Evaluating the level of harmonic distortion in a typical distribution feeder

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EVALUATING THE LEVEL OF HARMONIC DISTORTION IN A TYPICAL DISTRIBUTION FEEDER

By

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A thesis submitted in partial fulfillment of the requirements for the

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Abstract

Steady-state analysis of electrical power systems is largely based on linear and sinusoidal AC circuits which allow the concept of impedance, phasors and well-defined power quantities (i.e., real, reactive and apparent powers). In reality, however, the electric load which was once composed of linear elements (e.g., induction motors, incandescent lighting, etc ...) is becoming more and more nonlinear due to the wide-spread use of electronic components such as fluorescent lighting and variable-frequency drives that power the majority of electric motors. As a consequence, the current drawn by such devices is often distorted, thus containing a number of high frequency harmonics that are superimposed on the fundamental 60 Hz component. As these high-frequency harmonic currents flow through the power distribution apparatus, they in turn cause distortion in the voltage. The distorted voltage can in turn affect other loads that share a transformer or branch circuit with the original harmonic loads.

It has been shown that classical definitions of electric power; namely, active, reactive and apparent powers, do not fulfill the conditions caused by harmonics. Consequently, various power definitions and calculation methods have been proposed in the literature.

It is hypothesized that existing definitions of power other than the active part in non-sinusoidal circuits are based on a non-real (i.e., frequency) domain and rate theoretical in nature. Therefore, these are not only hard (often impossible) to interpret their physical meaning and make use of them, but also hard to implement in measuring devices. On the other hand, power definitions that are based on a real time domain are expected to have simpler physical interpretations and easier to measure. A simple definition of non-active power will be of great value to the power industry. It is also hypothesized that a typical electrical power distribution
system can handle significantly more non-linear loads than previously thought as modern electrical loads are less sensitive to distortion in the voltage supply.

The motivation that led to the proposed works stems from the fast moving events that are taking place in the electric utility industry. More specifically, many utilities are considering additional customer charges (such as charging the residential sector for peak demand, reactive power consumption, and renewable power generation) in order to ring more profits. The recently installed smart meters that primarily record energy consumption every 5 minutes and communicate wirelessly the local utility, do have the ability to measure other electrical quantities. The way these quantities are defined and measured is of critical importance to both the supplier and consumer.
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To my beloved family and Brian
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Chapter 1

Introduction

1.1 Harmonics

Harmonics are a mathematical way of describing distortion to a voltage or current waveform. The term harmonic refers to a component of a waveform that occurs at an integer multiple of the fundamental frequency \[1\]. And the objective of the electric utility is to deliver sinusoidal voltage at fairly constant magnitude throughout their system. This objective is complicated by the fact that there are non-linear loads on the system that produce harmonic currents. These non-linear elements generate network voltages with frequencies different from the network frequency or absorb currents with non-sinusoidal waveforms. The widespread and growing of these loads has greatly increased the flow of harmonic currents on facility distribution systems. The interest on problems related to non linear devices and their influence on the systems increased considerably since 1980. This is due to the development of new power semiconductor devices and, as a consequence, the development of new converters that affects linearity in electric power signals substantially. The increase on the utilization of electronic equipment modified the sinusoidal nature of electrical signals. These equipments increase the current waveform distortion and, as a consequence, increment the voltage waveform distortion \[2\] \[3\].
1.2 Causes of harmonics

Harmonics are caused by non-linear loads, that is, loads that draw non sinusoidal current from a sinusoidal voltage source. Some examples of harmonic producing loads are electric arc furnaces, static VAR compensators, inverters, DC converters, switch-mode power supplies, and AC or DC motor drives [1].

In the case of a motor drive, the AC current at the input to the rectifier looks more like a square wave than a sine wave. The rectifier can be thought of as a harmonic current source and produces roughly the same amount of harmonic current over a wide range of power system impedances. The characteristic current harmonics that are produced by a rectifier are determined by the pulse number. The following equation allows determination of the characteristic harmonics for a given pulse number [4]:

\[ n = kq \pm 1 \]  \hspace{1cm} (1.1)

where: \( n \) is the harmonic number (integer multiple of the fundamental), \( k \) is any positive integer and \( q \) is the pulse number of the converter.
This means that a 6-pulse (or 3-phase) rectifier will exhibit harmonics at the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, etc. multiples of the fundamental. The magnitudes of the harmonic currents will be the fundamental current divided by the harmonic number (e.g. the magnitude of the 5th harmonic would be about 1/5th of the fundamental current). A 12-pulse (or 6-phase rectifier) will, in theory, produce harmonic currents at the 11th, 13th, 23rd, 25th, etc. multiples. In reality, a small amount of the 5th, 7th, 17th and 19th harmonics will be present with a 12-pulse system (typically the magnitudes will be on the order of about 10 percent of those for a 6-pulse drive).

Variable frequency drives also produce harmonic currents at the output of the inverter which are seen by the motor. Most of these harmonics are integer multiples of the inverter operating frequency and not the power supply frequency, but little generalization can be made about their magnitude since this varies greatly with the type of drive and the switching algorithm for the inverter semiconductors. Some "inter-harmonic" currents may also be present at the input or the output of the drive. Inter-harmonics do not fit the classical definition of harmonics since they do not necessarily occur at integer multiples of the power supply or inverter fundamental frequency. Harmonics can occur on the input at the power system frequency plus or minus the inverter operating frequency [3] [4].

1.3 Harmonic effects

Power system problems related to harmonics are rare but it is possible for a number of undesirable effects to occur. Harmonics result in the neutral carrying a current which might equal or exceed the phase currents even if the loads are balanced. This dictates the de-rating or over sizing of neutral wires. High levels of harmonic distortion can cause such effects as increased transformer, capacitor, motor or generator heating, mis-operation of electronic equipment (which
relies on voltage zero crossing detection or is sensitive to wave shape), incorrect readings on meters, mis-operation of protective relays, interference with telephone circuits, etc. The likelihood of such ill effects occurring is greatly increased if a resonant condition occurs. Resonance occurs when a harmonic frequency produced by a non-linear load closely coincides with a power system natural frequency. There are two forms of resonance which can occur: parallel resonance and series resonance [6] [5] [4].

Parallel resonance occurs when the natural frequency of the parallel combination of capacitor banks and the system inductance falls at or near a harmonic frequency. This can cause substantial amplification of the harmonic current that flows between the capacitors and the system inductance and lead to capacitor fuse blowing or failure or transformer overheating. Series resonance is a result of a series combination of Inductance and capacitance and presents a low impedance path for harmonic currents at the natural frequency. The effect of a series resonance can be a high voltage distortion level between the inductance and capacitance.

Harmonic distortion can have both short-term and long–term effects on the distribution system equipment and connected customer loads. Short-term effects are mainly concerned with immediate damage, equipment malfunction, and the associated power losses due to harmonic currents and voltages. Long-term effects include thermal losses and reduced life span of equipment. These problems are often not visible to the power distribution service providers or customers until final failure of equipment occurs. Reduced lifespan of equipment necessitates costly repairs or replacements.
1.4 Power quality measurements and standards

Power quality refers to the perfect sinusoidal property of voltage and current waveforms in a power system. These behaviors of the waveform are measured and studied through different signal processing and at the end compared to standards given.

Fourier theory tells us that any repetitive waveform can be defined in terms of summing sinusoidal waveforms which are integer multiples (or harmonics) of the fundamental frequency. For the purpose of a steady state waveform with equal positive and negative half-cycles, the Fourier series can be expressed as follows [7]:

\[ f(t) = A_0 + \sum_{n=1}^{\infty} (a_n \cos(n\omega_0 t + \phi_n)) \]  

(1.2)

where: \( f(t) \) is a periodic function of frequency \( f_0 \), angular frequency \( \omega_0 = 2\pi f_0 \), and period \( T = 1/f_0 \), \( a_1 \cos(\omega_0 t + \phi_1) \) represents the fundamental component and \( a_n \cos(n\omega_0 t + \phi_n) \) represents the \( n^{th} \) harmonic component of amplitude \( a_n \), frequency \( n\omega_0 \) and phase \( \phi_n \) relative to the fundamental.

1.4.1 Total harmonic distortion

The most commonly used measure of the quality of a periodic waveform is the total harmonic distortion (THD). THD can be used to describe voltage or current distortion and is calculated as follows:

\[ THD(\%) = \sqrt{I_{H1}^2 + I_{H2}^2 + \cdots + I_{Hn}^2} \]  

(1.3)

Where: \( I_{Hn} \) is the magnitude of the \( n^{th} \) harmonic as a percentage of the fundamental (individual distortion)
1.4.2 Power factor

There are two different types of power factor that must be considered when voltage and current waveforms are not perfectly sinusoidal. The first type of power factor is the Input Displacement Factor (IDF) which refers to the cosine of the angle between the 60 Hz voltage and current waveforms. Distortion Factor (DF) is defined as follows:

\[ DF = \frac{1}{\sqrt{1 + THD^2}} \]  

(1.4)

The Distortion Factor will decrease as the harmonic content goes up. The Distortion Factor will be lower for voltage source type drives at reduced speed and load. Total Power Factor (PF) is the product of the Input Displacement Factor and the Distortion Factor as follows:

\[ PF = IDF \times DF \]  

(1.5)

In order to make a valid comparison of power factor between drives of different topologies, it is essential to look at Distortion Factor. The Displacement Power Factor may look attractive for certain types of drives, but the actual power factor may be somewhat lower when the effect of harmonics is taken into account [7] [6].

1.4.3 IEEE 519 standards

IEEE Std. 519, which is titled "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems", is the main document for harmonics in North America. This standard puts limits on individual and total distortion for current harmonics. The recommendation is from the point of view that harmonics should be within reasonable limits at the
point where the power system feeds more than one customer. There are a couple of concepts that must be grasped before applying the limits in this standard:

- The Point of Common Coupling (PCC) is generally defined as the utility/customer connection point. It is this point at which the current distortion limits apply.
- The other concept that is important is that of Total Demand Distortion (TDD).

Current TDD, Total Demand Distortion of the current waveform, is the ratio of the root-sum-square value of the harmonic current to the maximum demand load current. Maximum Load Current ($I_L$) is recommended to be the average current of the maximum demand for the preceding 12 months.

That is, $I_{TDD} = \frac{\sqrt{I_{H1}^2+I_{H3}^2+I_{H5}^2+...}}{I_L} \times 100\%$ \hspace{1cm} (1.6)

The idea behind the standard is that harmonic limits are placed on a customer on the basis of current distortion relative to the total plant load. The limits do not apply to a specific non-linear load in the plant. The harmonic current limits change depending on the ratio of short circuit current ($I_{SC}$) to maximum demand load current at the PCC (Short Circuit Ratio ($I_{SC}/I_L$)). This means that small customers on a power system have higher current distortion limits than large customers. The overall aim of the standard is to keep voltage distortion at the point of common coupling below 5% THD.

1.5 Costs of power losses in harmonic distorted networks

To estimate the costs of harmonics is much more difficult than these of other power quality costs. People usually have a good picture about the economic impact of harmonics like:
• Loss of production
• Unrecoverable downtime and resources
• Process restart costs
• Equipment damage

Examples of such costs have been assembled in several power-quality surveys all over the world. The results were always the same: the financial losses for the industries due to a power quality incident in electrical installations can easily reach millions of dollars per incident. Such incidents can be avoided by the implementation of appropriate equipment, e.g. harmonic filters.

In opposition to that very well examined numbers the quantifying of the amount of unusable power had never been easily possible. Even so the Institute of Electrical and Electronics Engineers (IEEE) developed a standard to more accurately segment and quantify energy consumption in three-phase electrical systems (IEEE 1459-2000); the effects (losses) of harmonics were not considered in the classical methods. Savings in reactive power can be easily calculated. However, cost reduction due to less wear on equipment, less troubleshooting, or even prevented production downtime are more difficult to quantify. Studies show that this amounts to billions in damages each year. In general it is possible to identify the effects of voltage and current harmonics for the equipment or the entire power system. The main effects are [8] [9]:

• Increased (additional) energy losses if compared with a harmonic free power system
• Premature aging of the equipment and loss of system and equipment reliability because of harmonics
• Lower performance and operating failures if compared with nominal conditions
1.6 Objectives

The objective of this thesis is to determine the harmonic level behavior within power distribution systems. The characteristics of the loads are required to enable modeling approaches to be applied to distribution systems during the installation phase to identify distributions harmonic capabilities. The distortion in the voltage and current waveforms is known to deteriorate the performance of the equipment/devices connected in the distribution systems. Analyzing harmonic levels is essential when attempting to set allowable limits and installing mitigation devices. In this thesis, a preliminary survey will be carried out in residential and commercial areas to identify the existing level of current and voltage harmonic and their characteristics. The voltage and current waveforms of some of the commonly used loads and their harmonics will be investigated. The effect of resonance due to shunt capacitors will also be considered. The total harmonic distortion is used as a harmonic index to identify the effects of different nonlinear loads.

Some AC power quantities, such as the reactive power, are not well defined for non-sinusoidal situations. Efforts are made in this work to understand and explain the problems of extending the reactive power definition to cover non-sinusoidal conditions. No single power definition can alone provide information on all these properties in a non-sinusoidal situation. The latest proposed definitions of reactive power in non-sinusoidal situations and comparison to earlier definitions in terms of physical meanings and practical considerations will be elaborated in my thesis work. The concept of “non-active power” will be presented in the time domain.
1.7 Structure of the thesis

Chapter 2 introduces power definitions in sinusoidal and non-sinusoidal situations and following the sequence from single phase to three phase system. Active, reactive and distortion power are discussed. Evaluation of apparent and reactive power as well as power factor under sinusoidal, non-sinusoidal, single phase and three phases balanced and unbalanced is also included in this chapter.

Chapter 3 describes the two important standards and guidelines of current emission limits that are IEE std. 519-1992 and IEC/TR 61000-3-6 principles. Harmonic analysis in time domain and frequency domain is also discussed. Basic concepts towards evaluating harmonic currents and voltages are presented.

Chapter 4 is on residential and commercial feeder's discussion. The effect of harmonic sources, their representations and measurement set up in three phase commercial and single phase residential are discussed. Non-linear load model and their harmonic characteristics, sample measurements in residential harmonic loads and commercial loads are included in this chapter. This chapter also reviews distribution system equipment’s response to harmonic effect, while working in harmonic environments including the resonance effect of capacitor banks.

In chapter 5, simulation of typical distribution system using Easy power simulation tool is experimented. Different case studies are examined and discussed.

Finally in chapter 6 conclusions and recommendations are stated. References used for this thesis paper and study are specified following this chapter.
Chapter 2

Power definition in non-sinusoidal situations

2.1 Introduction

Quantities used in electrical power systems are defined for sinusoidal conditions. Under non-sinusoidal conditions, some quantities can conduct to wrong interpretations, and others can have no meaning at all. Apparent power (S) and reactive power (Q) are two of the most affected quantities. Conventional power definitions are well known and implemented extensively. However, only the active power has a clear physical meaning even for non-sinusoidal conditions. It represents the average value of the instantaneous power over a fix period. On the other hand, the mathematical formulation of reactive power may cause incorrect interpretation, aggravated when the analysis is extended to three phase systems.

Although definitions of apparent, active, and reactive power for sinusoidal systems are universally accepted, the angle difference between voltage and current produces power oscillation between the source and the load. All research effort remark the importance of the power factor and the reactive power on the optimal economic dispatch. One of the initial proposals consists on dividing the power term into active, reactive and distortion power, and was the most accepted one. Although many researchers remark the important implications of non sinusoidal conditions, up today it is very difficult to define a unique power definition for electric networks under distorted conditions [9][10][11].
This chapter presents a critical review of apparent power, reactive power and power factor definitions. First, the most commonly used definitions for apparent power are presented, after that, reactive power and the power factor definitions are studied. These definitions are reviewed for single phase and three phase systems and are evaluated under different conditions such as sinusoidal, non sinusoidal, single phase, balanced and unbalanced three phase systems. Then, comparison to earlier definitions in terms of physical meanings and practical considerations will be discussed.

### 2.2 Electrical power definition under sinusoidal conditions

The classical definition of instant power for pure sinusoidal conditions is [9]:

\[ p(t) = v(t) \times i(t) \]  \hspace{1cm} (2.1)

Where \( p(t) \), \( v(t) \) and \( i(t) \) are the instant power, instant voltage and instant current.

Considering sinusoidal voltage and current signals represented by the equations \( v(t) = \sqrt{2} \times V \times \sin(\omega t) \) and \( i(t) = \sqrt{2} \times I \times \sin(\omega t - \varphi) \) respectively, and then Eq. (2.1) takes the following form:

\[ p(t) = V \times I \times \cos(\varphi) - V \times I \times \cos(\varphi) \cos(2\omega t) + V \times I \times \sin(\varphi) \sin(2\omega t) \]  \hspace{1cm} (2.2)

\[ p(t) = P \times (1 - \cos(2\omega t)) + Q \times \sin(2\omega t) \]  \hspace{1cm} (2.3)

The mean value of \( p(t) \) is known as active power \( P \) and can be represented by:

\[ P = V \times I \times \cos(\varphi) \]  \hspace{1cm} (2.4)
Where $V$ and $I$ are the root means square (R.M.S) value of the voltage and current signals respectively and $\varphi$ is the phase shift between $v(t)$ and $i(t)$. In a similar manner, the reactive power $Q$ is defined as:

$$Q = V \times I \times \sin(\varphi)$$ \hspace{1cm} (2.5)

The geometric sum of $P$ and $Q$ is known as apparent power $S$ and can be calculated as follow:

$$S = V \times I = \sqrt{P^2 + Q^2}$$ \hspace{1cm} (2.6)

Another important term related to the power definition is the relationship between the active powers with respect to the apparent power; it is known as the system power factor $PF$ and gives an indication of the system utilization efficiency:

$$PF = \frac{P}{S} = \cos(\varphi)$$ \hspace{1cm} (2.7)

These properties apply exclusively to pure sinusoidal signals; therefore in the case of non-sinusoidal conditions not all of these properties are fulfilled. Next section presents different power definitions proposed for that purpose.
2.3 Electrical power definitions under non-sinusoidal conditions

In order to represent a non-sinusoidal condition, let’s consider voltage and current signals with harmonic components, then the apparent power can be represented by the following equation:

\[ S^2 = \sum_{n=0}^{\infty} V_n^2 \times \sum_{n=0}^{\infty} I_n^2 = V^2 \times I^2 \]  

(2.8)

For simplicity, let’s assume the case where only harmonic signals are present within the current signals and a voltage signal with only a fundamental component, then:

\[ S^2 = V_1^2 \times \sum_{n=0}^{\infty} I_n^2 = V_1^2 \times I_1^2 + V_1^2 \times \sum_{n \neq 1}^{\infty} I_n^2 \]  

(2.9)

By definition, the active power is:

\[ P = \frac{1}{T} \times \int_0^T v(t) \times i(t) \times dt = V_1 \times I_1 \times \cos(\phi_1) \]  

(2.10)

And the reactive power \( Q \):

\[ Q = \sum_{n=1}^{\infty} V_n \times I_n \times \sin(\phi_n) = V_1 \times I_1 \times \sin(\phi_1) \]  

(2.11)

Examining the expressions given by Eq. (2.9) to (2.11) and comparing them with Eq. (2.6) can be concluded that if the signals have components in addition to the fundamental sinusoidal component, the following expression obeys:

\[ P^2 + Q^2 = V_1^2 \times I_1^2 \neq S^2 \]  

(2.12)
From the inequality represented by Eq. (2.12) it is observed that the sum of the quadratic terms of $P$ and $Q$ involves only the first term of Eq. (2.9). Hence, definitions of apparent and reactive power useful for sinusoidal conditions may produce wrong results, thus, new definitions for non-sinusoidal conditions are needed. There are proposals to extend apparent power and reactive power formulations for non sinusoidal situations; the most used ones are described next.

### 2.3.1 Reactive power and distortion power definitions

At the beginning, two important approaches were introduced by Budeanu in 1927 in frequency domain and Fryze in 1932 in time domain and after no contributions were made until 1970. One of the first power definitions that include the presence of harmonics was given by Budeanu where the active and reactive powers are defined by the following expressions [10]:

\[
P = \sum_n V_n \times I_n \times \cos \phi_n \tag{2.13}
\]

\[
Q_B = \sum_n V_n \times I_n \times \sin \phi_n \tag{2.14}
\]

where, $n$ is the harmonic number

Representing the active and reactive power by Eq. (2.13) and Eq. (2.14), the power triangle does not comply, therefore Budeanu defined a new term know as distortion power:

\[
D = \sqrt{S^2 - P^2 - Q_B^2} \tag{2.15}
\]

Based on the distortion power, a complementary or fictitious power is also defined:

\[
F = \sqrt{S^2 - P^2} = Q_B^2 + D^2 \tag{2.16}
\]
The physical meaning of Eq. (2.16) is a power oscillation between the source and the sink, however this only stand when all elements are purely linear and reactive (i.e. capacitors and inductors), which means that Eq. (2.16) cannot be used for reactive compensation design.

Based on this initial definition of distortion power, several other authors proposed different definitions of D as a function of R.M.S voltage and current harmonic signals and their phase shift.

(Filipski, 1984) proposed [12]:

\[
D = \sqrt{\sum_m \sum_n V_m^2 \times I_n^2 - V_n \times I_m \times I_n \times \cos(\varphi_m - \varphi_n)}
\] (2.17)

(Emanuel, 1990) proposed [13]:

\[
D^2 = \sum_{m,n=1,m \neq n} V_m^2 \times I_n^2 + V_n^2 \times I_m^2 - 2 \times V_m \times V_n \times I_m \times I_n \times \cos(\varphi_m - \varphi_n)
\] (2.18)

After that, (Czarnecki, 1993) recommended the following formula for D [14]:

\[
D = \sqrt{\frac{1}{2} \sum_m \sum_n V_m^2 \times I_n^2 - 2 \times V_m \times V_n \times I_m \times I_n \times \cos(\varphi_m - \varphi_n)}
\] (2.19)

Where \(V_n, V_m, I_m\) and \(I_n\) are the R.M.S. harmonics components and the harmonic angles are \(\varphi_m = \alpha_m - \beta_m, \varphi_n = \alpha_n - \beta_n\) with \(\alpha_n, \alpha_m, \beta_n, \beta_m\) the angle shift between the voltage and current harmonic components.
Similar definition than the one described by Eq. (2.17) was proposed by the IEEE Std. 100-1996 (Institute of Electrical and Electronic Engineering [IEEE], 1996). Yildirim and Fuchs (Yildirim & Fuchs, 1999) compared Eq. (2.17) to (2.19) and performed experimental measurements using different type of voltage and current distortions, recommending the following distortion definition [15]:

\[
D^2 = \sum_{m=0}^{h-1} \sum_{n=m+1}^{h} V_m^2 \times I_n^2 + V_n^2 \times I_m^2 - 2 \times V_m \times V_n \times I_m \times I_n \times \cos(\varphi_m - \varphi_n) \tag{2.20}
\]

Where \( h \) is the number of harmonics.

### 2.3.2 Reactive power definition proposed by Fryze

The reactive power definition proposed by Fryze is based on the division of the current into two terms; the active current term and the reactive current term (Fryze, 1932, as cited in Svensson 1999):

\[
i = i_a + i_r \tag{2.21}
\]

Considering that these terms are orthogonal, the following property applies:

\[
\frac{1}{T} \int_0^T i_a \times i_b \times dt = 0 \quad (orthogonal) \tag{2.22}
\]

Then, \( i_a \) can be calculated from the active power:

\[
i_a(t) = \frac{P}{V^2} \times v(t) \tag{2.23}
\]

Then, from Eq. (2.21), the reactive power \( i_r \) is:
\[ i_r(t) = i(t) - i_a(t) \] (2.24)

Based on these definitions and considering Eq. (2.16), the reactive power representation proposed by Fryze is:

\[ Q_F = V \times I_F = \sqrt{(V \times I)^2 - (V \times I_a)^2} = \sqrt{S^2 - P^2} = \sqrt{Q_B^2 + D^2} \] (2.25)

Eq. (2.25) shows that \( Q_F \) is a function of \( S \) and \( P \), therefore, the advantage of this representation is that there is no need to measure the reactive power. However, \( Q_F \) is always a positive magnitude, then, hence, it cannot be used for power flow analysis. On the other hand, since it is always positive, it can be compensated by injecting a negative current \(-i_r\) which makes it suitable for active filter design [16][17].

### 2.3.3 Reactive power definition proposed by Emanuel

Emanuel observed that in most cases, the principal contribution to the reactive power is due to the fundamental component of the voltage signal, then, he proposed the following definition for the reactive power term (Emanuel, 1990) [13]:

\[ Q_1 = V_1 \times I_1 \times \sin \varphi_1 \] (2.26)

Based on this definition, an additional term named complementary power can be formulated:

\[ P_c^2 = S^2 - P^2 - Q_1^2 \] (2.27)

Finally, both active and reactive terms can be represented by two terms; the fundamental and the harmonic component:
\[ S^2 = (P_1 + P_h)^2 + Q_F^2 \]  \hspace{1cm} (2.28)

Where \( Q_F \) is the reactive power defined by Fryze.

Expressing \( Q_F \) as a function of the fundamental and harmonic term:

\[ Q_F^2 = Q_1^2 + Q_h^2 \]  \hspace{1cm} (2.29)

And replacing Eq. (2.29) into Eq. (2.28), the apparent power is:

\[ S^2 = (P_1 + P_h)^2 + Q_1^2 + Q_h^2 \]  \hspace{1cm} (2.30)

Since \( Q_F \) is defined adding two different terms, the fundamental reactive power \( Q_1 \) and the harmonic reactive power \( Q_h \), this definition became an effective tool for active filters control and monitoring and power factor shift compensation design.

### 2.3.4 Definition proposed by Czarnecki

Based on previous definitions, Czarnecki proposed new definitions based on an orthogonal current decomposition that allows identifying different phenomena that cause the efficiency decrease of the electrical energy transmission (Czarnecki, 1993) [14].

The total current is decomposed in active, reactive, harmonic and disperses terms:

\[ I^2 = I_A^2 + I_R^2 + I_S^2 + I_H^2 \]  \hspace{1cm} (2.31)

The latest three terms are the ones responsible of the efficiency transmission decrease.

Where the reactive term is depends on \( B_h \) (Susceptance harmonic values) given by:
\[ I_R = \sqrt{\sum_{n=1}^{N} B_n^2 \times V_n^2} \quad (2.32) \]

Index K is the harmonic component that is not present in the N voltage terms, the harmonic term is calculated as:

\[ I_H = \sqrt{\sum_{n=K}^{N} I_n^2} \quad (2.33) \]

And the disperse current can be represented as follow:

\[ I_S = \sqrt{\sum_{n=N} \left( G_n - G \right)^2 \times V_n^2} \quad (2.34) \]

Where the equivalent load conductance is:

\[ G = \frac{P}{V^2} \quad (2.35) \]

And the n-order harmonic component of the load is:

\[ Y_n = G_n + jB_n \quad (2.36) \]

Using this decomposition, the apparent power can be expressed as:

\[ S^2 = P^2 + D_S^2 + Q_R^2 + D_H^2 \quad (2.37) \]

Where the reactive power, the distortion power and the harmonic power are respectively:

\[ Q_R = V \times I_R \quad (2.38) \]
\[ D_S = V \times I_S \quad (2.39) \]
\[ D_H = V \times I_H \quad (2.40) \]

One of the main features of this definition is that it is based on susceptance instead of voltages, currents and powers. For systems that contain currents with large harmonic values and voltage with small harmonic values, will present the problem of phase shift uncertainty and, as a consequence, large uncertainty of parameter \( B_n \). This issue may produce errors in the reactive current determination.

### 2.3.5 Definition proposed by Shepherd and Zand’s

According to [10], in their definition current is divided into three components which are:

**Active current:**
\[
I_R = \sqrt{\sum \frac{I_R^2}{n} \times \cos^2 \phi_n} \quad (2.41)
\]

**Reactive current:**
\[
I_X = \sqrt{\sum \frac{I_X^2}{n} \times \sin^2 \phi_n} \quad (2.42)
\]

and Distortion current is defined to be:
\[
I_D = \sqrt{I^2 - I_R^2 - I_X^2} \quad (2.43)
\]

And the proposed power equation related to this current decomposition:
\[
S^2 = S_R^2 + S_X^2 + S_D^2 \quad (2.44)
\]

where; \( S_R \), \( S_X \) and \( S_D \) are active, reactive and distortion apparent powers respectively and defined as:
\[
S_R = \sqrt{\sum_{1}^{n} V_n^2 \times \sum_{1}^{n} I_R^2 \times \cos^2 \phi_n} \quad (2.45)
\]
\[ S_X = \sqrt{\sum_{n=1}^{n} V_n^2 \times \sum_{n=1}^{n} I_n^2 \times \sin^2 \phi_n} \quad (2.46) \]

\[ S_D = \sqrt{\sum_{n=1}^{n} V_n^2 \times \sum_{z=1}^{z} I_z^2 + \sum_{u=1}^{u} V_u^2 \times \left( \sum_{n=1}^{n} I_n^2 + \sum_{z=1}^{z} I_z^2 \right)} \quad (2.47) \]

Where \( Z \): the harmonic number of current in which there is no voltage harmonics.

\( U \): the harmonic number of voltage in which there is no current harmonics.

The active and reactive apparent powers, in this case, provide meaningful data about line loading, therefore, efficiency.

**2.3.6 Definition proposed by Sharon**

Sharon’s power equations are based on shepherd and Zand’s reactive apparent power but Sharon’s active component of power is average power [10] and proposed as:

\[ S^2 = P^2 + S_Q^2 + S_C^2 \quad (2.48) \]

where; \[ S_Q = V \times \sqrt{\sum_{n=1}^{n} I_n \times \sin^2 \phi_n} \quad (2.49) \]

and; \[ S_C = \sqrt{S^2 - P^2 - S_Q^2} \quad (2.50) \]
2.3.7 Definition proposed by Kimbark

Kimbark’s power equation has, like Budeanu, two orthogonal components; active and
deactive. The active power is average power and Kimbark’s deactive power is divided in to
kimbark’s reactive power and distortion powers [10] and proposed as:

\[ Q_K = V_1 \times I_1 \times \sin\varphi_1 \] (2.51)

\[ D_K = \sqrt{S^2 - P^2 - Q_K^2} \] (2.52)

2.3.8 Definition proposed by the IEEE 1459-2000

This standard proposes the decomposition of both current and voltage signals into
fundamental and harmonic terms (Institute of Electrical and Electronic Engineering [IEEE], 2000)
[18] [9]:

\[ I^2 = I_1^2 + I_H^2 \] (2.53)

\[ V^2 = V_1^2 + V_H^2 \] (2.54)

Where the harmonic components include all harmonic terms and the direct current
component as well:

\[ V_H^2 = \sum_{h \neq 1} V_h^2 \] (2.55)

\[ I_H^2 = \sum_{h \neq 1} I_h^2 \] (2.56)
Based on these terms, the active power can be represented as the sum of the fundamental and harmonic components:

\[ P = P_1 + P_H \]  

(2.57)

Where the fundamental and harmonic components are respectively:

\[ P_1 = V_1 I_1 \cos \varphi_1 \]  

(2.58)

\[ P_H = \sum_{h \neq 1} V_h I_h \cos \varphi_h \]  

(2.59)

Similarly, the reactive power can be represented:

\[ Q = Q_1 + Q_H \]  

(2.60)

Where the fundamental and harmonic components are:

\[ Q_1 = V_1 I_1 \sin \varphi_1 \]  

(2.61)

\[ Q_H = \sum_{h \neq 1} V_h I_h \sin \varphi_h \]  

(2.62)

Considering that the square of the apparent power can be represented as a function of the voltage and current terms:

\[ S^2 = (VI)^2 = (V_1 I_1)^2 + (V_1 I_H)^2 + (V_H I_1)^2 + (V_H I_H)^2 \]  

(2.63)

Representing the apparent power S as the sum of fundamental and non-fundamental terms:
\[ S^2 = S_1^2 + S_N^2 \]  \hspace{1cm} (2.64)

It is possible to conclude by comparing Eq. (2.63) with Eq. (2.64), that the first term of the square of the apparent power, which is a function of the fundamental components, can be also represented as a function of the fundamental active and reactive components. These terms are:

\[ S_1^2 = (V_1 I_1)^2 = P_1^2 + Q_1^2 \]  \hspace{1cm} (2.65)

And term \( S_N \) is composed by the rest of the terms present in Eq. (2.63):

\[ S_N^2 = (V_1 I_H)^2 + (V_H I_1)^2 + (V_H I_H)^2 = D_I^2 + D_V^2 + S_H^2 \]  \hspace{1cm} (2.66)

Where the distortion power due to the harmonic current is:

\[ D_I = V_1 I_H \]  \hspace{1cm} (2.67)

And due to the harmonic voltage:

\[ D_V = V_H I_1 \]  \hspace{1cm} (2.68)

Finally the last term is known as the harmonic apparent power:

\[ S_H = V_H I_H \]  \hspace{1cm} (2.69)

Defining the relationship between the harmonic current and the fundamental current components as the total harmonic current distortion \( \frac{I_H}{I_1} = THD_I \) and similarly for the voltage \( \frac{V_H}{V_1} = THD_V \) then the equations can be represented as a function of the distortion:

\[ D_I = S_1 \times THD_I \]  \hspace{1cm} (2.70)
\[ D_V = S_1 \times THD_V \quad (2.71) \]
\[ S_H = S_1 \times THD_i \times THD_V \quad (2.72) \]

Finally, the apparent power can be decomposed into the active power \( P \) and the non-active power \( Q \):

\[ S^2 = (V \times I)^2 = P^2 + Q^2 \quad (2.73) \]

Since the harmonic power term is the only one that can have an active component, it can be formulated as follow:

\[ S_H^2 = (V_H \times I_H)^2 = P_H^2 + Q_H^2 \quad (2.74) \]

The power factor due to the fundamental component, also known as shift power factor is:

\[ PF_1 = \cos \varphi_1 = \frac{P_1}{S_1} \quad (2.75) \]

The total power factor is given by the following expression:

\[
PF = \frac{P}{S} = \frac{P_1 + P_H}{S} = \frac{\left(\frac{P_1}{S_1}\right) \times \left(1 + \left(\frac{P_H}{P_1}\right)\right)}{\sqrt{1 + \left(\frac{S_H}{S_1}\right)^2}}
\]

\[
= \frac{\left(1 + \left(\frac{P_H}{P_1}\right)\right) \times PF_1}{\sqrt{1 + THD_i^2 + THD_V^2 + (THD_1 \times THD_V)^2}} \quad (2.76)
\]
2.3.9 Comparison of different reactive and distortion power definitions

Table 2.1 shows measurements taken from combined harmonic current drawn by single phase two 1.6A, 50W Laptops, a 14W CFL and 75W 1.2A color Television with Model 8220 harmonic analyzer. Figure 2.1 and 2.2 are the waveforms and harmonic order percentage of the RMS voltage and current measured respectively. Using the information given in table 2.1 for the different definitions proposed for reactive power and distortion power, calculated distortion and reactive power results are given in Fig. 2.3 and Fig. 2.4.

<table>
<thead>
<tr>
<th>Harmonic orders</th>
<th>Voltage</th>
<th>Current</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>RMS</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
</tr>
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</tr>
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</tr>
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</tr>
</tbody>
</table>

Table 2.1 Harmonic data measurement of combined single phase loads
Fig 2.1 Current and voltage waveforms for combined non linear loads

Fig 2.2 Harmonic orders percentages.

Fig 2.3 Distortion power calculated using the definitions proposed in different times
In summary, Budeanu’s reactive and distortion power suggests that all for examined non-linear loads \((D_a>Q_a)\). The sum of all reactive power in a node is zero in Budeanu’s definition unlike the others. Reactive power calculated from Fryze’s definitions (Eq. 2.25) has almost all characteristics in a sinusoidal waveform, which is, if the reactive power reduced to zero the power factor will be unity and the reactive power completes the power triangle. Reactive power can be positive or negative depending on inductive or capacitive loads in case of most of the definitions proposed. Fryze’s and Sharon’s reactive power can be reduced to zero by inserting inductive or capacitive components. Kimbark suggests that the actual contribution of harmonic frequencies to reactive power is less than 3% of the total reactive power. IEEE proposed definition (Eq.2.61) always provides value of the fundamental components.
2.4 Electric power definitions for three phase systems

Similarly to a single phase system, the definition of apparent power for a three phase system under non sinusoidal conditions has no physical meaning, therefore may drives to wrong interpretations. The measurement, analysis and definition of the different terms of three phase power signal, where voltages and currents are unbalanced and distorted, have been studied in order to standardize the correct indexes that quantify the level of harmonic and distortion (Emanuel, 1999, 2004). As a consequence, nowadays, to have an accurate and consensual definition of apparent, reactive power and power factor for non-sinusoidal three phase systems becomes relevant. In the next section the most used definitions are discussed.

2.4.1 Apparent power definition for three phase non-sinusoidal systems

There are several definitions related to the calculation of apparent power for unbalanced three phase systems. Based on the single phase definitions, in a multiphase system (phase a, b, c) the apparent power vector is:

\[
S_V = \left( \sum_{k=a}^{c} P_k \right)^2 + \left( \sum_{k=a}^{c} Q_{bk} \right)^2 + \left( \sum_{k=a}^{c} D_k \right)^2
\]  \hspace{1cm} (2.77)

The arithmetic apparent power can be represented as the sum of all phase’s apparent power:

\[
S_A = \sum_{k=a}^{c} \sqrt{P_k^2 + Q_{bk}^2 + D_k^2}
\]  \hspace{1cm} (2.78)

For a phase k, \( P_k \) is the active power, and \( Q_{bk} \) and \( D_k \) are the reactive and distortion power defined by Budeanu, respectively. The definitions described by Eq. (2.77) and Eq. (2.78) are
identical and produce correct results for balanced load and sinusoidal voltage and current signals. However, for general unbalanced and/or distorted signals, it can be proved that [9] [21]:

\[ S_V \leq S_A \]  

(2.79)

In addition, the power factor index will also produce different results depending on which definition is used:

\[ PF_V = \frac{P}{S_V} \geq PF_A = \frac{P}{S_A} \]  

(2.80)

Where \( PF_V \) and \( PF_A \) are the power factors using the apparent power vector and the arithmetic definition respectively.

The following expression to calculate the apparent power is proposed in [21]:

\[ S = \sqrt{\frac{V_{ab}^2 + V_{bc}^2 + V_{ac}^2}{3} \left( I_a^2 + I_b^2 + I_c^2 \right)} \]  

(2.81)

Conceptually, Equation (2.81) illustrates that for a given three phase system it is possible to define an equivalent apparent power known as the effective apparent power that is defined as follows:

\[ S_e = 3 \times V_e \times I_e \]  

(2.82)

Where \( V_e \) and \( I_e \) are the R.M.S. effective voltage and current values respectively.

Recently, several authors proposed different mathematical representation based on Eq. (2.82). The most important one is the one developed by the IEEE Working Group (Institute of
Electrical and Electronic Engineering [IEEE], 1996) that was the origin of the IEEE Standard 1459-2000 (Institute of Electrical and Electronic Engineering [IEEE], 2000) [19][20].

2.4.2 Definition proposed by the IEEE 1459-2000

This standard assumes a virtual balanced system that has the same power losses than the unbalanced system that it represents. This equivalent system defines an effective line current $I_e$ and an effective phase to neutral voltage $V_e$ [19] [9].

$$I_e = \sqrt{\frac{1}{3}(I_a^2 + I_b^2 + I_c^2 + \rho \times I_n^2)}$$ (2.83)

Where, the factor $\rho = r_n/r$ can vary from 0.2 to 4, equivalent resistivity of the neutral path.

Similar procedure can be followed in order to obtain a representation for the effective voltage $V_e$. In this case, the load is represented by three equal resistances connected in a star configuration, and three equal resistances connected in a delta configuration, the power relationship are defined by the factor $\varepsilon = P_\Delta/P_\gamma$.

Considering that the power losses are the same for both systems, the effective phase to neutral voltage for the equivalent system is:

$$V_e = \sqrt{\frac{3 \times (V_a^2 + V_b^2 + V_c^2) + \varepsilon \times (V_{ab}^2 + V_{ac}^2 + V_{bc}^2)}{9 \times (1 + \varepsilon)}}$$ (2.84)

In order to simplify the formulations, the standard assumes unitary value of $\rho$ and $\varepsilon$, then Eq. (2.83) and (2.84) can be represented as:
\[ I_e = \frac{1}{\sqrt{3}} (I_a^2 + I_b^2 + I_c^2 + I_n^2) \]  
(2.85)

\[ V_e = \sqrt{\frac{3 \times (V_a^2 + V_b^2 + V_c^2) + (V_{ab}^2 + V_{ac}^2 + V_{bc}^2)}{18}} \]  
(2.86)

These effective current and voltage can also be represented as a function of positive, negative and zero sequence components of voltage and current:

\[ I_e = \sqrt{(I_+)^2 + (I_-)^2 + 4 \times (I_0)^2} \]  
(2.87)

\[ V_e = \sqrt{(V_+)^2 + (V_-)^2 + \frac{1}{2} \times (V_0)^2} \]  
(2.88)

Since one of the objectives of these formulations is to separate the fundamental term from the distortion terms, the effective values can be further decomposed into fundamental and harmonic terms:

\[ V_e^2 = V_{e1}^2 + V_{eH}^2 \]  
(2.89)

\[ I_e^2 = I_{e1}^2 + I_{eH}^2 \]  
(2.90)

Where the fundamental terms are:

\[ V_{e1} = \sqrt{\frac{3 \times (V_{a1}^2 + V_{b1}^2 + V_{c1}^2) + (V_{ab1}^2 + V_{ac1}^2 + V_{bc1}^2)}{18}} \]  
(\( \epsilon = 1 \))  
(2.91)
\[ I_{e1} = \sqrt[3]{\frac{1}{3} (I_{a1}^2 + I_{b1}^2 + I_{c1}^2 + I_{n1}^2)} \quad (\rho = 1) \] (2.92)

And the harmonic terms:

\[ V_{eH}^2 = V_e^2 - V_{e1}^2 \] (2.93)

\[ I_{eH}^2 = I_e^2 - I_{e1}^2 \] (2.94)

Considering these definitions, the effective apparent power can be calculated as follow:

\[ S_e^2 = (3 \times V_{e1} \times I_{e1})^2 + (3 \times V_e \times I_{eH})^2 + (3 \times V_{eH} \times I_{e1})^2 + (3 \times V_{eH} \times I_{eH})^2 \] (2.95)

Where the fundamental term of the effective apparent power is:

\[ S_{e1} = 3 \times V_{e1} \times I_{e1} \] (2.96)

The fundamental term can also be represented as a function of active and reactive sequence powers:

\[ (S_1^+)^2 = (P_1^+)^2 + (Q_1^+)^2 \] (2.97)

Where:

\[ P_1^+ = 3 \times V_1^+ \times I_1^+ \times \cos \varphi_1^+ \] (2.98)

\[ Q_1^+ = 3 \times V_1^+ \times I_1^+ \times \sin \varphi_1^+ \] (2.99)
Then, the square of the fundamental effective apparent power can be represented as the addition of two terms:

\[ S_{e1}^2 = (S_1^+)^2 + (S_u1)^2 \]  \hspace{1cm} (2.100)

Where, the term \( S_u1 \) is due to the system unbalance. Similarly, the non fundamental term \( S_{eN} \) can be represented by:

\[ S_{eN}^2 = (3 \times V_{e1} \times I_{eH})^2 + (3 \times V_{eH} \times I_{e1})^2 + (3 \times V_{eH} \times I_{eH})^2 \]  \hspace{1cm} (2.101)

Where the three terms can be represented as a function of the total harmonic distortion, defining the distortion power due to the current as:

\[ D_{el} = 3 \times V_{e1} \times I_{eH} = 3 \times S_{e1} \times THD_I \]  \hspace{1cm} (2.102)

The distortion power due to the voltage:

\[ D_{eV} = 3 \times V_{eH} \times I_{e1} = 3 \times S_{e1} \times THD_V \]  \hspace{1cm} (2.103)

And the effective harmonic apparent power:

\[ S_{eH} = 3 \times V_{eH} \times I_{eH} = 3 \times S_{e1} \times THD_V \times THD_I \]  \hspace{1cm} (2.104)

Finally, the harmonic active power can be calculated:

\[ P_H = \sum_{\substack{h \neq 1 \atop i=r,s,t}} V_{ih} \times I_{ih} \times \cos \varphi_{ih} = P - P_1 \]  \hspace{1cm} (2.105)

The main features of the formulations proposed by this standard are: \( P_1^+ \) can be separated from the rest of the active power component. In general \( P_H, P_1^-, P_1^0 \) can be neglected since they are
small with respect to $P_1^+$, therefore results obtained by measuring only this term is accurate enough. Identify $Q_1^+$ from the rest of the reactive power components, it allows to design the appropriate capacitor bank in order to compensate the power factor shift $cos\phi_1^+$. The non fundamental apparent power $S_{eN}$ allows evaluating the distortion severity and becomes a useful parameter to estimate the harmonic filter size to compensate the distortion [9].

2.4.3 Comparing arithmetic and vector from field measurement

Measurements, for this study, taken from university of Nevada, Las Vegas TBE building power control room, using FLUKE 1735 power analyzer instrument are given in figure 2.5.

![Measurement Table]

From the definition extension of Budeanu’s apparent power resolution, the arithmetic apparent power is calculated as the sum of the phase KVA’s and is 34.3. The distortions (Budeanu’s) for each phase are 2.70, 2.21 and 1.85. Therefore the total distortion will be the sum 6.76. The arithmetic sum of the total KVAR and the distortion is 7.858 which is different from the difference between the total KVA and KW, 8.22, and that is the major drawback the this definition. On the
other hand, the vector apparent power definition is free from the drawback discussed earlier but the fact that no flow direction can be assigned to the distortion power limits the definition.
Chapter 3

Literature reviews on harmonics of distribution system

3.1 Introduction

The IEEE Std. 519 establishes limits for harmonic voltage and current levels at the Point of Common Coupling (PCC) [26] [27] [28]. When estimating compliance to these limits for new or expanding facilities with multiple time varying harmonic loads, the summation of harmonics from the time varying loads becomes an important issue. The science of harmonic simulation has advanced a great deal in the past two to three decades. The problem of how to represent multiple harmonic sources and background harmonics so that future levels can be predicted when expanding an existing facility or building a new facility still represents a difficult task. When the loads are time varying loads the representation becomes even more complex.

In the IEEE Std. 519 “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”, there are tables for harmonic voltage and current limits for recommended practices for utilities and consumers [27]. However there is little guidance on how to apply these limits in particular with regards to the method used for determining the harmonic levels. If, for example, the loads did not vary with time and the system background harmonics were constant then this would be a non-issue; however that is far from practical. Most loads vary with time and background harmonics also vary but to a lesser degree than some of the more severe loads.

There are different techniques and approaches towards evaluating and studying the harmonic current emission in distribution system which is going to be discussed in this chapter.
Allocation of distribution and transmission system and the two important standards IEC/TR-61000-3-6 Principles and IEEE std.519 will also be discussed later in the chapter.

3.2 Summation laws

IEC/TR 61000-3-6 recommended methods to represent harmonic cancellation for both current and voltage harmonics [24]. The actual harmonic voltage (or current) at any point of a distribution system is the result of phasor summation of the individual components of each source. But two universal harmonic summation laws are commonly used for multi-sources without knowing phase angles [24] [25].

3.2.1 First summation law

This is a simple linear law making use of diversity factor (the ratio individual maximum demand to the utility total maximum demand) $k_{hj}$:

$$V_h = V_{h0} + \sum_j k_{hj} \times V_{hj} \quad (3.1)$$

Where, $V_{h0}$ = the background harmonic voltage of the supply network (the harmonic voltage present in the supply network with the j loads disconnected). But this law was removed on IEC/TR 61000-3-3: 2008 due to the lack of uncertainty for dominantly higher order of characteristic harmonics.

3.2.2 Second summation law

This summation law is proposed in the standard: this is a power law recommended as being more general and can be adopted for both harmonic voltage and current. Therefore, the net effect $V_h$ of voltages $V_{h1}, ... V_{hn}$ is
Where, $V_h =$ magnitude of resulting harmonic voltage (order h), $V_{hi} =$ magnitude of individual $i^{th}$ harmonic voltage (order h) to be combined, $a =$ exponent depending on the probability of actual value and the degree to which the individual harmonic voltage vary in magnitude and phase.

3.3 Harmonic analysis

To evaluate the harmonic current emission limits, two factors should be considered. One is consumers agreed on power capacity since all customers have the right to inject their full harmonic disturbance into the supply system. All customers, having equal maximum demand, have the right to receive equal harmonic voltage emission limits. The other influential factor is the short-circuit power, which depends on the distance from the source to the point of evaluation [25] [38].

The commonly used harmonic analysis methods can be divided into two categories:

1. Transient-state analysis techniques, such as time domain analysis
2. Steady-state analysis techniques, broadly classified as:
   a) Current injection methods
   b) Harmonic power flow methods

3.3.1 Time domain methods

Time domain harmonic analysis is common to transient analysis, but the transient itself is usually not the objective. In this approach the network is represented by a system of differential equations. The quasi-steady state is the solution of the equations after the transient, and the
harmonic information is obtained by applying DFT (Discrete Fourier Transform) on the resulting waveforms [35].

The system of equations which represents the network is built from the voltage-current relations of all elements, and arranged in a form which is convenient for solving. Several forms are proposed for the representation. The general state space form of the time domain model is given by:

\[
\dot{x}(t) = g_1\{t, [x(t)], [u(t)]\} \tag{3.3}
\]

\[
y(t) = g_2\{t, [x(t)], [u(t)]\} \tag{3.4}
\]

where \(t\) is the time, \([u(t)]\) is the input vector, \([x(t)]\) is the state vector of the system, \([\dot{x}(t)]\) is the first time derivative of the state vector, \([y(t)]\) is the output vector, and \(g_1\) and \(g_2\) are functions of the system.

For linear systems, Eq. (3.3) and (3.4) can be solved analytically, but in most cases the system is non-linear, and it is difficult to solve the system of equations analytically. Due to this, the equations are usually solved by numerical integration which is a standard procedure in all Electro-Magnetic Transient Programs (EMTP).

The solution of the time domain approach is accurate in all working conditions in which the equations give a fair representation of the non-linearity. It is very effective for calculating non-characteristic harmonics and takes into account unbalances, saturation of magnetic elements, asymmetries in firing angles, etc.

The biggest drawback of time domain simulation is that it requires a relatively large set of input parameters. For example, the control algorithms of converters are standard not made
available by the manufacturer, which influences the accuracy of their representation greatly. Another drawback of these methods is the complexity. For example, frequency dependencies of predominantly linear network elements (e.g. change of resistance due to skin effect) increase the model complexity considerably, while some of them can be efficiently implemented in frequency domain methods. Due to this, it is difficult to perform time-domain simulations of very large systems, and they are usually limited to a part of the system close to the disturbing load (e.g. a large converter). These reasons led to a very high popularity of frequency domain methods for harmonic simulation.

### 3.3.2 Frequency domain methods

Frequency domain methods represent the system by matrix equations for each frequency of interest, which removes the need for solving a set of differential equations. Equations for different frequencies can in general be linked, but in most cases the system is treated as frequency decoupled, which makes the final solution a linear sum of independent harmonic components [38].

Another characteristic of the frequency domain is that the non-linearity of network components has a linear representation at each harmonic frequency. For example, the frequency dependence of conductor resistance (due to the skin effect) is modeled by different values of resistance at each frequency. As the system of equations is solved separately for each harmonic, resistance is a linear element in each calculation step.

The solution of frequency domain methods represents a certain time interval, e.g. a single period of the fundamental frequency, which makes the result time invariant during this period – a quasi-steady state. If time changes are to be assessed in the frequency domain, a new solution has to be found for each time interval, using the previous as the starting point for the calculation. The
frequency of variations needs to be lower than the fundamental frequency if the time variations
are to be represented accurately.

The frequency domain harmonic analysis can further be subdivided into direct and iterative.

3.3.2.1 Direct method

The direct method is the simplest approach for harmonic analysis. It calculates harmonic
voltages on all bus bars based on a single constant harmonic source, using the nodal method which
is a linear matrix equation set:

\[ [V_h] = [Z_h][I_h] \]  \hspace{1cm} (3.5)

Where \([V_h]\) is the vector of harmonic voltages of the \(h^{th}\) order, \([Z_h]\) is a matrix of harmonic
impedances which connect all bus bars, and \([I_h]\) is an input vector of harmonic currents. For a single
source, there is a single none-zero element in the vector \([I_h]\).

If more harmonic sources are considered, the calculation can be repeated for each of the
sources, with the final solution being a linear combination of the particular outcomes. Under
unbalance, the method can be applied on sequence components, which requires solving three
single phase matrix sets of equations, or directly on phase components, with a single three phase
matrix equation set.

The drawback of the direct method is that it is limited in the representation of harmonic
sources. The voltage dependence of current sources can be modeled by a non-ideal current or
voltage sources, Norton or Thévenin equivalents, which improves the performance, but it does not
allow for a detailed representation available to iterative methods.
3.3.2.2 **Iterative method**

The shortages of the direct method can be compensated with an iterative approach. In the direct method, the voltage dependence of a current source (harmonic sources are usually modeled as current sources, but the same holds for voltage sources) can be described with an additional equivalent impedance, which changes the total current in respect to the voltage at its bus bar. If the current source of the Norton equivalent needs to be voltage dependent, an iterative approach is needed to match the current of the source to the bus bar voltage. At the first iteration, a set of harmonic voltages is assumed at the source bus bar (e.g. a clean sinusoidal voltage). The harmonic currents are then calculated based on the voltage, and injected to the system. The new voltage at the bus bar is then used to recalculate the source current, and the process is repeated until the difference between two iterations is acceptably small. In this way the problem can be treated with multiple sources as well. Also, the inter-dependency of sources is taken into account, which is not possible in the direct method.

The most common approach for solving the non-linear equation set is the harmonic power flow, which uses a Newton type algorithm for each harmonic frequency. This approach is based on the power flow used for the fundamental frequency, but with a possibility to link the iterations for different harmonics.

3.4 **Harmonic modeling**

Except by the approach for solving the equations, iterative methods can be subdivided by the representation of harmonic sources. Proposed models are Norton and Thévenin equivalent [37].


### 3.4.1 Norton equivalent

It is possible to convert any test system to its Norton equivalent circuit. Fig. 3.1 shows a general Norton equivalent circuit of a simple test system. In the figure, the utility side is represented by a current source $I_u^h$ and impedance $Z_u^h$. Similarly, the customer side is represented by a current source, $I_c^h$ and impedance $Z_c^h$.

![Norton equivalent circuit](image)

**Fig 3.1 Norton equivalent circuit**

Harmonic current sources in the equivalent Norton circuit can be determined from the measured voltage, $V_{PCC}^h$ and current, $I_{PCC}^h$ at the PCC by using the following equations:

\[
I_u^h = \frac{V_{PCC}^h}{Z_u^h} + I_{PCC}^h \tag{3.6}
\]

\[
I_c^h = \frac{V_{PCC}^h}{Z_c^h} - I_{PCC}^h \tag{3.7}
\]

For calculating the harmonic contributions from the utility and customer, the superposition theorem are applied by decomposing the system as shown in Fig. 3.2.
From the figure, the harmonic current contribution of utility side, $I_{u-PCC}^h$ and customer side, $I_{c-PCC}^h$ can be calculated as:

$$I_{u-PCC}^h = \frac{Z_u^h}{Z_u^h + Z_c^h} \times \bar{I}_u^h$$  \hspace{1cm} (3.8)$$

$$I_{c-PCC}^h = \frac{-Z_c^h}{Z_u^h + Z_c^h} \times \bar{I}_c^h$$  \hspace{1cm} (3.9)$$

### 3.4.2 Thévenin equivalent

Thévenin equivalent circuits are used to express the harmonic equivalent systems and find out the relationship between the harmonic impedance and harmonic voltage sources through the one-point measurements at PCC (point of common coupling). Fig.3.3 is a Thévenin equivalent circuit for the harmonic source detection. In this figure, the customer side is described as harmonic voltage source (V) and the harmonic impedance ($Z_c$), the utility side is expressed as $E$ and $Z_u$. The circuit is applicable to different harmonic frequencies. The task of harmonic source detection is to determine which side contributes more to the harmonic distortion at the PCC, subject to the constraint that measurements can only be taken at the PCC.
Fig 3.3 Harmonic source detection using thevenin equivalent

Contribution of each source to the harmonic current at PCC is as shown in Fig. 3.4, and the harmonic current will be:

\[ I = I_E - I_V \]  \hspace{1cm} (3.10)

\[ I_E = \frac{E}{Z} \]  \hspace{1cm} (3.11)

\[ I_V = \frac{V}{Z} \]  \hspace{1cm} (3.12)

Here, \( Z = Z_u + Z_c \), \( I_E \) and \( I_V \) are the currents when the voltage \( E \) and \( v \) are applied individually. \( |I_E| \) and \( |I_V| \) can be indices to denote the harmonics contributions. If \( |I_E| > |I_V| \), it means that the \( E \) side gives more contribution than that of the \( V \) side on the harmonic currents at PCC. From eq. 3.10 to 3.12, one can get;

\[ \text{if } |I_E| > |I_V|, \text{then } |E| > |V| \]  \hspace{1cm} (3.13)

Suppose we have known the values of \( V \) and \( I \) through the measurement already, if we can ‘measure’ the value of \( E \), then compare it with \( V \), the harmonic sources and their contribution can be detected correctly. According to the circuit theory, there exists equivalent impedance \( Z_{CT} \) to make\( |E| = |V| \). We call \( Z_{CT} \) as “critical impedance” and try to find it, use it to measure \( E \) and find out the larger one in the equivalent circuit.
3.5 Harmonic current emission limits

Even if the aim is to limit the harmonic voltages in the system, it is preferred to specify harmonic current emission limits. All existing harmonic standards can be broadly classified into two types: standards for system levels (MV, HV-EHV systems) (IEC-61000-3-6) and the standard for equipment levels (LV systems) (IEC-61000-3-4). The system standards deal with the connection of customers having large harmonic-producing loads to supply systems, while the equipment standard defines the limits for the harmonic current emissions of a piece of equipment. Since all equipment, whose inputs current is less than 16A per phase, should be in compliance with the international equipment standard IEC-61000-3-4 and the system standards IEC-61000-3-6, are of more concern to power utilities at present. The most important harmonic standards in power quality area are IEEE 519-1992 and IEC 61000-3-6 [26] [27] [28] [29] [30].

The IEC have developed a set of guidelines to help utilities keep harmonics under control. The most important at MV levels and above is IEC/TR 61000-3-6 which covers compatibility levels, planning levels, and methods for managing the connection of large disturbing customers. The procedures are fairly straightforward when applied to strong distribution systems, but are less clear regarding distribution systems with long feeders and transmission systems.
3.5.1 IEEE 519-1992 standards

Table 3.1 shows the IEEE 519 harmonic voltage limits while table 3.2 shows the harmonic current limit. The harmonic current limits specify the maximum amount of harmonic current that the customer can inject into the utility system. It also limits the overall harmonic distortion of the voltage supplied by the utility.

### Table 3.1 IEEE 519 harmonic voltage limit

<table>
<thead>
<tr>
<th>Bus Voltage at PCC</th>
<th>Individual Voltage Distortion (%)</th>
<th>Total Voltage Distortion THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 69 kV</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>69 kV to 161 kV</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>161 kV and above</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

### Table 3.2 IEEE 519 harmonic current limit

<table>
<thead>
<tr>
<th>Individual Harmonic Order (Odd Harmonics)</th>
<th>Maximum Harmonic Current Distortion in Percent of $I_L$</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{sc}/I_L$</td>
<td>&lt;11</td>
<td>11≤h&lt;17</td>
</tr>
<tr>
<td>&lt;20*</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>20&lt;50</td>
<td>7.0</td>
<td>3.5</td>
</tr>
<tr>
<td>50&lt;100</td>
<td>10.0</td>
<td>4.5</td>
</tr>
<tr>
<td>100&lt;1000</td>
<td>12.0</td>
<td>5.5</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>15.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed.

* All power generation equipment is limited to these values of current distortion, regardless of actual $I_{sc}/I_L$.

Where

- $I_{sc}$ = maximum short-circuit current at PCC.
- $I_L$ = maximum demand load current (fundamental frequency component) at PCC.
- TDD = Total demand distortion (RSS), harmonic current distortion in % of maximum demand load current (15 or 30 min demand).
- PCC = Point of common coupling.
3.5.2 IEC/TR-61000-3-6 principles

The voltages are 95% probability levels of distributions which are unlikely to be identical and there will be phase differences between the voltages which can become significant at higher frequencies. Time-varying harmonics are specified by their 95% probability values. The details of measurement and statistical analysis are given in IEC 61000-4-7. Diversity between harmonic sources is represented by the Summation Law, as described in Eqn. 3.2.

Compatibility levels are given as a reference for the setting of equipment immunity (immunity levels must be more than the compatibility level) and utility emission (planning levels - must be less than the compatibility level). Since the flow of harmonic current in general is from the LV part of the power system to the HV transmission system and then into generators, the harmonic profile of a typical power system shows the highest voltages at LV, reducing through the MV system to the HV system. To assist with allocating harmonic loads to different voltage levels, the planning levels are graded from higher values at LV to the smallest values at HV/EHV [31].

3.5.3 Distribution system harmonic allocation

Distribution systems generally have the following general features:

- radial topology
- can be broken down into subsystems supplied from a substation which have weak interactions with other parts of the system
- major loads and impedances generally well known
- line capacitance not important
- little change over the period covered by a harmonic study
The principles of distribution allocation are discussed relative to the system illustrated in Fig. 3.5

![Fig. 3.5 Distribution system showing MV subsystem and upstream supply](image)

It is assumed that the upstream system US, which may be HV or a higher level MV system, has reached its planning level \( L_{hUS} \) and can be represented by a harmonic source of this magnitude. Since the MV system is limited to its planning level \( L_{hMV} \), the voltage available for the total MV load \( S_t \) is, making use of the summation law (eqn. 3.2.) [31][32][33].

\[
G_{hMV} = \sqrt{\frac{a}{L_{hMV}} - L_{hUS}}
\]

The effects of transfer coefficient and LV loads are ignored in this discussion to simplify the presentation. \( E_{Uhi} \) is the harmonic voltage emission for load \( S_i \), which can be determined, again making use of the diversity equation (3.2) as:

\[
E_{Uhi} = \left( \frac{S_i}{S_t} \right)^{\frac{1}{a}} \times G_{hMV}
\]

The corresponding harmonic current emission is:
\[ E_{hi} = \frac{E_{uhi}}{Z_{hi}} \]

Where, \( Z_{hi} \) is the harmonic impedance at the point of connection of load \( S_i \). For distribution systems without capacitor resonance, this can be well approximated by \( h \) times the fundamental short-circuit reactance. Where the distribution system has short feeders, \( Z_{hi} \) will be relatively small.

If all the loads at the supply point take their full allocation, it is possible that the supply harmonic current will be very large. Determination of \( G_{hMV} \) requires differentiation across MV planning levels where one MV system supplies another.

### 3.5.4 Transmission system harmonic allocation

Allocation for transmission system is more complex and less precise than distribution harmonic allocation because of the following factors

- Meshed configuration causes greater interaction difficult to break up into non-interacting subsystems needs to be studied as a single system
- Line capacitance significant, causing resonances in harmonic impedances and the influence of a load on remote nodes
- Always changing because of varying generator allocations and at a slower timescale the switching of lines, transformers etc, load variations

Because of the continuous changes, it is useful to some extent to think of the system for modeling purposes as undergoing a transition through a number of fixed parameter scenarios. The difficulties caused by these scenarios cannot be exaggerated. Although any one scenario can be modeled, choosing the scenarios to be modeled is very difficult. Once a set of scenarios has been chosen, it is also necessary to decide the proportion of time that each scenario holds. Line
capacitance can mean that a slight change in scenario gives a major change in system behavior because of a sharp resonance.

Transmission allocation method approach is based on the allocation of harmonic voltage to each load in the transmission system based on:

\[ E_{\text{ulti}} = k_h S^\alpha \]

Where, \( k_h \) is the allocation constant and \( S \) apparent power, representation of loads in transmission level. The exponent term allows for diversity that is to give more harmonic current, relative to rating, for smaller loads. A load \( S_i \) is then given the same allocation whether the allocation is made to the whole or to the parts and then combined.

### 3.6 Harmonics measurements

With the steady increase of solid-state electronics in commercial and residential facilities, utilities face an increasingly challenging task to carry out reliable measurements due to the waveform distortion on voltage and current signals. This unfair race between fast growing customers joining the crowd of harmonic generators and utilities struggling to adapt appropriate measuring schemes can soon leave utilities far behind. Decisive efforts to control harmonic currents within industry limits before they converge at and disturb distribution substation monitoring equipment must be undertaken.

At harmonic source locations, the problem can be even worse. The unfiltered higher-frequency components of current at harmonic-producing loads may not give rise only to measurement equipment inaccuracies when they reach or exceed certain thresholds. They can produce communication interference, equipment heating problems, false protective device
tripping, and even instability conditions on voltage regulation systems in synchronous generators. This is particularly true in installations where customer substation transformers are loaded with mostly nonlinear loads. An even more delicate problem arises when a customer generates significant harmonic waveform distortion that affects adjacent utility customers. Because all customers can be regarded as harmonic producers to some extent, utilities may find it is difficult to pinpoint the right location of the harmonic source, particularly when resonant networks come into play. Utilities may need to carry out measurements at a number of locations involving suspected customers before they can decide the source of the problem to start discussing remedial measures.

From the electric utility perspective, the general objectives for conducting harmonic measurements may be summarized as follows:

- To verify the order and magnitude of harmonic currents at the substation and at remote locations where customer harmonic sources may be affecting neighboring installations
- To determine the resultant waveform distortion expressed in the form of spectral analysis
- To compare the preceding parameters with recommended limits or planning levels
- To assess the possibility of network resonance that may increase harmonic distortion levels, particularly at or near capacitor banks
- To gather the necessary information to provide guidance to customers in controlling harmonic levels within acceptable limits
- To verify efficacy of implemented harmonic filters or other corrective schemes
- To determine tendencies in the voltage and current distortion levels in daily, weekly, monthly as mentioned in IEEE standard 519-1992. In its current distortion
limits section, IEEE 519 suggests that the 15- (or 30-) min maximum demand averaged over a 12-month period should be used as the load current, to determine the ratio $I_{SC} / I_L$.

Consider the measurements of voltage and current to obtain spectral content up to the 40th harmonic using 200-ms measurement windows. The preferred test instrument must be based upon RMS calculation of each performance index over a synchronous contiguous 12-cycle window. The 12-cycle window has been adopted in the IEC standards for 60-Hz systems. This 12-cycle data can then be processed into 3-s, 10-min, and 2-h interval data for each index. Note that RMS index values would tend to decrease if larger measurement intervals were used.

3.6.1 Measurement concentration

If a utility engineer needed to decide the parameters to consider in evaluating harmonic distortion problems, most likely the decision would involve voltage and current waveforms. This is indeed the right choice because other parameters, such as real, reactive, and total power; energy; and even unbalance, can be calculated from these two quantities. As discussed before, distorted voltage and current waveforms can be expressed as Fourier or other time series. Harmonic distortion and all power quality indices can in fact be determined from these two basic parameters. Nevertheless, power quality monitoring equipment is presently designed to directly provide peak and true RMS voltage, current, and power quantities along with harmonic indices comprising total and individual harmonic distortion and transformer K factor, among others.
3.6.2 Measurement conducting points

Harmonic distortion occurrence in an electrical installation can sometimes be accessed through a simple inspection of the types of loads at a given customer installation. All this requires is familiarity with the characteristic harmonic spectrum of each type of common nonlinear load. However, considering additional waveform distortion caused by transformer saturation or resonant conditions, a more precise evaluation should be carried out. This involves direct measurements at selected locations — for example, the point of common coupling (PCC) and the node where nonlinear loads are connected.

It is understandable that the main location where measurements are to be conducted is the customer utility interface. This is so because compliance with IEEE and IEC harmonic limits must be verified at this location. In customer-owned transformer locations, the PCC is the point where the utility will meter the customer, generally the high-voltage side of the transformer. If the utility meters the low voltage side, then this becomes the PCC.

Also, measurements at LV-connected equipment locations are required when compliance with IEC (which covers all electrical and electronic equipment with an input current up to 16 A per phase) is sought or when harmonic filtering schemes must be designed at nonlinear loads locations. This is more likely to occur in the industrial or commercial environment where large harmonic-producing loads are operated and served from transformers feeding other sensitive loads.

Other instances in which harmonic measurements would be required are when studies are conducted to determine the reasons for abnormal operation or premature failure of equipment, unexpected relay protection tripping, or excessive telephone interference.
3.6.3 Measurement duration

The decision on the optimal period to conduct harmonic measurements may appear somewhat complicated. The reasons for this are diverse. In residential circuits, due to similarity in the types of electronic loads, the expected spectral content may be easily characterized in short-term measurements. However, care must be exercised when the feeder that supplies residential customers is the same from where large commercial installations are served. If commercial installations are involved, it may be possible to anticipate the types of harmonics because they will typically be linked to fluorescent lighting and power sources from diverse LV electronic equipment. Industrial installations, however, are a special case because they are usually composed of a mix of loads having a diversity of spectral contents, which may require long-term measurements to characterize harmonic content. This need may become more obvious if cyclic loads exist because measurements to characterize harmonics at the PCC would need to encompass all, or at least the most significant, duty cycles. Long-term measurements may also be required when investigating or trying to resolve the origin of suspicious disturbances affecting a number of customers.

IEEE 519 guidelines do not specify a definite measurement period for capturing harmonic waveform distortion. Under steady-state operation and where no loading variations occur, a few minutes recording may be sufficient and averaging over a few seconds should meet the requirements. However, due to the changing nature of loads in most situations, measurements over a few days may be needed to assure that load variation patterns and their effects on harmonic distortion are considered.

Long-term effects relate to thermal effects on different kinds of equipment such as transformers, motors, capacitor banks, and cables from harmonic levels sustained for at least 10
min. Very short-term effects relate to disturbing effects on vulnerable electronic equipment by events lasting less than 3 s, not including transients.

### 3.6.4 Measurement procedure

The process demands that recording instruments as well as voltage and current transducers comply with certain characteristics to assure that representative samples will be obtained. The analog input bandwidth relates to the frequency limit above which the signal is attenuated by more than 29.2%. A 1.5-kHz analog input bandwidth would limit the harmonic measurement up to the 25th harmonic in a 60-Hz system. This covers most frequencies of interest in practical applications. Considering Nyquist criterion, if the input signal contains frequencies higher than half the sampling frequency, the signal cannot be correctly interpreted and an analog input bandwidth greater than 3 kHz will be required. For all harmonic currents below the 65th (3.9 kHz in a 60-Hz system) to be processed properly, the sampling frequency should be at least twice the desired input bandwidth, or 8 k samples per second in this case, to cover 60-Hz systems. The requirement is for 95% or better accuracy and minimum required attenuation of 50 to 60 dB for 30-Hz; 30 to 50 dB for 120- to 720-Hz; 20 to 40 dB for 720- to 1200-Hz; and 15 to 35 dB for 1200- to 2400-Hz signals. The lower limit is for frequency domain and the higher limit is for time domain instruments. These limits have to do with the attenuation of high-frequency signals when the instrument is tuned at the fundamental frequency.

A large variety of instrumentation exists that can be used to carry out measurements and long-term recordings. Power quality analyzers are capable of carrying out measurements of RMS voltage and current and perform calculations of active, reactive, and apparent power. They also compute harmonic distortion of voltage and current signals presenting individual and total harmonic levels, and some of them can calculate V*t and I*t products and K factor. There are in-
door and out-door versions of monitoring equipment and some of them can be set up to carry out long term recordings.

3.6.5 Transducers

Transducers convert the parameter to measure in a signal of adequate amplitude to be processed by the measuring equipment. However, not only amplitude is important. It is essential that their frequency response have an appropriate bandwidth so as not to produce any signal distortion.

Depending on the system voltage and the network configuration and type of load, the voltage can be measured directly or through the potential transducers (PTs). With regard to current measurements, they can be carried out on the primary side using the current probes furnished with the measuring equipment or at the low-voltage side, usually at the utility meter location. Under uncertainty regarding their frequency response, transducers should be subjected to tests to determine that their bandwidth is adequate to carry out harmonic measurements.

Although IEEE-519 points out those most utility measuring current transducers (CTs) can be used with a precision of 97% in the frequency range up to around 5 kHz, it is recommended that tests be conducted on PTs to determine that their bandwidth is appropriate up to the frequency of interest. In the case of CTs (those installed at the substation by the power utility for electric current and watt-hour measurements), they have a frequency bandwidth up to 20 kHz with an error smaller that 3%. Properly grounded (complying with IEEE 518-1992 shielded coaxial cables are recommended for short distances to the measurement equipment. If distances are large over a few tens of meters, fiber optic links are highly recommended to avoid all types of interference on the sometimes small amplitudes’ signals.
Chapter 4

Residential and commercial Feeders

4.1 Introduction

Number and variety of non-linear devices and installations used by residential and commercial customers are increasing continuously. Therefore the effect of harmonics in the network is more and more considered in both the planning and the operation of distribution systems. This analysis is complex, because multiple factors influence the emission and propagation of harmonics through the network, like the network impedance, the voltage distortion and the time-variation of number and type of connected equipment.

One of the key aspects of a realistic harmonic analysis is a correct representation of summation of harmonic currents. The presence of different devices with different topologies at one connection point can cause a diversity of current harmonic phase angles and subsequently may lead to a lower magnitude of vector sum than the arithmetical sum of the harmonic currents. This is known as diversity effect (or cancellation effect) and has a high influence on the total harmonic distortion emitted by larger groups of non-linear loads into the grid. To quantify this effect commonly two different indices are used: summation exponent and diversity factor.

Most of the papers that address the diversity of harmonic currents consider only the effect of few devices in a single moment of time or a perfect steady state of harmonics. Variation of system, load and generation result in a time-varying harmonic currents and an additional statistical post-processing is required in order to calculate aggregated diversity indices. Parameters and methods used for this post-processing may have a considerable impact on the calculated diversity
index and are not yet defined. Furthermore, the accuracy of these indices depends on the accuracy of the measurement instrument. Inaccuracies of the current input channels may cause differences between vector sum and total current, which finally can result in erroneous diversity indices. If more than a single measurement instrument is required, also clock synchronization between the instruments may affect the accuracy of the diversity index calculation.

The analysis in this paper is based on measurement data of residential and commercial customers connected to the feeder. Residential and commercial loads are measured through power analyzer and compared to a model feeder in Easy power software to analyze the harmonic flow at different nodes through the feeder in the next chapter.

**4.2 Harmonic source representations**

The effects of harmonic sources on the power system will always be more appropriately assessed in the frequency domain — i.e., through a comprehensive Fourier analysis of the system. This requires using manufacturer or measured data to represent harmonic sources from every existing and future nonlinear load in the simulation study. This technique is used in this thesis to model the harmonic residential and commercial non-linear loads and the measurement set up is as shown in Fig 4.1. Harmonic current spectra of different harmonic generating equipment or appliances usually include magnitude and phase angle.
The representation of harmonics as ideal current sources assumes that voltages are not distorted. For some nonlinear devices, the representation is considered accurate as long as the real voltage distortion is below around 10%. Harmonic modeling techniques involve the representation of distortion-producing loads in a form in which they can realistically represent the harmonic sources in the power system network. Harmonic spectra of the load current describe spectral components of individual harmonic sources. In harmonic analysis, these current sources are injected on the electrical system at the point at which they are created, i.e., at the location of the nonlinear load. This is equivalent to superimposing the harmonic currents on the load current waveform.

Harmonic sources are generally dispersed and are usually modeled as current sources of a frequency corresponding to desired harmonic current. Most software tools include typical harmonic sources so that the user does not need to exercise additional efforts in building them to make an assessment of the problem, particularly during planning stages of a network. In some instances in which harmonic resonance is suspected to be the source of specific disturbances,
harmonic current spectra from measurements are preferred. These will provide a far more accurate representation of the harmonic source.

The degree of voltage signal distortion will depend on the amplitude of the harmonic current source and on its propagation on the network. The level of distortion will depend on how much harmonic current will flow toward the source and how much of it will be shared with adjacent facilities. Inductive and capacitive impedances play an important role in the harmonic current propagation phenomenon. Connecting service drops, transformers, and capacitor banks are some of the elements that can contribute to harmonic current damping or to the excitation of resonant frequencies that can produce significant amplification of voltage distortion.

Impedance scans are used to produce an overall representation of the system response as a function of frequency at specific network locations. This impedance vs. frequency characteristic is generally determined at locations where nonlinear loads, capacitor banks, or harmonic filters exist in the network. Impedance scans are an excellent tool to anticipate system response in planning network or load expansions.

4.3 Residential and commercial loads and their harmonic characteristics

The overall magnitude of harmonic currents in a distribution network typically follows the trend of fundamental current (i.e. power demand), as harmonic (non-linear) and linear tend to be simultaneously present in the network, particularly commercial loads, which operate distinct periods of time.
The increasing use of the power conditioners in which parameters like voltage and frequency are varied to adapt to specific residential and commercial processes has made power converters the most widespread source of harmonics in distribution systems. Electronic switching helps the task to rectify 50-/60-Hz AC into DC power. In DC applications, the voltage is varied through adjusting the firing angle of the electronic switching device. Basically, in the rectifying process, current is allowed to pass through semiconductor devices during only a fraction of the fundamental frequency cycle, for which power converters are often regarded as energy-saving devices. If energy is to be used as AC but at a different frequency, the DC output from the converter is passed through an electronic switching inverter that brings the DC power back to AC.

Converters can be grouped into the following categories:

- Large power converters like those used in the metal smelter industry and in HVDC transmission systems
- Medium-size power converters like those used in the manufacturing industry for motor speed control and in the railway industry
- Small power rectifiers used in residential entertaining devices, including TV sets and personal computers. Battery chargers are another example of small power converters.

Uninterruptible power supplies (UPSs), welders, and printers are among these low kilovolt ampere size power converter applications. It is common to see large commercial and public office buildings stuffed with computers and other peripheral devices. If they are additionally provided with UPSs to handle voltage sags and power supply interruptions, the amounts of harmonic
currents can substantially increase. Residential areas at specific times of the day act as fabulous harmonic sources produced by all kinds of entertaining devices.

The individual harmonics generated by battery charger circuits depend on the initial battery voltage. The overall harmonic content varies as a function of time and involves a random probability. As in other appliances that use DC current (TV sets, radio and stereo amplifiers, etc.) battery chargers produce zero sequence harmonics, which overload the neutral conductor of the three-phase distribution transformer that supplies the single-phase, low-voltage loads. This is because the phase angle of the third harmonic does not vary enough to produce harmonic cancellation, so they are added up algebraically.

As later discussed, fluorescent lighting also produces triple harmonics, for which a concurrent use of battery chargers and fluorescent lamps from the same circuit can make things even worse.

Unlike the types of loads described earlier, which nominal power is large enough to deserve an individual treatment, the loads we refer to in this section are important only when they represent a significant portion of the total load under concurrent operation. Monte Carlo method can be used in some applications to investigate the probability of exceeding preset levels of harmonics from TV sets as well as from electric vehicle battery chargers serving multiple locations within the network.

4.3.1 Non-linear loads

Large number of personal computers or TVs operating on the common branch circuit can distort the source voltage wave shape. The power supplies used in most personal computers (PCs) generate high levels of harmonic current at the point of common coupling (PCC).
Electronic lighting ballasts and compact fluorescent light (CFL) have become popular in the recent years due to their improved efficiency. The fluorescent lamp behaves as negative dynamic resistance that is required for the ballast to limit the improved efficiency. The fluorescent lamp behaves as negative dynamic resistance that is required for the ballast to limit the current, the electric arc characteristics of the fluorescent lights with magnetic and electronic ballasts. The electronic ballast consists with a half-bridge inverter and a LC filter which is responsible for nonlinear characteristics of the lamp.

Switch Mode Power Supply is an electronic power supply that incorporates a switching regulator to convert electrical power efficiently. Like other power supplies, an SMPS transfers power from a source, like mains power, to a load, such as a personal computer, while converting voltage and current characteristics. An SMPS is usually employed to efficiently provide a regulated output voltage, typically at a level different from the input voltage. The pass transistor of a switching-mode supply continually switches between low-dissipation, full-on and full-off states, and spends very little time in the high dissipation transitions. Switch-mode power supplies convert commercial AC power into the required high-frequency DC power using the high-speed switching of semiconductors.

High-rise buildings use a booster pump system on the domestic water supply to maintain adequate water pressure at all levels within the building. Conventional pump controls in this type of application can maintain the pressure within certain range, but an ASD-based system can maintain more precise control over a wider range of flow rates, while reducing energy requirements and pump wear. ASD is also applied in building HVAC (heating, ventilating, and air conditioning) systems.
Normally ASDs consist of an induction motor supplied by variable AC voltage derived from converters. Hence, the ASD consists of three major components; the first is the front end, which is usually a 6 or 12 pulse rectifier. The second is the inverter stage that converts the generated DC voltage to controllable frequency and AC voltage to control the speed of the motor. The last stage is the DC link (shunt capacitor) that couples the two main stages and help in reducing the ripples of the DC voltage in case of PWM (pulse width modulation) topologies. The harmonics injected by the inverter is mainly dependent on the inverter topology and the motor characteristics. Therefore, the ASD can be modeled with a common three phase bridge converter circuit together with a DC link circuit and a harmonic current source to represent the inverter and the motor. This conclusion calls for a simple representation of the converter and the motor collectively by a DC current source instead of a harmonic current source.

4.3.2 Sample measurements taken from few residential loads

Using the measurement setup given in Figure 4.1 measurements were taken from few residential loads which are 1.6A, 50W Laptops, a 14W CFL and 75W 1.2A color Television and few more with a Model 8220 harmonic analyzer.

Fig 4.2 1.6A, 50W Laptop 1
Fig 4.3 1.6A, 50W Laptop 2

Fig 4.4 Compact florescent lamp

Fig 4.5 120/60 Hz Microwave
Fig 4.6 Mobile phone charger

Fig 4.7 32' Color television

Fig 4.8 32' Color television
Fig 4.9 50' Color television

Fig 4.10 Refrigerator

Fig 4.11 Cloth washer
Single-phase power electronic loads shown in figures 4.2 - 4.12, Laptops and home equipments tend to have high current distortions, more than 100%. Harmonic distortion also depends upon electronic elements used in appliance’s circuitry. Here, from the non-linear loads considered, it is found that %THDI of Laptop 1 is 157.3 % whereas that of Laptop 2 is 164.9%, which shows difference in harmonic injections contribution from the same type of equipments. To evaluate the cancellation or summation effect on these non-linear loads, combined measurements were taken and it is given in figure 4.13-4.17. %THDI from the two laptops and CFL is summed to 137.4% where their individuals are laptop 1 (157.3%), laptop2 (164.9%) and CFL (103.8%). Further adding the television1 load, it cancelled some the harmonics orders, 11th and 13th, to %THDI of 108.8%.
Fig 4.13 Laptop2 and CFL

Fig 4.14 Laptop1, 2 and CFL

Fig 4.15 Laptop1, 2, CFL and television1
Fig 4.16 Refrigerator and ceiling fan

Fig 4.17 Refrigerator and incandescent lights
4.3.3 Measurements taken for commercial loads study

For commercial loads, two service panels that feed two buildings of University of Nevada, Las Vegas building TBE and SEB, Engineering Faculty buildings are measured. The parameters of the panel and the loads or circuits that these panels fed are summarized in Fig 4.18 and 4.19.

<table>
<thead>
<tr>
<th>Non-linear load</th>
<th>RMS</th>
<th>THD (%)</th>
<th>W</th>
<th>VAR</th>
<th>VA</th>
<th>PF</th>
<th>DPF</th>
<th>Tan</th>
<th>Angle (A-V) deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFL</td>
<td>V</td>
<td>113.2</td>
<td>1.8</td>
<td>-17</td>
<td>22</td>
<td>0.617</td>
<td>0.894</td>
<td>-0.501</td>
<td>-33</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LAPTOP</td>
<td>V</td>
<td>112.2</td>
<td>1.7</td>
<td>50</td>
<td>101</td>
<td>0.491</td>
<td>0.937</td>
<td>-0.342</td>
<td>-20</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>0.9855</td>
<td>157.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TV</td>
<td>V</td>
<td>112.2</td>
<td>1.8</td>
<td>75</td>
<td>137</td>
<td>0.549</td>
<td>0.998</td>
<td>-0.059</td>
<td>-4</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>1.128</td>
<td>150.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LAPTOP + CFL</td>
<td>V</td>
<td>112.8</td>
<td>1.9</td>
<td>65</td>
<td>123</td>
<td>0.594</td>
<td>0.932</td>
<td>-0.358</td>
<td>-21</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>0.9569</td>
<td>130.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TWO LAPTOP + CFL</td>
<td>V</td>
<td>112.6</td>
<td>1.8</td>
<td>117</td>
<td>234</td>
<td>0.545</td>
<td>0.939</td>
<td>-0.36</td>
<td>-20</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>2.162</td>
<td>137.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LAPTOP, CFL, TV</td>
<td>V</td>
<td>112.5</td>
<td>1.8</td>
<td>188</td>
<td>287</td>
<td>0.657</td>
<td>0.972</td>
<td>-0.235</td>
<td>-13</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>2.215</td>
<td>108.3</td>
<td></td>
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</tbody>
</table>
Three phase 4-wire “wye” type connections are commonly used in commercial buildings. In our case in each buildings, 480V three-phase, 4-wire feeders are carried to each floor, where 480V three-phase is tapped to a power panel or motors. General area fluorescent lighting, TBE building,
that uses 277V ballasts is connected between each leg and neutral; 208Y/120 three phase, 4-wire circuits are derived from step-down transformers for local lighting and receptacle outlets.

Fig 4.20 Building TBE power panel measurement using power analyzer FLUKE 1735

Fig 4.21 Building SEB power panel measurement using power analyzer FLUKE 1735
Large commercial buildings have many different sizes and types of loads. In these cases, measurements were taken using Fluke 1735, three phase power analyzer, the panels’ powers are distributed with 208/120 V transformers in delta-wye configurations. Since multiple loads are supplied, each generates triple harmonic currents on the neutral conductor as shown in fig.4.20 and 4.21 neutral harmonics profile. These currents circulate with in the delta primary causing overheating and short-end service life of the transformer.

4.4 Equipment operating in harmonic environment

In light of a steady increase in harmonic distortion in power systems, the specifications and selection criteria of electrical equipment in industrial installations should be revisited. For example, when distributed generators operate in facilities in which nonlinear loads predominate, the response of conventional generator designs with large sub-transient reactance has been shown to be ineffective and often ends in equipment failure after exposure to severe thermal stresses. There must be a threshold for operating parameters that allows equipment to withstand worst-case operating conditions regarding harmonic content and its diverse effects. This goes beyond the steady-state operation mostly assumed when specifying equipment and network components.

4.4.1 Generators

Generators used in the electric power industry are fundamentally designed to feed linear loads. However, when the type of load is predominantly nonlinear, generation systems must comply with certain requirements that allow them to operate in stable conditions and without being exposed to excessive heating and torque vibrations, which can make them exceed their permissible operating limits. Essentially, a nonlinear load produces a voltage waveform distortion at the generator terminals; this imposes the following consequences in the operation of a generator:
• Production of positive and negative sequence current contributions that generate torques and vibration mode shapes on the motor axis. The thermodynamic forces created in the rotor can prematurely wear out shaft bearings.

• Voltage waveform distortion on the supply circuit to the excitation system; this can produce voltage regulation problems.

• Excessive negative sequence currents; these can contribute to increased voltage unbalance.

The regulator must be able to handle harmonic distortion typical of 12-pulse types of converters. This list reveals features of synchronous generator designs to assure satisfactory performance of generating units in electrical environments highly exposed to harmonics.

4.4.2 Conductors

Power conductors used in distribution systems must be able to carry fundamental and harmonic currents without developing conductor overheating that would be translated to excessive losses. For this, it is important to select conductor sizes considering a permanent steady-state condition over current factor of at least 125%, following National Electrical Code NEC-1996, articles 430-24 and 220-10(b). In the latter article, it is recommended that conductor sizes be chosen to withstand 125% of the continuous currents plus the nonpermanent ones. Also, in installations with shielded cables where shielding is grounded at intervals, it is important to consider a margin to account for the effect of induced currents in the power conductors. An additional 10% to the current specified above holds reasonable. However, over-sizing conductors to take additional currents up to 100% of rated values in some VFD applications is sometimes common in industrial networks. This may occur in cases when the electric networks are designed for accommodating future load expansions.
4.4.3 Energy metering equipment

Measuring equipments initially calibrated on purely sinusoidal alternating current and subsequently used on a distorted electricity supply can be prone to error. The magnitude and direction of the harmonic power flow are important for revenue consideration as the sign of the meter error is decided by the direction flow.

Studies have shown that errors are due to harmonic content vary greatly as to the type of meter, and that both positive and negative metering errors are possible.

The classic energy measuring equipment is the Ferraris motor type kilowatt-hour meter. Its inherit design electromagnetic, producing driving and braking flues which impinge on it rotors, developing a torque. Secondary flux-producing elements are provided for compensation purposes too improve the instruments accuracy and to compensate for friction in the register. These flux-producing elements, providing primary and secondary torques, are essentially in nonlinear elements include the voltage and current elements and overload magnetic shunts, and the frequency sensitive elements include the disc, the quadrature and anti-friction loops.

DC power and harmonic voltages or currents lone should not produce torques, but will degrade the capability of a meter to measure fundamental frequency power. Direct currents distort the working fluxes and alter the incremental permeability of the magnetic elements. Fluxes produced by harmonic currents combine spurious fluxes of the same frequency that may be present due to the imperfection of the meter element and produce secondary torques.
Converter loads using the ‘burst firing’ principle can cause kilowatt-hour meters to read high by several percentage points (cases in excess of 6% have been quoted), largely attributable to the lack of current damping during the no load interval.

It appears that customers that generate harmonics are automatically penalized by a higher apparent electricity consumption, which may well offset the supply authority’s additional losses. It is therefore the customer’s own interest to reduce harmonic generation to the greatest possible extent.

Harmonics present a problem to measurement of VAR values, since this is a quantity defined with respect to sinusoidal waveforms.

**4.4.4 Capacitor banks**

Capacitors are typically installed in the electrical power system, including commercial and residential, as power factor correction devices. A serious concern arising from the use of capacitors in an electrical power system is the possibility of system resonance. This effect imposes voltages and currents that are higher than the case without resonance. The reactance of capacitor bank is inversely proportional to the frequency. As a result, the capacitor bank acts like a sink, attracting unfiltered harmonic currents.

Harmonic resonance in power system may be classified as parallel or series resonance, and both types are present in harmonic-rich environment. Parallel resonance causes current multiplication, whereas series resonance produces voltage magnification. Substantial damage to capacitor bank would result if the amplitude of the offending frequency is large enough during resonant conditions. Also, there is high probability that other electrical devices on the system would also be damaged.
For such reason, harmonic analysis must be performed before installation of a power factor improvement capacitor bank to ensure that resonance frequencies do not correspond with prominent harmonics contained in the currents and voltages [28][29][48].

IEEE states that a capacitor is designed to operate at maximum of 135% of its reactive power (KVAR) ratings. In addition, it must withstand a continuous RMS overvoltage of 110%, peak overvoltage of 120%, and an over current of 180% of nameplate rating. Although the standard did not specify the limits for individual harmonics, the above percentages can be used as basis to determine the maximum allowable harmonic levels.

4.5 Future harmonic sources

The challenge for electrical system designers in utilities and industry is to design the new systems and/or adapt the present systems to operate in environments with escalating harmonic levels. The sources of harmonics in the electrical system of the future will be diverse and more numerous. The problem grows complicated with the increased use of sensitive electronics in industrial automated processes, personal computers, digital communications, and multimedia.

Utilities, who generally are not regarded as large generators of harmonics, may be lining up to join current harmonic producers with the integration of distributed resources in the rise. Photovoltaic, wind, natural gas, carbonate full cells, and even hydrogen are expected to play increasingly important roles in managing the electricity needs of the future. Distributed generators that presently provide support to utilities, especially during peak demand hours, will be joined by numerous harmonic producing units, fueled by natural gas or even wind, called micro turbines.
4.6 Summary

It is essential to know the effects of the harmonics, sources of the harmonics for a power engineers to endure that the systems will work well within the safety zone, owing to standards. It is always needed to evaluate system harmonics where application of capacitor banks in systems where 20% or more of the load includes other harmonic generating equipment, if a facility has a history of harmonic related problems, including excessive capacitor fuse operation or damage to sensitive metering/relaying/control equipment and also during the Planning/design stage of any facility comprising capacitor banks and nonlinear harmonic generating equipment.

In facilities where restrictive Electric Power Utility Company Standards/Guidelines limit the harmonic injection back into their system to very small magnitudes and when coordinating and planning to add any emergency standby generator as an alternate/renewable power source, the system harmonic level must evaluated.
Chapter 5

Estimating harmonic level for typical distribution feeder

5.1 Introduction

The electric power grid is one of the most complex and costly investments made by mankind all over the world. An electrical grid is a vast, interconnected network for delivering electricity from suppliers to consumers of electric power. The modern day electric industry is poised to make the transformation from a centralized, producer-controlled network to one that is more distributed and consumer-interactive. This deregulated model creates healthy competition among the market forces and reduces the cost of electricity delivered. The move to a “smarter” grid promises to change the industry’s business model and its relationship with all stakeholders, involving utilities, regulators, energy service providers, technology and automation vendors and all the consumers. This transformation is made possible by bringing the philosophies, concepts and technologies from research labs to the utility and the electric grid.

For the last few years electrical engineers have been focusing on the power system studies using software tools. Recent advances in engineering sciences have brought a revolution in the field of electrical engineering after the development of powerful computer based software. The case study on this thesis is based on Easy Power, where different analyses like load flow, harmonic load flow and additional power analysis are performed. The simulation is based upon practical and measured data made to predict the actual effects of load on the entire power system.

The entire issue of power system measurements is aimed at collecting relevant data for assisting utility planning and operation in a number of aspects key to the efficient transmission and
distribution of electric energy. It is also intended to provide reliable energy consumption metering at commercial and residential facilities. A glimpse into the operation of a power system can allow us to realize the many instances when measurements are required. For example, the energy trading among different interconnected utilities/cooperatives requires reliable power delivery measurements that quantify the number of energy blocks that are bought and sold. The substation engineer looks at multiple panel instrumentation to guarantee that voltage and frequency are kept within specified limits and that the current on the different feeders follows the predicted demand, which must match the capacity of the substation transformer banks. Power factor is also observed to assure a proper balance between active and reactive power to minimize losses in the distribution system.

As loads fluctuate during the day in response to different demand patterns, utilities switch capacitor banks on and off to keep the voltage profile within tolerable limits. Under light load conditions, there is no need for reactive power compensation; this typically occurs during nighttime. As the load picks up, so does the voltage drop along distribution feeders and, at some distance from the substation, voltage may tend to decrease below permissible limits. It is then when strategically placed capacitor banks or inductive voltage regulators are “switched on” to help raise the voltage profile back to nominal values. The active and reactive power measurements at the substation are, therefore, key to energy dispatch operators to keep voltage regulation within tight limits. Another relevant measurement aspect is protection device coordination, which follows pre-established settings that allow protective devices to open as a response to large currents identified as faults. SCADA (supervisory control and data acquisition) systems communicate with substation and feeder remote terminal units, smart relays, and substation automation systems to monitor real-time status of the network and provide remote control of devices such as switches,
capacitor banks, and voltage regulators. The list involving measurement and monitoring of electric parameters can go on and on.

5.2 Simulation of case under examination

The data used for analyses purpose is in the form of one line diagram of complete power system network starting from power transformer at Grid up till the load are developed from IEEE PES Compressive test feeders website.

Each of the original test feeders had special characteristics that provided a test for the accuracy of the distribution component models and the convergence characteristics of the program being tested. The original four test feeders are:

- 13 Node Test Feeder – provided a good test of the convergence of a program for a very unbalanced system
- 34 Node Test Feeder – a very long feeder requiring the application of voltage regulators to satisfy ANSI voltage standards
- 37 Node Test Feeder – a three wire delta underground system
- 123 Node Test Feeder – a large system consisting of overhead and underground single phase, two phase and three phase laterals along with step voltage regulators and shunt capacitors

For the purpose of this study, 13 Node Test Feeder, given in figure 5.1, is used and implemented in easy power analysis software. The feeder displays some very interesting characteristics and provides a good test for the most common features of distribution analysis software:
- Short and relatively highly loaded for a 4.16 Kv feeder.
- One substation voltage regulator consisting of three single-phase units connected in wye.
- Overhead and underground lines with variety of phasing.
- Shunt capacitor banks
- In-line transformer
- Unbalanced spot and distributed loads

*Fig 5.1 One-line diagram of IEEE 13-bus test feeder*
The system data’s are as follows:

<table>
<thead>
<tr>
<th>Node</th>
<th>Load</th>
<th>Ph-1</th>
<th>Ph-1</th>
<th>Ph-2</th>
<th>Ph-2</th>
<th>Ph-3</th>
<th>Ph-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>kW</td>
<td>kVAR</td>
<td>kW</td>
<td>kVAR</td>
<td>kW</td>
<td>kVAR</td>
<td>kW</td>
</tr>
<tr>
<td>634</td>
<td>Y-PQ</td>
<td>160</td>
<td>110</td>
<td>120</td>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>645</td>
<td>Y-PQ</td>
<td>0</td>
<td>0</td>
<td>170</td>
<td>125</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>646</td>
<td>D-Z</td>
<td>0</td>
<td>0</td>
<td>230</td>
<td>132</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>652</td>
<td>Y-Z</td>
<td>128</td>
<td>86</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>671</td>
<td>D-PQ</td>
<td>385</td>
<td>220</td>
<td>385</td>
<td>220</td>
<td>385</td>
<td>220</td>
</tr>
<tr>
<td>675</td>
<td>Y-PQ</td>
<td>485</td>
<td>190</td>
<td>66</td>
<td>69</td>
<td>290</td>
<td>212</td>
</tr>
<tr>
<td>692</td>
<td>D-I</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>611</td>
<td>Y-I</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1158</td>
<td>668</td>
<td>973</td>
<td>627</td>
<td>113</td>
<td>753</td>
<td>0</td>
</tr>
</tbody>
</table>
Non linear loads are modeled in easy power from the measurement of harmonics data measured from residential loads. Non-linear load at single bus or multiple buses, feeder with or without capacitor bank and the effect of cable length and resonance resulted from impedance change through different types of cable are analyzed.
5.2.1 Single or multiple buses harmonic injection

Figure 5.3 shows the harmonic flow result through each buses and lines due to harmonic load injected at bus 12. The harmonic content applied to the load is given in chapter 2 table 2.1 from residential load measurement.
Fig 5.4 Voltage harmonic propagation at a single bus harmonic injection

Fig 5.5 Current harmonic propagation at a single bus harmonic injection
Fig 5.6 Harmonic flow from additional harmonic injection to different bus
Fig 5.7 Harmonic current orders due to multiple injections

Fig 5.8 Harmonic voltage orders due to multiple injections

Fig 5.3 –Fig 5.8 the harmonic characteristics of non-linear loads and their effect on different buses throughout the network feeder. The THD at the injected bus 12 in fig 5.3 shows
that 6.316% of the bus voltage and causes significant distortion through the network. From fig 5.4 bar chart, it can be observed that higher 5\textsuperscript{th} and 13\textsuperscript{th} voltage harmonic orders resulted from the residential loads. Buses located near the non-linear loads experienced more than 5% THD which is the IEEE-519 standard for harmonic voltage limits for buses less 69KV. The current THD is higher only at injection bus and also at the generator terminal and transformer-1 which will cause higher loss on branch or distribution power line connected to bus 12 and increase the k-factor for the TX-1. The other connected loads look less affected than TX-1 and generator terminal. The high current THD at the transformer and generator terminal will cause harmonic heating effect. Fig 5.5 shows the major current harmonic affected branches of the feeder. Fig 5.6 shows effect of additional non-load injection to another bus in the feeder with the 25% distortion of the one at bus 12. It can clearly be observed the summation of the harmonics at the same frequencies. Both bus-11 and bus -12 injected with THD of current 5.2% and 21.2% , no change on THD on the line connecting these loads which shows the harmonic current flow is towards the generator and shows where the additional source of harmonics. Additional voltage distortion level is observed to the connected buses. It can also be understood the K-factor increase on the transformer TX-1 and the effect on the generator and on more non- linear loads connected to different buses on the network.
5.2.2 Capacitor bank effect on the test feeder

Fig 5.9 Harmonic flow change due to capacitor banks added to the feeder
Fig 5.10 Harmonic current orders due to capacitor banks

Fig 5.11 Harmonic voltage orders due to capacitor banks
To consider the effect of capacitor banks in harmonic environment, capacitor banks at bus-5 200KVAR, bus-7 200KVAR, bus-12 150KVAR and bus-13 100KVAR are added to IEEE 13-bus test feeder. Capacitor banks contributed harmonic current damping or excitation of resonant frequencies effects are shown in fig5.9 bus-5, 7, 13 and 12 with the significant THD of 60.99%, 75.58%, 64.75% and 64.93% respectively. The high voltage distortion amplification effect can also be proved from bus-5 11.03%, bus-7 13.97%, bus-13 12.08% and bus-12 12.62% in THD summation. We can also observe that it is above the limit of IEEE 5% voltage distortion. This is because of the system resonance related to the reactance of the capacitor bank which is inversely proportional to the frequency. From fig 5.10 and 5.11 it can be seen the 5th order harmonic effect of the voltage and current harmonics. If the voltage is allowed to rise,
transformers will saturate and overheat. According to IEEE standard 1992, capacitor bank short
time overvoltage of about 130% should be limited to one minute. From this standpoint, we
conclude that the existence of the 5th harmonic of such magnitude in the system explains why
persistent tripping of the capacitors was experienced.

Capacitors are a natural low impedance path for harmonic currents and will, therefore,
absorb harmonic energies. This increase in capacitor current results in higher element
temperature which reduces the life of the capacitor. Also, because capacitors reduce the
network impedance, capacitors can actually increase the level of harmonic current on the
network. It is important to remember that while capacitors do not produce harmonic currents,
they can magnify their effects. Furthermore, harmonic voltages present on the network create
voltage stresses on the capacitor. When capacitors are added to the network, they set up a
parallel resonance circuit between the capacitors and the network inductance. Harmonic
current components that are close to the parallel resonance point are magnified (fig 5.12). The
magnified current causes serious problems such as excessive voltage distortion as shown in
fig.5.9 harmonic voltage propagation through the network. The larger the size of the capacitor
bank, the higher the risks, which is also be concluded from fig. 5.12 capacitor sizes and their
corresponding harmonic contributions.

5.3 Harmonic summation summary reports

Summary of a complete harmonic level evaluation report for Fig 5.9 are listed in the
following tables:
Harmonic summation summary report:

<table>
<thead>
<tr>
<th>Branch</th>
<th>From Bus</th>
<th>Base kV</th>
<th>MVAR</th>
<th>Rated (%)</th>
<th>VSUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAP-1</td>
<td>BUS-12</td>
<td>4.160</td>
<td>0.150</td>
<td>4.160</td>
<td>122.6%</td>
</tr>
<tr>
<td>CAP-2</td>
<td>BUS-13</td>
<td>4.160</td>
<td>0.100</td>
<td>4.160</td>
<td>121.2%</td>
</tr>
<tr>
<td>CAP-3</td>
<td>BUS-7</td>
<td>4.160</td>
<td>0.200</td>
<td>4.160</td>
<td>124.7%</td>
</tr>
<tr>
<td>CAP-4</td>
<td>BUS-5</td>
<td>4.160</td>
<td>0.200</td>
<td>4.160</td>
<td>119.6%</td>
</tr>
</tbody>
</table>

Table 5.3 Capacitor VSUM report

<table>
<thead>
<tr>
<th>Branch</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Base kV</th>
<th>Base kV</th>
<th>K-Duty</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX-1</td>
<td>BUS-1</td>
<td>BUS-2</td>
<td>115.000</td>
<td>4.160</td>
<td>1.152</td>
<td>98.2%</td>
</tr>
<tr>
<td>TX-2</td>
<td>BUS-7</td>
<td>BUS-6</td>
<td>4.160</td>
<td>4.160</td>
<td>3.998</td>
<td>73.8%</td>
</tr>
</tbody>
</table>

Table 5.4 Transformer de-rating report
<table>
<thead>
<tr>
<th>Branch</th>
<th>From Bus</th>
<th>Base kV</th>
<th>To Bus</th>
<th>Base kV</th>
<th>kW</th>
<th>KVAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAP-1</td>
<td>BUS-12</td>
<td>4.160</td>
<td></td>
<td></td>
<td>0.00</td>
<td>-162.86</td>
</tr>
<tr>
<td>CAP-2</td>
<td>BUS-13</td>
<td>4.160</td>
<td></td>
<td></td>
<td>0.00</td>
<td>-107.49</td>
</tr>
<tr>
<td>CAP-3</td>
<td>BUS-7</td>
<td>4.160</td>
<td></td>
<td></td>
<td>0.00</td>
<td>-220.88</td>
</tr>
<tr>
<td>CAP-4</td>
<td>BUS-5</td>
<td>4.160</td>
<td></td>
<td></td>
<td>0.00</td>
<td>-212.90</td>
</tr>
<tr>
<td>GEN-1</td>
<td>BUS-1</td>
<td>115.0</td>
<td></td>
<td></td>
<td>14.11</td>
<td>412.67</td>
</tr>
<tr>
<td>L-3</td>
<td>BUS-9</td>
<td>4.160</td>
<td></td>
<td></td>
<td>128.36</td>
<td>86.52</td>
</tr>
<tr>
<td>L-4</td>
<td>BUS-8</td>
<td>4.160</td>
<td></td>
<td></td>
<td>170.61</td>
<td>80.62</td>
</tr>
<tr>
<td>L-5</td>
<td>BUS-10</td>
<td>4.160</td>
<td></td>
<td></td>
<td>1158.71</td>
<td>664.57</td>
</tr>
<tr>
<td>L-6</td>
<td>BUS-5</td>
<td>4.160</td>
<td></td>
<td></td>
<td>230.64</td>
<td>132.81</td>
</tr>
<tr>
<td>L-7</td>
<td>BUS-4</td>
<td>4.160</td>
<td></td>
<td></td>
<td>170.37</td>
<td>125.59</td>
</tr>
<tr>
<td>L-8</td>
<td>BUS-7</td>
<td>4.160</td>
<td></td>
<td></td>
<td>401.47</td>
<td>292.37</td>
</tr>
<tr>
<td>TX-1</td>
<td>BUS-1</td>
<td>115.0</td>
<td>BUS-2</td>
<td>4.160</td>
<td>35.91</td>
<td>462.79</td>
</tr>
<tr>
<td>TX-2</td>
<td>BUS-7</td>
<td>4.160</td>
<td>BUS-6</td>
<td>4.160</td>
<td>3.44</td>
<td>21.29</td>
</tr>
<tr>
<td>X-1</td>
<td>BUS-2</td>
<td>4.160</td>
<td>BUS-3</td>
<td>4.160</td>
<td>65.41</td>
<td>113.01</td>
</tr>
<tr>
<td>X-2</td>
<td>BUS-4</td>
<td>4.160</td>
<td>BUS-3</td>
<td>4.160</td>
<td>42.81</td>
<td>39.06</td>
</tr>
<tr>
<td>X-3</td>
<td>BUS-5</td>
<td>4.160</td>
<td>BUS-4</td>
<td>4.160</td>
<td>25.71</td>
<td>23.48</td>
</tr>
<tr>
<td>X-4</td>
<td>BUS-3</td>
<td>4.160</td>
<td>BUS-6</td>
<td>4.160</td>
<td>138.81</td>
<td>225.11</td>
</tr>
<tr>
<td>X-6</td>
<td>BUS-8</td>
<td>4.160</td>
<td>BUS-9</td>
<td>4.160</td>
<td>25.39</td>
<td>22.72</td>
</tr>
<tr>
<td>X-7</td>
<td>BUS-9</td>
<td>4.160</td>
<td>BUS-10</td>
<td>4.160</td>
<td>25.39</td>
<td>22.72</td>
</tr>
<tr>
<td>X-8</td>
<td>BUS-11</td>
<td>4.160</td>
<td>BUS-12</td>
<td>4.160</td>
<td>44.40</td>
<td>41.77</td>
</tr>
<tr>
<td>X-9</td>
<td>BUS-10</td>
<td>4.160</td>
<td>BUS-13</td>
<td>4.160</td>
<td>554.88</td>
<td>899.00</td>
</tr>
<tr>
<td>X-10</td>
<td>BUS-3</td>
<td>4.160</td>
<td>BUS-10</td>
<td>4.160</td>
<td>556.15</td>
<td>903.32</td>
</tr>
</tbody>
</table>

Table 5.5 Branch losses report
<table>
<thead>
<tr>
<th>Branch</th>
<th>From Bus</th>
<th>Base kV</th>
<th>To Bus</th>
<th>Base kV</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-1</td>
<td>BUS-2</td>
<td>4.160</td>
<td>BUS-3</td>
<td>4.160</td>
<td>96.5%</td>
</tr>
<tr>
<td>X-2</td>
<td>BUS-4</td>
<td>4.160</td>
<td>BUS-3</td>
<td>4.160</td>
<td>99.4%</td>
</tr>
<tr>
<td>X-3</td>
<td>BUS-5</td>
<td>4.160</td>
<td>BUS-4</td>
<td>4.160</td>
<td>99.4%</td>
</tr>
<tr>
<td>X-4</td>
<td>BUS-3</td>
<td>4.160</td>
<td>BUS-6</td>
<td>4.160</td>
<td>100.0%</td>
</tr>
<tr>
<td>X-6</td>
<td>BUS-8</td>
<td>4.160</td>
<td>BUS-9</td>
<td>4.160</td>
<td>100.0%</td>
</tr>
<tr>
<td>X-7</td>
<td>BUS-9</td>
<td>4.160</td>
<td>BUS-10</td>
<td>4.160</td>
<td>100.0%</td>
</tr>
<tr>
<td>X-8</td>
<td>BUS-11</td>
<td>4.160</td>
<td>BUS-12</td>
<td>4.160</td>
<td>97.5%</td>
</tr>
<tr>
<td>X-9</td>
<td>BUS-10</td>
<td>4.160</td>
<td>BUS-13</td>
<td>4.160</td>
<td>100.0%</td>
</tr>
<tr>
<td>X-10</td>
<td>BUS-3</td>
<td>4.160</td>
<td>BUS-10</td>
<td>4.160</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

Table 5.6 Conductor de-rating report
Harmonic currents can be a major factor in power quality and efficiency issues within power distribution system and can be a complex subject to understand. Causes of harmonic currents can come from any number of nonlinear loads in the system, including commercial and residential loads, external power supplies for laptop computers, electronic ballasts, variable frequency drives, and more. The expectation is that without careful study and planning, harmonics in a power distribution system will continue to increase as the number and types of devices that generate harmonics are more widely adopted. Mitigation techniques for harmonics are available, but without proper analysis and planning, they may come at a cost to efficiency. Similarly, harmonics may increase as distribution system make improvements in efficiency and experience smart technologies. Careful study and analysis must be made to find the optimal balance of harmonic currents and efficiency in the in electric power system.

Single-phase definitions, defining instantaneous active and non-active powers and corresponding components, based on the properties of the power system have been introduced. A meaning, by virtue of the definitions’ relationship to power system properties, has been attributed to each of the components defined. New average powers and energy transfer definitions, linked to the running cost of electricity, have also been introduced. These average power and energy transfer definitions are based on the energy content of the waveform and therefore satisfy the principle of energy conservation which many present definitions do not comply with. The definitions, being generalized, form a (much quested for) common base for
the measurement of powers, compensation and mitigation of unwanted quantities in the power system, detection of source of distortion as well determination of power quality. The new definitions also encompass many of existing commonly used definitions. The new definitions are applicable in the presence of nonlinear load and harmonics which current power definitions have problems with. Definitions, under sinusoidal linear load irrespective of balance or unbalance conditions, corroborate the RMS based arithmetic powers, indicating that the RMS based arithmetic powers meet energy conservation under certain conditions. Numerous examples of measurements taken from commercial and residential non-linear loads have shown both the viability as well as the practical applicability of the new definitions. This enables the use of the definition algorithms in power meters for billing purposes, power analyzers or mitigation and compensation equipment.

In this paper, it has been reviewed some significant progresses in the area of power system harmonic analysis. Commonly accepted methods for conducting harmonic studies have been summarized. The area of harmonic analysis is still a very fertile ground for exploration. With the help of field measurement and 13-bus IEEE test feeder simulation analyzed in easy power, demonstration of possible harmonic level evaluation techniques, harmonics sources and effects and future directions of harmonic analysis are studied. The conclusion is that we need to approach the subject from a wider perspective. It is important to remember that there are still many problems remaining to be solved. The most difficult part facing us is how to extract the problems into a form that can be researched with clear directions.

The results of the analysis in chapter 5 revealed that utility companies should be concerned with the amount of harmonic distortion that is produced by the increased implementation of nonlinear devices. The analysis revealed that even at today’s low levels of
nonlinear device penetration that voltage distortion can exceed levels set by IEEE 519. The analysis further shows the amount of voltage distortion’s dependence on the system impedance as viewed from the residential customer. These results suggest that a utility may be able to predict the maximum levels of voltage distortion based on its system infrastructure. Through further analysis made, it has been determined harmonic impedances associated with residential customers will decrease the more nonlinear devices are implemented, which also suggests that existing harmonic resonance points on the system may change. Power quality problems can be controlled using a number of different methods. The first step is identifying the problem. Then the utility and customer need to work together to determine the best engineering and cost effective solution. Devices being applied to the power system are more susceptible to power quality variations than equipment’s applied in the past.

The increasing emphasis on overall power system efficiency is causing a continued growth in the application of shunt capacitor banks. This is occurring within customer facilities, as well as on the power system. Magnifications of capacitor switching transients may be the most important concern due to the fact that the transient over voltages, as been analyzed shown in chapter 5, can be very high and the energy levels associated with these transients can cause equipment failure.
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Curriculum vitae

Wessen Bogale

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Skill sets:

- Hardworking with organizational ability
- Good interpersonal skills
- Confident and talented
- Detail conscious
- Patience
- Leadership skills

Education Qualification:

- B.S.c in Electrical and Computer Engineering from Jimma University of Ethiopia (2009)
- M.S.c in Electrical Engineering at University of Nevada Las Vegas (anticipated graduation date spring 2015)

Technical expertise:

- Pspice, Power world, Grid lab, Open DSS, Easy Power
- MS office( word, excel, Power point ....)
- CAD
- C++, Matlab Simulink, System c, Verilog, High level synthesis design tools
**Project and internship experience:**

- Internship position at NVEnergy, distribution design service region department
- Harmonic distortion evaluation in a typical distribution feeder (thesis work)
- Material study on GAN structure and property
- Securing the grid from cyber attack
- Reactive power management in power grids
- Solution for over voltage on AC motors terminal driven by variable frequency drives
- Internship at Ethiopian Power Corporation on substation design
- Undergraduate degree final project on software development for visually impaired people

**Achievement:**

- Certificate of appreciation for outstanding project on undergraduate degree completion projects competition
- Certification for presentation on Ethiopian society of electrical engineers Seminar
- Certification of appreciation from Red Cross for volunteering to participate in fund raising

**Languages:** English and Amharic