CHAPTER 3

ELECTRIC POWER QUALITY

3.1 INTRODUCTION

The planning, design, and operation of industrial and commercial power systems require several studies to assist in the evaluation of the initial and future system performance, system reliability, safety and the ability to grow with production and operating requirements. The conventional ac electric power systems are designed to operate with sinusoidal voltages and currents. However, nonlinear loads and electronically switched loads will distort steady state ac voltage and current waveforms. Periodically distorted waveforms can be studied by examining the harmonic components of the waveforms. Reducing voltage and current waveform distortions to acceptable levels has been a problem in power system design from the early days of alternating current.

3.2 POWER QUALITY

It is the objective of the electric utility to supply its customers with a sinusoidal voltage of fairly constant magnitude and frequency. The generators that produce the electric power generate a very close approximation to a sinusoidal signal. However there are loads and devices on the system which have nonlinear characteristics and result in harmonic distortion of both the voltage and current signals. As more non-linear loads are introduced within a facility, these waveforms get more distorted. There
are different approaches for harmonic analysis of different non-linear loads. The voltage distortion caused by the harmonic producing load is a function of both the system impedance and the amount of harmonic current injected.

The utilization of electrical energy is relying more on the supply of power with controllable frequency and voltages while its generation and transmission take place at nominally constant levels. The discrepancy therefore, requires some form of power conditioning or conversion, normally implemented by power electronic circuitry that distorts voltage and current waveforms. A harmonic producing load can affect the neighboring sensitive loads if significant voltage distortion is caused. The voltage distortion caused by the harmonic producing load is a function of both the system impedance and the amount of harmonic current injected. The mere fact that a given load current is distorted does not always mean there will be undue adverse effects on other power consumers.

If the system impedance is low, the voltage distortion is usually negligible in the absence of harmonic resonance. However, if harmonic resonance prevails, intolerable harmonic voltage and currents are likely to result. In a practical power system, the frequency and voltages are deviated from their designated values. The nonlinear characteristics of many system components produce system harmonics which may degrade the signal transmission in nearby telephone lines. The power quality problems are surging with the proliferation of nonlinear devices which draw non-sinusoidal current waveforms when supplied by a sinusoidal voltage source. When these devices are present in an electric power system, they cause harmonic distortion of voltages and currents. Individually, single-phase non-linear load may not pose serious harmonic problem but large concentrations of these loads have the potential to raise harmonic voltages and currents to unacceptable high levels which results in increased neutral currents in four
wire system, over heating of distribution system components and mechanical oscillations in generators and motors. Other undesirable effects are capacitor and insulation failure due to harmonic resonance, unpredictable behavior of installed protection systems, rapid voltage fluctuations and overheating of transformer.

Power Quality is defined as “any power problem manifested in voltage, current, and/or frequency deviations that results in the failure and/or mal-operation of end user’s equipment”. Poor power quality may result either from transient conditions developing in the power circuit or from the installation of non-linear loads. Due to the increasing use of loads sensitive to power quality, e.g. computers, industrial drives, communications and medical equipment, the issue of power quality has gained renewed interest over the last two decades. Nowadays, power quality is an even more complex problem than in the past because the new loads are not only sensitive to power quality but also responsible for affecting adversely the quality of power supply.

3.2.1 Power Quality Problems

Following are the core terms and definitions that are used with power quality.

Voltage Sag - A voltage sag is a reduction in the RMS voltage in the range of 0.1 to 0.9 p.u. (retained) for duration greater than half a main cycle and less than 1 minute often referred to as ‘sag’. It is normally caused by faults, increased load demand and transitional events such as large motor starting.

Voltage Swell - A voltage swell is an increase in the RMS voltage in the range of 1.1 to 1.8 p.u. for a duration greater than half a main cycle and
less than 1 minute. It is normally caused by system faults, load switching and capacitor switching.

**Voltage Interruption** - A voltage interruption is the complete loss of electric voltage. Interruptions can be short duration (lasting less than 2 minutes) or long duration. A disconnection of electricity causes an interruption usually by the opening of a circuit breaker, line recloser, or fuse.

**Voltage Flicker** - A waveform may exhibit voltage flicker if its waveform amplitude is modulated at frequencies less than 25 Hz, which the human eye can detect as a variation in the lamp intensity of a standard bulb. Voltage flicker is caused by an arcing condition on the power system. Flicker problems can be corrected with the installation of filters, static VAR, or distribution static compensators.

**Voltage Notches** - Periodic transients occurring within each cycle as a result of the phase-to-phase short circuits. It is normally caused by caused by the commutation process in a.c.-d.c. converters.

**Voltage Unbalance** – A situation, in which either the voltages of a three phase voltage source are not identical in magnitude, or the phase differences between them are not 120 electrical degrees, or both.

**Frequency Deviation** - It is a variation in frequency from the nominal supply frequency above/below a predetermined level, normally ± 0.1%.

**Harmonics** - A harmonic of an electrical signal is defined as the content of the signal whose frequency is an integer multiple of the fundamental system frequency. That is, the third order harmonic will have a frequency of 3 times the fundamental frequency. Figure 3.1 Shows the
waveform with symmetrical harmonic components. It is a steady state periodic phenomenon that produces continuous distortion in voltage and current waveform. It is normally caused by saturable devices, power electronics devices and non linear consumer loads. Depending on the type of loads, subharmonics or interharmonics are also generated.

![Waveform with Harmonics](image)

**Figure 3.1 Example of voltage waveforms showing harmonics**

Harmonics are carried through the system from the source and can nearly double the amount of current on the neutral conductor in three phase four wire distribution systems. Overall electrical system performance and power quality is affected by the introduction of harmonics, such as Overheating of Transformers, Capacitors and Motors, Mal-operation Relays and Circuit Breakers, Communication Interference Problems, Unreliable operation of Electronic Equipment etc. Current Harmonics affect the system by loading the distribution system as the waveforms of the other frequencies use up capacity without contributing any power to the load. They also contribute to $I^2R$ losses in the system. Voltage harmonics are caused by the
current harmonics which distort the voltage waveform. These voltage harmonics affect the entire system not just the loads which are causing them. Their impact depends on the distance of the load causing the harmonics from the power source. In industrial facilities, adjustable-speed drives and other power electronic loads can generate significant amounts of harmonics. Solutions to problems caused by harmonic distortion include installing active or passive filters at the load or bus, or taking advantage of transformer connections that enable cancellation of zero-sequence components.

**Transients** – Voltage disturbances shorter than sags or swells, which are caused by sudden changes in the power systems. Transient disturbances are undesirable momentary deviation of the supply voltage or load current and caused by the injection of energy by switching or by lightning.

### 3.2.2 Power Quality Problems and Their Impacts

Poor power factors are responsible for a substantial increase in the currents flowing in power supply systems and consumer installations, causing a drop in the feeder voltage and increasing the losses. Harmonic currents can cause additional losses and voltage waveform distortions, and so cause poor power quality. Voltage and current harmonics have undesirable effects on power system components and operation. In some instances, interaction between the harmonics and power system parameters can cause harmonics to amplify with severe consequences.

Also, harmonics can lead to improper operation of protective devices, such as relays and fuses. Harmonic currents, particularly of the third order, cause overheating of transformers and neutral conductors. Consumers and distribution systems are sometimes forced to derate their transformers because of the heating effects of harmonic currents.
Neutral conductors of supply systems and installations have the same cross-sectional area as phase conductors. There is already evidence of the use of neutral conductors of larger cross-section in newer commercial installations to take account of the increased third harmonic currents. The retrospective installation of such larger neutral conductors in existing networks would result in increased costs, including significant increase in demand for copper and aluminum. Also, the flow of harmonic currents in power supply systems may affect telephone communication. Harmonic voltages in excess of the recommended limits can result in distributors having to replace their transformers, switchgear and lines at prohibitive cost. The resulting networks would be inefficient as harmonic distortion represents reactive power flow.

Due to the presence of unbalanced loads, voltages become unbalanced and negative and zero sequence voltages are generated, which if applied to an induction motor may give rise to extra losses and sometimes torque pulsation and reduction. The voltage quality and current quality affect each other by mutual interaction. Thus, both suppliers and consumers of electricity are responsible for maintaining the power quality parameters within the standards limits.

3.2.3 Power Quality Standard

Standards provide information and specifications on voltage level, regulation and quality intends to maintain and deliver to its customers. Standards are needed to achieve coordination between the characteristics the power supply system and the requirements of the end use equipment. This is the role of power quality standards. The methods have been established for measuring these phenomena and in some cases defining limits for satisfactory performance of both the power system and connected equipment. In the international community, both IEEE and IEC have created a group of
standards that addresses these issues from a variety of perspectives (Ghosh et al 2002).

### 3.3 STANDARDS OF VOLTAGE HARMONICS

The most common international standards setting limits on voltage quality are described below.

#### 3.3.1 IEEE Standards

Short duration voltage variations include variations in the fundamental frequency voltage that last less than one minute according to IEEE Standard 1159 and IEC definitions. These variations are best characterized by plots of the rms voltage versus time but it is often sufficient to describe them by a voltage magnitude and a duration that the voltage is outside of specified thresholds. Voltage variations can be a momentary low voltage (voltage sag), high voltage (voltage swell) or loss of voltage (interruption).

IEEE Standard 1159 specifies durations for instantaneous, momentary and temporary disturbances. In IEEE, standards work under way to define indices for characterizing voltage sag performance is being coordinated by IEEE P1564. The most common index used is System Average RMS Frequency Index (SARFIx). This index represents the average number of voltage sags experienced by an end user each year with a specified characteristic. The SARFI index and other alternatives for describing voltage sag performance are being formalized in the IEEE Standard 1564.
3.3.2 IEC Electromagnetic Compatibility Standards

A comprehensive framework of standards on electromagnetic compatibility is under development within the International Electro technical Commission (IEC). Electromagnetic compatibility (EMC) is defined as: the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment. There are two aspects to EMC. A piece of equipment should be able to operate normally in its environment and it should not pollute the environment too much. In EMC terms: immunity and emission. Immunity standards define the minimum level of electromagnetic disturbance that a piece of equipment shall be able to withstand.

The basic immunity standard IEC-61000-4-1 gives four classes of equipment performance: (i) Normal performance within the specification limits, (ii) Temporary degradation or loss of function which is self-recoverable, (iii) Temporary degradation or loss of function which requires operator intervention or system reset and (iv) Degradation or loss of function which is not recoverable due to damage of equipment, components or software or loss of data.

The maximum amount of electromagnetic disturbance that a piece of equipment is allowed to produce is defined in emission standards. Within the existing IEC standards, emission limits exist for current harmonics IEC 61000-3-2 and 61000-3-6 and for voltage fluctuations IEC 61000-3-3, 61000-3-5 and 61000-3-7. Most power quality phenomena are not due to equipment emission but due to operational actions or faults in the power system. As the EMC standards only apply to equipment, there are no "emission limits" for the power system.
3.3.3 The European Voltage Characteristics Standard

EN 50160 dealing with requirements concerning the supplier’s side characterizes voltage parameters of electrical energy in public distribution systems. On the user’s side, it is the quality of power available to the user’s equipment that is important. Correct equipment operation requires the level of electromagnetic influence on equipment to be maintained below certain limits. Equipment is influenced by disturbances on the supply and by other equipment in the installation, as well as itself influencing the supply. These problems are summarized in the EN61000 series of EMC standards, in which limits of conducted disturbances are characterized.

European standard 50160 gives the main characteristics of the voltage at the customer's supply terminals in public low voltage and medium voltage networks under normal operating conditions. Some disturbances are just mentioned below, for others a wide range of typical values are given and for some disturbances actual voltage characteristics are given. Standard EN 50160 gives limits for some variations. For each of these variations the value is given which shall not be exceeded for 95% of the time. The measurement should be performed with a certain averaging window. The length of this window is 10 minutes for most variations, thus very short time scales are not considered in the standard.

3.4 STANDARDS OF CURRENT HARMONICS

The most common international standards setting limits on harmonics are described in the following subsections.
3.4.1 IEEE Standards

The IEEE standard 519-1992 limits the level of harmonics at the customer service entrance or Point of Common Coupling (PCC). With this approach the customer’s current distortion is limited based on relative size of the load and the power supplier’s voltage distortion based on the voltage level.

IEEE 519 and IEC 1000-3-2 apply different philosophies, which effectively limit harmonics at different locations. IEEE 519 limits harmonics primarily at the service entrance while IEC 1000-3-2 is applied at the terminals of end-user equipment. Therefore, IEC limits will tend to reduce harmonic-related losses in an industrial plant wiring, while IEEE harmonic limits are designed to prevent interactions between neighbors and the power system.

The current harmonic limits given in IEEE Std.519-1995. For the current harmonic limits, Total Demand Distortion (TDD) calculation is used. THD calculation compares the momentary measured harmonics with the momentary measured fundamental component. TDD calculation compares the momentary (but steady-state) measured harmonics with the maximum demand current, which is not a momentary number at all. The difference between TDD and THD is important because it prevents a user from being unfairly penalized for harmonics during periods of light load (only the harmonic polluting loads are running).

During periods of light load it can appear that harmonic levels have increased in terms of THD (Total Harmonic Distortion) even though the actual current harmonics in amperes stayed the same. The Institute of Electrical and Electronic Engineers has drafted a Recommended Practice (IEEE Std.519,
1995) that provides limits for harmonic distortion. IEEE Std. 519 limits the current harmonics that can be drawn from the power system.

### 3.4.2 The International Electrotechnical Commission

EN 61000-3-2 Harmonic Emissions standards were first published as IEC 55-2 1982 and applied only to household appliances. It was revised and reissued in 1987 and 1995 with the applicability expanded to include all equipment with input current 16A per phase. The objective of EN 61000-3-2 (harmonics) is to test the equipment under the conditions that will produce the maximum harmonic amplitudes under normal operating conditions for each harmonic component. To establish limits for similar types of harmonics current distortion, equipment under test must be categorized in one of the following four classes:

**CLASS-A** : Balanced three-phase equipment and all other equipment except that stated in one of the remaining three classes.

**CLASS-B** : Portable electrical tools, which are hand held during normal operation and used for a short time only (few minutes)

**CLASS-C** : Lighting equipment including dimming devices.

**CLASS-D** : Equipment having an input current with special wave shape (e.g. equipment with off-line capacitor-rectifier AC input circuitry and switch mode power supplies) and an active input power 600W. Additional harmonic current testing, measurement techniques and instrumentation guidelines for these standards are covered in IEC 1000-4-7.
IEC has a standard, IEC 61000-3-2, that defines current harmonic limits for devices with a current rating less than or equal to 16A (Ingram et al 1998). This has been ratified as a Harmonized European Standard, EN 61000-3-2 and as a British Standard (BS EN 61000-3-2, 1995). Unlike its predecessor (IEC 555-2, 1982), no distinction is made between domestic and professional equipment, rack mounted and three phase equipment is specifically mentioned in BS EN 61000-3-2. For future, new standards and/or technical reports are currently being drafted.

For example, limits for interharmonics (IEC 61000-3-9) and emission limits for frequency range 2-9 kHz (IEC 61000-3-10) will apply to equipment with input current lower than 16 A. In addition, IEC 61000-3-14 will assess emission limits for the connection of disturbing installations to low voltage power systems. The limits specified in IEC for low voltage systems allow a THD of 8% and include limits for individual harmonic components, which decrease with frequency.

3.4.3 Energy Networks Association Engineering

The intention of the Energy Networks Association Recommendation G5/4, first published in 2001, was to try to ensure that the levels of harmonics in the Public Electricity Supply do not constitute a problem for other users of that supply. This is a primary function of EMC Management and Regulation and it forms part of the Distribution Code which is a statutory requirement placed on the UK Electricity Supply Industry. In addition, under legislation the supply industry has a duty to meet BS EN 50160, voltage characteristics of electricity supplied by public distribution systems, which includes magnitudes of harmonic voltage distortion among other parameters.
To facilitate the connection of non-linear equipment, G5/4-1 specifies current harmonic emission limits with the intention of limiting the overall voltage distortion to no more than the network planning levels specified in ER G5/4-1, which in turn are set to achieve compatibility. G5/4-1 identifies consumers by their point of common coupling (PCC) to the supply and applies limits at that point. G5/4-1 therefore applies to every consumer connected to the Public Electricity Supply, including domestic, commercial, shop and office consumers and industrial users. It forms part of the consumer’s agreement to connect and it is the responsibility of the individual consumer to ensure that the appropriate procedures to agree connection of new loads are followed.

It is also very important that the consumer understands the responsibilities placed on him by the supply utilities to avoid the possibility of having to implement costly remedial measures in the event of a problem. It is important to understand that G5/4-1 is effectively an “Installation Standard” and applies to the total harmonic generating equipment installed by a consumer. It is not a product or equipment standard and no single items of equipment can be said to comply.

3.5 POWER QUALITY MONITORING

Generally, the causes of power quality problems are complex and difficult to detect. To be able to solve power quality problems comprehensive knowledge of power quality issues is necessary. Two ways of obtaining information about the power quality are monitoring and stochastic prediction.

Monitoring is still the method most commonly used, but the trust in prediction techniques is likely to grow. The only way of getting an accurate picture of power quality is still by means of measuring. Solving power quality problems depends on obtaining meaningful data at the optimum location or
locations and within an appropriate time frame. In order to acquire useful and relevant data, instruments most suited for a particular application should be utilised. Using inappropriate or inadequate instruments can result in unrecognised power quality problems.

### 3.6 MITIGATING TECHNIQUES

The power quality problems can be viewed as the difference between the quality of power supplied and the quality of the power required for reliable operation of the load equipment. The mitigation device and point of connection is chosen according to its economic feasibility and reliability that is required. Innovative solutions employing power electronics are often applied when rapid response is essential for suppressing or counteracting the disturbances, while conventional devices are well suited for steady-state or general regulation.

There are two general approaches to mitigate the PQ problems. One, named as load conditioning, is to ensure that the process equipment is less sensitive to disturbances, allowing it to ride through the disturbances. The other is to install a line conditioning device that suppresses or counteracts the disturbances. Commercially available mitigation devices tend to protect against a group of PQ disturbances. Mitigation devices vary in size and can be installed at all voltage levels of a power system (high, medium and low voltages). Custom Power is a concept based on the use of power electronic controllers in the distribution system to supply value-added, reliable and high quality power to its customers.

CP devices or controllers include APFs and DVRs that have the ability to perform harmonic mitigation and voltage compensation functions in a distribution system to improve reliability and/or power quality. For simple load applications, selection of the proper mitigation device is fairly
straightforward. However, in large systems with many loads all aspects of the power system must be considered carefully. Also, when dealing with large systems it is necessary to know the different sensitive load requirements. Consideration must also be given to the potential interaction between mitigation devices, connected loads and the power system.

Improving the load equipment immunity to disturbances and adding appropriate correcting devices and control so that the equipment does not draw reactive and harmonic currents from the utility are solutions applicable only to new equipment, and hence they are local solutions. These solutions cannot solve the problem of polluting and sensitive load equipments that already exist, and their replacement and redesign are not always economically feasible. Also, incorporating additional modules that will improve the power factor and compensate for harmonic currents in very small equipment can considerably increase their overall cost and may not be a viable solution for customers. However, the power quality considerations should be kept in mind while designing new equipment.

Considering these drawbacks of local solutions, other more global strategies have to be applied. Power quality of an entire plant or a group of customers can be improved by inserting the independent compensating devices at the point of utility customer interface or other relevant points in the distribution grid. In this case the necessity of designing the individual equipments in conformity with power quality standards can be relaxed, and the polluting equipment that already existed is not a problem.

Power quality problems are as old as power distribution through feeders, and the partial mitigation of these problems existed even before the advent of power electronic controllers. These are so called conventional mitigation techniques. For example, to compensate for the load current harmonics, passive filters based on inductors and capacitors were used and are
still used in many power transmission and distribution applications. However, applying passive harmonic filters requires careful consideration. Series-tuned filters present low impedance to harmonic currents, but they also form a parallel resonance circuit with the source impedance. In some instances, a situation can be created that is worse than the condition being corrected.

The filtering characteristics of the shunt passive filter are strongly influenced by the source impedance, which is not accurately known and varies with the system configuration. Transformer connections employing phase shift are sometimes used for cancellation of triplen (3rd, 9th, 15th, etc.), 5th and 7th harmonic currents. Both passive filters and transformer connection have a disadvantage that they cannot respond to changing load and harmonic conditions.

Moreover, the use of passive elements at high power level makes these devices bulky. Conventionally, the power factor correction is performed by means of capacitor banks, synchronous condenser and static VAR compensators (SVCs). Harmonic resonance problems are sometimes found with the use of passive capacitor banks. Using the synchronous condenser the resonance problems are eliminated, but they are expensive and their operation and maintenance are more costly. Both capacitor banks and synchronous condenser have a slow response. SVCs generate a considerable amount of harmonics that may have to be filtered. Also, due to their high cost, the SVCs are not economical for small power users.

Tap switching and Ferro resonant voltage regulators were the only devices to compensate for under voltages and over voltages. However, it was not possible to compensate for short duration sags because the fast control devices were not available. It must be appreciated that the above discussed conventional techniques are not flexible enough. Therefore it is imperative
that better and flexible mitigating devices are used for power quality problems.

There are many custom power devices and they are divided in two groups: network-reconfiguring type and compensating type. The network reconfiguring group includes the following devices: solid-state current limiter (SSCL), solid-state breaker (SSB) and solid-state transfer switch (SSTS). These devices are much faster than their mechanical counterparts. The compensating devices either compensate a load, correcting its power factor, unbalance etc., or improve the quality of the supply voltage. These devices are either connected in shunt or in series or a combination of both.

The compensating group includes distribution static compensator (DSTATCOM) to compensate for load reactive power and current harmonics, dynamic voltage restorer (DVR) for voltage support, and unified power quality conditioner (UPQC) for both current and voltage compensation. The present work focuses on the last custom power device UPQC, which is a combination of a shunt and series device and can combine the functions of these two devices together.

3.7 CUSTOM POWER DEVICES

Harmonic current flowing through the impedance of power system results in harmonic voltage drop at the load bus and along the feeder. Faults on transmission or distribution system can cause voltage sag at the load bus and along the feeder. Custom power devices are a special category of power conditioning equipment, used to protect the entire facility from such voltage disturbances (Ghosh 2002). Custom power devices have to work within parts of a cycle, thanks to the advancements in power electronics technology, such that the load bus will not be affected by the supply disturbance. CP solutions can be categorized as network reconfiguring type or compensating type
The network reconfiguring devices are usually called switchgear and they include current limiting, circuit breaking and current transferring devices. Network reconfiguring types are Static Current Limiter, Static Circuit Breaker and Static Transfer Switch (STS). The compensating devices compensate a load, correct its power factor, unbalance or improve the quality of supplied voltage. Compensating types are Active Power Filter (also called as Distribution Static Compensator), Dynamic Voltage Restorer and Unified Power Quality Conditioner.

**3.7.1 Network Reconfiguring Devices**

A short-circuit fault always causes a voltage sag for some costumers. The severity of the voltage sag depends on fault current magnitude and duration. To reduce the severity of the voltage sag one has to reduce the fault-clearing time or/and to reduce the magnitude of the fault current. A considerable reduction in fault clearing time is achieved by using current limiting fuses, which are able to clear a fault within half a cycle, so that the duration of voltage sag will rarely exceed one cycle. However, because of the fuse element melting during the fault, this device needs human intervention for replacement after the fault clearance.

The solid state circuit breaker is a multi-operation device, which also provides a fault clearing time within one half-cycle. This is a device, based on a combination of Gate Turn Off (GTO) and thyristor switches, which can interrupt a fault current and can also perform auto-reclosing function. Additionally the solid state fault-current limiter significantly reduces the fault-current magnitude within one or two cycles. This is a GTO based device that inserts a limiting inductor in series with the faulted circuit as soon as the fault is detected. After fault clearing the inductor is removed from the circuit.
A limiter or breaker placed in a network must not adversely affect the downstream protective devices. The sensitive loads are usually connected to two incoming feeders through a load transfer switch. At any given time the load is supplied by one of the two feeders. In case of a severe voltage sag/swell or interruption in the supplying feeder the solid state transfer switch (SSTS) quickly transfers the load to a healthy feeder. This is usually a thyristor based device that can perform a sub-cycle load transfer. It can also be used as a bus coupler between two incoming feeders. The above mentioned devices belong to the family of so-called network reconfiguring devices.

### 3.7.2 Distribution Static Compensator (DSTATCOM)

![Schematic diagram of DSATCOM](image)

DSTATCOM is a shunt-connected custom power device. The primary aims of which are power factor correction, current harmonics filtering, load DC offset cancellation, load balancing. It can also be used for voltage regulation at a distribution bus. Being an active filtering device connected in shunt with the harmonic-producing load, DSTATCOM is often referred as shunt or parallel active power filter. DSTATCOM consists of a voltage source PWM converter equipped with a dc capacitor as storage.
element, interface inductor and matching transformer. Schematic diagram of UPQC is shown in Figure 3.2.

The effectiveness of an active power filter depends basically on the design characteristics of the current controller, the method implemented to generate the reference template and the modulation technique used. Various topologies of active filters have been developed for harmonic mitigation. Voltage-source PWM converter has a higher efficiency, lower cost, smaller physical size and other advantages. Also, the current-source PWM converter cannot be used in multilevel or multistep mode configurations to allow compensation in higher power ratings. The shunt active power filter operates as a current source and compensates current harmonics by injecting the harmonic components generated by the load but phase shifted by 180 degrees.

Moreover, with an appropriate control scheme, the shunt active power filter can also compensate for the load power factor. As a result, components of harmonic currents contained in the load current are cancelled by the effect of the active filter, and the source current remains sinusoidal and in phase with the respective phase-to neutral voltage. Thus, ideally a three-phase shunt active filter injects a set of three-phase currents such that the source currents become in phase with the source voltages, are DC offset and harmonic free, and are balanced. Also, the shunt active power filter has the capability of damping harmonic resonance between an existing passive filter and the supply impedance.

The shunt active power filter based on Voltage Source Inverter (VSI) structure is an attractive solution to harmonic current problems. The shunt active filter is a Pulse Width Modulated (PWM) voltage source inverter that is connected in parallel with the load. Active filter injects harmonic current into the AC system with the same amplitude but with opposite phase as that of the load. The principal components of the APF are the Voltage
Source Inverter (VSI), DC energy storage device, coupling inductance and the associated control circuits. The performance of an active filter depends mainly on the technique used to compute the reference current and the control strategy followed to inject the compensation current into the line.

The use of two or more PWM voltage source inverters connected in cascade is an interesting alternative to compensate high power nonlinear loads. Connecting in cascade two VSIs with different rated power allows the use of different switching frequencies, reducing switching stresses, and commutation losses in the overall compensation system. Of these two VSIs, one compensates for the reactive power demand and lower frequency current harmonics, while the other one compensates only high frequency current harmonics. The first converter requires higher rated power than the second and can operate at lower switching frequency.

There are two major approaches that have been proposed in the literature for harmonic detection, namely, frequency domain and time domain methods. The time domain methods require less computation and are widely followed for computing the reference current. The two mostly used time domain methods are synchronous reference (d-q-0) theory and instantaneous real-reactive power (p-q) theory.

There are several control strategies for current control namely, PI control, predictive current control, Sliding Mode Control (SMC) and hysteresis control. Among the various current control techniques, hysteresis control is the most commonly used method because of its simplicity in implementation. But, with fixed hysteresis band, the slope of the reference current is unpredictable, which leads to increase in switching frequency. Hysteresis current controller with fixed switching frequency which results in low current tracking error. But this method gives high value of THD with increased amount of neutral current.
The adaptive hysteresis band controller changes the hysteresis bandwidth as a function of reference compensator current variation to optimize switching frequency and Total Harmonic Distortion (THD) of the supply current. But in this method, the source current is found to possess large number of spikes which increases the THD value.

In the adaptive hysteresis band control, the hysteresis bandwidth is calculated with the help of a fuzzy logic controller (FLC). In this approach, the source current shaping can be achieved with minimum amount of spikes resulting in reduction in THD and reduction in neutral current to zero. The control scheme of a shunt active power filter must calculate the current reference waveform for each phase of the inverter, maintain the dc voltage constant, and generate the inverter gating signals. Also, the compensation effectiveness of an active power filter depends on its ability to follow the reference signal calculated to compensate the distorted load current with a minimum error and time delay.

The shunt component of UPQC can be controlled in two ways. Tracking the shunt converter reference current, when the shunt converter current is used as feedback control variable. The load current is sensed and the shunt compensator reference current is calculated from it. The reference current is determined by calculating the active fundamental component of the load current and subtracting it from the load current. This control technique involves both the shunt active filter and load current measurements.

Tracking the supply current, when the supply current is used as the feedback variable. In this case the shunt active filter ensures that the supply reference current is tracked. Thus, the supply reference current is calculated rather than the current injected by the shunt active filter. The supply current is often required to be sinusoidal and in phase with the supply voltage. Since the waveform and phase of the supply current is known, only its amplitude needs
to be determined. Also, when used with a hysteresis current controller, this control technique involves only the supply current measurement. Thus, this is a simpler to implement method. Therefore it has been used in the UPQC simulation model.

3.7.2.1 Load compensation using D-STATCOM

It is assumed that the DSTATCOM is operating in current control mode. Therefore its ideal behaviour is represented by the current source $i_r$. It is assumed that the load is reactive, non-linear and unbalanced. In the absence of the compensator, the current $i_s$ flowing through the feeder will also be unbalanced and distorted.

To alleviate this problem, the compensator must inject current such that the current $i_s$ becomes fundamental and positive sequence. In addition, the compensator can also force the current $i_s$ to be in phase with voltage. This fashion of operating the DSTATCOM is also called load compensation since in this connection the DSTATCOM is compensating the load current. From the utility point of view, it will look as if the compensated load is drawing a unity power factor, fundamental and strictly positive sequence current. The point at which the compensator is connected is called the utility customer point of common coupling. Denoting the load current by $I_l$, the Kirchhoff’s Current Law at the PCC yields

$$i_s = i_l - i_c$$  \hspace{1cm} (3.1)

The desired performance from the compensator is that it generates a current $i_c$ such that it cancels the reactive component, harmonic component and unbalance of the load current.
In general, there may be various feeder segments and load buses before the PCC. Therefore at best, the source and feeder impedances are the Thevenin equivalent obtained by looking into the network at PCC.

Let us denote the feeder resistance and inductance (Thevenin equivalent) as $R_s$ and $L_s$ respectively. Then the voltage at the PCC is

$$v_t = v_s - i_s R_s - L_s \frac{d i_s}{dt}$$  \hspace{1cm} (3.2)

Since the PCC is the terminal at which the compensator is connected, we thus term this voltage as the terminal voltage. Equation (3.2) clearly shows that if the source current is distorted, the voltage at the PCC also gets distorted. Since this voltage is then used in the compensating algorithm, this result in further distortion in the source current. So, in this thesis, Instantaneous symmetrical components theory, Instantaneous active and reactive Power theory and Fuzzy hysteresis band voltage and current control are proposed.

### 3.7.2.2 Voltage control of the dc bus

Another important task in the development of active filter is the maintenance of constant DC voltage across the capacitor connected to the inverter. This is necessary to compensate the energy loss due to conduction and switching power losses associated with the diodes and IGBTs of the inverter in APF, which tend to reduce the value of voltage across the DC capacitor.

Thus, the dc link voltage control unit is meant to keep the average dc bus voltage constant and equal to a given reference value. The dc link voltage control is achieved by adjusting the small amount of real power absorbed by the shunt inverter. This small amount of real power is adjusted by
changing the amplitude of the fundamental component of the reference current. The ac source provides some active current to recharge the dc capacitor.

Thus, in addition to reactive and harmonic components, the reference current of the shunt active filter has to contain some amount of active current as compensating current. This active compensating current flowing through the shunt active filter regulates the dc capacitor voltage. Usually a Proportional Integral(PI) controller is used for determining the magnitude of this compensating current from the error between the average voltage across the dc capacitor and the reference voltage. The PI controller has a simple structure and fast response.

As an alternative to PI controller, a simple linear control technique is proposed with application to a single-phase shunt active filter. This is a proportional gain type control and the proportional coefficient is calculated instantaneously as a function of the dc capacitor average voltage error. Here, calculation of the proportional coefficient is obtained through integration of a first-order differential equation.

Also, a residual steady-state error occurs with a proportional only controller. Instead of the PI controller, a Fuzzy logic controller is proposed for processing the dc capacitor average voltage error. The Fuzzy controller is claimed to have some advantages over the PI controller. It does not require an accurate mathematical model, can work with imprecise inputs and handle non-linearity, and it is more robust. Based on the simulation results, Fuzzy logic controller has a better dynamic behaviour than the PI controller. However, the steady-state performance of the Fuzzy controller is comparable to the PI controller.
3.7.3 Dynamic Voltage Restorer (DVR)

Various power circuit topologies of DVR are shown in Figure 3.3. DVR is a series-connected custom power device the aim of which is to protect sensitive loads from supply side disturbances except outages. Also, the DVR can act as a series active filter, isolating the source from harmonics generated by loads. The DVR consists of a voltage-source PWM converter equipped with a dc capacitor and connected in series with the utility supply voltage through a low pass filter (LPF) and a coupling transformer.

![Diagram of Dynamic Voltage Restorer (DVR)](image)

(a) Storage systems with auxiliary supply / Inverter side filtering

(b) Storage systems with grid itself / voltage source inverter

Figure 3.3 (Continued)
3.7.3.1 Equivalent circuit Of DVR

The equivalent circuit of DVR is shown in Figure 3.4. This device injects a set of controllable three phase ac voltages in series and synchronism with the distribution feeder voltages such that the load-side voltage is restored to the desired amplitude and waveform even when the source voltage is unbalanced or distorted.
Figure 3.4 The equivalent circuit of DVR

The DVR coupling transformer can experience saturation during the transient period after voltage sag starts. For preventing this, normally a rating flux that is double of the steady-state limit is chosen. An alternative method for preventing the coupling transformer saturation, which consists in limiting the flux-linkage during the transient switch-on period. The two important functions the coupling transformer of DVR are voltage boost and electrical isolation. However, it increases the DVR costs, requires space, contributes to DVR losses, and as mentioned above can be driven into saturation in some conditions.

The DVR acts as an additional energy source and introducing it into the system has effects seen both by system and customer. So, when applying a series device, careful considerations must be taken. For example, the DVR must coordinate with other protective devices, particularly those installed upstream.
Figure 3.5 (a) Rectifier supported DVR

Figure 3.5 (b) DC capacitor supported DVR
There are two different DVR structures. Rectifier supported DVR is shown in Figure 3.5 (a), and a capacitor supported DVR is shown in Figure 3.5 (b). The first one can absorb real power from the grid through a rectifier. This is not possible with the capacitor supported DVR, and therefore in the steady state it has to be operated in “no real power” exchange mode. In this case, the real power required for voltage sag compensation is drawn from the batteries connected across the dc link. The DVR cannot mitigate any interruptions, and unless it is rectifier supported it cannot mitigate very deep sags. The rectifier supported DVR injects current harmonics into the distribution network.

The series component of UPQC is controlled to inject the appropriate voltage between the point of common coupling and load, such that the load voltages become balanced, distortion free and have the desired magnitude. Theoretically the injected voltages can be of any arbitrary magnitude and angle. However, the power flow and device rating are important issues that have to be considered when determining the magnitude and the angle of the injected voltage.

3.7.4 Hybrid Filters

Hybrid filter topologies consist of both active and passive filters in different configurations. They effectively address and mitigate the problems of both passive filter and pure active filter solutions, and provide a cost-effective and practical harmonic compensation approach, particularly for high power non-linear loads. Thus, hybrid topologies improve significantly the compensation characteristics of simple passive filters, making the use of active power filter available for high power applications, at a relatively lower cost.
The series active filter acts as an active impedance, which prevents resonances in the shunt passive filter and improves its filtering characteristics. The series active filter is controlled in such a way as to present zero impedance for the fundamental and pure resistance for the harmonics. Thus, a small rated active filter improves the characteristics and eliminates the drawbacks of high-rated passive filter.

### 3.7.5 Unified Power Quality Conditioner (UPQC)

A Unified Power Quality Conditioner (UPQC) is a relatively new member of the custom power device family. It is a combination of shunt active filter and series active filter. The concept of UPQC was first introduced in 1996. It is speculated that almost any power quality issues can be tackled with this device. Generally power quality problems arise either because of supply voltage distortion or because of load current distortion. Since a UPQC has both series and shunt compensators, it can handle supply voltage and load current problems simultaneously when installed at the point of common coupling. It can protect sensitive loads from power quality events arising from the utility side and at the same time can stop the disturbance being injected into the utility from load side.

A UPQC is a device that is similar in construction to a Unified Power Flow Conditioner (UPFC). The UPQC, just as in a UPFC, employs two voltage source inverters having a common DC energy storage capacitor. One of these two VSIs is connected in shunt with the AC system while the other is in series with AC line. As similar to UPFC, UPQC also performs shunt and series compensation in a power distribution system. Since a power transmission line generally operates in a balanced, distortion (harmonic) free environment, a UPFC must only provide balanced shunt or series compensation. A power distribution system, on the other hand, may contain unbalance, distortion and even DC components.
The UPQC is a power electronics based compensator which works on the principle of active filtering. The UPQC system is inherently complex and requires sophisticated control systems to achieve the satisfactory performance. The UPQC is a custom power device that integrates the series- and shunt active filters, connected back-to-back on the dc side and sharing a common DC capacitor. A typical single line diagram of a UPQC compensated distribution system is shown in Figure 3.6. It employs two voltage source inverters that are connected to a common DC energy storage capacitor. One of these two VSIs is connected in series with the feeder and the other is connected in parallel to the same feeder.

![Figure 3.6 Single line diagram of a UPQC](image)

The shunt component is responsible for mitigating the power quality problems caused by the consumer: poor power factor, load harmonic
currents, load unbalance and DC offset. The shunt part of the UPQC consists of a VSI (voltage source inverter) connected to the common DC storage capacitor on the dc side and on the ac side it is connected in parallel with the load through the shunt interface inductor and shunt coupling transformer. The shunt interface inductor, together with the shunt filter capacitor is used to filter out the switching frequency harmonics produced by the shunt VSI. The shunt coupling transformer is used for matching the network and VSI voltages.

In order to achieve its compensation goals, the shunt active filter injects currents at the point of common coupling such that the reactive and harmonic components of the load currents are cancelled and the load current unbalance is eliminated. This current injection is provided by the dc storage capacitor and the shunt VSI. Based on measured currents and voltages the control scheme generates the appropriate switching signals for the shunt VSI switches. The particular currents and voltages to be measured depend on the applied control strategy. The shunt device is also used for providing a path for real power flow to aid the operation of the series connected VSI. Also, it maintains constant average voltage across the DC storage capacitor.

The shunt VSI is controlled in current control mode. The appropriate VSI switches are turned on and off at certain time instances such that the currents injected by the shunt active filter track some reference currents within a fixed hysteresis band (assuming a hysteresis controller is used) according to the compensation objectives. The VSI switches alternately connect the dc capacitor to the system, either in the positive or negative sense. When the dc capacitor voltage is connected in the positive sense, it is added to the supply voltage and the VSI current is increasing. In the case of the dc capacitor connected in the negative sense, its voltage is in opposition to the
supply voltage and the VSI current is decreasing. So, alternately increasing and decreasing the current within the hysteresis band, the reference current is tracked. This control technique is called “Hysteresis band control”.

The dc side capacitor serves two main purposes: it maintains the dc voltage with a small ripple in the steady state, and it serves as an energy storage element to supply a real power difference between the load and source during the transient period. The average voltage across the dc capacitor is maintained constant, and in order that the shunt active filter can draw a leading current, this voltage has to be higher than the peak of the supply voltage. This is achieved through an appropriate proportional integral control, by regulating the amount of active current drawn by the shunt active filter from the system.

The series component of the UPQC is responsible for mitigation of the supply side disturbances: voltage sags/swells, flicker, voltage unbalance and harmonics. It inserts voltages so as to maintain the load voltages at a desired level, balanced and distortion free.

The series part of the UPQC also consists of a VSI connected on the dc side to the same energy storage capacitor, and on the ac side it is connected in series with the feeder through the series Low Pass Filter (LPF) and coupling transformers. The series LPF prevents the switching frequency harmonics produced by the series VSI entering the system. The series coupling transformers provide voltage matching and isolation between the network and the VSI.
The series active filter compensation goals are achieved by injecting voltages in series with the supply voltages such that the load voltages are balanced and undistorted, and their magnitudes are maintained at the desired level. This voltage injection is provided by the dc storage capacitor and the series VSI. Based on measured supply and/or load voltages the control scheme generates the appropriate switching signals for the series VSI switches. The series VSI is controlled in voltage-control mode using the well-known pulse-width modulated switching technique.

In order to produce the injected voltage of desired magnitude, waveform, phase shift and frequency, the desired signal is compared with a triangular waveform signal of higher frequency, and appropriate switching signals are generated. The dc capacitor is alternately connected to the inverter outputs with positive and negative polarity. The output voltages of the series VSI do not have the shape of the desired signals, but contain switching harmonics, which are filtered out by the series low pass filter. The amplitude, phase shift, frequency and harmonic content of injected voltages are controllable.

Two possible ways of connecting the UPQC to the point of common coupling. In the Right-shunt UPQC compensation configuration, the shunt component is connected to the load side and the series to the supply side and the shunt component is connected to the supply side and the series component to the load side in the Left-shunt UPQC compensation configuration.

UPQC has attracted the attention of power engineers to develop dynamic and adjustable solutions to power quality problems. This led to the
development of advanced control techniques and novel topologies for UPQC. Control techniques play a vital role in the overall performance of the power conditioner. The rapid detection of the disturbance signal with high accuracy, fast processing of the reference signal, and high dynamic response of the controller are the prime requirements for desired compensation.

Fuzzy logic is utilized to control the compensation currents of the shunt converter. The adaptive detection technique is used to minimize the effects of noise or parameter variations. To generate reference signals simultaneously for the series and shunt converter, Abc-dq transform, wavelet transform, artificial intelligence, neural network, and pole-shift control methods are employed. DC voltage control can be fulfilled by proportional control and PI control. In the hysteresis method, space vector pulse width modulation and sinusoidal PWM strategy are preferred for series and shunt-side converter signal generation.

The following four tasks will be accomplished simultaneously by the UPQC.

1. Compensating the harmonics in the supply voltage and load current
2. Eliminating the disturbances due to voltage sags/swells at the supply side or changes in the load demand
3. Correcting the power factor at the supply side
4. Maintaining the power quality despite slight frequency variations in the supply voltage.

Two UPQC terms are defined in depending on the angle of the injected voltage: UPQC-Q and UPQC-P. In the first case (UPQC-Q) the injected voltage is maintained 90 degree in advance with respect to the supply
current, so that the series compensator consumes no active power in steady state. In second case (UPQC-P) the injected voltage is in phase with both the supply voltage and current, so that the series compensator consumes only the active power, which is delivered by the shunt compensator through the dc link.

In the case of quadrature voltage injection (UPQC-Q) the series compensator requires additional capacity, while the shunt compensator VA rating is reduced as the active power consumption of the series compensator is minimised and it also compensates for a part of the load reactive power demand. In UPQC-P case the series compensator does not compensate for any part of the reactive power demand of the load, and it has to be entirely compensated by the shunt compensator. Also the shunt compensator must provide the active power injected by the series compensator. Thus, in this case the VA rating of the shunt compensator increases, but that of the series compensator decreases. It can be concluded that the UPQC-Q and UPQC-P are two extreme cases and finding the optimum solution which is located in between is preferable.

The main advantage of UPQC is that it does not require any energy storage. It can be designed to mitigate any sag above a certain magnitude, independent of its duration. This could result in a device that is able to compete with the uninterruptible power supply typically used for the protection of low-power, low-voltage equipment. The main disadvantage of UPQC is the large current rating required to mitigate deep sags. For low power, low-voltage equipment this will not be a serious concern, but it might limit the number of large power and medium voltage applications.
3.7.5.1 Equivalent circuit of UPQC

A UPQC control system is used for simultaneous voltage regulation and current compensation in the presence of unbalance and harmonics in both load currents and source voltages. Equivalent circuit of a UPQC is shown in Figure 3.7. The UPQC is controlled in such a way that the voltage at load bus is always sinusoidal and at desired magnitude. The series active filter connected in series through an injection transformer is commonly termed as series filter.

![Figure 3.7 The equivalent circuit of a UPQC](image)

It acts as a controlled voltage generator. It has capability of voltage imbalance compensation, voltage regulation and harmonic compensation at the utility-consumer point of common coupling.

In addition to this, it provides harmonic isolation between a sub-transmission system and a distribution system. The second unit connected in parallel with load, is termed as shunt active filter. It acts as a controlled current generator. The shunt active filter absorbs current harmonics, compensate for reactive power and negative sequence current injected by the load. In addition, it controls dc link current to a desired value. The source voltage, terminal voltage at PCC and load voltage are $e_s$, $v_s$ and $v_{ch}$.
respectively. The source and load currents are $i_s$ and $I_{ch}$ respectively. The voltage injected by Series Active Filter is $v_c$ and $i_f$ is the current injected by Shunt Active Filter.

The UPQC connection in Figure 3.7 is called the left-shunt structure as the shunt VSI is connected on the left hand side of the series VSI. It is also possible to have a UPQC with a right-shunt structure. The main purpose of a UPQC is to compensate for voltage flicker/imbalance, reactive power, negative-sequence current and harmonics present in a distribution system. In other words, the UPQC has the capability of improving the power quality at the point of installation on power distribution systems. A UPQC modeled using a state space averaging technique to analyze its behavior. The enhancement of shunt active filter performance is achieved by applying a moving time window method. A UPQC control system is used for simultaneous voltage regulation and current compensation in the presence of unbalance and harmonics in both load currents and source voltages.

The main purpose of the UPQC is to regulate the critical load bus voltage $V_{ch}$. This is achieved through the series VSI. The primary goal of the shunt VSI is to supply real power to the dc capacitor. Additionally, the shunt VSC also eliminates the unbalance and harmonics from the bus voltage on the left hand side of the UPQC. The operation of UPQC that combines the operations a DSTATCOM and DVR .The series component of the UPQC inserts voltage so as to maintain the voltage at the load terminals balanced and free of distortion. Simultaneously, the shunt component of UPQC injects current into the AC system such that the currents entering the bus to which the UPQC is connected are balanced sinusoids. Both these objectives must be met irrespective of unbalance in either source or load sides.
3.7.5.2 Power circuit design considerations

The design of UPQC power circuit includes the selection of the following three main parameters,

- shunt interface inductors
- dc link reference voltage
- dc link capacitor

The design of the shunt interface inductor and the dc reference voltage is based on the following criteria.

- Limiting the high frequency components of the injected currents
- The instantaneous di/dt generated by the shunt active filter should be greater than the di/dt of the harmonic component of the load, so that the proper harmonic cancellation can take place.

On one hand, for a better harmonic cancellation and reactive power compensation a higher inductance is preferable, but on the other hand, too high inductance will result in slow dynamic response of the shunt compensator and it could not be possible to compensate for some of the load harmonics. A higher dc link reference voltage results in a higher di/dt of the shunt compensator, better dynamic response and reactive power compensation performance, but it also increases the stress experienced by the inverter switching devices. The dc capacitor size is selected to restrict the dc voltage ripple within reasonable limits. The dc voltage ripple is determined by both the amount of reactive power to be compensated and the active power supplied by dc capacitor during the transient.
To correct for the effects of supply voltage distortion, the series compensator is required to inject appropriate harmonic voltages. This unfortunately can present problems with unbalanced fluxes if conventional three limb injection transformers are used. To avoid this, three separate injection transformers are utilized. This allows the flux-linkage in each to be dealt with separately and remains true regardless of the external configuration, star or delta.

Advantages of UPQC are,

**Increased grid reliability** – reduced risk of mal-operation or failure of loads from power quality problems originating from the network.

**Harmonic protection** – greatly reduces the level of harmonics being injected back into the network from disrupting electrical loads.

**Renewable energy integration** – allows wind generation and other renewable energy supplies to be accommodated into electricity supply networks, by increasing their voltage ride through capability in the event of short duration grid voltage disturbances.

**Efficient DC bus control** – a novel adaptive controller ensures that during severe voltage/current disturbances the change in the dc link voltage is steady. It can follow the reference at all times to ensure injected voltage and current harmonics are kept to the minimum.

UPQC is much more flexible than separately configured DSTATCOM and DVR. However it is an expensive device and its use may be limited to particular sensitive situations with a high value on power quality. More research is necessary to investigate its full capability and minimize the
cost. Also for the purpose of cost justification new applications of UPQC must be explored.

3.8 CONCLUSION

Some types of the power quality problems are voltage sag/swell, interruption, voltage fluctuation, voltage unbalance, current harmonic, current unbalance and current unbalance. Among them, voltage sags/swells and current harmonics are the most common power quality problems. Some PQ reports indicate that poor PQ can cause large financial losses to different types of industries. The limits of PQ problems are generally set by IEEE and IEC standards. To minimize these harmonics in supply currents Three Phase Unified Power Quality Conditioner is used. It can be concluded here that a UPQC combines together the operation of two previously discussed custom power devices DVR and DSTACOM. In the next chapter, the control strategies of UPQC are discussed.