Electrical Energy Savings Calculation in Single Phase Harmonic Distorted Systems

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Single phase systems are reasonably well understood by professionals in the power system field. Systems with harmonics were previously not of interest as they mean little or nothing to vast majority of people. The growing concern of the effect and risk posed by systems having harmonic frequencies have led (among others) to increase in the extent of research, technical papers, conferences etc. on distorted power system networks.

The current in a single phase sinusoidal system are always in phase with the Voltage for a single frequency system having a unity power factor. The energy transfer can be said to be optimal for such a system having a fixed phase relationship. This cannot be said about a multiple phase system having some form of distortion which may have been as a result of current distortion from the load, source or combination of both. This viewpoint is explored in the work for when energy savings are to be reported where a comparison of two systems was to be made for when the systems are distorted by harmonics.

The work describes the basic power theory applicable for the scope of work, harmonics, energy savings reporting and methodology for doing such for simple non-distorted and distorted systems. A simple introduction is provided on the key points to guide the reader to understand the scope of work and the approach taken to solving the problems.
ACKNOWLEDGEMENT

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### NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BP</td>
<td>Baseline period</td>
</tr>
<tr>
<td>CDD</td>
<td>Cooling Degree Days</td>
</tr>
<tr>
<td>CFL</td>
<td>Compact Fluorescent Lamp</td>
</tr>
<tr>
<td>CV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>CV(RMSE)</td>
<td>Coefficient of Root Mean Square Error</td>
</tr>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>ECM</td>
<td>Energy Conservation Measure</td>
</tr>
<tr>
<td>EE</td>
<td>Energy Efficient</td>
</tr>
<tr>
<td>ESCo</td>
<td>Energy Service Companies</td>
</tr>
<tr>
<td>EVO</td>
<td>Efficiency Valuation Organisation</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transforms</td>
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<tr>
<td>HDD</td>
<td>Heating Degree Days</td>
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<tr>
<td>HVAC</td>
<td>Heating Ventilation and Air-conditioning</td>
</tr>
<tr>
<td>IDM</td>
<td>Independent Demand Management</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IPMVP</td>
<td>International Performance Measurement and Verification Protocol</td>
</tr>
<tr>
<td>kW</td>
<td>KiloWatt</td>
</tr>
<tr>
<td>kWh</td>
<td>KiloWatt Hour</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diodes</td>
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<tr>
<td>M&amp;V</td>
<td>Measurement and Verification</td>
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<tr>
<td>MBE</td>
<td>Mean Bias Error</td>
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<tr>
<td>MW</td>
<td>Mega Watt</td>
</tr>
<tr>
<td>MWh</td>
<td>MegaWatt Hour</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computers</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
</tr>
<tr>
<td>SANS</td>
<td>South African National Standard</td>
</tr>
<tr>
<td>SE</td>
<td>Standard Error</td>
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<tr>
<td>SLA</td>
<td>Service Level Adjustment</td>
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<td>SMP</td>
<td>Switch Mode Power</td>
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<tr>
<td>SWH</td>
<td>Solar Water Heating</td>
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<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>THDI</td>
<td>Total Harmonic Distortion in Current</td>
</tr>
<tr>
<td>THDV</td>
<td>Total Harmonic Distortion in Voltage</td>
</tr>
<tr>
<td>TOU</td>
<td>Time of Use Period</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supplies</td>
</tr>
<tr>
<td>VA</td>
<td>Volt-Amperage</td>
</tr>
<tr>
<td>VAR</td>
<td>Volt-Amperage Reactive</td>
</tr>
<tr>
<td>VSD</td>
<td>Variable Speed Drives</td>
</tr>
<tr>
<td>WTGS</td>
<td>What the Grid Sees</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

$\omega$  angular frequency measured in rad/s

$A_{\text{non routine}}$  non-routine adjustment

$A_{\text{routine}}$  routine adjustment

$B_{\text{adjusted}}$  adjusted baseline energy

$E_{\text{Baseline}}$  baseline energy

$E_S$  energy savings

$I_e$  effective line current

$I_n$  neutral current

$N_{BP}$  number of occupants in the baseline period

$P_F$  active fundamental power

$P_H$  active harmonic power

$R_\Delta$  resistance in a delta connection

$R^2$  R Square value

$R_Y$  resistance in wye connection

$S^2$  variance

$S_F$  fundamental apparent power

$S_N$  non-fundamental apparent power

$S_e$  effective apparent power

$T_{\text{amb}}$  outdoor dry bulb temperature

$V_e$  effective line-neutral voltage

$V_n$  neutral current

$\bar{Y}$  mean

$\theta_T$  true power factor

$E$  energy
\( I \)  instantaneous current

\( I \)  r.m.s. current

\( L \)  load type

\( O \)  Occupancy

\( P \)  active power

\( Q \)  reactive power

\( S \)  standard deviation

\( S \)  apparent power

\( v \)  instantaneous voltage

\( V \)  r.m.s. voltage

\( \tau + kT \)  period

\( A \)  adjustments

\( B \)  baseline period energy use

\( \cos \theta \)  power factor

\( Q \)  thermal Energy

\( R \)  reporting period energy use

\( T \)  period of oscillation.

\( k \)  constant term

\( p \)  instantaneous power

\( S \)  complex power

\( \theta \)  phase angle between the current and the voltage
CHAPTER 1: PROBLEM STATEMENT

1.1 INTRODUCTION

Over the years, energy efficiency and investment in energy efficiency projects have become increasingly popular [1]. This has been an approach to ensure the increasing demand for energy is met in all sectors of a nation’s economy as opposed to building new power stations and also as a measure to reduce budgets for the energy consumed. The introduction of energy efficiency in developed and some developing countries like South Africa, Brazil etc. has had a positive impact on the energy sector [2]. Efficiency has gained popularity in these economies and has helped to reduce the demand [3] and the need for building new power stations, thus ensuring the efficient utilization of MW generated and reduction and or prevention of environmental damage, something environmentalists have encouraged.

Energy efficient technologies are currently being used to replace existing less energy efficient technologies. Projects in energy efficiency are often being sponsored by the utilities through different interventions such as the mass rollout in the residential sectors and through rebate programmes e.g. solar water heating (SWH), energy efficient lighting, process optimization in others [3] etc. Investors and stakeholders have also developed an interest in energy efficiency heightened and fuelled by increasing energy cost and complimented by the rebate programme from joint collaboration by the utility and Government [3, 4]. The investors/companies that demonstrate energy savings through one or many of the different project classifications are given rebates or incentives for demand savings, energy savings and sometimes both. To get rebates or incentives from the joint collaboration of the Government and utility, the bearer must have proof of such energy/demand savings in his or her facility. Such facility is audited through Measurement and Verification (M&V) exercise to demonstrate that the savings were actually achieved.

This work discusses energy savings calculations in a distorted single phase system. M&V methodology based on the International Performance Measurement and Verification Protocol (IPMVP) [5] is applied to a harmonic distorted single phase system in conjunction with...
fundamental definitions of electric power quantities to determine electrical energy savings. It is of utmost importance to calculate and report energy savings correctly as utility companies pay out rebates or incentives to contractors/energy users for energy saved i.e. energy saved has a monetary value that must be quantified and reported accurately. For clarity, the methodology used in M&V energy efficiency projects is discussed. Measurement and calculations involving active power based on the IPMVP and active power calculation according to the Institute of Electrical en Electronics Engineers (IEEE) 1459 are also presented.

1.2 PROBLEM STATEMENT

The determination of energy savings involving energy efficiency projects are often thought of as simply establishing the difference between the energy consumption of one system/facility and another system within the same facility. Experience in the field shows that some project developers known as Energy Service Companies (ESCo’s) often make the mistake of comparing the energy use of two systems, without taking into account all energy governing factors that affect the facility or the measurement boundary of the systems concerned. The introduction of M&V has clarified this mistake when reporting energy savings for Demand Side Management (DSM) projects or more recently known as Independent Demand Management (IDM) [3] in South Africa. The IPMVP provides the methodology for reporting energy savings of energy related projects. Although sometimes incorrectly applied, the methodology based on the IPMVP is used in many countries to M&V energy and water projects. In this study, emphasis will be placed on energy savings.

This study focuses on M&V, the IPMVP general methodology of reporting energy savings and methodology for doing so when harmonics are present in the system. Case studies will be presented to provide insight into the determination of energy savings for an energy efficiency project.
1.3 OBJECTIVES

The objectives of this study are the following:

- To introduce the importance of correct power definition in energy saving reporting.
- To present the methodology used in M&V to model energy use of a system according to the IPMVP.
- To highlight the effect of harmonics on the energy use of a harmonic distorted single phase system using the measured active power drawn by that system.
- To investigate the methodology of calculating energy savings in a harmonic distorted single phase system.
- To introduce an improved approach in reporting electrical energy savings accurately by incorporating the definition of active power into the IPMVP standards.

To achieve the objectives stated above, case studies and examples were used in the different chapters for illustration and to provide more insight on the work.

1.4 SCOPE OF WORK

The introduction of the IPMVP [5] guideline for energy savings determination has clarified the methodology of energy saving reporting. This protocol among others was designed as a guide to simplify and unify the approach used to report energy savings, to encourage investment in energy efficiency and related projects and to present a platform where stakeholders can share common ground when investing in energy efficiency and energy management projects. An improved approach can be achieved by combining the guideline with the IEEE 1459 standard that contains the definitions of power quantities. This improvement is brought about by incorporating the fundamental meaning of power quantities from IEEE 1459-2010 [6] definitions of power and practical applications of power theory into the IPMVP standard.

The IPMVP methodology of calculating energy is based on the total active power consumed by a system or facility. According to the IEEE definitions of total active power, for a practical system with a non-linear voltage-current relationship, the total active power is a summation of the power due to the fundamental and those due to the harmonics [6]. It must be
remembered that a practical system might include distortion in the form of harmonics. This distortion in the system has an effect on the total active power as it acts either to increase or decrease the measured total active power of the system. The measuring instrument used to measure the total power measures power due to the fundamentals and those due to the harmonics. The total power is used in energy billing, savings determination and equipment ratings. However, it was noted that power due to the harmonics does not contribute towards useful power hence the motivation for this study.

The scope of work is limited to M&V methodology, application of power definitions based on the IEEE Standard 1459-2010 in electrical energy savings calculation, modelling energy use of a system based on the IPMVP and a method of improving the accuracy of energy savings reporting.

1.5 GOALS

The completion of this dissertation will provide more insight into calculating energy savings using the fundamentals of electric power quantities. The work explores the possibilities of achieving more accurate, more reliable and more credible results by incorporating the fundamental IEEE definitions of electrical power quantities into the methodology of reporting energy savings as detailed in the IPMVP and South African National Standard SANS 50010:2011 [7].

Examples and case studies to be presented combine theoretical meanings and practical applications of electric power definitions in the field of M&V where electrical energy savings are reported for stakeholders following the IEEE guideline. To begin with, the reader is introduced to the theoretical background of electrical engineering that is applicable to energy savings determination and followed by the introduction of the IMPVP. Some of the important sections that relate to the scope of work will be discussed for the reader to understand the relevant section of the work followed by the application and problem solving that is based on the introduction and background provided. The case studies to be presented will reflect the methodology as contained in the IPMVP used to M&V some projects.
For an energy efficiency project, the stakeholders are interested in the impact (energy savings) created as a result of the retrofit of a less energy efficient system with a more energy efficient one. Therefore, accurate reported energy savings are desired. When a system involves some distortion, the effect of the distortion on the total power should be taken into account when energy savings are to be reported. The effect of the distortion on the total active power when distortion is present in a system will be presented after presenting theoretical meaning of active power and the methodology used for calculating energy savings.

1.6 OVERVIEW OF DOCUMENT

The thesis is structured into seven chapters and an annexure. The first half of the work contains the introductory part while the other half contains the case studies, examples and application based on the theoretical background and definitions of power quantities as used by the IEEE and methodology as recommended by the IPMVP.

The chapters are broken down as follows:

- Chapter 2: This chapter presents the fundamentals of the electric power quantities. The power definition that includes the basic power definition, the arithmetic and vector power definition are discussed. The recent definition of electric power based on the effect as contained in the IEEE text is also presented. Measurements of electric power in applications such as variable speed drives (VSD) and background of single and poly-phase systems are discussed.

- Chapter 3: The power quality problem is discussed in this chapter. The general method for determining energy savings for a single phase system distorted by harmonics is presented. The chapter begins with an introduction to power quality problems with the emphasis on harmonic distortion. A case study is presented in this chapter and in Chapter 5 to illustrate the effect of harmonic distortion in energy savings determination.
• Chapter 4: This chapter provides an overview of the IPMVP options for determining energy savings. The methodology used to establish the baseline energy use is presented in the form of examples that include lighting systems, HVAC and a hybrid system that consists of mixed HVAC and SWH systems backed up by an electric heater. The methodology for establishing the baseline energy use is selected and used as an example in the work. The baseline is a crucial part of the savings determination process as the old systems are often destroyed as soon as they are replaced with more energy efficient ones.

• Chapter 5: Case studies on electrical energy savings for when harmonics are present are presented on the system being investigated in this chapter. Different scenarios are presented for single phase systems when different harmonics are present in the system.

• Chapter 6: This chapter discusses M&V reporting and uncertainties experienced. The project findings, the thesis shortcomings, future work that can be embarked on and the conclusion of the dissertation are also included in this chapter. Some of the important supporting documents used that may be of interest to the reader are attached in the annexure for more reading and references as may be required.

• Chapter 7: The work is concluded in this chapter. The results of the work is summarised and recommendations presented. Possible future research work as a continuity of the work is also noted.

1.7 CONCLUSION

The above section provides a brief overview of the problem statement, the scope of work and an overview of the research. Each chapter as indicated is treated in a way to help the reader to understand the work and the results that follow. The focus of the analysis in the document has been limited to single phase system only. Each of the chapters to follow is presented in such a manner that the particular subject is ring-fenced and concluded.
CHAPTER 2: BACKGROUND ON ELECTRIC POWER QUANTITIES

2.1 INTRODUCTION

In power and the electrical engineering field, the concept, design and calculations are based on definitions of power quantities. The design of equipment and equipment ratings are based on fundamental definitions e.g. apparent power is used as an indicator of equipment size, power factor as a measure of the utilization of the system i.e. the interaction between the connected loads on the source for which the load is being fed. Despite various inputs and efforts from different researchers, the controversy concerning the appropriate definition and quantification of apparent power in the presence of disturbance or, in an unbalanced or distorted system, still remains unsolved. This situation changed recently when the IEEE introduced the IEEE Standard 1459 2010 [6] that clarifies some of the discrepancies and queries regarding the acceptable apparent power definition.

In order to fully describe and present a clear understanding of the project topic, it is worth going back to the fundamentals and theory of power and apparent power, balance and unbalance and its occurrence in sinusoidal systems. This chapter discusses the basic theory for single-phase and poly-phase sinusoidal systems. A definition that applies to each of the cases is presented. The background and basic of electric power quantities that are deemed important for this work is presented using text form by Hadi Saadat [8] and the IEEE Standard 1459-2010 [6].

2.2 IMPORTANCE OF ELECTRICAL POWER

The design of power equipment, gathering of accurate data, calculation of power consumed by electrical equipment, calculation of losses in equipment etc. all depend on accurate and acceptable power definitions. These definitions that vary within for example an engineering discipline or related work should, however, be uniform across all the disciplines including all other non-engineering disciplines as far as power, apparent power concepts and definitions
are concerned. Apparent power for example is not only the pivot that holds the generation, transmission and distribution of electrical power in a power system network, but is also the governing factor among voltage, frequency, frequency spectral, skin and proximity effects that govern the power losses in electrical networks. Sizes of electrical equipment such as switch gear, transformers, rotating machines etc. are evaluated in Volt-Amperage (VA). This means that apparent power is of relevance for engineers and also especially for the utilities where energy consumption associated with capital cost are billed in terms of VA [9]. The active power as energy consumed by equipment, is also based on active power drawn by the equipment for a specific period.

The active power drawn by the load in a power system is used to measure its efficiency against the work done. Most consumers of electricity are interested in the active power drawn by the system as energy savings payments are based on the MW/kW and or MWh/kWh in various energy efficiency or energy management projects. These energy savings are based on the active power for a specified period of time. The active power is scaled from the apparent power by the power factor of that system. For an ideal system, the power factor is said to be optimal i.e. unity therefore the active power value is the same as the apparent power value but with different units. Active power carries units and sub-units of W while apparent power carries VA. For large power consideration the kW, MW etc. are used to describe the power linked to that system.

Power theory and definitions with its associated quantities published, presented as standards and used in applications such as designs, energy billing and pricing, instructional and learning purposes, work perfectly well for a single phase system and balanced poly-phase system [6]. The scope of this work is limited to a single phase system and therefore the emphasis is on active power consumed by a load in a single phase system. Field experience gained while conducting M&V for DSM programmes shows that active power definitions are not uniquely applied when energy savings are to be calculated.

Accurate reporting of energy savings is vital as this has monetary implications. Often the energy savings resulting from an energy efficiency project involves comparing the energy use of an existing system with the energy use of a new system deemed to be more energy
efficient. The energy calculations rely on accurate power measurements and reporting both for the existing system and the new system. This becomes paramount when the systems involved have non-linear loads that draw non-linear currents. An average power meter measures the total active power drawn by that load. It will be shown in the section to come that the total active power consists of the fundamental component of the sinusoid and a harmonic component. These components have power associated to both, i.e. the power due to the fundamental components and power due to the harmonic components. If the total power in the system is incorrectly reported, the results of which are incorrect energy savings, it can have serious financial consequences. The consequences are not queried by investors as they have little or no knowledge about what goes on in power electronic equipment. The viewpoint of incorrect power/energy quantities that results from measurement is further expressed in the later part of the document.

2.2 ELECTRICAL POWER DEFINITIONS

The generalisation of power definitions has been the discussion of many researchers over the years. The point of view of researches is that engineers and other users of electrical power definitions in various applications should have a uniquely acceptable power definition that caters for all applications. It was put forward [10] that the fundamental definitions of active, reactive, apparent power factors as in the case of a single phase sinusoidal system, should be adapted to the case of a poly-phase system. The generalization is also expected to be applicable to the more complicated cases i.e. unbalanced poly-phase systems. This has been the discussion surrounding apparent power definitions for some time. The difference in opinion on how engineers view the definition either for practical applications or the theoretical sometimes yielded similar results and sometimes not, depending on the applications [11].

Varying results from two or more measurements measured under the same conditions indicate that the apparent power concept has not been uniquely defined for the case of sinusoidal 3-phase unbalanced systems. An example is the distinguished functional definition from the European approach that was more theoretical and the American approach that was more of the practical [12]. Using the general definition, the distortion/disturbance in the
system and the symmetry approach, the definitions have all raised controversy over the years [13] This non-uniqueness was a cause for concern until the IEEE published the IEEE 1459-2010 that addresses some of the concerns raised by different researchers. Section 2.4 discusses the basic electric power definitions.

2.3 MEASUREMENTS OF ELECTRIC POWER QUANTITIES

The measuring of certain power quantities like active power has raised little or no debate at all. Over the years, measuring other power quantities like apparent power and non-active power have contributed to the debate about having a uniquely acceptable apparent power definition among researchers [14]. Measurements done when the system is distorted by harmonics or unbalanced for example differ from one another. These differences in measured values are closely linked to the conceptual design of the power measuring equipment. Some of them are known to work well under influences such as harmonics, others respond differently.

Active power of a consumer load is a function of the power factor. In a real world applications involving measurement on VSD, it was noted that three different meters responded differently when the system was subjected to harmonics [15]. This difference was linked to how the meters were designed. The first two meters gave power factor readings of 0.95, 0.96 and the third gave a reading of 0.88. In [7], it was argued that the first two meters calculated Vars by time-shifting the voltage samples by 90° at the rated frequency, hence gives an approximate displacement power factor. The third meter responded differently by calculating the power factor as the ratio of the active power to the apparent power i.e. apparent power calculated as the product of the Root Mean Square (RMS) voltage and current. This inconsistency therefore raised questions about the accuracy of metering equipment when harmonics are present for example.

The inconsistencies in measured value are directly linked to the fundamental principle and definition used in the design of those meters. This is a cause for concern for applications involving the determination of energy savings due to an energy efficiency intervention where an investor is expected to be rewarded for every kWh saved over a period of time. It is also a cause for concern for the utility in billing their consumers. Incorrect measurement obviously
results in incorrect billing. This can result in disputes between the large consumer of the electricity and the utility when they are billed based on the maximum demand for example.

A mismatch in measured values of the same quantity by power metering equipment is not acceptable. It is in the interest of end users of electric energy meters to have correct figures when doing measurements irrespective of the type of meter used and under what conditions i.e. distortion, unbalance, etc. Therefore there is a need for an acceptable standard that governs the design of power measuring equipment that will suit all applications irrespective of the nature or type of system being measured, type of meter used and under what conditions. In the meantime the interpretation of measured values should follow from its fundamental definitions in all applications as well for different cases whether the system is distorted or not.

### 2.4 ELECTRIC POWER THEORY AND FUNDAMENTALS

The basic theory behind power is investigated for the following three systems:

- single phase sinusoidal,
- balanced 3-phase sinusoidal and
- unbalanced 3-phase sinusoidal systems.

#### 2.4.1 SINGLE PHASE SINUSOIDAL SYSTEM

In a single phase sinusoidal system, a sinusoidal voltage source supplying a linear load produces a sinusoidal current. For a single frequency system, the angle between the voltage and the current is known as the phase angle. For a single phase system having a unity power factor, the voltage and current are always in phase. This current is separated from the voltage by an angle of $\theta$ known as the phase angle. The current in a single phase sinusoidal system is always in phase with the voltage provided the load is linear.

A non-linear load in a single phase system results in phase shift between the current and the voltage and also leads to distortion in the system. Distortion can be in the voltage or current sinusoid or in both. A simple schematic presentation of a single phase system is given in
Figure 2.1. In this system having a fixed phase relationship, the energy transfers can be said to be optimal.

![Single phase sinusoidal system](image1)

Figure 2.1: Single phase sinusoidal system

In the figure, consider the voltage and current to be both sinusoidal i.e. responses of the source and load respectively, the waveforms associated with the circuitry are illustrated in Figure 2.2. The angle between the voltage and the current is the phase angle also known as the power angle, denoted by \( \theta \) in equation 2.2.

![Waveforms associated with the circuitry](image2)

Figure 2.2: Waveforms associated with the circuitry

The expression for the instantaneous voltage and current as a function of the r.m.s. voltage and current, the angular frequency, phase angle and the time are

\[
v = \sqrt{2} V \sin(\omega t) \quad \text{..........................................................} (2.1)
\]

\[
i = \sqrt{2} I \sin(\omega t - \theta) \quad \text{..........................................................} (2.2)
\]

Where,

\( V \) and \( I \) are the r.m.s. voltage and current respectively
\[ \omega = 2\pi f \] is the angular frequency measured in rad/s

\[ \theta \] is the phase angle between the current and the voltage

\[ t \] is the time seconds

For a single phase sinusoidal system, where the voltage and current are both in phase, the waveform that depicts them is given in Figure 2.3. Hence, the phase angle is zero, this occurs for a purely resistive load where there no inductive or capacitive effect on the system.

Consider a single phase sinusoidal situation with a sinusoidal voltage and sinusoidal current flowing through the circuitry; the instantaneous active power as a result of the sinusoids is obtained by multiplying the instantaneous voltage by the instantaneous current. The instantaneous active power is unidirectional i.e. from source to the load and is the rate of flow of positive energy through the system. Mathematically written as

\[ p = vi \] ........................................................................................................ (2.3)

The active power \( P \) is the average of the instantaneous active power over a period of time. Active power or real power as it is generally known is found by the integration of the instantaneous power over time period \( t+kT \). Therefore the active power \( P \) is written as

\[
P = \frac{1}{kT} \int_{t}^{t+kT} p \, dt \] ............................................................................... (2.4)
The active power boils down to

\[ P = VI \cos \theta \]  

(2.5)

Where,

\[ T = \frac{1}{f} \] is the period of oscillation.

\( K \) is a positive integer number,

\( \tau \) is the time stamp.

The reactive power is written as

\[ Q = VI \sin \theta \]  

(2.6)

The apparent power is defined as the product of the r.m.s, values of the voltage and current

\[ S = VI \]  

(2.7)

The above definition then implies that for a single phase sinusoidal system, the apparent power can be defined as the maximal active power that can be delivered by a given voltage magnitude and given current magnitude \([2,10]\). Using the active power and reactive power approach, the apparent power measured in VA is the magnitude of the complex power.

The power factor is the ratio of the energy transmitted to the load over the maximum energy that can be transmitted provided the line losses are the same. Maximum energy is transferred to a load when the power factor is unity i.e. the active power is the same as the apparent power. Power factor is expressed as

\[ \cos \theta = \frac{P}{S} = \frac{VI \cos \theta}{VI} \]  

(2.8)
The complex power is the vector sum of the active power (W) and the reactive power (VAR). Mathematically, the complex power is given by

Complex power:
\[ S = P + jQ = VI^* \] \hspace{1cm} (2.9)

Apparent power:
\[ S = \sqrt{P^2 + Q^2} = VI \] \hspace{1cm} (2.10)

Where,

\( P \) and \( Q \) are the active power and reactive power respectively

\( V \) and \( I^* \) are the voltage and complex conjugate of the current phasor respectively.

2.4.2 THREE PHASE SINUSOIDAL SYSTEM – BALANCED CASE

A three phase generator contains three sinusoidal voltage sources having the same frequency and a 120° phase shift apart. This phase angle is achieved by positioning the three coils on the rotor apart at 120°. The system is balanced when the three phase systems consists of three sinusoidal voltages with the same voltage amplitude displaced by a phase angle of 120° [8]. The distribution of the system is thus 120° apart. The three phase sinusoidal waveform for a three phase system is shown in Figure 2.4.

![Figure 2.4: Three phase sinusoidal waveform for a three phase system](image-url)
Figure 2.5: Voltage phasor representation

The voltage phasor representation is shown in Figure 2.5. It is worth mentioning that for a balanced system, the magnitude of the phase voltage is the same while they are spaced apart at a 120° angle and the phasor addition gives zero or 360°. The line to neutral voltages (phase voltages) of a counter-clockwise positive rotating system is given by:

\[ v_a = \sqrt{2}V \sin(\omega t) \]  \hspace{2cm} (2.11a)
\[ v_b = \sqrt{2}V \sin(\omega t - 120^\circ) \]  \hspace{2cm} (2.11b)
\[ v_c = \sqrt{2}V \sin(\omega t + 120^\circ) \]  \hspace{2cm} (2.11c)

The line currents are given by

\[ I_a = \sqrt{2}I \sin(\omega t - \theta) \]  \hspace{2cm} (2.12a)
\[ I_b = \sqrt{2}I \sin(\omega t - \theta - 120^\circ) \]  \hspace{2cm} (2.12b)
\[ I_c = \sqrt{2}I \sin(\omega t - \theta + 120^\circ) \]  \hspace{2cm} (2.12c)

The apparent power can be determined for each of the phases by multiplying the line to neutral voltage by the line-to-line current.

For a balanced system

\[ V = V_a = V_b = V_c \]

and

\[ I = I_a = I_b = I_c \]
\[ P_a = V_a I_a \cos \theta_a, \quad P_b = V_b I_b \cos \theta_b, \quad \text{and} \quad P_c = V_c I_c \cos \theta_c \]

for phases a, b and c respectively. It also implies that for a balanced system, the phase angles of each of the phases are equal i.e.

\[ \theta = \theta_a = \theta_b = \theta_c \]

Therefore, the total power is given as

\[ P = 3V I \cos \theta \] \hspace{1cm} (2.13)

The instantaneous power delivered to a load from a three phase system is constant and not pulsating as in the case of a single phase sinusoidal system. Power analysis per phase of the three phase system is pulsating but the total instantaneous power is constant and it is three times that of each phase. The equation above assumes an ideal condition.

Similarly, the reactive power is given as

\[ Q = 3V I \sin \theta \] \hspace{1cm} (2.13)

The apparent power is discussed in the sections to follow after the discussion of the unbalanced system.

**2.4.3 THREE PHASE SINUSOIDAL SYSTEM – UNBALANCED CASE**

Often, quantities are not balanced in a practical three phase system. This can be found for example in systems where the source transmits power to loads consisting of control electronics connected to one phase of the three phase system and at the same time to another load say induction motor requiring all three phases. The control electronics requiring the single phase and the induction motor requiring three phases causes an imbalance in the current through the transmission line and hence results in an imbalance of the system. In addition to the imbalance in the current is the non-zero current that is set in the neutral conductor. This neutral current sets in as a result of the difference of potential between the neutral point at the source and that at the load.
Unbalance in the three phase system is defined as the ratio of the magnitude of the fundamental negative sequence voltage to the magnitude of the positive sequence voltage expressed as a percentage [8]. This definition makes use of the symmetry arrangements of the voltage phase and the phase angle. The definition can also be applied to define current unbalance.

For unbalanced systems, the voltage magnitudes are not the same (or with at least the magnitude of one phase voltage having a value different from the other two). The current phasors also have different magnitudes and are not shifted from each other by 120° (see Figure 2.7).

The lines to neutral voltages are expressed as follows:

\[ v_a = \sqrt{2} V_a \sin(\omega t + \alpha_a) \] ..............................................................(2.14a)

\[ v_b = \sqrt{2} V_b \sin(\omega t + \alpha_b - 120^\circ) \] ..............................................................(2.14b)

\[ v_c = \sqrt{2} V_c \sin(\omega t + \alpha_c + 120^\circ) \] ..............................................................(2.14c)
The current is also expressed as

\[ i_a = \sqrt{2}I_a \sin(\omega t + \beta_a) \] \hspace{1cm} (2.15a)
\[ i_b = \sqrt{2}I_b \sin(\omega t + \beta_b - 120^\circ) \] \hspace{1cm} (2.15b)
\[ i_c = \sqrt{2}I_c \sin(\omega t + \beta_c + 120^\circ) \] \hspace{1cm} (2.15c)

For the unbalanced system

\[ V_a \neq V_b \neq V_c \hspace{1cm} \text{and} \hspace{1cm} I_a \neq I_b \neq I_c \]

It could also mean that the unbalance(s) is (are) as a result of unequal phase angles for when the voltage is considered or for when the current is considered. The phase angle between the voltage and the current for each of the phases is given by

\[ \theta_a = \alpha_a - \beta_a , \hspace{1cm} \theta_b = \alpha_b - \beta_b , \hspace{1cm} \text{and} \hspace{1cm} \theta_c = \alpha_c - \beta_c \]

The total instantaneous power is the sum of the instantaneous power of the three phases

\[ p = p_a + p_b + p_c = v_a i_a + v_b i_b + v_c i_c \] \hspace{1cm} (2.16)

The active power corresponding to each of the phases is given by:

\[ P_a = V_a I_a \cos \theta_a , \quad P_b = V_b I_b \cos \theta_b , \quad \text{and} \quad P_c = V_c I_c \cos \theta_c \]

for phases a, b and c respectively. It also implies that for an unbalanced system, the phase angles of each of the phases are not equal i.e. \( \theta_b \neq \theta_b \neq \theta_b \).

The causes of unbalance in three phase systems include:

- load imbalance/source imbalance,
- combination of both source and load imbalance,
asymmetric voltage phasors in the systems and
unequal current magnitudes and phase angles.

The reactive components of the currents in each phase causes oscillations in the system, hence the reactive components of the power are given by [14]:

\[ Q_a = V_a I_a \sin \theta_a, \quad Q_b = V_b I_b \sin \theta_b, \quad \text{and} \quad Q_c = V_c I_c \sin \theta_c \]

The discussion of apparent power leads to the different views in more recent texts viz arithmetic and vector apparent power definitions in unbalanced 3-phase systems.

### 2.4.4 ARITHMETIC AND VECTOR APPARENT POWER DEFINITIONS

The approach for calculating apparent power for an unbalanced 3-Φ sinusoidal system is somewhat different to that of a single phase sinusoidal system and the balanced 3-Φ sinusoidal system. The approach used previously to calculate apparent power involves that of the arithmetic apparent power definition and vector apparent power definition. Both these definitions of apparent power gave different results [8]. For different voltage and current magnitudes and different phase angles, the new definition in the IEEE 1459-2010 uses the effective definition to calculate apparent power [2].

#### 1. ARITHMETIC APPARENT POWER [2]:

According to the arithmetic apparent power definition, the arithmetic active power \( P_A \) and reactive power \( Q_A \) are given in terms of the phase relationship, therefore the arithmetic apparent power is expressed in terms of the phase relationship.

\[ S_A = S_a + S_b + S_c \]

Where,

\[ P_A = P_a + P_b + P_c ; \quad Q_A = Q_a + Q_b + Q_c \]

\[ S_a = V_a I_a ; \quad S_b = V_b I_b ; \quad S_c = V_c I_c \]
Therefore,

\[ S_A = \sqrt{P_a^2 + Q_a^2 + P_b^2 + Q_b^2 + P_c^2 + Q_c^2} \] \hspace{1cm} (2.18)

The IEEE definition of apparent power says that “apparent power \( S \) is the product of the r.m.s. voltage \( V \) and current \( I \)” \[16\], the arithmetic definition contravenes the IEEE definition \[IEEE 1459\].

\[ S = VI = \sqrt{P^2 + Q^2} \neq S_A \] \hspace{1cm} (2.19)

2. **Vector Apparent Power** \[2\]

The vector apparent power is calculated from the active power from active and reactive power of the three phases. The active and reactive power are given as

\[ P = P_a + P_b + P_c \quad \text{and} \quad Q = Q_a + Q_b + Q_c \]

\[ S_V = |P + jQ| = \sqrt{P^2 + Q^2} \] \hspace{1cm} (2.20)

\[ P = \sqrt{(P_a + P_b + P_c)^2 + (Q_a + Q_b + Q_c)^2} \] \hspace{1cm} (2.21)

The IEEE recommends that both the arithmetic apparent power and the vector apparent power be renounced and proposes the effective apparent power definition. Renunciation of these definitions was due to the following reasons \[2\]:

- The arithmetic apparent power definition contravenes the definition of apparent power itself as contained in the IEEE glossary of terms.
- The arithmetic power factor and vector power factor calculated using the arithmetical and vector definitions are not the same and more significantly, it does not accurately measure the degree of utilization of the line.
- The linearity requirements of system power versus apparent power squared is not satisfied using the arithmetic and vector apparent power definitions.
2.4.5 EFFECTIVE APPARENT POWER DEFINITION [2]

The effective definition says that the effective apparent power is the product of the effective voltage and the effective current scaled by 3 for the three phase system. Mathematically represented as

\[ S_e = 3V_e I_e \]  \hspace{1cm} (2.22)

Where,

- \( V_e \) is the effective line-neutral voltage
- \( I_e \) is the effective line current

From the analysis involving arithmetic and vector power factors, it is evident that the both arithmetic and vector apparent power give different values. The effective apparent power as presented in the new IEEE 1459-2010 gives much more accurate results.

This concept explores the use of effective line current and line-to-neutral voltage for the computation of the effective apparent power both for the balanced and the unbalanced 3-\( \Phi \) systems by using the assumption that a virtual balanced circuit has exactly the same line power losses as the actual unbalanced circuit. For a four wire three phase system, the effective apparent power is given by equation 2.22.

**EFFECTIVE LINE CURRENT [2]:**

Using the balance of power loss for a three phase four wire systems see Figure 2.8,

Figure 2.8: Equivalent circuit diagram of unbalanced system
An expression for the effective line current derived from the equivalent circuit and the unbalanced 3-phase four wire systems is written as follows.

\[ 3rI_e^2 = r(I_a^2 + I_b^2 + I_c^3 + \rho I_n^2) \]  

……………………………………….. (2.23)

Where,

\[ I_a, I_b, I_c \] are the phase currents in phases a, b, c and \( I_n \) is the neutral current.

\[ \rho = \frac{r_n}{r} \] is the ratio of the neutral wire resistance to the line resistance.

To derive the expression above, an equivalent circuit is arrived at with the assumption that the equivalent circuit has the same line power loss as a virtual balanced circuit [2].

\[ I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2 + \rho I_n^2}{3}} \]  

…………………………………………… (2.24)

For a three wire systems, the neutral current is zero. Hence, the expression for the effective line current is reduced to:

\[ I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2}{3}} \]  

…………………………………………………….. (2.25)

**Effective Line-Neutral Voltage [2]:**

A similar approach as that for the effective line current is used for the expression of the effective voltage, using equivalence of power between the actual and an equivalent system. The equivalent system consists of a load having a combination of resistance in Y and \( \Delta \). The equivalent resistance in each of the configurations has a resistance \( R_Y \) and \( R_\Delta \) and power dissipated in this resistance is also denoted by \( P_Y \) and \( P_\Delta \) for the equivalent star and delta connected load.

The power in the actual system is given by:

\[ P = P_Y + P_\Delta = \frac{V_{a1}^2 + V_{b1}^2 + V_{c1}^2}{R_Y} + \frac{V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{R_\Delta} \]  

………………………………... (2.26)

Power in the equivalent system is given by:
\[ P = 3 \frac{V_e^2}{R_Y} + \frac{9V_e^2}{R_\Delta} \] (2.27)

The equivalence of power is therefore,

\[ \frac{V_a^2 + V_b^2 + V_c^2}{R_Y} + \frac{V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{R_\Delta} = 3 \frac{V_e^2}{R_Y} + \frac{9V_e^2}{R_\Delta} \] (2.28)

Hence,

\[ V_e = \sqrt{\frac{3(V_a^2 + V_b^2 + V_c^2) + 3(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)}{9(1+\zeta)}} \] (2.29)

Where,

\[ \zeta = \frac{P_\Delta}{P_Y} = \left( \frac{9V_e^2}{R_\Delta} \right) + \left( \frac{3V_e^2}{R_Y} \right) = \frac{3R_Y}{R_\Delta} \] (2.30)

For the case when \( \zeta = 1 \), the effective voltage is reduced to

\[ V_e = \sqrt{\frac{3(V_a^2 + V_b^2 + V_c^2) + 3(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)}{18}} \] (2.31)

Having discussed single and poly-phase sinusoidal systems, it is worth mentioning again that only the single phase system is investigated in this work.

### 2.5 CONCLUSION

The discussion in the above section is a simple background of power quantities that is deemed important for this work. More understanding can be obtained from texts on electric power quantities. The study is structured around the single phase system and little or no discussion will be provided on poly-phase systems as it falls out of the scope of the work. However, the methodology as used to determine energy savings in single phase systems is also applicable to poly-phase systems. The methodology used in M&M is presented in the chapters to follow but with the effects of harmonics included in the calculations. Case studies and examples in single phase systems are also presented using the standard definition of electric power quantities and application of the IPMVP protocol and SANS 50010 for reporting energy savings.
CHAPTER 3: POWER QUALITY PROBLEMS - HARMONICS

3.1 INTRODUCTION

The end user of electricity expects perfectly sinusoidal voltage at the main incomer as supplied by the utility company. As perfect sinusoidal voltages from the utilities are sometimes unachievable, the assumption that the voltage from the utility is perfectly sinusoidal might be misleading. Similarly the current drawn by a certain load is also not a perfect sinusoid, especially for non-linear loads. The inability of the utility company to provide the consumer of electricity with a perfect sinusoidal voltage is mostly due to what is referred to as power quality problems. Power quality problems are disturbances in power system networks which affect the quality of supply to the consumers.

Disturbances in power system networks occur in different forms depending on the consumer load and the supply system. Distortion in the form of harmonics is one of the power quality problems, initially thought to be associated with the use of industrial equipment such as arc furnaces, welders and also with transformers reaching saturation etc. Modern equipment including those used in commercial and domestic use are now known to generate harmonics \[17\]. For poly-phase systems, the power quality problems go beyond disturbance and unbalance is also known to be a problem where poly-phase systems are concerned. Other power quality problems are discussed further in the sections to follow.

This chapter discusses harmonic distortion in power system networks. It should be noted that harmonic distortion is one of the power quality problems that can be encountered in power system networks and is not the only power quality problem that perturbs electrical systems. The scope is limited to distortion in single phase sinusoidal systems. The focus is based on distortion of a system caused by a non-linear load in the system. Generally, Switch Mode Power (SMP) supplies are known to be present in modern power electronic equipment. These SMP supplies are a source of harmonic distortion in power electronic equipment.
Following the recent definition of active power and apparent power as contained in the IEEE 1459-2010, an average engineer or technician could be bewildered by power calculations which are the product of power definitions when one considers a distorted system.

3.2 CONCEPT OF HARMONICS

3.2.1 BACKGROUND ON HARMONICS

Power system networks are generally subjected to different types of loads which could be linear or non-linear. Linear loads are known to have a linear voltage-current relationship. Non-linear loads, however, have a non-linear voltage-current relationship i.e. the current drawn by the loads are not proportional to the applied voltage. Harmonics generated by non-linear loads vary in magnitude depending on the components within the load, operating voltage etc.

Harmonics, “the subject of this chapter” is a form of distortion in power system networks created by non-linear load(s). It affects the quality of supply and poses a risk of fire/damage to a substation, equipment, malfunction of devices [18] especially metering devices etc., to name a few. The cause, effect and mitigation techniques of power system harmonics are discussed in the following subsection of this chapter. An illustration approach is applied later to appreciate why distortion in the form of harmonics should be taken seriously. This will not only prevent a catastrophic event such as fire, but is also important in energy management or energy efficiency projects where accurate reporting of energy savings is vital [1, 19].

3.2.2 POWER QUALITY PROBLEMS

Power system networks are sometimes faced with problems that affect the quality of supply from the power station to the consumers. The deviation of voltage and its frequency from the rated value and the deviation of either the voltage waveform or the current waveform or even a combination of both the voltage and current waveform, all combine in what is called the power quality problems.
The power quality of a system is used to express the quality of the voltage supplied to a consumer and hence the current drawn by the consumer loads. Some power quality problems that are sometimes encountered in the power industries include:

- disturbance,
- unbalance,
- distortion,
- voltage fluctuations and flickers.

This classification of power quality problems is based on the different characteristics displayed by the voltage and current drawn by the load. Disturbance in a power system network can be voltage dips, voltage notches or transients caused by switching. Unbalance in systems is associated with poly-phase systems where the phases of a 3-phase system are unequally spaced and have different phase angles (see section 2.43). Distortion in a system is mainly in the form of harmonics. Harmonics is defined as the distortion of an ideal sinusoidal voltage waveform by the presence of a non-linear load in the system. Some of these power quality problems are experienced by field engineers when conducting field measurements. Maintenance Engineers and M&V Engineers often encounter weird measurements caused by harmonics during routine plant maintenance where equipment performance is of interest or during field measurement exercises for energy saving reporting.

### 3.2.3 DISTORTION IN POWER SYSTEM NETWORKS

Engineers face different power quality problems, some of which were discussed above. Experience gained during field measurements shows that currents drawn by some loads are often not perfectly sinusoidal in nature. The current drawn by the loads from the voltage source are distorted in one way or the other e.g. an electric arc furnace is known to draw non-linear current hence a source of harmonics in a power system network [20].

Distortions in power system networks are referred to as harmonics. Experience from field measurements shows that power measurements are affected by harmonics as will be illustrated in the sections to follow. Harmonics are present in a system when its ideal (or
nearly perfect) sinusoid is distorted by the interaction of the non-linear load in the network with the impedance of the same network.

Non-linear loads distort the perfect sinusoid of a sinusoidal system to such an extent that the distortion is repeated when cycles of the waveform are considered. Distorted waveforms that repeat for every cycle of the waveform considered are termed periodic. Hence harmonics are periodic with the harmonic frequencies being multiples of the fundamental frequency. Harmonic order is the ratio used to describe the ratio of the harmonic frequency to the supply frequency. To understand the concept of harmonics distortion we begin by considering a simple linear circuit having a linear load that draws a linear current through the line assumed to have only resistance. See Figure 3.1.

The current flowing through the circuitry follows from the applied voltage described by the frequency and amplitude. For linear systems, the frequency of the current is assumed to be constant provided the load consists of only resistive components. Sources of harmonics in power system networks are not uncommonly identified as these are peculiar and unique problems arising mostly from the use of power electronic equipment operating through electronic switching i.e. through the use of SMP supplies.

Figure 3.1: Undistorted single phase system
Again we consider another system consisting of a perfectly sinusoidal voltage source and having a load that draws a non-linear current through the line having some impedance. The voltage-current relationship is no longer linear thus, ohm’s law that says the current drawn by a load is proportional to the applied voltage no longer holds. This non-linear voltage-current relationship arises as a result of interaction of the line impedance and the load impedance. Figure 3.2 illustrates the current waveform through the circuitry.

![Current waveform in distorted single phase system](image)

**Figure 3.2: Current waveform in distorted single phase system**

### 3.2.4 SOURCE OF HARMONICS IN POWER SYSTEMS

In the 1920s distortions in the form of harmonics were initially thought to be associated with the use of valves. Heavy industrial equipment and processes such as industrial equipment were known to be one of the main contributors of harmonic distortion. Harmonic distortions are now not only linked to industrial loads but also with commercial and residential loads using switching mode power supplies e.g. PCs, uninterruptible power supplies (UPS) etc. These devices draw harmonics current with an identifiable spectrum; currents drawn by harmonics sources are odd multiples of the fundamental. It was proven that even harmonics cancel each other out in the spectrum. Inter-harmonics and sub-harmonics are also known to be present in a network with the use of certain equipment. Major sources of harmonics in power system networks are listed below [21]:

- Transformers
- Rotation machines
- Converters
- Variable frequency drives
- Fluorescent lamps
- Electric furnaces

Harmonics levels generated by different appliances vary as a result of the type and nature of the appliance. A study of the harmonics generated by LED lamps indicates that harmonics levels generated by the LED lamps from different manufacturers differ. Figure 3.1 [22] shows the different harmonics levels generated in an average home.

Figure 3.3: Different harmonics levels generated in an average home

3.2.5 EFFECTS OF HARMONIC DISTORTION

Harmonics as discussed in the above sections can sometimes have disastrous effects when the magnitude exceeds acceptable value or more than equipment operational ratings. In a distribution system, harmonic current adds to the fundamental components to increase the losses in the wires, in transformers and also increase losses of capacitor banks used for power factor correction. Losses due to heat also increase if harmonics are present in the network. Some of the main effects of harmonics in a system include among others:
- Resonance effect occurs if harmonics are present in a system.
- Harmonics lower the power factor resulting in problems with the quality of supply.
- In a poly-phase system, excessive neutral current flow through the neutral conductor is experienced due to the presence of harmonics, an undesirable effect.
- Telecommunication signal and power electronic equipment(s) are affected by interference caused by harmonics.
- Insulation stress levels increase when harmonics are present.
- Line losses, heating losses in conductors and equipment and transformer losses are increased when harmonics are present.
- Harmonics can also increase losses in a system where capacitor banks are installed for power factor correction.

3.2.6 MEASURE OF HARMONIC DISTORTION

Of importance is the degree of distortion in a system that will cause equipment failure or malfunction and also performance of such equipment when harmonics are present. The first of the effects of harmonics mentioned above i.e., equipment susceptibility and the second performance of equipment that affects supply are linked to voltage and current distortion respectively. The harmonics contents of a voltage and or current waveform is measured by the Total Harmonic Distortion (THD) of the system or the notch test.

The THD method is the most widely used and preferred method of determining the presence of harmonics in a system. This part of the work discusses only THD as the most widely used method to measure harmonics. THD is defined for two cases:

- THD in voltage and
- THD in current.

The THD in the voltage is defined as the ratio of the harmonic component of the voltage to the fundamental component of the voltage. The THD in the current is defined as the ratio of the harmonic component of the current to the fundamental component of the current.
Just as important as the presence of distortion in a system is the measure of distortion in the system. From a compensation point of view it is worth knowing how much distortion is present in a system. From the definition of current and voltage harmonics, it follows that the THD [6] in a system is given by:

\[
\begin{align*}
\text{THD}_I &= \frac{I_n}{I_F} = \sqrt{\frac{\sum_{h=1}^\infty I_h^2}{I_F^2}} \quad \text{..................................................(3.1a)} \\
\text{THD}_V &= \frac{V_n}{V_F} = \sqrt{\frac{\sum_{h=1}^\infty V_h^2}{V_F^2}} \quad \text{..................................................(3.1b)}
\end{align*}
\]

Acceptable levels of harmonics are based on the IEEE and IEC (for utilities and consumers operating within the European countries). Adherence to and operating within the acceptable levels of how much harmonics can be produced by the consumer and can be found in the voltage supplied by the utility which is governed by the IEEE 519-1992 [23] and IEEE 519-1998 [24] the most recent harmonic standard. In South Africa, NRS 048 [25] governs the harmonics level that can be produced by a consumer and injected into the power system grid. The local and international standards both govern the maximum amount of harmonics that can be produced and injected into the network by the consumer load(s) and the maximum amount of harmonics that can be present in the voltage as supplied by the utility company, measured at the interface between both parties. The standards were developed to accommodate the increasing use of industrial loads that draw non-linear currents which in turn produce harmonics in the system and also to provide an acceptable and convenient way of dealing with harmonics in power system networks between the utilities and the consumers.

The THD is often expressed in percentages. Equations 3.1a and 3.1b are used to calculate the THD is a system. For the numerical example, the THD\(_V\) and THD\(_I\) are calculated as 6.25% and 1.05% respectively. The IEEE has set the standard and measure of acceptable harmonics levels in systems. Maximum acceptable harmonic levels must fall within the values as indicated by IEEE-519:1992 [8].
3.2.7 SOLUTION TO HARMONIC DISTORTION

Harmonics in a power system network often result in considerable damage to equipment, reduction of power factor i.e. reduces the quality of power supply to the consumers and is also responsible for undesirable current in the neutral path as shown using the example. The use of filters helps reduce harmonics to a certain extent, although filters do not provide a complete solution to eliminate harmonics but helps reduce it to an acceptable level.

Harmonic filters are classified as either active filters, passive filters or a combination of both depending on the amount of compensation required. Combinations of passive and active filters are known to provide better solutions to suppressing harmonics in power system networks. The use of harmonic filters to reduce harmonic distortion in networks is subject to the end user requirement(s) and acceptable codes of conduct as dictated by the relevant standard i.e. the IEEE and IEC standards that govern the utility and consumer with regard to acceptable harmonic levels. The following factors are to be considered when using or designing harmonic filters:

- Degree of compensation required;
- Application and size of harmonic filter required;
- Response of filter to the dynamics of power system network and
- Effects of the filter on the quality of supply i.e. power factor consideration and resonance effect that might occur as a result of the filtering.

3.3 POWER CALCULATION IN DISTORTED SYSTEMS [2]

It was mentioned in the preceding section that harmonics result when non-sinusoidal currents are drawn by loads in alternating current circuits resulting in distortion of the voltage waveforms. Harmonic frequencies are a simple multiple of the fundamental frequency. The waveform repeats at certain periods hence they are considered to be periodic. The analysis of the distortions in a system is often achieved in the frequency domain. Since harmonics are periodic, its best analysed using the Fourier analysis provided the Fourier components can be determined. Using the Fourier analysis method, it is assumed that the distorted voltage and current signal converge with a period $2\pi$. Hence the voltage and current sinusoid can be represented by
\[ v(t) = V_0 + \sum_{n=1}^{\infty} V_n \cos(nwt - \alpha_n) \] \hspace{1cm} (3.2a)

\[ i(t) = I_0 + \sum_{n=1}^{\infty} I_n \cos(nwt - \beta_n) \] \hspace{1cm} (3.2b)

\( v(t) \) and \( i(t) \) are the instantaneous voltage and current respectively for \(-\infty < t < +\infty\).

The instantaneous voltage and current given above are the time varying signal, thus also are the harmonics associated with it. From a signal analysis point of view, the Fourier coefficients can be calculated using the equation above provided the following FFT conditions are met:

- The voltage and current signals are stationary;
- The sampling theorem is obeyed. Sampling of the waveform must be done to at least twice its frequency.
- The sampling period is an integer multiples of the fundamental and
- The sampled waveform does not contain inter-harmonics.

With these conditions fulfilled, one can conveniently analyse harmonics content in a waveform. To analyse harmonics using the Fourier method it is assumed that the AC signal is discrete in the frequency domain. Sinusoidal waveforms of specific amplitude and frequency are represented by the Fourier component, and sometimes DC components are also present. The fundamental component is the harmonic order 1. Components of higher orders are the referred to as harmonics components. The sinusoidal signal is the sum of the individual harmonics waveform in the time domain. Often the harmonic orders are considered separately with calculations based on the individual harmonic orders.

The analysis to follow assumes the reader has gone through the introductory chapter and is familiar with the basic concepts and terminologies of power systems, especially in the case as applicable to a single phase system (see section for background of power definitions and concepts). For a sinusoidal single phase system with distortion, the basic power theory still applies but with modifications.
The r.m.s. voltage/current consists of the fundamental and harmonic components. The r.m.s. values for the voltage and current can be computed using equation 3.3a and 3.3b.

\[ V^2 = V_F^2 + V_H^2 \]  \hspace{1cm} (3.3a)
\[ I^2 = I_F^2 + I_H^2 \]  \hspace{1cm} (3.3b)

Where, \( V_H^2 = \sum_{h \neq 1} V_h^2 \), \( I_H^2 = \sum_{h \neq 1} I_h^2 \)

In the equation above and sections to follow, \( F \) and \( H \) denote the fundamental and harmonic components of the waveform respectively. The power factor value affects the active and reactive power calculation. The power factor is calculated from the active power and the apparent power. To do this, it is worth reviewing the basic active and apparent power definitions. Reactive power is not the focus of this chapter and will therefore receive less discussion. For analysis and convenience, the active power and apparent power definitions are repeated here.

### 3.3.1 ACTIVE POWER

The active power delivered to non-linear load is defined to include the harmonic component as present in the voltage and or current waveform. We define the total active power delivered to the load as the product of the r.m.s. voltage, the r.m.s. current and cosine of the phase angle between the voltage and the current waveform. The cosine of the phase angles between the voltage and the current waveform is the power factor. However, when effects of harmonics are taken into account, the power factor should be expressed as the “true power factor”.

The active power (P) definition says that

\[
P = V. I. \cos \theta = \sqrt{(V_F^2 + V_H^2)} \cdot \sqrt{(I_F^2 + I_H^2)} \cdot \cos \theta
\]

\[
= (V_F^2 \cdot I_F^2 + V_F^2 \cdot I_H^2 + V_H^2 \cdot I_F^2 + V_H^2 \cdot I_H^2) \cdot \cos \theta
\]

\[
= (S_F + S_H + D_I + D_V) \cdot \cos \theta \hspace{1cm} \text{.......................... (3.4)}
\]
3.3.2 APPARENT POWER

Apparent power definition:

\[ S^2 = V^2.I^2 \]

\[ S^2 = (V_F^2 + V_H^2)(I_F^2 + I_H^2) \]

\[ = V_F^2.I_F^2 + V_F^2.I_H^2 + V_H^2.I_F^2 + V_H^2.I_H^2 \]

\[ = S_F + S_H + D_I + D_V \]

\[ S = \sqrt{S_F^2 + S_H^2 + D_I^2 + D_V^2} \] \hspace{1cm} (3.5)

Where,

\[ S_F = V_F.I_F \quad , \quad S_H = V_F.I_H \quad , \quad D_I = V_F.I_H \quad \text{and} \quad D_V = V_H.I_F \]

In the above expressions \( S_F; S_H; \) \( D_I; \) and \( D_V \) are the fundamental apparent power, harmonic apparent power, current distortion power and voltage distortion power respectively. The sum of the harmonic apparent power, current distortion power and voltage distortion power is the non-active power \( S_N. \)

3.3.3 POWER FACTOR

As discussed in the preceding sections, the power factor is a measure of the utilization of the supply system, the definition for an undistorted single phase system raises no debate. For the system considered the power factor when there are no harmonics, is essentially calculated by dividing the total active power by the system apparent power. For the system, the instantaneous voltage and current is given by equation 3.6a and 3.6b. Equation 3.6b shows that the current lags the voltage by \(-30^\circ\). The power factor is the phase shift between the voltage and the current. In this case the power factor is 0.87 i.e. cosine of the angle between the voltage and the current i.e. \(\cos 30^\circ\).

\[ v(t) = \sqrt{2}(100\sin\omega t) \] \hspace{1cm} (3.6a)

\[ i(t) = \sqrt{2}[60\sin(\omega t - 30^\circ)] \] \hspace{1cm} (3.6b)
3.3.4 TRUE POWER FACTOR

The definition of the power factor remains the same as those in the sinusoidal system or undistorted system. It is defined as the “ratio of the active power supplied to the load to the maximum output power supplied to the receiving end of the line for a constant line power loss and a constant load r.m.s. voltage and waveform” [2].

Recall that the active power supplied to a load in a distorted system consists of the active fundamental power and the active harmonic power. The total active power including the effect of harmonics is expressed as

\[ P = P_F + P_H \] .......................................................... (3.7)

\[ P_F = I_F V_F \cos \theta_F \] ................................................... (3.8)

\[ P_H = I_{H_3} V_{H_3} \cos \theta_{H_3} + I_{H_5} V_{H_5} \cos \theta_{H_5} \] ................................................... (3.9)

Where, \( \theta_{H_3} = \alpha_3 - \beta_3 \), and \( \theta_{H_5} = \alpha_5 - \beta_5 \)

The power factor is expressed as true “power factor” when there is harmonic distortion in the system.

\[ \theta_T = \frac{p}{s} = \frac{p_F + p_H}{\sqrt{s_F^2 + s_N^2}} \] .................................................. (3.10)

\( S_F, S_N \) are fundamental apparent power and non-fundamental apparent power. Both fundamental and non-fundamental apparent powers are functions of the total harmonic distortion in the system. For simplicity we consider the fundamental, the third and the fifth being the dominant parts of the waveform in the system. Even harmonics are known to cancel out, therefore only the odd harmonics are considered up to and including the 5\(^{th}\) harmonics.

We used the same example as in the previous chapter to analyse and compute the power factor in a system with harmonics. The sinusoidal voltage and current are given as follows:

\[ v(t) = \sqrt{2}[100 \sin \omega t + 15 \sin(3\omega t + 10°) + 20 \sin(7\omega t + 110°)] ........... (3.11a) \]
\[ i(t) = \sqrt{2}[60\sin(\omega t - 30^{\circ}) + 60 \sin(3\omega t + 105^{\circ}) + 20\sin(7\omega t + 204^{\circ})] \ldots \text{(3.11b)} \]

The sinusoid contains the fundamental and harmonic components. From the waveform, the components are calculated as follows:

\[
V_H = \sqrt{V_{H_3}^2 + V_{H_5}^2} = \sqrt{15^2 + 20^2} = 25
\]

\[
I_H = \sqrt{I_{H_3}^2 + I_{H_5}^2} = \sqrt{60^2 + 30^2} = 67.08
\]

\[
P_H = P_{H_3} + P_{H_5} = V_{H_3}I_{H_3}\cos\theta_{H_3} + V_{H_5}I_{H_5}\cos\theta_{H_5}
\]

\[
= 15 \times 60 \times \cos(-95^{\circ}) + 20 \times 30 \times \cos(-94^{\circ}) = -120
\]

\[
S_F = V_F I_F = 100 \times 60 = 6000
\]

\[
S_H = V_H I_H = 25 \times 67.08 = 1677.05
\]

\[
D_I = V_F I_H = 100 \times 67.08 = 6708 \quad \text{and}
\]

\[
D_V = V_H I_F = 25 \times 60 = 1500
\]

Emanuel showed that non-fundamental active power consists of the harmonic power, the distortion power in the current and distortion power in the voltage. Using the expression for these power quantities, the values are determined as follows:

\[
S_N = \sqrt{S_H^2 + D_I^2 + D_V^2} = \sqrt{1677.05^2 + 6708^2 + 1500^2} = 7075.29
\]
Substitute for \( P_F, P_H, S_F \) and \( S_N \) in the true power factor equation

\[
\theta_T = \frac{P_F + P_H}{\sqrt{S_F^2 + S_N^2}}
\]  

(3.12)

\[
\theta_T = \frac{P_F + P_H}{\sqrt{S_F^2 + S_N^2}} = \frac{5196 - 120}{\sqrt{6000^2 + 7075^2}} = 0.5
\]

This approach to calculate the active power in a distorted system is still in agreement with the fundamental definition of active power and effectively includes the use of the “true power factor”. This is unlike the case of an undistorted system where there is a close relationship between the applied voltage and current drawn by the load following the assumption that the waveforms are perfect sinusoids.

For a linear system the power factor calculated by ignoring the effects of harmonics is referred to as displacement power factor. This essentially involves calculating the power factor by dividing the active power by the apparent power, thus assuming that no harmonics are present in the system. However, it should be noted that harmonics influence the power factor to a great extent of approximately 50% was seen in the calculations above and maybe more when other examples are considered.

### 3.3.5 POWER FACTOR CORRECTION

The power factor is an indication of the quality of supply of a power system. As defined in the preceding section, it is defined as the ratio of the total active power to the total apparent power. It is a measure of the utilization of the system. A power factor of unity is optimal but a power factor of 0.5 indicates that the network is underutilized. This underutilization arises because of the harmonics components in the system.

Power system networks with a lower power factor are often compensated to bring the power factor closer to unity. This essentially involves reducing the reactive components of the
power. Unity indicates that the utilization of the system is optimal. One method of power factor compensation is using capacitor banks connected in shunt to bring the power factor close to unity. Power factor correction techniques involving the use of a capacitor bank to bring the power factor close to unity does not only correct the power factor, but also increases the reactive power consumed by the non-linear load drawing harmonic current. Increasing the reactive power is undesirable in a network as this result in power losses and over-heating of the system.

### 3.4 CONCLUSION

Accurate measurements, calculations and reporting of energy consumed by equipment under investigation are of importance in M&V and other engineering projects where energy consumed by connected loads are of importance. When power measurements are to be conducted on power system load, such system should be observed for the type of load i.e. linear or non-linear. This helps in determining the measurement approach, the type of metering equipment required and the energy savings calculation for the M&V exercise, especially when it comes to energy savings reporting.

For distorted single phase systems, like the case of the CFL discussed above, the basic principle and definition of active, reactive, apparent power and power factor still apply but they need to be adjusted to accommodate the distortion in the system. The next chapter uses examples to discuss and analyse the distortion in the form of harmonics for a single phase system. Calculated power quantities will include the effects of harmonics.
4.1 INTRODUCTION
Energy savings are often thought of as the difference between the energy consumption of an existing system compared with the energy consumption of a newly installed system. The energy use of an existing system is referred to as the baseline energy while the energy use of a newly installed system is referred to as the reporting period energy use. The methodology and approaches used by the IPMVP [1] and SANS 50010 [13] are discussed in Chapter 4. Knowing the baseline energy use and reporting period energy use of a particular facility, it is easy to determine the energy savings for that facility. However, it must be mentioned that simply taking the difference between the baseline and post-retrofit energy consumption is not essentially the energy savings, without taking into account other energy driving factors. These energy driving factors influence the energy of such a system.

Determining the baseline and post-retrofit energy use of a facility involves correlating the energy use as a function of relevant energy drivers i.e. energy use is often represented as essentially a mathematical model that truly represents the energy consumption of that facility. This chapter discusses the methodology used by M&V teams to determine baseline energy and actual energy use for a particular facility/plant. Energy use either as baseline or post-retrofit energy are often modelled as a function of the major energy driving factors. Some of the modelling approach and energy models developed for some of the M&V projects that the author has been directly involved in are presented here as part of the dissertation. The scope is limited to lighting, heat pumps and HVAC projects.

4.2 BACKGROUND
Recently, the South African the utility Eskom [26] in conjunction with the South Africa Revenue Service (SARS), has offered rebates to commercial and industrial consumers who demonstrate potential for energy savings in their facilities. To benefit from the rebate programme, there client must prove to the utility that there is a potential for energy savings
by retrofitting their existing system with a more energy efficient one. To do this the M&V teams are contracted by the utility to determine how much energy (kW and kWh) can be saved as a result of replacing the old system with a new one that will bring about reduction in the energy consumed by the client’s facility.

The M&V teams are independent technical auditors contracted to determine the impact as a result of an energy intervention. The method used to determine the energy savings is discussed in Section 4.2. The principle behind the method will also be discussed. The full methodology used for energy savings calculation can be found in the IPMVP.

4.2.1 BACKGROUND ON MEASUREMENT AND VERIFICATION

Measurements and verification involve using measurements to reliably determine actual energy savings created by an energy management programme for a particular facility by following a defined protocol i.e. the IPMVP, SAN50011 etc. [5, 7]. Energy savings determined through M&V activities involve comparing measured energy use before and after implementation of the retrofit, making appropriate adjustments to account for changes that occur during the project phase. The applicable M&V methodology involves comparing the measured energy use before a retrofit takes place and the measured energy use after the retrofit. For example an energy efficient project that involves the replacement of incandescent lamps with energy efficient CFL’s.

4.2.2 PRINCIPLES OF MEASUREMENT AND VERIFICATION

The IPMVP was published by Efficiency Valuation Organisation (EVO) to increase investment in energy and water efficiency, increase demand reduction and renewable energy projects. Benefits associated with using the IPMVP include among others: increasing energy savings, reducing the cost of financing energy efficiency projects, create and improve understanding of energy management as a public tool etc. Adherence to the IPMVP means adhering to the basic M&V principles of

- accuracy,
- completeness,
- conservativeness,
- consistency,
- relevancy and
- transparency.

4.2.3 METHODOLOGY OF MEASUREMENT AND VERIFICATION

Using the concept and methodology according to the IPMVP [11] and SAN 50010 [12], the energy saving \( E_S \) is determined as the difference of the measured baseline energy use and the measured reporting period energy use while making appropriate adjustments. The energy relationship is given by the following equation.

\[
E_S = B - R \pm A \tag{4.1}
\]

Where:

- \( E_S \) is the energy savings or the impact generated as a result of the intervention;
- \( B \) is the baseline period energy use;
- \( R \) is the reporting period energy use;
- \( A \) are the adjustments.

Adjustments in the equation above depend on factors such as change in facility operational cycle, modification of plant or assembly line for an increased/decreased production etc. It should be noted that the measuring period and adjustments differ from project to project, facility to facility, accuracy requirement required to be achieved, duration of the project and most importantly the budget. Activities involved in the M&V process includes [27]:

- Installation, calibration and maintenance of installed meters;
- Data gathering and screening;
- Development of computational methods and estimates;
- Computations/calculations with measured data and
- Reporting, quality assurance and third party verification.
4.3 ENERGY SAVINGS REPORTING

Energy savings reporting in M&V uses two approaches to report energy savings. These approaches take into account the baseline period energy use, the reporting period energy use and adjustment to the energy equations to accommodate tracked changes that might have taken place during the life of the project from when a baseline was developed up to the reporting period. Energy savings according to the IPMVP are reported using the following formats:

- Avoided energy use and
- Normalised savings.

4.3.1 AVOIDED ENERGY USE

Energy savings are generally reported using one of the options listed in Section 4.3. The choice of suitable method depends on a number of factors such as the type of project, metering period, budget etc. The avoided energy use method of energy savings reporting involves reporting energy savings in the reporting period conditions. In this method the pre-retrofit energy/consumption of a particular facility that falls within the measurement boundary is quantified in the reporting period condition i.e. the energy savings as a result of the invention is determined in the reporting period condition relative to what the same plant or facility would have used if it was operating in the current period prior to the retrofit or implementation of the energy conservation measures.

Often, the pre-retrofit energy which essentially is the baseline energy use is adjusted to the reporting period conditions. Hence, the adjustment term in equation 4.1. The adjustment term in the equation not only brings the baseline energy use from its pre-retrofit conditions to the reporting period condition, but also allows to accommodate changes that might have occurred at the plant/facility before the energy savings is reported, for example during metering where some changes might have occurred at the plant e.g. production volume, occupancy, weather etc. This adjustment could be a routine or non-routine adjustment. Using this method, the energy saving equation in 4.1 is rewritten as

\[ E_s = B_{\text{adjusted}} \pm A_{\text{non routine}} - R \] \hspace{1cm} (4.2)
The adjusted baseline in equation 4.2 simply combines the baseline energy use and routine adjustment. This adjusts the baseline energy to reporting period conditions.

4.3.2 NORMALISED SAVINGS

Normalised savings methods of reporting energy savings involve the adjustment of both the baseline energy use and reporting period energy use. Sometimes this adjustment might only be necessary for one of either the baseline energy or the reporting period energy use. Whatever the case may be, the energy use is adjusted to a fixed set of conditions as will be necessary during reporting. The relationship is given as

\[
E_s = (B \pm A_{\text{routine}} \pm A_{\text{non routine}}) - (R \pm A_{\text{routine}} \pm A_{\text{non routine}}) \quad \ldots \ldots \quad (4.3)
\]

It is important to note that adjustment terms in the baseline energy use and the reporting period energy use may differ.

4.4 OPTIONS TO DETERMINE ENERGY SAVINGS

To determine the energy use or energy consumed by a plant, the M&V team uses three approaches as detailed in the IPMVP and the SANS 50010 [13]. Each of the methods used to determine the energy use has its own benefits and shortcomings. The available methods include

- retrofit isolation,
- whole facility measurement and
- calibrated simulations.

4.4.1 RETROFIT ISOLATION [13]

Retrofit isolation involves measuring energy limited to the retrofitted equipment or section of a particular facility. The measurement boundary is narrowed down to the equipment or portion of the facility which is in the Energy Conservation Measure (ECM) field of interest. This method of determining the energy use is mostly used for projects where independent and
static factors are of significant importance. Retrofit isolation is subdivided into two methods. Changes to a facility having direct influence on energy use but which falls outside the measurement boundary are not accounted for under the retrofit isolation method. The retrofit isolation method is classified as

- retrofit isolation – key parameter measurement and
- retrofit isolation – all parameter measurements.

Key parameter measurement involves measuring the key energy driving factor with the measurement boundary as stipulated or agreed in what is referred to as the Measurement and Verification Plan as agreed by the stakeholders before the commencement of retrofit i.e. before a baseline agreement was signed by the stakeholders. Measuring key parameters within the measurement boundary allows for estimation and assumptions based on e.g. pre-retrofit data for baseline energy use. The all parameter method involves the measurement of all the parameters that are energy driving factors within the measurement boundary. Key parameter and all parameter measurements are referred to as Option A and B respectively in the IPMVP.

4.4.2 WHOLE FACILITY MEASUREMENTS

Whole facility measurements involve measuring the energy use of the whole facility using utility meters, sub-meters within the measurement boundary (facility or within that section of the facility where the ECM is taking place. This method takes into account all energy driving factors in the facility or within the measurement boundary. Independent variables e.g. weather, production volume etc. are also measured/determined within the measurement boundary as these have effects on the energy use. Often, the whole facility option involves adjustment to the reporting period condition.

These adjustments are determined using a suitable method e.g. modelling the energy use as a function of the energy driving factors. Modelling the energy use of a facility is explored in this work in the area of lighting, heat pumps and HVAC systems as indicated in Section 4.6.1. Modelling the energy use of facility is not only used to adjust energy use of a facility as applicable to whole facility measurement or Option C method as it is often referred to in the IPMVP. It is also used to determine the baseline energy and the reporting period energy projects that use the retrofit isolation method.
4.4.3 CALIBRATED SIMULATIONS
Calibrated simulations involve simulating the energy use of a facility using a computer simulation package. The method requires that the simulator is experienced. Simulated energy use should match that of actual meter data. This method allows that the whole building energy usage or part thereof be simulated. Simulated energy is often calibrated against a set calibration data for example against 12 months energy data, independent variables etc. for improved accuracy.

4.5 CASE STUDY 1 - LIGHTING SYSTEM
Energy use of a facility that involves only lighting is determined generally using the retrofit isolation and whole building methods. To determine the energy use of a facility, the power consumption of the lighting system involved is often modelled as a function of the supply voltage. The adjustment term in the energy equations mentioned so far, particularly in the whole building retrofit isolation option, is determined using models that predict the relationship between the dependent variable and the independent variables. Modelling energy use as function of the independent variable essentially entails finding mathematical relations that correctly predict the relationship between the dependent variable and the independent variable(s) with error estimates that fall within acceptable values as specified by the IPMVP [1].

In M&V, the dependent variable is energy, for this lighting example, a linear voltage relationship exists between energy and power hence, the power is modelled as a function of the supply voltage. Modelling of the energy use is sometimes used in the retrofit isolation method (Options A&B) and also in the whole facility method to determine the adjustment term. Typical M&V steps for a lighting project include:

1. Obtain samples of old and new fittings.
2. Establish the voltage vs. power curve.
3. Verify numbers from: site visits, invoices and crushing certificates.
4. Verify operating hours from interviews, timer inspections during site visits, meter data etc.
5. Measure voltages during site visits/obtain any available meter data.
A simple model for a lighting project is shown in Figure 4.1. For the example, the dependent variable is the power modelled as function of the independent variable voltage and ignoring all other interactive effects that may have a direct or indirect influence on the measurement. The power consumption is modelled for different operating voltage; the power-voltage relation at different operating voltage is modelled for a specific case as

\[ y = 0.3385x - 27.064 \]  

Where,  
\[ y = \text{Power (W)} \]
\[ x = \text{Voltage (V)} \]

27.064 is the constant term in the model, this represents residual term due to the independent variable in the model. Knowing the operating voltage, it becomes easy to determine the power consumed by the lighting system, hence the energy provided and the operating times of the lighting system are known.

\[ E = \sum P[t] \]  

Figure 4.1 shows the power-voltage relations for the lighting system mentioned above. The power at an operating voltage ranging from 200V to 250V can be determined using the model. In the power-voltage model, the \( R^2 \) value is 0.9983. This indicates that the regression model (often referred to as method of least squares) is a true representation of the relationship between the powers drawn with respect to the voltage levels. The IPMVP dictates that \( R^2 \) value be \( \geq 75\% \) for a model that correlates dependent variables and the independent variables.
4.6 CASE STUDY 2 - HVAC SYSTEM

Building energy use is often modelled as a function of the occupants, the cooling degree days and or heating degree days. The linear regression method is mostly used as it presents an approximate model that suitably correlates the energy use as a function of either the occupants or of the weather conditions. An example of a monthly energy model for typical facility is given in equation 4.6.
\[ E = \alpha \cdot \text{HDD} + \beta \cdot \text{CDD} + \gamma \cdot \text{Occupancy} + k \] ………………………………… (4.6)

In the equation above,

HDD is heating degree days;

CDD is cooling degree days.

The constants \( \alpha, \beta \) are the total specific thermal loss and total specific thermal gain respectively. These terms are measures of the change in the HDD and CDD. \( \gamma \) is the constant adjustment for the occupancy. \( k \) is the constant term that typically represents the base load in kWh.

Modelling energy use as a function of the temperature is classified as follows:

- Heating - during cold weather
- Cooling - during hot weather
- Both heating and cooling

We present two scenarios for building energy use in relation to heating and cooling. Figure 4.2 and 4.3 shows building energy use in response to changes in the indoor temperature. In Figure 4.2, the energy use in region 1 shows that at low building temperature, the energy use is higher than at cooler temperature i.e. the occupants respond to the lower indoor temperature but turning on heating devices to warm up the building. At higher temperature, the occupants respond by turning on cooling devices to heat up the rooms, this can be seen in region 2. Hence, the energy use for the building is represented by the energy-temperature plot in Figure 4.3.
Figure 4.2: Building energy use vs. temperature (heating and cooling)

Figure 4.3 is somewhat similar to Figure 4.2 but with horizontal portion that suggests energy use is fairly stable. This region is an indication that when the building temperatures are bearable to the occupants, no heating or cooling devices are switched on; hence the relationship models the energy use of the building as a function of the temperature.

In some situations only heating or cooling is done in some buildings, the energy use then will correspond to Figure 4.2.
The energy model in equation 4.6 is used when building energy use involves heating and cooling. The energy use desired is often for either cooling or heating. The HDD then becomes zeros when the energy use involves only cooling. The CDD also becomes zero when only heating is of interest. However, it should be noted that every project is unique. Therefore the energy model above should take into account energy driving factors for that building of interest.

![Figure 4.4: Building energy use vs. temperature (all cases)](image)

Modelling the energy use (dependent variables) as a function of the building temperature is a common approach in projects involving HVAC systems. The model, however, should adhere to the IPMVP principles of accuracy, completeness and conservativeness. Modelling energy use should agree with the IPMVP guideline. This guideline dictates that error estimates should fall within a mean bias error (MBE) of ±7% and CV(RMSE) of ±15%:

Before proceeding with discussion on this section, it worth mentioning that every project is unique and as a result there are different energy driving factors that should be accounted for when developing an energy use model for a building or plant. This section discusses proposed M&V plan that was used to develop baseline for a typical HVAC project. It was proposed that the baseline energy model will be developed using quality daily, weekly, or monthly data as supplied by the ESCo that will be independently verified by the M&V team. Occupancy figures as supplied to the M&V team were assumed to be correct. The baseline model correlates the energy use as a function of the energy driving factors e.g. weather data and occupancy of the building under investigation. Energy use of the building was modelled using the baseline energy equations in the section below.
The energy equation for savings determination is stated in a slightly different form. The “would have been energy” in equation 4.7 is essentially the baseline energy in the reporting period condition. The energy saving equation says that the difference between “would have been” energy and post-implementation (actual) energy is the energy savings i.e.

\[
\text{Savings} = \text{"would have been" energy} - \text{actual energy}
\]  

(4.7)

In the equation, the “would have been” energy is the energy that the old system would have used had it been operating under the conditions of the new system; this is called avoided cost (see the IPMVP) or most often referred to as “what the grid sees” (WTGS). The energy consumption of the old system is dependent on weather and occupation levels of the building. Hence the baseline energy or would have been energy is therefore written as a function of the energy driving factors as in equation 2 (occupancy and weather).

\[
E_{\text{Baseline}} = E_{\text{Baseline}}(\text{Weather, Occupancy})
\]  

(4.8)

The case study investigates energy efficiency intervention at a residence where existing electrical geysers were to be retrofitted with energy efficient heat pumps. The new system to be installed was expected to use less energy to meet the service level required at the residence i.e. heating and cooling. The electrical heating element of the geysers in the hostels was to be disconnected and removed permanently. This project was classified as energy efficient (EE) in a commercial type sector. Determining the energy savings as a result of the intervention was the focus of the exercise. To determine the energy savings, the energy use of the existing system and the new system must be determined. The difference of the energy use before and after the intervention after an appropriate adjustment is the energy savings. These savings determined have monetary values thus the need for accurate, consistent and reliable results in the values reported.

The set up consists of block of hostels where electrical geysers are used for heating purposes. Conventional type space heaters and air conditioning units are used in the residences. The proposed new systems are the heat pump that does the heating and cooling for the hostels. To determine the energy savings as a result of retrofitting the existing system with an energy efficient system, the energy use of the old and the new systems must be known. The same methodology applies to determine the pre- and post-retrofit energy use of the building,
Hence, the discussion of the pre-retrofit energy use of the system. Figure 4.5 shows the line diagram of the residence.

![Figure 4.5: One line diagram of residence](image)

Metering equipment was installed for the pre-retrofit condition (same will be done for the post-retrofit condition). Installed metering includes a kW logger that records half-hourly kW data for an indicated period i.e. baseline period. Temperature data for the residence area was acquired from the South African Weather Service for the nearest weather station to the hostel location. Weather data supplied was in hourly intervals for the same period. The management of the residence also supplied the occupancy figures of the hostel from 1980 to date.

With the given information, the objective was to find a correlation of the energy consumption of the residence with the occupancy and average weather temperature. It was expected that the energy use of the residence would be in response to energy driving factors.
The energy parameter for energy use models sometimes involve other driving factors which affect the energy use of that facility. The energy model is therefore designed to cater for these factors. For the example which is being discussed, the baseline energy is still a function of the load type (heating/cooling), the ambient temperature and or the occupancy figure. The relationship shown is between the building energy use and temperature shown in Figures 4.2 to 4.3.

The baseline equation for the client is written as functions of the major energy governing factors i.e.

\[ E_{Baseline} = m_1 \cdot L + m_2 \cdot T_{amb} + m_3 \cdot 0 + k \]  \hspace{1cm} (4.9)

The building energy use is in response to heating and cooling. The baseline energy therefore consists of both heating and cooling factors and a change over point from cooling to heating and vice versa. The change over point describes the load type cooling/heating load. Hence, the load type is accommodated in the baseline equation, as

\[ E_{Baseline} = E_{Baseline}(L, T_{amb}, 0) \]  \hspace{1cm} (4.10)

Where;

- \( L \in (0; 1) \) is the load type.
- \( L=1 \) for \( T_{amb} \leq T_{Crossover} \) being heating;
- \( L=0 \) for \( T_{amb} > T_{Crossover} \) being cooling
- \( T_{amb} \) is the outdoor dry bulb temperature at the hostel and
- \( O \) is the occupancy level of the entire hostel.

In the above expressions, the cooling occurs when the ambient temperature exceeds the cross over temperature. Heating occurs when the ambient temperature falls below the cross over temperature.

Baseline energy is calculated using the baseline equation. Baseline energy can be determined using daily, weekly or monthly data. The choice of data for baseline development depends on
factors such as budget, size of project, accuracy required, metering requirements, amount of data required for baseline development etc. For more information, see the IPMVP. This guideline provides insight on the amount of data required for baseline determination. Energy savings are reported to the utility based on the TOU period. The Megaflex TOU period is used for a typical project. This involves reporting the impact for the identified TOU period with 24 hours period split into 48 half-hourly intervals. Thus, the energy use over a 24 hour period is given as

$$E = 0.5 \sum_{t=0}^{24} P(t)$$ \hspace{1cm} (4.11)

The energy use is derived from the active power consumption at time (t) over a period of 48 half-hours. The energy use for the different period of the TOU for weekday and weekend are written as

$$E_{Weekday} = 0.5 \sum_{t=0}^{24} P[t]_{Weekday}$$ \hspace{1cm} (4.11a)

$$E_{Saturday} = 0.5 \sum_{t=0}^{24} P[t]_{Saturday}$$ \hspace{1cm} (4.11b)

$$E_{Sunday} = 0.5 \sum_{t=0}^{24} P[t]_{Sunday}$$ \hspace{1cm} (4.11c)

$$P[t]_{Weekday}, P[t]_{Saturday}, P[t]_{Sunday}$$ is the electrical power demand in MW for weekday, Saturday and Sunday respectively for each of the 48 half-hours of the day. Reporting energy savings using the avoided cost often requires adjustment of the baseline energy to the reporting period conditions done using the Service Level Adjustment factor (SLA). The SLA is defined as

$$SLA = \frac{"would have been energy"}{aE_{Weekday} + bE_{Saturday} + cE_{Sunday}}$$ \hspace{1cm} (4.12)

Where,

SLA is the service level adjustment,

$$a = \text{number of weekdays in the accumulation period}$$

$$b = \text{number of Saturdays in the accumulation period}$$

$$c = \text{number of Sundays in the accumulation period}$$
The would have been energy is given by

$$E_{Baseline\ adjusted} = m_1 L_{actual} + m_2 T_{amb\ actual} + m_3 O_{actual} + k \ldots \ (4.13)$$

Where, $P[t]_{Weekday}$, $P[t]_{Saturday}$ and $P[t]_{Sunday}$ give the electrical power demand in MW for each of the 48 half-hours of the day. The adjusted baseline profiles are thus given by;

$$P[t]_{Weekday\ Adjusted} = SLA \times P[t]_{Weekday} \ldots \ (4.14a)$$

$$P[t]_{Saturday\ Adjusted} = SLA \times P[t]_{Saturday} \ldots \ (4.14b)$$

$$P[t]_{Sunday\ Adjusted} = SLA \times P[t]_{Sunday} \ldots \ (4.14c)$$

The baseline represents the electricity use of the building before the energy efficiency measures were implemented. The baseline period was from 1 January 2012 to 25 July 2012. To develop the baseline it was necessary to quantify the following:

- The average daily and monthly electric energy;
- The average electric demand profiles for weekdays, Saturdays and Sundays;
- The occupancy for the baseline period.

The same quantities need to be determined after implementation in order to determine savings. The impact of the project is then the difference between the adjusted pre-implementation electricity use and the post-implementation energy use.

The pre-implementation metered data acquired was used in the baseline development. Electric data and hourly temperature data from January to July was received from the client. Of the seven months electric data available, only six months was deemed to be of good quality, hence the baseline period was from 1 January 2011 to July 2011 excluding February.

The summary of the energy consumption, occupancy and average monthly temperature of the hostel is provided in Table 4.2. Average occupancy for summer and winter months are 385 and 473 respectively.
Table 4.2: Baseline demand (kWh) for baseline period

<table>
<thead>
<tr>
<th>Month</th>
<th>Average Monthly Temperature(OC)</th>
<th>Occupancy/Month</th>
<th>Monthly kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-11</td>
<td>19</td>
<td>322</td>
<td>165 653</td>
</tr>
<tr>
<td>Mar-11</td>
<td>18</td>
<td>393</td>
<td>270 263</td>
</tr>
<tr>
<td>Apr-11</td>
<td>14</td>
<td>409</td>
<td>308 791</td>
</tr>
<tr>
<td>May-11</td>
<td>13</td>
<td>448</td>
<td>320 487</td>
</tr>
<tr>
<td>Jun-11</td>
<td>9</td>
<td>462</td>
<td>549 784</td>
</tr>
<tr>
<td>Jul-11</td>
<td>10</td>
<td>483</td>
<td>572 994</td>
</tr>
</tbody>
</table>

4.6.1 ENERGY CONSUMPTION AND OCCUPANCY

Pre-implementation metered data supplied to the M&V team was used in the baseline development. Electric data from January to July was available for baseline development. Of the seven months electric data available, only six months was deemed to be of good quality, hence the baseline period was from 1 January to July 2012 with February excluded. Some missing data for example includes February electric data.

It was noted that some kW data were missing for the month of February. Therefore February was excluded from the baseline even though temperature data was available. Supplied kW data for July was recorded up to the morning of 25 July 2012; kW data was extrapolated to include the remaining days in July. Hence, July kWh were highlighted in Table 4.2. Extrapolating for the remaining seven days improves the accuracy of the model. Figure 4.6 shows the baseline energy as functions of occupancy.

Based on the information received, the monthly energy use was correlated as a function of the occupancy for the same period.
In the model

\[ y = 2.494.4x - 681.756 \quad R^2 = 0.80 \]  \hspace{1cm} (4.15)

\( y \) is the energy consumption,

\( x \) is the occupancy for the indicated period.

In the above model, \( R^2 \) value of 0.80 means that the occupancy explains 80% of the variation in energy. \( R^2 \) is a measure of the extent to which variations in the dependent variable (energy consumption) from its mean value are explained by the regression model. \( R^2 \) value is written mathematically as

\[
R^2 = \frac{\text{Explain variation in } Y}{\text{Total variation in } Y} \hspace{1cm} (4.16)
\]

The above expression is simplified as

\[
R^2 = \frac{\sum(Y_i - \bar{Y})^2}{\sum(Y_i - \bar{Y})^2} \hspace{1cm} (4.17)
\]

Where,

\( \bar{Y}_i \) = model predicted energy value for a particular data point using the measured value of the independent variable (i.e. obtained by using the X values in the regression model)
\( \bar{Y} \) = mean of the monthly measured energy values. Mean values are calculated by dividing the total energy by the number of months involved.

\( Y_i \) = actual observed monthly energy use

The summary of uncertainty in the model is provided in Table 4.3. CV (RMSE) and MBE for the model are discussed as follows.

CV(RMSE) is referred to as the coefficient of variation of the root mean square error (RMSE). RMSE is a measure of the accuracy of the model used to predict the energy use as a function of independent variable. In this case the independent variable is monthly hostel occupancy.

\[
CV(RMSE) = \frac{SE_{\hat{Y}}}{\bar{Y}} \]

(4.18)

To determine CV(RMSE), the standard error of the estimates must first be determined using equation 4.18

\[
SE_{\hat{Y}} = \sqrt{\frac{\sum(\hat{Y}_i - Y_i)^2}{n-p-1}} \]

(4.19)

Where,

- \( n \) is the number of data points,
- \( p \) is the number of independent variables,
- \( \hat{Y} \) is the predicted energy value from the regression model.

The MBE is used to indicate overall bias in the regression estimates. Positive bias indicates that the regression estimates overstate the actual values and vice versa. MBE is calculated using equation 4.20.

\[
MBE = \frac{\sum(\hat{Y}_i - Y_i)}{n} \]

(4.20)

The IPMVP recommends \( R^2 \) square value to be greater than 0.75, CV(RMSE) ± 15%, MBE of ± 5%.

A summary of the uncertainty in the model is provided in Table 4.3.
<table>
<thead>
<tr>
<th></th>
<th>Actual</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV(RMSE)</td>
<td>22%</td>
<td>± 15%</td>
</tr>
<tr>
<td>MBE</td>
<td>0%</td>
<td>± 5%</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.80</td>
<td>&gt; 0.75</td>
</tr>
</tbody>
</table>

Table 4.3: Baseline model accuracy – energy consumption and occupancy

Figure 4.7 indicates that as the occupancy in the residence increases, the energy consumption increases. Table 4.2 and Figure 4.7 show the occupancy for the different months in the baseline period and the corresponding energy demand for the same period. It can be seen that the occupancy of the hostel increased from about 322 in January to about 483 in July. The energy use is therefore expected to increase due to the increase in the number of occupants in the hostel.

The occupancy level was determined by grouping the number of occupants that sign in (and sign out) to the hostel in a specific month of a particular year from January 1980 to July 2012 into different months of the year, then calculating the occupancy for the months of interest separately. Months of interest are January to July 2012. To determine the occupancy for January 2012 for example, the sum of the occupancy up to and including December 2012 was added to the number of occupants that signed in to the hostel in January 2012.

According to the occupancy information supplied to the M&V team, it was noted that no occupant(s) signed out of the hostel from 1980 to when the information was supplied to the M&V team. This occupancy information cannot be independently verified by the M&V team, therefore it was assumed to be correct.
4.6.2 ENERGY CONSUMPTION AND TEMPERATURE

Table 4.2 shows the energy consumption for the different months in the baseline period and corresponding average monthly temperature. The relationship between the baseline energy demand and average monthly temperature is given in Figure 4.8.

\[ y = -36495x + 875759 \]
\[ R^2 = 0.9014 \]  

\[ y \] is the energy consumption, 
\[ x \] is the average monthly temperature for the indicated period.
In the above models, the $R^2$ value of 0.90 indicates that temperature is a major energy driver. Figure 4.8 shows that the energy use of the hostel is higher at lower temperatures and lower at higher temperatures. This relationship suggests that heating takes place when the temperature is lower. This is borne out by the graph in Figure 4.9. This relationship was discussed in Section 4.6 of this document. Table 4.4 shows the uncertainty in the model.

![Monthly Energy Use (Jan to Jul 2012)](image)

Figure 4.9: Monthly energy consumption for January to July 2012

<table>
<thead>
<tr>
<th></th>
<th>Actual</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV(RMSE)</td>
<td>16%</td>
<td>± 15%</td>
</tr>
<tr>
<td>MBE</td>
<td>0%</td>
<td>± 5%</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.90</td>
<td>&gt; 0.75</td>
</tr>
</tbody>
</table>

Table 4.4: Baseline model accuracy – energy consumption and average monthly temperature

The model meets acceptable $R^2$ and MBE values as dictated by the IPMVP but does not meet CV(RMSE) estimates i.e. CV(RMSE) of ± 15% is recommended by the IPMVP. The last result was to develop a separate baseline for the high demand season (winter period) and lower demand season (summer period) against which the impact will be determined. These separate baselines were developed using the half-hourly kW data supplied to the M&V team.
4.6.3 BASELINE MODEL

The above models did not meet the IPMVP criteria. The model suggests the monthly energy consumption of the hostels change with occupancy and season. Therefore, the baseline model should be developed to represent the energy consumption as a function of the major energy driving factors that correctly model the energy use and also meet the IPMVP criteria. It was therefore decided to develop separate baselines for the low demand season and for the high demand season. The model that meets the required accuracy level is a model that correlates the energy use as a function of occupancy and the season i.e.

\[ E_{Baseline} = E(\text{Occupancy, season}) \]  

The baseline model as a function of hostel occupancy and the season (winter and summer) is written as:

for summer:

\[ E_{Baseline} = N_{BP} \left( \frac{E}{\text{Occupancy}} \right)_{\text{summer}} \text{ if } \text{month}_{BP} \in \{\text{Sept, Oct, \ldots May}\} \] 

or

for winter:

\[ E_{Baseline} = N_{BP} \left( \frac{E}{\text{Occupancy}} \right)_{\text{winter}} \text{ if } \text{month}_{BP} \in \{\text{June, \ldots Aug}\} \]

Where,

- \( E_{Baseline} \) is the adjusted baseline energy
- \( N_{BP} \) is the number of occupants in the baseline period
- BP is the baseline period

The model was developed by multiplying the average of the monthly energy consumption per occupant by the number of occupants in the baseline period. Table 4.2 shows the monthly kWh with January, March, April and May classified as low demand season and June, July classified as high demand season. For clarity, the seasons are classified as:

- Low demand season – for months including September, October to May
- High demand season – for months including June, July, August
Using the occupancy figures and monthly energy consumption (Table 4.2), an example of the modelled energy consumption for January is illustrated as follows:

\[
\begin{align*}
\text{January energy consumption} & = 165,653 \text{kWh} \\
\text{January occupancy} & = 322 \\
\text{January energy consumption per occupant} & = 514.45 \text{kWh}
\end{align*}
\]

In a similar manner the other month’s energy consumption per occupant are 687.69, 754.99, 715.37, 1190.01 and 1186.32 kWh for March, April, May, June and July respectively. The average energy consumption per occupant is 668.13 kWh and 1188.17 kWh for the low demand season and high demand season respectively.

Using the model in equations 4.21a and 4.21b, the modelled energy consumption for January is calculated as follows.

\[
E_{\text{baseline(Jan)}} = \text{Number of occupants in Jan} \times \text{average energy consumption per occupant} \quad \text{..(4.22)}
\]

\[
= 322 \times 668.13 \text{kWh} \\
= 215,136.52 \text{kWh}
\]

In a similar manner, the modelled energy consumption for the other months can be determined. See Table 4.2.

The savings equation at post implementation is therefore the difference between the baseline energy in a particular assessment period and the actual energy of the same assessment period i.e.

For summer (low demand season)

\[
E_{\text{savings}} = N_{AP} \left( \frac{E}{\text{Occupancy}} \right)_{\text{summer}} - E_{\text{Actual if month}}_{AP} \in \{\text{Sept, Oct, ... May}\} \quad \text{..(4.23a)}
\]

Or

For winter (high demand season)

\[
E_{\text{savings}} = N_{AP} \left( \frac{E}{\text{Occupancy}} \right)_{\text{winter}} - E_{\text{Actual if month}}_{AP} \in \{\text{June, ...., Aug}\} \quad \text{..(4.23b)}
\]
The baseline model and the monthly kWh for the baseline period (low demand season and high demand season) is shown in Table 4.5.

<table>
<thead>
<tr>
<th>MONTHLY kWh</th>
<th>MODELLED MONTHLY kWh</th>
<th>OCCUPANCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>165,653</td>
<td>215,136.52</td>
<td>322.00</td>
</tr>
<tr>
<td>270,263</td>
<td>262,573.46</td>
<td>393.00</td>
</tr>
<tr>
<td>308,791</td>
<td>273,263.47</td>
<td>409.00</td>
</tr>
<tr>
<td>320,487</td>
<td>299,320.38</td>
<td>448.00</td>
</tr>
<tr>
<td>549,784</td>
<td>548,933.04</td>
<td>462.00</td>
</tr>
<tr>
<td>572,994</td>
<td>573,884.54</td>
<td>483.00</td>
</tr>
</tbody>
</table>

Table 4.5: Monthly kWh demand and occupancy

The error in the model is given Table 4.6:

<table>
<thead>
<tr>
<th>Actual</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV(RMSE)</td>
<td>10.3% ± 15%</td>
</tr>
<tr>
<td>MBE</td>
<td>-0.67% ± 5%</td>
</tr>
<tr>
<td>R²</td>
<td>0.94 &gt; 0.75</td>
</tr>
</tbody>
</table>

Table 4.6: Baseline model accuracy – baseline energy consumption as functions of occupancy and season

Even though the error of the model relative to the actual measured baseline values for some months is high, overall the model is sufficiently accurate and more accurate than the regression analysis above. As can be seen above, the occupancy and season do not explain all of the variations in energy consumption, but are the two most significant energy drivers. The results from the analysis of the case studies above are presented in Section 4.6.4

4.6.4 AVERAGE DEMAND PROFILES

4.6.4.1 WINTER BASELINE (HIGH SEASON)

<table>
<thead>
<tr>
<th>Weekday (MW)</th>
<th>Morning Off-peak</th>
<th>Morning Standard</th>
<th>Morning Peak</th>
<th>Midday Standard</th>
<th>Evening Peak</th>
<th>Evening Standard</th>
<th>Evening Off-peak</th>
<th>6am-10pm weekdays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Demand</td>
<td>0.730</td>
<td>0.868</td>
<td>0.867</td>
<td>0.780</td>
<td>0.949</td>
<td>0.768</td>
<td>0.700</td>
<td>0.821</td>
</tr>
</tbody>
</table>

Table 4.7: Average weekday baseline demand per TOU period – winter

<table>
<thead>
<tr>
<th>Saturday (MW)</th>
<th>Morning Off-Peak</th>
<th>Morning Standard</th>
<th>Midday Off-Peak</th>
<th>Evening Standard</th>
<th>Evening Off-Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Demand</td>
<td>0.702</td>
<td>0.802</td>
<td>0.799</td>
<td>0.846</td>
<td>0.685</td>
</tr>
</tbody>
</table>

Table 4.8: Average weekend baseline demand per TOU period – winter
Figure 4.7: Average weekday baseline TOU demand – winter

Figure 4.8: Baseline for weekday in winter months

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4.6.4.2 **SUMMER BASELINE (LOW SEASON)**

<table>
<thead>
<tr>
<th></th>
<th>Morning Off-peak</th>
<th>Morning Standard</th>
<th>Morning Peak</th>
<th>Midday Standard</th>
<th>Evening Peak</th>
<th>Evening Standard</th>
<th>Evening Off-peak</th>
<th>6am-10pm weekdays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Demand</td>
<td>0.353</td>
<td>0.460</td>
<td>0.421</td>
<td>0.356</td>
<td>0.489</td>
<td>0.388</td>
<td>0.322</td>
<td>0.396</td>
</tr>
</tbody>
</table>

Table 4.9: Weekday baseline demand per TOU period – summer

<table>
<thead>
<tr>
<th></th>
<th>Morning Off-peak</th>
<th>Morning Standard</th>
<th>Midday Off-peak</th>
<th>Evening Standard</th>
<th>Evening Off-peak</th>
<th>Sunday Off-peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Demand</td>
<td>0.354</td>
<td>0.387</td>
<td>0.367</td>
<td>0.423</td>
<td>0.338</td>
<td>0.356</td>
</tr>
</tbody>
</table>

Table 4.10: Weekend baseline demand per TOU period - summer
The baseline for summer months for weekdays, Saturdays and Sundays is shown in Figure 4.17, 4.18 and 4.19 respectively. These baselines were developed using the electric data supplied to the M&V team for the period January to May 2012 excluding February. Table 4.19 and 4.20 summarises the Megaflex TOU demand for summer months.
Figure 4.13: Baseline for weekdays in summer months

Figure 4.14: Baseline for Saturday in summer months

Figure 4.15: Baseline for Sunday in summer months
4.6.5 BASELINE ASSUMPTIONS

The following assumptions were made in establishing the project baseline:

- Meter data used for the calculation are a correct representation of the residence usage for the period of interest.
- Analysis of the line diagram was deemed to be correct and correctly matches the data supplied for the residence as indicated by the client.
- Occupancy data used for the model are a true reflection of the occupancy at the residences.
- Weather data used for baseline analysis is representative of the weather at the nearest weather location. This weather data is assumed to be applicable to the residences as well.

4.7 CASE STUDY 3 – HYBRID SYSTEM

4.7.1 PROJECT DESCRIPTION

A typical hybrid system that was investigated consists of a hybrid of a heat pump, SWH system backed up by an electric heater. This system was designed to meet the hot water demand to a gymnasium and some office areas of the building concerned. This hybrid system was used to retrofit an existing electric heating system with the aim to meet the increasing demand for hot water at the facility due to building upgrade and expansion. The energy use of the hybrid system was to be determined for impact calculation and a possible rebate from the utility.

The project was sponsored by the utility concerned and was classified as an energy efficiency project for a commercial sector. The project aims at improving the energy efficiency of the hot water system which feeds the gymnasium and office areas of the buildings involved. The improvement to the hot water system was to be achieved by a hybrid of a large solar water heater and heat pump system added to the existing hot water plant without compromising the service level of the facility. The task was to determine the energy consumption of the hybrid system from which the energy savings/impact can be determined. To do this the energy consumption of the existing system was determined and compared with the energy consumption of the new system. The implementation of the project and how the impact was determined is described in the following subsections.
The intervention took place on the hot water system supplying the gymnasium and the office areas. The hot water system was retrofitted with some solar panels and 42 kW heat pumps. The hybrid system was designed to supply 48 000l of hot water per day to the different areas of the building. Before the intervention, the water was heated by a less energy efficient electrical heater in the water cylinders. The water heating is done by the three units involved.

The SWH system heats the water by using the energy acquired by the collector plates. Heating elements serving as a backup for a period of high demand when the temperature falls below certain set temperature also heats the water. The heat pumps also release some heat energy into the water serving as an additional unit to ensure the demand is met. Figure 4.20 illustrates the setup of the supply to the gymnasium and the building. The elements in tank 4 are used as a 3rd stage backup during periods of maintenance or high usage and are set to turn off at 40 degrees Celsius.
4.7.2 BASELINE MODEL

The hybrid system was modelled as functions of the energy driving factors. Energy use of the hybrid system was modelled as a function of the quantity of hot water demand, the efficiency of the plant and weather conditions. The efficiency of the plant depends on the demand for hot water and the ambient temperature. Therefore the efficiency can be modelled as a function of the independent variables, efficiency and the temperature.

\[ n = n(Q, T_{amb}) \] \hspace{1cm} (4.24)

Where \( n \) is the efficiency of the plant at a certain hot water demand level \( Q \) and ambient temperature \( T_{amb} \). Efficiency of the system is defined as the ratio of the output energy to the input energy. The output energy is the energy absorbed by the water being heated while the input energy is the electrical energy used to heat the water. For this case, the efficiency is written as:

\[ n = Q/E \] \hspace{1cm} (4.25)

Where \( E \) is the electric energy input to the system as measured by the electric energy meters.

This is because at low levels of hot water demand the plant losses will be relatively large and at high levels of water demand the losses will be small relative to the thermal energy delivered. Furthermore the efficiency of the plant depends on weather conditions. At low temperatures the efficiency is low hence the losses are higher than during hot weather conditions.

Therefore the electric energy consumption of the plant (pre-implementation) is a function of hot water demand and ambient temperature.

\[ E = E(O,T_{amb}) \] \hspace{1cm} (4.26)

Therefore the baseline data must be correlated with hot water demand and ambient temperature. The model is in the form:

\[ E = m_1 Q + m_2 T_{amb} + C \] \hspace{1cm} (4.27)

In the expression above, the ambient temperature might have little or no effect on the system. This implies that \( m_2 \) is zero, which reduces equation 4.27 to

\[ E = m_1 Q + C \] \hspace{1cm} (4.28)
Post implementation, the adjusted baseline energy use is then given by:

\[ B_{peu} \pm A_b = E(Q_{actual}, T_{ambient}) \]  

(4.29)

4.7.3 BASELINE DEVELOPMENT

The model of the baseline represents the electricity use in the building before the energy efficiency measures are implemented which was for the period, 15 September 2010 to 27 October 2010. To develop the baseline it is important to quantify the following:

- The electric energy and the thermal energy;
- The average electric energy profiles for weekdays, Saturdays and Sundays;
- The outlet temperature (C);
- The inlet temperature (C);
- The daily water usage in litres.

To calculate the thermal energy, water consumption and the difference between outlet temperature and inlet temperature (ΔT) are required. The electric energy is measured using energy meters.

The same quantities need to be determined after implementation in order to determine savings. The “would have been” electricity use can be determined form the calculated post-implementation thermal energy. The impact of the project is then the difference between pre-implementation electricity use and post-implementation energy use.

A summary of the average weekday, water consumption, outlet temperature, inlet temperature, thermal energy delivered and electric energy are tabulated in Table 4.11.

<table>
<thead>
<tr>
<th></th>
<th>Daily Inlet Water Temp (°C)</th>
<th>Daily Outlet Water Temp (°C)</th>
<th>Daily Water Consumption (l)</th>
<th>Daily Electric Energy Used (kWh)</th>
<th>Daily Thermal Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekday Average</td>
<td>20.9</td>
<td>51.4</td>
<td>26284.0</td>
<td>1206.69</td>
<td>914.70</td>
</tr>
</tbody>
</table>

Table 4.11: Average weekday values
4.7.4 RESULTS - DAILY WATER USAGE

4.7.4.1 DAILY OUTLET WATER TEMPERATURE

The outlet water temperature for the period is as shown in Figure 4.21. The maximum value of the outlet water temperature was found to be 55 °C, while the minimum outlet water temperature was found to be 49.5 °C.

![Daily Outlet Water Temperature](image)

Figure 4.16: Average outlet water temperature

4.7.4.2 DAILY INLET WATER TEMPERATURE

The inlet water temperature for the period is as shown in Figure 4.22. The temperature creeps or spikes are caused by backward flow of water inside the tank towards the inlet pipe when there is no water flowing out of the tank. The temperature probe on the inlet pipe then measures the temperature of the inlet water diluted by the hot water from the tank.
4.7.4.3 WATER USAGE

Daily water consumption was found to be as shown in Figure 4.23. The water consumption is higher on weekdays than on weekends.

4.7.5 RESULTS - ELECTRIC ENERGY AND THERMAL ENERGY

Figure 4.24 shows the plot of electric energy against thermal energy. The electric energy represents the energy that is used to heat and deliver hot water while the thermal energy represents the energy delivered by the system. The scatter plot shows that there is a strong correlation between electric energy and the thermal energy as $R^2$ is equal to 0.9875, which is 98.8% and is greater than 75%.

Figure 4.17: Average inlet water temperature

Figure 4.18: Daily water usage
From the plot the following equation was found and it can be used to determine the SLA.

\[
\text{Daily Electric Energy} = 1.0279 \times \text{Thermal Energy} + 264.53 \quad (4.29)
\]

4.7.5.1 **AVERAGE WEEKDAY, SATURDAY AND SUNDAY PROFILES**

Figure 4.25 to Figure 4.27 show the average weekday, Saturday and Sunday half-hourly and TOU profiles. The demand is higher on weekdays than on Saturday and Sunday.
Figure 4.21: Average Saturday profile

Figure 4.22: Average Sunday profile.

Table 4.12 and 4.13 show the average weekday and weekend demand profiles.

Table 4.12: Average weekday demand impact

<table>
<thead>
<tr>
<th></th>
<th>Morning Off-peak</th>
<th>Morning Standard</th>
<th>Morning Peak</th>
<th>Midday Standard</th>
<th>Evening Peak</th>
<th>Evening Standard</th>
<th>Evening Off-peak</th>
<th>24 Hour Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Demand</td>
<td>0.018</td>
<td>0.049</td>
<td>0.079</td>
<td>0.078</td>
<td>0.058</td>
<td>0.023</td>
<td>0.030</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Table 4.13: Average weekend demand impact

<table>
<thead>
<tr>
<th></th>
<th>Morning Off-peak</th>
<th>Morning Standard</th>
<th>Midday Off-peak</th>
<th>Evening Standard</th>
<th>Evening Off-peak</th>
<th>Sunday Off-peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Demand</td>
<td>0.016</td>
<td>0.022</td>
<td>0.016</td>
<td>0.014</td>
<td>0.008</td>
<td>0.012</td>
</tr>
</tbody>
</table>
4.7.6 PROJECT ASSUMPTIONS

The following assumptions were made during the baseline development process:

- The electrical energy meter will only measure the loads (heat pumps, elements, water pumps etc.) associated with hot water production for the duration of the project. (If this changes the M&V team needs to be informed.)

- There will be no changes to the boiler system during the post-implementation phase which will affect its efficiency significantly. If such changes are made (e.g. improving boiler insulation) then the M&V team needs to be informed.

4.8 CONCLUSION

The chapter discussed the methodology used to determine baseline energy and actual energy use for a particular facility/plant. To determine the energy savings a baseline needs to be established against which the impact can be verified. This was presented in the chapter using case studies for some projects. Baseline methodology, however, varies with technology. An appropriate method can be applied provided it conforms with the IPMVP or to SANS50010 or project undertakings in South Africa. Savings determination methods for a harmonics distorted system is discussed in the next chapter.
5.1 INTRODUCTION

Saving energy in today’s environment is very important, calculating the energy saving is also important for a cost and efficiency comparison of two systems. When the system is linear (resistive load) and sinusoidal, the current in the system is always in phase with the voltage for a single phase system. Calculating energy savings is relatively simple when two systems are compared with each other. This is well documented in the IPMVP for energy savings calculation. This is not true for a non-sinusoidal single phase system or multiple phase system having some form of distortion which may have been the result of voltage or current distortion from the load. For example, a non-linear load such as power electronic equipment creates distortion of the voltage and current waveforms in a network [10].

This chapter proposes a way of energy savings calculation by using the IEEE 1459. It is proposed that for a single phase system, only the fundamental active power is used for this calculation as the higher active power harmonics do not contribute to energy savings. This distortion and unbalance in the network pose the question about the quality of supply i.e. the power factor for example. This is a major concern for determining the quality of load and the supply system for a system having more non-linear loads [28]. To start off the fundamental concepts of power and energy and M&V will be discussed when dealing with calculations for a single phase distorted system.

5.2 ENERGY SAVING

5.2.1 UNDISTORTED SINGLE PHASE SYSTEM

Consider a power system network having a sinusoidal voltage source and producing sinusoidal current through the load. Assume that the system is a perfect one, having only resistive components. The voltage and current in the system are in phase and are then said to be in phase with one another. The power/energy calculation in such a system is simple provided that the operating time and conditions are known. The energy is the integral of the
power drawn by the appliance over the period of time. This useful power is referred to as the active power. The active power has a physical fundamental meaning for the case of undistorted systems especially for equipment design and performance evaluation [29]. There is no debate about calculating the active power for a single phase sinusoidal system. For convenience, the active power is the product of the r.m.s. voltage and r.m.s. current and the phase angle between the voltage and the current. This is apparent as the system is linear and no harmonics or inter-harmonics are present. Inter-harmonics are still a debatable issue currently.

\[ v(t) = V \sin(\omega t) \]………………...(5.1)

\[ i(t) = I \sin(\omega t - \theta) \]………………...(5.2)

\[ P = IV \cos\theta \]………………...(5.3)

Using the M&V methodology, energy saving generated as a result of a retrofit is reported using equation 5.1. However, for a non-sinusoidal single phase system, the energy saving or impact reported does not take into account of the presence of harmonics in the system. This can be seen in the case of CFLs mentioned above. The MW saving as a result of the replacement of incandescent lamps with CFLs is simply taken as the difference of the measured MW of the incandescent (before retrofit) and the measured MW of the CFLs (after retrofit) with some adjustments for e.g. operational profile before and after implementation of the energy efficiency projects. Measurements in the laboratory depicted as industrial projects show that the replacement of incandescent lamps with CFLs lead to a reduction in active power consumption, hence a reduction in the loading of the grid commonly “referred to as what the grid sees”. It is concluded that CFLs do indeed save energy [30]. CFLs are known to be energy efficient but they introduce harmonics and hence, harmonic power is associated with the harmonics introduced in the network i.e. from the load to the source.

The energy savings computed as the difference between the measured baseline energy use and the actual energy use take into account the power loss due to the harmonics in the system i.e. the total power consumption of the CFLs is the sum of the fundamental active power plus the harmonic active power. For the purpose of M&V reporting, the approach should have been to report on fundamental active power and ignore the power due to the presence of the harmonics of the CFLs. See Figure 5.1.
5.2.2 DISTORTED SINGLE PHASE SYSTEM

Consider a power system network having a sinusoidal voltage source and producing sinusoidal current through the load. Consider the system to be a distorted system i.e. both voltage and current waveforms are distorted by harmonics which are simple integer multiples of the fundamental frequency. The non-linear system can be decomposed into discrete systems with harmonic frequencies by using the Fast Fourier transform (FFT) analysis. Using the FFT method, the non-linear system is decomposed into a series of networks with fundamental components and harmonic components. The decomposed network can be analysed separately. Linear superposition of the decomposed single frequency is the overall response of the system. A simple non-linear system is discussed as follows.

Let the source voltage be \( v(t) \) and the current through the circuitry to the load be \( i(t) \). For simplicity, we consider the waveforms to have harmonics up to the fifth harmonics.

\[
\begin{align*}
v(t) &= V_F \sin \omega t + V_{H_3} \sin(\omega t + \alpha_3) + V_{H_5} \sin(\omega t + \alpha_5) \ldots (5.4) \\
i(t) &= I_F \sin(\omega t - \beta_F) + I_{H_3} \sin(3\omega t + \alpha_3 - \beta_3) + I_{H_5} \sin(5\omega t + \alpha_5 - \beta_5) \ldots (5.5)
\end{align*}
\]

The r.m.s. value of the voltage and current are

\[
V = \sqrt{V_F^2 + V_{H_3}^2 + V_{H_5}^2} \ldots (5.6a)
\]
\[ I = \sqrt{I_F^2 + I_{H_3}^2 + I_{H_5}^2} \] .................................................. (5.6b)

Hence, the apparent power is

\[ S = VI = \sqrt{V_F^2 + V_{H_3}^2 + V_{H_5}^2} \cdot \sqrt{I_F^2 + I_{H_3}^2 + I_{H_5}^2} \] .................................................. (5.7)

Consider the case where, the power delivered to the load includes the fundamental and the harmonic contents. The fundamental active power delivered to the same load is given by

\[ P_F = I_F V_F \cos \theta_F \] .................................................. (5.8a)

Where, \( I_F \) and \( V_F \), are the fundamental current and fundamental voltage respectively. \( \theta_F \) is the fundamental phase angle between the fundamental voltage and fundamental current.

\[ \theta_F = \alpha_F - \alpha_F \] .................................................. (5.8b)

A similar analogy applies to the harmonics components. In this case the third and the fifth harmonics are considered. The active harmonic power component is the sum of the third active harmonic power and the fifth active harmonic power. Hence, the total active harmonic power is given by:

\[ P_H = V_{H_3} I_{H_3} \cos(\alpha_3 - \beta_3) + V_{H_5} I_{H_5} \cos(\alpha_5 - \beta_5) \] .................................................. (5.9)

Where \( \alpha_3 - \beta_3 \) and \( \alpha_5 - \beta_5 \) are the phase angle of the harmonic active voltage and the harmonic active current for the third and the fifth harmonics respectively.

The total active power in the presence of harmonics is therefore the sum of the active power in the fundamental and that in the harmonic content. Harmonic contents are to include the third and the fifth harmonics. Hence the \( P_{TOTAL} \) is given by

\[ P_{TOTAL} = P_F + P_H \] .................................................. (5.10a)

\[ P_{TOTAL} = I_F V_F \cos \theta_F + V_{H_3} I_{H_3} \cos(\alpha_3 - \beta_3) + V_{H_5} I_{H_5} \cos(\alpha_5 - \beta_5) \] .... (5.10b)
5.2.3 NUMERICAL ILLUSTRATION

Consider again voltage source $v(t)$ producing a sinusoidal current $i(t)$ through a given load and also consider this voltage and current sinusoid as having the fundamental and harmonic components

\[ v(t) = \sqrt{2}[100\sin \omega t + 15\sin(3\omega t + 10^\circ) + 20\sin(7\omega t + 110^\circ)] \] ......... (5.11a)

\[ i(t) = \sqrt{2}[60\sin(\omega t - 30^\circ) + 60\sin(3\omega t + 105^\circ) + 20\sin(7\omega t + 204^\circ)] \] … (5.11b)

The voltage, current amplitude and the phase angle of $v(t)$, $i(t)$ are tabulated in Table 5.1.

Using the numerical illustration above, the fundamental active power and the harmonic active power are calculated as follows:

\[ P_F = I_F V_F \cos \theta_F = 60 \times 100 \times \cos 30^\circ = 5196 \text{ W} \]

\[ P_3 = I_{H3} V_{H3} \cos(\alpha_3 - \beta_3) = 60 \times 15 \cos(-95^\circ) = -78 \text{ W} \]

\[ P_5 = I_{H5} V_{H5} \cos(\alpha_5 - \beta_5) = 20 \times 30 \cos(-94^\circ) = -42 \text{ W} \]

\[ P_H = P_3 + P_5 = -78 \text{ W} - 42 \text{ W} = -120 \text{ W} \]

\[ P_{TOTAL} = P_F + P_H = 5196 \text{ W} - 120 \text{ W} = 5076 \text{ W} \]

<table>
<thead>
<tr>
<th></th>
<th>Voltage(V)</th>
<th>Current(A)</th>
<th>Phase Angle(\theta)</th>
<th>Active Power(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUNDAMENTAL</td>
<td>100</td>
<td>60</td>
<td>30^\circ</td>
<td>5196</td>
</tr>
<tr>
<td>3RD HARMONICS</td>
<td>15</td>
<td>60</td>
<td>-95^\circ</td>
<td>-78</td>
</tr>
<tr>
<td>5TH HARMONICS</td>
<td>20</td>
<td>30</td>
<td>-94^\circ</td>
<td>-42</td>
</tr>
</tbody>
</table>

Table 5.1: Fundamental and harmonics components of voltage and current waveforms

From the calculation, the harmonic power contribution is negative. This implies that the total active power is less than what it should be in the absence of harmonics. It also implies that the active fundamental power is more than the total active power. For this numerical example, the fundamental active power is 5196W, the total power is 5076.
<table>
<thead>
<tr>
<th>Harmonic Type</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>3\textsuperscript{rd} Harmonics</td>
<td>-78</td>
<td>78</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>5\textsuperscript{th} Harmonics</td>
<td>-42</td>
<td>42</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5.2: a, b, c, d – Energy use after intervention – four possible scenarios

Harmonic power contribution in a system can be negative or positive, sometimes they cancel both not in all cases. This implies that the total active power when harmonics are present in a system can be less or more than the fundamental active power. For this numerical example, the fundamental active power is 5196W, the total power is 5076.

This approach to calculate the active power in a distorted system is still in agreement with the fundamental definition of active power and effectively includes the use of the “true power factor”. This is unlike the case of an undistorted system where there is a close relationship between the applied voltage and current drawn by the load following the assumption that the waveforms are perfect sinusoids.

5.3 ENERGY SAVINGS CALCULATIONS IN A SINGLE PHASE SYSTEM

In a M&V exercise what matters to the utility, the client and the ESCo’s are the energy savings determined without compromisin the service levels of the facility. The question therefore is that for metering equipment, designed to measure active power for non-sinusoidal single phase system or one phase of distorted poly-phase system, “what should the meter read when plugged-in to take power measurements and what should M&V report as the energy savings”?

Due to the presence of harmonics in a system, we present the energy savings reporting for a facility with measured baseline energy and also consider four different scenarios when calculating the energy. Power measurement for the baseline period is used to determine the baseline energy at the start of an M&V intervention. The reporting period energy is calculated from the reporting period measured power. The measured power consists of the fundamental active power, active harmonic power for the third and the fifth harmonic with
the assumption that higher order harmonics have a negligible influence on the total power. Measured power for the baseline period and the post-retrofit period are presented in Table 5.3.

<table>
<thead>
<tr>
<th></th>
<th>Energy use before</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_F$</td>
<td>5196</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>$P_3$</td>
<td>-78</td>
<td>-78</td>
<td>78</td>
<td>0</td>
<td>-200</td>
</tr>
<tr>
<td>$P_5$</td>
<td>-42</td>
<td>-42</td>
<td>42</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>$P_{TOTAL}$</td>
<td>5076</td>
<td>2880</td>
<td>3120</td>
<td>3000</td>
<td>2700</td>
</tr>
</tbody>
</table>

**Saving Calculations:**

<table>
<thead>
<tr>
<th></th>
<th>$P_F$</th>
<th>$P_{TOTAL}$</th>
<th>$P_F$</th>
<th>$P_{TOTAL}$</th>
<th>$P_F$</th>
<th>$P_{TOTAL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_F$</td>
<td>2196</td>
<td>2196</td>
<td>2196</td>
<td>2196</td>
<td>2196</td>
<td>2196</td>
</tr>
<tr>
<td>$P_{TOTAL}$</td>
<td>2196</td>
<td>1956</td>
<td>2076</td>
<td>2376</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference in Watt</td>
<td>0</td>
<td>240</td>
<td>120</td>
<td>-180</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3: Calculated energy savings

Scenario 1 is measured power with third and fifth harmonics having -78W and -42W respectively. Scenario 2 has 78W and 42W for the same third and fifth harmonics. Scenario 3 has no harmonic components. Scenario 4 has -200W and -100W for third and fifth harmonics.

From Table 5.3 it is evident that the fundamental active power is the same for all the scenarios, although the total power differs. These differences in the total power raise questions about the accuracy of energy saving reported for an M&V exercise noting that the reported savings have monetary values. Comparing the energy use before retrofit and Scenario 1, the harmonic content cancels out. For energy use before retrofit and Scenario 2, 3 and 4 the harmonic contents add up and do not cancel out. Therefore, the question is what should be recorded as the power measured during an M&V exercise where every Watt counts. It is proposed that the IEEE 1459 fundamental active power is used only in energy calculation in the presence of harmonics.

It is important to note that harmonics can be either from the load or the source as the sign indicates that in Table 5.3. The negative sign implies harmonics originate from load while the positive implies that harmonics originate from the source.
5.4 DISCUSSION OF RESULTS
The analysis above indicated that harmonics influence the total active power of a system, hence the energy as well. In M&V, reported energy savings have monetary values and implications. The IPMVP was developed to provide a means of determining energy savings and promoting investment in the energy sectors. It was shown that the total active power drawn by a system with harmonics is not a true representation of the active power that should be used for energy savings calculations. Traditionally, the total active power is often calculated using the measured power quantities i.e. voltage, current and power factor or is measured directly by metering equipment. The design of metering equipment is based on the traditional fundamental definitions which do not essentially take into account power losses (or additions) due to harmonics in the system. It can be seen from the example that the total active power drawn by equipment whose voltage-current relationship is non-linear might be greater or less than the fundamental power.

With these illustrations and reflecting back on adherence to the IPMVP it implies that using the total active power to calculate energy savings when there are harmonics in the system jeopardises the IPMVP principles of accuracy, completeness, conservativeness and consistency.

5.5 CONCLUSION
This chapter discussed the effects of harmonics in a single phase system and methodology of how improved accuracy can be achieved in reporting energy savings by M&V teams using the IPMVP and IEEE 1459. This is an approach that can be incorporated into the IPMVP for improved and more accurate energy saving reporting.

The inclusion of the effects of harmonics in energy savings calculations result in more accurate results as was shown in this chapter. It was shown that the influence of harmonics in a system can lead to under/over reporting of energy savings. This chapter therefore proposes that only fundamental active power is used for energy saving calculations as the higher order active power harmonics do not contribute towards energy savings. It is also arguable that energy billing of the consumers by their respective utilities should be done using the fundamental components only by ignoring the power/energy due to the harmonics.
6.1 INTRODUCTION

The basic principle of the IPMVP is that reported energy savings must be accurate and correct. Reporting accurately and correctly means that a certain level of accuracy is required when doing measurements and verification. The case study in Chapter 4 discussed the methodology used to correlate the energy use of a plant as a function of the energy governing factors. It was noted that energy models used to correlate the relationship between the dependent variable and independent variable(s) must adhere to the IPMVP principles. Meeting the accuracy level as specified by the IPMVP alone says that the energy model is good enough for energy savings reporting. However, improvements can be made in the reported energy savings by increasing the accuracy level of such model i.e. by the inclusion of the uncertainty level in the values reported.

Modelling the energy use of plant is based on data acquired by metering equipment. As mentioned in Chapter 3, power measuring equipment is affected by harmonics. It is also arguable that measuring equipment introduces certain errors in the values reported. This error is known as instrumental error or measurement errors. Instrumental error is known to be higher for small and cheaper power measuring equipment and small for more expensive or sophisticated equipment. Modelling errors and sampling errors can also be a player when reporting energy savings which lead to either over reporting or under reporting of the energy savings.

6.2 ACCURACY OF ENERGY SAVINGS REPORTED

Energy savings are not measured; it is computed between two known energy values i.e. the difference between the baseline energy use and actual energy use. The energy use, both baseline and actual or post-implementation energy use is the result of power measurement over time. As discussed in Chapter 5 that power measuring equipment is subjected to effects such as harmonics. Harmonics are not the only contributing factor to the inaccuracy of
measured power, the power instruments themselves operate by estimates of the values being measured. Reported energy savings therefore should be reported within certain levels of accuracy as measured values could fall within a certain bracket around the mean values as measured by the metering equipment. Chapter 3 discussed case studies where the energy savings are reported at an accuracy level. The IPMVP gave certain criteria that energy models must conform with. Experience in the analysis of the data collected during the M&V exercise shows that some analysed data meet certain accuracy levels but do not meet the others as specified by the IPMVP. More discussion on this is presented in this chapter.

The energy use of plant is often modelled as functions of the energy driving factor or a combination thereof. Modelling the energy use as a function of the energy driving factor is the simplest when the independent variable is not more than one. All cases, however, should still adhere to the protocol and the principle of reporting energy savings. Adherence means that reported energy savings must be correct, accurate, persistent etc. It was noted that meeting one of the accuracy levels is not sufficient to say that the model energy use of plant is correct and accurate enough. The $R^2$ value is the simplest method of determining whether the energy model correctly predicts the relationship between the dependent and independent variable(s). It assumes a linear relationship exists between the dependent variable and the independent variable. Sometimes the $R^2$ value criteria are met but not in all cases. This was evident in the case studies presented.

6.3 CONFIDENCE LEVEL AND PRECISION [5]

Reported energy savings should include statements that describe the confidence that values reported are correct to a certain level of probability and precision level. The probability that energy savings reported are correct is referred to as the confidence. However, having a confidence level is incomplete without a precision level. The IPMVP describes confidence as the likelihood or probability that the estimated savings will fall within a certain precision range. Recall that values measured by power measuring equipment makes use of the sampling at a particular instant from which a value output is given as what was being measured. This output is based on the probability distribution of the sample concerned. To obey the IPMVP principle of accuracy, this probability must be quoted with its associated precision level. Precision level is defined as the measure of the absolute or relative range.
within which the true value being measured is expected to occur with some specified level of confidence. Expressed confidence level must be accompanied by the precision statement.

6.4 ERROR AND UNCERTAINTY [5]

Electrical energy savings to be reported must have a reasonable level of uncertainty that must be managed by controlling random errors and possible bias in the data being used. The quality of the measurement equipment, the sampling approach chosen, the assumptions made and method of analysis all come into play and may result in the introduction of errors and uncertainty in reported energy savings. The result of which is a statistical estimate of the expected values that includes some statistical variations using measure of central tendencies (mean, median, mode etc.). The use of the statistical mean, range, standard deviation etc. helps to quantity the level of uncertainty in the reported values. Sources of errors that lead to over/under reporting of energy savings can be classified as

- modelling errors,
- sampling errors and
- measurement errors.

As the name suggests, modelling errors are associated with modelling the energy use as functions of the energy governing factors. Sampling errors are associated with sampling of the parameters to be measured, i.e. using wrong population size or using a biased method of sampling. Measurement error is linked to the errors introduced by the measuring equipment themselves e.g. errors due to inaccurate sensors, drift of the measuring equipment etc. Measurement errors are mostly noticeable when wrong sized metering equipment is used for measurement in ranges that it is not recommended for.

To be accurate and complete, electrical energy savings must be expressed with their associated confidence and precision levels. The confidence in a reported value defined as the likelihood that the reported energy savings, will fall within a certain precision range i.e. the probability that the metered target will fall within a specified range. Precision in reported energy saving is the assessment of the error margin in the values reported. Various analysis methods can be used to check the accuracy of a model. Some of the most common ones are discussed here. It is also important to note is that some methods of checking the accuracy of
models are sometimes more suitable than others. For illustration and application purpose the ones often used in M&V applications are:

- Coefficient of determination;
- Standard error of the estimate;
- T- Statistic.

6.4.1 COEFFICIENT OF DETERMINATION

The preceding section discussed the precision and the uncertainty that must be expressed when energy savings are reported. This method of assessing the accuracy of a model makes use of the \( R^2 \) value based on using the least square as tool to express the relationship between a dependent variable (energy use) as function of the independent variable.

When the energy use of plant or facility is modelled as a function of the independent variable, the \( R^2 \) value is an indication of how the model correctly matches the actual values. This is known as linear regression. The IPMVP dictates that adherence to the protocol requires that the \( R^2 \) value or better is acceptable to say a model is correctly representing the energy use of that plant. The simplest form of the linear regression is the single variable function where the energy use is a function of one variable. Complex forms of the regression analysis results when the energy use is a function of more than one independent variable.

To express the energy use as a function of more than one independent variable involves the use of Excel or a similar package to do the regression. In Excel, the function LINEST is used to correlate the energy use as a function of the independent variables when the energy use to be modelled depends on more than one variable. By developing a multivariable function, the plant energy use is modelled with an associated \( R^2 \) value similar to a single variable function. Meanwhile, the model still needs to conform to the IPMVP requirements. The \( R^2 \) value must still be greater than 75%. A typical model involving the use of the regression method is shown in Figure 6.1.
As can be seen the model meets the IPMVP $R^2$ value criterion of 75% (i.e. 85%). This means the 85% variation in the thermal energy of the change house is explained by the model for the period concerned.

### 6.4.2 STANDARD ERROR OF THE ESTIMATE

The standard error of the estimate is used to check the accuracy of a model that is used to predict the energy value for a given independent variable in the energy model. To use the standard error of the estimate, the RMSE, the CV and a similar measure known as the MBE are calculated to check possible bias in the regression. An example of how to apply this on a model is presented here. The baseline model of Figure 6.1 is used for illustration purposes. The IPMVP recommends that CV(RMSE) and MBE must fall within ±15% and ±7.5% respectively.

### 6.4.3 T-STATISTIC

The T-statistic is used to determine the statistical significance of an estimate. A comparison is made between certain critical t-values from a t-table and the value obtained through the statistical test of the estimate. This test is used because the coefficients as determined through regression models are subjected to some variations of the estimate from the true relationships.
6.5 UNCERTAINTY

In Chapter 5 the power measurements when harmonics are present in a single phase system were discussed. The result of the analysis for the different scenarios is repeated here for easy reference. Using the total power to calculate the energy savings gave different result from when the fundamental power is used. The results also indicated that the energy savings calculation based on the total power can be misleading as the harmonics in the system can lead to under/over reporting of the energy savings. However, ignoring the harmonic components of the system yields better and more accurate results.

A comparison of the two cases when harmonic components are ignored and when harmonic components are included in the energy savings calculation were shown in the Chapter 5. A difference of 10.9% for example is very serious when a comparison is drawn from the energy savings reported when the harmonic component is included in the calculation as opposed to when harmonics are excluded when determining the energy savings. This can also become more serious when such data is to be used to model the energy use as functions of the energy drivers bearing in mind that modelling and sampling also introduce more errors in the values to be reported as the energy savings.

Similar to models presented in Chapter 4, the energy relationship for the typical model is written as

\[
\text{Daily Electric Energy} = 0.0021 \times \text{Daily thermal energy} + 7.3033 \quad \ldots (6.1)
\]

In Chapter 4, the models are presented with the results of the uncertainty involved. In this section, the method used to determine the uncertainty is discussed as follows. Following the IPMVP criteria, the errors and uncertainty in the model are computed using the measured and calculated values. The following are measured:

- Inlet and outlet water temperature;
- Electric demand (kW) used to heat the water over the period;
- Volume of water used by the occupants of the change house.

The above data were recorded at 5 minute intervals. These measured values are then converted from 5 minutes to daily values. The daily electric data is then plotted against the thermal energy calculated by using the relationship
\[ Q = mc\Delta \theta \] .................................................. (6.2)

where:

\( Q \) is the thermal energy,

\( m \) is the mass of the water used in kg,

\( c \) is specific heat capacity of water and

\( \Delta \theta \) is the change in temperature of the water used by the occupants.

The result of the daily thermal and electric energy is shown in Columns 2 and 3 of Table 6.1.

<table>
<thead>
<tr>
<th>Day</th>
<th>Daily Q</th>
<th>kWh</th>
<th>predicted kWh</th>
<th>%error</th>
<th>(predicted-mean)^2</th>
<th>(actual-mean)^2</th>
<th>(Predicted-Actual)^2</th>
<th>Predicted-Actual</th>
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</thead>
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<tr>
<td>Day 1</td>
<td>14021</td>
<td>37</td>
<td>36.75</td>
<td>-0.01</td>
<td>0.55</td>
<td>0.21</td>
<td>0.08</td>
<td>-0.28</td>
</tr>
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<td>Day 2</td>
<td>15865</td>
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<td>40.62</td>
<td>-0.02</td>
<td>9.80</td>
<td>16.07</td>
<td>0.77</td>
<td>-0.88</td>
</tr>
<tr>
<td>Day 3</td>
<td>17332</td>
<td>41</td>
<td>43.70</td>
<td>0.07</td>
<td>38.59</td>
<td>10.02</td>
<td>9.28</td>
<td>3.05</td>
</tr>
<tr>
<td>Day 4</td>
<td>16556</td>
<td>42</td>
<td>42.07</td>
<td>0.00</td>
<td>20.99</td>
<td>19.76</td>
<td>0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>Day 5</td>
<td>16764</td>
<td>42</td>
<td>42.51</td>
<td>0.01</td>
<td>25.19</td>
<td>23.03</td>
<td>0.05</td>
<td>0.22</td>
</tr>
<tr>
<td>Day 6</td>
<td>11816</td>
<td>32</td>
<td>32.12</td>
<td>-0.01</td>
<td>28.88</td>
<td>25.55</td>
<td>0.10</td>
<td>-0.32</td>
</tr>
<tr>
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<td>1830</td>
<td>10</td>
<td>11.15</td>
<td>0.16</td>
<td>693.96</td>
<td>778.81</td>
<td>2.45</td>
<td>1.56</td>
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<td>Day 8</td>
<td>16844</td>
<td>37</td>
<td>42.68</td>
<td>0.15</td>
<td>26.89</td>
<td>0.13</td>
<td>30.72</td>
<td>5.54</td>
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<td>42.37</td>
<td>0.03</td>
<td>23.81</td>
<td>13.36</td>
<td>1.50</td>
<td>1.22</td>
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<td>41.62</td>
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<td>18.69</td>
<td>0.04</td>
<td>-0.19</td>
</tr>
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<td>39.10</td>
<td>-0.08</td>
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<td>10.07</td>
<td>-3.17</td>
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<td>0.18</td>
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<td>1.75</td>
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<td>0.25</td>
<td>39.74</td>
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<td>38.30</td>
<td>16.33</td>
<td>4.61</td>
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</tr>
<tr>
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<td>17517</td>
<td>42</td>
<td>44.09</td>
<td>0.05</td>
<td>43.54</td>
<td>19.87</td>
<td>4.58</td>
<td>2.14</td>
</tr>
<tr>
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<td>43.65</td>
<td>0.05</td>
<td>37.93</td>
<td>15.99</td>
<td>4.67</td>
<td>2.16</td>
</tr>
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<td>40.40</td>
<td>-0.25</td>
<td>8.49</td>
<td>265.36</td>
<td>178.91</td>
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<td>12880</td>
<td>33</td>
<td>34.35</td>
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<td>9.84</td>
<td>16.30</td>
<td>0.81</td>
<td>0.90</td>
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<td>SUM</td>
<td>287877</td>
<td>750</td>
<td>750.61</td>
<td></td>
<td>1799.13</td>
<td>2118.60</td>
<td>324.41</td>
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<td>37</td>
<td>37.53</td>
<td></td>
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</tbody>
</table>

Table 6.1: Error analysis

The uncertainty in the above model is determined as follows:
Mean $\bar{Y}$:

$$\bar{Y} = \frac{\sum Y_i^2}{n} = \frac{750}{20} = 37.5 \text{ kWh}$$

Variance $S^2$:

$$S^2 = \frac{\sum(Y_i - \bar{Y})^2}{n - 1} = \frac{2118.60}{20 - 1} = 111.5 \text{ kWh}$$

Standard Deviation $s$:

$$s = \sqrt{S^2} = \sqrt{111.5} = 10.6 \text{ kWh}$$

Standard Error SE:

$$SE = \frac{s}{n} = \frac{10.6 \text{ kWh}}{20} = 0.53$$

$R^2$ Value:

$$R^2 = \frac{\sum(\bar{Y}_i - \bar{Y})^2}{\sum(Y_i - \bar{Y})^2} = \frac{1799.13}{2118.60} = 0.85$$

Mean Bias Error ($MBE$)

$$MBE = \frac{\sum(\bar{Y}_i - \bar{Y})^2}{n} = \frac{0.82}{20} = 4.1\%$$

Root Mean Square Error ($RMSE$)

$$RMSE = \sqrt{\frac{\sum(\bar{Y}_i - Y_i)^2}{n - P - 1}} = 4.3$$

Coefficient of Root Mean Square Error ($CV$)
\[ CV(RMSE) = \frac{RMSE}{\bar{Y}} = \frac{4.3}{37} = 11.6\% \]

From the statistical tables, t values for 20 entries is 2.09 given that the confidence level expected is 95%, the precision of the model is calculated as follows

Absolute Precision: \[ t \times SE = 2.09 \times 0.53 = 1.11 \]

Relative Precision:

\[ \frac{t \times SE}{\bar{Y}} = 0.029 \]

The precision is a measure of the expectation. The reported values in every savings reported in M&V must carry the accuracy or precision level in the values being reported. To be complete, the mean value of the daily electric data in the above example must read 95% confidence that the true mean-daily electric energy consumption lies in the range between 36.4 and 38.6 i.e. there is 95% confidence that the mean value of the daily energy consumption for the 20 day period is 37.5±2.9%

### 6.6 CONCLUSION

This chapter discussed the need and method of reporting energy savings more accurately. To comply with the IPMVP principles, energy savings reported should include accuracy level in the values being reported. Error analysis and methods of quantifying the uncertainties in energy models presented above can be applied when energy savings are to be reported.

Although, more time and budget is needed when error analysis is to be done for energy projects, but it might be worth the effort. Using the correct sample size reduces sampling errors, using the correct metering equipment improve the confidence levels and modelling errors is reduced by chosen the correct energy governing parameter as the independent variable and checking for the variation with the dependent variables i.e. the energy use.
CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

7.1 INTRODUCTION

The work presented methodology of calculating electrical energy savings in single phase harmonic distorted system. The methodology and approach that can be used to achieve a more credible energy saving result was presented. Case studies using these approaches in M&V were presented. The combination of the fundamental of electric circuits, IPMVP methodology of determining energy saving and the IEEE definitions of electric quantities all combine were applied in this work. The possibilities of achieving more accurate, more reliable and more credible results by incorporating the fundamental IEEE definitions of electrical power quantities into the methodology of reporting energy savings as detailed in the IPMVP and South African National Standard SANS 50010:2011 was also presented. The conclusion and recommendations from the work is presented in section 7.2.

7.2 CONCLUSION AND RECOMMENDATIONS

The preceding chapters discussed a single phase system in the presence of harmonics. The methodology used in M&V to M&V’ed energy efficiency projects was discussed. An example of harmonic distorted systems in single phase system where determinations of the energy used by the system were compared for when the effect of harmonics was included and when it was ignored. Also discussed in the work was the methodology for reporting energy savings. The following conclusions can be inferred from the work:

- In Chapter 4 the case studies were presented on different technologies. The methodology used in M&V according to the IPMVP and SANS 50010 was presented. It was shown that for an energy model to be accurate enough, it must meet the IPMVP criterion which includes $R^2$ square value of $\geq 75\%$, CV (RMSE) of $\pm 15$ and MBE of $\pm 5$ among others. Case studies on the HVAC system show that a model can meet the R2 value criteria but not CV and MBEs. Therefore, for a model to be deemed accurate and correct enough, other IPMVP accuracy criteria should be applied.
Energy saving reporting when harmonics are present in a system should be treated as a special case. The example presented shows that using the total power measured to calculate the energy use of a system/technology is wrong and misleading. This is evident by referring to Chapter 5, where it was shown that the total power measured when harmonics are present in the system is the sum of the power due to the fundamental components of the power and the power due to the harmonic component. Power due to the harmonic component does not contribute to energy savings for when a retrofit is used to replace an existing technology that is less energy efficient. This distortion power, however, does not contribute to energy saving. Moreover, this power may lead to the over/under reporting of power measurement which in turn results in incorrect energy calculations. Emanuel showed in his book [14] that the harmonics components of the power measured constitute what was referred to as distortion power. This can have various consequences in energy efficiency projects where the energy (MWh) or the demand (MW) savings reported has monetary values. This also leads to the next conclusion for that of a poly-phase system.

The methodology used in Chapter 5 for calculating the total power for the single phase system can be extended to poly-phase systems since harmonics do not only affect single phase systems. In Chapter 2 a brief description of a poly-phase system was presented. For energy efficiency projects, the power drawn by the load involved can have harmonic contents. This should also be taken into consideration. The challenge with this is that it might result into more complex calculations and probably increase the cost of the project as more analysis will have to be done.

In Chapter 5 it was shown that the methodology used according to the IPMVP for a single phase system to determine energy savings should be updated to accommodate the harmonic components for the pre- and post-implementation cases. This will ensure that the systems involved in the energy efficiency intervention are correctly represented i.e. a good comparison of the energy use by the two systems (as it is always better to compare apples with apples and not with oranges). Misrepresentation of the energy use of the systems involved in energy efficiency projects obviously might result in disputes among stakeholders. This may be problematic as the concept
of harmonics and its effect on the system could be difficult to explain to those who do not have an engineering background.

- Energy savings should be reported with a certain level of accuracy. In Chapter 6, it was shown that measured active power quantities are estimates of the expected values, therefore reported energy values should include a certain level of accuracy/precision i.e. the likelihood that reported energy values (or MW values) fall within a certain range since there is no certainty that an exact value will be obtained if the measurements are repeated. Reporting energy values (i.e. savings) in M&V can become expensive depending on the nature and accuracy level to be reported. This is so as a designer will have to take into consideration factors like metering selection, methodology, sample size etc. and the cost of doing such should be factored into the budget at the initial design stage. For a multifaceted energy efficiency intervention, uncertainty and accuracy calculations will result in extremely complex mathematical calculations, a larger budget and more time. In the draft document on reporting protocol regarding uncertainty in M&V, 80%/20% criterion is recommended as acceptable uncertainty level [31] in South Africa. However, this will depend on the applications and what is acceptable to the stakeholders. From the international viewpoint, the confidence and precision levels differ depending on application and the standard being applied [32,33,34]. No requirement was set by the IPMVP [5, 33].

7.3 FUTURE WORK

The effect of harmonics in the determination of energy savings was discussed in Chapter 4 for a single phase harmonic distorted system. The same methodology can be extended and applied for a poly-phase system. It is arguable that the extension of the method used in the single phase harmonic distorted to the poly-phase harmonic distorted system will result in increased complexity and issues with design of metering equipment as they are currently designed to measure total power, but may be worth it for completeness and accuracy.
8 REFERENCES


[34] Ontario Power Authority (OPA), Evaluation Measurement & Verification Framework for Ontario Power Authority (OPA) Conservation and Demand Management (CDM) Programs.