2.1 INTRODUCTION

Power Quality (PQ) comprising of voltage and current qualities is of increasing concern to utilities and their customers. The Voltage Quality describes the way in which the power supply affects the equipments and it is a part of the quality of the supply. Current Quality describes the way in which the equipment affects the power system and is a part of the “quality of consumption”. Most of the PQ problems are due to harmonics. The increased harmonic content in the power system has prompted the need to give them greater attention.

In order to get an accurate picture of PQ, field measurements are needed in industrial environment. Two industries having nonlinear loads are chosen for the present study. These measurements contribute to the overall understanding of PQ problems. It also helps in the process of getting both utility and customer power systems to work together in developing solutions to the problems. Hence PQ field measurements and assessment (Arrillaga et al 2000) are performed for detecting and locating the PQ disturbances.

The analysis and identification of PQ disturbances based on visual inspection of the waveforms are found to be laborious, inefficient and error prone. The current state of the art to detect PQ disturbances available in the commercial market is based on the implementation of the Discrete Fourier
Transform (DFT) by various algorithms. However, the Fourier Transform (FT) is less efficient in tracking signal dynamics and due to lack of time-scale resolution, the DFT based analysis has been replaced by Wavelet Transform (WT). The non-stationary disturbances such as transient behaviour, cavities and discontinuities are closely investigated by wavelet transforms. When WT is applied to PQ disturbance signal and it produces a Multi Resolution Decomposition (MRD) matrix, which contains time domain information of the signal at different scales. This property has made wavelets a promising tool for detecting and extracting disturbance features for various types of PQ events.

This chapter emphasizes on the need for developing PQ centre to detect, identify, understand and solve PQ issues. The details of the investigations carried out during the industrial PQ survey and the wavelet approach to PQ assessment are also discussed.

### 2.2 NEED FOR POWER QUALITY CENTRE

In India, the awareness of the PQ exists amongst a very small section of electronic equipment users and manufactures. In general, the customers do not have the expertise or time to focus on identifying and solving the PQ problems. Many manufactures are also unaware of the type of disturbances that occur on power systems. Hence, it is an utmost need of the hour to develop a PQ centre for addressing various PQ issues in the power system. Also, it is the commitment of the educational institutions to develop such a centre to investigate and provide facility for every one to work together in developing solutions to these problems. The investigations will usually involve problems of compatibility between supply system and PQ requirements of specific equipment (or) process. The investigation requires monitoring, to characterize both the PQ and the equipment sensitivity.
Simulations are needed for extrapolation to other system conditions and to evaluate possible solutions from technical perspective. Figure 2.1 illustrates the general procedure for performing power quality investigations. Once the equipment sensitivity is known and the system performance is characterized, possible techniques to solve the PQ problems could be identified.

![Diagram of the general procedure for evaluating PQ problems](image)

**Figure 2.1 Procedure for evaluating PQ problems**

Analysis carried out in the PQ centre addresses the electric utility engineers about the sensitivity and characteristics of the end-use equipment. The collaborative project with industries and PQ centre has improved PQ at both utility and customer side.

### 2.3 INVESTIGATION OF POWER QUALITY ON LOW-TENSION INDUSTRY

The usage of solid state devices has pervaded the industrial, commercial and domestic sector. This is especially true in commercial
buildings such as a Software park, where the use of Uninterruptible Power Supplies (UPS), printers, scanners, fax machines, etc., are widespread. This has resulted in significant increase in harmonic content raising serious PQ issues. Regardless of the industrial sector polluting the PQ, the commercial sector also causes noticeable PQ problems. PQ monitoring is designed to identify and eliminate the disturbances on both utility as well as consumer side. Monitoring a commercial building provides information about the system disturbances, disturbance effects on the functioning of equipment and solutions to eliminate them. Even if the power system supplies a sinusoidal voltage of constant magnitude and frequency to a customer, depending on the load, the current drawn may or may not be sinusoidal. Also, non-sinusoidal current flowing through line impedance corrupts the voltage. All the above emphasize a detailed study on PQ disturbance data to predict the performance of the different types of loads such as motor loads, UPS, etc.

This thesis presents the field study carried out on the UPS loads in Software park, Chennai, Tamil Nadu, India. There are three types of UPS systems in use namely off line, line interactive and on line. The off line and line interactive type UPS are directly connected to load without any frequency or harmonic correction. The harmonics present in mains are passed on to the loads. Similarly the load harmonic currents are passed on to incoming line without any filtering. Hence, UPS systems are mostly associated with harmonic problems.

The single line diagram of the Software park chosen for the field study is shown in Figure 2.2. There are six transformers each of 2500 kVA, 33 kV / 433V feeding the loads in Software park. Capacitor banks of 600 kVar are connected on the secondary side of each transformer. The total load sanctioned is 9150 kVA and the maximum demand reached so far is 7500 kVA. The short circuit current (Isc) rating of the transformer-6 (T-6) is
43.52 kA and the load current \( (I_{load}) \) is 3333.53 A. Hence, the Short Circuit Ratio (SCR) for the transformer-6 is 22.35 that fits in the range (20-50) mentioned in Table A1.1 (Appendix 1). The transformers-1, 2, 3 and 4 are dedicated for lighting and induction motor loads. There are medium power UPS and high power UPS connected with both the transformers-5 and 6. The measurements are carried out on the input side of UPS-1 (OFF line type) of 60 kVA rating, connected through UPS Raising Main-1 (UPS RM-1) to a dedicated transformer-5. UPS-4 (line interactive type) of 400 kVA connected through UPS Raising Main-4 (UPS RM-4) to another dedicated transformer-6. Field measurement studies are conducted to measure power factor, current harmonics, voltage harmonics and percentage THD to evaluate the influence of the UPS in the PQ pollution. The field measurements provide useful data for trouble shooting PQ problems in terms of distorted wave shapes, low power factor and high THD.

### 2.3.1 Equipment used for Field Measurement

Measurements are made with the harmonic analyzer MAVOWATT 45-S and FLUKE 41/43-B for the record of parameters such as real power, apparent power, reactive power, RMS current, true power factor and percentage THD of voltage and current.
Figure 2.2 Single line diagram of the Software park, Chennai, Tamil Nadu, India
2.3.2 Measurements and Observations made at the Software park

Field measurements are conducted on the input side of UPS-1 of 60 kVA rating and UPS-4 of 400 kVA rating to measure input current THD and input power factor operating at partial load. The test parameters comparison for both the UPS and the waveforms recorded at R-phase on the input side of UPS-1 (60 kVA) are shown in Table 2.1 and Figure 2.3 respectively. The current harmonics of the order 5 and 7 are found predominant compared to other harmonics for the UPS-1 operating on Tamil Nadu State Electricity Board (TNEB) utility supply (Figure 2.3(c)). The Crest Factor (CF) measured was 1.9 and is found to exceed the limits. The input true power factor is found to be low (< 0.75).

The input current THD and voltage THD trend plots were recorded using the analyser at 10 seconds interval for a period of 16 hours. The current THD trend and voltage THD trend at the R-phase of 60 kVA UPS-1 are shown in Figures 2.4 and 2.5 respectively. The IEEE 519-1992 for current and voltage distortion limits are furnished in Table A1.1 and Table A1.2 respectively. These Tables A1.1 and A1.2 are given in Appendix 1. When compared with IEEE 519 standards as shown in Table A1.1, it is observed that percentage current THD is 8 to 9 times above the allowable THD value of 8% and voltage THD is 2 to 3 times above the allowable THD value of 5% (Figures 2.4 and 2.5). Field studies done at the UPS systems signifies that a suitable active power filter has been suggested for design to suppress the current harmonic content within the limits and to improve the input power factor of UPS. The design of shunt active power filter for current harmonics mitigation and input power factor improvement in the UPS-4 is discussed in section 6.1 of Chapter 6.
Figure 2.3  Waveforms captured at the input side of 60 kVA UPS
(a) Voltage and current waveforms of R-Phase (b) Power of R-Phase
(c) I-THD in R-Phase (d) V-THD in R-Phase

Table 2.1  Comparison of the parameters measured in UPS

<table>
<thead>
<tr>
<th>UPS Load Capacity</th>
<th>Phase</th>
<th>RMS Profile</th>
<th>Power Profile</th>
<th>True Power Factor</th>
<th>DPF</th>
<th>Current THD in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPS-1 60 kVA (Input Side)</td>
<td>R</td>
<td>35.1 A 233.6 V</td>
<td>5.88 kW 8.21 kVA</td>
<td>0.71</td>
<td>0.87</td>
<td>53.80</td>
</tr>
<tr>
<td>UPS-4 400 kVA (Input Side)</td>
<td>R</td>
<td>110.0 A 238.0 V</td>
<td>17.40 kW 25.80 kVA</td>
<td>0.67</td>
<td>0.83</td>
<td>55.10</td>
</tr>
</tbody>
</table>
The voltage harmonics, current harmonics and power factor are measured on each of the secondary side (433V) of transformers-3, 5 and 6 operating under TNEB supply to study the effect of harmonic pollutants injected into the source. The power factor and THD measurements are recorded at the transformer secondary without and with capacitor banks in the network. Table 2.2 shows the comparison of individual harmonics measured at the secondary side of transformers-3, 5 and 6 without capacitor banks in the R phase. The percentage THD and power factor measured at the secondary side of transformers-3, 5 and 6 without capacitor banks in the R-Phase is given in Table 2.3. The UPS load occupants are located only at the transformers-5 and 6. Many high power UPS loads are located at transformer-6. Hence, the transformer-6 is chosen for a detailed study.
Figure 2.6 shows the percentage current THD trend measured at the secondary side of transformer-6. The current harmonics and the frequency response of current harmonics recorded at the three phases of the secondary side of transformer-6 are given in Table 2.4 and Figure 2.7 respectively. It is found that 5 and 7 current harmonic orders are predominant as shown in Figure 2.7.

Table 2.2 Comparison of harmonics measured at the secondary side of transformers 3, 5 and 6

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Secondary Side of T-3</th>
<th>Secondary Side of T-5</th>
<th>Secondary Side of T-6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I (%)</td>
<td>V (%)</td>
<td>I (%)</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>7.7</td>
<td>0.8</td>
<td>2.6</td>
</tr>
<tr>
<td>5</td>
<td>2.6</td>
<td>2.2</td>
<td>10.9</td>
</tr>
<tr>
<td>7</td>
<td>0.9</td>
<td>0.5</td>
<td>4.4</td>
</tr>
<tr>
<td>9</td>
<td>1.7</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>11</td>
<td>0.9</td>
<td>0.3</td>
<td>3.5</td>
</tr>
<tr>
<td>13</td>
<td>1.7</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>15</td>
<td>0.9</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>17</td>
<td>0.9</td>
<td>0.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 2.3 Comparison of percentage THD and power factor measured at the secondary side of transformers 3, 5 and 6

<table>
<thead>
<tr>
<th></th>
<th>Secondary Side of T-3</th>
<th>Secondary Side of T-5</th>
<th>Secondary Side of T-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-THD (%)</td>
<td>19.02</td>
<td>20.60</td>
<td>21.62</td>
</tr>
<tr>
<td>V-THD (%)</td>
<td>4.91</td>
<td>8.62</td>
<td>10.31</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.88</td>
<td>0.87</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Waveform distortions at the secondary side of transformers, THD of both voltage and current were monitored without and with the capacitor
banks in the system. Capacitor banks of 600 kVAr are available on the secondary side of each transformer. Table 2.5 shows the comparison of THD and power factor without and with capacitor banks in the secondary side of transformer-6. The addition of the capacitor banks in the network caused small increase in current. It is the reason for the increase in current THD levels at transformer secondary point (22.9% to 35.3%) (Table 2.5). Also, it increased the network impedance and resulted in increased voltage THD levels at transformer secondary point (5.8% to 9.5%) (Table 2.5).

![Figure 2.6 Percentage I-THD Vs duration for the measurement taken in R-Phase](image)

![Figure 2.7 Frequency response of current harmonics recorded at the secondary side of transformer-6](image)
Table 2.4  Current harmonic recorded at the secondary side of transformer-6

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Current in (%)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>Y</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3.39</td>
<td>1.38</td>
<td>4.32</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>13.21</td>
<td>14.14</td>
<td>15.11</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8.82</td>
<td>10.69</td>
<td>11.15</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.00</td>
<td>0.00</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.02</td>
<td>1.03</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.34</td>
<td>1.03</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.68</td>
<td>0.35</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.5  Comparison of percentage I-THD, percentage V-THD and Power Factor for without and with capacitor banks

<table>
<thead>
<tr>
<th>Secondary Side of T-6</th>
<th>Without Capacitor Banks</th>
<th>With 600 kVAr Capacitor Banks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I-THD in %</td>
<td>V-THD in %</td>
</tr>
<tr>
<td>R</td>
<td>22.9</td>
<td>5.8</td>
</tr>
<tr>
<td>Y</td>
<td>24.3</td>
<td>5.9</td>
</tr>
<tr>
<td>B</td>
<td>25.4</td>
<td>5.9</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.89</td>
<td></td>
</tr>
</tbody>
</table>
2.4 INVESTIGATION OF POWER QUALITY ON HIGH-TENSION INDUSTRY

This work presents the field measurements carried out at various locations of the steel plant such as Point of Common Coupling (PCC), disturbing load points like AC Electric Arc Furnace (AC EAF), Arc furnace (AF) bus, Induction Furnace (IF) bus and the machine shop at the Main bus. PQ problems noticed during the investigations include poor power factor, harmonic distortion in load current and load voltage due to furnace. EAF produce significant harmonics, which leads to additional loading resulting in the rise of temperature of the transformer. This leads to the deterioration of insulation and consequent reduction in the life of the transformer. Data collected during these investigations have been analyzed and presented in graphical and tabular form.

The simplified single line diagram of the steel plant considered for the study is shown in Figure 2.8. The fault level is 160 MVA at the feeding substation. The SCR ratio for the steel plant network is 55 which fits in the range (50 < 100) mentioned in Table A1.1 (Appendix 1).

2.4.1 Details of the AC EAF

Investigations were conducted in the steel plant having a furnace of 4 tonne capacity connected to 2 MVA, 11kV/250 V dedicated transformer. The voltage harmonics, current harmonics, THD and power factor are measured on the secondary side of the transformer. The EAF is a highly nonlinear load resulting in PQ problems. The arc furnace operations are divided into three stages. They are detailed as follows.
Figure 2.8 Single line diagram of the steel plant, Chennai, Tamil Nadu, India
i. Drilling period – The power consumption during this period is very less. In a typical arc furnace this period lasts between 3 and 4 minutes. It is observed that irregular variations in the electric arc occur during this period. This is due to the heterogeneous nature of the scrap material.

ii. Melting period - During this period, the electric arc is surrounded by melting scrap. This forms more homogeneous material than in the drilling period. In this period, full voltage and power is used. It lasts between 25 and 30 minutes.

iii. End of melting period and reheating - This period uses low voltage and higher current than the melting period. It involves short arcs and lasts for about 30 minutes.

The total power consumed by the furnace during the entire stage of operation is divided into six baskets. The active power consumed by the EAF based upon the voltage and current measurements at the secondary side of the furnace transformer is shown in Figure 2.9. Measurement was conducted for one complete heat cycle of five hours duration. The graph reveals the stochastic nature of the arc furnace over one complete heat cycle. The melting process in a 4 tonne AC EAF is shown in Figure 2.10.
2.4.2 Measurements and observations made at the steel plant

The furnace load varies irregularly and abruptly from cycle to cycle, especially in the early and mid period of melting. It is regarded as an
unbalanced time varying, nonlinear load. Thus, the load current contains harmonics whose magnitude changes randomly with time. Harmonic measurements are made during melting and refining periods of EAF. The individual harmonics and percentage THD of current and voltage, power factor at the PCC, IF bus, Main bus (machine shop) are compared in Tables 2.6 and 2.7 respectively. The voltage distortion is almost negligible at PCC when compared with Main bus and IF bus. The intensive field measurement study at the IF bus signifies the predominant presence of 3, 5 and 7 current harmonic orders. A low operating power factor of 0.56 is found at the IF bus when compared with Main bus and PCC. The study at machine shop reveals the predominant presence of 5 and 7 order current harmonics. A better operating power factor of 0.81 is found at the Main bus due to existing power factor correction capacitor banks when compared with PCC and IF bus.

**Table 2.6 Comparison of individual harmonic content**

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>PCC</th>
<th>IF bus</th>
<th>Main bus (machine shop)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current (%)</td>
<td>Voltage (%)</td>
<td>Current (%)</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>0.07</td>
<td>0.53</td>
<td>3.21</td>
</tr>
<tr>
<td>5</td>
<td>2.03</td>
<td>1.14</td>
<td>9.51</td>
</tr>
<tr>
<td>7</td>
<td>0.07</td>
<td>0.26</td>
<td>4.62</td>
</tr>
<tr>
<td>9</td>
<td>1.35</td>
<td>0.11</td>
<td>1.82</td>
</tr>
<tr>
<td>11</td>
<td>0.07</td>
<td>0.09</td>
<td>0.71</td>
</tr>
<tr>
<td>13</td>
<td>0.00</td>
<td>0.10</td>
<td>0.41</td>
</tr>
<tr>
<td>15</td>
<td>1.35</td>
<td>0.04</td>
<td>0.72</td>
</tr>
<tr>
<td>17</td>
<td>0.07</td>
<td>0.01</td>
<td>0.61</td>
</tr>
</tbody>
</table>
The percentage THD and power factor for the three phases during melting and refining stages of furnace at full load condition is given in Table 2.8. The predominant individual harmonic content of furnace and percentage THD of current and voltage during furnace operations are given in Table 2.9 and 2.10 respectively. The predominant presence of 2, 3, 5, 9 and 15 order harmonics is observed during melting stage. The analysis also shows that the harmonic amplitude decreases as the harmonic order increases. As the pool of molten metal grows, the arc becomes more stable, resulting in steady currents with less distortion and harmonic. The current waveform becomes symmetrical about the time axis. Maximum current THD of 41.91% is observed during the melting stage of EAF. A sporadic voltage THD value as high as 28.54% is recorded during times of erratic furnace arcing conditions. The trend of current THD during melting and refining stages is shown in Figure 2.11 and Figure 2.12 respectively. A poor operating power factor is found at AF bus during melting and refining stages of EAF as shown in Table 2.8. Hence, it is necessary to install filter banks at AF bus to improve the power factor and mitigate the current and voltage harmonics during the EAF operation.
Table 2.8  Summary of data collected from 2 MVA EAF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase</th>
<th>2 MVA EAF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Melting</td>
</tr>
<tr>
<td>%THD in Current</td>
<td>R</td>
<td>41.91</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>35.69</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>36.19</td>
</tr>
<tr>
<td>%THD in Voltage</td>
<td>R</td>
<td>28.54</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>25.23</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>22.41</td>
</tr>
<tr>
<td>Power Factor</td>
<td>R</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 2.9  Individual harmonic content of Arc Furnace

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Furnace Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Melting (Active Arc)</td>
</tr>
<tr>
<td></td>
<td>Current (%)</td>
</tr>
<tr>
<td>2</td>
<td>10.7</td>
</tr>
<tr>
<td>3</td>
<td>14.3</td>
</tr>
<tr>
<td>5</td>
<td>17.1</td>
</tr>
<tr>
<td>9</td>
<td>7.1</td>
</tr>
<tr>
<td>15</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Table 2.10 Total harmonic distortions during Arc Furnace operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Melting (Active Arc)</th>
<th>Refining (Stable Arc)</th>
<th>Allowable Limit of IEEE 519-1992</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current THD (%)</td>
<td>41.91</td>
<td>38.81</td>
<td>12.00</td>
</tr>
<tr>
<td>Voltage THD (%)</td>
<td>28.54</td>
<td>15.32</td>
<td>5.00</td>
</tr>
</tbody>
</table>

Figure 2.11 Percentage current THD trend during melting

Figure 2.12 Percentage current THD trend during refining

Power quality field measurements have shown that the majority of problems are localized within customer facilities. Hence, an intelligent analysis tool with high level of engineering expertise is required to
understand, identify and classify various PQ problems which are dealt with in the next section.

2.5 WAVELET APPROACH TO POWER QUALITY ASSESSMENT (Sharmeela et al 2006)

This approach decomposes a given disturbance signal into a smoothed and detailed version of the original signal. The performance evaluation of the proposed approach has been conducted under a variety of PQ disturbances including sag, swell, harmonics, flicker and impulsive transient on the basis of simulations in MATLAB environment and recorded PQ disturbances using standard equipments. The evaluation results demonstrate the effectiveness of the proposed scheme.

2.5.1 Wavelet Approach for Power Quality Disturbances

Wavelet analysis requires a two-function description, the scaling \( \varphi(x) \) and the wavelet \( \psi(x) \). The function \( \varphi(x) \) is a solution of a two-scale difference equation.

\[
\varphi(x) = \sqrt{2} \sum_{k \in \mathbb{Z}} h_k \varphi(2x - k) \tag{2.1}
\]

with normalization \( \int_{\mathbb{R}} \varphi(x) \, dx = 1 \). The function \( \psi(x) \) is defined by

\[
\psi(x) = \sqrt{2} \sum_{k \in \mathbb{Z}} (-1)^k h_{1-k} \varphi(2x - k) \tag{2.2}
\]

The coefficients \( h_k \) are called the filter coefficients, and it is through careful choice of these coefficients the wavelet functions with desired
properties are constructed. A wavelet system is an infinite collection of translated and scaled versions of $\phi$ and $\psi$ defined by:

$$\psi_{j,k}(x) = \sqrt{2^j} \phi(2^j x - k), \quad j, k \in \mathbb{Z}$$  \hspace{1cm} (2.3)

$$\psi_{j,k}(x) = \sqrt{2^j} \psi(2^j x - k), \quad j, k \in \mathbb{Z}$$  \hspace{1cm} (2.4)

where $\mathbb{Z}$ is the set of integers.

It is possible to construct finite-length sequences of filter coefficients satisfying all of these conditions, resulting in compactly supported $\phi$ and $\psi$ that have space-frequency localization. The derived wavelet basis is well localized in space since the total energy of a wavelet is restricted to a finite interval. This section presents a novel approach for disturbance detection and classification in a power system network using wavelets. The Discrete Wavelet Transform (DWT) is performed by the decomposition of high pass filters and the scaling is performed by the decomposition of low pass filters as shown in Figure 2.13. One of the filters is a high pass filter called the wavelet filter and the other is a low pass filter called the scaling filter.

This filter organization is called as filter bank. The wavelet decomposition by the filter bank provides computation savings. One half of the coefficients belong to the details (the higher frequency components) and the other half of the coefficients to the approximations (the lower frequency components) of the signal. Down-sampled outputs of the high pass filter are called detail coefficients. Down-sampled outputs of the low pass filters are called approximation coefficients. The detail and approximation coefficients
provide the exact representation of the signal and no information is lost during down sampling. Decomposing the approximation coefficients gives a further level of the detail and approximation coefficients (Burrus et al 1998 and Rao et al 2004).

![Figure 2.13 One-stage signal decomposition](image)

The reconstruction of the details is performed by up-sampling the detail coefficients and filtering the un-sampled coefficients using reconstruction of high-pass filters. An up-sampled signal has approximately twice the length of the signal before the up sampling. The reconstruction is performed by up sampling the approximation coefficients and filtering the un-sampled coefficients using reconstruction of low pass filters is as shown in Figure 2.14.

![Figure 2.14 One-stage signal reconstruction](image)

The wavelet transform analysis is sensitive to signals with irregularities but is “blind” to constant signals. This property is very useful to
detect and localize power quality disturbances. The disturbances are classified according to the frequencies that characterize the power quality events. The filtered signal of a particular level in the wavelet decomposition tree is used to analyze the presence of a particular class of power quality disturbance. An appropriate level has to be selected for each class of disturbance. Thus, for detecting and classifying various disturbances, different filter levels are taken and analyzed. These filtered signals contain information about the PQ disturbances and the proposed method uses this signal to detect and classify the disturbances.

2.5.2 Disturbance Modeling and Analysis

2.5.2.1 Objective

The objective of wavelet approach is to detect and classify the PQ disturbances. The power system network encounters various kinds of power quality disturbances that are classified according to frequencies, which characterize the PQ events. The low frequency disturbances are voltage fluctuations, voltage sag and voltage swell. High frequency phenomena include transients and harmonics. Thus, the disturbances characterized by frequencies are detected by using appropriate filter levels of the wavelet filter bank. There may be additional problems associated with PQ, which are not considered in this work.

2.5.2.2 Power quality disturbances

The characteristics and feasibility of the proposed algorithm is analyzed using five different synthesized power quality disturbance signals. In this section, a brief explanation of the five synthesized disturbance signals is presented.
The deviation from a perfect sine wave is represented by harmonics, which are nothing but sinusoidal components having a frequency that is an integral multiple of the fundamental frequency. Harmonics, the by-products of power electronic converters is shown in Figure 2.15(a). Voltage fluctuation, associated with visual “flicker” in lights, is a modulation of the fundamental component caused by reactive load variations. A typical fluctuating voltage is shown in Figure 2.15(b). Voltage swells are defined as the increase of fundamental frequency voltage for a short duration lasting for half a cycle to 1 min. The typical values are 110-180% of the rated system voltage. A 40% swell disturbance lasting for 400ms is simulated and shown in Figure 2.15(c).

Voltage sag caused by faults in the network or by a sudden large change of load is described as a drop of 10-90% of the rated system voltage lasting for half a cycle to 1 min. 40% voltage sag lasting for 20 cycles is shown in the Figure 2.15(d). A transient is that part of change in a system variable that disappears during transition from one state operating condition to another. Transients are classified into two categories. They are impulsive transients and oscillatory transients. In this thesis, impulsive transient is considered for analysis. An impulsive transient is a sudden, non-power frequency change in unipolar voltage and current. The polarity of the transient can be positive or negative. Impulsive transients have a very fast rise time as well as very fast decaying time. The waveform with impulsive transient occurring at 80th ms is shown in Figure 2.15(e).
Figure 2.15  Various power quality disturbances  
(a) Harmonics  
(b) Voltage flicker  
(c) Voltage swell  
(d) Voltage sag  
(e) Impulsive transient

2.5.2.3  Modeling of power quality disturbances

The general prototype of the test system is given in Figure 2.16 for generating harmonics, voltage sag, voltage swell, voltage flicker and impulsive transient. It comprises of 33kV/11kV transmission system represented by Thevenin’s equivalent feeding three 11kV feeders connected at BUS-1. There are five locations in this system chosen for observation.

The Feeder-1 feeds the steel plant consisting of AC Electric Arc Furnace (EAF) of 4 tonne capacity connected to the furnace at BUS-2 through
a 2 MVA, 11 kV/250 V dedicated transformer. Here EAF is the non-linear load, producing voltage fluctuations in the distribution system. It is observed that, when the furnace is in operation, the voltage fluctuates at BUS-2 and other residential consumers supplied from BUS-1 experience visible lighting (voltage) flicker. Breaker Brk-1 controls the connection of Feeder-1 to BUS-1. The connection of Feeder-2 to BUS-1 is controlled by Brk-2 operation. It consists of a six-pulse converter connected to BUS-3 and generates current harmonics for the analysis. Feeder-3 comprises of an 11kV/230V transformer supplying through Feeder-5 to LOAD-1 and Feeder-6 to LOAD-2. The Brk-3 controls the connection of Feeder-3 to BUS-1. The system frequency and the peak of the supply voltage are taken to be 50 Hz and 230 V respectively. The LOAD-1 and LOAD-2 are taken to be balanced R-L load.

There is an impact of lightning near the secondary side of the 11kV/230V transformer located at feeder 3 resulting in momentary spike in the BUS-4 voltage known as impulsive transient. When the system is operating at steady state, a Single Line-Ground (SLG) fault through a fault resistance of 0.66 Ω has been created at R-phase in BUS-5. The duration of the fault is 20 cycles. The R-phase at BUS-5 experiences voltage sag caused by this SLG fault. After this period, the system is restored to its pre-fault state. However, the other phase voltages of BUS-5 exhibit a voltage swell. Thus, the voltage swell considered here is due to the temporary rise in the voltage of an unfaulted phase during the SLG fault.
2.5.2.4 Choice of wavelet

The choice of mother wavelet plays a significant role in detecting and localizing various types of disturbances. Each of these mother wavelets has a special property that makes it suitable for a special kind of signals. In power quality disturbance detection, the disturbances are generally classified into harmonics, fast transients and slow transients. A wavelet with flat band-pass filter characteristics and a cut-off as sharp as possible are required to analyse harmonics. The ‘Meyer’ wavelet has these properties and it is applied to detect the presence of harmonics. In the fast transient case, the waveforms are marked with sharp edges, abrupt, rapid changes and a fairly short duration in time. In this case, shorter wavelets such as Daubechies4 (Db4) and ‘Db6’, due to their compactness are particularly good in detecting and localizing such disturbances. In the slow transient case, the waveforms are marked with a slow change or smooth amplitude change. ‘Db4’ and ‘Db6’ are not able to catch such disturbances. However, if longer wavelets such as ‘Db8’ and ‘Db10’ are used, the time interval is long enough and such wavelets senses the slow changes.
2.5.2.5 Methodology for disturbance detection

In the proposed scheme multiple filtering is applied to the signal and the resulting filtered signals are processed to detect and classify the disturbances present in the signal. The disturbances are passed through the four-level wavelet filter and then through soft-thresholding. This process removes the noises with lower magnitude than the feature carrying information. In this scheme, the disturbances are classified according to frequencies that characterize the power quality events. The disturbance signals are recovered from the sub band level of the analysis filter, based on the frequency of each disturbance. Each disturbance has unique compatibility with different wavelet functions.

The transient disturbances are better detected by using ‘Db3’ wavelet. The detail empirical coefficients are threshold using soft-threshold at the first level wavelet sub band, which carries the high frequency transient disturbance. The voltage flicker is obtained in the fourth level approximate empirical coefficients of the wavelet sub band using ‘Db5’ wavelet function. The integral multiples of 50 Hz, called harmonics are identified in first level detail empirical coefficient of the wavelet sub band using ‘Meyer’ wavelet. The fundamental power frequency present in the input sag and swell disturbance signal is identified in the first level approximation empirical coefficients of the wavelet sub band using ‘Meyer’ or ‘Db10’ wavelet function. The magnitude variation of fundamental power frequency gives the presence of voltage sag and swell.

The recovered signal from each wavelet block is converted into a train of pulses of one cycle with unique amplitude, A {x(n)} where x(1), x(2), x(3), x(4) and x(5) are the Pulse Amplitude (PA) of impulsive transient,
flicker, harmonic, sag and swell disturbances respectively, by comparing with Thresh$_p$. A $\{x(n)\}$ varies depending on the type of disturbance.

The Thresh$_p$ is the threshold limit assigned to each disturbance and is calculated as,

$$\text{Thresh}_p = \alpha \times \text{Voltage}$$  (2.5)

where parameter $\alpha$ is predefined for each disturbances.

The train of pulses obtained from each disturbance for a cycle is added, and its magnitude is called Thresh$_c$. The Thresh$_c$ limits is calculated as,

$$\text{Thresh}_c = \beta \times \text{Sampling Frequency}$$  (2.6)

where parameter $\beta$ is predefined for each disturbance. For impulsive transient, the $\beta$ value is $\beta = \left( \frac{f}{F_s} \right) V_m + V_{impulsive}$, where $f$ is the frequency of the disturbance signal, $F_s$ is the sampling frequency and $V_m$ is voltage magnitude of the disturbance signal. In general, the disturbances are identified in terms of pulses of unique amplitude using Thresh$_p$ where as the classification of the disturbances and the time of occurrence of the disturbances is identified using Thresh$_c$.

### 2.5.3 Algorithm for Detecting the Power Quality Disturbances

1. The disturbance signals have to be sampled at the sampling frequency, $F_s$. 
2. The Wavelet coefficient for each disturbance is obtained (the selection of WT is purely based on the type of disturbance).

3. Soft-threshold is applied to remove redundant data.

4. Inverse WT is taken (the level of reconstruction is depending on the type of disturbance).

5. \( \text{Thresh}_p \) is calculated using the relation, \( \text{Thresh}_p = \alpha \times \text{Voltage} \), where \( 0.1 \leq \alpha \leq 1 \)

6. The recovered signal from each wavelet block is converted into a train of pulses of one cycle with unique amplitude, \( A\{x(n)\} \) where \( x(1), x(2), x(3), x(4) \) and \( x(5) \) are the pulse amplitude of impulsive transient, flicker, harmonic, sag and swell disturbances respectively, by comparing with \( \text{Thresh}_p \).

7. If \( A(x) \) is greater than \( \text{Thresh}_c \), then the system recognizes it as respective disturbance.

8. Calculate \( \text{Thresh}_c \) as, \( \text{Thresh}_c = \beta \times \text{Sampling Frequency} \), where \( 0.001 \leq \beta \leq 0.1 \).

9. If the disturbance under consideration is more than \( \text{Thresh}_c \) of that disturbance, then it is concluded that particular kind of disturbance is present.

2.5.4 Results and Discussion

The performance of wavelet approach for PQ disturbances has been evaluated using simulated data obtained by MATLAB simulations and recorded disturbances using standard equipments.
2.5.4.1 Case A - simulated disturbance data

The proposed algorithm is tested with five different simulated disturbances generated at a sampling rate of 1 kHz and system voltage of 230 V using MATLAB. This is shown in Figure 2.17(a). The algorithm detects and classifies the power quality disturbances as shown in Figure 2.17(b). In this A \{x(5)\}=10 indicates the presence of voltage swell, A\{x(2)\}=2 indicates the presence of voltage flicker, A\{x(3)\}=5 indicates the presence of current harmonic, A\{x(4)\}=15 indicates the presence of voltage sag and A\{x(1)\}=20 indicates the presence of impulsive transient.

A disturbance is said to occur if the sum total in the signal corresponding to the same disturbance after every one cycle is greater than the threshold limit set for it and simultaneously the sum total of the pulses in the other signals for the same cycle are less than their threshold limits. Thus, the type and time of occurrence of the disturbance are found.

Figure 2.17  (a) Simulated disturbances  (b) Simulation results showing the presence of power quality disturbances  (c) Spectrogram of disturbances
The spectrogram is a method for viewing the frequency content of a power quality disturbance signal as it changes with time as shown in Figure 2.17(c). The spectral amplitude values are converted to color with deep blues representing low values ranging through greens and yellows to deep red for the high values. It splits the signal into overlapping segments and estimates the short-term, time-localized frequency content of the disturbance signal (Takata et al, 2002). The spectrogram clearly contrasted the different disturbances taken at different scales.

2.5.4.2 Case B - recorded disturbance data

The power quality disturbances such as impulsive transient, voltage sag, and voltage swell are generated as per the standards of IEC 61000-4-5 (Surge) and IEC 61000–4–11 (Voltage sag (dip) and swell) respectively using sophisticated instruments available at Centre for Electromagnetics, Chennai, Tamil Nadu, India. The current and voltage harmonic waveforms are recorded from six-pulse SCR bridge rectifier based UPS load at UPS Manufacturing Industry, Chennai, Tamil Nadu, India. These disturbances are recorded and analysed using the wavelet based algorithm.

2.5.4.2.1 Recorded impulsive transient

Impulsive transient is synthesized as per the standards of IEC 61000-4-5, which relates to immunity requirements, test methods and range of test levels. The characteristics of the test generator are that it simulates the transient disturbance as closely as possible. Figure 2.18 shows the recorded impulsive transient (positive) of peak magnitude = 2 kV, rise time = 1.2 µs and pulse width = 50 µs using Digital Storage Oscilloscope (DSO).
Figure 2.18 Recorded impulsive transient using DSO

Figure 2.19 (a) Recorded impulsive transient (b) Simulation results showing the presence of impulsive transient (c) Spectrogram of impulsive transient

In this case, the waveform is marked with sharp edge and a fairly short duration in time. Here, ‘Db3’ with its corresponding pulse amplitude are
used to identify the presence of impulsive transient. The presence of impulsive transient and the spectrogram of the disturbance signal are shown in Figure 2.19 (a) to (c).

2.5.4.2.2 Recorded voltage sag

Voltage sag is taken as per the standards of IEC 61000-4-11 testing and measurement techniques of voltage sags and short term interruptions. In this test case, ‘Db10’ and corresponding pulse amplitude are used to identify the presence of voltage sag. Figure 2.20 shows the record of 40% voltage sag lasting for five cycles using DSO. The presence of voltage sag and the spectrogram of the disturbance signal are shown in Figure 2.21 (a) to (c).

![Figure 2.20 Recorded voltage sag using DSO](image)

**Figure 2.20** Recorded voltage sag using DSO
2.5.4.2.3 Recorded voltage swell

Voltage swell is taken as per the standards of IEC 61000-4-11 testing and measurement techniques of short term voltage variations. In this test case, ‘Db10’ and corresponding pulse amplitude are used to identify the presence of voltage swell. Figure 2.22 shows the record of 70 % voltage swell lasting for five cycles using DSO. The presence of voltage swell and the spectrogram of the disturbance signal are shown in Figure 2.23 (a) to (c).
2.5.4.2.4 Recorded harmonics from UPS load

The distorted voltage (V) and current (I) waveforms are recorded at the input side of six-pulse SCR bridge rectifier based UPS load as shown in Figure 2.24. It has been found that Meyer wavelet give best results in terms
of localization and percentage correctness of detection of harmonics. The presence of current and voltage harmonics and the spectrogram of the disturbance signal are shown in Figure 2.25(a) to (c) and Figure 2.26(a) to (c) respectively.

![Figure 2.24](image)

**Figure 2.24** Record of distorted voltage and current waveforms using DSO

![Figure 2.25](image)

**Figure 2.25** (a) Real record of current harmonics (b) Simulation results showing the presence of current harmonics (c) Spectrogram of current harmonics
2.6 SUMMARY

This chapter has focussed in addressing PQ problems through field measurements at low tension and high tension industrial facilities and PQ assessment are summarized below:

- An urging need to setup a centre for PQ to act as research and teaching facility has been highlighted.
- Field measurements have been conducted at the input side of UPS in the Software park. The investigations reveal that low power factor, 5 and 7 order harmonics are predominant compared to the limits specified by the IEEE 519 standards. The percentage THD in line current is 7 to 8 times above the
allowable margin. Hence, a suitable active power filter has been suggested and implemented to improve the power factor and suppress the current harmonics content within the limits as specified by the standards.

- Field measurements have been recorded in the steel plant during melting and refining stages. It provided data and information regarding the level of harmonic pollution due to furnace load. Also, the melting process is analyzed from electrical view point showing the active power consumed by the EAF. Investigations conducted at the steel plant have highlighted an alarming need to focus on harmonics and poor power factor problems. Hence, a cost effective solution has been suggested for harmonic reduction and power factor correction.

- Wavelet based power quality disturbance detection algorithm has been presented to detect and classify disturbances, which works for any number of cycles and can be customized for any sampling rate. This detection algorithm ensures a positive promise for the future development of fully automated PQ monitoring systems with classification ability.

The increasing use of Power Electronic (PE) equipment has led to PQ related disturbances in power systems by electric utilities and industrial power customers. Hence, forthcoming chapter explores the investigations carried out on the mitigation techniques for compensating PQ related disturbances such as voltage variations and harmonics caused by PE equipment.