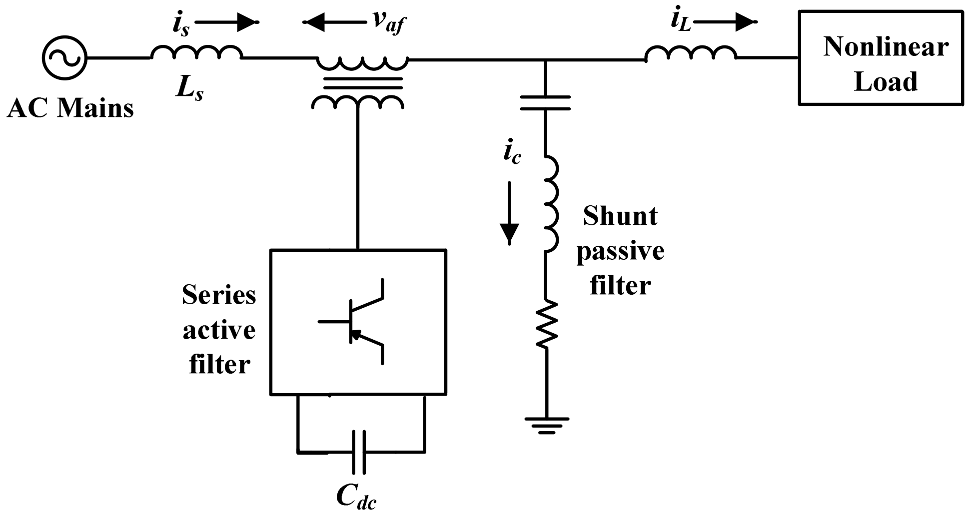


**Figure 1.6 Combination of series active filter and shunt passive filter**

In this topology active power filter does not compensate the load harmonic content but it operates as a harmonic isolator between the source and the load [39]-[44].

So, performing as an isolator instead of performing a full compensation reduces the rating of the series active filter. However, in this topology the protection of the APF is crucial as it is connected to the supply in series. The series connection of APF decreases the reliability of this topology.

Another hybrid filter topology proposed in 1990 was formed by connecting active power filter in series with the passive filter as shown in Figure 1.7. In the series connection, three current transformers were used to match the VA rating of the APF and the passive filter. Parallel and series resonance risk of the passive filter is damped by utilizing the active filter. The compensation principle of the system is investigated deeply in [45]-[48].

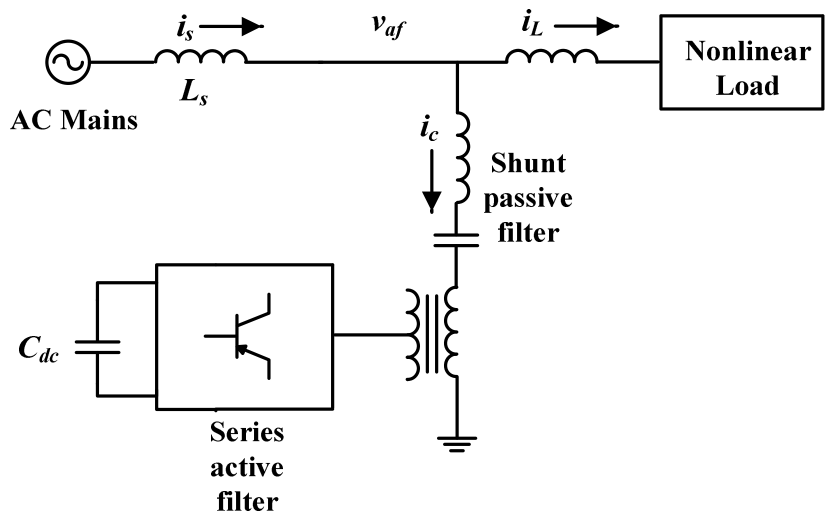


**Figure 1.7 Series APF connected in series with the shunt passive filter**

Both of the topologies represented in Figure 1.6 and Figure 1.7 include an active power filter, passive filter and a three phase transformer. Comparison between their compensation performance, filtering characteristics and reliabilities can be found in [49].

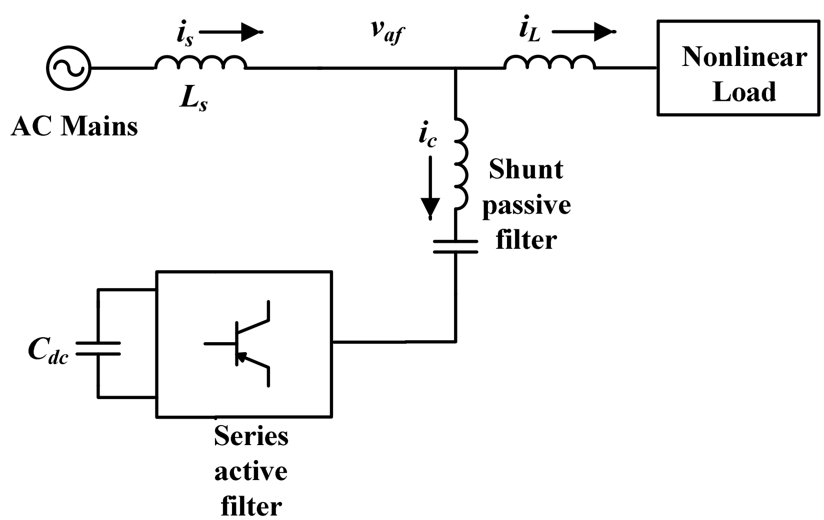


**Figure 1.8 Transformer less shunt hybrid power filter**

Existence of a transformer in the circuit topology inevitably increases the cost of the system which makes the topology non preferable. As a result, a shunt hybrid power filter topology named transformer-less hybrid filter was proposed which uses a single $LC$ passive filter for each phase and a small rated voltage source converter based active power filter [50]. The series connection between the $LC$ passive filter and the voltage source converter is completed without using any matching transformer as shown in Figure 1.8.

## 1.5 Problem Statement

### 1.5.1 Scope of this Thesis

In recent years, voltage and current harmonics have become a serious problem both in transmission and distribution systems, due to the widespread usage of non-linear industrial load such as diode/thyristors rectifiers, electric arc furnaces (EAF) and motor drives, etc. Increased use of modern power electronics equipments leads to pollution of power distribution systems. This pollution appears in the form of harmonic contamination, unbalance and distortion in the system voltages. Harmonic voltage and harmonic current thus injected in the utility by non-linear loads, cause power quality deterioration at PCC. On the other hand, the power electronics equipments connected are highly sensitive to these very irregulations of the supply [3], [51].

Harmonic distortion in power distribution systems can be suppressed using two approaches namely, passive and active filtering. To reduce such harmonics, PFsare commonly employed. With diverse applications involving reactive power together with harmonic compensation; passive filters are found suitable due to low cost, simplicity, reliability and control-less operation [4]. Although simple and least expensive, the use passive elements do not always respond correctly to the dynamics of the power distribution systems and inherits several shortcomings [52].

In recent years active methods for power quality control have become more attractive compared with passive ones due to their fast response, smaller size, and higher performance. Therefore, maintaining quality of power has emerged as one of the most prominent challenges for the utilities, fixed compensation and resonance with the supply system, which are normally overcome by active filters. In order to obtain a better performance than those of the conventional passive filter solutions, APFs have been worked on, developed and simulated. Among various configurations listed in the literature, conventional shunt connected voltage source active power filter is widely used in industrial applications [53].

Active filters have been explored in shunt, series and combination of shunt & series configurations to compensate distortions in current and voltage [7]-[10]. Unfortunately, for large power applications, the losses and the rating of the APF increase considerably. The main drawback of active filter is that its rating is sometimes very close to load (up to 80%) in some typical applications, such as EAF distribution networks, and thus it becomes a costly option for power quality improvement in a number of situations. In response to these factors, CF is proposed which consists of a small rated series active power filter and conventional shunt passive filter. The composite filters is one of the best options owing to reduced size cost (about 10% of the load size), reduced cost, simple design, better control and high reliability compared to other options of power quality improvement [11], [13], [54]-[55].It has the capability of reducing voltage and current harmonics of voltage type harmonic producing loads-such as an electric arc furnace at a reasonable cost.

### 1.5.2 Contribution of this Thesis

This thesis presents design, analysis and simulation of a CF for targeting the power quality issues in distribution network. The distribution network consists of non-linear loads such as Electric arc furnaces, DC Rectifiers, DC drives, etc. The increasing popularity of EAF in metallurgical industries to melt scrap causes significant impacts on power system and electrical power quality. EAF is one of responsible source for deteriorating the power quality in the network by introducing odd & even harmonics, propagating voltage flickers and causing voltage unbalance [56]-[58]. Hence an EAF is chosen as a typical industrial non-linear load to demonstrate power quality problems. An effort is made to propose EAF model to demonstrate typical EAF with its harmonic, voltage flicker and unbalanced behavior together using combination of Exponential and Hyperbolic V-I Characteristics [58]. Performance of the proposed EAF model is analyzed and compared with that of existing Cassie-Mayr EAF Model [59]. Design and simulation of composite filter for power quality improvement of EAF distribution network is presented. Various control strategies for series active filter control are surveyed in the literature [60]-[63]. Control strategy based on the dual formulation of the electric power vectorial theory for non-sinusoidal and unbalanced voltage is proposed. In [62] the same theory is implemented for balance and resistive load. Here an attempt is made to apply the same theory for unbalanced and non-sinusoidal voltage conditions for randomly varying load as an EAF. Performance of the composite filter is evaluated in 3-Φ, 3-wire EAF distribution network under various load voltage conditions by simulation.

The motivations behind the work presented in this thesis are:

- To propose novel EAF model to demonstrate typical PQ issues of distribution network such as harmonics, voltage flicker and unbalanced behavior together. To compare performance characteristics of the proposed EAF model with that of existing Cassie-Mayr EAF Model to validate the same. To simulate typical distribution network along with the EAF along with other auxiliaries to analyze the distribution network from power quality point of view keeping IEEE 519-92 Standards in view.
- To design passive filter for power quality improvement of the distribution network. To design series active filter with appropriate fast response control technique for improving the passive filter compensation characteristics without depending on the system impedance and avoiding the series/shunt resonance problems. The reference signal of the compensation voltage needed by the series APF is to be obtained by detecting both source current and load voltage. Main task is to combine and to simulate both the filters and thus to form composite filter to solve PQ issue of the distribution network with overall reducing rating of the filter.
- To construct state-space averaging model of proposed composite filter to analyze system stability by proposed control strategy.
- To carry out simulation of the distribution network with the composite power filter to validate its performance. The simulations are carried out in MATLAB environment using SIMULINK and power system block set toolboxes.
- To analyze and to compare performance of the composite filter with that of the passive filter for various cycles of EAF connected in distribution network.
- To investigate and to evaluate composite filter performance in 3-Φ, 3-wire distribution network under various load conditions-refining cycle, melting cycle considering sinusoidal flicker, melting cycle considering random flicker and unbalance load voltages.

The proposed composite filter performs satisfactorily for various load conditions such as refining cycle, melting cycle and unbalance with overall reducing rating of the filter. The present work is likely to contribute significantly to the area of power quality enhancement.

### 1.5.3 Outline of this Thesis

A brief description of the research work reported in the thesis is given below:

**Chapter 1**: In this chapter the background of power quality issues, power quality problems and the available solutions are discussed briefly. Also certain active power filters topologies have been briefly discussed. Moreover, this chapter includes the brief details of references which have been referred for this thesis work.

**Chapter 2**: In this chapter, harmonic survey carried out for various nonlinear loads is displayed and discussed. EAF operation is studied. EAF modeling and simulation is carried out. Performance characteristics for various EAF operational cycles are compared with the existing EAF model.

**Chapter 3**: In this chapter basic compensation principle for passive filter is studied. The passive filter design constraints are discussed. Design of the passive filter is carried out.

**Chapter 4**: In this chapter, basic compensation principle of composite filter is studied. Various control schemes are studied in brief. New control scheme is designed for the functioning of the composite filter. Mathematical model is derived for the composite filter. System stability analysis is done to confirm satisfactory functioning of the proposed composite filter.

**Chapter 5**: In this chapter, application of composite filter for various power quality issues in the EAF distribution network is evaluated by simulation. At first, evaluation of passive filter performance is carried out for various EAF cycles-refining cycle, melting cycle considering sinusoidal flicker, melting cycle considering random flicker and unbalance load voltages. Secondly, performance evaluation of series active filter along with the passive filter-composite filter-performance is carried out for various EAF cycles.

**Chapter 6**: This chapter gives the main outcomes of the thesis and scope of the future works.