CHAPTER 2
POWER QUALITY

2.1 INTRODUCTION

In recent years, there has been an increased emphasis on the quality of power delivered to factories, commercial establishments, and residences. This is due in part to the prevalence of harmonic-creating systems in use. Such harmonic-generating equipment contributes to the harmonic burden the system must accommodate. In addition, utility switching and fault clearing produce disturbances that affect the quality of delivered power.

One of the biggest problems in power quality aspects is the harmonics content in the electrical system. Generally, harmonics may be divided into two types: voltage harmonics and current harmonics. Current harmonics is usually generated by harmonics contained in voltage supply and depends on the type of load such as resistive load, capacitive load, and inductive load. Both harmonics can be generated by either the source or the load side.

Harmonics generated by load are caused by nonlinear operation of devices, including power converters, arc-furnaces, gas discharge lighting devices, etc. Load harmonics can cause the overheating of the magnetic cores of transformer and motors. On the other hand, source harmonics are mainly generated by power supply with non-sinusoidal voltage waveform. Voltage
and current source harmonics imply power losses, electromagnetic interference and pulsating torque in AC motor drives.

Much of the equipment in use today is susceptible to damage or service interruption during poor power-quality events. Everyone with a computer has experienced a computer shutdown and reboot with a loss of work resulting. Often this is caused by poor power quality on the power line. Poor power quality also affects the efficiency and operation of electric devices and other equipment in factories and offices.

IEEE has done significant work on the definition, detection, and mitigation of power quality events. IEEE Standard 1100 (IEEE 1999) defines power quality as the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment. Electrical equipment susceptible to power quality or more appropriately to lack of power quality would fall within a seemingly boundless domain. All electrical devices are prone to failure or malfunction when exposed to one or more power quality problems. The electrical device might be an electric motor, a transformer, a generator, a computer, a printer, communication equipment, or a household appliance. All of these devices and others react adversely to power quality issues, depending on the severity of problems.

2.2 POWER QUALITY PROBLEMS

The quality of electric power has become an important issue for electric utilities and its customers. As a result, power quality study is gaining interest. Degradation in quality of electric power is normally caused by power line disturbances such as voltage sag/swell with and without harmonics, momentary interruption, harmonic distortion, flicker, notch, spike and transients, causing problems such as malfunctions, instabilities, short lifetime,
failure of electrical equipments, etc. In an electric distribution network, faults may cause voltage sag or momentary interruption whereas switching off large load or charging of a large capacitor bank may lead to voltage swell. On the other hand, use of solid-state switching devices and nonlinear and power electronically switched loads such as rectifiers or inverters may cause harmonic distortion and notching in the voltage and current. Use of arc furnaces may lead to flickers. Ferro-resonance, transformer energization, or capacitor switching may cause transients and lightning strikes may lead to spikes.

Table 2.1 Power Quality Phenomena

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<tr>
<th>Category</th>
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<td>Events</td>
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<td>Harmonic Distortion</td>
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<td>Interharmonics</td>
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<td>Noise</td>
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Harmonic pollution on a power line can be quantified by means of Total Harmonic Distortion (THD). High harmonic distortion can negatively impact a facility’s electric distribution system, and can generate excessive
heat in motors, causing early failures. Heat also builds up in wire insulation causing breakdown and failure. Increased operating temperatures can affect other equipment as well, resulting in malfunctions and early failure. In addition, harmonics on the power line can prompt computers to restart and adversely affect other sensitive analog circuits. The different types of power quality problems are summarized in Table 2.1.

In a realistic distribution system, in order to improve power quality, these disturbances need to be identified before appropriate mitigating action can be taken. Therefore, normally these types of disturbances (normal waveform is also included for the classification from other disturbances) which occur frequently in a distribution network are considered as samples for training a soft computing based power quality assessment mechanism.

The major reasons for the increased interest in power quality can be summarized as follows:

- **Metering:** Poor power quality can affect the accuracy of utility metering.

- **Protective Relays:** Poor power quality can cause protective relays to malfunction.

- **Downtime:** Poor power quality can result in equipment downtime and/or damage, resulting in a loss of productivity.

- **Cost:** Poor power quality can result in increased costs due to the preceding effects.

- **Electromagnetic Compatibility:** Poor power quality can result in problems with electromagnetic compatibility (EMC) and noise.
2.2.1 Harmonics

Harmonic currents have been present in the electricity supply system for many years. Initially they were produced by the mercury arc rectifiers used to convert AC to DC current for railway electrification and for DC variable speed drives in industry. More recently the range of types and the number of units of equipment causing harmonics have risen sharply, and will continue to rise, so designers must now consider harmonics and their side effects very carefully.

Any periodic waveform can be shown to be the superposition of a fundamental and a set of harmonic components. By applying Fourier transformation, these components can be extracted. The frequency of each harmonic component is an integral multiple of its fundamental. There are several methods to indicate the quantity of harmonics content. The most widely used measure is the total harmonics distortion, which is defined in terms of the amplitudes of the harmonics, at frequency $n\omega_0$, where $\omega_0$ is frequency of the fundamental component whose amplitude is $H_1$ and $n$ is an integer.

Harmonic frequencies are integral multiples of the fundamental supply frequency, i.e. for a fundamental of 50 Hz, the third harmonic would be 150 Hz and the fifth harmonic would be 250 Hz. Harmonic distorted waveform is clearly not a sine wave and that means the normal measurement equipment, such as average reading RMS-calibrated multi-meters, will give inaccurate readings. Note also that there could also be many zero crossing points per cycle instead of two, so any equipment that uses zero crossing as a reference will malfunction. Such a waveform contains non-fundamental frequencies and the equipment should be capable of identifying them.
2.2.2 Short Interruptions (< 1 min)

Disappearance of the supply voltage in all phases by some definitions also defined as in “…one or more phases”. Usually qualified by an additional term indicating the voltage drop or retained voltage and duration of the interruption (e.g. Momentary, Temporary, or Sustained). The values depend on the standard followed. Some definitions interpret short interruption as a special kind of voltage dip.

2.2.3 Long Interruptions (>1 min)

Disappearance of the supply voltage in all phases by some definitions also defined as in “...one or more phases”. Usually qualified by an additional term indicating the voltage drop or retained voltage and duration of the interruption (e.g., Momentary, Temporary, or Sustained).

2.2.4 Voltage Dips and Swells

A voltage dip is a short-term reduction in, or complete loss of, RMS voltage. It is specified in terms of duration and retained voltage, usually expressed as the percentage of nominal RMS voltage remaining at the lowest point during the dip. A voltage dip means that the required energy is not being delivered to the load and this can have serious consequences depending on the type of load involved. There are two main causes of Voltage dips; starting of large loads either on the affected site or by a consumer on the same circuit and faults on other branches of the network. Voltage swells are temporary increase in RMS value of AC voltage with the magnitude of the retained voltage between 110% and 180% of the rated voltage.
2.2.5 Transients/Surges (Switching/Lightning)

A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity. Causes include switching or lightning strikes on the network and switching of reactive loads on the consumer’s site or on sites on the same circuit. Transients/surges can have magnitudes of several thousand volts and so can cause serious damage to both the installation and the equipment connected to it.

2.2.6 Flicker

Flickers are short duration voltage changes, resulting from switching, short circuits and load changing. The permissible magnitude of light flicker is regulated by International Standards, based on perception criteria. Excessive flicker can cause migraine and is responsible for some instances of the so-called ‘sick building syndrome’.

2.2.7 Unbalanced System

A three-phase power system is called balanced or symmetrical if the three-phase voltages and currents have the same amplitude and are phase shifted by 120° with respect to each other. If either or both of these conditions are not met, the system is called unbalanced or asymmetrical. It is implicitly assumed that the waveforms are sinusoidal and thus do not contain harmonics.

In most practical cases, the asymmetry of the loads is the main cause of unbalance. At high and medium voltage level, the loads are usually three-phase and balanced, although large single- or dual-phase loads can be connected, such as AC rail traction (e.g. high-speed railways) or induction
furnaces (large metal melting systems employing highly irregular powerful arcs to generate heat).

Low voltage loads are usually single-phase e.g. computers or lighting systems, and the balance between phases is therefore difficult to guarantee. In the layout of an electrical wiring system feeding these loads, the load circuits are distributed amongst the three-phase systems, for instance one phase per floor of an apartment or office building or alternating connections in rows of houses. Still, the balance of the equivalent load at the central transformer fluctuates because of the statistical spread of the duty cycles of the different individual loads.

Abnormal system conditions also cause phase unbalance. Phase-to-ground, phase-to-phase and open-conductor faults are typical examples. These faults cause voltage dips in one or more of the phases involved and may even indirectly cause over-voltages on the other phases. The system behaviour is then unbalanced by definition, but such phenomena are usually classified under voltage disturbances, since the electricity grid’s protection system should cut off the fault.

2.2.8 Voltage Value (long term under-voltages and over-voltages)

Long term voltage variations generally last for periods over several seconds. They are not the result of system faults. They may be caused by load variations, system switching operations and general system voltage regulation practices. Long term voltage variations can be either over-voltages or under-voltages, depending on the cause of the variation. They can influence voltage value sensitive equipment e.g. this under/over-voltage protected or voltage controlled equipment e.g. motors, overstress insulation.
2.2.8.1 Under-Voltages

An under-voltage is a decrease in the RMS AC voltage (to less than 90% of rated voltage) at the power frequency for duration longer than several seconds (or even 1 minute).

2.2.8.2 Over-Voltages

An over-voltage is an increase in the RMS AC voltage (to more than 110% of rated voltage) at the power frequency for duration longer than several seconds (or even 1 minute).

2.2.9 Earthing and EMC

Earthing of installations and equipment is an issue that crosses the boundaries of the various disciplines involved in the construction and equipping of a modern commercial or industrial building. In general, any Earthing System needs to satisfy three demands:

- **Lightning and Short Circuit:** The Earthing System must protect the occupants, prevent direct damage such as fire, flashover or explosions due to a direct lightning strike and overheating due to a short-circuit current.

- **Safety:** The Earthing System must conduct lightning and short-circuit currents without introducing intolerable step-voltage and touch-voltages.

- **Equipment Protection and Functionality:** The Earthing System must protect electronics by providing a low impedance path to interconnect equipment. Proper cable routing, zoning and shielding are important aspects and serve the purpose of preventing sources of disturbance from interfering with the operation of electrical equipment.
Although requirements for these three aspects are often specified separately, the implementation of them requires an integrated systems approach.

EMC is defined in the IEC 61000 series (IEC 2003), as the ability of an equipment or system, to function satisfactorily in its electromagnetic environment, without introducing intolerable electromagnetic disturbances to anything in that environment. Maintaining this compatibility in practice requires great care in the design and implementation of the installation and the earthing system.

2.3 EFFECTS OF POWER QUALITY PROBLEMS

The effects of power quality problems vary from one piece of equipment to another and with the age of the equipment. The quality of electric power is vital for both, electric utilities and its customers. The major problems faced by the stake holders are

- **Consumer Side**
  - Intermittent failure of computer equipments
  - Interference with data communication equipments
  - Malfunction of Process Controllers
  - Stalling of motors on start up
  - Inaccurate Power Metering
  - Constant risk of fatal electrical shock

- **Utility Side**
  - Increased Transmission and Distribution losses
  - Overloading of Cables, Transformers and Switchgears
  - Tripping of Circuit Breakers and residual current devices
  - Incorrect operation of solid state relays
2.4 POWER QUALITY MONITORING

In order to improve power quality, the sources and causes of the disturbances must be known before appropriate mitigating actions can be taken. A feasible approach to achieve this goal is to incorporate detection capabilities into monitoring equipment so that events of interest will be recognized, captured, and classified automatically. Hence, good performance monitoring equipment must have functions which involve the detection, localization, and classification of transient events. In particular, when the disturbance type has been classified accurately, the power-quality engineers can define the major effects of the disturbance at the load and analyze the source of the disturbances so that an appropriate solution can be formulated (IEEE 1981 and IEEE 1993).

In a modern power system, the objective of continuous supply of electric energy has made the power quality become an issue of utmost importance. In order to maintain an expected level of electric power quality, some practices have been suggested to help to restrict the ever-increasing level of waveform distortion caused by the proliferation of nonlinear electronic circuits. Many utilities have also installed dedicated monitoring devices such that the warning alarms can be earlier acquired in order to detect all possible power-quality events. A typical power quality monitoring system is shown in Figure 2.1.
One of the important issues in power quality analysis is to detect and classify disturbance waveforms automatically in an efficient manner. To detect, to solve, and to mitigate the power quality problem, many utilities perform power quality monitoring for their industrial and key customers. In the deregulated market, the power quality monitoring would be an effective means for providing better customer services as well as reinforcing competitiveness among the utilities. The selection of monitoring locations will depend on the facility design, the critical loads, the power conditioning equipment and the specific objectives of monitoring. At the minimum, the monitoring should include the utility supply locations, outputs of power conditioning equipment and the backup generators.

Monitoring multiple locations over an extended period of time will provide a profile of the conditions on the distribution network. Current and voltage profiles should be measured for periods when the circuit is under typical loading. Measurements taken during periods when the circuit is lightly loaded may provide an inaccurate picture of the harmonic conditions. The
traditional reactive approach of power quality monitoring may not be appropriate for all situations. Measurement of power quality requires the use of proper instrumentation to suit the application. The user of the instrument must be well trained in the use and care of the instrumentation. The engineer should be knowledgeable in the field of power quality.

2.5 POWER QUALITY SOLUTIONS

Solving power quality problems depends on acquiring meaningful data at the optimum location or locations and within an expedient time frame. In order to acquire useful and relevant data, instruments most suited for a particular application should be utilized. The wide range of power quality solutions employed at present and found in literature may be categorized as follows:

- Hardware
  - Active Harmonic Filters
  - Micro SMES for Power Quality
  - Large SMES for Transmission / Distribution
  - PWM Based Higher Power Compensators
  - FACTS Controller, Custom Power Devices
  - Transfer Switches

- Software
  - Wavelet Theory
  - Expert Systems
  - Fuzzy Logic
  - Genetic Algorithms
  - Neural Network
2.6 POWER QUALITY ASSESSMENT

Power quality assessment methods are a hot research area. Proliferation of non-linear loads and their financial impact has made the stakeholders of the electric utility to be more apprehensive about power quality. Power quality deviations degrade the performance and efficiency of customer loads and utility equipment. Improvement of power quality has a positive impact on sustained profitability of the distribution utility on the one hand and customer satisfaction on the other. To assess the power quality of a system, it is desirable to understand the factors, total demand distortion and power factor.

TDD, which is recommended in the IEEE Standard 519–1992 (1993), is an index that quantifies the harmonics distortion level in the current waveform. Power factor is fundamentally an index of the quality of power that allows a user in a deregulated market to select an electricity provider on the basis of level of quality of the delivered power.

2.7 TOTAL DEMAND DISTORTION

It is useful to measure and limit harmonics in electric power systems in order to avoid operational problems and equipment deterioration. The general intent of IEEE Standard 519 is to limit harmonic current from individual customers and to limit distortion of the system voltage provided by
utilities. Customers should not cause excessive harmonic currents to flow and utilities should provide a nearly sinusoidal voltage. The goal of applying the harmonic limits specified in IEEE Standard 519 is to prevent one customer from causing harmonic problems for another customer or for the utility.

When talking about harmonics in power installations it is the current harmonics that are of most concern because the harmonics originate as currents and most of the ill effects are due to these currents. No useful conclusions can be drawn without the knowledge of the spectrum of the current harmonics but it is still common to find only the THD figures quoted.

THD is a measure of how much harmonic content is there in a waveform. The THD of a waveform is given by

\[
\text{THD} = \sqrt{\frac{V_{\text{rms}}^2 - V_{1,\text{rms}}^2}{V_{1,\text{rms}}^2}}
\]  

(2.1)

where, \(V_{\text{rms}}\) is the RMS value of the total waveform and \(V_{1,\text{rms}}\) is the RMS value of the first harmonic. The THD of a sine wave is 0 \% and the THD of a square wave is 48 \%. When harmonics propagate around a distribution system, they do so as voltages. It is very important that both voltage and current values are measured and that quoted values are explicitly specified as voltage and current values. Conventionally, current distortion measurements are suffixed with ‘I’, e.g. 35% THD\(_I\), and voltage distortion figures with ‘V’, e.g. 4% THD\(_V\).

The Total Demand Distortion (TDD) was introduced in IEEE Standard 519 (IEEE 1993) to measure the current distortion level instead of the THD that was introduced in the earlier version of the IEEE Standard 519 (IEEE 1981). According to IEEE Std. 519 (IEEE 1993), the TDD is defined
as the total root-mean square harmonic current distortion in percent of the maximum demand load current.

\[
TDD = \sqrt{\sum_{h=2}^{\infty} \frac{I_h^2}{I_L^2}}
\]  
(2.2)

where, \(I_L\) is the maximum demand of load current (fundamental frequency component) at the point of common coupling (PCC). The permissible distortion limits for the TDD depend on the ratio of the maximum short circuit current to the maximum demand load current, which is \(I_{sc}/I_L\). Therefore TDD values alone are not enough to reveal whether the current distortion is within the allowable limits or not.

The THD expresses harmonics as a percent of fundamental (50/60 Hz) current at the time of the measurement. The TDD expresses harmonics as a percent of maximum demand load current. The difference between THD and TDD is important because it prevents a user from being unfairly penalized for harmonics during periods of light load. Some loads such as drives have higher THD at light load even though they are drawing less total harmonic current in amperes and thus causing less harmonic voltage distortion. The consideration of minimizing the harmonic current production during equipment design has taken on greater importance, as reflected by technological improvements in fluorescent lamp ballasts, adjustable speed drives, battery chargers, and uninterruptible power supplies (UPS).

### 2.8 POWER FACTOR

Power factor is a power quality issue in that low power can sometimes cause equipment to fail. In many instances, the cost of low power factor can be high; utilities penalize facilities that have low power factor
because they find it difficult to meet the resulting demands for electrical energy. Operating in a high power factor environment ensures that the power system is functioning efficiently. It also makes economic sense. Apparent power in an electrical system can be defined as being equal to voltage times current. Power factor may be viewed as the percentage of the total apparent power that is converted to real or useful power.

Apparent power and power factor are not physical quantities by themselves, but they characterize physical phenomena, however in a way that may depend on the situation considered. The caution is that in some special situations the same quantity may characterize more than a single phenomenon, but this is not necessarily the case in other or more general situations. Hence it may be necessary, to generalize a single concept, introduced for particular situations, by more than one concept in more general situations. In sinusoidal situations, power factor definition is unique and expressive. However in non-sinusoidal situations and/or nonlinear load different power factors are proposed to express these situations. New definitions of electrical quantities in non-standard situations are needed because of the changes in the situation in power systems. Definitions of the power factor related to various quality aspects may be useful to compare and optimize the effectiveness of techniques for compensation of the loads with respect to the various quality aspects. The capability of present day microprocessors also enable manufacturers to design equipments capable of metering electrical quantities even when they correspond to advanced mathematical models. Therefore there is a need for alternative definitions of apparent power and power factor under these conditions.

For a linear single-phase system supplied from sinusoidal source, there is a clear definition for the apparent power and power factor. Let the voltage and current be given by
\[ v(t) = \sqrt{2} V_{\text{rms}} \sin(\omega t) \]  
\[ i(t) = \sqrt{2} I_{\text{rms}} \sin(\omega t + \varphi) \]  

The active power is defined as the useful power transferred from the source to the load. The active power is equal to

\[ P = V_{\text{rms}} \cdot I_{\text{rms}} \cdot \cos(\varphi) \cdot \frac{1}{T} \int_0^T v(t) \cdot i(t) \, dt. \]  

Here \( T \) is the period of the sinusoidal wave. The apparent power is defined (Willems 2004) as the maximal active power that can be transmitted for the given rms value (or magnitude) of the voltage and given rms value (or magnitude) of the current. It can be expressed as

\[ S = V_{\text{rms}} \cdot I_{\text{rms}} \]  

The power factor is then defined as the ratio

\[ \text{PF} = \frac{P}{S}. \]  

In sinusoidal situations, the power factor can be used as a measure of the efficiency of the utilization of the equipment, the efficiency of the power transmission, and the oscillatory character of the power transfer (Willems 2004 and Willems 2005). On the other hand, in Non-Sinusoidal situations, the power factor as defined cannot handle these properties at the same time. Willems (2005) proposed separate definitions for the apparent power and the power factor to characterize the power transmission efficiency and the power oscillations. He defined the transmission efficiency power factor (TEPF) as
Here, $P$ and $S$ are the active and apparent power as defined in equations (2.5) and (2.6). Willems also defined the rms power as the rms value of the instantaneous power which can be shown to be given by

$$S = \sqrt{P^2 + \frac{1}{2}}S^2.$$  \hspace{1cm} (2.9)

In order to evaluate the oscillatory behavior of the transmitted power, Willems defined the oscillating power as the rms value of the oscillating components of the instantaneous power

$$S_{osc} = \left(\frac{1}{\sqrt{2}}\right)S.$$  \hspace{1cm} (2.10)

Therefore, the oscillation power factor (OSCPF) is defined as the ratio

$$OSCPF = \frac{P_{rms}}{TEPF} \frac{P}{\sqrt{P^2 + S^2_{osc}}} \frac{TEPF}{\sqrt{(1/2) + TEPF^2}}.$$  \hspace{1cm} (2.11)

Note that the maximum value of the oscillation power factor is 0.816 and occurs in case of pure resistive load which explains the unavoidable oscillation even in the sinusoidal situation while the minimum value is zero which occurs in case of the pure reactive element where there is continuous oscillation with zero average or active power. Another important power factor that is useful for monitoring separately the fundamental power from the harmonic power as well as easily applying in many engineering economic techniques such as power factor correction was recommended by the IEEE Working Group (IEEE 1996). They recommended the separation of the
fundamental power components from the non-fundamental components and hence calculating the fundamental active and fundamental apparent power as

\[ P_1 = V_1 \cdot I_1 \cdot \cos \varphi_1, \quad S_1 = V_1 \cdot I_1. \]  

(2.12)

The displacement power factor (DPF) is defined by the ratio

\[ \text{DPF} = \frac{P_1}{S_1}. \]  

(2.13)

Typically, electrical utilities charge a penalty for power factors below 0.95. The method of calculating the penalty depends on the utility. In some cases, the formula is simple, but in other cases the formula for the power factor can be much more complex. The alternative definitions of apparent power and power factor are very useful in making a systematic approach for the assessment of power quality using fuzzy logic (Zimmermann 1996) and Adaptive Neuro-Fuzzy Inference System (Jang 1993), particularly in the current deregulated scenario. Fuzzy approaches to real problems are an effective alternative to previous, traditional methods.