CHAPTER 6
IMPACT OF POWER QUALITY ON SENSITIVE ELECTRONIC LOADS

6.1 INTRODUCTION

Owing to the increasing use of modern electronic devices, harmonic currents generated in the distribution systems create a new problem of ‘power quality’ in power systems. Power quality is an issue that is becoming more and more significant to electricity consumers at all levels of usage. Generally power quality refers to the degree to which voltages and currents in a system correspond to sinusoidal waveforms. The sensitive power electronic equipment and non-linear loads are widely used in industrial, commercial and domestic applications, this leads to harmonic distortions in voltage and current waveforms. Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency. The total harmonic distortion of current is the combination of all the harmonic frequency currents to the fundamental. The current harmonics are a problem because they cause bigger losses to the customer and utility power system components [63]. There are three methods of estimating harmonic load content: the Crest factor (CF), Harmonic Factor or percentage of Total Harmonic Distortion (%THD) and K-Factor [63]. The THD Percentage can be defined in two different ways; as a percentage of the fundamental component (%THDF, the IEEE definition of THD) or as a percentage of the r m s (%THDR, used by the Canadian Standards Association and the IEC) [64].
6.2 CAUSES OF DISTURBANCES IN POWER SYSTEMS

Although a noteworthy literature on power quality is now available, most engineers, facility managers, and consumers remain uncertain as to what constitutes a power quality problem. Furthermore, due to the power system impedance, any current (or voltage) harmonic will result in the generation and circulation of voltage (or current) harmonics and affects the entire power system [64]. Fig 6.1 illustrates the impact of current harmonics generated by a nonlinear load on a typical power system with linear loads.

Fig 6.1 Propagation of harmonics (generated by a nonlinear load) in power systems.
6.3 EFFECTS OF HARMONICS

To some extent Harmonic load currents in distribution system are generated by all nonlinear residential loads. These loads include - Switched Mode Power Supplies, Electronic fluorescent lighting ballasts and small uninterruptible power supplies units etc. The majority of modern electronic units use SMPS which draws pulses of current. These pulses contain hefty of harmonics. The electronic fluorescent lighting ballasts assert improved efficiency. The main benefit of using electronic ballast is that the light intensity can be maintained over an extended natural life by feedback control of the running current. Its great drawback is that it generates harmonics in the supply current [65]. Compact fluorescent lamps (CFLs) provide significant energy saving over incandescent lighting. As a result CFLs are being promoted as part of energy conservation programs for many electric utilities. CFLs, like all discharge lights, create harmonics on the supply system because of the control systems, limiting the plasma (an electric arc) current, which produces light [66].

The distribution transformers are most vulnerable to overheating and premature failure. The failure rate of these transformers is very high in India, i.e. around 25% per annum, when compared to International norms of 1-2% per annum. The life of a transformer is dependent upon the life of its insulation. Transformer insulation deteriorates with time and temperature. Transformer temperature, in turn, is related to loading i.e. the winding I²R losses. Loads with highly distorted current waveforms also have a very poor
power factor, because of this; they use excessive power system capacity and could be a cause of overloading. Even residential loads have been continuously increasing with the increase in use of electronic apparatus (Television sets, Personal Computers, CFLs etc.). The outcome is the increasing level of harmonic currents on power supply systems. It was found that with increasing set up currents, the neutral conductor's current (because of 'triple n' harmonics) increases sharply for nonlinear loads, as shown in Fig 6.2.

![Graph showing neutral currents with increasing fundamental current loadings](image)

**Fig 6.2** Increase of neutral currents with increasing fundamental current loadings

**6.4 MODELING OF ELECTRICAL LOADS**

**6.4.1 TRADITIONAL LINEAR LOAD MODELS**

Generation, transmission, and distribution are essential components to the overall power system model. The research and understanding of the static and dynamic behaviour of source-side components have led to their detailed models. The static and dynamic behavior of the composite load, however, has typically been harder to represent.
Modelling system load is complicated because the load is composed of millions of individual components connected to the system at any instance in time. These loads continuously change due to the time of day, weather, and state of the economy. There is also much uncertainty on how individual loads react differently to small and large voltage and frequency variations. It is impractical to represent all loads in a stability study, a fact that has led to the development of simplified composite load models [67].

Load models are typically located in stability studies at the network bus and are represented as an average power. These models therefore include all components down line from the substation which can be seen in Fig 6.3 looking from bus A toward the individual feeders. These components include transformers, power lines, shunt capacitors, and voltage regulators in addition to the end-user load.

Static and dynamic load models are two types of load models most often used in stability studies. Static models represent system active and reactive load as an algebraic function of voltage and frequency. These models are best suited for loads where the steady state response to change in voltage and frequency is reached quickly. Dynamic loads models, represented with differential equations, take into account the past and present values of voltage and frequency. Dynamic loads typically take longer to reach steady state than static loads; however, they are commonly represented with the static load models [67].
6.4.2 Static Models

The three generic static load models are constant impedance, constant current, and constant power. In the constant impedance model, the load power varies with the square of voltage. In the constant current model, the load power varies in proportion with voltage. The load power, in the constant power model, does not change with voltage. These responses are typical for small perturbations in voltage but may not accurately reflect the response due to larger voltage sags. Voltage sags greater than 20% can cause sensitive loads to trip off-line. These models, however, have been accepted in practice and are used in many transient stability programs [67].

6.4.3 Exponential Model

The most common and widely practiced static load model is the exponential load model derived in [68]. The static exponential model represents the change in active power $P$ and reactive power $Q$ as an
algebraic function of voltage and frequency. The active and reactive exponential models are described by

\begin{align}
P &= P_0 \left[ \frac{V}{V_o} \right] \left( \frac{dP}{dV} \right) \left[ 1 + K_{pf} (f - f_o) \right], \\
Q &= Q_0 \left[ \frac{V}{V_o} \right] \left( \frac{dQ}{dV} \right) \left[ 1 + K_{qf} (f - f_o) \right]
\end{align}

(6.1) (6.2)

where \( P_0 \) ans \( Q_0 \) are the total active and reactive load, respectively; \( K_{pf} \) and \( K_{qf} \) are the active and reactive load frequency characteristics; \((f - f_0)\) is the deviation in system frequency; \( dV \ dP \) and \( dV \ dQ \) are the active and reactive load power characteristics, respectively; and \( V \) and \( V_o \) are the actual and nominal RMS voltages, respectively. Since the system frequency is not an inherent variable in most stability programs, the response due to frequency is typically neglected. The active and reactive exponential load models defined in (6.1) and (6.2), respectively reduce to

\begin{align}
P &= P_0 \left[ \frac{V}{V_o} \right] \left( \frac{dP}{dV} \right) \\
Q &= Q_0 \left[ \frac{V}{V_o} \right] \left( \frac{dQ}{dV} \right)
\end{align}

(6.3) (6.4)

Constant power, current, and impedance loads have characteristics equal to 0, 1, and 2, respectively. For composite system load, the exponential model active power characteristic typically ranges from 0.5 to 1.8, and the reactive power characteristic typically ranges from
1.5 to 6. Due to magnetic saturation in transformers and motors, the reactive load is significantly higher than constant impedance. The most commonly accepted linear load model characteristics are constant current for active load and constant impedance for reactive load [68].

### 6.4.4 Polynomial Model

Another common static load model is the polynomial load model which is also referred as the “ZIP” model. This model represents the composite load as a combination of constant impedance, constant current, and constant power loads. The load power varies with the change in system voltage. The polynomial model is defined as

\[
P = p_1 \left( \frac{V}{V_o} \right)^2 + p_2 \left( \frac{V}{V_o} \right)^1 + p_3
\]

(6.5)

\[
Q = q_1 \left( \frac{V}{V_o} \right)^2 + q_2 \left( \frac{V}{V_o} \right)^1 + q_3
\]

(6.6)

where \( p_1, p_2, \) and \( p_3 \) are the constant impedance, constant current, and constant active power load, respectively; and \( q_1, q_2, \) and \( q_3 \) are the constant impedance, constant current, and constant reactive power load, respectively.

### 6.4.5 EPRI Model

The Electric Power Research Institute (EPRI) developed its own static load model under several research projects starting in 1976. By 1987,
the model had gone through many revisions and can be found in [69]. EPRI’s model represents the active load with two components, the first frequency and voltage dependent and the second only dependent on voltage. The reactive load also has two components. The first is the total reactive load, and the second is the total reactive load minus shunt capacitance.

**6.5 HARMONIC POWER FOR NONLINEAR LOADS**

The equivalent circuit of a non-linear load is shown in Fig 6.4. It can be modelled as a linear load in parallel with a number of current sources, one source for each harmonic frequency. The harmonic currents generated by the load – or more precisely converted by the load from fundamental to harmonic current – have to flow around the circuit via the source impedance and all other parallel paths. As a result, harmonic voltages appear across the supply impedance and are present all over the installation. Source impedances influence the harmonic voltage distortion resulting from a harmonic current.

Fig 6.4. Equivalent circuit of Non-linear load
Whenever harmonics are suspected, or when trying to verify their absence, the current must be measured.

The Fourier series represents an effective way to study and analyze harmonic distortion. It allows inspecting the various constituents of distorted waveform through decomposition. Generally, any periodic waveform can be expanded in the form of a Fourier series

\[ f(t) = A_0 + \sum_{h=1}^{\infty} (A_h \cos \omega_0 t + B_h \sin \omega_0 t) \]

\[ = A_0 + \sum_{h=1}^{\infty} C_h \cos (\omega_0 t + \theta_h) \]  \hspace{1cm} (6.7)

where \( f(t) \) is a periodic function of frequency \( f_0 \), angular frequency \( \omega_0 = 2\pi f_0 \) and period \( T = 1/f_0 \)

\( C_1 \cos(\omega_0 t + \theta_1) \) represents the fundamental component

\( C_h \cos(\omega_0 t + \theta_h) \) represents the \( h \)th harmonic of amplitude \( C_h \), frequency \( h\omega_0 \) and phase \( \theta_h \)

\[ A_0 = \frac{1}{T} \int_0^T f(t) \, dt \]

\[ A_h = \frac{2}{T} \int_0^T f(t) \cos(\omega_0 t) \, dt \]

\[ B_h = \frac{2}{T} \int_0^T f(t) \sin(\omega_0 t) \, dt \]

\[ C_h = \sqrt{A_h^2 + B_h^2} \]

\[ \theta_h = -\tan^{-1}\left(\frac{B_h}{A_h}\right) \]
6.5.1 Measures of Harmonic distortion:

A distorted periodic current or voltage waveform expanded into a Fourier series is expressed as follows

\[
i(t) = \sum_{h=1}^{\infty} I_h \cos(\ h \omega_0 t + \phi_h)
\]

\[
v(t) = \sum_{h=1}^{\infty} V_h \cos(\ h \omega_0 t + \theta_h)
\]

(6.8)

Accordingly, the following relationship for active power and reactive power supply are

\[
P = \frac{1}{2} \sum_{h=1}^{\infty} V_h I_h \cos(\ \theta_h - \phi_h)
\]

\[
= \sum_{h=1}^{\infty} V_{h_{rms}} I_{h_{rms}} \cos(\ \theta_h - \phi_h)
\]

(6.9)

Reactive power is defined as

\[
Q = \frac{1}{2} \sum_{h=1}^{\infty} V_h I_h \sin(\ \theta_h - \phi_h)
\]

\[
= \sum_{h=1}^{\infty} V_{h_{rms}} I_{h_{rms}} \sin(\ \theta_h - \phi_h)
\]

(6.10)

6.5.2 Voltage distortion factor

Voltage distortion factor VDF, also known as voltage total harmonic distortion is defined as

\[
VDF = \frac{1}{V_1} \sqrt{\sum_{h=2}^{\infty} V_h^2}
\]

(6.11)
6.5.3 Current distortion factor

Analogously, Current distortion factor CDF, further known as Current total harmonic distortion is defined as

\[
CDF = \frac{1}{I_1} \sqrt{\sum_{h=2}^{\infty} I_h^2}
\] (6.12)

where

- \( I_h \) is the \( h^{\text{th}} \) harmonic peak current
- \( V_h \) is the \( h^{\text{th}} \) harmonic peak voltage
- \( \theta_h \) is the \( h^{\text{th}} \) harmonic current phase
- \( \Phi_h \) is the \( h^{\text{th}} \) harmonic voltage phase
- \( \omega_0 \) is the fundamental angular frequency, \( \omega_0 = 2\pi f_0 \)
- \( f_0 \) is the fundamental frequency, \( f_0 = 50\text{Hz} \)

Where \( V_1, I_1 \) represent the fundamental peak voltage and current respectively. With

\[
V_{\text{rms}} = \sqrt{\sum_{h=1}^{\infty} V_{h \text{ rms}}^2} = V_{\text{rms}} \sqrt{1 + (VDF)^2}
\]

and

\[
I_{\text{rms}} = \sqrt{\sum_{h=1}^{\infty} I_{h \text{ rms}}^2} = I_{\text{rms}} \sqrt{1 + (CDF)^2}
\] (6.13)

The apparent power is

\[
S = V_{\text{rms}} I_{\text{rms}} = \sqrt{\sum_{h=1}^{\infty} V_{h \text{ rms}}^2 I_{h \text{ rms}}^2}
\]

\[
= V_{\text{rms}} I_{\text{rms}} \sqrt{1 + (VDF)^2 \sqrt{1 + (CDF)^2}}
\]

\[
= S_1 \sqrt{1 + (VDF)^2 \sqrt{1 + (CDF)^2}}
\] (6.14)
Where $S_1$ is the apparent power at fundamental frequency and the power factor is

$$
pf = \frac{P}{S} = \frac{P}{S_1} \frac{1}{\sqrt{1 + (VDF)^2} \sqrt{1 + (CDF)^2}}
$$

$$
= pf_{disp} \cdot pf_{dist}
$$

$$
pf_{disp} = \frac{P}{S_1}
$$

$$
pf_{dist} = \frac{1}{\sqrt{1 + (VDF)^2} \sqrt{1 + (CDF)^2}}
$$

(6.15)

where

$p_{fdisp}$ is the displacement power factor

$p_{fdist}$ is the distortion power factor

### 6.6 Stochastic Analysis of the Effect of Using Harmonic Generators (Non linear Loads) in Power Systems

#### 6.6.1 Sensitive Electronic Loads

Switch mode electronic devices including Compact Fluorescent Lamp (CFL) and personal computers introduce capacitive power factor and current harmonics to the power system. Since middle 80’s and with the expanding use of nonlinear switch mode electronic loads, concerns arose about their effect on the power systems. In many IEEE documents, it is recommended to study the effect of electronic loads. Switch mode devices have a capacitive power factor between 55 and 93 percent (All experts), which can cause the increase of reactive power and power loss. The power loss in an office building wirings due to the current harmonics may be more than twice that of the linear
load equipment [70]. Capacity of the transformers may be reduced more than 50 per cent in the presence of harmonic components [71].

CFL is a more efficient and durable replacement of the traditional incandescent lamp. Replacing traditional light bulbs by CFLs has several advantages including energy saving, increase in the capacity of plants and distribution transformers, peak shaving, less carbon emission and customer costs. On average, 20 percent of the total use of electricity is consumed in lighting [72]. However, the increase in the number of electronic devices especially the CFLs in power systems must be carefully planned.

Replacing the incandescent light bulbs with CFLs means replacing the system’s major ohmic load with a capacitive load of high frequency harmonic components. In areas where lighting is a major use of electricity, e.g. places where natural gas or other fossil fuels are used for heating purposes, unplanned replacing of incandescent lamps with CFLs can introduce unexpected negative effects on the system. Also, in areas with a considerable number of other switch mode devices e.g. commercial areas with many office buildings it is important to plan the number of CFLs carefully. Most of the present studies on the effect of switch mode devices are based on tentative experiments and power factor measuring before and after using the devices in the power system [73], and proposing a model for the network has been less discovered.

In order for studying such effects, it is better to classify the system equipment to the substation equipment and consumer side
equipment. Dramatic changes in power quality indicators of the distribution systems may cause disorders or even damages in the consumer equipments. Such disorders are especially important for sensitive appliances such as medical and hospital devices.

In this chapter review of novel approach for studying the effect of switch mode devices and present a novel stochastic modelling approach for analysing the behaviour of the power system in the presence of switch mode devices. This studies the major Key Performance Index (KPI) of the power system and study how these KPI will be affected by adding the current harmonics.

6.6.2 Modelling of Electronic ballasts (EB)

Electronic ballasts (EB) used in public lighting in comparison to similar devices used in interior lighting can have circuits for regulation of output power according to preset switching profile (ON-OFF-DIM cycles with reduced power in dimming mode). Electronic ballasts cannot be connected to networks with central voltage regulator because decreased supply voltage for ballast may malfunction the lighting operation. Light dimming in EB is possible thanks to controlled high-frequency oscillator.
Input filter (see Fig 6.5) limits the effect of current deformation and protects against random high-frequency pulses that may appear in supply network (e.g. as a result of switching processes). Next stage of signal processing consists of two transistors used to generate a high-frequency signal for maximized power. The frequency must be above the range of audible sound, i.e. 20 kHz (upper limit lies about 100 kHz). Choke is wired in series with lamp. Choke is responsible for limitation of current through lamp. Capacitor connected parallel to the lamp is used for creation of the ignition voltage.
Fig 6.7 Behaviour of voltage and current in a discharge lamp
Magnetic (conventional) ballasts (energy efficiency index EEI = B1, B2, C, D according to CELMA) consist of choke, capacitor and starter. Thermal losses are prevailing in this type of ballasts. Losses are originated in windings of the choke by flowing currents and also by hysteresis of the core. Level of losses depends on mechanical construction of the ballast and wiring of its windings.

Simple choke is a dominant ballast type for high-pressure discharge lamps. It has single winding on a core; due its construction it is simple and cheap. Choke is connected in series with lamp (Fig. 6.6). The Choke only limited regulation possibilities by input voltage. Ignition current is very high, thus, the whole circuit must be constructed to withstand such currents. During operation of magnetic ballast, non-harmonic currents flow as a result of nonlinearity of the lamp.

**6.6.3 Modelling of CFL ballast circuit**

The common 220V power system voltage is not enough to start the fluorescent lamps. Therefore, CFLs include a ballast circuit for providing the starting high voltage. In traditional fluorescent lamps, inductive ballasts are widely utilized. However, electronic ballasts which are used in CFLs have much better quality [74]. Electronic ballasts are composed of a rectifier and a DC-AC converter. Fig 6.8 shows the general block diagram of a ballast circuit.
Fig 6.8 Block diagram of a CFL ballast circuit.

Several circuits are simulated in MATLAB software for this project. Fig. 6.9 shows one sample CFL ballast circuit model. This circuit is similar to that of [75] with slight changes. The input full wave rectifier and the large input capacitor make the current have narrow high peaks at short intervals and almost zero value elsewhere. Fig. 6.10 shows the output voltage and current of the circuit in Fig 6.9. Frequency analysis shows that the CFL current is made up of odd harmonic components of the main frequency (50 or 60 Hz). The CFL is modelled by a number of current sources with the proper harmonic values. Equation (6.16) shows the mathematical model for a CFL when the voltage is assumed to be a cosine function.

\[
v_{\text{CFL}} = V \cos(2\pi ft)
\]

\[
i_{\text{CFL}} = \sum_{n=0}^{\infty} I_{2n+1} \cos[2\pi (2n+1) ft + \Phi_{2n+1}] = \sum_{n=0}^{4} I_{2n+1} \cos[2\pi (2n+1) ft + \Phi_{2n+1}]
\]

(6.16)

The more the number of harmonics is, the more accurate the model will be. In this study the first five odd harmonics (1, 3, 5, 7, and 9) are used. A schematic of the model is shown in Fig 6.11. The power factor of this circuit is 93%. In order for having a flexible model for different
market suppliers, the power factor is chosen flexible in the simulation experiments.

Fig 6.9 Simulation of a CFL ballast circuit

Fig.6.10. Sinusoidal voltage and resulting current wave shape for a CFL ballast circuit
Fig. 6.11. Circuit model of a switch mode device.

The values of the current and phase in Equation 6.16 are summarized in Table 1 for the circuit in Fig 6.9.

Table 6.1 Peak value and phase of the current harmonics for the CFL

<table>
<thead>
<tr>
<th>Current Harmonic</th>
<th>First</th>
<th>Third</th>
<th>Fifth</th>
<th>Seventh</th>
<th>Ninth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak I_{2n+1} (A)</td>
<td>0.2</td>
<td>0.182</td>
<td>0.162</td>
<td>0.138</td>
<td>0.112</td>
</tr>
<tr>
<td>PhaseΦ_{2n+1} (Rad)</td>
<td>0.260</td>
<td>3.499</td>
<td>0.609</td>
<td>4.000</td>
<td>0.799</td>
</tr>
</tbody>
</table>

6.6.3.1 Different circuit configurations of CFL

Many electrical devices, especially electronic devices, can produce a harmonic distortion of the shape (sine wave) of the electric waveform. This distortion degrades the quality of the electricity and can subsequently decrease the effectiveness and efficiency of the equipment. Total Harmonic Distortion is defined as a ratio of the sum of all the harmonics over the magnitude of the fundamental power. Most magnetic ballasts have a total harmonic distortion between 18% and 35%. Most electronic ballasts have the total harmonic distortion below 20% with some below 10%. It is advised to purchase ballasts that have low distortion specifications.
Fig 6.12 displays a block diagram of typical CFL ballast available in India. The first block contains the protection, filtering and current peak limiting components. Block 2 is the full diode bridge filter to the converter the ac line into a dc stage. Block 3 is the smoothing capacitor with a typical value of either 4.7 μF or 10 μF. It provides the dc input voltage of the resonant inverter for the tube in block 4. The ripple on the dc voltage, measured by the crest factor (peak divided by RMS value), influences tube life. Increasing the filter capacitor reduces the ripple but increases the peak of the AC current waveform and hence the harmonics in it. Some other ballast designs also reduce the harmonic content but increase the crest factor. Addition of filtering or using a more sophisticated design can reduce the harmonic content but also increases the complexity and cost of the CFL. CFLs can be divided into four main categories in terms of their ballast circuitry and their attempt on improving the power-factor.
6.6.3.2 No Power-Factor Correction (Simple Case)

Fig 6.13 shows a simple CFL with no filtering and hence nothing to improve the power-factor. Sometimes even the resistor in the ac lead is the absence, and the source impedance is relied upon to limit the capacitor charging peak. This circuit has very high harmonic current levels, which depend on the dc capacitor size and $R$, but is the cheapest to manufacture.

![Simple CFL Ballast Circuit with no filtering](image)

**Fig 6.13 Simple CFL Ballast Circuit with no filtering**

6.6.3.3 Passive Power-Factor Control

One way of increasing the ballast power-factor and to reduce the harmonic content of the input current waveform is the use of passive filtering. There are many types of passive filter arrangements, one of which is shown in Fig 6.14.

![Passive Filtering Circuit](image)

**Fig 6.14 Passive Filtering Circuit**
Obviously, the more extensive the filtering is, the better the ac current waveform, but higher the cost. The advantage of this passive LC filtering technique is its simplicity and ease of implementation. However, the major drawback is the physical size and weight, which makes it unattractive due to the limited space and inherent power loss [75].

6.6.3.4 Valley-Fill

Another possible solution is to use valley-fill circuit (or equivalent), shown in Fig 6.15. In this circuit, the filter capacitor following the diode rectifier is split into two different capacitors C1 and C2, which are alternately charged and discharged using the three diodes. However, this circuit contains large DC voltage ripple, which produces lamp power and luminous flux fluctuation. As a result, it will reduce the lamp’s lifetime.

Fig 6.15 Valley-Fill Filtering Circuit

The improved valley-fill circuit shown in Fig 6.16 adds to two identical small capacitors C3 and C4 as a voltage doubler to enhance the current waveform near crossover point. It continues to
draw the current from the ac source during the cross-over period, which helps to extend the input current conducting angles. One resistor is connected to the bottom of C2 in order to remove the charging current spikes at the voltage peak. This is a cost effective way of improving power factor as well as reducing the harmonic current injection level [76].

Fig 6.16 Improved Valley-Fill Circuit

The measured harmonic spectra of different CFLs has allowed the identification of four categories of CFL; poor, average, good and excellent, which are associated with the ballast circuits used (Fig 6.13-6.16). Simulated time domain waveforms and their corresponding harmonic spectra as recorded and displayed in Figure 6.17-6.20.
Fig 6.17 Wave form and harmonic spectra of No filtering Circuit

Fig 6.18 Wave form and harmonic spectra of Passive filtering Circuit

Fig 6.19 Wave form and harmonic spectra of Valley-fill filtering Circuit

Fig 6.20 Wave form and harmonic spectra of Active filtering Circuit
6.6.4 Circuit model for other electronic devices

Personal computers and other electronic equipment such as printers, etc. generate current harmonics in the power system too, because they all include a rectifier. The harmonic components of personal computers are calculated and provided in the literature [70], [75]. Fig 6.21 shows the relative value of these components. Therefore, similar models to that of Fig 6.9 for modelling such electronic devices are used.

Fig 6.21 Relative values of the current harmonics for a personal computer.

6.7 Stochastic modelling of switch mode devices in power system

Phase of a harmonic generating device is not a constant value. But it is a random variable that varies in a specific range that can be provided by the manufacturer. Therefore, the model in Equation (6.16) will be modified to that of Equation 6.17
In this model, \( m \) is the device number in the network. In practice, the total number of devices \( M \) is a large number. For each device it has a phase shift \( \Delta \Phi_m \) from the central phase. Distribution of \( \Delta \Phi_m \) can be assumed to be uniform or Gaussian depending on the manufacturer’s data sheet.

In other words for the uniform distribution:

\[
\Phi_c - \Phi_{\text{max}} < \Delta \Phi_m < \Phi_c + \Phi_{\text{max}},
\]

\[
P(\Delta \Phi_m = \Phi) = \frac{1}{2\Phi_{\text{max}}}
\] (6.18)

In the above equation, \( \Phi_{\text{max}} \) is the maximum phase shift from the theoretical phase lag \( \Phi_c \). If the probability distribution is Gaussian, \( \Delta \Phi_m \) is obtained from equation 6.19:

\[
P(\Delta \Phi_m = \Phi) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(\Phi - \varphi)^2}{2\sigma^2}}
\] (6.19)

Where \( \varphi \) and \( \sigma \) are the mean and variance of the phase lag. The current value for a large number \( M \) of CFLs with the above specifications is equal to \( i \) in Equation 6.18:

\[
i = \sum_{m=0}^{M} i_m = \sum_{m=0}^{M} \sum_{n=0}^{4} I_{2n+1} \cos\left[2\pi(2n+1)ft + \Phi_{2n+1} + (2n+1)\times \Delta \Phi_m \right]
\] (6.20)

Finding the Probability Density Function (PDF), expectation and variance of current in the above equation is complicated. Instead, this can rely on numerical simulation to find the PDF of power system current. In this experiment, power system is composed of a thousand CFLs. The average phase lag of these CFLs is fifteen degrees and has a
uniform distribution of range 15±10 degrees. It uses a Parzen window [76] approach to find the PDF of the peak output current. Fig 6.22 shows the result. The mean value and standard deviation of the current in this experiment are 611.5 and 2.45. It may notice that if the variance in the phase shift is not considered, meaning that do not assume the CFL phase to be a random variable, the peak current will be equal to 701 Amperes. While designing the dimension of network, this means at least 13% more capacity. Different results can be obtained for different values of phase range for the electronic devices.

Fig 6.22 Relative values of the current harmonics for a personal computer.
6.8 EXPERIMENTAL STUDY

The experimental study was conducted to determine the energy losses, on account of the residential sensitive electronic loads. In order to find out the magnitude of harmonic currents caused by electronic loads, various tests were conducted in the lab. For the purpose of analysis Power Quality Analyser 3196 was used to capture the signals. The residential appliances that are taken into consideration depicted both linear as well as nonlinear loads. Incandescent lamp and fluorescent tube with magnetic choke act as linear loads, whereas UPS, ceiling fan, personal computers, fluorescent tube with electronic ballast, CFL, TV and mobile phone chargers are nonlinear loads. Readings are given in Table 6.2 where DPF is ‘Displacement’ power factor and it is the cosine of the angle between fundamental rms voltage and fundamental rms current. TPF is True power factor ‘measured in the presence of all harmonics’ and is the ratio of $P_{\text{meas}}$ in Watts and measured Volt Amperes i.e. $V_{\text{Ameas}}$. Waveforms for different loads are shown from Figure 6.23 to 6.33. They clearly show the current distortion due to nonlinear loads. The waveforms of current no longer remain ‘sinusoidal’ for these loads.
### Measurement results for Electronic Appliances

<table>
<thead>
<tr>
<th>Description</th>
<th>% THD of Current</th>
<th>DPF</th>
<th>True PF</th>
<th>P in Watts</th>
<th>VA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent Lamp</td>
<td>3.35</td>
<td>0.999</td>
<td>1.0</td>
<td>85.46</td>
<td>85.46</td>
</tr>
<tr>
<td>Fluorescent Tube with magnetic choke</td>
<td>8.47</td>
<td>0.587</td>
<td>0.585</td>
<td>51.32</td>
<td>88.32</td>
</tr>
<tr>
<td>UPS</td>
<td>50.99</td>
<td>0.462</td>
<td>0.414</td>
<td>16.06</td>
<td>39.87</td>
</tr>
<tr>
<td>Fluorescent Tube with Electronic choke</td>
<td>108.98</td>
<td>0.849</td>
<td>0.577</td>
<td>22.4</td>
<td>25.68</td>
</tr>
<tr>
<td>Television Set</td>
<td>150.32</td>
<td>0.978</td>
<td>0.538</td>
<td>68.02</td>
<td>69.78</td>
</tr>
<tr>
<td>Computer 1</td>
<td>72.8</td>
<td>0.999</td>
<td>0.809</td>
<td>119.98</td>
<td>120.28</td>
</tr>
<tr>
<td>Computer 2</td>
<td>148.17</td>
<td>0.974</td>
<td>0.545</td>
<td>107.37</td>
<td>109.64</td>
</tr>
<tr>
<td>Compact Fluorescent Lamp</td>
<td>136.95</td>
<td>0.874</td>
<td>0.524</td>
<td>14.95</td>
<td>17.44</td>
</tr>
<tr>
<td>Ceiling Fan</td>
<td>68.33</td>
<td>0.791</td>
<td>0.657</td>
<td>18.33</td>
<td>29.87</td>
</tr>
<tr>
<td>Mobile Charger 1</td>
<td>161</td>
<td>0.979</td>
<td>0.51</td>
<td>3.85</td>
<td>3.91</td>
</tr>
<tr>
<td>Mobile Charger 2</td>
<td>219</td>
<td>0.96</td>
<td>0.386</td>
<td>5.82</td>
<td>5.91</td>
</tr>
</tbody>
</table>
Fig. 6.23. Incandescent Lamp

Measured with all harmonics present

VAR=0.0, P=84.83, $V_{rms}=227.29$, $I_{rms}=0.375$ and Losses=0.63

Fig. 6.24. Fluorescent Tube with magnetic choke

Measured with all harmonics present

VAR=71.14, P=51.2, $V_{rms}=232.86$, $I_{rms}=0.376$ and Losses=0.12
Fig. 6.25. UPS

Measured with all harmonics present

VAR=35.3, P=15.93, V_{\text{rms}}=236.1, I_{\text{rms}}=0.164 \text{ and } \text{Losses}=0.13

Fig. 6.26. Fluorescent tube Electronic Choke

Measured with all harmonics present

VAR=31.36, P=21.8, V_{\text{rms}}=229.41, I_{\text{rms}}=0.167 \text{ and } \text{Losses}=0.6
Fig. 6.27. Television Set

Measured with all harmonics present

VAR = 105.71, P = 67.85, $V_{\text{rms}} = 233.82$, $I_{\text{rms}} = 0.536$ and Losses = 0.17

Fig. 6.28. Computer 1

Measured with all harmonics present

VAR = 87.03, P = 119.36, $V_{\text{rms}} = 234.56$, $I_{\text{rms}} = 0.632$ and Losses = 0.62
Fig. 6.29. Computer 2

Measured with all harmonics present
VAR=163.58, P=106.7, V_{rms}=233.85, I_{rms}=0.834 and Losses=0.67

Fig. 6.30. Compact Fluorescent Lamp

Measured with all harmonics present
VAR=24.13, P=14.57, V_{rms}=228.26, I_{rms}=0.124 and Losses=0.38
Fig. 6.31. Ceiling Fan
Measured with all harmonics present
VAR=21.01, P=18.29, V_{rms}=212.56, I_{rms}=0.131 and Losses=0.04

Fig. 6.32. Mobile phone charger 1
Measured with all harmonics present
VAR=6.46, P=3.81, V_{rms}=232.9, I_{rms}=0.032 and Losses=0.04

Fig. 6.33. Mobile phone charger 2
Measured with all harmonics present
VAR=13.72, P=5.02, V_{rms}=231.2, I_{rms}=0.0627 and Losses=0.8
6.9. IMPACT OF VARIATION OF INPUT VOLTAGE

The impact of variations in the input voltage on the input currents of each of the appliances tested is examined in this section. Understanding the implications of variation to the input current of appliance due to changes in the input voltage; is essential for complete understanding of the manner in which appliances may impact on the electricity distribution system. An accurate understanding of appliance behaviour in different input voltage conditions is also essential if accurate appliance models are to be developed for simulation.

Two tests have been designed to assess the impact of variations in input voltage on appliance input current behaviour. The first test examines appliance behaviour at the upper and lower limits of the Indian low voltage range. The first of these tests involved supplying the appliances at 253 V RMS which is at the upper limit of the range, and the second involved supplying the appliances with 207 V RMS which is at the lower limit of the range. The remaining test involved supplying the appliances with distorted input voltages.

The values are put in a tabular form to facilitate the comparison between values and the results obtained using the undistorted nominal value (230 V RMS), the data in each table is presented as a percentage of the values obtained when the nominal voltage was applied. For example, a value of 100% means that the value obtained for the test was equal to the value obtained when the appliance was supplied with an undistorted voltage of 230V RMS.
The data in Tables 6.3 specify the behaviour of the RMS current, displacement power factor and fundamental current are relatively insensitive to changes in the supply voltage magnitude. The results for total harmonic current are more diverse. CFL, TV and the UPS show considerable variation in total harmonic current for one or both of the voltage magnitude tests. It is remarkable that the CFL, TV and UPS appear to have electronics on the input which aim to lessen current waveform distortion. It may be assumed that these circuits are more sensitive to changes in input supply voltage than even simple devices such as the SMPS of the PC.

The data Table 6.4 indicate that there is little variation in the displacement power factor when the appliances are supplied with harmonic test waveform. However, there is considerable variation seen total harmonic current. Further, the variations seen here are much greater than the input voltage magnitude. This indicates that appliance behaviour is more sensitive to changes in input voltage distortion contrasting to changes in input voltage magnitude.

Fig 6.34 shows the harmonic currents of various devices under the sinusoidal supply voltage condition. These values represent a ‘worst case’ pollution level at this moment in the MV-grid. It is further used in the simulation to analyze the performance of model network in a polluted grid condition. Fig. 6.35 shows the harmonic currents at the beginning of a LV feeder. THD (i) value is around 16% at the beginning of the LV feeder, whereas THD (i) at a high load house terminal varies between 26-28% and at a low load house terminal
between 48-49% [10]. The harmonic spectrum at two house terminals with high load and low load respectively are compared in Fig.6.36.

**TABLE 6.3**
THD (I) VALUES OF DIFFERENT DEVICES USED IN VARYING INPUT VOLTAGE MAGNITUDE

<table>
<thead>
<tr>
<th>Appliance</th>
<th>RMS Input Voltage 253V</th>
<th>RMS Input Voltage 207V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THD(i)</td>
<td>DPF</td>
</tr>
<tr>
<td>TV</td>
<td>118</td>
<td>103</td>
</tr>
<tr>
<td>Computer-1</td>
<td>88</td>
<td>100</td>
</tr>
<tr>
<td>CFL-1</td>
<td>156</td>
<td>100</td>
</tr>
<tr>
<td>Computer-2</td>
<td>152</td>
<td>101</td>
</tr>
<tr>
<td>UPS</td>
<td>88</td>
<td>100</td>
</tr>
<tr>
<td>Ceiling Fan</td>
<td>76</td>
<td>79</td>
</tr>
<tr>
<td>CFL-2</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>Incandescent Lamp</td>
<td>101</td>
<td>100</td>
</tr>
</tbody>
</table>

**TABLE 6.4**
THD(I) VALUES OF DIFFERENT DEVICES – HARMONIC TEST WAVEFORM

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Harmonic Test Waveform 1</th>
<th>Harmonic Test Waveform 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THD(i)</td>
<td>DPF</td>
</tr>
<tr>
<td>TV</td>
<td>128</td>
<td>101</td>
</tr>
<tr>
<td>Computer-1</td>
<td>103</td>
<td>100</td>
</tr>
<tr>
<td>CFL-1</td>
<td>142</td>
<td>97</td>
</tr>
<tr>
<td>Computer-2</td>
<td>154</td>
<td>104</td>
</tr>
<tr>
<td>UPS</td>
<td>87</td>
<td>100</td>
</tr>
<tr>
<td>Ceiling Fan</td>
<td>79</td>
<td>81</td>
</tr>
<tr>
<td>CFL-2</td>
<td>114</td>
<td>100</td>
</tr>
<tr>
<td>Incandescent Lamp</td>
<td>102</td>
<td>100</td>
</tr>
</tbody>
</table>
Fig. 6.34 Harmonic currents spectrum of devices used in ‘low load’ case

Fig. 6.35. Harmonic currents of LV feeder (clean grid)

Fig.6.36. Harmonic currents at different house terminals- (clean grid)
Fig 6.37 shows the experimental set up, which contain all types of sensitive electronic loads.

A study was conducted in a residential campus consisting of 100 houses. It was found that on an average each residence is having fluorescent tubes with magnetic choke as well as electronic ballast, compact fluorescent lamps, personal computer, UPS, television set, mobile phone chargers, stereo system, ceiling fans, food processor, microwave oven, refrigerator, air cooler and incandescent lamps as loads. Then power loss due to harmonics i.e. $P_{\text{meas}} - P_f$ is calculated for each house. It is found to be more or less 8 to 10 Watts. Considering 6 to 8 hours/day operation of these loads, the number of energy units consumed because of harmonics for 100 houses, comes out to be 150 to 250 kWh per month. This extra energy loss is solely due to harmonics. This loss corresponds to the sample size of 100 residences but as the number of houses increases, the cumulative loss is enormous.