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Harmonic management in mv distribution systems

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HARMONIC MANAGEMENT IN MV DISTRIBUTION SYSTEMS

A thesis submitted in fulfilment of the

requirements for the award of the degree

DOCTOR OF PHILOSOPHY

from

UNIVERSITY OF WOLLONGONG

by

DUANE ROBINSON, BE(ELEC)

School of Electrical, Computer and Telecommunications Engineering

2003

To Beverly

Abstract

With many distribution customer loads being sensitive to excessive harmonic voltage distortion, electricity distribution network service providers should now be looking towards preventative measures to ensure that voltage distortion levels remain within limits set by the appropriate standards. Measures will need to be taken at the planning stage to ensure distribution systems are able to meet harmonic limits recommended by standards as distortion due to loads increases. This thesis describes the development of harmonics planning and analysis tools that allow effective system modelling and comparison with standards, particularly in the planning phase where details of loads are usually not accessible.

In this thesis development of statistical harmonic models of residential, commercial and industrial load types to simulate the global behaviour of distorting loads at distribution substations is presented. Both time and phase diversities are included in the representative load models. A method to estimate the 95th percentile cumulative probability level of harmonic voltage distortion in an MV distribution system as required by the present Australian harmonic standard (AS/NZS 61000.3.6) is also developed. Results from a harmonic monitoring programme carried out on a typical MV distribution system are used to establish parameters for the load models and also to confirm the relative accuracy of the proposed distortion level prediction technique.

A generalised method to extend the IEC 61000-3-6 approach of allocating allowable harmonic emissions to the case where customers are distributed along an MV distribution system feeder having significantly different fault levels is presented. The method involves the determination of an 'allocation constant' using the agreed loading

of all customers and the system harmonic impedances. This approach typically requires an extensive amount of data that may not always be available to distribution network service provider engineers. An extension to the method has thus been established to cater for the situation where only limited data is available. This is achieved by looking at several extreme cases that classify the most common MV distribution system feeder configurations and through the use of correction factors for the 'allocation constant'.

Several example systems have been studied to illustrate the harmonic management tools described above. These case studies include identification of the key indicators for harmonic performance of a distribution system.

Certification

I, Duane Robinson, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical, Computer and Telecommunications Engineering at the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualification at any other academic institution.

…………………

Duane Robinson

27 November 2003

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Contents

List of symbols

α	exponent of the second summation law
A_h	Fourier series coefficient for h^{th} harmonic
B_h	Fourier series coefficient for h^{th} harmonic
CBD	central business districts
C_h	magnitude of h^{th} harmonic voltage or current
CP95	cumulative probability 95^{th} percentile
DC	direct current
DNSP	distribution network service provider
E_{Ihi}	allowed harmonic current emission limit of order h for i^{th} consumer
E_{Uhi}	allowed harmonic voltage emission limit of order h for i^{th} consumer
FFT	fast Fourier transform
f	frequency
GDP	gross domestic product
G_{hMV}	global harmonic voltage emission of order h for all loads supplied at MV
h	harmonic order
i	single customer or load
I_h	harmonic current of order h
k	harmonic emission allocation constant
L_{hHV}	harmonic voltage planning level of order h for HV
L_{hMV}	harmonic voltage planning level of order h for MV
MV	medium voltage
n	number of customer PCCs along the weakest feeder only
PCC	point of common coupling of the customer
PFC	power factor correction

r	number of parallel feeders
rms	root mean square
s	circuit segment number
S_{Fj}	total capacity of all loads along j^{th} feeder
S_i	apparent maximum demand of i^{th} customer
S_t	total available power at saturation of the supply system capacity
T	period
TDD	total demand distortion
THD_I	total harmonic current distortion
THD_V	total harmonic voltage distortion
T_{hHM}	HV/MV harmonic voltage transfer coefficient for h^{th} order harmonic
U_h	harmonic voltage of order h
U_{h0}	background harmonic voltage of order h
U_{hi}	harmonic voltage of order h for i^{th} customer
u(t)	periodic function of voltage or current
ψ_h	phase of h^{th} harmonic voltage or current
Z_{hi}	magnitude of h^{th} order harmonic impedance of the distribution system at i^{th} PCC

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Chapter 1

Introduction

1.1 Harmonics in distribution systems

Harmonic distortion has been identified as existing within power systems since the advent of alternating current electricity distribution systems [1]. Harmonic disturbances are also possibly the most researched and published of all the power quality disturbances, especially over the past two decades. The interest in harmonics can largely be attributed to the advancing power electronics usage and growth in the number of new load technologies connected to distribution systems that are sensitive to excessive harmonic voltage levels. The increased penetration of these new technologies is for the most part driven by the desire to have more energy efficient equipment and greater control of equipment operation. Increased efficiency and control typically means the equipment includes some type of semiconductor based power electronic front end. The same new technologies, in general produce increased levels of harmonic current emissions that in turn raise the levels of harmonic voltages existing on the system. In conjunction with this the growing trend of electricity being sold as a product under contractual agreements means that guaranteeing an acceptable level of power quality disturbances is becoming of greater importance to both electricity distribution network service providers (DNSP) and customers alike.

Indications in the literature suggest that harmonic voltage levels in transmission and distribution systems are increasing [2-4]. Increasing levels of voltage harmonics creates a concern for customers with sensitive equipment and also for electricity DNSPs that face increased losses throughout their power systems. The increased losses burden DNSPs with additional costs that have to be recovered to ensure profit margins are not

decreased. There are suggestions by [5] that in Canada and some major European countries the cost of network modifications and losses due to harmonic distortion effects may represent as much as 1% of a country's gross domestic product (GDP).

As stated earlier it is well known that harmonic voltage distortion within power systems is due to the interaction of harmonic current emissions from a variety of sources and the impedance of the power system. The sources of harmonic emissions can include large industrial loads connected at transmission or distribution levels, smaller commercial and residential distribution system customer loads, distributed generation installations, the power system itself, and to a lesser extent traditional generation equipment.

Harmonic current emissions originate from all types of non-linear loads. Non-linear loads are broadly classified as loads which draw non-sinusoidal current even when the supply voltage is perfectly sinusoidal [6]. Non-linear loads include saturated magnetic circuits, such as those in power system transformers and rotating machines, arc furnaces, fluorescent lighting and of course power electronic loads. Power electronic loads by far are the most significant harmonic contributors relative to the amount of energy they draw. Some of the more common power electronic loads include

i) Switch mode power supplies - present in computers, televisions, microprocessors
ii) Rectifiers – present in dc motor drives, regulated power supplies, battery chargers,
iii) Inverters – present in variable speed ac drives,
iv) Static VAr compensators,
v) Cyclo-converters, and
vi) High voltage DC transmission converters.

Mitigation techniques are often required to suppress the levels of harmonic emissions resulting from the above mentioned power electronic equipment.

1.2 Effects and problems caused by harmonics

Harmonic distortion can have both short-term and long-term effects on distribution system equipment and connected customer loads. Short-term effects are mainly concerned with immediate damage, equipment malfunction, and the associated power losses due to harmonic currents and voltages. Long-term effects include thermal losses and reduced life span of equipment.

Although harmonic voltage and currents within most distribution systems are quite small relative to the fundamental component, increased impedance of the network at harmonic frequencies often gives rise to significant power losses. These power losses include direct copper losses due to an effective increase in the level of rms current in the presence of harmonics in combination with increases in conductor resistance due to skin effect. Increased iron losses due to harmonics are also significant within the iron cores of most magnetic materials. Iron losses include hysteresis losses, where losses increase approximately in proportion to the harmonic frequency, and eddy current losses, where losses increase in proportion to the square of the harmonic frequency. Iron losses result in reduced efficiency of equipment and also raise core temperatures creating thermal stresses and degrading insulation levels. Harmonics are also a major cause of metal losses and dielectric stress in capacitor banks causing additional heating and loss of life [7, 8]. Insulation stress due to higher peak voltages from harmonics can also result in cable insulation breakdown and disruption to supply.

In some circumstances capacitors can combine with source and load inductance to form a parallel resonant circuit. In the presence of a harmonic resonance, harmonic voltages and currents may be amplified. The resulting voltages may highly exceed the voltage rating of capacitors or other connected equipment and the consequence is capacitor damage or blown fuses.

Complete or partial load disruption can also occur due to the presence of harmonics. Harmonics interfere with protective relays, metering devices, control circuits, communication circuits, and customer electronic equipment. Sensitive equipment can experience malfunction or complete component failure. Shortened incandescent lamp lifetime and failure of some types of fluorescent lights have also been recorded in [7, 9].

While some of the above mentioned problems and effects associated with harmonics occur over short-term durations, more significant long-term problems such as degrading insulation due to thermal stresses are usually of most concern. These problems are often not visible to the DNSP or customer until final failure of equipment occurs. Reduced lifespan of equipment necessitates costly repairs or replacements. Thus it is important for both DNSP and customer to be proactive with regards to measurement and mitigation of harmonic distortion problems.

1.3 Representation of harmonics

This section outlines some of the fundamental concepts and important mathematical relationships for representation and analysis of harmonic distortion in power systems. The following equations will be referred to throughout this thesis when developing system models and describing harmonic distortion.

1.3.1 Harmonic components

A method to represent any non-sinusoidal periodic function *u(t)* using an infinite series of sine and cosine functions and coefficients as shown in equation (1.1) was first proposed by Baron Jean Fourier in 1822 [10]

$$\begin{aligned} u(t) &= A_0 + \sum_{h=1}^{\infty}\left[A_h \cos(h\omega_0 t) + B_h \sin(h\omega_0 t)\right] \\ &= A_0 + \sum_{h=1}^{\infty} C_h \cos(h\omega_0 t + \psi_h) \end{aligned} \tag{1.1}$$

where *u(t)* is a periodic function of frequency f_0, angular frequency $\omega_0 = 2\pi f_0$, and period $T = 1/f_0 = 2\pi/\omega_0$. $C_1\cos(\omega_0 t+\psi_1)$ represents the fundamental component, and $C_h\cos(h\omega_0 t+\psi_h)$ represents the h^{th} harmonic component of amplitude C_h, frequency $h\omega_0$ and phase ψ_h relative to the fundamental.

Generally, for power systems the fundamental frequency is either 50Hz or 60Hz. Australian power systems are typically operated at 50Hz and thus harmonic frequencies will appear as multiples of 50Hz (100Hz, 150Hz, 200Hz, etc.). The Fourier series coefficients C_1, C_2, …C_h and relative phases ψ_1, ψ_2, …ψ_h make up the harmonic spectrum of the waveform and are found using equations (1.2) to (1.6)

$$A_0 = \frac{1}{T}\int_0^T u(t)dt = \frac{1}{2\pi}\int_0^{2\pi} u(t)dx,\ where\ x = \omega_0 t \tag{1.2}$$

$$A_h = \frac{2}{T}\int_0^T u(t)\cos(h\omega_0 t)dt = \frac{1}{\pi}\int_0^{2\pi} u(t)\cos(hx)dx \tag{1.3}$$

$$B_h = \frac{2}{T}\int_0^T u(t)\sin(h\omega_0 t)dt = \frac{1}{\pi}\int_0^{2\pi} u(t)\sin(hx)dx \tag{1.4}$$

$$C_h = \sqrt{A_h^2 + B_h^2} \tag{1.5}$$

$$\psi_h = \tan^{-1}\left(\frac{A_h}{B_h}\right) \tag{1.6}$$

Conversely, if the harmonic spectrum of a given current or voltage waveform $u(t)$ is known the original waveform can be constructed using the Fourier series summation

$$u(t) = \sum_{h=1}^{\infty} U_h \cos(h\omega_0 t + \psi_h) \tag{1.7}$$

where U_h is the h^{th} harmonic peak current or voltage, ψ_h is the h^{th} harmonic phase, ω_0 is the fundamental angular frequency, $\omega_0=2\pi f_0$, and f_0 is the fundamental frequency, typically 50Hz.

1.3.2 Total harmonic distortion (THD)

Although the harmonic content of a power system may be quite small relative to the fundamental in most circumstances, for exactness the rms value of a current or voltage waveform requires the harmonic content to be considered such that

$$U_{rms} = \sqrt{\sum_{h=1}^{\infty}\left(\frac{1}{\sqrt{2}}U_h\right)^2} \tag{1.8}$$

where U_{rms} is the rms value of voltage or current. The rms voltage or current can also be used to quantify the level of distortion of the waveform. The total harmonic distortion of voltage or current waveform (THD_U) is calculated using equation (1.9)

$$THD_U = \frac{1}{U_1}\sqrt{\sum_{h=2}^{\infty} U_h^2} = \sqrt{\left(\frac{U_{rms}}{U_{1rms}}\right)^2 - 1} \tag{1.9}$$

where THD_U represents voltage or current total harmonic distortion (alternatively represented as THD_V and THD_I respectively) and U_{1rms} is the rms fundamental voltage or current. Alternatively rms voltage or current can be represented in terms of total harmonic distortion

$$U_{rms} = \sqrt{\sum_{h=1}^{\infty} U_{h\,rms}^2} = U_{1\,rms}\sqrt{1 + THD_U^2} \tag{1.10}$$

As distribution system fundamental voltage and current rarely remain static in magnitude at different times throughout the day, the definition for total harmonic distortion may at times provide a misleading value for the harmonic distortion level [2]. This is especially true for distribution system fundamental currents that fall close to zero at certain periods of the day, resulting in large values of THD_I. For this reason a modified index for harmonic distortion may be used with the harmonic content of the waveform expressed as a percentage of a fixed nominal value rather than the fundamental value, giving total demand distortion (TDD_U)

$$TDD_U = \frac{1}{U_{nom}} \sqrt{\sum_{h=2}^{\infty} \frac{1}{\sqrt{2}} U_h^2} \tag{1.11}$$

Total demand distortion is specified in [6, 11] instead of THD for harmonic current distortion for the above mentioned reasons. The fixed value U_{nom} is required to be specified and may be a maximum rms value, maximum demand, average or selected nominal system value.

1.4 Harmonic monitoring programmes

Until recently electricity DNSPs in Australia have been primarily reactive with regard to harmonic distortion problems. Harmonic measurements are typically not undertaken unless a problem is reported which cannot be attributed to conventional distribution system problem sources, such as high or low voltages and power interruptions. Often DNSPs are unaware of growing levels of harmonic distortion within their power systems until a problem occurs.

By maintaining a proactive approach to harmonic distortion problems, DNSPs can identify problematic loads, better plan the layout and operation of their systems to help reduce harmonic distortion levels, and ensure an acceptable level of power quality is being supplied to their customers. With contractual agreements between transmission utilities, DNSPs, and customers becoming commonplace, a greater emphasis is being placed on the level of power quality disturbances by regulators to ensure all parties maintain compliance with the relevant power quality standards.

To be proactive, the best approach for DNSPs to take with regard to harmonic distortion is to carry out regular power quality monitoring programmes on various sections of their power systems. Identifying problems areas early allows planning engineers to prioritise work to ensure harmonic levels remain below recommended levels. Identification of excessive harmonic levels may also indicate a nearby harmonic resonance. If harmonic resonances are recognised at an early stage, capacitors and other power system equipment may be prevented from suffering reduced life spans through proper mitigation, effectively creating savings on equipment replacement or repair costs.

Continuous monitoring of harmonic levels in distribution systems allows an assessment of present levels of harmonics to be made, keeping check on the rate at which levels are increasing or decreasing. This is important information for planning new distribution systems or upgrades. Levels can also be benchmarked against the acceptable levels according to the relevant power quality standards. DNSPs should have a procedure for implementing harmonic monitoring programmes to ensure efficient processing of data and effective reporting of results. Within Australia there have been only a few monitoring campaigns published to allow an assessment of how harmonic levels are

growing in typical distribution systems. This may be partially attributed to the cost of instrumentation, time, labour, lack of requirements from regulators, and complexities of metering in carrying out such surveys.

1.5 Harmonic standards

To properly manage harmonic distortion levels in distribution systems there are two approaches that may be taken: either a DNSP controls the level of harmonic emissions by implementing emission limits on their customers, or they install mitigation techniques as required, such as lower impedance conductors and harmonic filters, to limit voltage levels and effects of excessive harmonic voltages and currents.

To implement restrictions on emission from customers, DNSPs require legal documentation that can be used to regulate customers. Thus, selection of an appropriate dedicated harmonic emission standard is required. In this way standards control harmonic levels emitted from customers to ensure no excessive voltage distortion appears within the distribution system. In Australia the standard that limits harmonic emissions from customers connected to the power system has been AS 2279.2-1991 [12] in various forms, for a period of 25 years. This standard provided a simple method of determining acceptable sizing of converter installations as well as providing a guide for assessing emission limits for other harmonic producing installations. The application of AS 2279.2 is reasonably straightforward and customer equipment can be relatively easily assessed for harmonic compliance, i.e. whether the customer is emitting acceptable levels of harmonic distortion or not.

With the dramatic increase in the use of high efficiency equipment and other power electronic load technologies there now exists more significant harmonic producing loads in distribution systems than ever before. These loads have an enormous amount of diversity in their design and operating conditions. The AS 2279.2 harmonic standard does not include the detail required to account for the extreme diversity of loads, and thus Australian Standards looked to the international community to determine a new, more applicable standard.

Two major international standards were being used by the international community for assessment and guidance in the area of power system harmonics when a replacement for AS2279.2 was required at the turn of the century. The first applicable standard, IEEE 519:1992 [13], has it origins in the USA. However, this standard provides assessment and guidance based on typical data from distribution systems in the USA, which are typically meshed systems consisting of different transformer configurations and customer connection terminations than that of typical Australian distribution systems. Additionally, the operating frequency of power systems in the USA is 60Hz, though this does not have a large bearing on the application of the IEEE 519 standard.

Australian distribution systems are typically radial in nature with the exception of some networks existing within central business districts (CBD). Feeder lengths are also typically much longer than in the USA. Australian distribution systems are actually a closer match to European systems with their transformer configurations and operating voltages. For this reason and due to the World Trade Organisation agreement on technical barriers [14], Standards Australia has adopted the internationally accepted technical report IEC 61000-3-6:1996 [15] as the new harmonic standard, identified as

AS/NZS 61000.3.6:2001 [16]. The above IEC technical report was originally published as a guide only, with recommendations on how to manage harmonic distortion in power systems, rather than to be implemented as a clearly defined harmonic standard, as was the case with AS 2279.2.

The increased complexity of the new harmonic standard and some of the pitfalls in creating that complexity form the basis for the research reported in this thesis. A more detailed assessment of AS/NZS 61000.3.6 (IEC 61000-3-6) and AS 2279.2 is provided in Chapter 2. The research presented attempts to provide a coordinated approach to applying IEC 61000-3-6 and expanding some of its keys concepts to use in the management of harmonic distortion in distribution systems.

1.6 Objective of the thesis

The aim of this thesis is to develop a methodical and comprehensive approach to harmonic analysis that may be used by a DNSP during the planning or design stage of a distribution system to estimate the harmonic performance. As knowledge of the harmonic nature of future loads during the planning stage will be relatively undefined, analysis tools require pragmatic estimation techniques to broadly identify the performance of the system. Thus before analysis tools are developed a study must be undertaken to identify the properties of typical distribution system loads.

The first objective of this thesis is to determine the macro-characteristics of the harmonic emission behaviour within power distribution systems. Macro-characteristics of loads are required to enable pragmatic modelling approaches to be applied to distribution systems during the design phase. This is required to determine the

harmonics capabilities of a particular distribution design. Identifying the macro-characteristics of different load types is achieved in this thesis through the observation of results from a benchmark harmonic monitoring programme and complementary simulations.

The second objective is to provide harmonic planning techniques for DNSP engineers, which can be implemented on general distribution systems to control the level of harmonic voltage distortion. This includes a suitable method to allocate allowable harmonic distortion contributions to customers connected to a power distribution system. This is achieved through generalising procedures suggested by the relevant standards and also realising the important variables that determine the harmonic capabilities of the power distribution system.

A method to predict the level of harmonic distortion in a distribution system will also be presented. Analysis techniques for accurate modelling of the distribution system in the presence of harmonics are developed to allow for such a prediction. Forecasting and quantification of the growth of harmonics at particular points in the system, taking into account the development of industrial technology over the next decade and development of general guidelines for identifying the most suitable connection point for future large distorting loads may be addressed utilising such a prediction technique. General planning strategies for maximising the harmonic capability of distribution systems will also be investigated.

1.7 Structure of thesis

A brief summary of the contributions of each of the remaining Chapters of this thesis is provided below.

Chapter 2: In this chapter a literature review on the present situation of harmonics in distribution systems throughout the world and trends in growth from harmonic monitoring programmes are presented. The various strategies employed by standards to control harmonics are discussed. An introduction to and history of the summation law, a principle concept used in this thesis is presented.

Chapter 3: A method to estimate the level of voltage harmonic distortion existing in an MV power distribution system is proposed. The suggested method is based on macro-modelling where the large amount of data required for cumbersome detailed simulations is not available. The advantages and limitations of this method are discussed.

Chapter 4: A new approach to the allocation of harmonic emissions to customers on long MV feeders is developed. A sensitivity analysis of the method is also determined. The proposed method allows the harmonic standard IEC 61000-3-6 to be implemented when only a limited amount of data is available, specifically for the typical yet complex example of loads connected along a feeder having significantly different fault levels.

Chapter 5: The global behaviour of multiple harmonic loads connected to a power distribution system is analysed. The procedure for implementing a benchmark harmonic monitoring programme of a distribution system is presented. An outline for presentation

of results and discussion of relevant outputs are included. Identification of MV distribution system aggregated load models is determined using data from field measurements.

Chapter 6: This chapter provides a review of the complexities involved in allocation methods when significant system capacitance or power factor correction (PFC) capacitors are present within the distribution system network. An assessment of some simplifying rules is also provided.

Chapter 7: The application of harmonic allocation methods to three real case studies is provided. The three case studies provided include an example of allocation of harmonic emissions to a customer situated along a long MV feeder, assessment of existing harmonic distortion levels within a distribution system, and an evaluation of a system containing numerous PFC capacitors.

Chapter 8: The final chapter will summarise the significant conclusions from this thesis and suggest areas of future work to complete the research.

Chapter 2

Overview of harmonic monitoring in distribution systems

2.1 Introduction

There is a general concern within distribution network service providers (DNSP) about the growth of harmonic distortion in power systems. However, as excessive harmonic distortion levels usually only cause gradual degradation of power system equipment and loads, effective warning on problems associated with harmonic distortion can often only be achieved through a careful programme of monitoring. Such extensive harmonic monitoring programmes are both costly and time-consuming for a DNSP to undertake. Optimising the effectiveness of harmonic monitoring programmes is thus of interest to a DNSP.

This Chapter reviews literature on harmonic monitoring programmes that have been undertaken both nationally and internationally on transmission and distribution systems in an attempt to identify the state-of-the-art practices in monitoring campaigns. Of particular interest is establishing the optimal method of measurement, identification of load types monitored, and effective presentation of results.

For a DNSP to effectively manage harmonics a projection of future harmonic levels is required. To evaluate growth of harmonic distortion over the next decade or so a model of distribution system load increases and changes in load technology are required in conjunction with a benchmarking of present levels of harmonics. This Chapter includes presentation of monitoring results from various distribution systems to help benchmark existing harmonic levels. In the few international instances where comprehensive

monitoring programmes have been completed there is a general consensus of steady harmonic distortion growth.

Finally an introduction to the harmonic summation law is presented. The summation law is a statistical tool used to approximate the net magnitude of contributions from a number of harmonic sources incorporating both time and phase diversity. The summation law is a principle concept used in this thesis and provides the backbone of the theory developed in the remaining chapters.

2.2 Harmonic monitoring programmes

The number of harmonic monitoring programmes completed internationally has increased gradually over the past decade. To allow the results of such monitoring programmes to be analysed effectively and measured against previous or future programmes there are a number of factors that should be considered to ensure the integrity of the resulting conclusions. To be included in these considerations are the following

(i) Method of measurement,

(ii) Presentation of results, and

(iii) Load or source type identification.

The cited literature on harmonic monitoring at both national and international levels has indicated the need to standardise this practise to ensure the ability to include monitoring results into future references. While some of the published monitoring programmes are carried out to establish existing harmonic distortion levels, usually monitoring programmes result from a complaint by a customer or a specific investigation by a

DNSP. While satisfying the requirements of the initiator the published results of these programmes are of limited use for future reference. The following sections provide discussion on (i)-(iii) above to help ensure the full potential of harmonic monitoring programmes are achieved.

2.3 Method of measurement

The method of measurement used in the cited literature, spanning the last decade, has varied depending on the requirements of the harmonic monitoring programmes. The first consideration to be emphasised by the literature is the type of monitoring equipment used. It is important to laboratory test measurement devices before being used in the field to establish device accuracy and consistency. Regular calibration is often not the only requirement to establish instrument accuracy, the algorithms used by instrument manufacturers to calculate the harmonic components often need to be verified as indicated in work by [17]. Figure 2.1 illustrates a typical monitoring system for a simple harmonic monitoring programme.

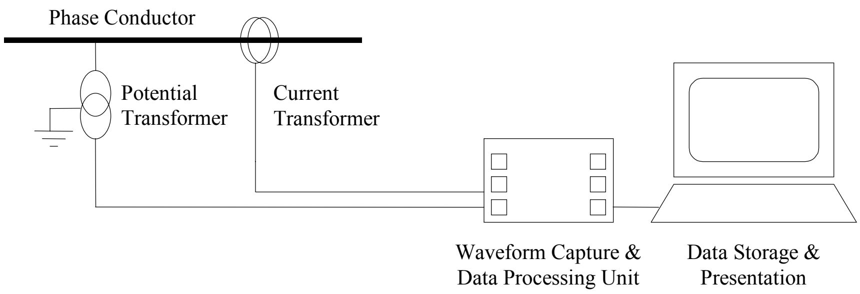


Figure 2.1 Symbolic illustration of a harmonic monitoring system

It has been widely accepted through the literature that metering current transformers and potential transformers are the most appropriate points of measurement. Metering current transformers are nearly always available at both feeder and load connection points and their bandwidth is usually sufficient to measure up to the 50th harmonic. However, it has

been found that some harmonic instruments do not measure accurately to such higher order harmonics and thus care is to be taken [17]. In the case where potential transformers are not available capacitive voltage dividers have been shown to give good results for voltage harmonic measurements [18]. Capacitive voltage transformers tuned to the fundamental frequency however are not suitable for harmonic measurements.

Harmonic distortion measurements are usually determined from a single cycle or averaged over a small number of cycles utilising Fourier analysis. The recently introduced IEC 61000-4-30:2003 [19] specifies 8-10 cycles to be used to establish harmonic components but it is anticipated that it will be a while before instrument manufacturers comply with this standard. The Fast Fourier Transform (FFT) technique is used to determine the magnitude and phase of each of the harmonic components from the sampled waveform. Instrument manufacturers do not usually specify the details of the sampling or algorithms used for harmonic analysis. This information is often important when measurements from different instruments are being compared.

Instrument sampling times must also be selected carefully. IEC 61000-3-6 [15] and IEC 61000-4-7:2002 [20] specify that both 3 second and 10 minute samples are required, however present harmonic monitoring instruments are often unable to provide such data over extended periods due to memory limitations. To establish good weekly trends of harmonics, measurements should be taken at least every half hour. Previous surveys have sampled the system at 1-3 minute intervals to establish more accurate trends [21, 22]. Where possible measurements should always be taken of magnitudes of individual voltage and current harmonics rather than overall THD, as THD rarely portrays a clear picture of problem areas. The most common harmonics from the

literature cited include the 3rd, 5th and 7th. Measurements should also be completed in each of the seasons to establish seasonal variation [23].

2.4 Presentation of results

Presentation of results has been often a topic for discussion in the cited literature [18, 24, 25]. The first argument raised is whether to use the fundamental or rated quantities as a base for harmonic distortion calculation. From the literature cited, few instances present harmonic distortion using rated quantities as a base for voltage and current as per equation (1.11) [18, 24]. These monitoring programmes were completed early in the last decade with most recent programmes conforming to the IEEE 519 standard [13] using total harmonic distortion as shown by equation (1.9).

The choice of which of the above quantities to use for the harmonic distortion calculation is to be resolved in the newly drafted standard by IEEE [26]. This standard suggests the use of nominal system rms voltage for voltage harmonic distortion calculations, and maximum demand load current for current harmonic distortion calculations. By using the maximum demand load current instead of the fundamental current the problem of high harmonic distortion values resulting during low demand periods is eliminated.

Data collected from harmonic monitoring programmes needs to be analysed on a statistical basis to extract meaningful figures. The existing definitions and benchmark data analysis techniques used for processing collected data from harmonic benchmark monitoring programmes are outlined in [25].

The cumulative frequency curves and histograms are good tools to establish the extent of harmonic problems. The 95% cumulative probability value (CP95) is often used to provide the level of harmonic distortion for comparisons with other results. CP95 is the statistical quantity representing the harmonic distortion value that is greater than 95% of data obtained for each site s found using equation (2.1).

$$\frac{\sum_{-\infty}^{CP95_s} f_s(x_i)}{\sum_{-\infty}^{\infty} f_s(x_i)} = 0.95 \tag{2.1}$$

where x_i is the steady state harmonic distortion measurement number i, and $f_s(x_i)$ is the probability distribution function of the sampled harmonic (or THD) values for site s. For presentation of harmonic monitoring results as an index the CP95 value requires two additional descriptors, the type of monitoring location that represents site s, and the duration from which the samples were obtained, e.g. one week.

To obtain a harmonic index for a system from within which a number of measurements have been taken at different locations, [25] suggests combining each site to get the system THD index (STHD95) by obtaining the 95% cumulative probability value using the individual site CP95 values and equation (2.2).

$$\frac{\sum_{-\infty}^{STHD95} f_t(CP95_s) \times L_s}{\sum_{-\infty}^{\infty} f_t(CP95_s) \times L_s} = 0.95 \tag{2.2}$$

where L_s is the connected kVA served by site s, and $f_t(CP95_s)$ is the probability distribution function of individual site CP95 values. An improved method for combining sites is suggested in [27] by normalising all sites to an appropriate limit, but this technique is still in the preliminary stages of development.

There are a number of other relationships given in [25] that are useful concepts for analysing harmonic survey data. Use of statistical methods allows the results to be evaluated effectively without the interference of harmonic transients that can distort results. Of the literature cited only a few report results in a form that addresses the issue effectively [21, 28].

To adequately benchmark harmonic levels, results should contain at least the maximum, minimum, and CP95 values for the individual voltage and current harmonics, and also the total harmonic distortion in tabulated form.

2.5 Load type identification

If harmonic monitoring results are to be used to predict future levels of harmonic distortion in distribution systems, the load types from which results are obtained must be recorded. Results from measurements at a point of common connection (PCC) should also specify the nature of the loads represented at that PCC. A good example of this is given in [24], which specifies the location, plant type (i.e. aluminium plant), shifts worked, significant load type, and equipment ratings.

In [29] data is distinguished using three categories of load sectors; industrial (I), commercial (C) and residential (R). Sites within the monitoring programme are classified using the particular type of load (it may be a combination of two, i.e. industrial and residential). Typical industrial loads are given as lighting, electric motors, power electronic devices etc. while commercial loads are lighting, elevators, computers etc. Residential loads are defined as lighting lamps and household appliances. This method of identifying load types is the most common and the recommended method to

use. The usefulness of this method is reflected by the nature of the typical loads for each category. A distribution feeder can be easily categorised by the industrial, commercial and residential ratio if the customer loads are known.

A third way of identifying the load type is by the current waveform the load draws. Loads can then be comprised of linear loads (sinusoidal current), or one of three classes of non-linear loads. This method is utilised in [30], noting that method is usually used for estimations in forecasting harmonic growth rather than in the harmonic monitoring programme phase. This method is an extension of the industrial, commercial and residential method in that it categorises the current waveform from a particular load type, and the load type can then be assigned as industrial, commercial or residential.

2.6 Previous monitoring programmes

Throughout Europe, Asia and USA a number of distribution system harmonic monitoring programmes have been completed. The purpose of these programmes has been to monitor the existing levels of harmonic distortion on the distribution systems, while also establishing the growth patterns of the levels of harmonic distortion for the future. None of the reported programmes however offer coordinated voltage and current measurements across a number of sites at various intervals throughout a year.

Harmonic monitoring programmes in Australia have been limited usually only to areas of customer complaint. However, this trend is changing as indicated by DNSP participation in a pilot study by [31]. Due to the lagging nature of Australian business in taking up new commercial and industrial technologies the harmonic growth found

overseas paints a reasonable picture of the future of harmonic growth on a national level.

Harmonic monitoring programmes performed around the world over a decade ago showed that harmonic levels were relatively low and were of little concern due to the tolerance of the existing electrical equipment. A programme in the USA presented in [18] involved four years of data collection. The results of [18] shown in Table 2.1 highlights that at most of the sites monitored, harmonic distortion was well within the recommended limits [13]. Only at one site were the limits exceeded and this was due to the circuit resonating at the 5^{th} harmonic because of customer capacitors. Results show that industrial and commercial loads typically give rise to higher harmonic distortion than residential loads.

Table 2.1 Voltage and current distortion levels from [18]

Location	Average voltage distortion level (%)	Dominant voltage harmonic and distortion level (%)	Average current distortion level (%)	Dominant current harmonic and distortion level (%)
Residential (Res)	1.01	5^{th} /0.54	2.58	5^{th} /1.58
Commercial (Com)	1.92	5^{th} /1.71	3.13	3^{rd} /2.65
Industrial (Ind)	2.53	5^{th} /2.26	2.79	5^{th} /2.48
Res & Com	1.14	3^{rd} /0.89	3.84	5^{th} /2.72
Industrial	2.29	5^{th} /1.06	2.52	5^{th} /1.41
Res & Com	1.68	5^{th} /1.49	2.36	5^{th} /1.72
Res, Com, & Ind	4.15	5^{th} /3.93	15.33	5^{th} /14.97

Another harmonic monitoring programme in the USA by [24] included measurements from 37 substations and 39 individual load sites. Of the sites monitored 48.7% were distribution substations, 14.5% heavy industry, 30.3% light industry (less than 5MVA), and 6.5% were commercial sites. As expected the principal harmonics were the odd

harmonics ranging from the 3rd to 13th. The substations primarily serving industrial and commercial sites had rather high values of current distortion as compared to the substations primarily serving residential customers, which had less than 5% current distortion. As with the results from [18] the above results suggest that the industrial, commercial, residential load classification method is useful. The monitoring programme in [24] also found that some distribution system sites were already exceeding IEEE recommended limits for current harmonics. Four of the 39 test sites were found to exceed the limits while at least another ten were close to exceeding the limits. No sites exceeded the voltage THD limit of 5% although three sites had values greater then 4%.

The monitoring programmes discussed in [18] and [24] looked at the levels of harmonic distortion only. Other programmes were interested in the trends of the harmonic distortion over periods of time. The usual patterns of harmonic distortion levels are similar to that of the system loading in that each 24 hours will display peak periods at particular times. Over a period of one week, harmonic monitoring results of [21] in the USA found that these repeatable patterns were very similar during weekdays with weekend levels providing their own individual patterns. An example of a weekly harmonics trend is given in Figure 2.2 that includes the associated histogram illustrating the frequency of the distortion magnitudes.

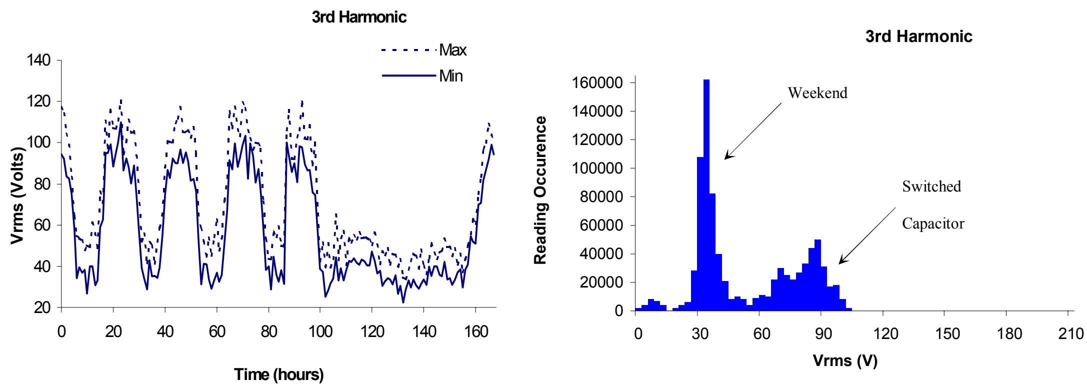


Figure 2.2 Seven day recording of harmonic voltages and histograms [21]

The levels of THD monitored at distribution feeders presented in [21] were found to be well within the US guidelines with levels lower than 2% for 99% of the time. Results from [21] also highlight the effects of switching of PFC capacitors on the individual harmonics. These effects of switching capacitors are made evident by the resulting peaks in the histograms of presented data in Figure 2.2.

Further monitoring programmes have continued in the USA [28] to highlight the behaviour of harmonic distortion at customer bus locations. The monitoring programmes completed at small industrial and commercial sites found that they displayed similar daily trends to that of earlier programmes. In some instances the 3rd harmonic demonstrated higher levels than the 5th harmonic. The 3rd harmonic voltage also indicated a growth from 0.25% to 1.0% over the period of a decade. Although this would not be the case in Australia due to the use of delta-star distribution transformers, it highlights the possible dramatic growth levels of harmonic distortion.

Results of a harmonic monitoring programme carried out on a distribution system in United Kingdom are presented in [32]. This covered monitoring conducted on industrial loads over a period of two weeks with samples of the supply voltage at 11kV and 33kV

taken every 20 seconds. Measurements were taken first to assess the background voltage distortion and then the interaction between the background distortion and particular distortion producing loads were assessed. The results of the monitoring showed that the levels for each of the dominant harmonics i.e. 3^{rd}, 5^{th} (most dominant) and 7^{th} had their own repeatable daily pattern. Both the 5^{th} and 7^{th} harmonics produced similar daily trends. Peak values of individual voltage harmonics were shown to be around 2% of the fundamental voltage. The collected results were used by [33] to produce mathematical models which allowed the prediction of the resulting individual harmonic magnitude and phase for the connection of a distorting load to a distribution system with known levels of background harmonic distortion.

Monitoring data obtained from residential loads in France [34] indicated that household appliances are a major contributor to harmonic distortion levels. The conclusion is drawn that harmonic distortion limits of today will soon be exceeded if emission levels of household appliances are not reduced. It is suggested that the level of THD is relative to the number of harmonic loads rather than the total power rating of the distorting loads.

A major monitoring programme conducted by [23] fours years after [32] involving 46 different substations in the United Kingdom indicated that levels of harmonic distortion on distribution systems had increased. The most significant individual harmonic, the 5^{th} harmonic, was found to have typical peak levels of 2.5%-3.0% at some locations. This was mainly due to the increased use of power electronic devices connected at lower voltages.

Monitoring of harmonic voltage in Northern Taiwan also indicates the same growth patterns as in other areas around the world. Taiwan power utilities are finding that acceptable harmonic distortion levels are already being exceeded with levels of THD above 3% on 50% of the transformers surveyed [35]. The effects of the high harmonic distortion levels are being noticed through damage to distribution system capacitors. Power transformers have also had to be derated due to the effects of harmonic currents.

The need for Australian industry to analyse their harmonic problems in a joint effort with their DNSP is proposed in [22] to ensure that future levels do not grow to the extent that will cause sensitive equipment malfunction. The effective use of harmonic filters is also reported in [22] where harmonics in the supplying 132kV system were found to be higher than that of the industrial customer 33kV distribution system where filters were installed. It is stated in [22] that harmonics are often not usually considered when PFC capacitors are installed within industrial plants.

A monitoring programme carried out on the electrical distribution system of several commercial buildings in the USA is reported in [36]. The method of monitoring was to first take initial measurements using true-rms and averaging multimeters. The true-rms meter provided measurements of the peak and rms current, while the averaging multimeter provided measurement of the fundamental component. The crest factor and distortion factor for each of the sites was then calculated using equations (2.3) and (2.4).

$$Crest\ Factor = \frac{I_{peak}}{I_{rms}} \tag{2.3}$$

$$Distortion\ Factor = \frac{I_{rms}}{I_1} \tag{2.4}$$

From the calculations, sites with high crest or distortion factors were selected for further analysis using a power analyser to determine the levels of harmonics. This method can save time when determining where high levels of harmonic voltages of currents may be present, and may help determine where to locate permanent monitoring devices. The results of this survey found that the sites had voltage THD values between 2.0% and 4.5%.

Throughout all harmonic monitoring programmes in the cited literature it has been found that the 5th harmonic was the most significant. Due to this, THD usually followed the pattern set by the level of 5th harmonic. Also noticeable in the studied literature was the suggestion that levels of harmonic distortion were increasing at a rate so that present day harmonic tolerances would soon be exceeded. The changing nature of loads connected to distribution systems is also a concern for DNSPs.

2.7 Future projection of harmonics

Growth of harmonic voltages in power systems over recent years is to be expected as harmonic distortion problems are largely derived from power electronic devices, which are predominant in existing growth technologies. Load growth studies by utilities in the USA in the late 1990s expected that over 50% of power system loads would be supplied through power electronics systems by the year 2000 [37]. Some of the cited literature suggests that acceptable harmonic distortion levels stipulated by various standards may be exceeded in some parts of the power system in the years 2000 to 2010 [21, 28]. Measurement of growth of harmonic distortion levels requires well coordinated long-term monitoring programmes to be established. These types of studies are becoming possible through the introduction of permanent power quality monitoring instruments

installed at substations and the increase of metering devices containing power quality monitoring functionality.

Future projections should be based upon data obtained from previous harmonic monitoring programmes and assumptions on existing load development and load growth models. Load growth estimations should consider technologies such as adjustable speed drives (ASD) in air conditioners and washing machines, televisions, personal computers, and future loads such as electric vehicle battery chargers [38, 39]. The increase in numbers and loadings of households and industrial sites should be incorporated into the forecast. The sensitivity of the distribution system being studied is one of the major concerns when attempting to predict the effects of harmonic distortion growth.

Attempts have been made to project the level of voltage THD for typical distribution system feeders supplying typical residential, commercial and industrial customers over a period of a decade or so [30, 40]. Of a major consideration is the harmonic susceptibility of the distribution feeders. Some projections of distorting load growth have suggested that short feeders are more immune to the effects of harmonic currents [40]. Based on this and the associated effects of distribution system capacitor connections it has been shown that for short feeders with no parallel resonances, voltage THD growth could be as low as 0.01% per year [40], while for longer feeders with high harmonic susceptibility, growth could be as much as 0.35% per year.

A study reported in the UK [5], based on harmonic monitoring programmes of residential areas during 1979-1999, indicate harmonic growth of 1% per 10 years for

voltage THD and 1.4% per 10 years for 5^{th} harmonic voltage. However due to organisational constraints there was no consideration given to seasonal variations and the measurement periods were not taken at the same time of each year. Thus future projections based on these results could not be considered reliable.

Other areas that need to be considered when attempting to project harmonic distortion growth are the harmonic self-compensation effect [41], generalisation of distribution system loads, i.e. breaking down load into percentage of non-linear load, and identification of distribution system parameters that affect harmonic susceptibility.

2.8 Relevant harmonic standards

Most countries have their own regulatory standards to control the levels of harmonic distortion in distribution power systems. More recently a number of countries have collectively started applying similar harmonic control methodologies and recommended limits through the adoption of international standards such as IEC 61000-3-6 [15] and IEEE 519 [13]. Other similar standards exist such as EN 50160 [42], however the IEC and IEEE standards are the most commonly applied.

In an attempt to control the levels of harmonic voltage distortion within distribution systems, most standards apply limits to harmonic current emissions in the hope that if customers are limited appropriately the net effect of all customer emissions will result in an acceptable level of harmonic voltage distortion. IEEE 519 restricts customer harmonic current emissions to a value derived from the short circuit level at the point of connection and the size of customer's non-linear load. The recommended harmonic current limits from IEEE 519 are given in Table 2.2. As a consequence of these limits it

is assumed the voltage levels will not exceed those given in Table 2.3. However it has been found by [43] that most "utility versions" (adaptations) of the standard required customers to also comply with the voltage limits, and thus may be disconnected if they cause excessive voltage even when their current emissions are within specifications of Table 2.2.

Table 2.2 IEEE 519 current distortion limits for general distribution systems [13]

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd harmonics)						
I_{SC}/I_L	h<11	11≤ h<17	17≤ h<23	23≤ h<35	h ≥35	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonic limits above.						
Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.						
*All generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L						
Where I_{SC} = maximum short-circuit current at PCC I_L = maximum demand load current (fundamental frequency component) at PCC						

Table 2.3 ANSI/IEEE 519 voltage distortion limits [13]

Bus voltage at PCC	Individual V_h, %	Voltage THD, %
V < 69kV	3.0	5.0
69 ≤ V < 161kV	1.5	2.5
V ≥ 161kV	1.0	1.5

The IEC approach differs slightly from the IEEE standard in that it considers future customers in the harmonic allocation. IEC 61000-3-6 provides formulas to estimate the allowed current emission for each customer such that all customers, including future ones, share the harmonic absorbing capability of the system [43]. While the recommended harmonic voltage levels from the IEC standard are more generous than

those of the IEEE standard, the allowable customer harmonic current contributions are usually more restrictive, although this will depend much upon circuit configuration. Overall, while being more complex, the IEC standard has a better philosophy in that it incorporates future loads and also makes customers responsible for harmonic voltages on the system.

In January 2001, Standards Australia adopted the IEC 61000-3-6 technical report as AS/NZS 61000.3.6. This new standard supersedes the existing AS 2279.2 that has been in use in various forms as the harmonics standard for distribution systems in Australia for the last 25 years. The need for the new standard has come with the more prolific use of power electronics within distribution systems. The philosophy of AS 2279.2 was based on there being only a few large non-linear loads within each distribution system. The allocation of customer's permissible harmonic currents is based either purely on load size or, in more extenuating circumstances, the amount of harmonic distortion existing on the system prior to connection of the new load, usually creating a 'first-come-first-served' scenario as with IEEE 519. The approach of AS 2279.2 does not adequately allow for future harmonic producing load growth.

The largest difference between IEC 61000-3-6 and AS 2279.2 is that time variation, leading to diversity, is introduced to account for the multiple types and operating modes of the non-linear loads with the system [44]. Also harmonic voltage planning levels for the new standard, given in Table 2.4, are larger at lower frequencies and fall off with increasing frequency to smaller values. This differs from the AS 2279.2 recommended limits, which are constant for even and odd harmonics as indicated in Table 2.5.

Table 2.4 Planning levels for harmonic voltages in MV, HV and EHV systems [15]

Odd harmonics non-multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Order h	Harmonic voltage %		Order H	Harmonic Voltage %		Order h	Harmonic Voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1.6	1.5
7	4	2	9	1.2	1	4	1	1
11	3	1.5	15	0.3	0.3	6	0.5	0.5
13	2.5	1.5	21	0.2	0.2	8	0.4	0.4
17	1.6	1	>21	0.2	0.2	10	0.4	0.4
19	1.2	1				12	0.2	0.2
23	1.2	0.7				>12	0.2	0.2
25	1.2	0.7						
>25	$0.2 + 0.5\frac{25}{h}$	$0.2 + 0.5\frac{25}{h}$						
NOTE – Total harmonic distortion (THD): 6.5% in MV networks; 3% in HV networks								

Table 2.5 AS 2279.2 Harmonic voltage ratio limits at any point on the system [12]

Supply system	Voltage at point of common coupling kV	Total harmonic voltage ratio %	Individual harmonic voltage ratio %	
			Odd	Even
Primary and secondary distribution	≤ 33	5	4	2
Transmission and sub-transmission	22, 33 and 66	3	2	1
	≥ 110	1.5	1	0.5

The selection of an appropriate harmonic standard to regulate emissions from customers remains the decision of the DNSP. However it is anticipated that acceptance of the new AS/NZS 61000.3.6 will follow if the difficulties in its application are addressed. An application guide for the new standard has recently been produced [45] to aid in the interpretation of principles in AS/NZS 61000.3.6.

2.9 The summation law

IEC 61000-3-6 incorporates statistical quantities to assess and allocate harmonic emissions to distribution customers. One of the key principles of the IEC approach is the use of summation laws to simplify calculations of net harmonic current from a number of distorting loads. The summation laws are adopted to account for time, magnitude and phase diversity of several harmonic loads without completing a detailed harmonic study. The first summation law is based on weighting factors that depend on load types, and the second summation law is based on the power law. The second summation law is a more general approach to combining the harmonic contributions from a number of loads and is thus considered more applicable in most circumstances. This summation law relies on the power law to incorporate the diversity of loads allowing frequency domain studies to predict cumulative probability levels of time varying harmonics.

Historically, loads that produced significant harmonic emissions were generally limited to industrial applications of thyristor rectifiers. The limited types of distorting loads allowed the summation of a number of loads to be completed using the arithmetic sum of the loads and additional diversity factors, as suggested by [46] in 1967 and later used in earlier versions of AS 2279.2. This approach was limited in its application and as more types of harmonic distorting loads were connected to the power system a more general statistical method for combining a large number of loads was required.

In 1972 [47] extended the application of the recommendations in [46] to include an rms rule as shown by equations (2.5) and (2.6). The rms rule was used to determine the

resulting permissible harmonic current of multiple power electronic installations, as the arithmetic sum rule seemed too pessimistic for most cases.

$$\textit{Assessed harmonic current} = kA_{rms} \tag{2.5}$$

$$A_{rms} = \sqrt{A_1^2 + A_2^2 + \ldots + A_n^2} \tag{2.6}$$

where A_1, A_2, etc. are the rms harmonic currents of the individual loads and k is adjusted for the probability of exceedance desired. [47] suggests that the rms rule with k=1.85 be used for three or more sources producing harmonics with independent phase control, provided no single load exceeds 55% of the total harmonic load at the particular frequency. [48] also addressed the problem of the addition of a number of harmonic sources. Sources with constant amplitude and randomly varying phase angles were considered showing that the probability of exceedance of the various percentiles (75th, 95th, 99th etc.) could be approximated by the rms rule and various values of k.

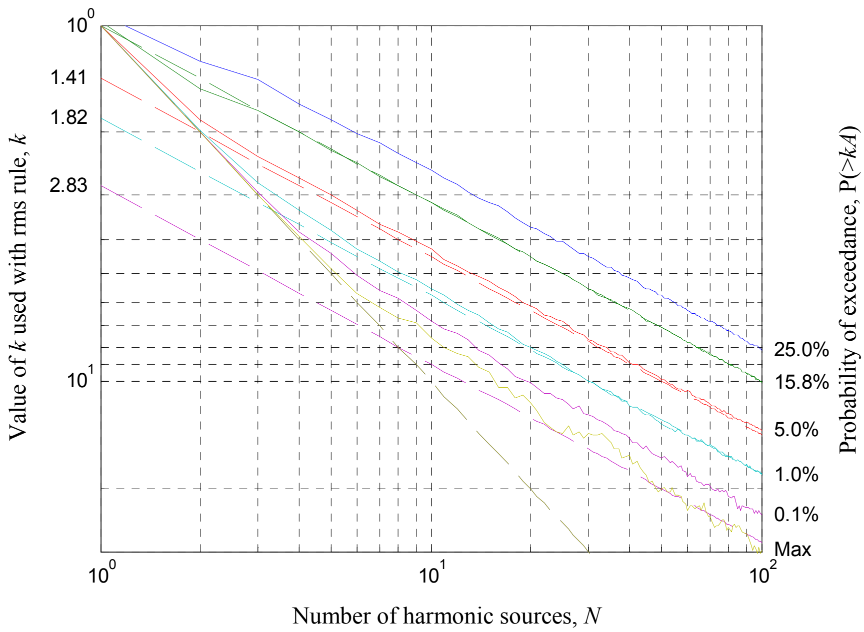


Figure 2.3 Probability of N harmonics of amplitude A exceeding kA [48]

Figure 2.3 illustrates the percentile exceedances of a Monte Carlo study for the addition of N harmonic sources with constant amplitude and uniformly random phase angle [48].

A comparison to the rms rule using various values of k is also displayed using dashed lines. It can be seen that the rms rule provides a good approximation to the stochastic process for values of N greater than 10.

The work of [47] and [48] was complimented by [49] by including random amplitude in addition to random phase. Unlike the earlier work, [49] used phasors instead of the instantaneous sine wave components to demonstrate that through the central limit theorem the resulting distribution of the addition of randomly varying harmonics could be approximated as a Rayleigh distribution. [49] did not directly contribute to the summation law but recognised that the nature of the harmonic producing loads should be first determined to ensure that the requirements of the theoretical work were fulfilled.

Further statistical analysis of the summation of a number of harmonic sources is presented in [50]. This includes a similar study to [49] with the inclusion of normal distributions of amplitude and phase, however the rms rule is modified to the form of equation (2.7). Values of k and α for the 95th percentiles are determined for various magnitudes of uniformly random amplitude and phase and are provided in Table 2.6.

$$A = k\sqrt[\alpha]{\sum A_i^{\alpha}} \qquad (2.7)$$

Table 2.6 k and α for summation law using uniform distribution of amplitude and phase [50]

Range of phase angle θ_i	Range of amplitude A_i	N=2		N>2	
		k	α	k	α
0-360	0-1	1.0	2.0	1.0	2.0
	0.5-1	1.3	2.0	1.3	2.0
	1	1.0	1.0	1.7	2.0
0-270	0-1	0.9	1.6	0.9	1.6
	0.5-1	1.0	1.4	1.0	1.4
	1	1.0	1.0	1.3	1.4
0-180	0-1	0.8	1.3	0.8	1.3
	0.5-1	0.9	1.2	0.9	1.2
	1	1.0	1.0	1.2	1.2
0-90	0-1	0.9	1.2	0.9	1.2
	0.5-1	0.9	1.1	0.9	1.1
	1	1.0	1.0	1.0	1.0

Field measurements are included in [50] to establish the types of distributions most suited for modelling actual systems. Results showed that lower order harmonics are reasonably stable and approximately normally distributed whereas higher order harmonics are uniformly distributed. Approximate values for k and α for ranges of harmonic h are suggested by [50] as follows for 95th percentiles

- h = 3, 5, 7: k=1, α=1 (valid for harmonics with fixed amplitude, whose phase angle may randomly vary between 0° and 90°)
- h = 11, 13: k=1, α=1.4 (valid for harmonics whose amplitude may vary between half maximum and maximum and whose phase angle may randomly vary between 0° and 270°)
- h > 13: k=1, α=2 (valid for harmonics whose magnitude may randomly vary between 0 and maximum and whose phase angle may randomly vary between 0° and 360°).

The early work on the summation rule was based on the distributions of random amplitude and phase of the individual harmonics. Also considered in [50] is the introduction of harmonics varying randomly over periods of time. The only disadvantage with this method is that to verify results experimentally the harmonic nature of each of the individual loads within a distribution system need to be determined. A final technical report [51] has been completed in relation to the summation law as a draft version of IEC 61000-3-6. In the draft document no reasoning is given for the values of α used but suggest α=1 for n<5, α=1.4 for 5≤n≤10, and α=2 for n>10. These values differ to those indicated above by the work in [50].

2.10 Summary

Harmonic monitoring programmes undertaken overseas and within Australia have been reviewed. There is a large amount of inconsistency between how measurements are taken and results reported. Conformance to guidelines specified in recently introduced international standards are however helping to rectify these inconsistencies. If DNSPs aim to fully utilise the results from harmonic monitoring programs undertaken periodically or for specific investigations, measurement and reporting procedures need to be developed to ensure these results can be used effectively for future reference.

The levels of harmonic distortion on an international basis have been investigated through a literature review of results from harmonic monitoring campaigns. The trend is of gradual harmonic growth with some literature estimating existing planning levels may be exceeded within the next decade. This review highlights the need for a commitment to monitoring of harmonic levels within distribution systems to allow utilities and customers to plan adequately for harmonic growth. International regulatory

document IEC 61000-3-6 and IEEE Standard 519 are gradually being adopted in an attempt to ensure harmonic voltages within MV distribution systems remain at acceptable levels.

In January 2001 Australia adopted a new harmonic standard governing emission limits of distorting loads in MV and HV power systems. The new standard AS/NZS 61000.3.6 is an adaptation of the international technical report IEC 61000-3-6. AS/NZS 61000.3.6 replaces AS 2279.2, which was first introduced in 1979 and has been the basis of setting the standards for harmonics in Australia. Some work is still required to overcome the complexities in the newly adopted standard.

Statistical techniques are required to combine the contributions from individual distorting loads and the summation rule has been suggested as a useful tool to achieve this. The limitation of the summation rule is that measured data does not exactly follow the required pattern of the theoretical data used to obtain the required indices. However the summation rule is designed only to give an accurate approximation of the 95th percentile cumulative probability levels. For use in the application of harmonic standards it is suggested the summation rule would be suitable and is adopted as one of the key principles of the theory and methodologies developed in following chapters.

Chapter 3

Estimation of harmonic levels in MV distribution systems

3.1 Introduction

Results from harmonic monitoring programmes presented in Chapter 2 have suggested a general trend of growth in harmonic distortion levels. Electricity distribution network service providers (DNSP) should now be looking towards preventative measures to ensure that voltage distortion levels are within limits set by the appropriate standards [16]. These measures will need to be taken at the planning stage to ensure distribution systems will be able to meet harmonic standards as the distortion levels due to loads rise.

To evaluate the harmonic performance of a distribution system design the DNSP will require the ability to estimate distortion levels. The problem of estimating harmonics at the design stage of a distribution system is very different to the normal investigation of a particular harmonic load. The study must encompass many loads generating harmonics and whose harmonic spectrum and daily variation are poorly specified. For such modelling the aim is not to accurately model every individual load but to determine methods for representing the statistics of large aggregations of load.

To develop a method for estimating distortion levels this Chapter investigates the diversity of small and medium sized harmonics producing loads common to MV distribution systems. Results from a harmonic monitoring programme of seven sites in an MV distribution system outlined in Chapter 5 are also utilised to establish aggregated load models. A breakdown of these loads into the residential, commercial, and industrial load sectors is carried out. This small part of the measurements from the monitoring

programme is required to give the parameters of the residential, commercial and industrial load sectors. The remainder of the monitoring results have been used to validate a proposed method to estimate distortion levels.

The assumptions required to allow a pragmatic approach to harmonic modelling are also addressed in this Chapter. Finally the Chapter will report on a method that can be used to establish typical harmonic distortion levels within a distribution system and therefore predict the effect of a change in network or load conditions. The method applies to MV radial distribution systems and incorporates background distortion from the upstream supply. The method to be described is able to be set up in a spreadsheet rather than requiring specialist simulation software and allows calculation of sensitivities to various planning parameters so that the important ones can be identified.

3.2 Diversity of loads in MV distribution systems

Within MV distribution systems there exists an endless diversity of load types that draw distorted current from the power supply system. The usual behaviour of these loads means that while the amount of distortion in their current may depend on the level of harmonics existing on the system, they will usually draw non-linear current even when the supply voltage is nearly sinusoidal. The harmonic currents drawn by these non-linear loads in turn produce harmonic voltages on the system in proportion to the distribution system harmonic impedance.

With the growing use of power electronic devices to achieve efficiency and flexibility, substantial increases in harmonic distortion will become apparent if harmonics are not considered in distribution system design. The difficulty is not on how to model each of

the individual loads as the DNSP engineer is not interested in this detail. Instead, a method of modelling the combined aggregate effect of many different distorting loads at each of the distribution transformers within the distribution system is required.

The harmonic content of currents drawn by distorting loads varies depending on operating mode, equipment components and network properties. The phase of each of the individual harmonics also varies with the same parameters. Thus addition of multiple harmonic distorting loads in the frequency domain computed directly using arithmetic addition provides a pessimistic model of harmonic distortion and hence phasor addition has to be considered. To account for this behaviour harmonic planning techniques must incorporate load and time diversity in their approach to control the harmonic distortion levels. As a preliminary to producing harmonic models suitable for planning techniques it is essential to first look at some measurements that illustrate load type diversity.

Table 3.1 shows the current waveforms of various domestic loads within a household supplied by Integral Energy in the Sydney area, captured using a Fluke 41 Power Harmonic Analyser (see Appendix A for specifications). The harmonic components of each of the load current waveforms are listed in Table 3.2 alongside a graphical representation of the harmonic spectrum. It can be seen that the phase of the harmonic currents vary significantly over the different load types. It is to be noted that most of these loads are single phase. Greater diversity would be expected if more three phase loads were also included in the study.

Table 3.1 Current waveforms of common domestic loads

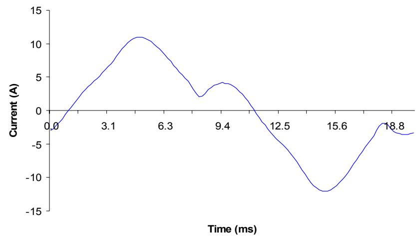
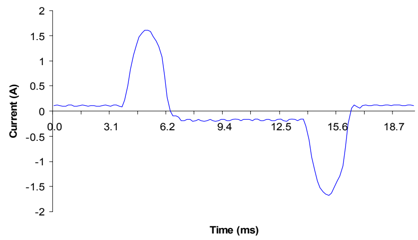
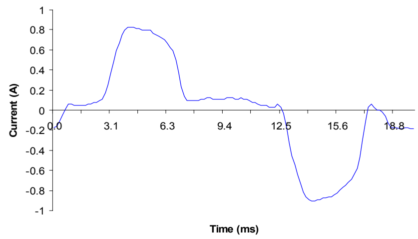
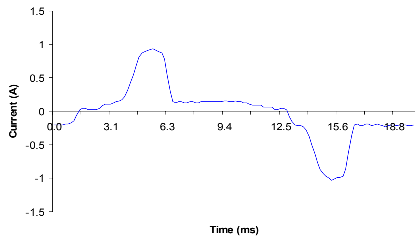
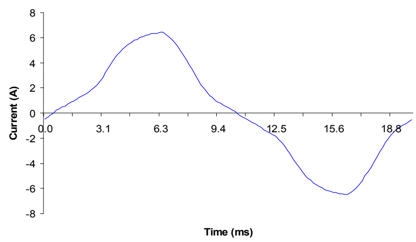
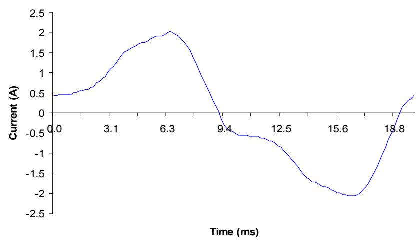
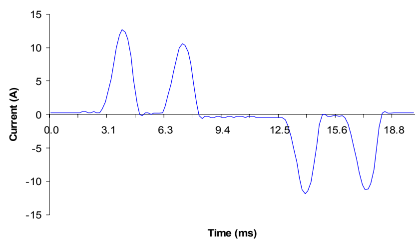
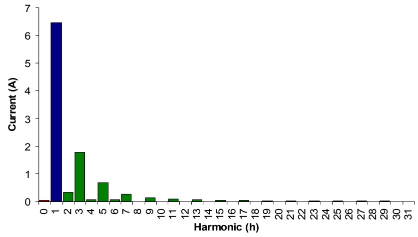
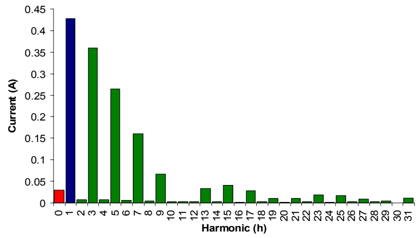
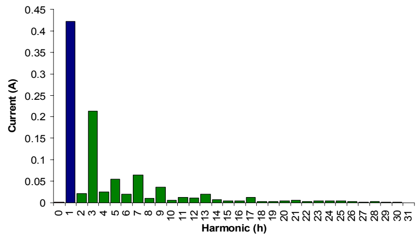
1000W 27L Microwave Oven (Cooking on high)	
100W Pentium 120MHz Processor (Running a programme)	
96W Compact Audio System (Playing compact disk at 80% sound volume)	
82W 51cm Colour Television (Normal operating mode)	
1000W Vacuum Cleaner (Normal operating mode)	
6kg Washing Machine (On wash cycle with agitator)	
3 Phase Air Conditioner – Inverter driven (Normal operating mode)	

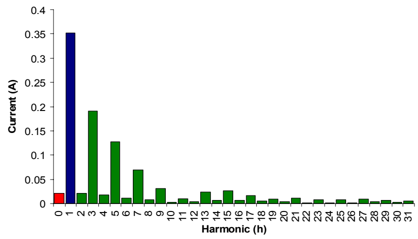
Table 3.2 Harmonic components of current from common domestic loads

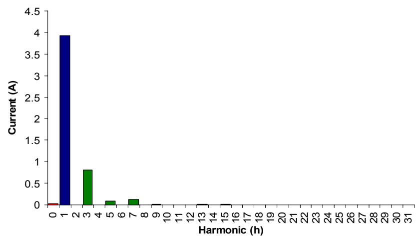
<table>
<tr><td>1000W 27L Microwave Oven

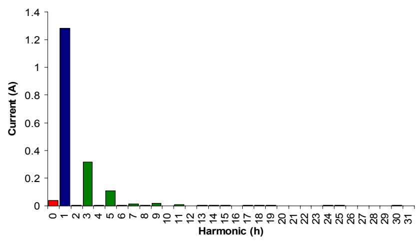
$I_1 = 3.46A \angle -8°$
$I_3 = 1.78A \angle -152°$
$I_5 = 0.68A \angle -57°$
$I_7 = 0.25A \angle -68°$</td><td></td></tr>
<tr><td>100W Pentium 120MHz PC

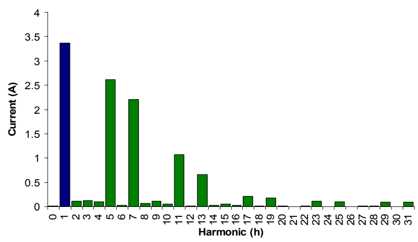
$I_1 = 0.43A \angle 15°$
$I_3 = 0.36A \angle 176°$
$I_5 = 0.26A \angle -13°$
$I_7 = 0.16A \angle 160°$</td><td></td></tr>
<tr><td>96W Compact Audio System

$I_1 = 0.42A \angle -6°$
$I_3 = 0.21A \angle -169°$
$I_5 = 0.05A \angle -1°$
$I_7 = 0.06A \angle -9°$</td><td></td></tr>
<tr><td>82W 51cm Colour Television

$I_1 = 0.35A \angle -18°$
$I_3 = 0.19A \angle 176°$
$I_5 = 0.13A \angle -27°$
$I_7 = 0.07A \angle 141°$</td><td></td></tr>
<tr><td>1000W Vacuum Cleaner

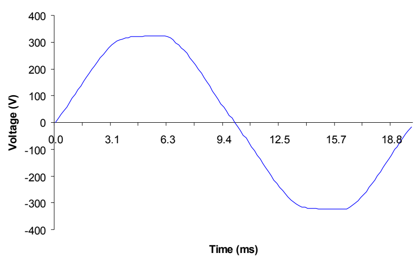
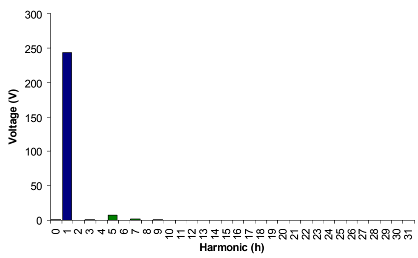
$I_1 = 3.93A \angle -11°$
$I_3 = 0.81A \angle 134°$
$I_5 = 0.09A \angle -176°$
$I_7 = 0.13A \angle -73°$</td><td></td></tr>
<tr><td>6kg Washing Machine

$I_1 = 1.28A \angle -1°$
$I_3 = 0.32A \angle 112°$
$I_5 = 0.11A \angle 138°$
$I_7 = 0.01A \angle -94°$</td><td></td></tr>
<tr><td>3 Phase Air Conditioner – Inverter driven

$I_1 = 3.37A \angle -4°$
$I_3 = 0.12A \angle -155°$
$I_5 = 2.62A \angle 132°$
$I_7 = 2.20A \angle -68°$</td><td></td></tr>
</table>

From Table 3.1 it is clear that all the loads tested draw distorted current. The level of voltage distortion existing on the supply will also have an effect on the level of current distortion caused by each load. This has been documented in [52] for the case of capacitive filtered rectifiers within switch mode power supplies (SMPS). For these rectifiers the shape of the current waveform depends on the peak value of the voltage supply waveform. Large groups of these rectifiers draw significant levels of 3^{rd} harmonic current that tend to flatten the voltage waveform, reducing the peak of the current waveform to each rectifier and the overall amount of current distortion. A quick comparison of the single-phase load waveforms in Table 3.1 (most of which contain a SMPS) and the voltage waveform of Table 3.3 shows the typical single-phase load current pulses are approximately in phase with the voltage peaks.

Table 3.3 Typical supply voltage waveform for Tables 3.1 and 3.2

Supply Voltage $V_1 = 243.06V \angle 0°$ $V_3 = 1.28V\ (0.53\%) \angle 98°$ $V_5 = 7.27V\ (2.99\%) \angle -175°$ $V_7 = 1.86V\ (0.76\%) \angle 11°$ $V_{THD} = 3.10\%$	 

One of the most prolific uses of power electronics involves the application of capacitor filtered diode rectifiers. When single-phase and three-phase diode rectifiers are mixed within distribution systems, it is possible that the total harmonic distortion may

decrease. This is due to the cancellation of individual harmonics, such as the 5th and 7th harmonics, which can occur with near 180° difference in the phase angle [53].

The three-phase inverter driven air conditioner load of Table 3.1 illustrates a typical three-phase load powered through a capacitor-filtered rectifier, which has a trough at the peak of the voltage waveform. By combining the three-phase and single-phase loads it can be realised that the peak of the single-phase load partially fills up the trough in the current waveform of the three-phase load, as reported in [53]. Also with controlled converters operating at different firing angles some compensation can occur by harmonic currents being slightly out of phase producing net harmonic current levels less than what would be obtained by direct addition. The diversity of loads illustrated above creates a difficult problem for estimating the aggregate harmonic distortion emissions from multiple loads at a distribution transformer.

The problem of modelling these loads for planning purposes is how to combine the harmonic currents of various loads to obtain a suitable net harmonic current and calculate the resulting harmonic voltage contribution. It is very difficult to include all parameters and find the maximum harmonic voltage that will occur on the distribution system. This is because each of the harmonic producing loads will have different phase angles for each of the harmonic components as discussed above and also because it is very unlikely that all loads will be producing their maximum harmonic current all at the same instance in time. Harmonic planning techniques must also include the varying nature of distribution system harmonics over time for assessment of harmonic voltage levels.

3.3 Residential, commercial and industrial load characteristics

From a DNSP perspective it will be assumed that the loads on a feeder can be classified as residential, industrial and commercial load types, each having an average aggregate harmonic current characteristic that is roughly constant throughout the network.

To illustrate which harmonics are of most significance within a typical distribution system the harmonic content of a number of combined loads measured on the LV side of distribution transformers are shown in Figures 3.1 to 3.3. These harmonic spectrums were obtained from LV monitoring locations within Integral Energy's Homepride zone distribution system. The harmonic content of the current measured at the sending end of an MV feeder connected to the Homepride zone substation is also illustrated in Figure 3.4. While there is no indication of the phase of each harmonic, it can be seen that the 3rd, 5th and 7th harmonics are the dominant harmonics for the residential, commercial and industrial load sectors at LV. These are the characteristic harmonics of most single-phase power electronic loads, with the 5th and 7th also being the dominant harmonics for three-phase power electronic loads.

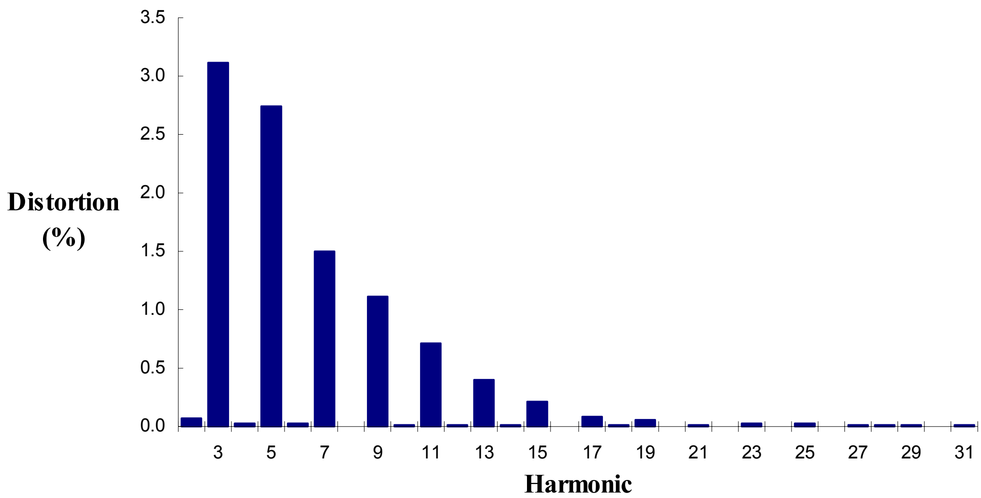


Figure 3.1 Residential distribution transformer harmonic current snapshot ($THD_I = 4.64\%$)

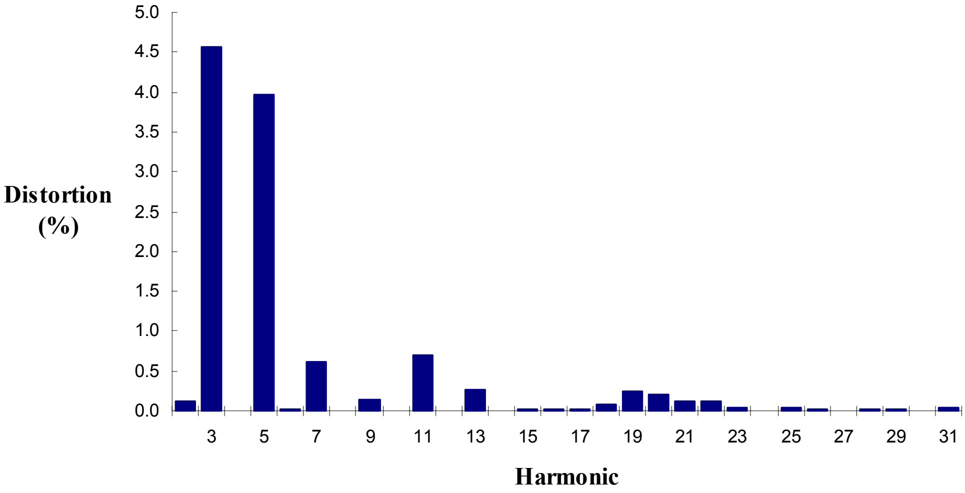


Figure 3.2 Commercial distribution transformer harmonic current snapshot ($THD_I = 6.19\%$)

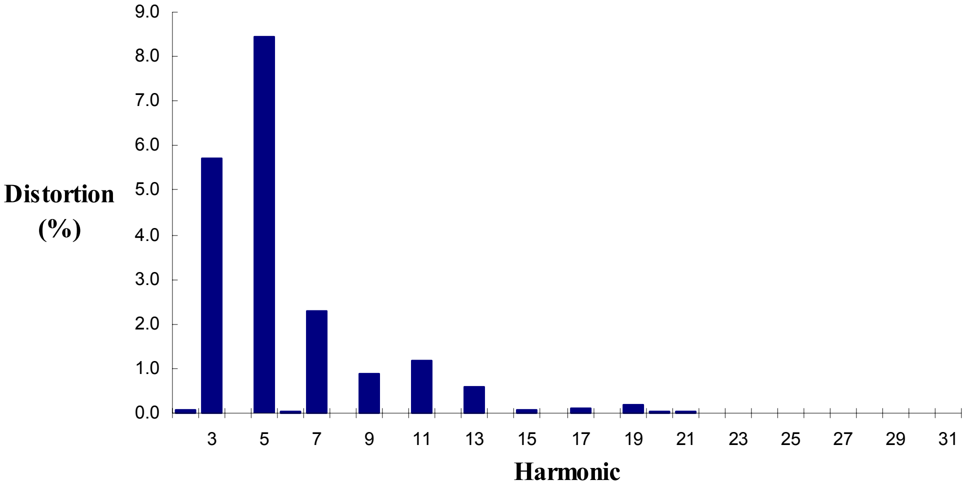


Figure 3.3 Industrial distribution transformer harmonic current snapshot ($THD_I = 10.59\%$)

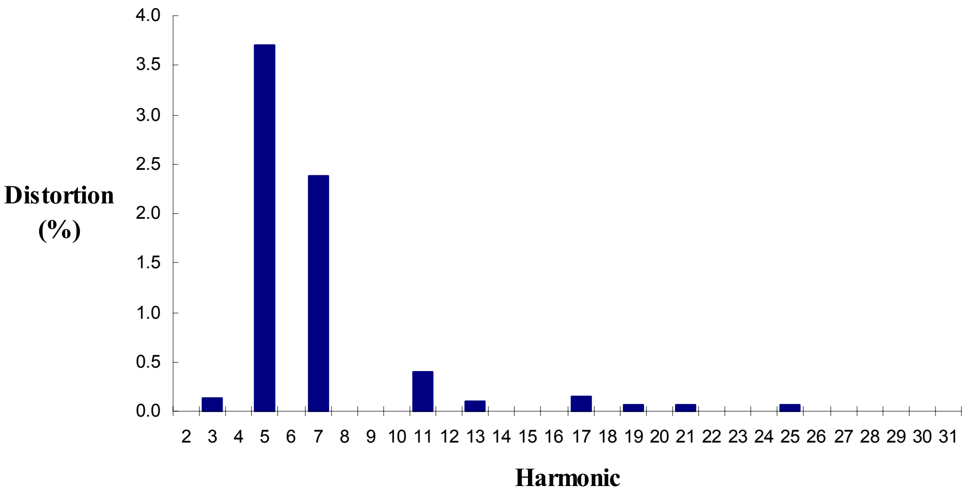


Figure 3.4 Zone substation feeder harmonic current snapshot ($THD_I = 4.59\%$)

Table 3.4 summarises the results from the harmonic distortion monitoring programme giving the 95th cumulative probability values for the fundamental and 5th harmonic current for the three LV locations, averaged over the entire monitoring period. The subscript '1CP95' indicates the fundamental component 95th percentile cumulative probability level. It is required to characterise the load types so that the 95th percentile cumulative probability levels of harmonic distortion can be predicted from known network impedances, load magnitudes and compensations. Assuming that similar load compositions at any power level will have the same spectrum, each load type can be characterised conveniently by the I_{5CP95}/I_{1CP95} as shown in the right hand column. This shows that the residential load has much less distortion than the commercial and industrial types as would be expected. Over the course of the entire monitoring programme it was found that the ratio of 95th percentile 5th harmonic to 95th percentile fundamental varied by less than 10% for any given week of data. Note that the I_{5CP95}/I_{1CP95} ratio for the industrial case is representative of light industry, as large industry will usually require further consideration and in depth harmonic analysis, especially when loads such as arc furnaces are installed.

Table 3.4 Fundamental and 5th harmonic current 95th percentile values

Harmonic Monitor Site	I_{1CP95} (A)	I_{5CP95} (A)	I_{5CP95}/I_{1CP95}
Residential	133	3.36	0.025
Commercial	617	43.3	0.071
Industrial	1469	170.9	0.116

Each load type is a mixture of linear and non-linear equipment that varies throughout the day. Since the two components vary independently to some extent, the fraction I_5/I_1 will also vary throughout each day. Noting that variation of the 95th percentile ratio is less than 10% provides the basis to assume that the ratio of the statistics I_{5CP95}/I_{1CP95} is constant for all loads of a given type (residential, commercial and industrial). These

ratios can be found from current measurements alone at the supply point to a pure residential, commercial or industrial load. Ideally it would be advantageous to repeat the measurements from the monitoring programme on numerous other MV distribution systems. However, cost and access to systems makes this task difficult to complete in the time frame of the thesis.

The statistical harmonic models of residential, commercial and industrial load types above have been developed to simulate the global behaviour of distorting loads at distribution substations. The load models represent aggregates of loads and are specifically intended for calculation of harmonic emissions for comparison with the relevant standards. Both time and phase diversities are included in the representative load models for frequency domain analysis.

3.4 Assumptions to allow estimation of distortion levels

Harmonic distortion surveys that have been completed over the past decade have shown that the 5^{th} harmonic is the most significant harmonic and usually accounts for over 80% of the total harmonic distortion (THD) within MV systems [21, 22, 54]. This is due to the rapid fall off of harmonics with frequency, produced by present power electronic technology (even more rapid than the fall off of voltage limits) and the removal of most 3^{rd} harmonics by delta-star transformers stepping down to the LV system. Present trends suggest that the 5^{th} harmonic will continue to dominate for many years. A key assumption in this method of estimating harmonic levels is that if the 5^{th} harmonic voltage is within acceptable limits, there will most likely be no harmonic problems. This assumption will need to be revisited where there are power factor correction capacitors

giving amplification over some frequency range away from the 5^{th} harmonic and this will be discussed further in Chapter 6.

From the harmonic distortion monitoring programme results it was verified that the amount of total harmonic voltage distortion is dominated by the 5^{th} harmonic. This characteristic may be used to predict the amount of total harmonic distortion existing on the system if the 5^{th} harmonic distortion level can be established.

3.5 Key concepts for estimating distortion levels

There are numerous commercially available software packages, such as PSCAD/EMTDC [55], PSPICE [56], SIMULINK [57], and SUPERHARM [58], which can be used to simulate the behaviour of harmonics within distribution systems and estimate resulting distortion levels. These packages include the ability to perform studies in time domain, frequency domain, or a combination of both. A common requirement in the use of all these simulation packages for modelling purposes is a detailed knowledge of both the distribution system and customer loads. For MV distribution systems customer loads are most likely to include a mixture of many small and medium sized loads incorporating a variety of power electronic products. It would be a difficult and impractical task for a DNSP to model all of these loads individually in a software package for planning purposes. It is desired to have a method of establishing harmonic distortion levels within MV distribution systems using a more applicable simplistic approach while maintaining an acceptable level of accuracy.

The method for establishing harmonic levels within a distribution system uses some of the concepts that are given in IEC 61000-3-6 [15]. Two concepts used throughout this

thesis are the evaluation of emission levels by statistical means and the second summation law.

Emission Levels - The IEC standard suggests that the emission levels of harmonic voltage distortion should be evaluated using a statistical approach to take time variations into account [15]. Broadly, it is proposed that a harmonic survey should be taken over a period of at least a week and that the signal analysis should be along the strict guidelines of [59] with the maximum and 95th percentile of the cumulative probability distribution (CP95) determined. The resulting value must be less than the planning level for the appropriate voltage level, of which suggested values are given. This prevents a DNSP being penalised for a high value of harmonics that might occur for only 5% of the day (1.2 hours).

Second Summation Law – The law is used to combine the 95th percentile cumulative probability values of harmonic currents or voltages to give their overall combined value. It is designed to give a value less than that which would be given by direct addition to take account of time and phase diversity, as discussed in Chapter 2.

The second summation law is required to combine the statistical values, as direct addition for simplified analysis does not suffice. Consider the data sets in Table 3.5, where the first set has 90 values of “1”, followed by 5 of “2” and then 5 of “3” giving a 95th percentile cumulative value of 2. The second set shown will have a 95th percentile cumulative value of 3. The sum of these two sets will have 100 values all of “4” giving a 95th percentile cumulative value of 4, yet the sum of the individual 95th percentile cumulative values is 5.

The second summation law is assumed to have the form

$$V_h = \sqrt[\alpha]{\sum V_{hi}^{\alpha}} \tag{3.1}$$

where

V_h = magnitude of resulting harmonic voltage (order h)

V_{hi} = magnitude of individual i^{th} harmonic voltage (order h) to be combined.

α = exponent depending on the probability of actual value exceeding the calculated value and the degree to which the individual harmonic voltages vary in magnitude and phase.

Table 3.5 Example values of sampled data

% of Data	Set 1	Set 2	Sum (set 1+set 2)
90%	1	3	4
5%	2	2	4
5%	3	1	4
CP95	2	3	5

For the above example, α should be 1.51. As presented in Chapter 2, for the 5^{th} harmonic it is suggested by [15] that α=1.4 be used, with a higher value for some of the higher order harmonics.

3.6 Method to establish distortion levels

In order to establish typical levels of harmonic voltages a model of the distribution system under study must be first produced. The parameters required to model an MV distribution system for the proposed calculation method are listed below.

- The impedance, total rated capacity and total maximum demand of the HV/MV zone substation transformer.
- Fault level of HV transmission feeder to establish harmonic impedance of HV transmission system.

- Number of feeders and approximate number of distribution transformers per feeder.
- Approximate lengths and impedances of lines (either underground or overhead).
- Approximate proportion of residential, commercial and industrial loading for each feeder.

During the design process only a qualitative estimate of voltage harmonic distortion levels is required. To establish these typical levels of harmonic voltage distortion some approximations must be made. The assumptions required to simplify a system such as the distribution system on which the harmonic monitoring programme was performed (shown in Figure 5.6, of Chapter 5) are listed below.

(i) The system is balanced with no zero sequence. This can be justified by the results from the harmonic monitoring programme in Chapter 5, which illustrate that even at the LV levels the loading of each phase is well balanced.

(ii) The 5^{th} harmonic is the most significant harmonic. This is true for most balanced MV distribution systems [21, 22, 54] and is reinforced by the results of the harmonic monitoring programme presented in Chapter 5 and Figures 3.1 to 3.4 above.

(iii) As typical distribution system feeders are less than 10km in length the capacitance of the feeders is assumed negligible.

(iv) All impedances (conductors and transformers) are considered to be inductive with the resistive component assumed to be negligible at the 5^{th} harmonic. Resistive components may be included if available, noting that this will reduce the simplicity of the method without adding significant accuracy.

(v) 5^{th} harmonic currents drawn by individual loads are independent of each other and are summated using the second summation law defined by equation (3.1).

(vi) Residential, commercial and industrial type loads are spread out evenly over the length of each feeder.

The first step in predicting the harmonic voltage distortion throughout a system is to estimate the level of harmonic currents. Using the number of customers per LV distribution system and number of MV substations in conjunction with the proportion of residential, commercial and industrial loads the total harmonic current drawn at the HV/MV zone substation can be determined.

The individual load harmonics are summated together as given by equation (3.2) (α=1.4 for the 5th harmonic) to find the total harmonic current drawn from the HV transmission system.

$$I_{5total}^{1.4}=I_{5load1}^{1.4}+I_{5load2}^{1.4}+I_{5load3}^{1.4}+\ldots \qquad (3.2)$$

The level of distortion at the MV bus of the zone substation (V_{5MV}) is then the summation of the HV background distortion (V_{5BG}) and the voltage distortion arising from the impedance of the HV transmission line and the HV/MV zone substation transformer (V_{5HV}). The background distortion is the distortion that appears on the downstream system due to the interconnection of other loads via the upstream supply.

$$V_{5BG}^{1.4}+V_{5HV}^{1.4}=V_{5MV}^{1.4} \qquad (3.3)$$

If known, the background distortion level can be directly applied or else the approximation outlined in section 7.2.2 of [15] can be used by assuming the distortion level at HV is the same proportion as the distortion level at MV when compared to the harmonic limits. For example the recommended harmonic limit for the 5th harmonic at

HV is 2% and for MV the limit is 5% thus the background distortion can be calculated as shown by equation (3.4).

$$(k2\%)^{1.4}+V_{5HV}^{1.4}=(k5\%)^{1.4} \quad (3.4)$$

where k is the existing proportion of recommended harmonic voltage limit.

From the MV zone substation the distortion levels downstream of each of the feeders is calculated by the summation of the voltage distortions due to each of the individual loads and the background distortion. This is achieved by multiplying the harmonic current, approximated by the size of load and typical harmonic current level, with the harmonic impedance seen by that load back to the MV zone substation bus. For the 5th harmonic, the harmonic impedance is approximated by 5 times the fundamental impedance. Figure 3.5 illustrates the process of the harmonic voltage calculation.

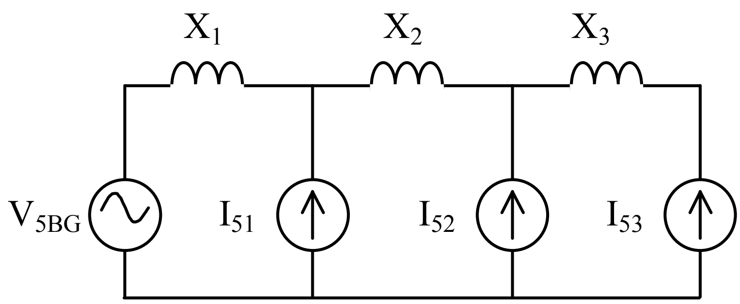


Figure 3.5 MV feeder equivalent circuit for voltage distortion calculation

The harmonic voltage distortion at the connection point after impedance X_1, which is due to the 5th harmonic currents produced by the individual loads downstream and the background distortion, is given by equation (3.5) as follows.

$$V_{5X1}^{1.4}=V_{5BG}^{1.4}+(I_{51}X_1)^{1.4}+(I_{52}X_1)^{1.4}+(I_{53}X_1)^{1.4} \quad (3.5)$$

3.7 Study system and harmonic monitoring results

The study system on which the harmonic monitoring programme was performed is the Homepride zone distribution system, which will be further described in Chapter 5. One of the assumptions in the calculation of 95th percentile harmonic voltage distortion levels is that an approximate proportion of the residential loads, commercial loads and industrial loads are known. Further, typical values of harmonic currents can be assigned to each of the residential, commercial and industrial loads for calculation of the harmonic voltage distortion. To establish typical values of harmonic currents the results from the monitoring programme are utilised. The resulting weekly average 95th percentile cumulative probability results for each of the seven sites monitored are given in Table 3.6.

Table 3.6 Results of monitoring at Homepride for fundamental and 5th harmonic

Harmonic Monitor Site (Voltage Level)	**I_{1CP95} (A)**	**I_{5CP95} (A)**	**V_{5CP95} (%)**
Residential transformer (415V)	119.7	3.0	1.45
Commercial Transformer (415V)	548.9	48.9	2.89
Industrial transformer (415V)	1404.6	193.0	1.63
Residential feeder (11kV)	173.5	5.5	1.54
Commercial feeder (11kV)	114.6	3.8	1.54
Industrial feeder (11kV)	153.7	8.2	1.54
Homepride zone substation transformer (11kV)	1205.3	17.1	1.54

The magnitudes of harmonic currents were obtained from measurements taken in the harmonic survey. The typical levels of per unit 5th harmonic current produced by residential, commercial and industrial load types given in Table 3.4 were established from the data collected over the entire three year monitoring programme. Similar figures could be used during the design phase of similar distribution systems to establish typical harmonic levels and help identify future harmonic problems.

3.8 Application of method to the study system

Relevant details of the Homepride zone distribution system required to establish approximate harmonic distortion levels are listed below.

- Zone substation rating is 50MVA.
- Typical maximum demand at 33kV/11kV zone substation transformer is 0.45pu (approximated by 95th percentile of fundamental current).
- Load is approximately 30% residential, 40% commercial, and 30% industrial.
- 10 Feeders are equally loaded.
- There are no power factor correction (PFC) capacitors installed in the system, but these should be easy to allow for in the approach given here. This will be discussed further in Chapter 6.
- Residential feeders (classified as 85% residential load and 15% commercial load) typically consist of 10 substations.
- Commercial feeders (classified as 86% commercial load and 14% residential load) typically consist of 7 substations.
- Industrial feeders (classified as 75% industrial load, 20% commercial load and 5% residential load) typically consist of 5 substations.
- Figure 3.6 represents a simplified layout of the Homepride zone MV distribution system. The residential, commercial and industrial feeders are shown with the corresponding number of distribution transformers connected. The "other feeders" consist of other residential, commercial and industrial feeders.

Except for large customers who have direct connection to the feeder (usually industrial customers) each of the MV substations will have an LV distribution system that is also

owned by the DNSP. The LV distribution system typically consists of overhead or underground cable with lengths up to 500m.

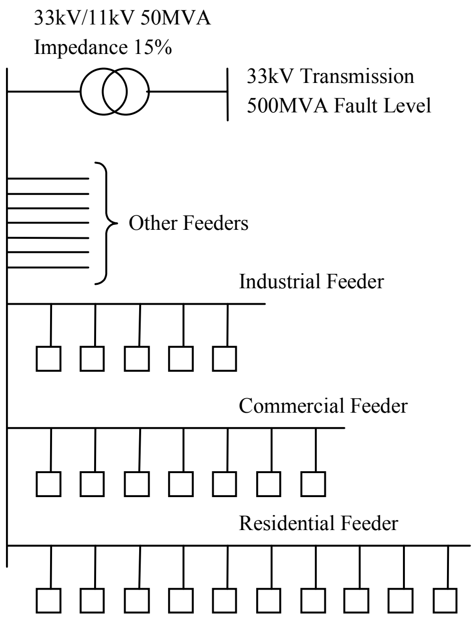


Figure 3.6 Simplified layout of Homepride zone MV distribution system

A layout of the LV distribution system is shown in Figure 3.7. The number of customers connected to each substation will vary from site to site but the loading should remain approximately the same due to the rating of the transformer.

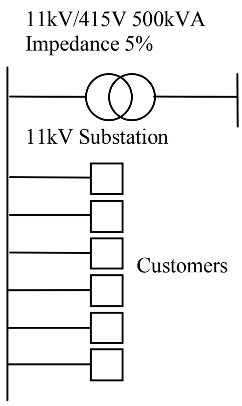


Figure 3.7 LV distribution system layout

Each of the feeders was modelled as a combination of residential, commercial and industrial loads. Using the typical values of harmonic currents for each load type, with the second summation law the total 5th harmonic current drawn by the MV system was determined. With the total harmonic current satisfactorily matching the actual measured current the progressive harmonic voltages at points further down the system could be evaluated.

Comparisons of the calculated 95th percentile results from the simulated model and the measured results are given in Table 3.7. As can be seen from the results the method used to establish typical harmonic levels gives a reasonably accurate account of the 95th percentile harmonic voltage levels occurring on the MV distribution system.

Table 3.7 Comparison of calculated and measured 95th percentile values

Site	Calculated	Measured
$I5_{TOTAL}$	23.2A	17.1A
$V5_{11kV\ BUS}$	1.50%	1.54%
$V5_{11kVRES}$	1.52%	-
$V5_{11kVCOM}$	1.51%	-
$V5_{11kVIND}$	1.53%	-

Site	Calculated	Measured
$V5_{415VRES}$	1.64%	1.45%
$V5_{415VCOM}$	2.33%	2.89%
$V5_{415VIND}$	1.76%	1.63%

3.9 Sensitivity results

A sensitivity analysis on the model was completed to establish which parameters have the greatest effect on the outputs of the model. The 5th harmonic voltage level at the MV busbar was chosen as the representative output for the analysis. Each of the input variables were increased individually by a factor of 1% and the percentage change in the

output variable was established, Figure 3.8 illustrates the resulting sensitivity for the 5th harmonic voltage at the MV busbar.

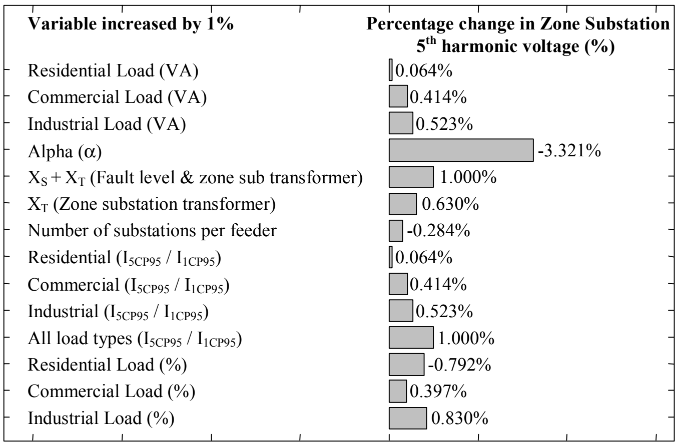


Figure 3.8 Sensitivity of the 5th harmonic voltage

The results of the sensitivity analysis illustrate that 5th harmonic voltage is less sensitive to errors in the 'known quantities' of distribution system parameters such as line impedance, fault levels, but particularly sensitive to the 'unknown quantity' of the exponent α. The value used for α is based on approximated statistical distributions of harmonic phase and amplitude obtained through experience [50]. Recommended values for the range of alpha for each individual harmonic are given in [15].

Although the distribution system surveyed showed good correlation with the calculated results from the model, the sensitivity analysis highlights the need for an appropriate value for α to be used. Where possible, measurements of harmonic amplitude and phase should be obtained to confirm an approximate uniform distribution for the lower order harmonics, an assumption that has been used in establishing α=1.4 [50].

As the 5th harmonic voltage from the model has shown greatest sensitivity to the value of α, a further study over the full range of α was completed. As expected the

relationship of the magnitude of α to error in the resulting 5th harmonic voltage was exponential. Figure 3.9 illustrates the exponential relationship for percentage change in the 5th harmonic voltage depending on the value of α used. If the diversity of the individual harmonics was not considered, direct addition of harmonic components (α=1) would largely over estimate the resulting value for the 5th harmonic voltage. By adjusting the value of α for zero error between the calculated and measured results it was found that α=1.42 gave the most suitable results. This necessary increase in the value of alpha (allowing greater diversity) could partially be attributed to the normal distribution of the 5th harmonic rather than the assumed uniform distribution.

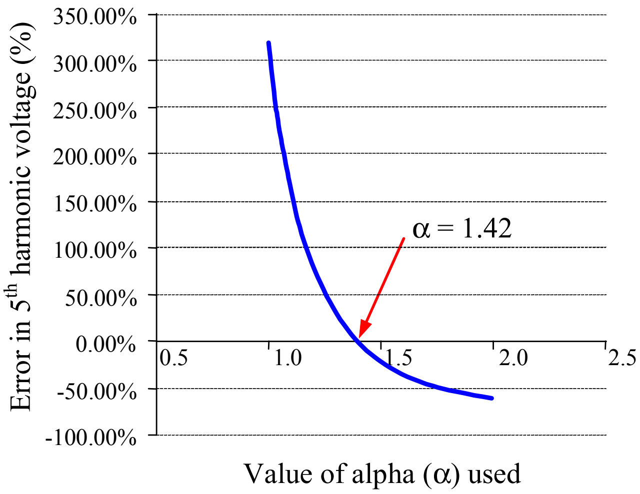


Figure 3.9 5th harmonic voltage sensitivity to alpha

3.10 Summary

Statistical harmonic models of residential, commercial and industrial load types have been developed to simulate the global behaviour of distorting loads at distribution substations. The load models represent aggregates of loads and are specifically intended for calculation of harmonic emissions for comparison with the relevant standards. Both time and phase diversities are included in the representative load models for frequency domain analysis.

A method has been developed to estimate the 95th percentile cumulative probability level of harmonic voltage distortion in an MV distribution system as required by the present Australian harmonic standard AS/NZS 61000.3.6 (adapted IEC 61000-3-6). This method includes techniques to overcome the difficulties in determining distortion levels when feeders are not being loaded to their fullest extent, and allows for cases when levels of background distortion may not be as high as limits set by the standard. The implementation of these techniques will be illustrated in Section 7.2. The method provides a useful tool to combine the effects of non-precise distribution system loads at the planning stage or to evaluate distortion levels of existing systems.

By assigning typical harmonic currents to residential, commercial and industrial load sectors a simplified harmonic analysis of voltage distortion levels within a distribution system can be completed. The benefit of this analysis is that only a reduced order of system data is required to produce reasonably accurate results. This technique is applicable to most radial MV distribution systems. The harmonic prediction technique has proven to be successful when compared to actual harmonic measurements obtained from a harmonic monitoring programme on a suburban MV radial distribution system. Application to additional study systems with harmonic monitoring data is required to verify the technique. However, the time and cost constraints of this project did not allow for supplementary harmonic monitoring programs to be completed and is an area for further work. The ability to estimate harmonic voltage levels will enable distribution system designers to better understand the harmonic capabilities of distribution systems.

Estimation of harmonic voltage levels within radial distribution systems using the second summation law from [15] has shown to be successful. The value of exponent α

recommended by [16] has produced good results for the study system in this case, but a sensitivity analysis has illustrated that α needs to be chosen carefully.

The work described in this Chapter contributes to the development of distribution system planning guidelines to enable the design engineer to maximise the harmonic capabilities of a distribution system. This can be achieved by optimising parameters such as impedance values of lines and transformers, feeder lengths, allocation of load types to particular connection points, location and size of power factor correction capacitors, and connection of detuning reactors.

Chapter 4

Allocation of harmonic emissions to MV distribution system customers

4.1 Introduction

In the planning stage of an MV distribution system it is necessary to ensure only acceptable levels of harmonic current emissions are contributed from each distribution substation to ensure that the harmonic voltages recommended by standards are not exceeded. With a suitable method for estimating harmonic voltage levels established in Chapter 3, this Chapter will look at extending the method to include a general policy for allocating harmonic emissions.

The harmonic standard IEC 61000-3-6 outlined in Chapter 2 comprises a number of stages and tests to determine harmonic emission allowances for customers connected to MV or HV networks. Stage 1 has three tests that base acceptance on load size as compared to the short circuit level at the connection point. Stage 2 contains three tests of increasing complexity depending on the amount of information known about the system. There is also a Stage 3 where excessively distorting loads are allowed connection on a temporary and precarious basis. It is perceived that most distorting loads will be assessed under Stage 2 of the standard.

The application of guidelines from IEC 61000-3-6 is somewhat more difficult than the superseded standard AS 2279.2 in that it includes time-varying situations and the use of statistical quantities. Of particular importance is the section of the standard concerning loads distributed along a feeder having significant variation in fault level. IEC 61000-3-

6 briefly covers this section in Stage 2, Test 3. The application of the principles suggested by the standard for this section is poorly described and only a non-practical trivial example is provided.

This Chapter presents the guiding principles of IEC 61000-3-6 that are used to allow allocations of harmonic emission to customers distributed throughout a power system. A general approach to harmonic emission allocation for customers spread along several MV feeders with significant variations in fault levels is then developed. This method is designed to encompass the poorly described section of the IEC 61000-3-6. This method is designed such that when applied to the simplest system it aligns exactly with the guidelines outlined in IEC 61000-3-6, while retaining the ability to be applied to far more complex systems.

Allocating harmonic emissions to distribution system customers using the developed method may often require an extensive amount of data. This Chapter will also investigate the use of approximations that may simplify the allocation process and eliminate the need for extensive data. Finally the method is applied to some general study systems to evaluate the harmonic emission allocation technique and the associated simplifying approximations.

In the method described to allocate harmonic emissions to individual customers, the presence of power factor correction (PFC) capacitors is not considered other than as part of the harmonic impedance. PFC capacitors can cause system resonances at problematic frequencies and thus are an important consideration for harmonic analysis, an aspect that will be further investigated in Chapter 6.

4.2 Principles of IEC 61000-3-6

The guidelines specified in the new standard are somewhat more difficult to apply than in the previous harmonics standard AS 2279.2 [12]. These guidelines attempt to ensure allocation of harmonic emission rights to customers is more equitable. A key concept is that customers with the same maximum demand and the same point of common coupling (PCC) are entitled to equal harmonic emission rights. The PCC is defined as the nearest point in the power system to which another customer might be connected.

To account for time variation, customer harmonic contributions and DNSP harmonic levels are generally assessed using the 95th percentile cumulative probability (CP95) level. As the 95th percentile levels are statistical quantities direct summation is inadequate for combining contributions from a number of customers. As mentioned in Chapter 2, two summation laws are proposed by the standard:

(i) The first summation law makes use of diversity factors that require knowledge of the load type and is suited to more individual cases.

(ii) The second summation law is a more general method that accounts for time diversity of the individual loads on a larger scale, and is given by equation (3.1) where the exponent α depends on the harmonic order h, and its recommended value for the 5th harmonic is 1.4.

The second summation law provides the basis for the proposed methodology for allocating harmonic emission rights to customers within an MV distribution system.

Although the standard encourages an equitable allocation of harmonic 'rights' to all customers having the same maximum demand, where customers see different fault levels the question arises as to whether these 'rights' are to equal harmonic voltage,

equal harmonic current, or some other right. It can be shown that allocating equal harmonic voltage rights allows greater use of the system's harmonic absorption capability, but customers towards the end of a weak feeder receive lower currents. The allocation of equal current is fairer but underutilises the harmonic absorption capability. The standard recommends a mid-way policy of equal harmonic power, which can be shown to be equivalent to a harmonic current allocation varying with the square root of the fault level.

IEC 61000-3-6 assumes that the harmonic voltage at the MV level is a combination of the emissions from the MV loads and the background distortion of the HV transmission system. Thus a fraction T_{hMV} of the HV harmonic planning level L_{hHV} must be included in the MV harmonic voltage planning level L_{hMV}. Using the second summation law the acceptable global harmonic contribution G_{hMV} from the MV distribution system alone can be calculated using equation (4.1).

$$G_{hMV} = \sqrt[a]{L_{hMV}^{a} - (T_{hHM} L_{hHV})^{a}} \tag{4.1}$$

An extensive amount of data is required to calculate the value of T_{hHM} as per IEC 61000-3-6. The most conservative approach is to assume all upstream harmonic voltages are transferred to the downstream. Thus fraction T_{hHM} is assumed here as unity.

For the purpose of this work only the 5^{th} harmonic is considered as it has been shown to be the most predominant and problematic for most MV distribution systems [21, 23]. Thus, assessment is made on the basis of the 5^{th} harmonic alone. Three reservations need to be considered [60].

(i) In the future there may be a change in power electronic technology that will provide a spectrum of current emission different to present day,

(ii) Relatively small high frequency harmonics may provide exceedances of limits as IEC planning levels become smaller with increasing frequency, and

(iii) Resonances caused by PFC capacitors without detuning reactors can cause amplification around a particular harmonic order giving prominence to a harmonic order in a higher frequency range.

4.3 The allocation constant *k*

When loads are spread out along a feeder and connected to points having different fault levels, allocation of harmonic current emissions becomes difficult and the methods of the standard need to be extended. To achieve the constant harmonic power policy recommended in Section 4.2, the harmonic current emissions need to be allocated in proportion to maximum demand S_i and inversely proportional to the square root of the harmonic impedance Z_{hi} at the PCC. A suitable strategy is to allocate harmonic current emissions E_{Ihi} using equation (4.2)

$$E_{Ihi} = \frac{kS_i^{\frac{1}{\alpha}}}{\sqrt{Z_{hi}}} \tag{4.2}$$

where *k* is termed the allocation constant [60]. The same value of *k* is used for all loads supplied from a common substation. Its value is chosen such that when the substation reaches its maximum capacity, and all loads are contributing their maximum permitted harmonic contribution, the magnitude of the considered harmonic voltage will have a value not exceeding the limits suggested by IEC 61000-3-6. It is easy to show that this voltage will occur at the far end of the 'weakest' feeder.

The power $^1/_\alpha$ is used in equation (4.2) for the maximum demand as a consequence of customers connected at the same PCC typically consisting of similar or identical types of loads. Thus for the case of all customers connected directly to the same PCC the loads combine using the summation law to produce an undiversified aggregate load.

Exact calculation of k is possible but complex and requires an enormous amount of data. To illustrate this process a distribution system with each non-linear load modelled as an equivalent harmonic current source is considered. At harmonic order h, the resulting voltages are related to the currents as shown by equation (4.3).

$$[V_h] = [Z_h][I_h] \tag{4.3}$$

In equation (4.3) $[V_h]$ is the unknown harmonic voltage vector, $[Z_h]$ is the harmonic impedance matrix, and $[I_h]$ is the harmonic current vector. For a system with N nodes the expanded form of equation (4.3) is as follows

$$\begin{bmatrix} V_{h1} \\ V_{h2} \\ \vdots \\ V_{hi} \\ \vdots \\ V_{hN} \end{bmatrix} = \begin{bmatrix} Z_{h11} & Z_{h12} & \cdots & Z_{h1j} & \cdots & Z_{h1N} \\ Z_{h21} & Z_{h22} & \cdots & Z_{h2j} & \cdots & Z_{h2N} \\ \vdots & \vdots & & \vdots & & \vdots \\ Z_{hi1} & Z_{hi2} & \cdots & Z_{hij} & \cdots & Z_{hiN} \\ \vdots & \vdots & & \vdots & & \vdots \\ Z_{hN1} & Z_{hN2} & \cdots & Z_{hNj} & \cdots & Z_{hNN} \end{bmatrix} \begin{bmatrix} I_{h1} \\ I_{h2} \\ \vdots \\ I_{hj} \\ \vdots \\ I_{hN} \end{bmatrix}$$

Using direct addition the harmonic voltage at node i is given by equation (4.4).

$$V_{hi} = \sum_{j}^{N} Z_{hij} I_{hj} \tag{4.4}$$

As the 95th percentile level voltages are combined using the second summation law equation (4.4) must be rewritten to include the exponent α as shown by equation (4.5).

$$V_{hi}^{a} = \sum_{j}^{N} Z_{hij}^{a} I_{hj}^{a} \tag{4.5}$$

Note that the phase of the harmonic currents and voltages are not considered in equation (4.5) but are assumed to be taken care of by the use of the summation law exponent α.

Evaluating equations (4.2) and (4.5) and assuming the maximum harmonic voltage to be less than the global harmonic contribution G_{hMV} the value of k can be determined from equation (4.6).

$$k = \frac{G_{hMV}}{\max_i \left(\sum_j^N \frac{Z_{hij}^a \cdot S_j}{Z_{hjj}^{\frac{a}{2}}} \right)^{\frac{1}{a}}} \qquad (4.6)$$

Evaluation of equation (4.6) requires the projected maximum demand and system harmonic impedance at each PCC along every feeder within the local MV distribution system. To reduce the need for an extensive amount of data some assumptions can be made to determine an approximate value of the harmonic allocation constant k.

4.4 Incomplete data approach

Although the 'weakest' feeder is strictly defined by equation (4.6), in most cases it will also be the feeder with the lowest fundamental voltage when the system is loaded to the fullest extent. Knowledge on the 'weakest' feeder allows an approximation to k to be obtained when other data is not readily available. Three methods of approximating k when limited data is available are provided here:

(i) A pessimistic approach assuming all loads other than the 'weakest' feeder loads are connected to the zone substation busbar (equivalent to assuming all other feeders to be of zero length).

(ii) An approach when all feeders are similar, i.e. all feeders are assumed to have the same loading and fault level distribution as the 'weakest' feeder.

(iii) The use of (i) incorporating correction factors.

4.4.1 A pessimistic approximation to k

To illustrate how to reduce the amount of data required to calculate the value of the allocation constant k the radial MV distribution system shown in Figure 4.1 is considered.

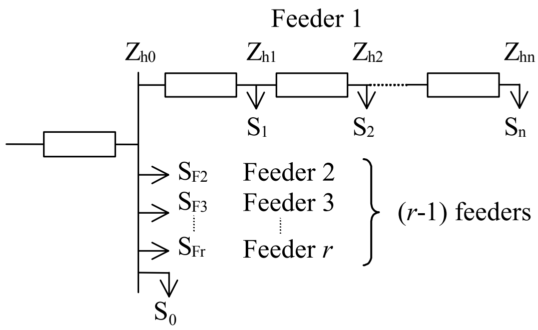


Figure 4.1 Example radial MV distribution system
(S_n in feeder 1 is maximum expected demand at each takeoff point;
S_{Fr} is the maximum expected loading on feeder r)

To simplify the expression for k given by equation (4.6) it is assumed that all feeders other than the 'weakest' feeder have zero harmonic impedance, i.e. all loads from the other feeders are connected at the supply busbar. This assumption simplifies the amount of data required considerably and can be justified realising that the assumption overestimates the current on the remaining feeders and hence will be pessimistic.

Assuming that the highest harmonic voltage level will occur at the end of the 'weakest' feeder the value of k can be estimated using equation (4.7).

$$k \approx \frac{G_{hMV}}{\left(\sum_{i=1}^{n} S_i Z_{hi}^{\frac{a}{2}} + S_0 Z_{h0}^{\frac{a}{2}} + (S_{F2} + ... + S_{Fr}) Z_{h0}^{\frac{a}{2}} \right)^{\frac{1}{a}}} \tag{4.7}$$

The approximation to k consists of three terms in the denominator. These terms are the harmonic contribution from the 'weakest' feeder, the harmonic contribution from any local load at the zone substation busbar and the harmonic contribution from the loads on the other (r-1) feeders.

This approximation requires the projected maximum demand of each customer (S_i) and the system harmonic impedance (Z_{hi}) at all PCC points along the 'weakest' feeder, and also an estimate of the total maximum demand from the other feeders (S_{F2}, S_{F3}, .., S_{Fr}). Further, the approximation will always ensure a slightly pessimistic result for the value of k since it underestimates Z_{hi} for the other feeders and therefore allocates too much when equation (4.2) is applied.

4.4.2 Approximation to k when all feeders are similar

Various studies using the approximate value of k from equation (4.7) have shown that this approach is most inaccurate when there are a number of weak feeders all of similar nature. In the case where all feeders are similar in loading and impedance, a less pessimistic approximation to k may be calculated.

In this case the harmonic contribution at the zone substation busbar due to each of the other feeders will be equal to that of the 'weakest' feeder. To reflect this the third term in the denominator of equation (4.7) is modified to give equation (4.8).

$$k \approx \frac{G_{hMV}}{\left(\sum_{i=1}^{n} S_i Z_{hi}^{\frac{a}{2}} + S_0 Z_{h0}^{\frac{a}{2}} + (r-1) \sum_{i=1}^{n} S_i \frac{Z_{h0}^{a}}{Z_{hi}^{\frac{a}{2}}} \right)^{\frac{1}{\alpha}}} \tag{4.8}$$

Less data is required to evaluate k using equation (4.8) than is required for equation (4.7) but the application is useful only when all feeders are of similar nature. It will be shown in Section 4.5 that this method provides the optimal current allocation for the trivial example provided in IEC 61000-3-6 standard. However, it is perceived that this approximation to k will be rarely appropriate for real systems.

4.4.3 Correction factors for the pessimistic approximation of k

By considering the relationship between the harmonic allocation constant and ratio of impedance at either end of a feeder the pessimistic value of k from equation (4.7) can be corrected to be less pessimistic if the additional data is available.

By substituting the ratio of sending end to receiving end harmonic impedance into the exact expression for k given by equation (4.6) a suitable adjustment factor can be determined. To adjust the value of k from equation (4.7) to be less pessimistic the harmonic emission contribution from the other feeders, the 3rd component of denominator in equation (4.7), should be divided by the correcting factor given by equation (4.9).

$$F_{hr} = \left(\frac{Z_{hnr}}{Z_{h0}} \right)^{\frac{1}{2\alpha}} \tag{4.9}$$

where Z_{hnr} is the harmonic impedance at the end of feeder r. While this expression is rather complex it may be suited to certain applications where additional data is

available. If the system impedance (Z_{hnr}) at the end of each of the other feeders is not known a rule-of-thumb value of √2 for F_{hr} has been found to be suited to most systems.

4.5 Case study examples

To illustrate the application of the harmonic allocation constant *k*, two example systems are provided. The first is a homogenous example from the IEC 61000-3-6 standard. The homogenous example demonstrates the agreement of the harmonic allocation constant method with the IEC 61000-3-6 approach, incorporating the various correction factors. For the homogenous case the IEC 61000-3-6 approach matches the exact approach outlined in Section 4.3. The second case study is a distribution system consisting of a reduced number of feeders, but with greater variation in the loading and fault levels along each feeder. The additional complexity in the variation of loading and feeder strength of this example is used to demonstrate the deficiencies in the IEC 61000-3-6 approach.

4.5.1 Homogenous example

The harmonic allocation constant method is applied in conjunction with each of the consecutive methods outlined in the IEC 61000-3-6 standard, to the example distribution system provided in Annex E of IEC 61000-3-6. The 20kV distribution network example is shown in Figure 4.2.

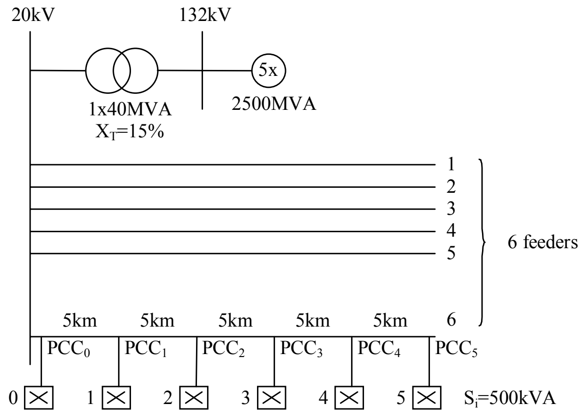


Figure 4.2 Homogeneous MV distribution network with six identical feeders

The system consists of six 20kV overhead feeders of 25km length fed by one HV/MV 40MVA transformer. The 50Hz inductive reactance of the lines is assumed to be approximately 0.35Ω/km and the resistance is ignored. It is assumed that all loads are directly supplied at MV and the system is at full capacity.

The example calculations are performed only for the 5^{th} harmonic. The planning levels for the 5^{th} harmonic are assumed to be L_{hMV}=5% and L_{hHV}=2% as per IEC 61000-3-6. Using these values and the recommended value of α=1.4 for the 5^{th} harmonic the resulting value for the global harmonic voltage emission G_{hMV} from equation (4.1) is 3.97%.

All feeders in the example are identical, thus any feeder can be chosen as the 'weakest' feeder for the calculation of the harmonic allocation constant, k. Table 4.1 shows the results from an exact calculation of k, and the three approximation methods described previously. As all feeders are identical in this example the approximation using the assumption of similar feeders produces the same value as the exact value of k.

Table 4.1 Allocation constant k using different calculation methods

Calculation method	**Allocation constant *k***
I. Exact value	9.20%
II. Pessimistic value	6.88%
III. Similar feeders value	9.20%
IV. Adjusted pessimistic value	9.09%

Table 4.1 suggests the adjusted pessimistic value gives good results as compared to the exact value of *k*. The adjusted pessimistic approximation should be used when feeders are not all similar and only limited data is available.

The resulting harmonic current allocations of each load along the feeder are shown in Figure 4.3 for the different methods of calculating *k*.

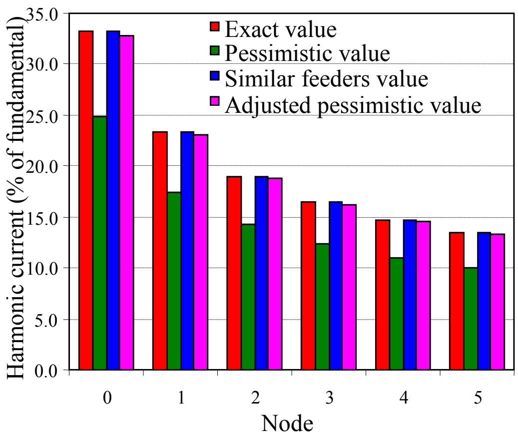


Figure 4.3 Harmonic current allocations using methods I-IV to calculate *k*

As can be seen in Figure 4.3 each approximation method provides a suitable value for *k*. The voltages arising from the allocated harmonic currents calculated using the second summation law are shown in Figure 4.4.

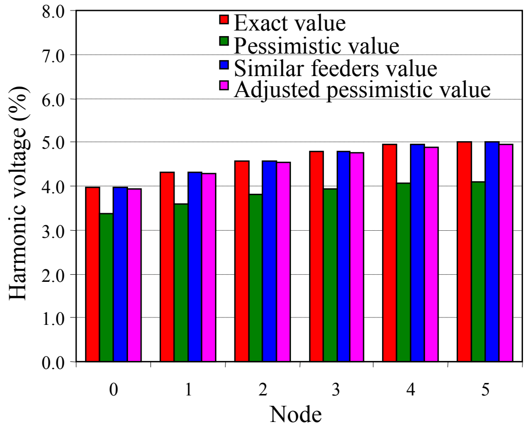
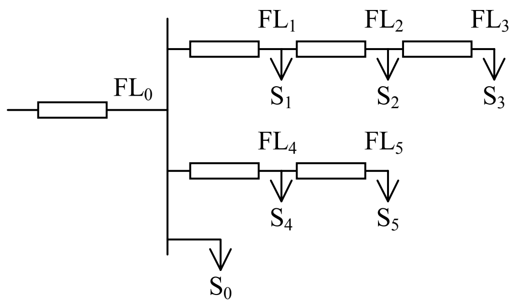


Figure 4.4 Harmonic voltages arising at each node using methods I-IV to calculate *k*

4.5.2 Extreme example

To fully test the application of the proposed method, and highlight the deficiencies of the IEC 61000-3-6 method, the system in Figure 4.5 containing one weak feeder, one strong feeder and a large load at the busbar can be considered.



FL_0=250MVA	S_0=5MVA
FL_1=61MVA	S_1=1MVA
FL_2=35MVA	S_2=1MVA
FL_3=24MVA	S_3=1MVA
FL_4=222MVA	S_4=1MVA
FL_5=200MVA	S_5=1MVA

Figure 4.5 Extreme MV distribution system example

As the top feeder in Figure 4.5 is easily identifiable as the weakest feeder the calculation for the harmonic allocation constant, *k* is

$$k \approx \frac{G_{hMV}}{\left(\sum_{i=1}^{n} S_i Z_{hi}^{\frac{\alpha}{2}} + S_0 Z_{h0}^{\frac{\alpha}{2}} + (S_{F2} + S_{F3} + \ldots + S_{Fr}) Z_{h0}^{\frac{\alpha}{2}}\right)^{\frac{1}{\alpha}}}$$

$$\approx \frac{3.97\%}{\left(0.02\cdot 4.10^{\frac{1.4}{2}} + 0.02\cdot 7.14^{\frac{1.4}{2}} + 0.02\cdot 10.42^{\frac{1.4}{2}} + 0.10\cdot 1.00^{\frac{1.4}{2}} + (0.02+0.02)\cdot 1.00^{\frac{1.4}{2}}\right)^{\frac{1}{1.4}}}$$

$\approx 7.97\%$

The acceptable harmonic emissions for each of the loads are calculated using the resultant value of *k*. For example, for the load at node 3 the 5th harmonic current allocation is

$$E_{Ih3} = \frac{kS_3^{\frac{1}{\alpha}}}{\sqrt{Z_{h3}}} = \frac{7.97\cdot 0.02^{\frac{1}{1.4}}}{\sqrt{10.42}} = 0.15\% \text{ (on a 50MVA base)} = 7.56\% \text{ (on own base)}$$

Table 4.2 provides the harmonic emission calculation results using the IEC 61000-3-6 standard approaches and the proposed allocation method.

Table 4.2 Comparison of different allocation schemes for the extreme case

PCC node No.	Load Size MVA	Fifth harmonic impedance Z_h=5 (pu)	Stage 2, Test 1 E_{Ihi} (%)[1)]	Stage 2, Test 3 E_{Ihi} (%)[1)]	Proposed Stage 2, Test 3 (%)[1)]
0	5	1.00	24.2	5.9	15.4
1	1	4.10	9.3	14.4	12.0
2	1	7.14	5.4	10.9	9.1
3	1	10.42	3.7	9.1	7.6
4	1	1.13	34.0	27.6	23.0
5	1	1.25	30.6	26.2	21.8
Resulting harmonic voltages using the above current allocations are given below					
Resulting U_{hi} at Node 0			4.2%	2.9%	3.7%
Resulting U_{hi} at Node 3			4.9%	5.0%	5.0%
[1)] % of load current of each single consumer of maximum demand S_i relative to own base					

In this example the disadvantages of the previous IEC 61000-3-6 methods are illustrated. In the first approximation, Stage 2, Test 1, it can be noted that the harmonic emission allowance for the far end load on the weakest feeder is quite small and the loads on the strong feeders receive a much larger allowance. In Stage 2, Test 3 the allocation for the loads at the end of the weakest feeder is seen as being fairer. However,

the emission allocation is not determined by load size, and thus the allowance given to the local load on the busbar is small considering the load is half the system capacity.

The proposed method is a good compromise between the other two methods in that the local load at the busbar receives a larger proportion of the harmonic emission allowance as it represents a large proportion of system capacity. At the same time the loads at the end of the weakest feeder have received a considerable emission allowance.

4.6 Choice of allocation policy

To demonstrate the effect of applying the different allocation policies to customers along a feeder the results of applying equal harmonic current, equal harmonic power and equal harmonic voltage policies for the example distribution system of Section 4.5.1 are analysed.

The harmonic current allocations from applying the equal harmonic current, power and voltage policies are shown in Figure 4.6.

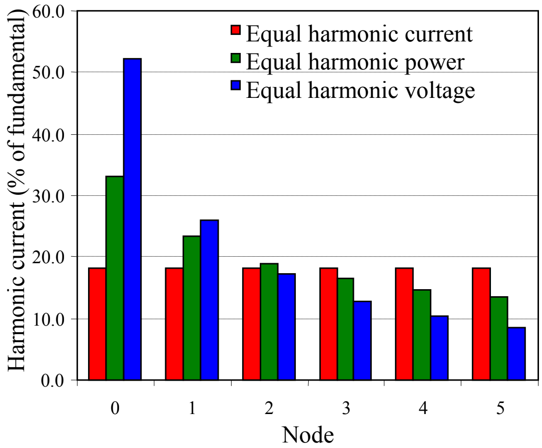


Figure 4.6 Acceptable emissions for equal harmonic current, power and voltage

Summing the total allocation of harmonic current from all loads in the system provides a measure of how well the distribution system's absorption capability is being utilised. For the case study example in Section 4.5.1 the use of equal harmonic power and equal harmonic voltage policies increase the amount of total harmonic current allowed to be injected into the system by 10% and 15% respectively. The equal harmonic voltage allocation however over penalises the customer at the end of the feeder (node 5).

Taking the increase in total harmonic current into consideration and comparing the different values in Figure 4.6 it can be found that the allocation using the equal harmonic power policy has provided a suitable increase in the systems harmonic capacity without unduly penalising customers at the end of the feeder. The voltages arising from the different current allocations are shown in Figure 4.7.

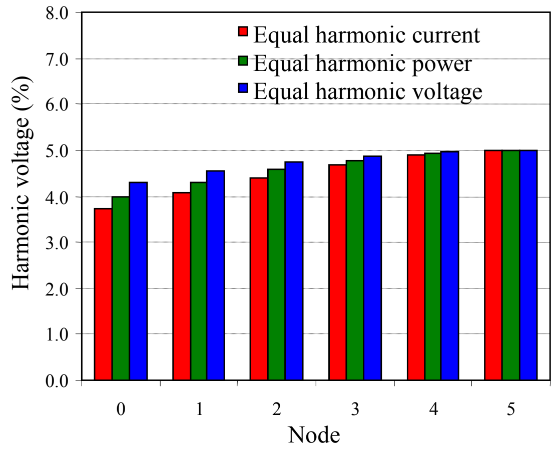


Figure 4.7 Harmonic voltages arising at each node using different allocation policies

4.7 Summary

A generalised method has been developed to extend the IEC 61000-3-6 approach of allocating allowable harmonic emissions to the case where customers are distributed along an MV distribution system feeder having significantly different fault levels. The method involves the determination of an 'allocation constant' using the agreed loading

levels of all customers and the system harmonic impedances. The allocation of harmonic emission levels using the equal harmonic power rights policy has shown to be the most useful for determining an ‘allocation constant’ that is ‘fairest’ to all customers. The work presented in this Chapter is an area that IEC 61000-3-6 fails to cover adequately making the AS/NZS 61000.3.6 standard unsuitable for application to real systems.

The approach of allocating emissions to customers described above typically requires an extensive amount of data. This data may not always be available to the DNSP engineer. An extension to the generalised method has thus been completed to cater for the complex situation where only limited data is available. This is achieved by looking at several extreme cases that categorise the most common MV distribution system feeder configurations, and through the use of correction factors for the 'allocation constant'.

The developed method has been applied to several study systems. This has allowed the approximate methods to be compared against the exact form for a range of cases, where the approximate methods have been shown to provide acceptable results when only limited data is available. Application to real systems, including monitoring of the subsequent performance, is an area for further work.

Chapter 5

Identification of MV distribution system aggregated load models

5.1 Introduction

Accurate harmonic modelling of distribution systems requires a detailed knowledge of the system parameters and the associated loads connected to the system. Often such details are unavailable or impractical to obtain. Chapter 3 has demonstrated that pragmatic modelling of distribution systems can often provide sufficient accuracy when only limited data is available. To obtain data on the typical behaviour of customer loads for pragmatic modelling, investigations into a number of typical distribution systems must be first carried out.

As part of this thesis a harmonic monitoring programme was completed on a typical MV distribution system owned by Integral Energy with the intention of establishing the harmonic behaviour of aggregates of load at MV distribution system substations. The monitoring involved measurements of the harmonic current and voltage from the residential, commercial, and industrial load sectors. It was proposed that simultaneous measurements of current and voltage from the different load sectors would allow the effect on the net distribution system harmonic voltages to be determined. In addition, a further purpose of the monitoring programme was to benchmark present day harmonic voltage distortion levels in a typical MV distribution system.

Several harmonic monitoring programmes have been undertaken both overseas [32-34] and in Australia [22], however there seems to be no consistent approach to conduct,

analyse and present the monitoring results. The monitoring programme undertaken in relation to this thesis is the first systematically conducted monitoring programme of its kind to be completed in Australia, including measurement of both harmonic current and voltage at each of the monitoring locations. As a preliminary to the monitoring programme being implemented four major aspects had to be considered:

(i) Choice of harmonic monitor,

(ii) Choice of monitoring sites,

(iii) Which harmonics to measure, and

(iv) Processing and presentation of results.

This Chapter presents discussion on items (i)-(iv). Several of the monitoring instrument types considered for implementation of the monitoring programme are tested to ensure consistency in reporting harmonic voltage levels. While final selection of the type of monitoring instrument and monitoring sites was not completed as part of this thesis a short commentary on the process is presented. Preliminary results from the monitoring program are used to determine which harmonics are of most importance and thus should be recorded as part of the study.

An investigation into the trends of the harmonic voltages and currents from the residential, commercial and industrial load sectors is performed to identify a suitable measure for pragmatic customer load modelling. A small amount of the data collected from the monitoring programme is used to both establish the load models used in Chapter 3 and to verify the accuracy of using such models to predict harmonic distortion levels in distribution systems. Processing and presentation of other significant results from the monitoring programme are also included in this Chapter.

It is proposed that the monitoring programme would give a clear picture of present day harmonic levels on MV distribution systems and also provide some indication as to the growth of harmonic levels and the prevailing headroom that remains before limits recommended by standards are exceeded.

5.2 Selection of monitoring instrument

There are a number of instruments available in the present market for making a frequency domain study of a time-varying system. The instruments range from versions with limited features to fully expandable models with various signal-processing options. With such a diverse range of instruments available it is important to understand the requirements of a harmonic monitoring programme before the instrument selection is carried out.

5.2.1 Relevant standards

The standard outlining the measurement techniques and accuracy requirements of harmonic monitoring instruments in Australia is AS/NZS 61000.4.7 [59], an adaptation of IEC 61000-4-7 [20]. This standard is quite complex in that it requires a strictly specified sampling window and calculation of harmonic orders up to the 50^{th}. The standard classifies the measurement requirements according to the rate of change of the harmonic levels being recorded. As distribution system loads change continually the appropriate classification for most harmonic monitoring programs is 'fluctuating harmonics'. Under 'fluctuating harmonics' classification, IEC 61000-4-7 specifies that the sampling window be strictly synchronized, must not overlap and there must be no gaps, i.e. every cycle of the supply in the survey period must be sampled exactly once.

There are some practical difficulties in meeting the IEC 61000-4-7 standard with presently available instrumentation as the standard is relatively new and some parts are not clearly expressed [17]. Also there are no default tests that can be used to establish if a particular instrument meets the standard at this stage. Consequently compliance with the measurement standard of IEC 61000-4-7 could not be confirmed for the available harmonic monitoring instruments at the time of instrument selection.

As the purpose of monitoring is to establish present day harmonic levels with reference to present day limits it was necessary to understand the requirements of the harmonic standards that the monitoring results would be compared against. IEC 61000-3-6 [15] requires measurement of the following parameters for compliance from a DNSP perspective

(i) The greatest 95% probability daily value of $U_{h,vs}$ (rms value of individual harmonic components over 'very short' 3 second periods) should not exceed the planning level.

(ii) The maximum weekly value of $U_{h,sh}$ (rms value of individual harmonics over 'short' 10 minute periods) should not exceed the planning level.

(iii) The 99.9% weekly value of $U_{h,vs}$ should not exceed 1.5 to 2 times the planning level.

The recommended planning levels from IEC 61000-3-6 where given in Table 2.4 of Chapter 2. The above requirements (i)-(iii) are designed for strict assessment of the harmonic levels in a DNSP's power system. However logging of 'very short' 3 second intervals over a period of one week was beyond most power quality instruments due to the intense memory requirements. Without constantly downloading data via a

communications network 3 second logging filled the memory within 2 hours for the instruments that had a ‘very short’ interval selection. Expansion of memory obviously needs to be addressed in future designs of harmonic monitoring instruments.

Due to the restricted memory of the monitoring instruments a compromise between (a) selection of parameters to record and (b) at what logging intervals had to be established. For the purpose of the monitoring programme it was desired to establish weekly harmonic current and voltage trends at each of the monitoring sites. At least two weeks of data would be required to establish weekly patterns. For most of the available monitoring instruments logging data at 10 or 15 minute intervals suited the available instrument memory. Logging at such intervals can be justified knowing that damage due to harmonics usually occurs over longer periods of time, i.e. high levels of harmonics for a period of less than 3 seconds will not significantly affect overheating of induction motors. It was also assumed that approximate trends of harmonic loads could be established without adopting a ‘very short’ interval for logged data.

5.2.2 Instrument accuracy

The selection process for the harmonic monitors used in the benchmark survey involved laboratory tests to confirm the consistency and limitations of the various makes of monitoring instruments (for confidentiality reasons the meters will be referred to as Meters A-E). These tests included the following

(i) Comparison tests involving simultaneous logging of a laboratory supply outlet by the available monitors over a period of one day, and

(ii) Logging constant voltage harmonics from a programmable waveform generator including measurement comparisons with a Voltech PM3000A (a power analyser

of high accuracy but inadequate to record time-varying harmonics over an extended period in the field).

Comparison tests revealed that some of the available instruments are seemingly unreliable in recording fluctuating harmonics. This was possibly as a result of their sampling process, where harmonics are recorded using a snapshot without any averaging. Results from some of the monitoring instruments during the comparison tests are illustrated in Figures 5.1 and 5.2. Meter C shows definite operational problems in Figure 5.1 with recordings of near zero harmonic levels during the tests for the 5th harmonic. In Figure 5.2 Meter F was found to give spurious results with the magnitude of the higher order harmonics on the laboratory supply possibly being too small in magnitude for the resolution of the instrument.

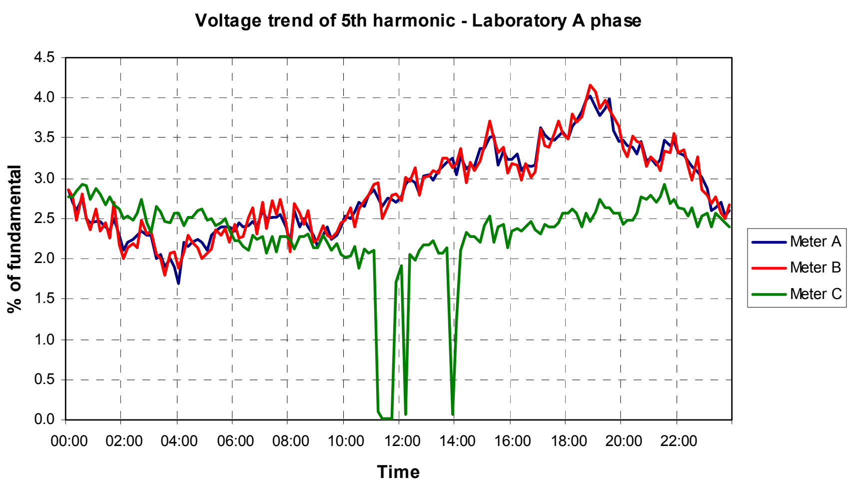


Figure 5.1 Comparison of harmonic monitoring instruments at 5th harmonic [17]

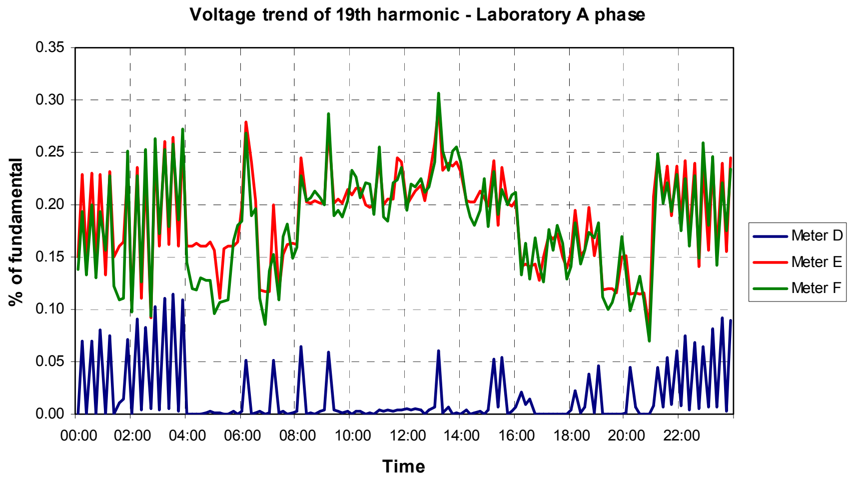


Figure 5.2 Comparison of harmonic monitoring instruments at 19th harmonic

The waveform generator, which is essentially a programmable voltage source inverter [61], was used to check coherence between the individual meters for quasi-stationary harmonic voltages. Harmonics of various phase and magnitude were applied to the monitoring instruments. Of the monitoring instruments tested three gave spurious results as shown in Figures 5.3 and 5.4. Meter C produced consistently higher harmonics than the PM3000A and other instruments. It was noted that all meter manufacturers were unwilling to provide an accurate description of how harmonic calculations were performed by the instruments. Meters A and E show fluctuating harmonic voltage levels when the PM3000A and other instruments record levels as near constant. The magnitude of these errors is small and it is suspected that they are caused by higher order harmonics (near 10kHz) produced by the waveform generator causing some difficulties with measurement of the fundamental waveform by the instruments.

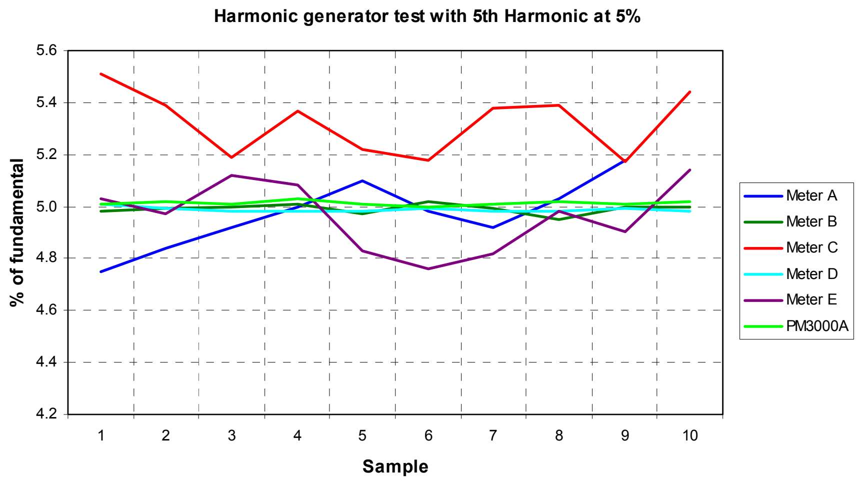


Figure 5.3 Waveform generator test of monitoring instruments at 5^{th} harmonic

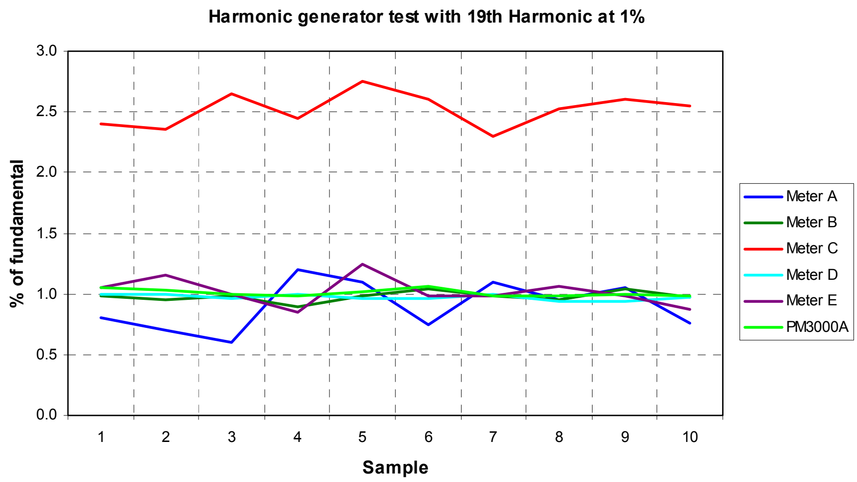


Figure 5.4 Waveform generator test of monitoring instruments at 19^{th} harmonic

The different makes of instruments becoming available for different periods of the testing phase complicated the evaluation. In one set of tests it was found that only one of the three monitors being evaluated was able to give non-spurious results for both tests, however most instruments provided reasonable consistency for the waveform generator tests. It was also noted that some instruments performed well at lower frequencies but poorly at higher frequencies such as at the 19^{th} harmonic.

5.2.3 *Instrument price*

The price of the instruments considered for the harmonic monitoring programme varied from $1,500 to $9,000 for different makes and models. Software capabilities and flexibility of the meters were the greatest price driving factors. Accuracy of the instruments was unable to be confirmed and thus no comparison can be made between price and accuracy. From a DNSP's perspective an instrument that is capable of performing all required tasks at the lowest price would be a compelling reason for its selection.

5.2.4 *Further instrument considerations*

Once the requirements of the standards used to evaluate results are established and a price range is settled, there are still a number of factors to consider before the appropriate monitoring instrument can be selected. Some further important considerations when selecting a harmonic monitor include the following (in no particular order):

(i) Types and number of parameters which can be recorded,

(ii) Available memory for data storage,

(iii) Data storage and transfer formats,

(iv) Sampling speed,

(v) Environmental requirements (such as ruggedness), and

(vi) Additional functions.

The Integral Energy system is spread out over an area of 24,500 square kilometres and the University of Wollongong is situated near one extreme of the system. Thus, for geographical reasons it was important that the harmonic monitoring instruments had

remote set-up, initiation and downloading capabilities, as it was possible that the chosen monitoring site would be a considerable distance away from the University.

For numerous cases monitoring programmes will not be performed solely for the purpose of monitoring harmonics but rather as a component of a complete power quality survey. As such there may also be additional factors that should be considered in instrument selection not mentioned here. In the future it is perceived that most standard customer metering instruments will contain functionality that will allow utilities to monitor power quality disturbances such as harmonics on a continuous basis.

5.2.5 Instrument selection

The instrument used for the harmonic monitoring programme was selected through consultation with Integral Energy. Using the criteria discussed in the previous sections, including results from the earlier instrument tests, the meter selected was an EDMI Mk3 Energy Meter from Electronic Design and Manufacturing International Pty. Ltd, as shown in Figure 5.5. Further details of the EDMI Energy Meter can be found in Appendix B.

Figure 5.5 EDMI 2000-04XX Energy Meter [62]

5.3 Monitoring site selection

The purpose of the harmonic monitoring programme was to produce results that are typical to MV distribution systems as a whole rather than being specific to an individual MV distribution system. Ideally a number of study systems should be used to produce such results. However, due to limited access to DNSP and customer systems, availability of monitoring instruments, time constraints, and financial limitations, only one system could be monitored for this project. The site selection process was critical to extract results that would be representative of typical MV distribution systems.

The criteria for selecting a suitable monitoring site were that the distribution system had high impedance and thus anticipated harmonic problems, and a good mix of residential, commercial and industrial load types. It was also considered that future measurements could be made to establish the growth of harmonics with the introduction of new load types rather than growth in load. For this reason a distribution system that was nearly fully loaded and unlikely to change configuration over the next few years was preferred. To isolate harmonic emission contributions from residential, commercial and industrial load types it was hoped that a substation could be found with three feeders consisting solely of each load type. It was initially hoped that a zone substation could be found where measurements at all sites could be completed at 11kV.

In consultation with Integral Energy a suitable zone substation was found for the harmonic monitoring programme to satisfy the necessary criteria. Homepride is a typical 33/11kV zone substation in the Liverpool area of Sydney that supplies ten 11kV radial feeders. The zone substation is supplied at 33kV from the bulk supply point of Western Liverpool transmission network. Figure 5.6 gives the layout of the zone

substation and feeder system for the harmonic monitoring programme. The substation maximum demand was approximately 22MVA (80% of capacity with N-1 transformer redundancy) and the short circuit level at the 11kV busbar was approximately 213MVA. The high impedance zone substation transformers, each having a leakage reactance of approximately 17%, combined with some substantially long overhead feeders suited the requirement of the distribution system to have relatively high impedance.

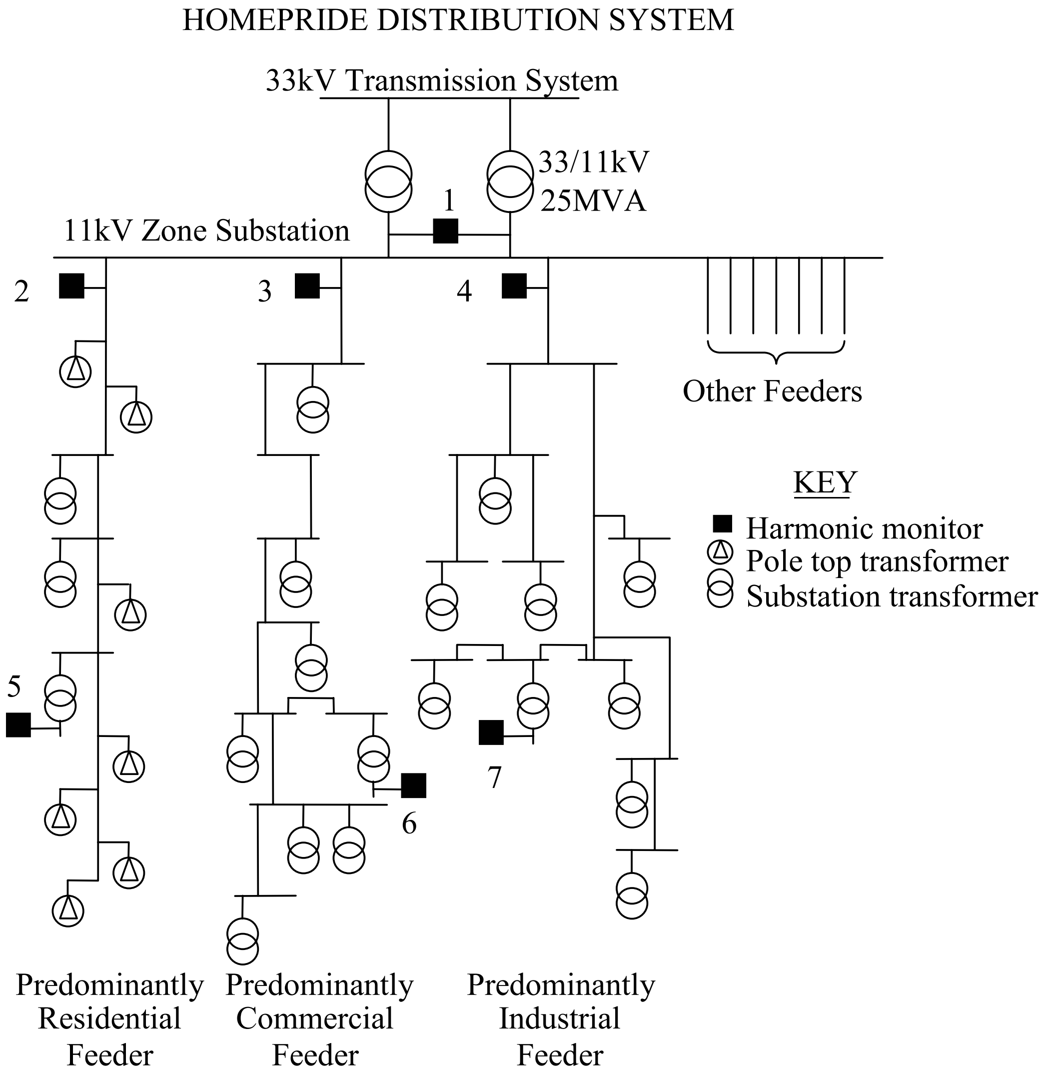


Figure 5.6 Single line diagram illustrating the Homepride zone distribution system

Typically most MV distribution systems in Australia are radial in structure while HV and EHV systems tend to be meshed. With the Homepride distribution system being

radial it was decided to install 7 monitors, a monitor at each of the residential, commercial and industrial sites, a monitor at the sending end of the three individual feeders, and a monitor at the zone substation incoming supply. The sites to be monitored within the distribution system are outlined in Table 5.1.

Table 5.1 Harmonic monitoring instrument positions

Site ID	*Purpose of monitoring instrument*
1	Measure total voltage and current at the 11kV zone substation busbar
2-4	Measure the voltage and current at sending end of each of the predominantly residential, commercial and industrial feeders
5-7	Measure voltage and current at typical residential, commercial and industrial sites along the feeder

Measurements at sites 1-4 were made by means of the substation voltage and current transformers. It is suggested in [59] that there should be no problems with the voltage transformers used as they were magnetic type. Work presented in [63] had established that the current transformers would have adequate bandwidth for these measurements. Further, on older Integral Energy distribution systems, metering voltage and current transformers are not usually available for the B phase at the 11kV busbar, thus at sites 1-4 measurements were to be recorded for V_{ab}, V_{cb}, I_a and I_c only.

The EDMI Mk3 Energy Meter was not weatherproof and had to be connected at an enclosure. The MV side of distribution transformers is not accessible for most metering applications. Instead sites 5-7 were monitored on the LV side of 11kV/415V distribution transformers using direct connection for the voltage leads and clip-on current transformers for the current sensing. All three line-to-neutral voltages and line currents were recorded at the LV locations [17].

Sites 1-4 in Figure 5.6 are all within the substation at the sending end of the feeders identified as being of a predominant load type. Site 5 was the last enclosed type substation (pad mount) along the feeder route located approximately 2km from Homepride zone substation. The remaining 2km of feeder is overhead with pole-top mounted transformers. The site fed a recently developed residential area. Site 6 supplies a Westfield shopping centre with a couple of large supermarkets and many small shops. Site 7 supplies a factory manufacturing paper product such as paper towels, toilet paper and tissues.

Based on distribution customer details obtained from Integral Energy the three feeders in question have an estimated proportioning of load type as follows:

(i) Predominantly residential feeder – 85% residential, 15% commercial

(ii) Predominantly commercial feeder – 90% commercial, 10% residential

(iii) Predominantly industrial feeder – 75% industrial, 20% commercial, 5% residential

The load breakdown of the three LV sites is estimated to be:

(i) Site 5: Residential transformer – 90% residential, 10% commercial

(ii) Site 6: Commercial transformer – 100% commercial

(iii) Site 7: Industrial transformer – 100% industrial

5.4 Selection of harmonics to measure

The memory capabilities of the EDMI Mk3 Energy Meter at the time of purchase limited recordings to the fundamental current and voltage in each phase, the current and

voltage THD in each phase, and only three individual harmonics in each phase. For the initial harmonic monitoring programme the harmonics chosen were as follows:

(i) 5^{th} harmonic: had been shown to dominate in previous national and international harmonic surveys [21, 22, 54] and perceived as the most problematic.

(ii) 19^{th} harmonic: highest harmonic of importance for the then existing Australian harmonic standard AS 2279.2 [12]

(iii) 49^{th} harmonic: close to the highest harmonic of importance for the new Australian harmonic standard AS/NZS 61000.3.6 [16]

After the initial monitoring programme had been completed it was found that the 19^{th} harmonics and 49^{th} harmonics were of insignificant magnitude. Some spot checks of the harmonic spectrum of the current and voltages at the individual monitoring sites found that the 3^{rd} and 7^{th} harmonics were the next most significant harmonics. The harmonic monitors were then reconfigured to record the 3^{rd} and 7^{th} harmonic currents and voltages at each of the monitoring sites.

The harmonic monitors were set to record the 3 second average fundamental and harmonic voltages and currents on each of the three phases. The initial monitoring programme was planned to produce two weeks of harmonic data. The memory restrictions of the monitoring instruments dictated that each parameter was recorded only every 15 minutes. This was later shortened to every 10 minutes to more closely comply with IEC 61000-3-6 but had the disadvantage of having to download twice to obtain a full two weeks of data. The monitoring programme was to be repeated after 12 months to obtain an indication of harmonic growth. Seasonal effects of load types, such

as air-conditioners in summer, created the need to download more frequently to illustrate the harmonic levels through different seasons.

5.5 Results from harmonic measurements at selected sites

The monitoring programme was completed in three phases:

(i) Four weeks of monitoring to benchmark harmonic levels and the contributions from the residential, commercial and industrial load sectors,

(ii) Two weeks of monitoring after twelve months from the initial study and then annually for the duration of the project with the aim to establish growth of harmonic distortion levels, and

(iii) Ongoing monitoring to establish seasonal changes, global behaviour of the different load types, and to confirm the validity of the monitoring programmes in (i) and (ii) above.

The data retrieved from the harmonic monitoring programme spans from August 1999 to December 2002. The monitoring programme involved 20 downloads of two week long blocks of data from the EDMI Mk3 Energy Meters, numerous snapshot captures of the harmonic content of currents and voltages at each of the monitoring locations, and instantaneous waveform captures at the Homepride zone and commercial substation locations. In total about 200Mb of data was collected for analysis.

Considering the large amount of data obtained in a harmonic monitoring programme it was necessary to summarise the data into a format that can be easily analysed. Careful presentation of results is necessary to ensure that the important characteristics of the monitoring data are not lost in summarising. For this monitoring programme the data

from the seven monitoring locations has been organised into three main sections including daily and weekly trending of harmonics, the type of statistical distribution, and the correlation between the harmonics in each of the three phases.

5.6 Harmonic voltage and current trends

The initial harmonic monitoring programme consisted of four weeks of monitoring with two consecutive downloads of two week long blocks of data from each of the seven EDMI Mk3 Energy Meter locations. This included monitoring data from 21 August 1999 to 17 September 1999. The aim of this monitoring programme was to examine the harmonics to determine the contribution to the system harmonic levels from the residential, commercial and industrial load sectors. The expected outcome in simple terms was to determine the existing harmonic situation in a typical 11kV distribution system.

Figure 5.7 shows typical recordings at the Homepride zone substation 11kV busbar daily and weekly harmonic voltage trends averaged over the two line-to-line phases measured. The 5th harmonic and the voltage THD are very close to each other verifying that the 5th harmonic is the dominant distorting component. The 19th harmonic is low at approximately 0.1%, which is close to the limit of resolution of the instrument. The 49th harmonic recorded was insignificant. Figure 5.8 illustrates how the daily harmonic voltage trends for the 5th harmonic and THD are repeated, in an approximate form, over each of the weekdays and somewhat different over the weekend period.

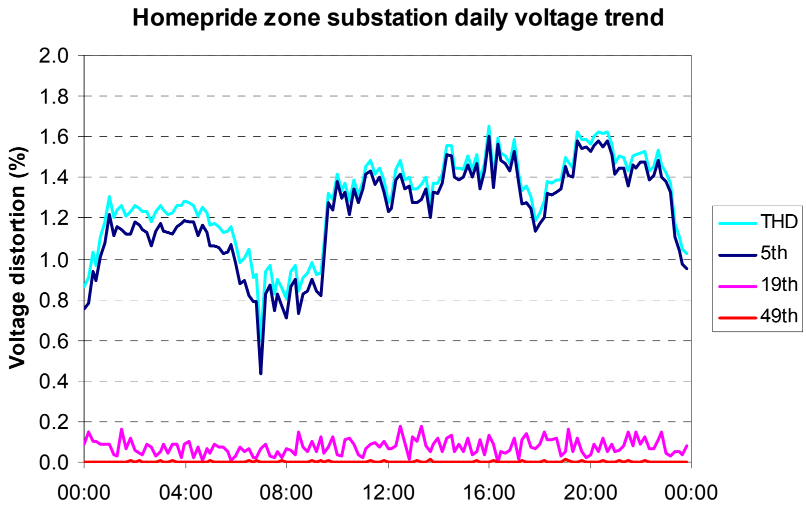


Figure 5.7 Homepride zone (site 1) weekday harmonic voltage trend (5th, 19th, 49th)

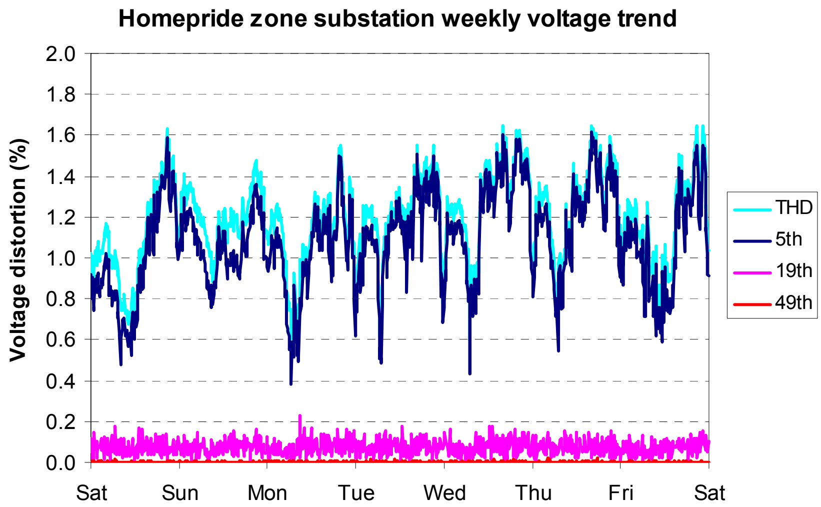


Figure 5.8 Homepride zone (site 1) weekly harmonic voltage trend (5th, 19th, 49th)

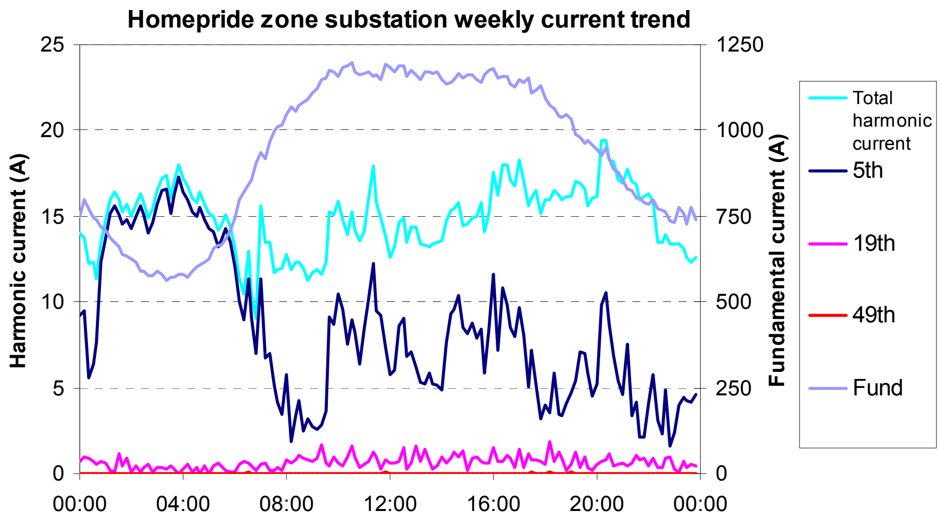


Figure 5.9 Homepride zone (site 1) weekday harmonic current trend (5th, 19th, 49th)

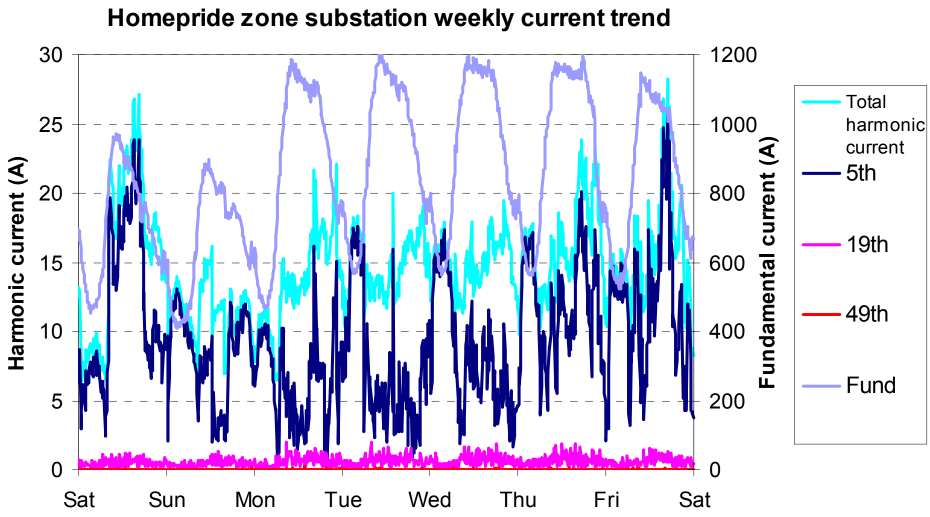


Figure 5.10 Homepride zone (site 1) weekly harmonic current trend (5^{th}, 19^{th}, 49^{th})

The harmonic current trends for Homepride are shown in Figure 5.9 and 5.10. There is a noticeable difference in the magnitude of the 5^{th} harmonic current and the current THD. This suggests that the 5^{th} harmonic may not be the most dominant harmonic component of the current for some parts of the day. Snapshots of the harmonic content of the current confirmed that the 7^{th} harmonic was of similar order of magnitude as the 5^{th} harmonic during some periods of the day.

As illustrated in Figures 5.7 to 5.10 the initial monitoring program found that the 19^{th} harmonic and 49^{th} harmonic were insignificant in magnitude. Previous monitoring programs overseas [21, 22] had found that the more common problematic harmonics included 3^{rd}, 5^{th} and 7^{th}. Although a large component of the 3^{rd} harmonic is blocked by the MV/LV delta-star transformers used widely in Australia, if the system is unbalanced or the harmonics are out of phase a significant level of 3^{rd} harmonic can exist on the MV system as well. After a number of harmonic snapshots of all monitoring locations it was confirmed that the dominant harmonics were indeed the 3^{rd}, 5^{th} and 7^{th} harmonics.

It was decided to alter the monitoring programme to replace the 19th and 49th harmonic recordings with the 3rd and 7th harmonics.

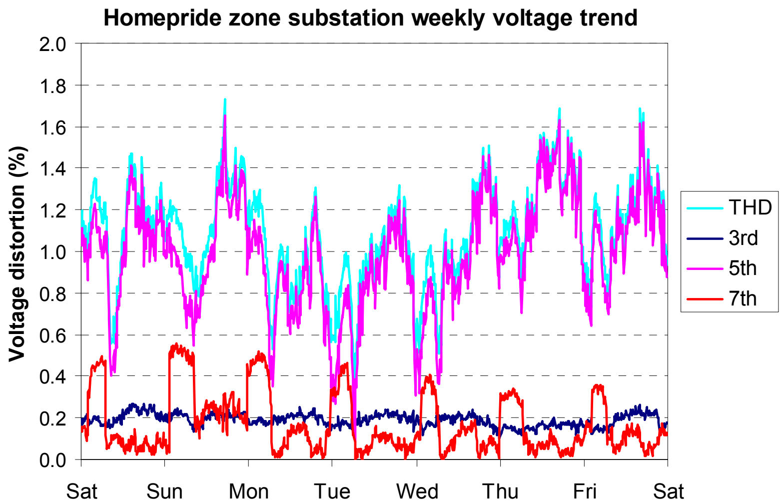


Figure 5.11 Homepride zone (site 1) weekly harmonic voltage trend (3rd, 5th, 7th)

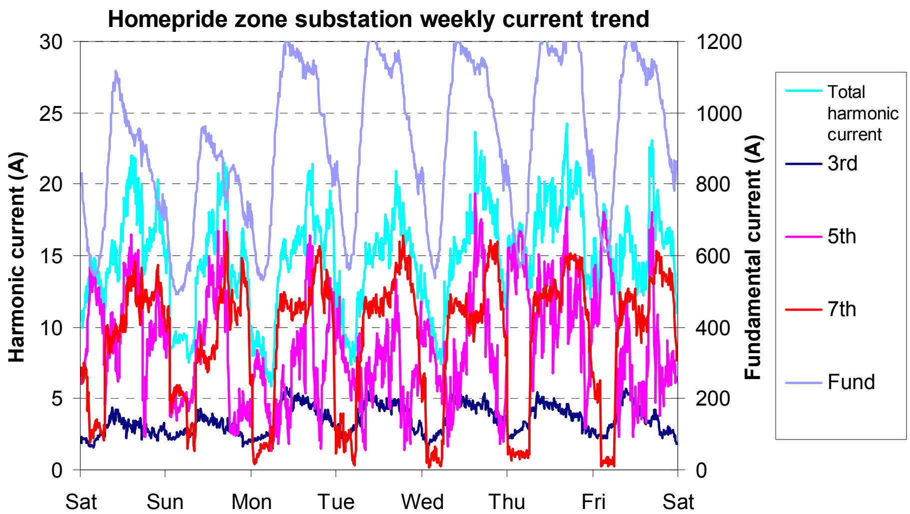


Figure 5.12 Homepride zone (site 1) weekly harmonic current trend (3rd, 5th, 7th)

The weekly harmonic voltage and current trends for the new harmonics recorded are shown in Figure 5.11 and 5.12. The 3rd, 5th and 7th harmonics make up the major components of the current THD. Although the 5th harmonic current has the highest peak magnitude, the 7th harmonic current is the largest harmonic component for a significant period of each day. Interestingly the peak 7th harmonic current periods correspond to low 7th harmonic voltage recordings and vice versa. This is due to the 7th harmonic

current producing a voltage out of phase with the existing 7th harmonic background voltage distortion or larger loads decreasing network impedance and thus acting as a harmonic filter as documented in [64]. However it would be difficult to find the source of these harmonics without further coordinated monitoring. The 3rd harmonic displays the more expected trend of increasing harmonic current producing an increase in harmonic voltage.

The weekly harmonic voltage and current trends for the remaining six harmonic monitoring sites (sites 2-7) are shown in Figures 5.13 to 5.21. At all monitoring locations it was found that the harmonic magnitudes followed a similar trend each day. The magnitude of the 3rd harmonic current at the residential and commercial sites was more significant than at the other locations, mostly due to the abundance of single phase loads. The harmonic voltage at the residential substation, illustrated in Figure 5.13, remained slightly less than the Homepride zone substation busbar harmonic voltage for the entire monitoring period. This suggests that the contribution to the total harmonic voltage at the zone substation from the residential loads was relatively small. This is seemingly not consistent with suggestion that significant increase in harmonic voltage levels in Europe are due to the use of televisions in the late afternoon periods [5].

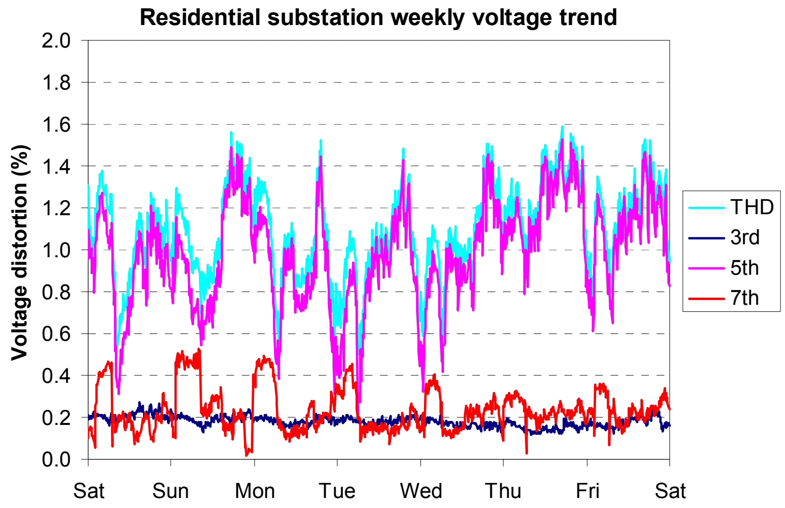


Figure 5.13 Residential substation (site 5) weekly harmonic voltage trend

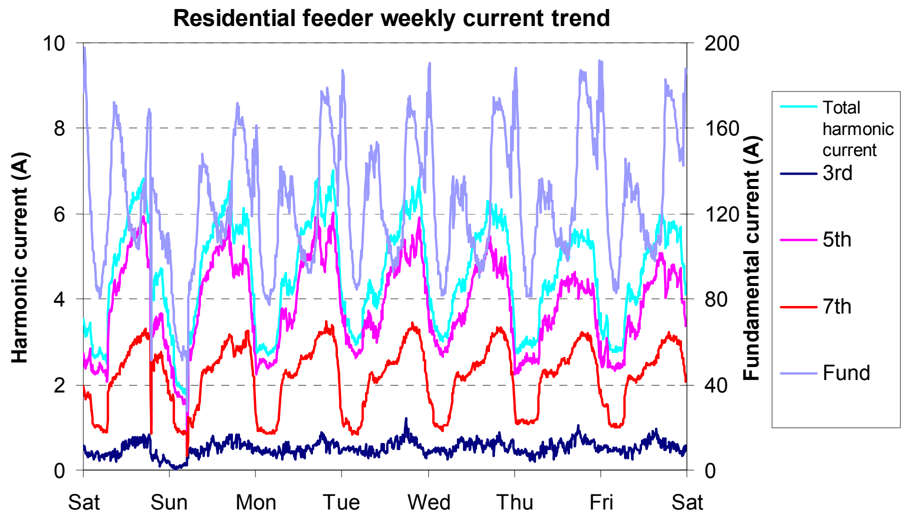


Figure 5.14 Residential feeder (site 2) weekly harmonic current trend

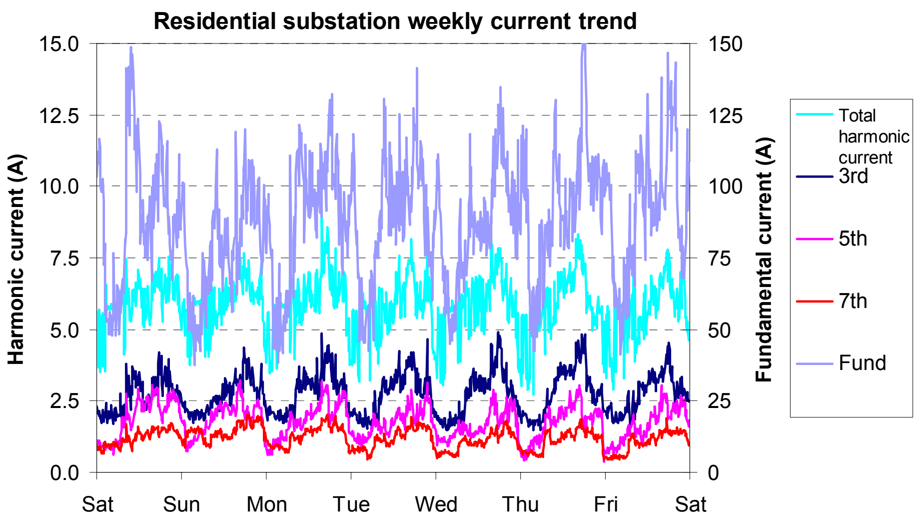


Figure 5.15 Residential substation (site 5) weekly harmonic current trend

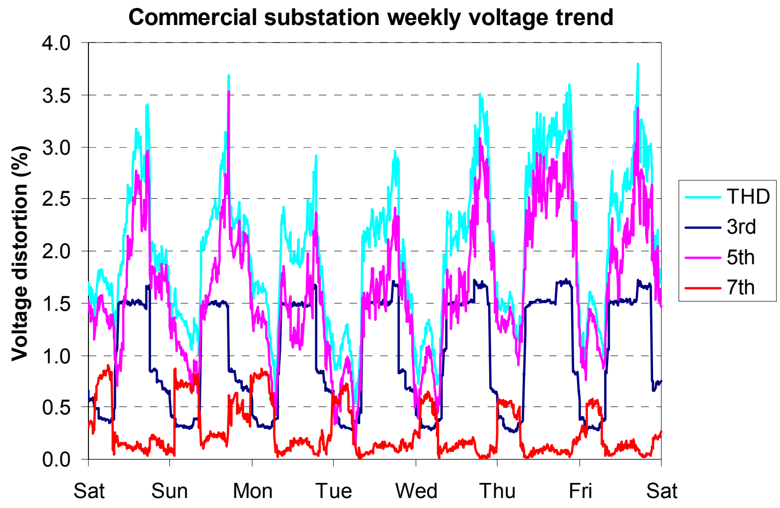


Figure 5.16 Commercial substation (site 6) weekly harmonic voltage trend

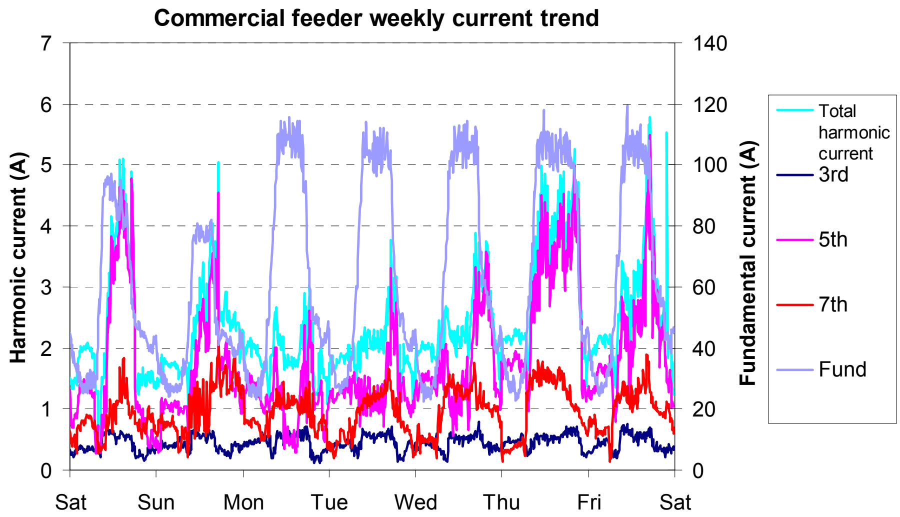


Figure 5.17 Commercial feeder (site 3) weekly harmonic current trend

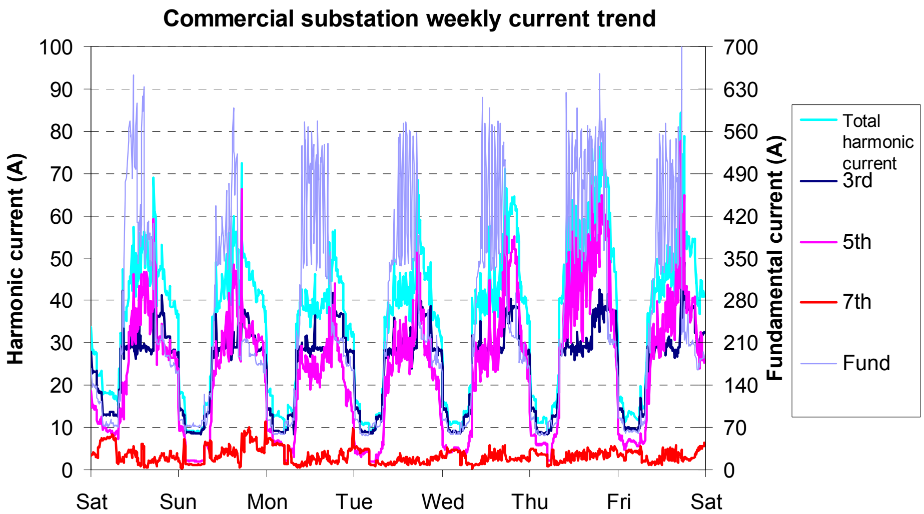


Figure 5.18 Commercial substation (site 6) weekly harmonic current trend

The commercial substation had distortion levels up to twice the level of the Homepride zone substation busbar harmonic voltage. The largest voltage distortion was produced by the commercial substation reaching a maximum value of around 5% during the initial monitoring period, and up to 6% a number of times during the three year monitoring period. Figures 5.17 and 5.18 illustrate that the 3rd and 5th harmonics are the significant harmonic components of the current on the commercial feeder. The industrial and commercial feeders seem to contribute approximately the same level of 7th harmonic current while that of the residential feeder is significantly higher.

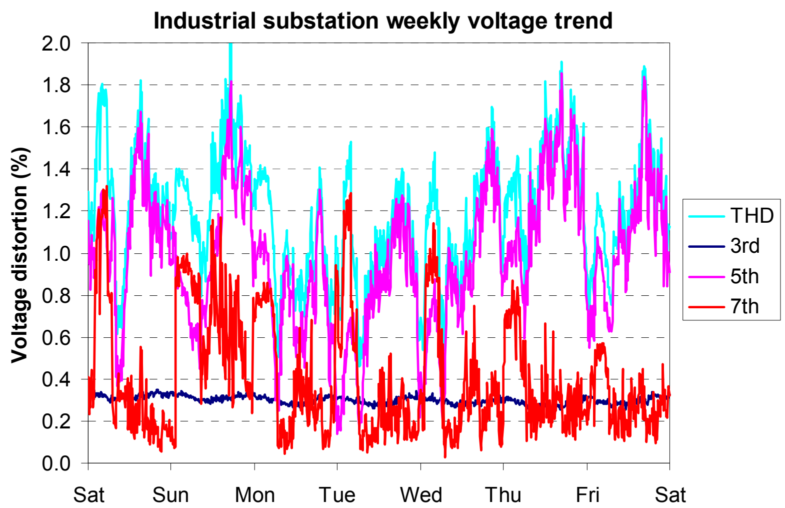


Figure 5.19 Industrial substation (site 7) weekly harmonic voltage trend

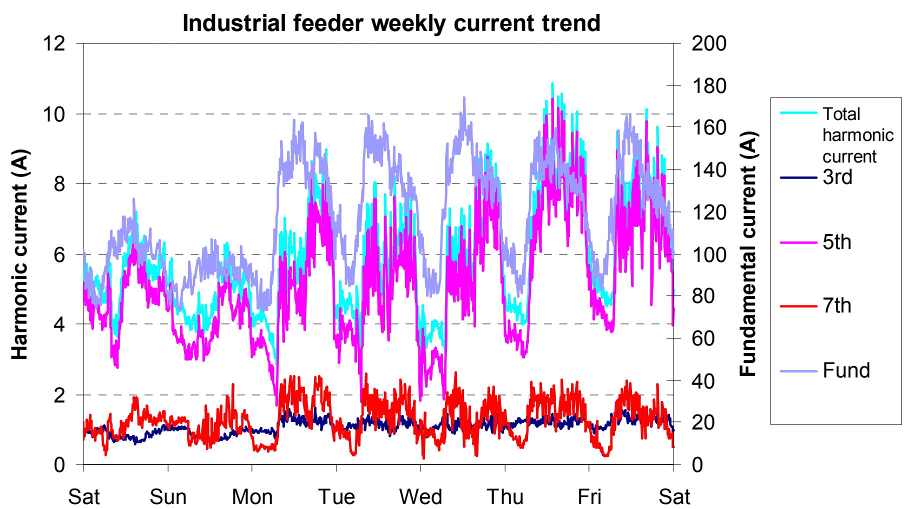


Figure 5.20 Industrial feeder (site 4) weekly harmonic current trend

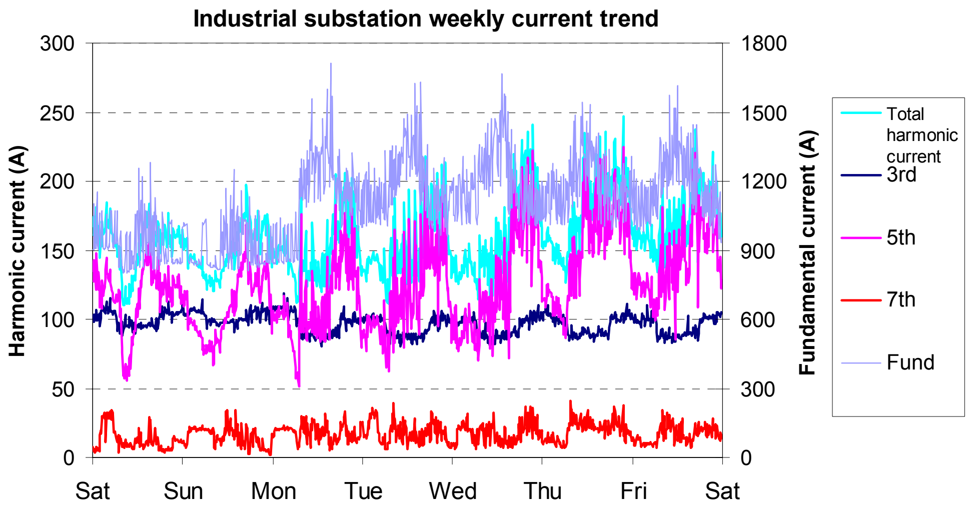


Figure 5.21 Industrial substation (site 7) weekly harmonic current trend

Figures 5.11, 5.13, 5.16 and 5.19 illustrate that the maximum harmonic voltage levels occur during normal working hours. The blocking of the 3rd harmonic by the delta-star MV/LV transformers is also substantiated by the high levels of 3rd harmonic current at the LV load sites but not at the sending end of the MV feeders. Figure 5.21 shows a sustained high level of fundamental current for the seven day monitoring program. This is typical of an industrial load where the manufacturing operation continues 24 hours a day seven days per week with limited downtime.

There is a small increase in the 95th percentile 5th harmonic voltage level at the industrial substation compared to that at the corresponding feeder sending end. However, the industrial load draws significant 3rd and 5th harmonic currents. The line impedance between the Homepride zone substation and the industrial substation is low and thereby the increase in 95th percentile cumulative probability voltage due to the high harmonic current is minimal.

The voltage trends from all sites illustrate the dominance of the 5th harmonic voltage. This agrees with the results from previous surveys conducted overseas and discussed in Chapter 2. The dominance of the 5th harmonic is also illustrated using a scatter graph of 5th harmonic voltage versus THD as shown in Figure 5.22. The high correlation of the scatter graph illustrates how the THD rises in proportion to the 5th harmonic. This result allows the work of Chapter 3 of estimating voltage THD levels to be based primarily on the 5th harmonic.

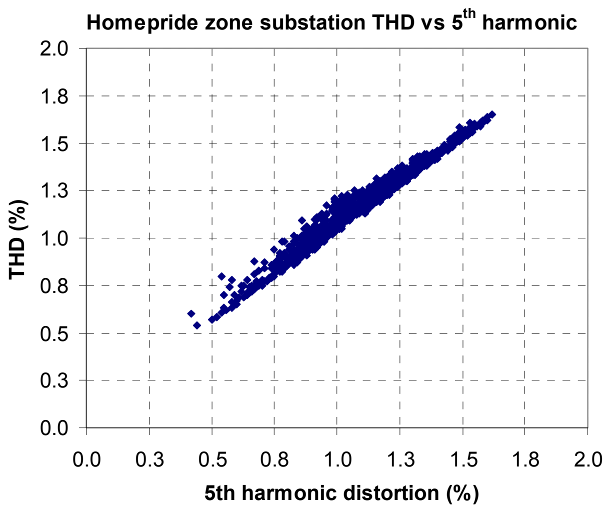


Figure 5.22 Homepride zone (site 1) THD versus 5th harmonic

5.7 Harmonic voltage and current cumulative probability

From the harmonic voltage and current trends it can be seen that the changing load causes harmonic levels to constantly fluctuate (albeit in a repeating pattern) over the monitoring period. Due to faults and the most adverse combination of customer loads it would be difficult for a DNSP to control the level of harmonics 100% of the time. For these reasons it is necessary to incorporate statistical techniques to provide an assessment method of MV distribution systems.

The concept of the 95th percentile cumulative probability used in [16] has already been introduced in Chapter 2. An advantage of the cumulative probability method is it enables comparisons without spurious or fluctuating data affecting the reported indices. For the 95th percentile this is a direct result of the highest 5% of readings, containing most of the outliers, being excluded from the cumulative probability indicator. Selection of the 95th percentile rather than the 99th or 100th (maximum) can be justified using data from the monitoring programme. Figure 5.23 illustrates weekly 95th, 99th and 100th percentiles for the 7th harmonic voltage at the industrial site. As illustrated the variation of the latter percentiles show a large variation for adjacent weeks, whereas the 95th percentile, while still demonstrating weekly variations produces a more stable index.

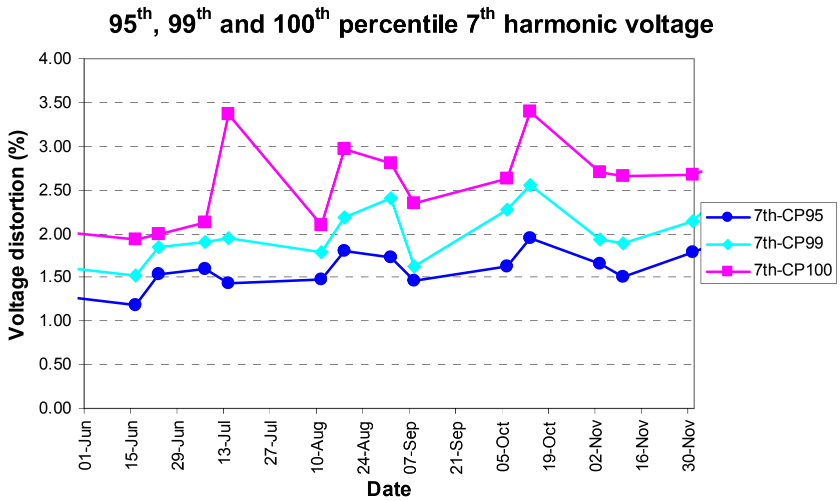


Figure 5.23 95th, 99th and 100th percentile 7th harmonic voltage at industrial substation (site 7)

Figures 5.24 to 5.35 illustrate the 3rd, 5th and 7th harmonic voltage and current cumulative probability plots for all the monitoring locations throughout the Homepride network of Figure 5.6. The 19th and 49th harmonics have not been included due to their magnitude being relatively insignificant. The cumulative probability plots and histograms illustrate that the magnitude of the 5th harmonic voltage and current

approximates a normal distribution for all monitoring locations. The 3rd harmonic also follows this trend at all locations except at the commercial substation. The 7th harmonic voltages and currents do not follow this normal distribution.

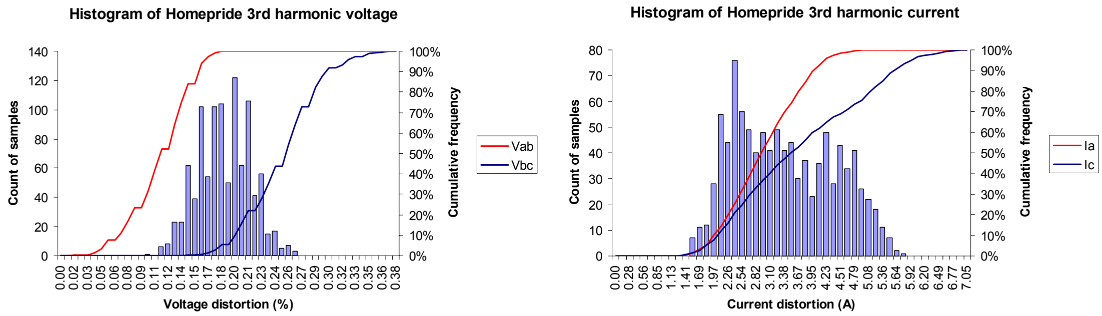


Figure 5.24 Homepride zone substation (site 1) 3rd harmonic histogram

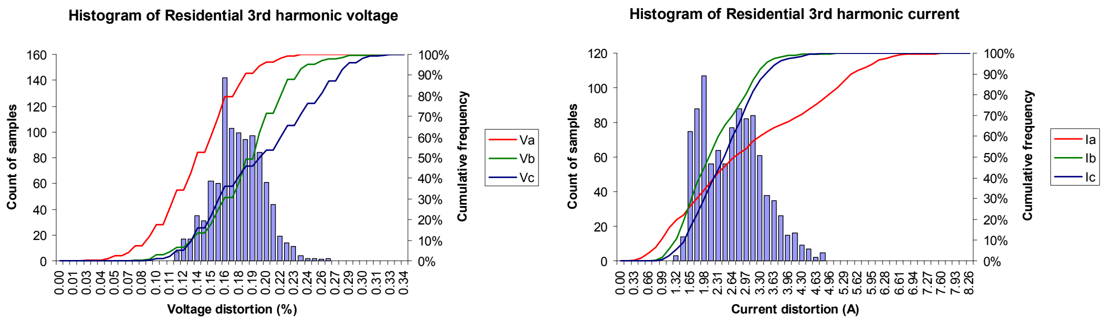


Figure 5.25 Residential substation (site 5) 3rd harmonic histogram

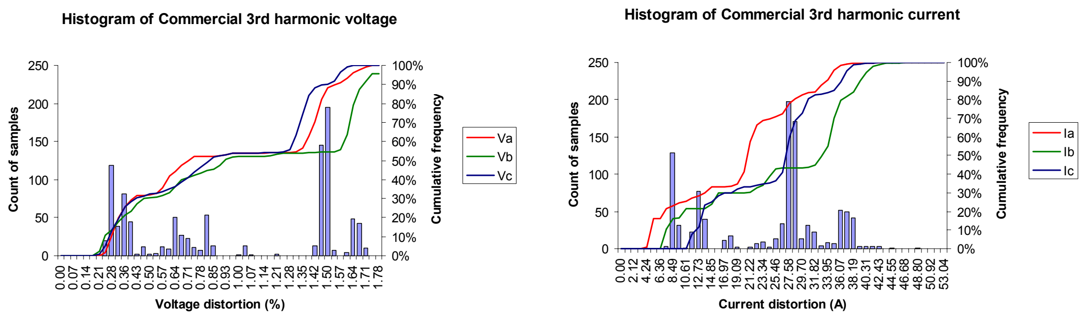


Figure 5.26 Commercial substation (site 6) 3rd harmonic histogram

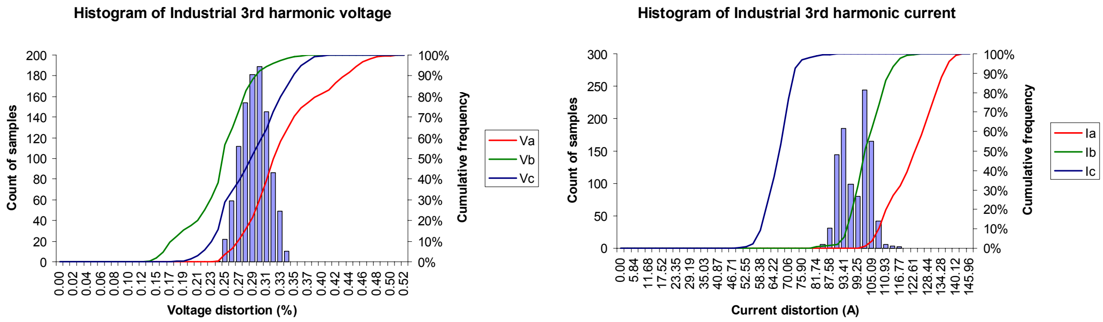


Figure 5.27 Industrial substation (site 7) 3rd harmonic histogram

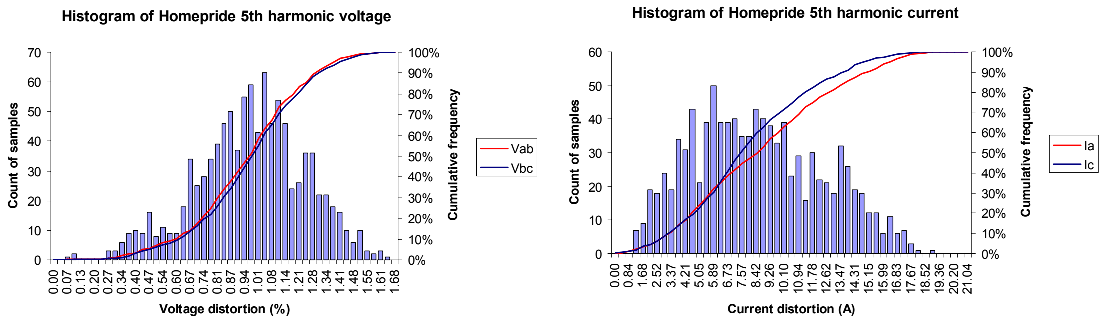


Figure 5.28 Homepride zone substation (site 1) 5th harmonic histogram

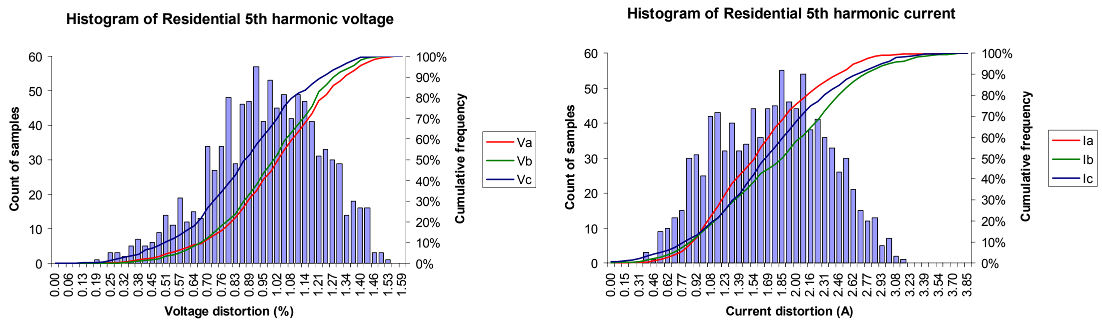


Figure 5.29 Residential substation (site 5) 5th harmonic histogram

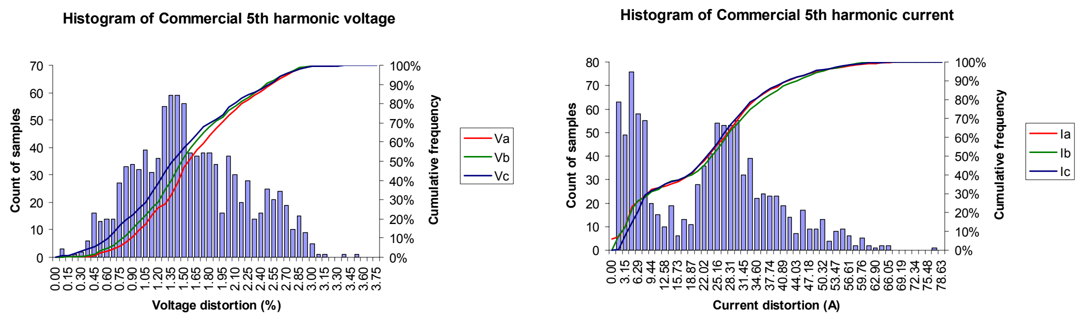


Figure 5.30 Commercial substation (site 6) 5th harmonic histogram

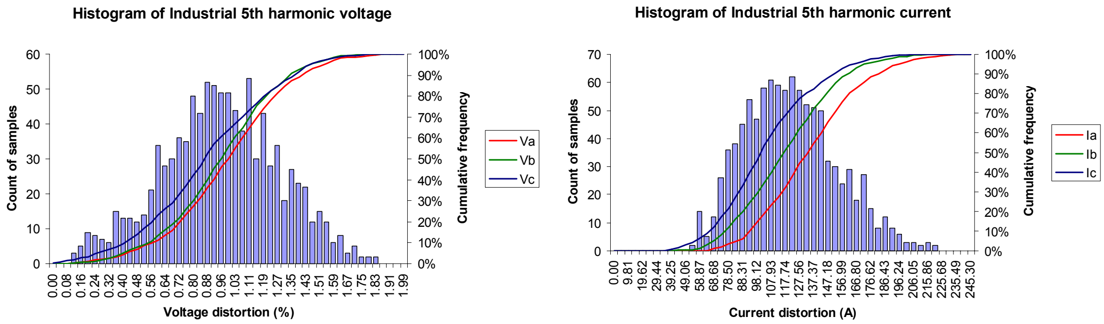


Figure 5.31 Industrial substation (site 7) 5th harmonic histogram

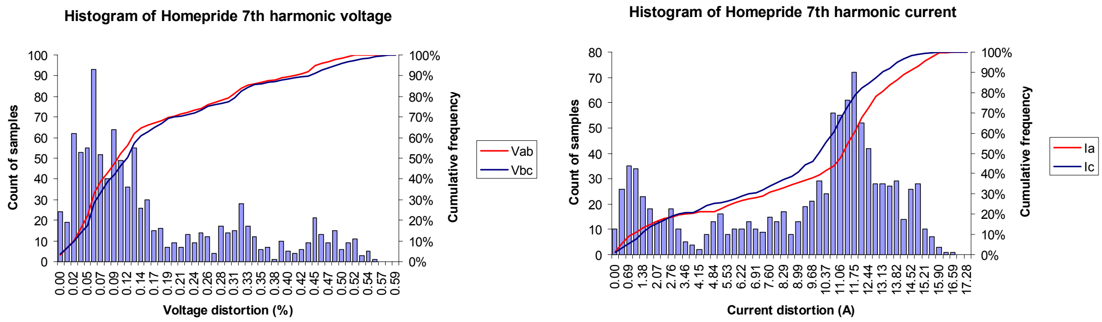


Figure 5.32 Homepride zone substation (site 1) 7th harmonic histogram

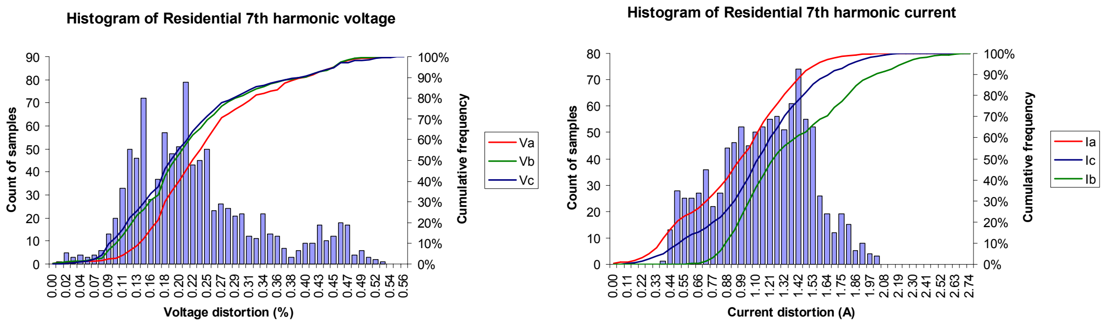


Figure 5.33 Residential substation (site 5) 7th harmonic histogram

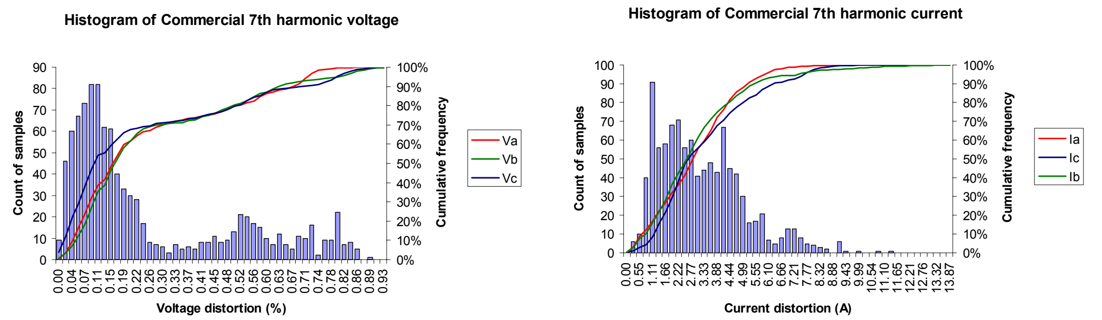


Figure 5.34 Commercial substation (site 6) 7th harmonic histogram

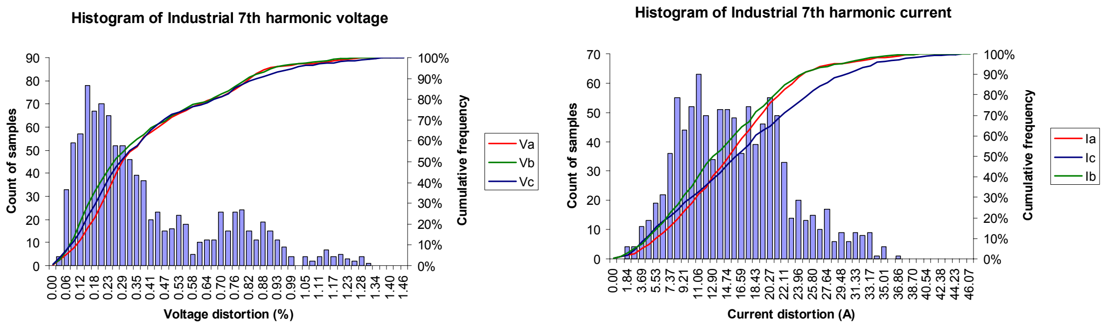


Figure 5.35 Industrial substation (site 7) 7th harmonic histogram

The 95th percentile cumulative probability value for the 5th harmonic voltage at the Homepride zone substation is 1.54%, well below the recommended planning level of 5% provided by the IEC 61000-3-6 standard. Table 5.2 provides the 95th percentile values of the Homepride zone substation, residential, commercial and industrial monitoring locations for the 3rd, 5th, 7th and 19th harmonic voltages and currents over the initial monitoring period.

Table 5.2 95th percentile values for all sites over initial monitoring period

Harmonic voltage (maximum of each phase)							
Site/Description		**Fund**	**3rd**	**5th**	**7th**	***19th**	**THD**
1	Homepride zone Substation	11097V	0.24%	1.54%	0.47%	0.14%	1.63%
5	Residential substation	248V	0.22%	1.45%	0.45%	0.15%	1.53%
6	Commercial substation	251V	1.67%	2.89%	0.74%	0.13%	3.28%
7	Industrial substation	249V	0.33%	1.63%	1.02%	0.13%	1.80%
Harmonic current (maximum of each phase)							
Site/Description		**Fund**	**3rd**	**5th**	**7th**	***19th**	**THD**
1	Homepride zone Substation	1205.3A	5.17A	17.06A	15.46A	1.24A	2.96%
2	Residential feeder	173.48A	0.82A	5.47A	3.32A	0.12A	5.79%
3	Commercial feeder	114.56A	0.71A	3.79A	2.06A	0.14A	6.58%
4	Industrial feeder	156.65A	1.44A	8.22A	2.21A	0.25A	5.74%
5	Residential substation	119.74A	3.96A	2.97A	1.76A	0.22A	11.76%
6	Commercial substation	548.88A	38.18A	48.89A	6.86A	0.94A	26.47%
7	Industrial substation	1404.6A	108.67A	192.98A	28.89A	3.24A	20.12%
* The 19th harmonic was monitored at a different period but is included to indicate relative magnitude							

The commercial site shows the highest level of voltage distortion at 3.28% with the 5th harmonic contributing to over 85% of the distortion. The LV sites are expected to have significantly higher distortion levels due to the additional impedance of the MV/LV distribution transformer.

The residential site (1.53%) however has a slightly lower distortion level than at the Homepride zone substation (1.63%), possibly due to the residential loads contributing a harmonic voltage that cancels the background voltage distortion. It is also noted that the 5th harmonic voltage is lower at the remote end of the residential feeder (1.45%) compared to that at the zone substation (1.54%). This prompted further investigation. Using the instantaneous feature of the monitoring instruments, several waveform captures were carried out at both the Homepride zone substation and at the residential transformer. A representative sample of these waveforms in the form of a harmonic spectrum is shown in Figures 5.36 and 5.37.

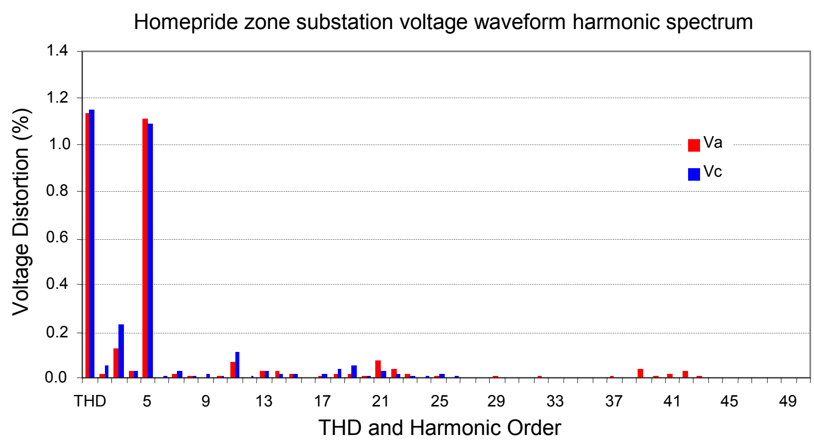


Figure 5.36 Spectrum of Homepride zone (site 1) instantaneous voltage waveform capture

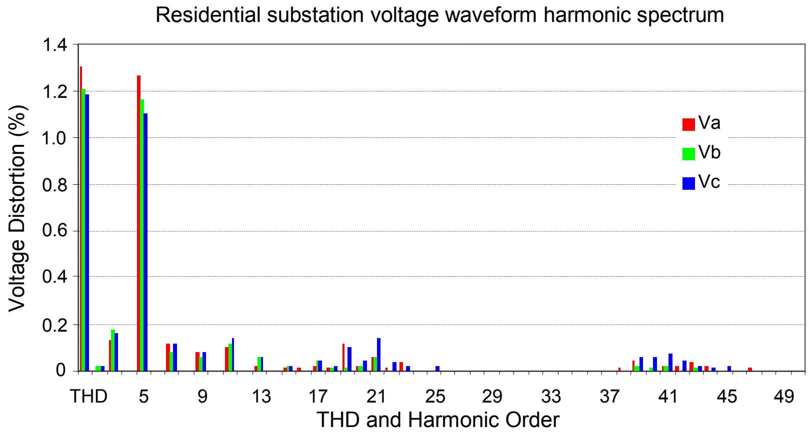


Figure 5.37 Spectrum of residential substation (site 5) instantaneous voltage waveform capture

Each of the readings from Figures 5.36 and 5.37 confirms the expectations for an increase in harmonics towards the remote end of the feeder. However, there remains the possibility the harmonic voltage contributions from the residential site being out of phase with the zone substation voltage creating a lower net voltage at the residential site. This raises the question of discrepancies with the overall cumulative probability and shows that most comparison techniques should not be used in isolation. Each technique should be used as a tool to add greater understanding to what is known about the system.

5.8 Harmonic levels compared to standards

As discussed in Chapter 2, Standards Australia has recently adopted the IEC 61000-3-6 harmonic standard as AS/NZS 61000.3.6 to replace AS 2279.2. The harmonic voltage limits for MV distribution systems recommended by AS 2279.2 and IEC 61000-3-6 were given in Tables 2.4 and 2.5 of Chapter 2 respectively. The introduction of the new IEC standard has incorporated an increase in the harmonic levels of the most problematic 5^{th} harmonic from 4% to 5% while the 7^{th} harmonic remains at 4%. For the

other harmonic orders the harmonic voltage limits have decreased and fall off with increasing harmonic order.

As AS 2279.2 does not use statistical techniques to analyse harmonic voltages the maximum harmonic voltages at each of the monitoring locations should be first found. These maximum voltage levels for the initial monitoring period are presented in Table 5.3. The benchmark harmonic monitoring programme has found that the 'head room' available in relation to the recommended harmonic voltage limits at the MV voltage levels is quite significant at most locations. The maximum values of harmonic levels and THD at the various sites normalised using the limits specified in AS 2279.2 and IEC 61000-3-6 are given in Table 5.4. From this table it is evident that no exceedances are noted except from the commercial site where the 5th harmonic and THD are close to the limits based on AS 2279.2.

Table 5.3 Maximum values for all sites over initial monitoring period

Harmonic voltage (maximum of each phase)						
Site	**Description**	**3rd**	**5th**	**7th**	***19th**	**THD**
1	Homepride zone Substation	0.38%	1.96%	0.59%	0.33%	2.03%
5	Residential substation	0.36%	1.74%	0.56%	0.34%	1.82%
6	Commercial substation	1.92%	3.86%	0.98%	0.30%	4.19%
7	Industrial substation	0.52%	2.14%	1.96%	0.34%	2.36%
* see Table 5.2 footnote						

Table 5.4 Harmonic voltage levels normalised to recommended limits

AS 2279.2						
Site	**Description**	**3rd**	**5th**	**7th**	***19th**	**THD**
1	Homepride zone Substation	10%	49%	15%	9%	41%
5	Residential substation	9%	44%	14%	9%	36%
6	Commercial substation	48%	97%	25%	9%	84%
7	Industrial substation	13%	54%	49%	9%	47%
IEC 61000-3-6						
Site	**Description**	**3rd**	**5th**	**7th**	***19th**	**THD**
1	Homepride zone Substation	6%	31%	12%	12%	25%
5	Residential substation	6%	29%	11%	13%	24%
6	Commercial substation	42%	58%	19%	11%	50%
7	Industrial substation	8%	33%	26%	11%	28%
* see Table 5.2 footnote						

5.9 Annual growth in harmonic distortion levels

Determining the level of harmonic distortion growth over a three year monitoring period is difficult due to seasonal changes and daily fluctuations of harmonic levels. The level of harmonics are largely dependent on weather conditions due to the use of loads such as inverter driven air conditioners and also the length of daylight hours which in some ways may influence the use of non-linear loads. To determine the growth it would be preferable to have periodic data over the full three years so that a true trend could be established. However at the beginning of the program the data from the harmonic monitors were not periodically downloaded. A less than ideal way of determining harmonic growth over the monitoring period is to determine the 95th percentile probability at the same time in each year. As the initial monitoring studies were completed at the same time each year a very crude comparison of the 95th percentile harmonic levels can be made. The 95th percentile harmonic voltage values for the two week period beginning in mid August in each year of the monitoring programme are given in Table 5.5. As the most problematic harmonic is the 5th

harmonic, only the 5th harmonic and the THD will be included for the harmonic growth study. Also the 3rd and 7th harmonics were not logged over the entire monitoring period. The corresponding harmonic current growths are presented in Table 5.6.

Table 5.5 Harmonic voltage 95th percentile values for August during monitoring (1999 – 2001)

Harmonic voltage distortion growth by 95th percentile					
Site	**Location**		**1999**	**2000**	**2001**
1	Homepride zone substation	5th	1.57%	1.54%	1.29%
5	Residential substation	5th	1.47%	1.45%	1.25%
6	Commercial substation	5th	2.65%	2.89%	2.40%
7	Industrial substation	5th	1.80%	1.63%	1.33%
1	Homepride zone substation	THD	1.63%	1.58%	1.39%
5	Residential substation	THD	1.54%	1.53%	1.34%
6	Commercial substation	THD	3.07%	3.28%	2.86%
7	Industrial substation	THD	2.00%	1.80%	1.93%

Table 5.6 Harmonic current 95th percentile values for August during monitoring (1999 – 2001)

Harmonic current distortion growth by 95th percentile					
Site	**Location**		**1999**	**2000**	**2001**
1	Homepride zone substation	5th	18.02A	16.93A	15.62A
5	Residential substation	5th	2.88A	2.83A	3.56A
6	Commercial substation	5th	43.36A	50.55A	40.38A
7	Industrial substation	5th	134.22A	185.51A	168.53A

Tables 5.5 and 5.6 do not indicate clear harmonic growth trends. As mentioned a more detailed study comprising of periodic downloads is required to establish true harmonic growth trends. For the final two years of monitoring the data from the monitoring instruments were downloaded each month to establish the seasonal harmonic trends. The following section presents the results of that study.

5.10 Seasonal changes in harmonic distortion levels

For the years of 2001-2002 the harmonic monitoring instruments at the Homepride system were frequently downloaded to establish seasonal trending. A similar study [25] found that in the USA the lowest levels of harmonic voltages existed during the summer months. The levels from the study [25] varied from 1.3% to about 1.8% throughout the year. A similar variation was found on the Homepride system as shown in Figure 5.38. A significant difference however was that the highest harmonic voltage levels occurred during the summer months of 2001 and then during autumn of 2002.

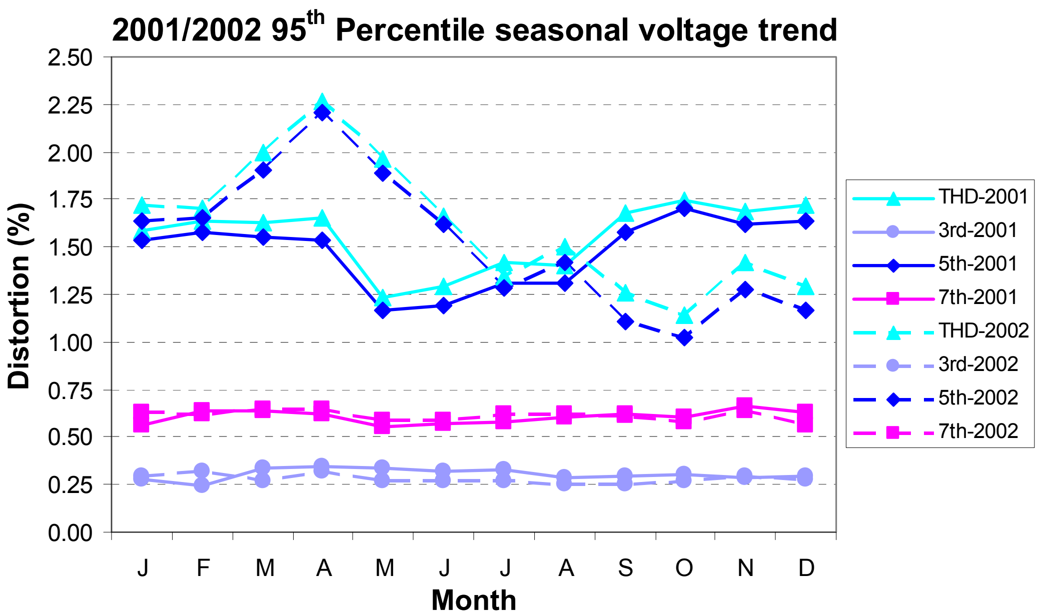


Figure 5.38 Seasonal 95th percentile voltage trend for Homepride zone (site 1)

To establish harmonic growth trends it would be necessary to repeat the seasonal harmonic voltage trend study over a period of a number of years. The study presented in [25] found that while the seasonal trend continued each year it was found that the THD levels increased by 10% each year. Although an initial large increase in distortion is observed during the first half of 2002 further work needs to be completed to establish the true growth trends at the Homepride zone distribution system. Integral Energy also

reported that a large industrial customer had been disconnected from Homepride zone substation in the second half of 2002 which may have contributed to the fall in harmonic levels illustrated in Figure 5.38.

5.11 Residential, commercial and industrial load harmonic characteristics

From the above monitoring programme results it is seen that the amount of total harmonic voltage distortion is dominated by the 5th harmonic. This characteristic may be used to predict the level of total harmonic distortion existing in the system by applying a suitable multiplying factor to the 5th harmonic, if the 5th harmonic distortion level can be established.

Table 5.7 summarises the results from the monitoring programme using the 95th cumulative probability values for the fundamental and 5th harmonic current for the three LV locations, averaged over the entire monitoring period. The subscript '1CP95' indicates the fundamental component 95th percentile cumulative probability level. It is required to characterise the load types so that the 95th percentile cumulative probability levels of harmonic distortion can be predicted from known network impedances, load magnitudes and compositions of load types. Assuming that similar load compositions at any power level will have the same spectrum, each load type can be characterised conveniently by the I_{5CP95}/I_{1CP95} as shown in the right hand side column. This shows that the residential load has much less distortion than the commercial and industrial types as would be expected. Over the course of the entire monitoring programme it was found that the ratio of 95th percentile 5th harmonic to 95th percentile fundamental varied by less than 10% for any given week of data.

Table 5.7 Fundamental and 5th harmonic current 95th percentile values (A)

Harmonic Monitor Site	I_{1CP95}	I_{5CP95}	I_{5CP95}/I_{1CP95}
Site 5 – Residential	133	3.36	0.025
Site 6 – Commercial	617	43.3	0.071
Site 7 – Industrial	1469	170.9	0.116

Assuming the data in Table 5.7 is typical to most distribution systems, the above residential, commercial and industrial load models may be used to estimate harmonic distortion levels for the 5th harmonic and thus the THD during the planning phase of a distribution system. The method to estimate harmonic distortion levels is outlined in Chapter 3. An area for future work is to verify that the data in Table 5.7 is typical to other distribution systems.

5.12 Relationship of harmonics on individual phases

If two sets of data across all three phases correlate very well then the likely load type is three-phase as variations in the load affect all phases similarly. This method of comparison enables the phase-to-phase comparison of data as shown in Figures 5.39 to 5.42. At the 5th harmonic it can be seen that good correlation exists between A, B and C phases for both voltage and current for most of the monitoring sites. This means as A phase varies, B and C phase vary in similar proportions. The harmonic current at the residential site is the exception (Figure 5.40), although the spread of data points is expected as the residential substation would consist almost entirely of single-phase loads. Scatter graphs for the 3rd, 7th and 19th harmonics can be found in Appendix C. At the 3rd and 19th harmonics the phase to phase correlation is less obvious and the large spread of data points indicates very little dependency between A, B and C phase at all the monitoring sites.

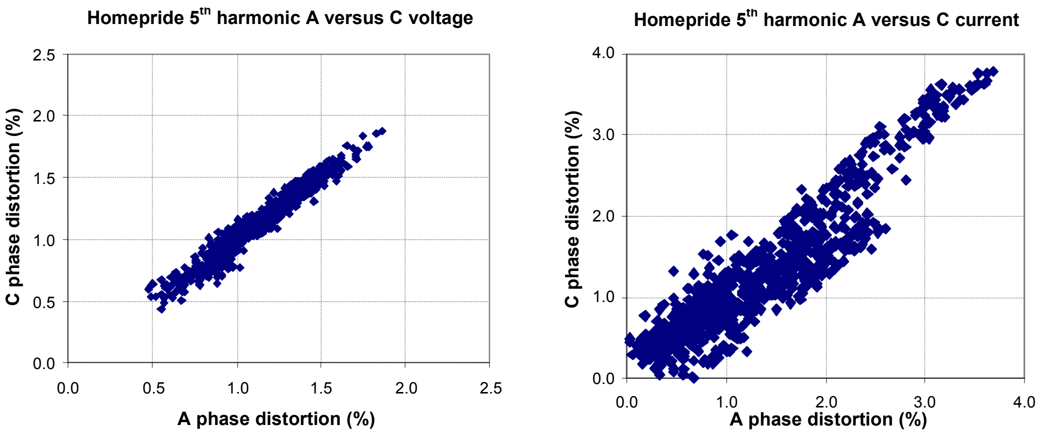


Figure 5.39 Homepride (site 1) 5th harmonic A and C phase voltage and current

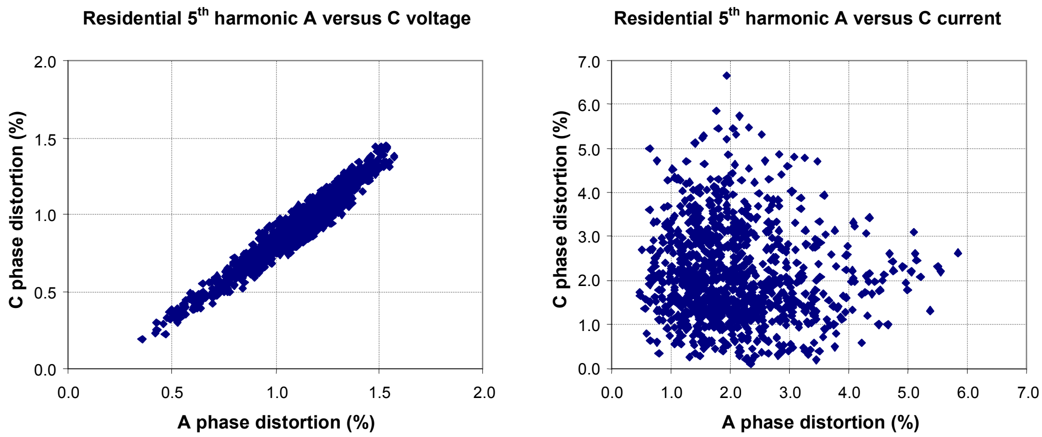


Figure 5.40 Residential (site 5) 5th harmonic A and C phase voltage and current

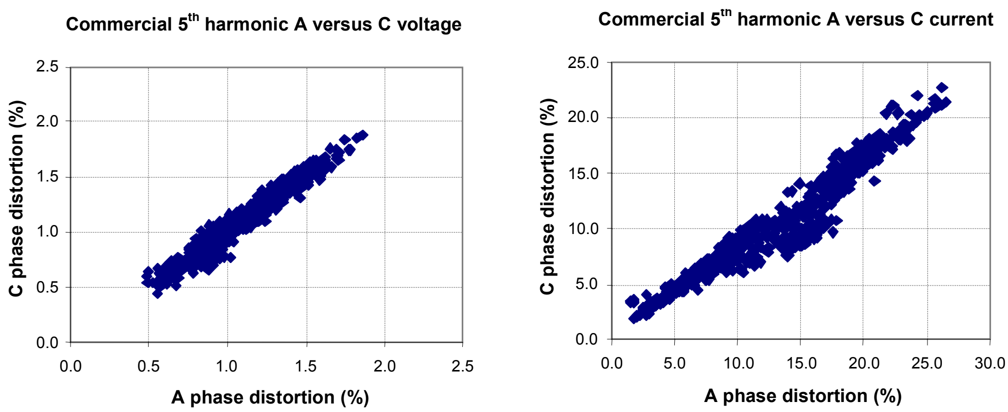


Figure 5.41 Commercial (site 6) 5th harmonic A and C phase voltage and current

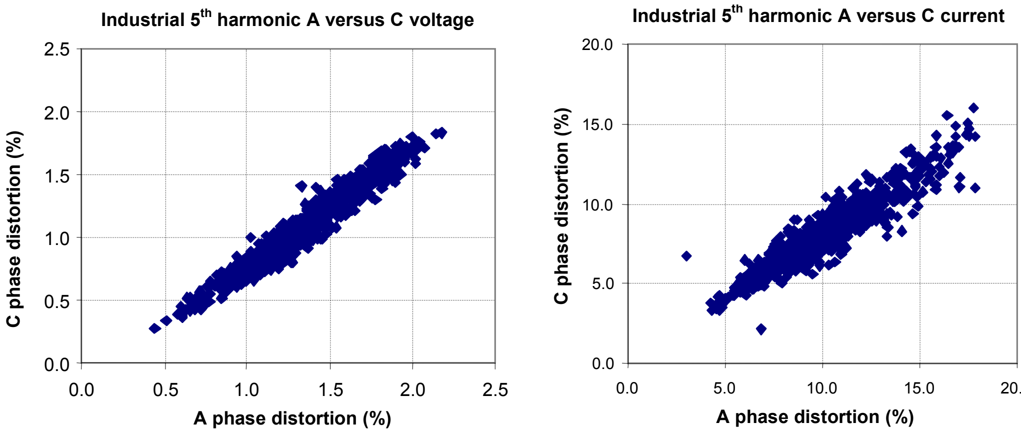


Figure 5.42 Industrial (site 7) 5th harmonic A and C phase voltage and current

A useful method for interpreting scatter graphs is the correlation coefficient ρ. This coefficient varies in the range $-1 \leq \rho \leq 1$, where a value of 1 (or –1) implies perfect correlation and zero indicating no correlation. This may give some additional insight as to whether the load is predominantly single-phase or three-phase type.

The scatter graphs of Figure 5.41 of the commercial substation demonstrate good correlation between the phases. This is a result of the load at the commercial sites being mostly three-phase air conditioning and lighting balanced over all three phases. This balanced load current results in symmetrical voltage correlation.

The correlation coefficients of Table 5.8 support the graphical representations of Figures 5.39 to 5.42 with the 5th and 7th harmonics showing good correlation for voltage and current at all sites other than for the residential substation for 3rd and 19th harmonics where very little dependency can be found. However the 95th cumulative probabilities for the 3rd and 19th harmonics on each of the phases were found to be similar across the three phases (where available) for the seven monitoring locations. The figure calculated for the correlation coefficient would suggest that it would be required to monitor all

three phases, however use of the cumulative probability method on one phase would be sufficient to give the required information on harmonic levels. The 95th cumulative probability also appears to be less sensitive to fluctuations at low levels of distortion.

Table 5.8 Correlation coefficients for initial period of monitoring programme

Harmonic		3rd	5th	7th	19th
MV Harmonic voltage correlation coefficients					
Homepride zone substation	A vs. C	0.322	0.988	0.988	-0.005
Residential feeder	A vs. C	0.400	0.988	0.981	0.788
Commercial feeder	A vs. C	0.378	0.983	0.980	0.049
Industrial feeder	A vs. C	0.379	0.983	0.982	0.004
MV Harmonic current correlation coefficients					
Homepride zone substation	A vs. C	0.772	0.829	0.993	0.169
Residential feeder	A vs. C	0.639	0.990	0.995	0.107
Commercial feeder	A vs. C	0.692	0.916	0.965	0.235
Industrial feeder	A vs. C	0.005	0.962	0.913	0.188
LV Harmonic voltage correlation coefficients					
Residential	A vs. B	-0.519	0.980	0.963	0.899
	A vs. C	-0.018	0.981	0.973	0.679
Commercial	A vs. B	0.985	0.986	0.985	0.017
	A vs. C	0.986	0.974	0.970	0.013
Industrial	A vs. B	-0.277	0.975	0.950	0.144
	A vs. C	-0.777	0.983	0.945	0.251
LV Harmonic current correlation coefficients					
Residential	A vs. B	0.368	0.662	0.584	0.158
	A vs. C	-0.364	0.457	0.471	0.304
Commercial	A vs. B	0.870	0.956	0.866	0.947
	A vs. C	0.975	0.991	0.841	0.969
Industrial	A vs. B	0.282	0.914	0.660	0.359
	A vs. C	0.655	0.873	0.441	0.325

5.13 Minimum requirements of a harmonic monitoring programme

The information from the monitoring program was recorded over a substantial period of time that allows the minimum monitoring requirements to be estimated. The minimum monitoring period can be found by breaking the monitoring period into smaller separate weekly records as shown in Table 5.9 using the Homepride zone MV readings over the first month of recording. It can be seen that the maximum deviation from the overall

average reading of 1.54% is 0.14%, which is within acceptable accuracy of 0.2%. Thus monitoring over a period as short as one week gives useful information without being biased too much by short-term trends. Note that there is an additional long-term seasonal trend that needs to be considered. Figure 5.38 shows a seasonal variation of approximately 0.6% in 2001. Table 5.9 again reinforces the balanced nature of the system with different phases sharing similar trends.

Table 5.9 Weekly 95th percentile values for Homepride zone substation 5th harmonic voltage

	5th harmonic voltage V_{ab} (% of fundamental)			
(Site 1)	Week 1	Week 2	Week 3	Week 4
V_{ab}	1.48%	1.68%	1.61%	1.45%
V_{cb}	1.46%	1.66%	1.56%	1.45%

The weekly readings have been further broken down into daily 95th percentile cumulative probability values in Table 5.10 for which the following can be noted:

(i) The weekend usually has high harmonic levels although the first Sunday has one of the lowest levels recorded,

(ii) Friday always indicates the lowest level,

(iii) No one day is typical of the week as a whole, and

(iv) The smallest subset of days giving useful results is Sunday-Tuesday, which has an average differing from the weekly value by about 0.6%.

Table 5.10 Daily 95th percentile values for Homepride zone substation 5th harmonic

	5th harmonic voltage V_{ab} (% of fundamental)							
(Site 1)	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Total
Week 1	1.44	1.28	1.35	1.45	1.56	1.53	1.47	1.48
Week 2	1.73	1.90	1.55	1.53	1.32	1.26	1.24	1.68
Week 3	1.76	1.75	1.50	1.54	1.35	1.44	1.37	1.61
Week 4	1.58	1.50	1.34	1.41	1.52	1.43	1.34	1.45

Maximum harmonic levels occurred on weekdays (Monday-Friday) at 4-5pm and 7-9pm, different to what is reported for US levels in [18]. However, significant 95th percentile harmonic levels on Sunday are consistent with [18] in that higher levels also occur away from the peak loading periods. This may reflect harmonic loads such as personal computers and lighting being on for a relatively long time of the day and the effect of other loads absorbing harmonics at peak load periods.

5.14 Summary

Inconsistencies have been found with some types of harmonic monitoring instruments. The indifferent performance of the selected instruments suggests that testing prior to field application is necessary before undertaking harmonic measurements.

A harmonic monitoring programme has been designed and implemented on a typical MV distribution system to establish harmonic voltage and current characteristics from the residential, commercial, and industrial load sectors. The monitoring program has been carried out using simultaneous measurement of harmonic voltages and currents at several sites within an MV distribution system. This coordinated approach in obtaining results has overcome some of the problems with synchronising and reporting data outlined in [25, 28].

Statistical harmonic models of residential, commercial and industrial substation loads have been developed to simulate the global behaviour of distorting loads at distribution substations. The load models represent aggregates of loads and are specifically intended for calculation of harmonic emissions for comparison with the relevant standards. Both time and phase diversities are included in the representative load models. The

monitoring programme results have also been used to confirm the relative accuracy of distortion level prediction techniques introduced in Chapter 3.

The monitoring programme has established seasonal trends of harmonics with voltage distortion levels being significantly higher in both summer and autumn months. Benchmarking of harmonic voltage distortion levels against the relevant standards has also been completed with results suggesting that the amount of headroom remaining before recommended limits are reached is sufficient to allow for some further growth in emission levels from customer loads for the monitored system.

Results from the monitoring programme indicate a small amount of growth in harmonic voltage levels for the study system over the three-year period. However, the amount of growth in harmonic voltage levels is considerably less than the seasonal variations and thus no strong conclusions can be made regarding future variations. Continual monitoring to establish firm growth patterns is an area for further work.

The harmonic current trends reflected voltage trends as expected for each of the substations monitored. The largest voltage distortion was produced by the commercial substation, reaching daytime peaks of 3-4% 5^{th} harmonic and a few peaks of 5% through the entire three year monitoring programme.

A study of the variation of harmonics over the three phases throughout the period of a week suggest that monitoring of a single phase in most cases will provide a sufficient indication of harmonic levels on all three phases. Analysis of daily harmonic trends has shown that no single day provides sufficient indication of harmonic levels for the entire

week. As a minimum requirement harmonic monitoring should be completed over a whole week.

Chapter 6

Effects of system capacitance on harmonic levels

6.1 Introduction

The work presented in the previous chapters has shown harmonic impedance to be a crucial factor in the calculations required for allocation of acceptable harmonic emissions and the prediction of harmonic voltage levels. In this chapter the effects of system capacitance are considered in the modelling of a distribution system and determination of harmonic impedance. Typical sources of significant system capacitance in distribution systems include power factor correction (PFC) capacitors and distribution line shunt capacitance on long feeders.

The introduction of significant system capacitance can give rise to harmonic resonances at frequencies within the harmonic range covered by IEC 61000-3-6 [15]. Harmonic resonances can lead to a significant increase in the harmonic impedance and subsequently high harmonic voltage if resonance occurs at a problematic frequency. Thus system capacitance has to be considered when calculating the harmonic impedance at any given point within the network. Calculations may also have to consider a range of network configurations and loading conditions to ensure that the worst-case harmonic resonances are identified.

Although a documented example for the calculation of harmonic impedance at the point of common connection (PCC) for a customer connected to a system with a PFC capacitor has been provided in IEC 61000-3-6, the example considers only the effects of a single capacitor. The detailed modelling difficulties due to loading variations are discussed but not addressed in the standard. A method to estimate harmonic impedance

when multiple PFC capacitor installations exist is also proposed in the standard but there are no clear guidelines on how to apply the method.

The aim of this chapter is to investigate the level of complexity required in modelling system capacitance that will provide acceptable results in the calculation of harmonic impedance in order to minimise computational effort. The work begins by first investigating detailed modelling techniques for distribution systems. Initially the models will be used to determine the lengths of distribution feeders at which significant harmonic resonances occur due to the capacitance of cables and lines. The complexity in incorporating damping effects of customer loads and multiple capacitor installations will also be explored. The applicability of a pragmatic approach to the determination of harmonic impedance introduced in the standard will be the concluding investigation in this chapter.

6.2 Modelling of the system

For the purpose of pragmatic modelling, previous chapters have modelled transformers and distribution lines and cables as single-phase series resistances and inductances with sufficient accuracy to enable estimations of the harmonic voltage contributions from customers to be established. Pragmatic techniques such as these are required to allow distribution planning to be carried out when detailed knowledge of the system is not available. To include system capacitance when modelling a distribution system further detailed models of system components have to be used to ensure that an accurate estimation of impedance and resonant frequencies are obtained.

6.2.1 Line and cable impedance

For pragmatic calculations at frequencies above the fundamental the series resistance of a distribution line may be neglected due to the dramatic increase in reactance with frequency. For such studies the fundamental impedance is assumed to be predominantly inductive and multiplying the fundamental reactance by the harmonic order *h* as shown in (6.1) approximates the harmonic impedance.

$$Z_h \approx h \times X_1 \tag{6.1}$$

It is suggested by [65] that (6.1) will provide reasonable accuracy (better than 20%) for MV systems where the reactance of the HV/MV transformer is high compared to the high voltage supply system impedance. This type of pragmatic modelling is assumed to be acceptable when

(i) Higher order harmonics are not of primary concern,

(ii) Distribution system feeder lengths are short and mostly overhead, and

(iii) No PFC capacitors are present.

For overhead distribution systems with short feeders resonance due to distribution line shunt capacitance will typically appear at relatively high frequencies and thus is usually of little concern for system harmonic planning. In special circumstances where high frequencies are prominent in customer equipment emissions, for example with high pulse number converters, these higher frequencies will need to be considered. For underground feeders resonant frequencies may appear at much lower frequencies and therefore distribution feeder shunt capacitance will need to be included in the calculation of system impedance when allocating harmonic emissions to distribution system customers.

To establish appropriate lengths of feeders beyond which shunt capacitance will cause resonance at problematic frequencies in relation to the nominal PI model shown in Figure 6.1 [66]. In Figure 6.1 the conductance G, susceptance B, and reactance X combine to give the admittance $G_L + jB_L = 1/(R_L + jX_L)$ with $Y_C = 1/jX_C$, $X_L=\omega L$, and $X_C=1/\omega C$ at frequency ω ($rads^{-1}$).

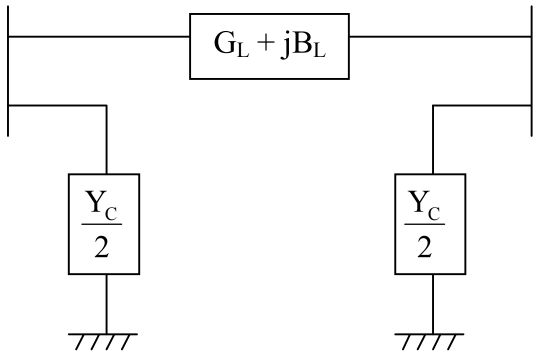


Figure 6.1 Admittance model of transmission line [66]

It has been shown that the nominal PI model can be improved in accuracy by dividing the distribution line into a number of subsections of nominal PI models [67]. Additionally, in preference to subsections the model can be improved using the evaluated distributed parameters equations (6.2) to (6.5) with series impedance, Z', and shunt admittance, Y' [65]. This new model is usually entitled the equivalent PI model.

$$Z = R + jX_L \quad (6.2)$$

$$Y = j\omega C \quad (6.3)$$

$$Z' = \frac{Z \sinh\sqrt{YZ}}{\sqrt{YZ}} \quad (6.4)$$

$$\frac{Y'}{2} = Y\frac{\tanh\frac{\sqrt{YZ}}{2}}{\sqrt{YZ}} \quad (6.5)$$

The increase in resistance and the reduction in inductance of conductors due to skin effect may also be considered when modelling distribution lines and cables. There are a number of analytical methods for estimating the magnitude of skin effect [65, 66, 68] that typically involve complex calculations based on conductor construction and Bessel functions. In each case the resistive component is most affected with only a small decrease in the inductance.

For transmission lines [68] suggests the harmonic impedance incorporating skin effect may be represented by equation (6.6) where h is the harmonic order, R_1 is the line series resistance at 50Hz and R_h is the line series resistance at harmonic order h.

$$R_h = \sqrt{h} \times R_1 \tag{6.6}$$

However, equation (6.6) does not show close agreement with the values suggested by equation (6.7) from [65] or the methods from [66], suggesting that (6.6) may overestimate the resistive component, especially for lower order harmonics.

$$R_h = R_1\left(1 + \frac{0.646\ h^2}{192 + 0.518\ h^2}\right) \tag{6.7}$$

According to equation (6.7) the increase in resistance due to skin effect at the 5^{th} harmonic will be approximately 8%. For harmonics near the 20^{th} the increases will be as much as 60%. However, due to the inductive component of the series impedance increasing linearly with frequency the increase in the overall impedance will typically represent less than 3% due to skin effect. Skin effect has been thus neglected in the present study as the specific application is designed for lower order harmonic frequencies and MV/LV distribution systems rather than EHV/HV transmission systems where skin effect is more prolific.

6.2.2 Transformers

For harmonic studies transformers are modelled using a combination of series and parallel inductive and resistive components. Generally, harmonic modelling of transformers can be completed with sufficient accuracy using the model shown in Figure 6.2 [65].

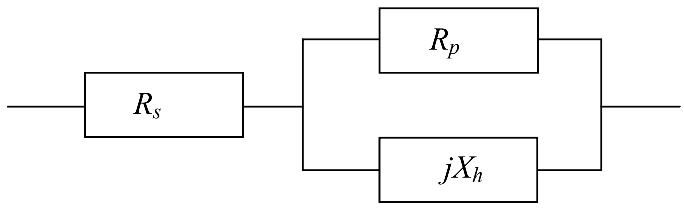


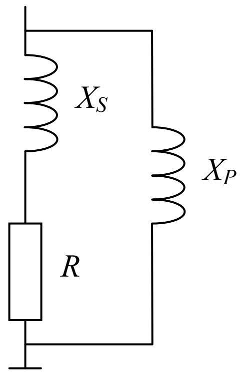
Figure 6.2 Transformer harmonic model, where $X_h = hX_1$

As transformers have a high reactance to resistance ratio, typically in the range of 10-20, for pragmatic modelling the resistances in the above model can be ignored and the transformer is modelled as a single series reactance. For the detailed modelling undertaken in this chapter full model shown in Figure 6.2 will be used.

6.2.3 Load models

For harmonic analysis load models need to incorporate both simple and complex loads. Simple passive loads such as lighting and heating may be represented as equivalent resistances. For pragmatic harmonic studies induction motors can also be represented using passive components, typically series inductance and resistance. Complex loads, such as an thyristor controlled AC loads, whose harmonic impedance will vary according to the phase angle of the thyristor firing [69] require detailed modelling and go beyond the scope of this thesis.

As planning engineers will often be more concerned with aggregates of load rather than individual load types [65] recommends that distribution loads be modelled using the model shown in Figure 6.3. In relation to the figure, V is the nominal voltage of the network, P_1 is the minimum active power of the load, and ϕ_1 is the power factor angle. Development of suitable aggregate load models is an area for further investigation.



where

$$R = V^2 / P_1$$

$$X_S = 0.073 \cdot h \cdot R$$

$$X_P = \frac{h \cdot R}{6.7 \tan\phi_1 - 0.74}$$

Figure 6.3 CIGRE model for normal aggregate distribution loads [65]

6.2.4 Power factor correction capacitors

PFC capacitors are installed within distribution systems to increase the utilisation of the system at the fundamental frequency. PFC capacitors are modelled as a simple shunt capacitor. A series resistance may be included in the model to improve accuracy around resonant frequencies [16].

6.3 Critical lengths of feeders

As the magnitude of the distribution line shunt capacitance is relative to the length of the line, for harmonic planning purposes it is important to know the critical lengths of feeders at which distribution line shunt capacitance needs to be considered.

Harmonic resonances due to the cable or line impedance are due to the interaction of the shunt capacitive reactance and the series inductive reactance. For example a system

model as illustrated in Figure 6.4 is considered. The system consists of a transformer connected to a purely inductive upstream system, creating an assumed fault level of 100MVA at an 11kV busbar. The busbar is connected to a single feeder of variable length.

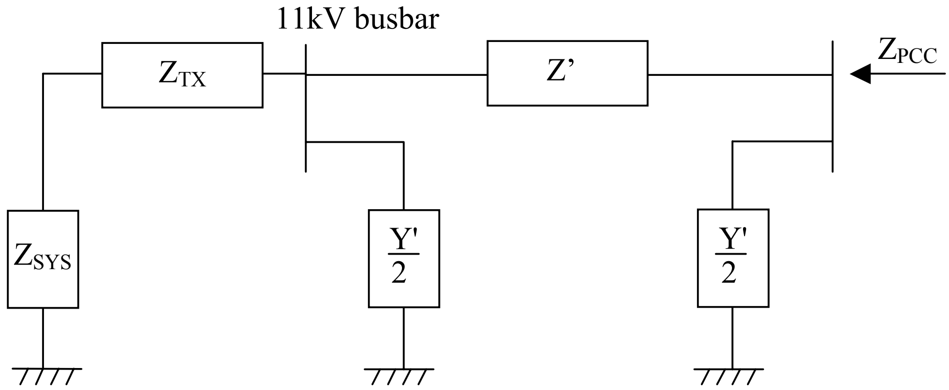


Figure 6.4 Simple system to estimate critical lengths of feeders

Using typical overhead line parameter values of R=0.3Ω/km, X_L=0.3Ω/km and X_C=300kΩ.km for the equivalent PI model the harmonics at which resonance occurs due to the series impedance and shunt admittance for a given length of feeder was investigated with the results illustrated in Figure 6.5. The same study has also been completed for an underground cable using R=0.12Ω/km, X_L=0.06Ω/km and X_C=3kΩ.km as illustrated in Figure 6.6.

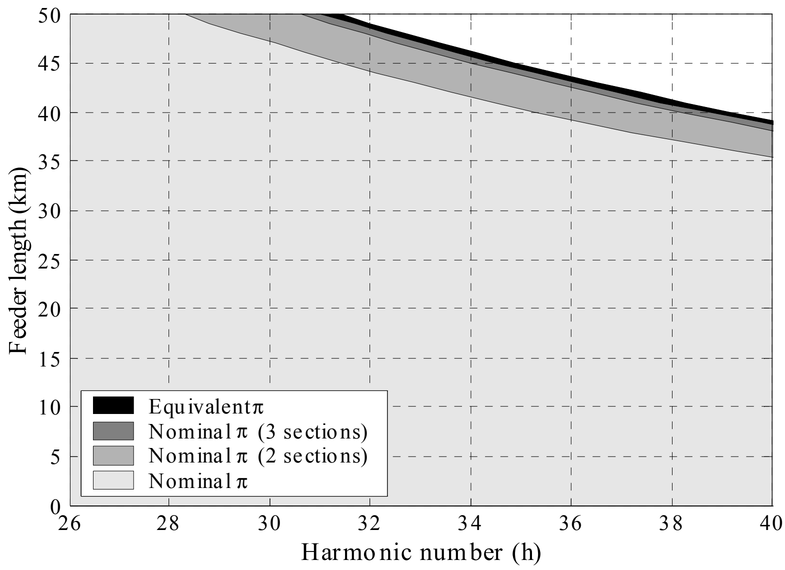


Figure 6.5 Harmonic at which first resonance occurs for overhead line lengths

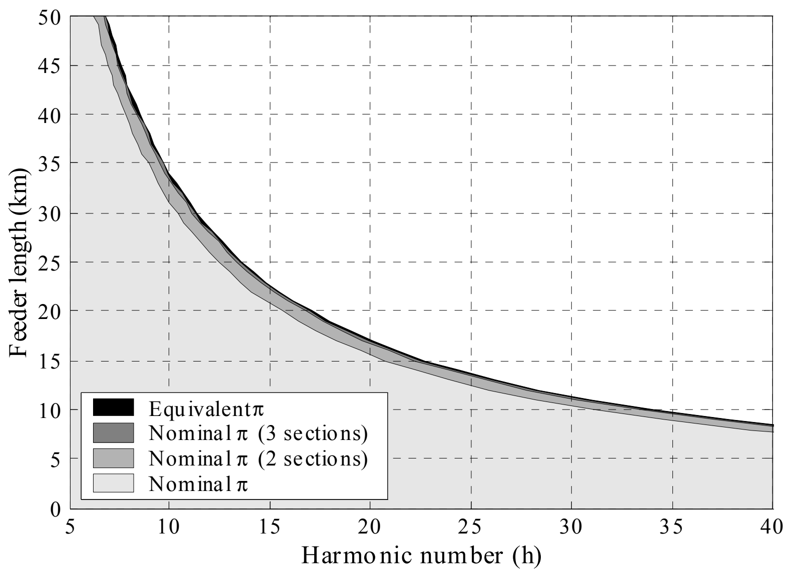


Figure 6.6 Harmonic at which first resonance occurs for underground cable lengths

A feeder length of up to 50km was considered although realistically lengths greater than about 15km would be considered rare at MV distribution level. Figure 6.5 illustrates that for overhead lines there is no significant contribution from the feeder shunt capacitance and thus shunt capacitance may be neglect for pragmatic harmonic studies involved with allocating harmonic emissions.

Figure 6.6 suggests that feeder lengths of underground cables greater than approximately 7km need to have the shunt capacitance included in the modelling as resonance may occur at frequencies between the 30th and 40th harmonics. Experience has shown that harmonic planning is really only achievable at distribution level for lower order harmonics [70]. The resonance at the higher order harmonics has not shown to be of significant importance in most cases. Recommendations in [45] are that feeder shunt capacitance will have a negligible effect on the harmonic impedance if the $h \times l$ product is less than 300 for overhead line or 50 for underground cable, where line h is the harmonic of concern and l is the length of the feeder in kilometres. Figures 6.5 and 6.6 suggest that this is conservative for typical Australian distribution systems. Thus distribution line shunt capacitance may be neglected for most harmonic studies.

6.4 Detailed approach to determining system impedance

The installation of PFC capacitors can dramatically change the distribution system harmonic impedance. Parallel or series resonance problems can occur at problematic harmonics such as the 3rd, 5th and 7th harmonics if PFC capacitor installation design is not completed carefully. The resonant frequency produced from the installation of PFC capacitors can be approximated by equation (6.8).

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{6.8}$$

where f_r is the resonant frequency, L is the system inductance, and C is the capacitance of the PFC capacitor. The resonant harmonic order h_r can also be estimated using Q_C, the capacitor reactive volt-amperes and S_{SC}, the fault level at the point of capacitor connection as given by equation (6.9).

$$h_r = \sqrt{\frac{S_{SC}}{Q_C}} \tag{6.9}$$

6.4.1 Location and sizing of PFC capacitors

Depending on the power factor requirements and the policy of a particular DNSP, PFC capacitors may be installed locally to the MV busbar of zone substations, at more remote locations further downstream on distribution feeders, and within customer installations. The fundamental frequency performance of the system is the primary consideration when designing PFC capacitor installations. DNSP planning engineers must also bear in mind the harmonic performance of the distribution system to reduce the possibility of a dramatic increase in levels of harmonic voltages due to system resonance.

6.4.2 Typical resonant frequencies for different systems

As distribution systems are largely designed to standard practises and procedures of the DNSP, system impedances at various levels of the distribution system will often be similar. PFC capacitors also usually come in banks of standard sizes, i.e. 2.5MVAr in distribution substations and 300kVAr for pole mounted banks, although this will vary depending on the DNSP. As pole mounted capacitor banks may be installed at any location along a feeder it is highly unlikely that any typical resonant frequencies would exist. For zone substations capacitor bank sizes will generally be around 10%-20% of substation rating to correct power factor back to near unity.

From the data obtained from Integral Energy planning engineers, fault levels at distribution zone substations vary typically from 150MVA to 250MVA. Given that a typical zone substation will be rated at approximately 25MVA, capacitor banks totalling 5MVA will be usually expected to be installed. Using equation (6.9) the resulting harmonic resonance will be between the 5^{th} and 10^{th} harmonic, implying that most

substation capacitor installations may lead to resonances around the problematic 5th and 7th harmonics. Thus, great care needs to be taken to ensure resonances do not coincide with these harmonics, especially considering switched capacitors can often lead to multiple resonant frequencies. Detuning reactors may be necessary in some instances to shift resonant frequencies away from the problematic 5th and 7th harmonics.

6.4.3 De-tuning of PFC capacitors

De-tuning of PFC capacitors is achieved by connecting a reactor in series with the capacitor. This effectively shifts the resonant frequency created by the capacitor installation to a less problematic harmonic or sub-harmonic. Figure 6.7 illustrates the effect of including a de-tuning reactor on the harmonic impedance for the simple model of a distribution system. The circuit without the de-tuning reactor has a parallel harmonic resonance at the 7th harmonic. Once the correct de-tuning inductor is installed, both series and parallel resonance frequencies are shifted away from the 7th harmonic. Particularly, the series resonance is now located at 4.5th harmonic and hence the resulting impedances at the problematic 5th and 7th harmonics are both reduced.

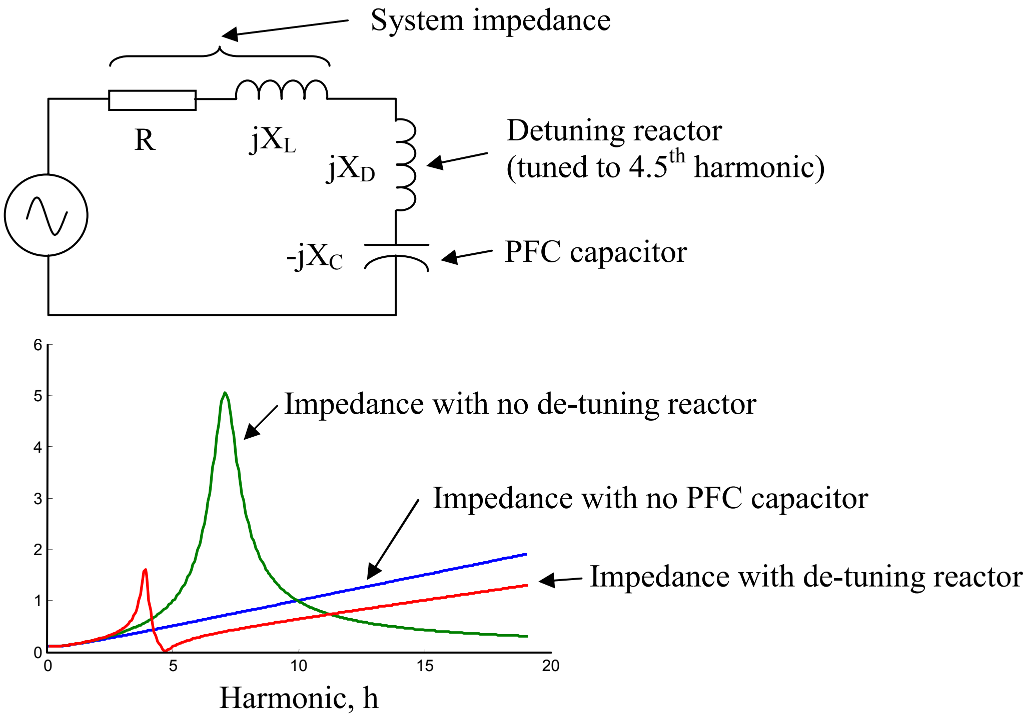


Figure 6.7 Simple distribution model illustrating de-tuning of PFC capacitor

PFC capacitors will generally have small in-rush reactors installed for protection and thus the addition of a slightly larger reactor will often not increase the cost by significant levels. The increase in cost for a detuned capacitor bank will be approximately 30% more than without detuning. This figure applies to smaller capacitor banks (less than 5MVA) as the proportion of cost increases with larger banks, i.e. for capacitors installed within transmission and sub-transmission systems. Further details of planning issues regarding PFC capacitors and the application of de-tuning reactors to reduce harmonic voltages are discussed in [71].

6.4.4 Effects of load damping

Slight variations in system harmonic impedance are expected as a network is reconfigured and different loads are connected or disconnected. For a distribution system with insignificant system capacitance the variations in the harmonic impedance

will usually not be extensive enough to cause intolerable errors in the calculations of harmonic emissions or estimations of harmonic voltage levels. However, if significant system capacitance is present the variations in network impedance at certain frequencies may be considerable due to the effects of harmonic resonance.

Passive loads have a damping effect on the magnitude of harmonic resonance. To study the extent of damping the load model illustrated in Figure 6.3 is utilised in a harmonic impedance study of an overhead distribution system illustrated in Figure 6.8. The system consists of six feeders fed via two 25MVA transformers, each feeder containing six 500kVA customers with a power factor of 0.85 lagging. The distance between two adjacent customers is 2km. The system models outlined in Section 6.2 are used to complete the study. The overhead line parameters are R=0.3Ω/km, X_L=0.3Ω/km and X_C=300kΩ.km. An X:R ratio of 20:1 is used for the system impedance on the 33kV busbar.

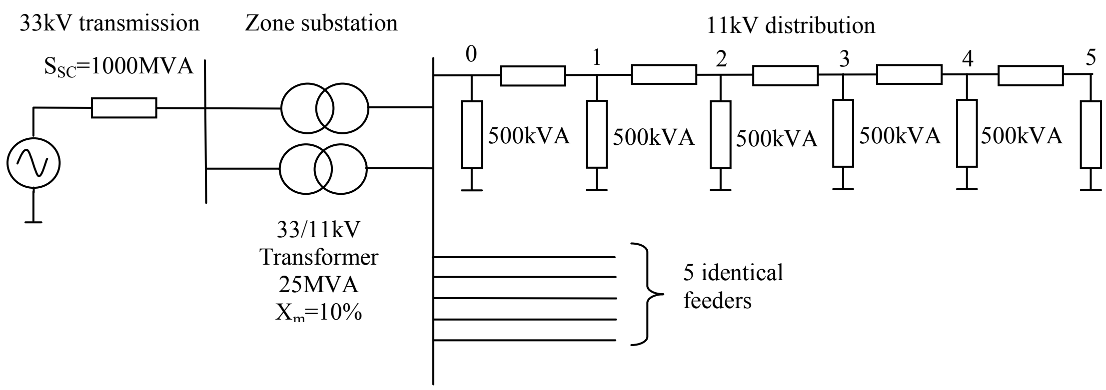


Figure 6.8 Homogeneous distribution system for load damping study

The harmonic impedances seen by customers (at nodes 0-5) in Figure 6.8 are illustrated in Figure 6.9 for both full load damping and no load damping considered. To correct the power factor two 5MVAr capacitor banks are installed at the zone substation 11kV

busbar resulting in a harmonic resonance at the 5.8th harmonic. The resulting harmonic impedances seen by each customer are illustrated in Figure 6.10.

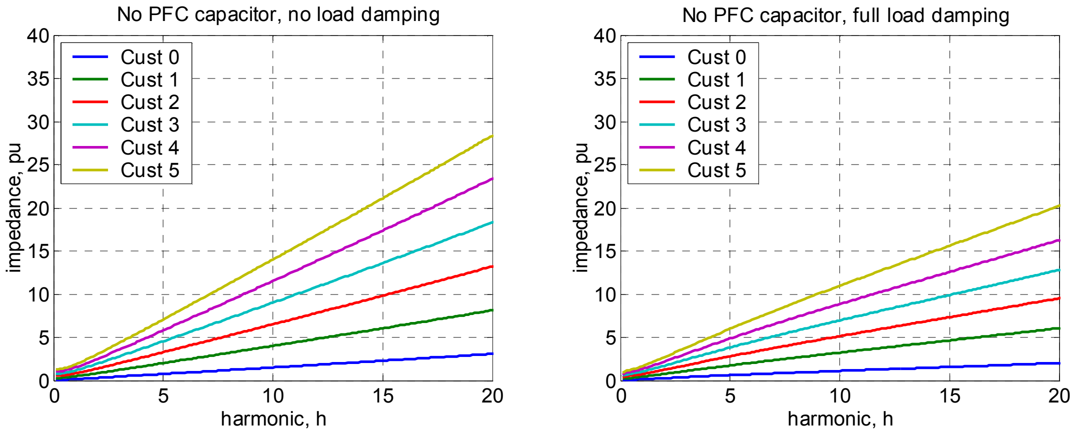


Figure 6.9 Harmonic impedance with no PFC capacitors installed

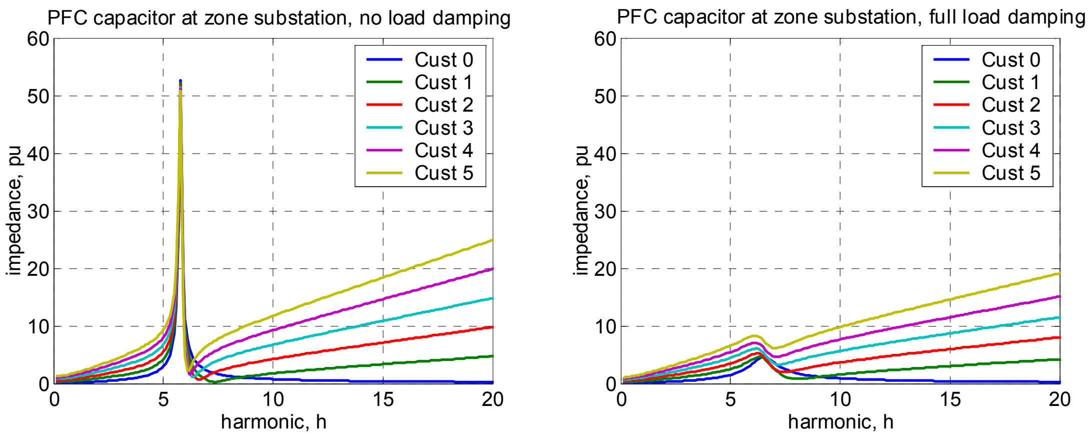


Figure 6.10 Harmonic impedance with PFC capacitor installed at zone substation

As an alternative to installing a capacitor at the zone substation busbar, each feeder can be installed with a capacitor at a single location along the length of the feeder. The size of the capacitor is chosen to be the optimum size and location as per recommendations in [72]. The capacitors are rated at 2/3 of the total reactive volt-amperes of each feeder and are installed at 2/3 the total length from the zone substation. The resulting harmonic impedances are illustrated in Figure 6.11.

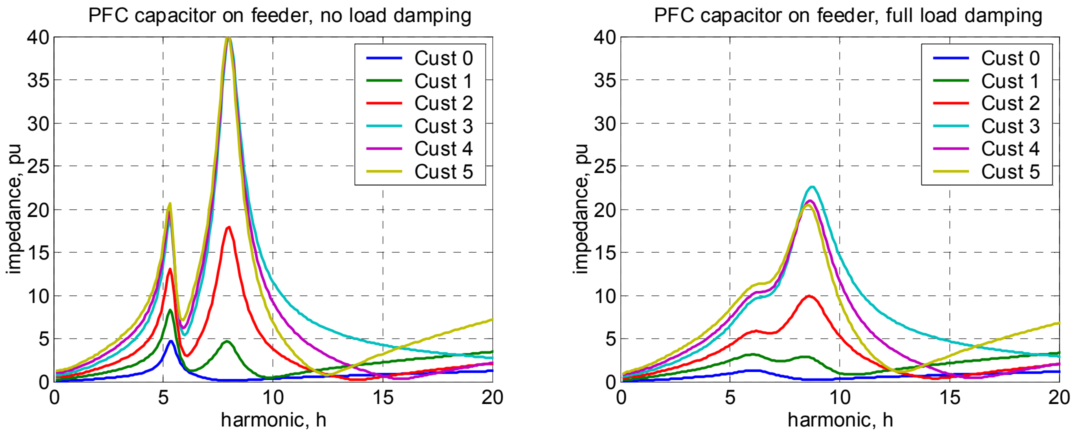


Figure 6.11 Harmonic impedance with PFC capacitor installed at 2/3 of feeder length

From Figures 6.9 to 6.11 it can be seen that the effects of load damping on the harmonic impedance are significant. For the cases where a PFC is present the harmonic impedances at the resonant frequencies have reduced considerably while the resonant frequencies themselves have changed only slightly. Damping at only full load is considered here. Damping due to lighter loads produces less significant reductions in resonant frequencies for the same sized PFC capacitor. It is noted that capacitor banks would generally have a fixed and switched component, thus at light loads less capacitance would be in service leading to a different resonant frequency (at a higher order harmonic).

6.4.5 Complexity with a number of capacitors present

In Figure 6.11 two harmonic resonance frequencies can be identified. The two resonances frequencies are due to the capacitor on the study feeder and a combination of the capacitors on the remaining feeders. The inclusion of multiple capacitor installation will often create multiple harmonic resonances. Also, disconnection of one or more feeders or one of the zone substation transformers will dramatically shift the resonant frequencies that exist. When allocating harmonic emissions to a customer, knowledge of

all possible distribution system configurations should be considered such that the worst case scenario can be identified.

Multiple resonant frequencies and network configurations also lead to additional difficulties in attempting to de-tune PFC capacitors. Detailed analysis should always be completed in these cases to ensure problematic resonance do not occur.

6.5 Pragmatic approach in determining system impedance

As detailed modelling of the system may not be practical during the planning stage of a distribution system, it is necessary to develop a pragmatic approach that may be used to model the system effectively in the presence of significant system capacitance. While being straightforward to implement a pragmatic approach should also provide results within suitable levels of accuracy.

Detailed approaches to system modelling are well documented in [11, 13, 15, 65] for the case of a single PFC capacitor. The effects of system resonance have been studied extensively but the work described has always involved complex and detailed calculations [73, 74]. Dedicated software packages such as PSCAD/EMTDC [55], Superharm [58], or PSpice [56] may be used for detailed analysis of multiple capacitor installations to calculated harmonic impedances. Also mathematical packages such as MATLAB® may also be used. However, all of these methods are very time consuming.

IEC 61000-3-6 suggests a simplified method to determine the harmonic impedance in the presence significant capacitance by calculating an envelope impedance curve. The

impedance curve is illustrated in Figure 6.12 with $Z_h=2hX_1$ up to the 8th harmonic and $Z_h=hX_1$ beyond the 8th harmonic.

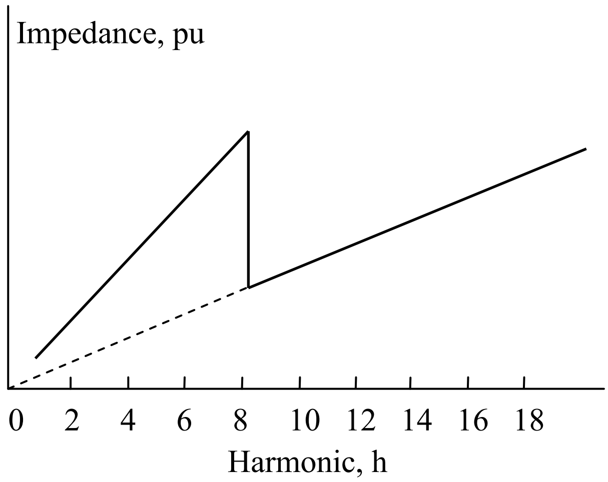


Figure 6.12 11kV worst case impedance curve from [16]

This method has been refined in [45], however still usually leads to an "over-assessment" of the harmonic impedance. For comparison the damped harmonic impedance of Figure 6.11 is compared with a curve equal to two times the impedance with no PFC capacitors present (dashed lines overlayed) as shown in Figure 6.13.

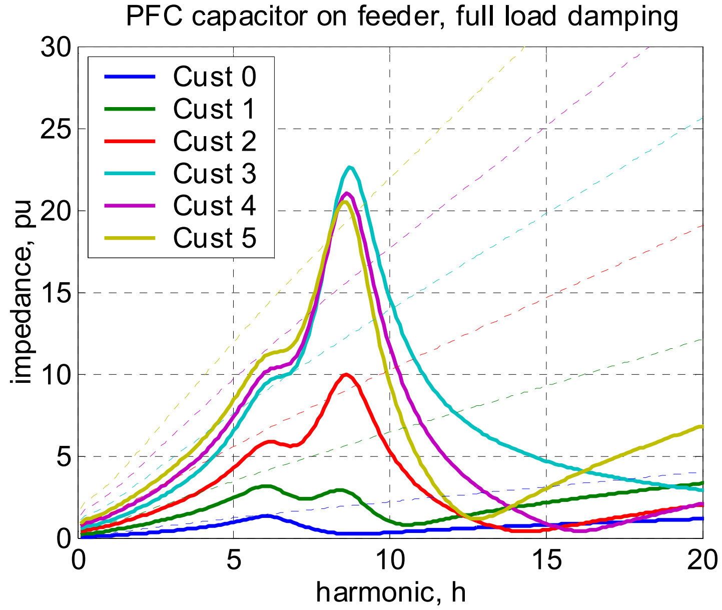


Figure 6.13 Harmonic impedance with full load damping and two times impedance

As shown in Figure 6.13 the calculated harmonic impedance only protrudes beyond the two times impedance curve at the resonant frequency. This suggests that the envelope impedance curve is a suitable tool for estimating the harmonic impedance. Trials on variations of the example illustrated in Figure 6.8 also yielded similar results.

Further verification is required to ensure that the envelope impedance curve provides acceptable results for all possible system configurations, i.e. multiple capacitor installations and parameter variations. This is an area to be addressed in future work.

6.6 Allocation of harmonic emissions with capacitors present

For the allocation of harmonic emissions to a customer located electrically near a PFC capacitor installation it will be assumed that the envelope impedance curve recommended in IEC 61000-3-6 will provide a suitable pessimistic approach in determining the harmonic impedance. In the event of an allocation derived from this method being unacceptable to a customer a detailed study will be required whereby the harmonic models for various distribution system components introduced in this Chapter are utilised.

Detuning of PFC capacitors using series inductors can help reduce the parallel resonance effect by shifting the resonant frequency to a non-problematic harmonic. Thus DNSP planning engineers should ensure that PFC capacitor installation take into account the harmonic performance of a distribution system. In this manner emission allocation for problematic harmonics need only be completed using the assumption that there is no significant system capacitance.

6.7 Summary

In this Chapter consideration has been given to the effects of PFC capacitors, distribution line and cable shunt capacitance on the harmonic performance of MV distribution systems. The effects on harmonic impedance are important when estimating harmonic voltage levels and during the procedure of allocating harmonic emissions to distribution system customers. Various models for distribution system components have been introduced for use in detailed harmonic studies.

Using detailed analysis it has been determined that cable and line lengths at distribution level will be usually short enough for resonance due to distribution line shunt capacitance not to occur at the problematic lower order harmonics. Thus distribution line shunt capacitance may be assumed to be negligible for pragmatic harmonic studies. Installation of PFC capacitors within distribution system is often required to improve the power factor, improve voltage stability and reduce losses. While these performance parameters are based on the fundamental frequency, it is important for DNSP planning engineers to also consider the harmonic performance. This is due to harmonic resonant frequencies typically created by PFC capacitors installed within zone substations and on feeders often coinciding with problematic lower order harmonic frequencies. By de-tuning PFC capacitors correctly resonance at problematic harmonics can be reduced. This has a drawback practically in that it imposes high cost in design and installation.

For detailed harmonic analysis damping at resonant frequencies due to connected loads has shown to be significant. Thus if system capacitance is being modelled consideration to the effects of damping from loads should also be given. Modelling of loads is very difficult at harmonic frequencies where further research needs to be undertaken. The

CIGRE model used here is considered reasonable but possibly not suitable for all systems without further research.

Provided resonance frequencies are not at the problematic harmonics, the envelope impedance curve method described in IEC 61000-3-6 to estimate harmonic impedances should provide suitably pessimistic results. If resonant problems are anticipated more in depth harmonic studies should be completed to determine harmonic problem areas.

Areas for future work in determining harmonic impedance in the presence of significant system capacitance include development of a less pessimistic yet straightforward pragmatic method to estimate harmonic impedance when PFC capacitors are electrically near a customer's installation.

Chapter 7

Application of harmonic planning methods to MV distribution systems

7.1 Introduction

A general method for allocating acceptable harmonic emissions to MV customers has been established in Chapter 4 based on the guiding principles outlined in the IEC 61000-3-6 standard. The new method allows the same ideology of allocating harmonic emissions to be applied to general systems with complexity beyond the simple examples presented in the standard. Harmonic emission allocations to three real case studies are provided in this chapter to illustrate the practical application of the new method. The case studies presented include an assessment of existing harmonic distortion levels within a distribution system, an example of an allocation of harmonic emissions to a customer situated along a long MV feeder, and an evaluation of a system containing numerous power factor correction (PFC) capacitors.

The first case study system is the Homepride zone distribution network. Details of this distribution network can be found in Chapter 5. The system is presented here to illustrate assessment of existing harmonic voltage levels on the network. More specifically identifying the critical impedances of the system and applying suitable harmonic planning levels throughout the network.

The second case study is the Katoomba Zone MV distribution network. This study traces the application of the new harmonic emission allocation method to an MV customer wishing to connect to the end of a relatively weak feeder. This case study was

the first application of the new allocation method to a real system. Discussion is presented on the difficulties encountered including the interpretation of the pragmatic procedures incorporated in the new method to complex load operation.

The third case study involves the Springhill sub-transmission substation. This study addresses the practical application of pragmatic measures when dealing with the presence of power factor correction (PFC) capacitors. The system analysed contains sub-transmission, distribution, and a number of large industrial customers. The difficulty of harmonic allocations within a network that experiences significant changes in harmonic impedance due to PFC capacitor switching is specifically addressed.

In the three case studies use of the generalised methods presented in this thesis for harmonic voltage management are illustrated. Each case study involves collection of suitable data, application of harmonic models, and assessment of harmonic voltage levels or customer emissions. A dependence on reliable data to complete the studies is highlighted. Specific discussion on the above-mentioned issues is presented and the deficiencies in the existing harmonic standard are highlighted.

7.2 Case study 1: Homepride zone distribution system

The Homepride zone distribution system is located in the western suburbs of Sydney. Homepride is an 11kV distribution network owned and operated by Integral Energy containing ten MV feeders supplying residential, commercial and industrial customers. A majority of the feeders are predominantly overhead lines, however there is a significant amount of underground cable included in some sections of the feeders. The

distribution system had a maximum demand of approximately 80% of capacity in the year 2000. A schematic layout of Homepride was given in Figure 5.6 of Chapter 5.

Using data from the harmonic monitoring programme reported in Chapter 5 the following section demonstrates the practical application of harmonic management techniques introduced in Chapters 3 and 4. More specifically this case study presents discussion on the following issues

(i) Identifying the critical impedances within the system,

(ii) Assessing harmonic levels given the loading of the distribution system, and

(iii) Applying suitable harmonic limits to different points within the system.

7.2.1 Identifying the critical impedances of the system

Harmonic voltages appear in distribution systems when non-sinusoidal currents from distorting loads flow through the system. The harmonic voltages resulting from these currents are proportional to the system harmonic impedance seen by the distorting load. Thus, reducing the harmonic impedance of a system will lead to a 'stronger' system, i.e. a system that has the ability to absorb a greater magnitude of harmonic current without producing excessive harmonic voltage levels. For this reason it is important to identify critical impedances that exist within the system. An assessment can then be made as to where the impedance is most cost effective to reduce to provide increased harmonic performance.

Using an appropriate base a diagram showing the harmonic impedance from the transmission system down to the end of an LV distributor can be constructed. Figure 7.1 illustrates the calculated 5^{th} harmonic impedance seen through the different sections of

the Homepride system and to the end of an LV distributor for customers at a residential site (Site 4 of Figure 5.6 in Chapter 5).

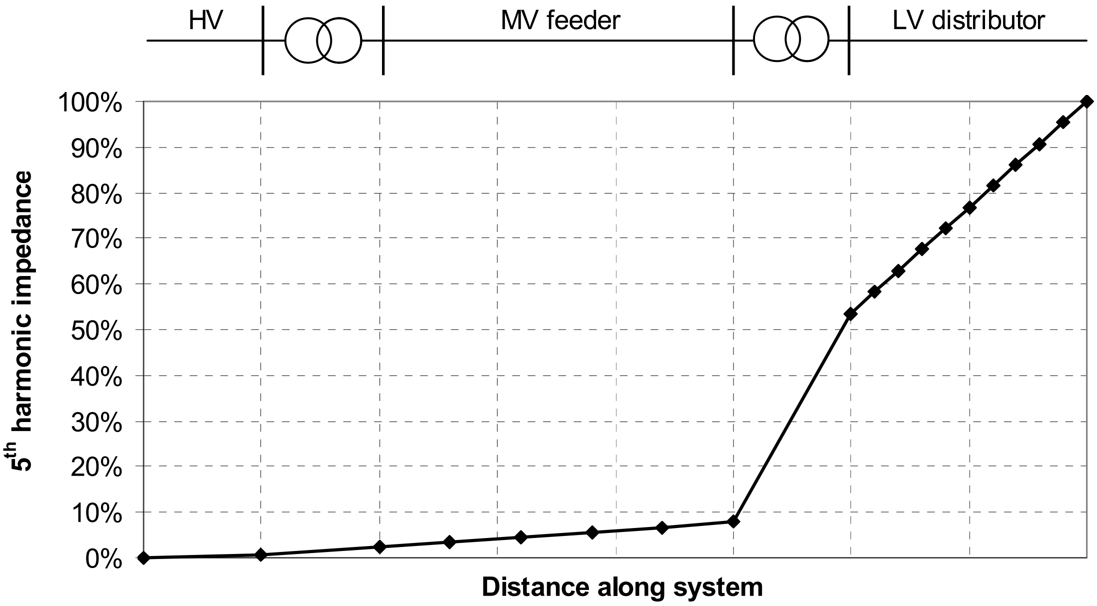


Figure 7.1 5th harmonic impedance seen by load as percentage of total impedance

The HV section of the system in Figure 7.1 includes the source impedance of the transmission system at (0.0015+j0.0271) per unit on a 100MVA base, three parallel-connected 132kV/33kV 120MVA sub-transmission transformers, and a length of 33kV overhead sub-transmission line. The zone substation transformer is the equivalent of two 33/11kV 20MVA transformers connected in parallel for (N-1) redundancy. The MV feeder consists of both overhead and underground lines and the LV distributor is a length of overhead line. The load on the zone substation consists approximately of 50% LV customers and 50% MV customers.

As illustrated in Figure 7.1 the impedance seen by a distorting load connected to the LV distribution system is mainly due to the MV/LV transformer and LV distributor line. Thus the voltage distortion contribution due to a single LV distorting customer will predominantly occur along the LV distribution system and across the MV/LV

distribution transformer. However, as each customer on the LV distribution system will typically represent less than 0.1% of the entire zone substation load the resulting harmonic voltage may never become significant. Thus harmonic voltages from an aggregate of all the loads within the distribution system need to be examined when determining critical impedances. This is necessary to test whether the small contributions of many customers will produce a significant overall voltage distortion at different points within the distribution system.

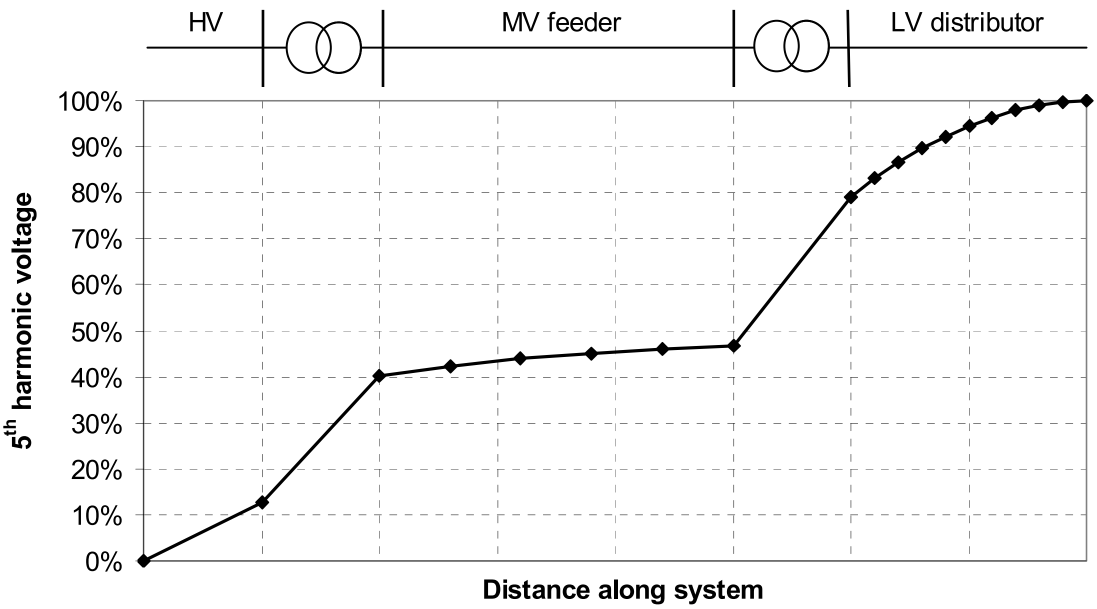


Figure 7.2 5^{th} harmonic voltage as percentage of level at end of distributor

A plot of the calculated 5^{th} harmonic voltage distortion throughout the distribution system due to a combination of smaller harmonic loads was completed using the second summation law and is shown in Figure 7.2. For this study MV customers were considered to give a similar harmonic contribution to that of an equivalent sized combination of LV customers. Figure 7.2 illustrates that if harmonic contributions from many customers are considered the largest harmonic voltage distortion increases occur at the high impedance locations of the system transformers.

The small increase in harmonic voltage levels along the MV feeder shown in Figure 7.2 suggest connecting a distorting load at the end of the feeder will produce the worst case of harmonic voltage distortion, however not significantly different from having the same load at the beginning of the a feeder. This is due to the HV/MV transformer providing most of the harmonic impedance across which the harmonic voltage is developed when all distorting load currents are combined.

Figure 7.2 also suggests that if a DNSP plans to control harmonic voltage levels in a distribution system by reducing system impedance, the best locations to do so are at the HV/MV zone substation transformer or the MV/LV distribution transformer. Reduction of the impedance of the MV/LV distribution transformers would be difficult to justify for an existing system, as this would require the replacement of hundreds of transformers, however may be viable during the planning phase of a new system.

Assuming most of the harmonic current injected in to the system by various customers will flow through the zone substation transformer, reducing its impedance by a factor of 10% will also reduce harmonic voltage levels at the zone substation by 10%. At the end of the LV distributor this reduction of harmonic voltage will appear as 2% overall due to the voltage increases downstream from the zone substation transformer. Alternatively, if an MV/LV distribution transformer impedance is reduced by 10% the harmonic voltage level at the end of the LV distributor will reduce by 4%. A slightly larger reduction in harmonic levels will obviously occur for MV customers, who typically connect to the system via their own MV/LV distribution transformer with no LV distributor lines. Use of aerial bundled conductors or underground cables along MV

feeders and LV distributors will also reduce the level of harmonic voltages, however not by magnitudes as significant as that obtained by modifying transformer impedances.

Cost is a significant factor when deciding on harmonic mitigation techniques during the planning phase of network design. A nominal figure obtained from Integral Energy for the replacement cost of a zone substation transformer is approximately $550 000. For a distribution transformer the cost is $25 000. Moving cable underground can cost up to $450 per metre, offering less significant harmonic impedance reductions, but has additional benefits of reduced voltage sags due to motor starts and arguably better suburban streetscape environment. Thus reducing the harmonic impedance of transformers and lines for existing systems would rarely prove to be a cost effective method of harmonic mitigation.

Reducing system harmonic impedance during the design phase of a distribution network is advantageous as it leads to a reduction in losses and increases the systems harmonic absorption capability. Reduced system impedance evidently means an increase in fault levels. This is not usually a problem if DNSP customers are aware of ratings required for protection and switchgear. Reducing system impedance also reduces the impact of other power quality disturbances, including voltage fluctuations, voltage sags and voltage regulation. The cost of additional copper or aluminium in conductors will obviously remain the most significant factor affecting decisions related to reducing system impedances. The most cost effective method of mitigating harmonic problems will often be the installation of harmonic filters or active compensators.

7.2.2 Consideration of existing loading when assessing harmonic levels

When assessing harmonic distortion levels within a distribution system it is important to measure or have an indication of the loading on the system. The term loading here is used to express the fraction of the total available capacity of the system that has already been allocated to existing customers and does not include diversity. The loading is usually a figure well known to the DNSP and is often expressed as the undiversified maximum load.

Without the loading of the system a true indication of whether customer loads are taking up their harmonic entitlements is not possible. For example, consider a system with a harmonic voltage planning level of 5% for the 5^{th} harmonic. If through a harmonic monitoring programme the 95^{th} percentile 5^{th} harmonic voltage was measured to be 4%, the DNSP may initially consider the system to have acceptable harmonic voltage levels. However, if the system was only one third loaded it is expected that measured harmonic levels should be less than 4%. Harmonic voltage levels should thus be measured against a scaled harmonic voltage planning level. The scaled harmonic voltage planning level can be determined using the second summation law from IEC 61000-3-6 and equation (7.1).

$$L'_{hMV} = L_{hMV} \cdot \sqrt[\alpha]{\frac{S'_T}{S_T}} \qquad (7.1)$$

where L'_{UhMV} is the scaled harmonic voltage planning level for order *h* at MV, L_{UhMV} is the harmonic voltage planning level for order *h* at MV, S'_T is the system undiversified existing loading, S_T is the system total available power, and α is the exponent of the summation law.

Using the scaled harmonic voltage planning level it is possible for a DNSP to assess whether customer loads are taking up their full harmonic entitlement and whether there is room to allow additional harmonic loads to be connected. If the scaled harmonic voltage planning levels were used, the one third loaded system mentioned above would be identified as having excessive harmonic voltage levels and cost effective mitigation may be able to be achieved before harmonic levels become more problematic.

For Homepride, results from the harmonic monitoring programme at the commercial site recorded in April 2002 are considered. The system is loaded to 24MVA with a capacity of approximately 27.5MVA, allowing for 10% transformer overloading. The resulting THD_V and 5^{th} harmonic voltage distortion levels at the LV commercial site were found to have 95^{th} percentile values of 4.17% and 3.81% respectively.

For the 5^{th} harmonic a summation law exponent of $\alpha = 1.4$ is recommended by IEC 61000-3-6. Using equation (7.1) to evaluate the recommended harmonic planning levels

$$
\begin{aligned}
L'_{5LV} &= L_{5LV} \cdot \sqrt[\alpha]{\frac{S'_T}{S_T}} \\
&= 5.00\% \cdot \sqrt[1.4]{\frac{24}{27.5}} \\
&= 4.54\%
\end{aligned}
$$

The recorded 95^{th} percentile level can then be expressed as a percentage of the scaled harmonic planning level

$$
\begin{aligned}
U_{5\,COM\,LV} &= \frac{4.17\%}{4.54\%} \\
&= 92\%
\end{aligned}
$$

Thus, the measured levels are quite close to the recommended harmonic planning levels considering the loading of the system. Note that a 5th harmonic planning level of 5% has been assumed for LV sites for this case. Such a level is considered to be quite conservative in that the planning level recommended by IEC 61000-3-6 for the 5th harmonic at MV is 5%, thus the planning level at LV would be expected to be slightly higher than this in most cases.

7.2.3 Applying suitable limits to different points within the system

An important aspect of harmonic planning for a DNSP is the selection of harmonic voltage planning levels at the different points within their distribution systems and indeed further upstream in the sub-transmission and transmission systems. The IEC approach to determining suitable harmonic voltage distortion planning levels in distribution systems is to ensure that levels remain below equipment susceptibility levels. That is, compatibility levels are determined for a broad range of equipment, and then planning levels for the DNSP are set slightly below this to attempt to ensure the compatibility levels are never reached. Determining compatibility levels for equipment is an area of power quality that requires significantly more research and will change as technology also changes. For this thesis it will be assumed that the compatibility levels recommended by the IEC are well substantiated.

For transmission systems (HV and EHV) the harmonic voltage planning levels suggested by IEC 61000-3-6 are 3% for voltage THD and 2% for the 5th harmonic. This means expected harmonic voltage contributions from upstream HV and EHV networks should be at most 2% for the 5th harmonic. Although no planning levels are specified in the IEC standard for the lower extreme of the system, i.e. at the end of LV distributors,

compatibility levels for MV and LV systems are provided. Thus the standard provides some guidance for the planning levels for the upstream and downstream extremities of distribution systems, however insufficient guidance is provided to determine suitable planning levels for points on the system between the extremities, e.g. the zone substation busbar.

The Homepride system 5th harmonic voltage level at the zone substation 11kV busbar in September 1999 was measured to be 1.61% (95th percentile). This is well below the recommended planning level of 5.0% for the 5th harmonic. However it would be unwise for harmonic planning levels at the MV busbar to be set at 5.0% as this does not allow for any harmonic voltage increases along MV feeders, distribution transformers, and LV distributors.

To determine what the levels of harmonic voltage distortion should be at the zone substation busbar, the entire Homepride distribution system is considered as a long feeder having distribution points with varying fault levels. The harmonic voltage through the system and along the weakest MV feeder to the LV distributor (at which the worst harmonic voltage is assumed to occur) is considered. To simplify calculations of the harmonic voltages a representative system as illustrated in Figure 7.3 is utilised. The procedure for allocating harmonic emissions outlined in Chapter 4 is then utilised to determine appropriate voltages expected at each point on the system given that the maximum 5.0% (for the 5th harmonic) will occur at the end of an LV distributor. Fault levels for HV, MV and LV locations are selected to be indicative of typical sub-transmission and distribution systems in Australia that match reasonably closely to the Homepride system.

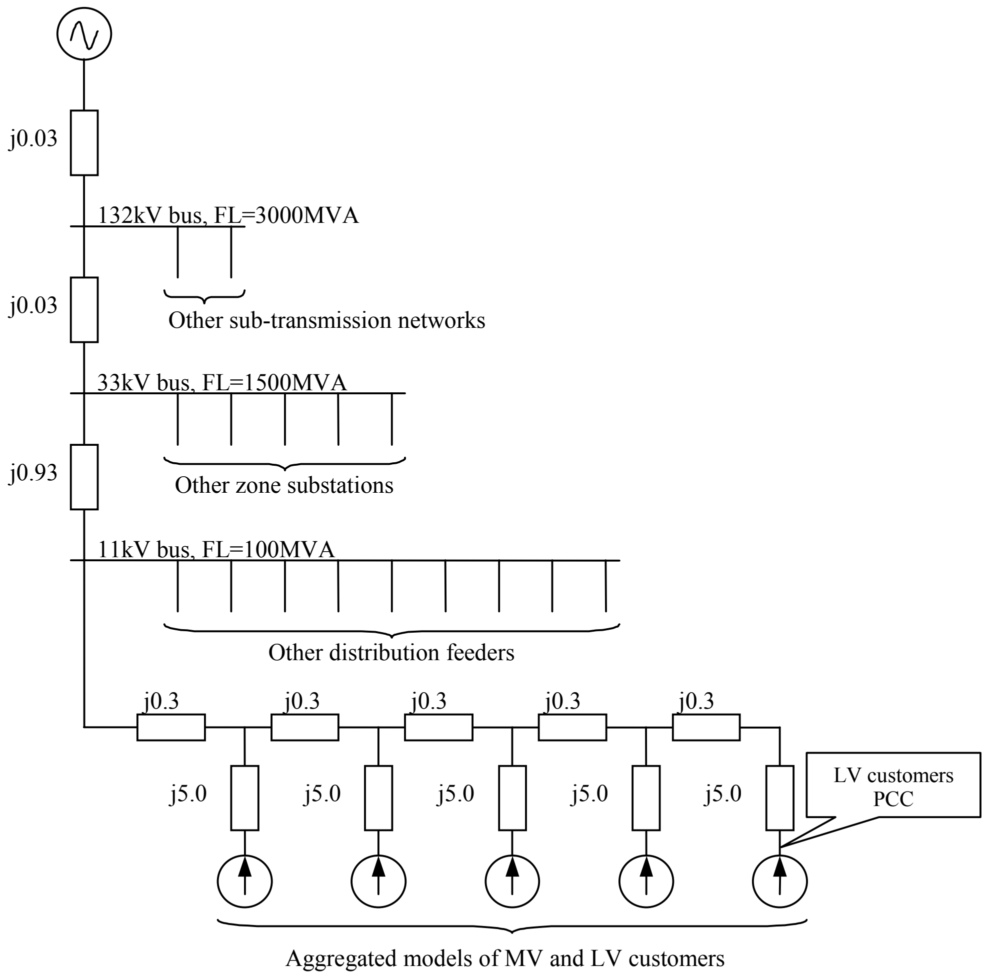


Figure 7.3 Indicative schematic layout of a typical radial distribution system

The estimated harmonic voltages are established using the second summation law. A background harmonic voltage is included in the calculations such that when the system reaches the recommended harmonic limit at the LV customer's PCC, the background harmonic voltage combined with the harmonic voltage due to the system will equal the recommended HV harmonic limit at the 132kV bus. Put more simply, it is assumed the HV system will reach the respective limits the same time as the LV system. The resulting values of the harmonic voltages at each voltage level are shown in Tables 7.1 for the 5th harmonic.

Table 7.1 Indicative 5^{th} harmonic voltage levels for typical power system

Location	**5^{th} harmonic voltage**
Background	0.9%
132kV bus	2.0%
33kV bus	2.5%
11kV bus	4.0%
11kV above PCC	4.4%
PCC LV customer	5.0%

From the results in Table 7.1 it could be suggested that indicative planning levels for the sub-transmission 33kV bus and distribution 11kV bus should be approximately 2.5% and 4.0% for the 5^{th} harmonic respectively. As many systems may be weaker than the study system in Figure 7.3, and because most of the system impedance seen by customers appears at distribution level, it may be suitable for a DNSP to use a slightly more conservative value for sub-transmission planning levels where possible. Use of the HV planning levels at sub-transmission level is one suitable method to ensure fewer harmonic problems at LV. It is assumed planning levels for harmonic orders other than the 5^{th} harmonic could be found by similar means or by appropriate scaling of the values in Table 7.1 to suit the planning levels recommended by IEC 61000-3-6.

The HV harmonic voltage limits here have been fixed at the planning levels suggested by the standard for the 132kV busbar at 2.0%. The harmonic current from the MV distribution system itself will contribute a voltage component to this level. In Australia the HV and EHV systems are typically meshed networks and thus it is difficult to determine what this current contribution might be without detailed modelling, and goes beyond the scope of this thesis.

7.3 Case Study 2: Katoomba zone distribution system

Pragmatic modelling of MV distribution systems and associated loads attempts to reduce the complexity involved in determining effects of loads on the system and in most cases the general approach will be sufficient. However, the complex behaviour of individual loads may often provide additional difficulty when applying the procedures to allocate harmonic emissions to customers. This case study presents the harmonic assessment of a customer seeking approval for connection to Integral Energy's Katoomba zone distribution system. In particular this section presents discussion on the following

(i) Assessment of background harmonic voltage levels,

(ii) Calculation of acceptable customer harmonic current emissions, and

(iii) Accounting for load interaction with system harmonic voltages.

The customer of interest (to be called *Customer A*) is located in the Blue Mountains north of Sydney. A schematic of the Katoomba zone distribution system to which *Customer A* is connected is illustrated in Figure 7.4, showing distribution transformers and the 10 year projected maximum demand along the feeder to which *Customer A* is connected.

The connection point for *Customer A* is located near the end of the MV feeder at distribution transformer 23 (Tx 23). The customer is located in a mountainous area making connection to a stronger (higher fault level) alternative feeder considerably expensive. The fault level at the selected point of common connection (PCC) is 44MVA.

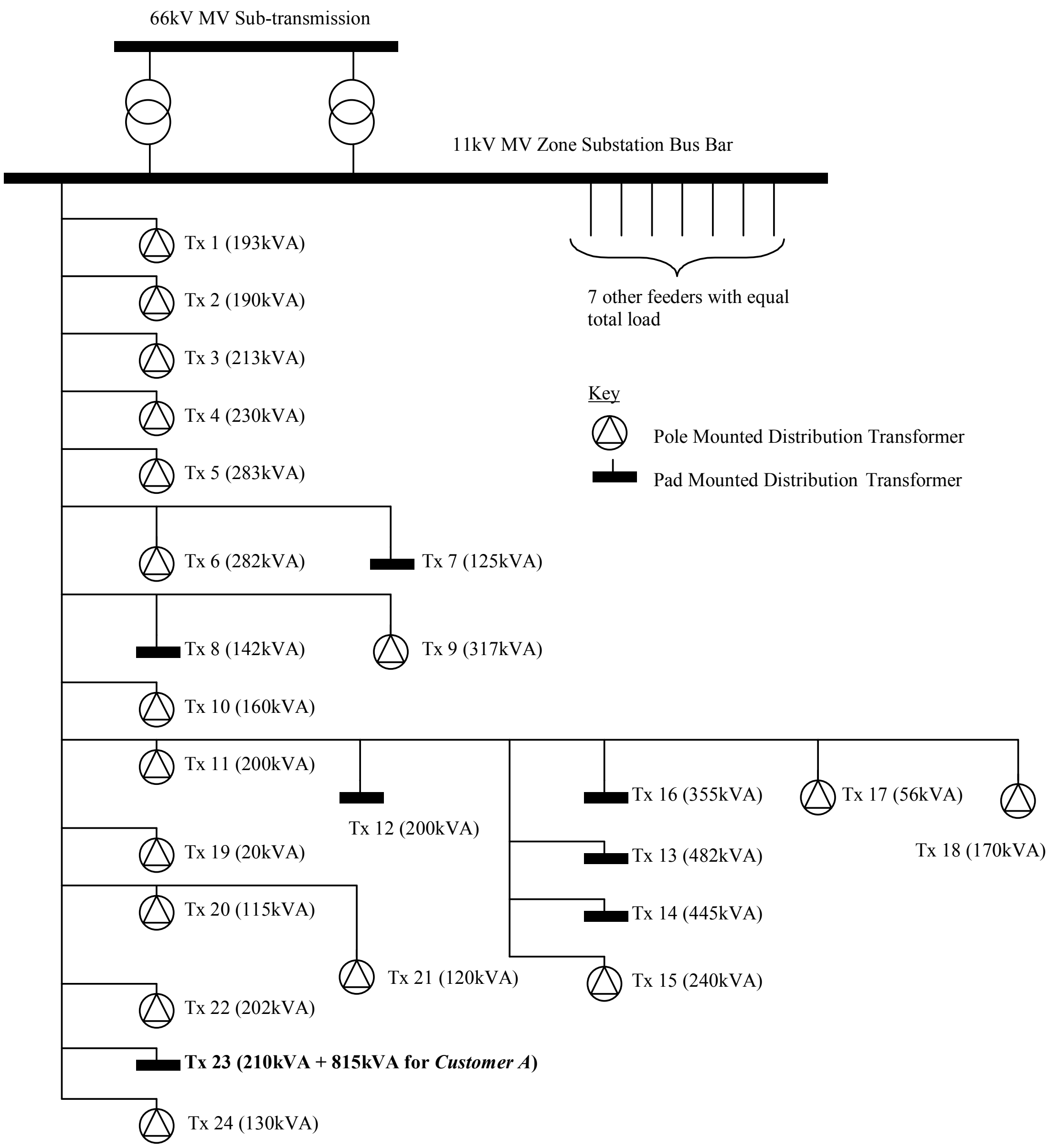


Figure 7.4 Schematic layout of Katoomba distribution system feeding *Customer A*

Customer A's load consists of a six pulse 530kW regenerative DC drive system and 50kW of auxiliary equipment with an overall approximate maximum demand of 815kVA. There is also a pre-existing load of 210kVA of the same customer at the PCC. The load configuration for *Customer A* is illustrated in Figure 7.5. Passive harmonic filters were included in the original installation by *Customer A* to reduce the levels of 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics injected back into the distribution system.

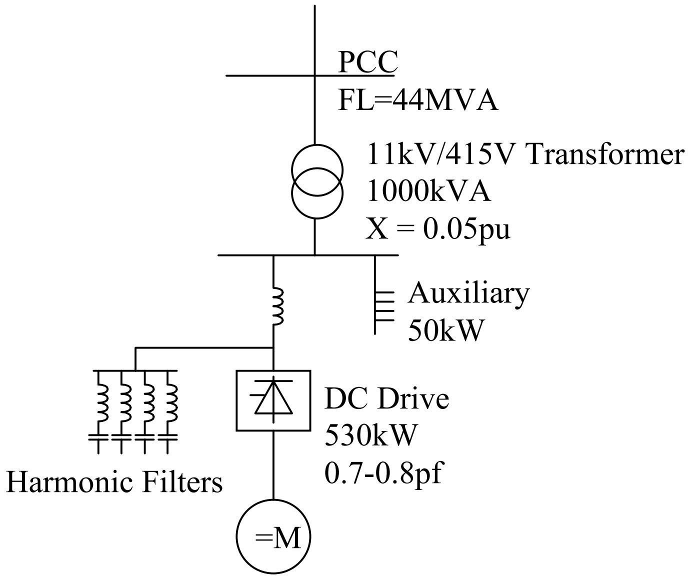


Figure 7.5 Schematic layout of *Customer A*'s load

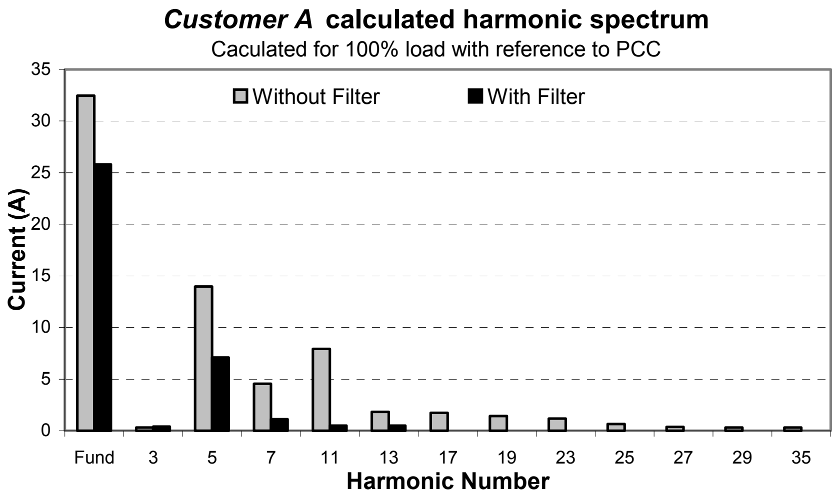


Figure 7.6 Calculated harmonic spectrum of *Customer A*'s installation at PCC

Customer A provided details of the load operation for the DNSP to make an appropriate assessment of whether connection should be granted. Design calculations performed by *Customer A* found that with harmonic filters connected the harmonic spectrum of the load current produced a maximum 5th harmonic at 28% of fundamental as shown in Figure 7.6. This 5th harmonic current is significantly above the 20% or less, a value typically expected for a similar sized six pulse DC drive system [37].

Assessment of *Customer A*'s installation was completed after the design and installation phase had already been completed. Ideally the customer and DNSP should consult prior to installation to ensure that the design is acceptable regarding the level of harmonic emissions and possible mitigation requirements before a connection agreement is obtained. A further difficulty for this installation was that it occurred during period of transition when Australia was transferring to a new harmonic standard from AS 2279.2 to AS/NZS 61000.3.6 (adapted IEC 61000-3-6) and there were some concerns on which standard was most appropriate to apply. Only a discussion regarding IEC 61000-3-6 is presented here.

7.3.1 Assessment of background harmonic voltage levels

The first stage of assessment was to determine the existing levels of voltage harmonics on the distribution system. From voltage distortion profiles provided by the DNSP the existing 95th percentile 5th harmonic distortion was found to be approximately 2.72% with THD at approximately 2.84%. Although this is well within the recommended planning level of 5% for the 5th harmonic from IEC 61000-3-6 it is important to verify that this level is also in proportion with the existing loading. Also verification of the growth in harmonic voltage levels is possible if measurements are taken before and after new customer connections are completed.

Recommended planning levels for the 5th harmonic voltage at HV and MV of 2% and 5% respectively are assumed. Note that the MV planning level includes a contribution from HV planning level. The second summation law (α=1.4 for 5th harmonic) is used to determine the allowable contribution from MV and LV (G_{hMV+LV}) when the system is fully saturated as follows.

$$
\begin{aligned}
G_{hMV+LV} &= \sqrt[\alpha]{L_{hMV}^{\alpha} - L_{hHV}^{\alpha}} \\
&= \sqrt[1.4]{5\%^{1.4} - 2\%^{1.4}} \\
&= 3.97\%
\end{aligned} \qquad (7.2)
$$

Taking into account the overload capacity and maximum utilisation factor of the HV/MV transformer, the total power available to the distribution system was calculated to be 27.6MVA. Considering the system was only loaded to 20MVA, the allowable harmonic contribution from MV for the partially loaded case can be determined as follows

$$
\begin{aligned}
G_{hMV+LV(partially\,loaded)} &= \left(\frac{S_i}{S_t}\right)^{\frac{1}{\alpha}} \times G_{hMV+LV} \\
&= \left(\frac{20MVA}{27.6MVA}\right)^{\frac{1}{1.4}} \times 3.97\% \\
&= 3.15\%
\end{aligned}
$$

Combining the allowable contribution from the MV partially loaded case, and assuming the HV system is at the same level of loading (i.e. not utilising the full 2% of recommended 5th harmonic limit) the recommended 5th harmonic voltage limit for the system in existing configuration is as follows

$$
\begin{aligned}
L_{hHV(partially\,loaded)} &= \left(\frac{20MVA}{27.6MVA}\right)^{\frac{1}{1.4}} \times 2.00\% \\
&= 1.59\%
\end{aligned}
$$

$$
\begin{aligned}
L_{hMV(partially\,loaded)} &= \sqrt[1.4]{3.15\%^{1.4} + 1.59\%^{1.4}} \\
&= 3.97\%
\end{aligned}
$$

As the HV contribution is of the same proportion as the MV the above recommended 5th harmonic voltage limit could have been calculated directly from the combined harmonic limit of 5.0% for the 5th harmonic as follows

$$L_{hMV(partially\ loaded)} = \left(\frac{S_i}{S_t}\right)^{\frac{1}{\alpha}} \times L_{hMV(fullyloaded)}$$

$$= \left(\frac{20MVA}{27.6MVA}\right)^{\frac{1}{1.4}} \times 5.0\%$$

$$= 3.97\%$$

Thus the existing 95th percentile level of 5th harmonic voltage distortion is within the planning levels recommended by IEC 61000-3-6. Performing this calculation provides an indication of whether customers are taking up their emission entitlements. The DNSP may choose to utilise spare harmonic capacity to allow a particular customer additional harmonic emission rights if required.

7.3.2 Calculation of acceptable harmonic current emissions

To determine acceptable harmonic emissions for *Customer A*'s installation according to IEC 61000-3-6 the consecutive stages and tests of the standard need to be completed as required. The acceptable harmonic current emissions at the given PCC as determined according to Stage 1 and the initial tests from Stage 2 are illustrated in Figure 7.7. Calculations related to these stages are given in Appendix E, Sections E.1 and E.2 respectively.

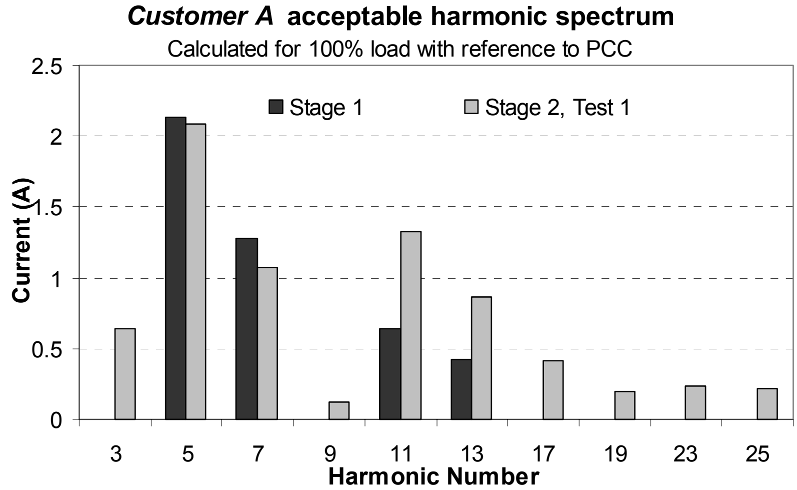


Figure 7.7 Calculated acceptable harmonic spectrum for *Customer A*'s installation

It can be seen that the harmonic currents indicated by *Customer A* in Figure 7.6 exceed the acceptable emissions, thus the installation fails Stage 1 and Stage 2, Test 1 of the standard and the more detailed harmonic allocation using Stage 2, Test 3 is required.

For the Stage 2, Test 3 to be completed the generalised method introduced in Chapter 4 is necessary due to the inadequacies of the approach outlined in the standard to be able to deal with non-homogenous systems. Application of Stage 2, Test 3 is presented in the remainder of this section. It is expected this test will provide a more generous recommended allowable harmonic emission limit. The application of a Stage 3 study may be ultimately applied at the discretion of the DNSP if connection is granted. This stage is designed to allow connection of customers on a temporary and precarious basis.

As the amount of data required to perform the calculation of acceptable current emissions is extensive, and not all required data was available, the following assumptions were made

- The 5^{th} harmonic is the only harmonic voltage of concern for this study, and

- All feeders supplied by the zone substation have identical total loadings to that of the feeder supplying *Customer A*

Three different scenarios are considered in determining an acceptable harmonic voltage contribution from *Customer A* using the method outlined in Chapter 4 for compliance with Stage 2, Test 3 of IEC 61000-3-6. The three scenarios are as follows:

(i) The feeder on which the installation is to be installed is the "weakest feeder" and all other feeders are significantly "stronger".

(ii) The feeder on which the installation is to be installed is the "weakest feeder" and some other feeders are significantly "stronger".

(iii) The feeder on which the installation is to be installed is "identical" to all other feeders supplied by the zone substation, i.e. all other feeders are equally "weak".

From a simple load flow calculation utilising MATLAB®, it was found that the PCC for *Customer A* produced the lowest fundamental voltage and thus was considered to be at the end of the weakest feeder.

The first stage in scenario (i) calculations is to determine a value for the harmonic current 'allocation constant' for the model system. The method suggested in Chapter 4 for determining the value of the 'allocation constant' is given by equation (7.3).

$$k \approx \frac{G_{hMV}}{\left(\sum_{i=1}^{n} S_i Z_{hi}^{\frac{\alpha}{2}} + S_0 Z_{h0}^{\frac{\alpha}{2}} + (S_{F2} + S_{F3} + \ldots + S_{Fr}) Z_{h0}^{\frac{\alpha}{2}}\right)^{\frac{1}{\alpha}}} \qquad (7.3)$$

The harmonic voltage planning level at HV and MV are assumed to be 2% and 5% respectively. Thus the global harmonic voltage emission, G_{hMV}, for all loads at MV in

this scenario is 3.97%. Assuming that there are no local loads at the zone substation MV busbar equation (7.3) can be simplified to equation (7.4).

$$k \approx \frac{G_{hMV}}{\left(\sum_{i=1}^{n} S_i Z_{hi}^{\frac{\alpha}{2}} + (S_{F2} + S_{F3} + ... + S_{Fr}) Z_{h0}^{\frac{\alpha}{2}}\right)^{\frac{1}{\alpha}}} \tag{7.4}$$

MATLAB® was used to determine the value of the 'allocation constant' for the model, given the values of load sizes and network impedances. A spreadsheet could just as well be used for this calculation. Using a 1MVA base the value of the 'allocation constant' *k* was found to be 1.28%. Calculation given by equation (7.5) is then used to determine the allowable harmonic current and voltage allocation. The total load at the PCC (Tx 23 of Figure 7.4) is 1025kVA (including the 815kVA for *Customer A*).

$$\begin{aligned} E_{Ihi} &= \frac{k S_i^{\frac{1}{\alpha}}}{\sqrt{Z_{hi}}} \\ &= \frac{1.28\% \times 1.025^{\frac{1}{1.4}}}{\sqrt{0.0888}} \\ &= 4.37\% \end{aligned} \tag{7.5}$$

Customer A's installation is not the only load connected at this PCC, i.e. does not make up the total load connected. The second summation law from IEC 61000-3-6 can be used to determine contributions from *Customer A* as compared to the total load. Equation (7.6) is used to allocate the respective harmonic emission to *Customer A*.

$$\begin{aligned} I_{hi} &= \left(\frac{S_i}{S_M}\right)^{\frac{1}{\alpha}} I_{hM} \\ &= \left(\frac{0.815}{1025}\right)^{\frac{1}{1.4}} 4.37\% \\ &= 3.71\% \end{aligned} \tag{7.6}$$

This value for allowable harmonic current (on 1MVA base) corresponds to a 5th harmonic voltage allocation of V_5 = 0.33% (on *Customer A*'s load base) and a 5th harmonic current allocation of I_5 = 1.95A. This value is much lower than the calculated harmonic current in Figure 7.6.

As it is most likely that the study feeder is not the only weak feeder on the zone substation the first scenario result is viewed as being pessimistic. By assuming that there are other feeders similar in nature, the rule of thumb 'divide by √2' introduced in Chapter 4 may be applied to the third term in the denominator of equation (7.3) as per scenario (ii).

Scenario (iii) assumes that all feeders connected to the zone substation are identical in configuration, impedance, and load size. With this assumption a different value for the harmonic current 'allocation constant' is calculated. As all feeders are assumed to be identical, and that there are no local loads, equation (7.3) can be simplified to equation (7.7).

$$k \approx \frac{G_{hMV}}{\left(\sum_i S_i Z_i^{\frac{\alpha}{2}} + (n-1) \sum_i S_i \frac{Z_0^{\alpha}}{Z_i^{\frac{\alpha}{2}}} \right)^{\frac{1}{\alpha}}} \qquad (7.7)$$

The results from scenarios (i)-(iii) are presented in Table 7.2. It can be seen that the harmonic voltage allocation from scenarios (ii) and (iii) give similar magnitudes.

Table 7.2 5th harmonic voltage allocation for scenarios (i)-(iii)

Scenario	Allocation constant	Voltage allocation	Current allocation
(i) Other feeders very strong	k=1.28%	V_5=0.33%	I_5=1.95A
(ii) Other feeders stronger	k=1.56%	V_5=0.40%	I_5=2.37A
(iii) Other feeders equally weak	k=1.70%	V_5=0.44%	I_5=2.58A

The values of 5th harmonic voltage contribution calculated by the company responsible for *Customer A*'s installation suggested a value of V_5 = 1.13%, which was derived from a 5th harmonic current of I_5 = 5.7A provided in Figure 7.6. For the above method of applying IEC 61000-3-6 the calculated values are less than half the values calculated by the company commissioned to install the load. Thus, it was perceived that the installation would fail the IEC 61000-3-6 requirements.

If the installation was to comply with IEC 61000-3-6 the 5th harmonic current should be approximately half that of the value calculated by the installing company. This may require reconfiguring the load, decreasing the feeder impedance, or the addition of larger harmonic filters that are able to absorb a greater amount of harmonic current. Of course discretion of the applicability of IEC 61000-3-6 and the above results to *Customer A* lies with Integral Energy.

7.3.3 Accounting for load interaction with system harmonic voltages

As the installation of *Customer A* was operational prior to assessment, field measurements of harmonic voltage and current could be used to determine compliance with IEC 61000-3-6. A component of the measured harmonic current would be due to the system harmonic voltage, however it will be assumed negligible compared to the harmonic current emissions derived purely from the DC drive. A capture of one full

load cycle of the DC drive for the 5th harmonic voltage and current on the LV side of the distribution transformer was obtained as illustrated in Figure 7.8.

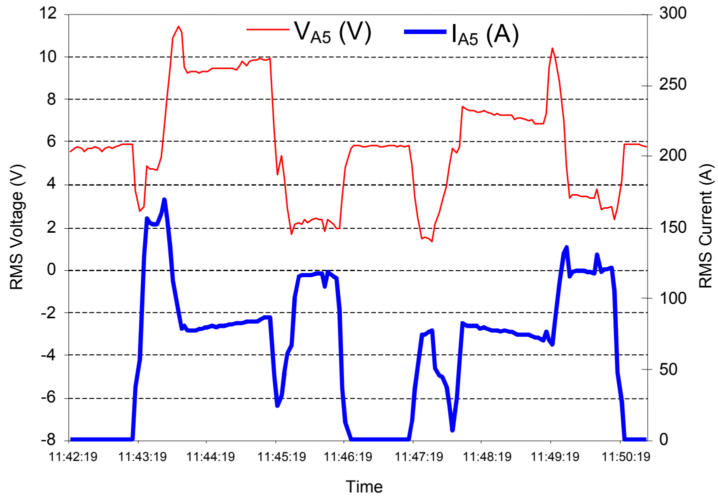


Figure 7.8 Full load cycle of 5th harmonic rms voltage and current

To verify that the loading of the drive did not alter the harmonic current significantly loads of 0.21 Tonne (low), 0.93 Tonne (medium) and 3.53 Tonne (full) were applied and the resulting 5th harmonic currents obtained are illustrated in Figure 7.9. As the variation of 5th harmonic current was not significant for the purpose of compliance it was assumed the pattern of harmonics in Figure 7.8 repeated 50-60 times over an eight hour period, seven days a week.

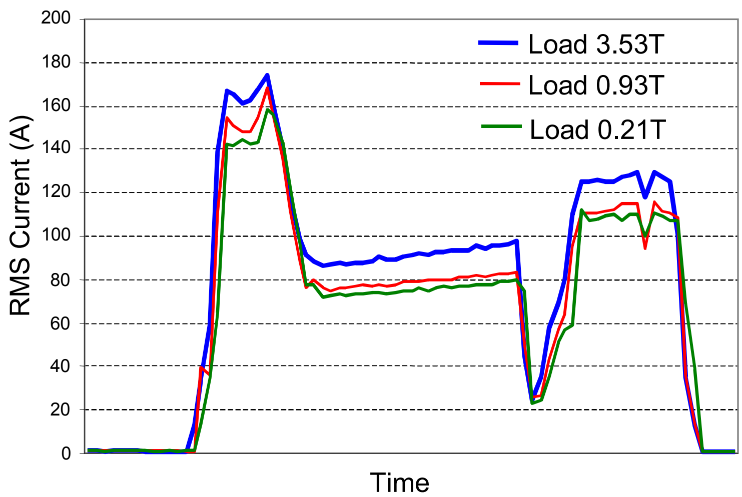


Figure 7.9 Half load cycle 5th harmonic rms current for various loading

The 95th percentile values of the 5th harmonic current on the MV side of the transformer was estimated by interpolating values from Figure 7.8 over a full week resulting in a current of 115.2A (LV) and 4.3A (MV). This exceeds the allocated 2.58A. The 95th percentile value for the 5th harmonic voltage on the LV side was calculated to be 4.0%, indicating a value considerably less than this on the MV side due to the drop across the transformer impedance. This leaves a considerable margin to the recommended planning level of 5.0%.

It can be seen in Figure 7.8 that during approximately 40% of each cycle *Customer A*'s equipment was seemingly reducing the network 5th harmonic voltage levels by injecting an out-of-phase component of 5th harmonic current. IEC 61000-3-6 does not consider the connection of load types that have a compensating effect on the system distortion, indicating a problem with the inflexible application of the summation law. Perhaps the customer should not be penalized for producing such harmonic currents. If the out-of-phase harmonic components are excluded from calculations, the resulting 95th percentile 5th harmonic current was considerably less at 3.0A (MV), only exceeding recommended values by a small amount.

Although Customer A's load has failed assessment in this case study if it could be established that the background harmonic distortion were low relative to the existing feeder load, there may be scope to grant *Customer A* compliance under Stage 3 of IEC 61000-3-6 ("Temporary and precarious basis"). To assess the extent of the background harmonic distortion levels a further study would have to be completed which requires data of present background levels, present loading along feeder, and potential loading along feeder.

7.4 Case study 3: Springhill sub-transmission substation

This section presents a discussion on a harmonics monitoring campaign carried out at the sub-transmission point of supply of a distribution network with the objective of benchmarking background harmonic distortion levels prior to refurbishment of the substation and to ensure emissions from HV customers and the downstream MV networks are within acceptable levels.

Springhill sub-transmission substation is owned by Integral Energy and located approximately 100km south of Sydney. Proposed refurbishment of the substation included replacement of seven 132/33kV 60MVA transformers, with transformers of ratings 60MVA or 120MVA, and refurbishment of one other 60MVA transformer, effectively upgrading the total capacity of the substation by approximately 30%.

To determine existing levels of harmonics a two-week harmonics monitoring campaign was undertaken. Assessment of harmonics levels was carried out, where possible, as per guidelines from the relevant standard IEC 61000-3-6, although instrument limitations prevented an exact assessment being completed. Data from the monitoring campaign was utilised to assist in modelling the sub-transmission substation and surrounding network to establish how the refurbishment would affect harmonic distortion levels. Some of the issues encountered with the monitoring program and assessment relevant to this thesis are discussed here and include

(i) Evaluating the impact of multiple combinations of switched capacitors,

(ii) Lack of clearly defined planning levels for sub-transmission systems, and

(iii) Calculation of acceptable emissions for MV customers.

7.4.1 System layout

A single line diagram of the Springhill sub-transmission substation is illustrated in Figure 7.10.

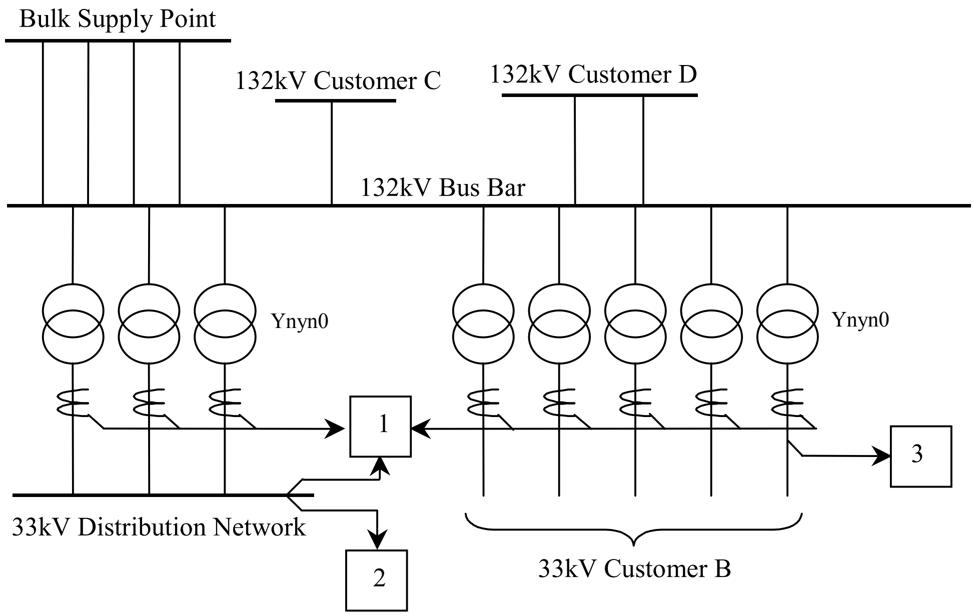


Figure 7.10 Springhill sub-transmission substation single line diagram

Substation load is comprised of three large industrial customers and Integral Energy's own 33kV network. Industrial *Customer B* is fed at 33kV via five 60MVA transformers, two other industrial customers (*Customer C* and *Customer D*) are fed at 132kV and Integral Energy's own 33kV distribution network is supplied via three 60MVA transformers. Integral Energy's 33kV network includes some smaller industrial customers and a significant amount of commercial and domestic load.

7.4.2 Assessment of levels and emissions

IEC 61000-3-6 suggests that the topology of a network is an important consideration when selecting harmonic voltage planning levels. Indicative planning levels for both MV and HV are provided by the standards. For effective harmonic management MV

planning levels should be assessed at the most extreme points on the system where it is expected harmonic levels will be highest, i.e. the end of distribution feeders for harmonics, thus utilising MV planning levels for this sub-transmission study was not perceived practical. There is no clear indication given by the standard on how to select planning levels for points in the network between transmission and extremes of distribution. The substation 33kV busbar in this study is defined as being sub-transmission, and accordingly planning levels should, in principle, appear somewhere between the HV and MV planning levels. However, fault levels at the 33kV busbar were closely matched to that of the 132kV busbar, and thus for this project the HV planning levels were used for both transmission (132kV busbar) and sub-transmission (33kV busbar). The allocation of suitable planning levels throughout a network has since been addressed in [45].

In order to compare DNSP harmonic levels (or consumer harmonic current emissions) to planning levels, the minimum measurement period specified in IEC 61000-3-6 is one week, with measurement of the following [15]:

(i) *greatest 95% daily value of $U_{h,vs}$ (or $I_{h,vs}$) (rms value of individual harmonic components over very short 3 second period) should not exceed the planning level,*

(ii) *maximum weekly value of $U_{h,sh}$ (or $I_{h,vs}$) (rms value of individual harmonics over short 10 minute periods) should not exceed the planning level, and*

(iii) *99.9% weekly value of $V_{h,vs}$ (or $I_{h,vs}$) should not exceed 1.5 to 2 times the planning level (or emission limit).*

However most field harmonic monitoring instruments are not able to measure and store data at 3 second intervals for a whole week (or even a single day) due to memory limitations. Also as damage due to harmonic voltages is rarely caused by excessive short-term levels but more usually exposure to longer term levels, a more practical method of assessment is using the EN 50160 standard [42] method of using only the 95th percentile 10 minute mean rms values of each of the individual harmonics (voltage and current). For the purpose of a harmonic assessment of Springhill this method will be used in conjunction with the appropriate IEC 61000-3-6 indicative planning levels.

7.4.3 Power factor correction capacitor considerations

A study of the effects of power factor correction (PFC) capacitors at and 'electrically nearby' the Springhill sub-transmission substation was required to ensure no critical harmonic resonance would occur that might cause excessive harmonic voltages. The simulation study was completed for the substation before and after refurbishment, with the altered harmonic impedance of the transformers, the most significant modification. As there were nine capacitor banks in the vicinity of the sub-transmission substation the number of possible combinations of capacitors connected at any one time could be up to 512 combinations, suggesting an excessive number of iterations of simulations. A number of capacitor banks were switched based on time and load, thus it was possible to reduce the number of possible capacitor combinations by a factor of 10 based on the normal operating conditions of the substation before simulations were carried out.

MATLAB® was used to model the entire study system generating Tableau matrices calculated at each increment of frequency with individual power system components modelled as per recommendations in [65]. Simulations under various loading conditions

were carried out to identify possible harmonic resonances. Figure 7.11 illustrates the resulting harmonic impedance curves at the 33kV distribution network busbar for six different capacitor combinations with no load damping considered.

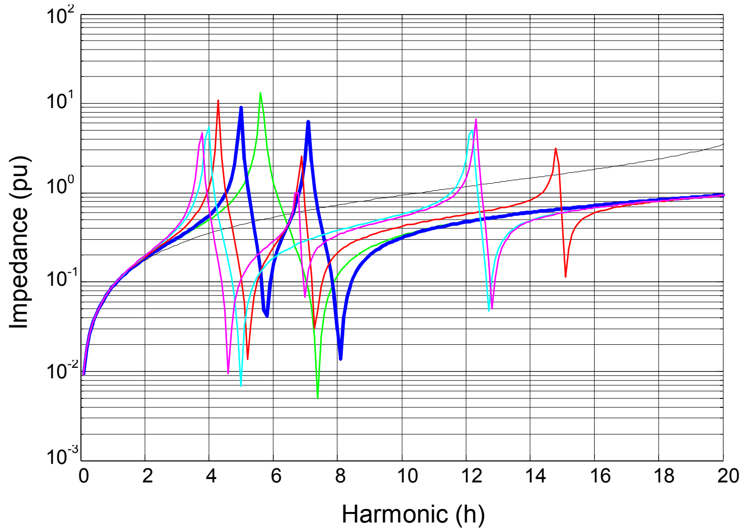


Figure 7.11 33kV harmonic impedance for 6 different capacitor combinations (no damping)

From Figure 7.11 it can be seen that one of the capacitor combinations creates a resonance at both the 5th and 7th harmonic. It was found that this particular condition only exists for a very short time interval as capacitors within the same bank are gradually switched in.

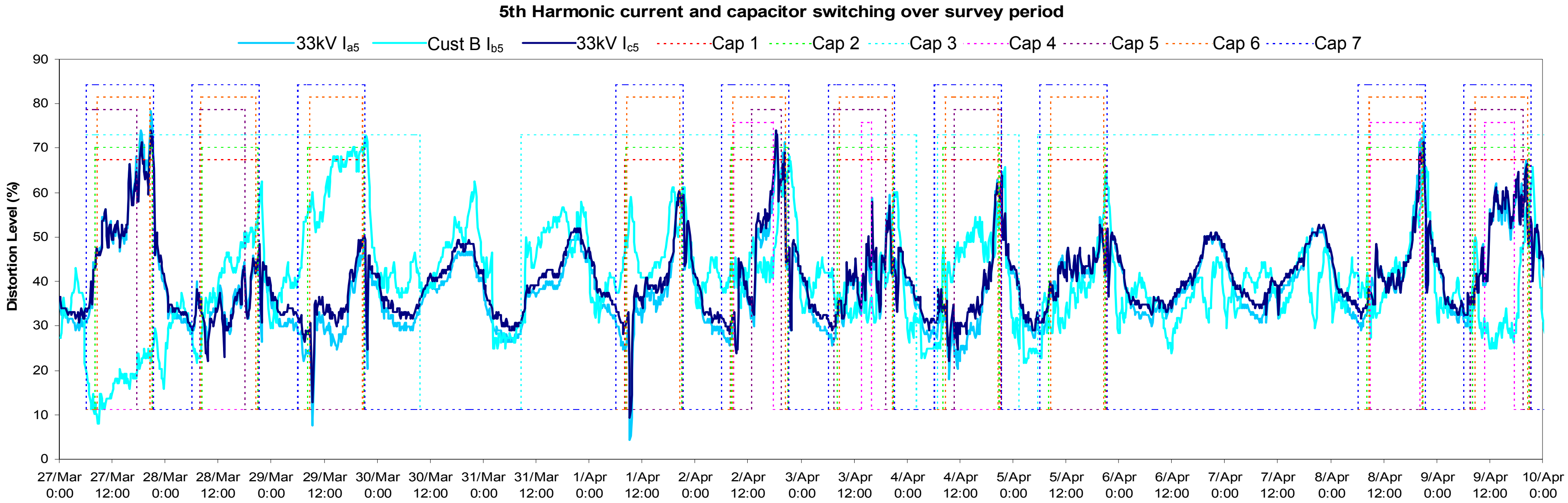


Figure 7.12 Capacitor switching vs 5th harmonic current at 33kV bus

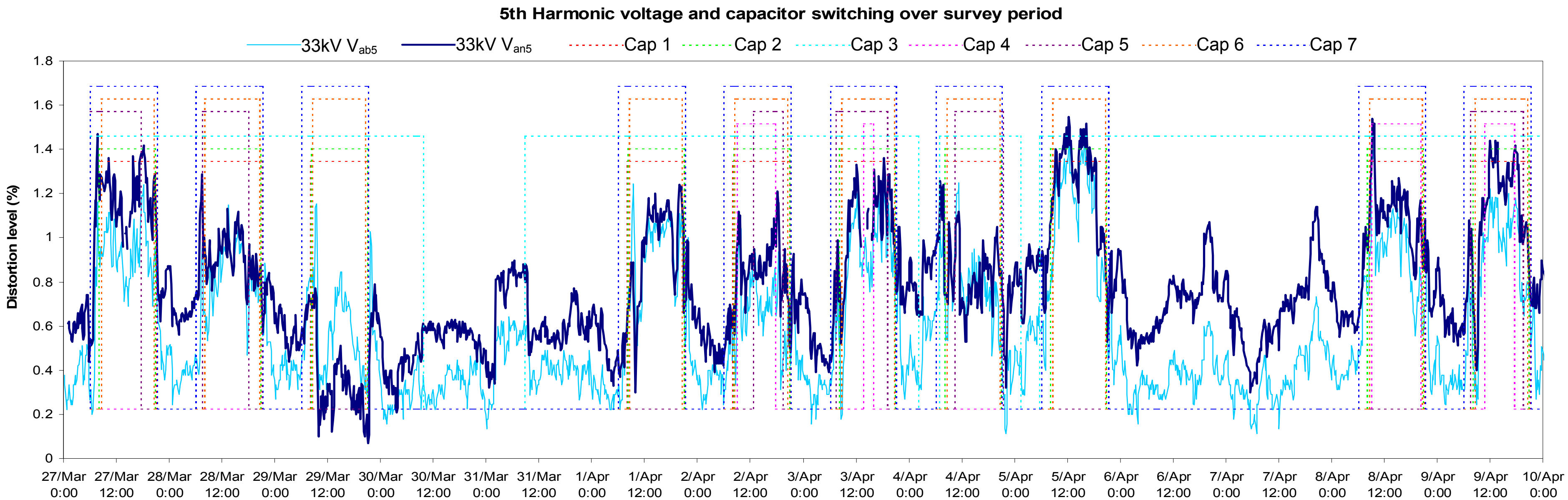


Figure 7.13 Capacitor switching vs 5th harmonic voltage at 33kV bus

The harmonic voltage for the very short interval for which this capacitor combination existed was examined in conjunction with the appropriate block of survey data where an insignificant rise in 5th and 7th harmonic voltage levels was found. Figures 7.12 and 7.13 illustrate the variation of 5th harmonic current and voltage at the 33kV busbar for various switched capacitor combinations (capacitors 1-7). Although some small transients in harmonic voltage and current coincide with capacitor switching instances no problematic resonances seem to occur.

The harmonic resonance is possibly reduced greatly due to effects of load damping which essentially trim down the peak of the harmonic resonance. A simulation of the same capacitor combinations with a very light loading of 30% of normal load was considered and results are illustrated in Figure 7.14. For the simulations the load was represented by an inductor in parallel with a series combination of inductor and resistor, as per Figure 6.3 of Chapter 6.

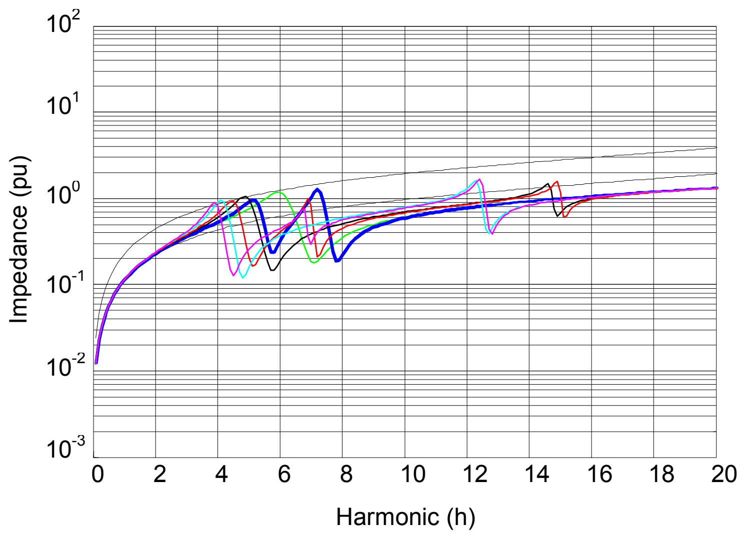


Figure 7.14 33kV harmonic impedance for 6 different capacitor combinations with damping due to 30% loading

As can be seen in Figure 7.14 harmonic resonances are greatly attenuated by even a small amount of load damping. The level of attenuation in fact reduces the magnitude of resonances to below twice that of the case with no capacitors present (Upper line in Figure 7.14). This seems to align with the findings in Chapter 6 of using twice the harmonic impedance with no capacitors to provide a pessimistic approximation of harmonic impedance with capacitors present. The simulations completed indicated that the shift in resonant frequencies due to the changing impedance of substation transformers did not create any new problematic harmonic resonances.

Of the problematic harmonic resonances identified in the detailed harmonic study only one such capacitor combination occurred during the survey period. It was also noted that the several capacitor banks were usually permanently switched in and others switched in during rare extremely high load periods. Thus a further reduction in capacitor combinations could have been achieved.

After the refurbishment of Springhill substation the impedance seen by the Integral Energy 33kV network will decrease. This may give rise to different resonant frequencies. A study of the harmonic impedance seen by the *Customer B* and Integral Energy 33kV networks using the new transformer details should also be performed.

7.4.4 Assessment of emissions

Acceptable harmonic emissions from *Customer B* and the 33kV distribution network were calculated as per Stage 2 Test 1 of IEC 61000-3-6. Calculations are presented here for the 5th harmonic only. A worst-case harmonic impedance of $2 \times Z_h$ (up to 8th harmonic) applies due to the large number of neighbouring capacitor banks possibly

causing resonant effects. The maximum demand of *Customer B* is calculated as follows by equation (7.8)

$$S_i = 3 \times 60\text{MVA transformers} = 180\text{MVA} \quad (7.8)$$

The rated capacity of the sub-transmission system at the PCC to which *Customer B* is connected is

$$S_t = \sum S_{out} = 300 + 180 + 60 + 60 = 600\text{MVA} \quad (7.9)$$

Allocation of acceptable harmonic voltage and current contributions are then calculated using equations (7.10) and (7.11) and assuming a planning level of 2% for the 5th harmonic, and a fundamental source impedance of 0.0337∠86.9°pu (100MVA base). Calculations for the other harmonics are not presented here but were completed using a simple spreadsheet.

$$E_{Uhi} = L_{hHV} \sqrt[\alpha]{\frac{S_i}{S_t}} \quad (7.10)$$

$$= 0.02 \sqrt[1.4]{\frac{180}{600}}$$

$$= 0.00846 \text{ pu}$$

$$E_{Ihi} = \frac{E_{Uhi}}{Z_h} \quad (7.11)$$

$$= \frac{0.00846}{2 \times 5 \times 0.0337 \sin(86.9°)}$$

$$= 0.0252 \text{ pu (100MVA base)}$$

$= 11\text{A}$ (5^{th} harmonic) at 132kV, or

$= 44\text{A}$ (5^{th} harmonic) at 33kV

Figure 7.15 illustrates acceptable harmonic emission limits calculated for *Customer B* plotted against maximum harmonic current measured during the monitoring campaign. Although the 5th harmonic current in Figure 7.15 is shown as exceeding the acceptable emission limit this may be regarded as acceptable by the utility due to the following

(i) The harmonic impedance used for the allocation was approximated as twice the impedance with no PFC present. This is conservative considering the amount of load damping illustrated in Figure 7.14.

(ii) Harmonic emissions from other customers (*Customer C* and *Customer D*) are lower than their allowances.

(iii) Harmonic voltage levels are not approaching recommended HV planning levels.

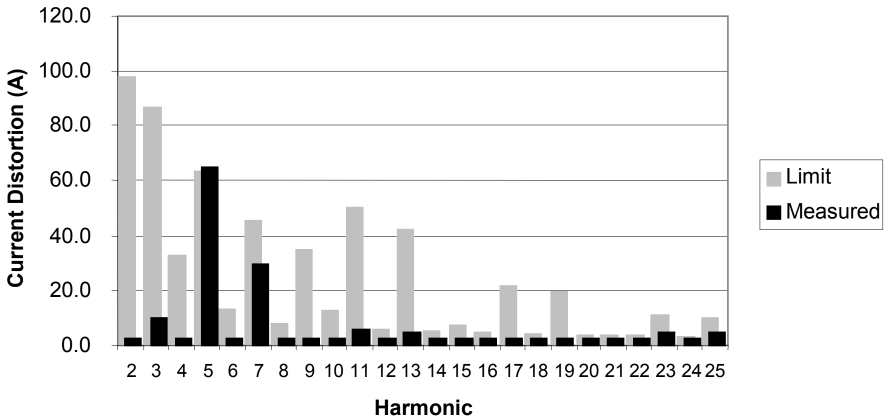


Figure 7.15 *Customer B* allocated and measured maximum harmonic current.

Theoretically, after substation refurbishment the allocation of harmonic emissions would require recalculation, as the total capacity of the sub-transmission substation is to increase. This would mean a slight reduction in current allocation to *Customers B*, *C*, and *D* but an increase for the 33kV distribution network. It would be very difficult and perhaps unrealistic for utilities to impose such changes in allocations if previous emission agreements with customers had been established.

If required, the harmonic voltages on the 132kV busbar can be interpolated from the 33kV distribution network results by combining the 33kV harmonic voltage, currents and impedance using the second summation law. It is expected that harmonic voltages on the 33kV busbar would be higher than that of the 132kV busbar, thus there is no need to complete such a calculation in this instance, as the levels of distortion do not approach the planning levels.

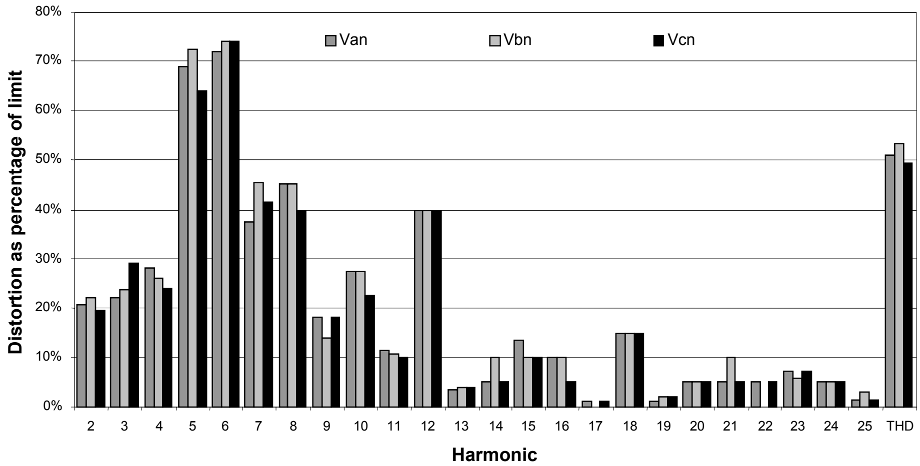


Figure 7.16 33kV network harmonic distortion as a percentage of HV planning level

Benchmarking of results is achieved by reporting harmonic voltage as a percentage of recommended planning levels. If emission levels from all customers are at their limits and voltage disturbance levels are well below the planning levels, there may be scope for allowing an increase of customer emissions if requested. Figure 7.16 illustrates the harmonic voltage levels expressed as a percentage of HV planning levels for each phase of the 33kV distribution network.

It is noticeable in Figure 7.16 that the 6th harmonic voltage is at an unexpectedly large percentage of recommended planning level. The values illustrated in Figure 9 were obtained from line-to-neutral measurements. The high value of 6th harmonic could be

attributed to the presence of zero sequence created by measuring the system line-to-neutral. This was confirmed by low line-to-line measurements using another instrument. This is consistent with the system being reasonably balanced and the 6^{th} harmonic appearing as a zero sequence triplen harmonic and thus cancelling in the line-to-line voltages. It is proposed that line-to-neutral measurements may not provide an adequate representation of three wire systems for harmonic assessment.

7.5 Summary

In three case studies investigated, the difficulties encountered highlight the complexity and shortfalls of the IEC 61000-3-6 standard. Some of the shortfalls include

(i) No clear direction to set harmonic voltage planning levels at points within the distribution network other than at the transmission level and end of distribution feeders.

(ii) No generalised approach to allocating suitable emission limits to customers spread along a distribution feeder having significantly different fault levels.

(iii) No straightforward approach to calculating harmonic impedances in the presence of significant system capacitance

Assessment of existing harmonic voltage levels on a system has been demonstrated using a weighted approach that depends on the level of loading on the system. The significant harmonic impedances of a distribution network have been identified as the zone substation and distribution transformers. A reduction in these impedances will increase a network's ability to absorb harmonic currents without exceeding harmonic voltage planning levels. An attempt at determining harmonic planning levels through a

distribution network has been made. This method will have to be implemented on a number of typical systems to ensure that suitable planning levels are selected.

Successful implementation of a harmonic emission allocation method for loads spread along a feeder has been completed. Use of the different approximations outlined in Chapter 4 to estimate the value of the harmonic allocation constant has been demonstrated.

Pragmatic modelling of networks containing significant system capacitance have been shown to over-estimate the harmonic impedance thus resulting in pessimistic harmonic emission allocations. Detailed harmonic analysis has shown to be difficult due to the number of different network configurations that may exist, including capacitor switching.

Application to a number of different systems is required to better refine the approaches to harmonic emission allocation and determination of harmonic impedance outlined in Chapter 4 and Chapter 6 respectively.

Chapter 8

Conclusions

8.1 Conclusion and recommendations

This thesis has described the development of guidelines and associated tools for harmonic distortion level management in medium voltage (MV) electrical distribution systems. The implementation of such guidelines is necessary to allow effective management of harmonic emissions from distribution customer installations.

Statistical harmonic models of residential, commercial and industrial load types have been developed to simulate the global behaviour of distorting loads at distribution substations. The load models represent aggregates of loads and are specifically intended for calculation of harmonic emissions for comparison with the relevant standards. Both time and phase diversities are included in the representative load models.

A harmonic monitoring programme has been designed and implemented on a typical electrical MV distribution system to establish parameters for the three types of statistical harmonic load models mentioned above, and also to confirm the relative accuracy of distortion level prediction techniques presented.

Suggestion of significant growth in harmonic voltage distortion levels internationally by the literature reviewed has been verified to a limited extent by the harmonic monitoring campaign. To determine an effective measure of harmonic growth, i.e. 0.1% per year or similar, a minimum monitoring time of three years is recommended to ensure seasonal variations do not distort results. Excessive levels of harmonic voltage distortion can cause equipment malfunction or destruction, reduced lifetime of power system

equipment and connected customer loads, and increased power system losses. This emphasises the need for distribution utilities to become more vigilant in their approach to managing harmonic distortion levels on their electrical distribution systems.

For the past 25 years the harmonics standard for electrical distribution systems in Australia has been AS 2279.2. While the procedures in this standard could be implemented with relative ease, the increasing complexity and diversity of load technologies existing on electrical distribution systems has made the standard obsolete. The adoption of the international technical report IEC 61000-3-6 in 2001 as the present harmonic standard in Australia has overcome some of the unaddressed issues in AS2279.2. The new harmonic standard AS/NZS 61000.3.6 however is not as clearly defined as its predecessor and there are some ambiguous sections that do not allow for a clear approach to be taken with regard to allocation of acceptable emissions and assessment of customer installations. Some of the tools and guidelines developed in this standard seek to clarify the ambiguous sections of the new standard.

A method has been developed to estimate the 95th percentile cumulative probability level of harmonic voltage distortion on an electrical MV distribution system as required by IEC 61000-3-6. This method includes techniques to overcome the difficulties in determining distortion levels when feeders are not loaded to their fullest extent, and allows for cases when levels of background distortion may not be as high as limits set by the standard. The method provides a useful tool to combine the effects of non-precise distribution loads at the planning stage or to evaluate distortion levels of existing systems.

A generalised method has been developed to extend the IEC 61000-3-6 approach of allocating allowable harmonic emissions to the case where customers are distributed along an MV distribution system feeder having significantly different fault levels. This is an area that IEC 61000-3-6 fails to cover adequately to allow application to real systems. The method involves the determination of an 'allocation constant' using the agreed loading of all customers and the system harmonic impedances.

The generalised approach of allocating emissions to customers described above typically requires an extensive amount of data. This data may not always be available to the utility engineer. An extension to the generalised method has thus been completed to cater for the complex situation where only limited data is available. This is achieved by looking at several extreme cases that categorise the most common MV distribution system feeder configurations, and through the use of correction factors for the 'allocation constant'.

A preliminary look at the effect of power factor correction capacitance on the harmonic guidelines developed has shown that the presence of capacitors usually require detailed analysis for effective harmonic management. The present standards approach of using 'twice the impedance' is illustrated to be a useful tool when resonances do not occur at problematic harmonics.

The planning guidelines developed have been applied to example systems, both with and without the presence of power factor correction capacitors, to illustrate the harmonic management tools. This includes identification of the key indicators for a distribution system's harmonic performance.

8.2 Further work

The harmonic monitoring program implemented on the typical distribution system has illustrated the diversity of harmonic distortion levels. An overall growth in harmonic levels has been found although the seasonal variation in the levels is significantly larger. A long-term harmonic monitoring program of many distribution systems throughout Australia would establish a better indication of the growth trends of harmonic distortion levels. This would also allow a comparison of harmonics indices between DNSPs to determine the performance of a particular provider.

The results presented in this thesis suggest that in most cases a detailed harmonic study is required when multiple capacitor installation exist within a distribution system. Such detailed studies require a significant amount of time and data. It is proposed that a rule of thumb, similar to the 'twice the impedance' suggested by IEC 61000-3-6 used in this thesis, needs to be further developed to allow a simpler approach for use in conjunction with the present standard.

This thesis has focused on the application of harmonic management tools for MV distribution systems. In Australia these systems are typically radial, with the exception of some meshed networks located in inner city locations where a stronger supply is required. Further work is required to extend the harmonic management tools introduced in this thesis to meshed distribution networks and transmission systems, which are typically configured as meshed networks.

Finally, compatibility levels for power system equipment remain an area yet to be fully explored by power quality researchers. While the IEC compatibility levels have been

assumed to be valid in this thesis, there is no documented evidence as to why these particular limits were selected other than they being reasonable based on existing harmonic measurements.

Statement of original contributions

As technology develops many customer loads are becoming increasingly sensitive to excessive harmonic voltage distortion. Conversely, loads are also producing relatively higher levels of harmonic emissions as technology drives for greater use of power electronics to increase controllability and efficiency. Electricity distribution network service providers (DNSPs) should now be looking towards preventative measures to ensure that voltage distortion levels are within limits set by the appropriate standards. Measures will need to be taken at the planning stage to ensure that the distribution systems will be able to meet harmonic standards as load distortion rises. Tools will also need to be developed to allow effective system modelling and comparison with standards, especially in the planning phase where details of loads are usually not accessible.

The original contributions in this thesis include the following to aid in the management of harmonics in MV distribution systems:

(i) Statistical harmonic models of residential, commercial and industrial load types have been developed to simulate the global behaviour of distorting loads at distribution substations. The load models represent aggregates of loads and are specifically intended for calculation of harmonic emissions for comparison with the relevant standards. Both time and phase diversities are included in the representative load models.

(ii) A method has been developed to estimate the 95th percentile cumulative probability level of harmonic voltage distortion in an MV distribution system as required by the present international harmonic standard IEC 61000-3-6. This method includes techniques to overcome the difficulties in determining distortion

levels when feeders are not loaded to their fullest extent, and allows for cases when levels of background distortion may not be as high as limits set by the standard. The method provides a useful tool to combine the effects of pragmatic modelling of distribution loads at the planning stage or to evaluate distortion levels of existing systems.

(iii) A generalised method has been developed to extend the IEC 61000-3-6 approach of allocating allowable harmonic emissions to the case where customers are distributed along an MV distribution system feeder having significantly different fault levels. This is an area that IEC 61000-3-6 fails to cover adequately to allow application to real systems. The method involves the determination of an 'allocation constant' using the agreed loading of all customers and the system harmonic impedances.

(iv) The approach of allocating emissions to customers described in (iii) typically requires an extensive amount of data. This data may not always be available to the DNSP engineer. An extension to the method of (iii) has thus been completed to cater for the complex situation where only limited data is available. This is achieved by looking at several extreme cases which categorise the most common MV distribution system feeder configurations, and through the use of correction factors for the 'allocation constant'.

(v) A harmonic monitoring programme has been designed and implemented on a typical MV distribution system to establish parameters for the three types of statistical harmonic load models in (i), and also to confirm the relative accuracy of distortion level prediction techniques mentioned in (ii).

(vi) A preliminary look at the effect of power factor correction capacitance on (i)-(iv) has shown that the presence of capacitors usually requires detailed analysis for

effective harmonic management. The approach of IEC 61000-3-6 of using 'twice the impedance' is illustrated to be a useful tool when resonances do not occur at problematic harmonics.

(vii) Example systems have been studied to illustrate the harmonic management tools described in (i)-(iv). This includes identification of the key indicators for a distribution system's harmonic performance.

Publications based on worked performed on this thesis

I. Robinson, D., V. Gosbell and S. Perera. *Harmonic allocation constant for implementation of AS/NZS 61000.3.6*. in *Proc. of Australasian Universities Power Engineering Conf. (ISBN 1 76067 068 X)*. 23-26 September 2001. Perth. p. 142-147.

II. Robinson, D., V. Gosbell, S. Perera and A. Baitch. *Application of Australia's new harmonic standard to a long MV feeder*. in *Proc. of 6th Inter. Transmission and Distribution Conf.* 11-14 November 2001. Brisbane. Paper No.1.

III. Robinson, D., V. Gosbell, S. Perera and A. Baitch. *Application of Australia's new harmonic standard to a long MV feeder*. Journal of Electrical & Electronics Engineering Australia, 2002. Vol.21(No.3): p. 1-9.

IV. Gosbell, V., D. Robinson and S. Perera. *The application of IEC 61000-3-6 to MV systems in Australia*. in *Proc. of ERA Technology Inter. Conf. on Quality and Security of Electrical Supply*. February 2001. Thames. p. 7.1.1-7.1.10.

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Appendix A

Fluke 41 Power Harmonics Analyser specifications

The Fluke 41 Power Harmonics Analyser (Serial 6050090) was used to perform harmonic measurements on various domestic loads. Specifications for the Analyser are listed below.

Measurement Accuracy	
Voltage	**Range and Resolution:** 5.0 V to 600 V rms (AC+DC); ±5.0 V to ±933 V peak **Accuracy:** rms: ±(0.5 % + 2 digits); Peak or DC: ±(2 % + 3 digits) (Add 2 digits if < 15 V rms)
Current (1mV/A) Isolated input	**Range and Resolution:** 1.00 A to 1000 A rms (AC+DC); ±1.0 A to ±2000 A peak **Accuracy:** rms: ±(0.5% + 3 digits)+probe specs; Peak or DC: ±(2 % + 4 digits) + probe specs
Watts/Volt-Amps (1mV/A) isolated input	**Range and Resolution:** 0.0W(VA) to 600 kW(kVA) average; 0.0W(VA) to ±2000 kW(kVA) peak **Accuracy:** AC+DC: ±(1 % + 4 digits) + probe specs
Harmonics (harmonic level >5% using Smooth 20)	**Volts:** : Fundamental to 13th ±(2 %+2 digits); At 31st ±(8 %+2 digits); **Amps or Watts:** Fundamental to 13th ±(3 % + 3 digits) + probe specs; At 31st ±(8 % + 3 digits) + probe specs
Frequency	**Range & Resolution:** 6.0 Hz to 99.9 Hz **Accuracy:** ±0.3 Hz
Input Bandwidth	DC, 6 Hz to 2.1 kHz
Crest Factor (CF)	**Range & Resolution:** 6.0 Hz to 99.9 Hz **Accuracy :** ±0.3 Hz
Power Factor (PF)	**Range & Resolution:** 0.00 to 1.00 **Accuracy:** ±0.02
Displacement Power Factor (DPF)	**Range & Resolution:** 0.00 to 1.00 **Accuracy:** ±0.04 to ±0.03 (0.30 to 0.89) ±0.02 (0.90 to 1.00)
Phase	**Range & Resolution:** -179 ° to 180 ° **Accuracy (Fundamental):** ±2 ° + probe specs
K-Factor (KF)	
% THD-F	**Range & Resolution:** 0.00 % to 799.9 % **Accuracy:** ±(0.03 Reading + 2.0 %)
% THD-R	**Range & Resolution:** 0.0 % to 99.9 % **Accuracy:** ±(0.03 Reading + 2.0 %)

Information obtained from *http://au.fluke.com/auen/products/41B.htm*

Appendix B

EDMI Mk3 Energy Meter specifications

The Mk3 revenue meter was used as the primary instrument for the harmonic monitoring programme on the Homepride zone distribution system. Key Features of the meter include; four quadrant energy measurement, time of use, load profile, pulse inputs/outputs, high accuracy, remote reading, waveform capture, sag and swell analysis (half cycle resolution), quality of supply (on board harmonic analysis) [62].

Basic Specs	
Voltages Nominal Min. to Max. Burden	 57 to 240V (Phase to Neutral) 45 to 290V < 10 VA / phase @ Vn (3 Phase) (As per IEC62053-61)
Auxiliary Supply	110 V (others available on special order)
Current Nominal Range Standard Range Extended Short Time Over-Current Starting Current Burden	 **1 A (C.T.) 5 A (C.T.)** 0.05A-1.2A 0.25A-6A 0.05A-4A 0.25A-20A 20 times the I_{max} for 0.5 second < 0.10% of I_n (I_b for WC) <0.5 VA / phase
Measurement Modes	Single Phase (3 circuits) 3 Phase 3 Wire 3 Phase 4 Wire
Pulse Outputs	Voltage, Current, Pulse Width, Polarity
Pulse Inputs	Voltage
Temperature Range	Operating -10°C to +60°C Storage -40°C to +85°C
Time Keeping	Accuracy(internal) ±30 sec / month Backup Time 2 years without power Backup Type Lithium Battery
Data Storage (configuration and TOU Load Survey)	FlashRAM, indefinite storage period. Battery Backed Up RAM.
Communications	Local ANSI Type 2 OPTICOM. Isolated RS485 or RS232. SCADA.

Information obtained from *http://www.edmi.com.au/products/powerquality/mk3.cfm*

Appendix C

Results of the Homepride harmonic monitoring programme

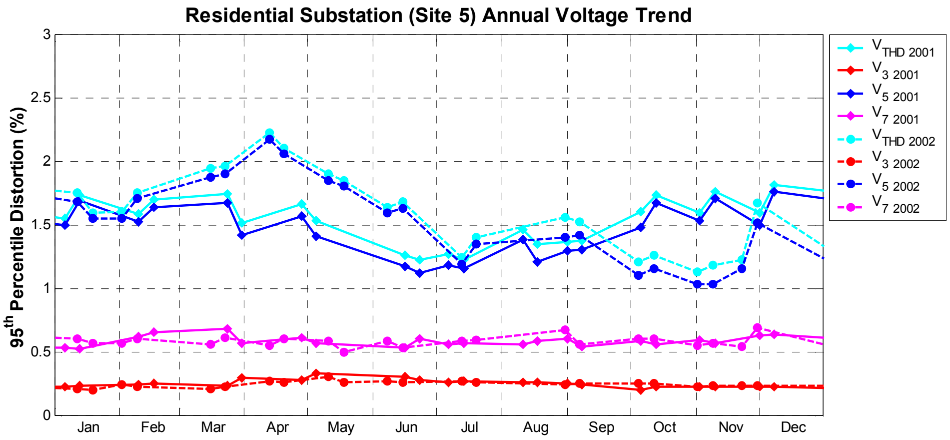

Figure C.1 Residential substation 95^{th} percentile annual harmonic voltage trend

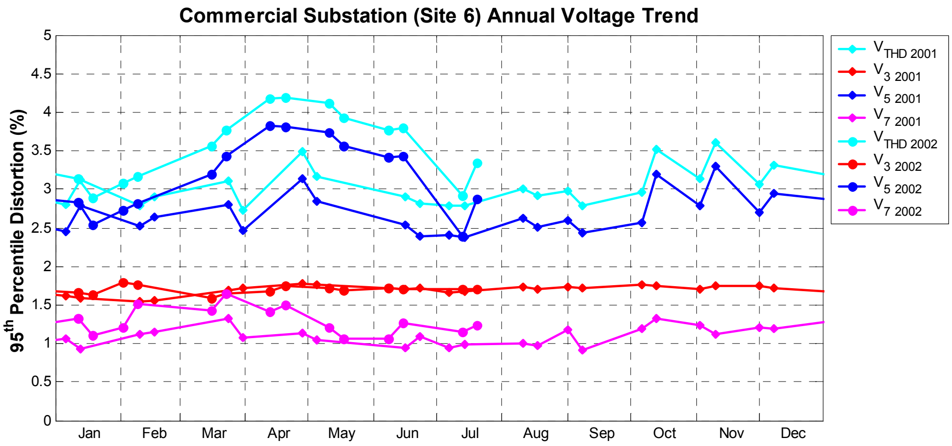

Figure C.2 Commercial substation 95^{th} percentile annual harmonic voltage trend

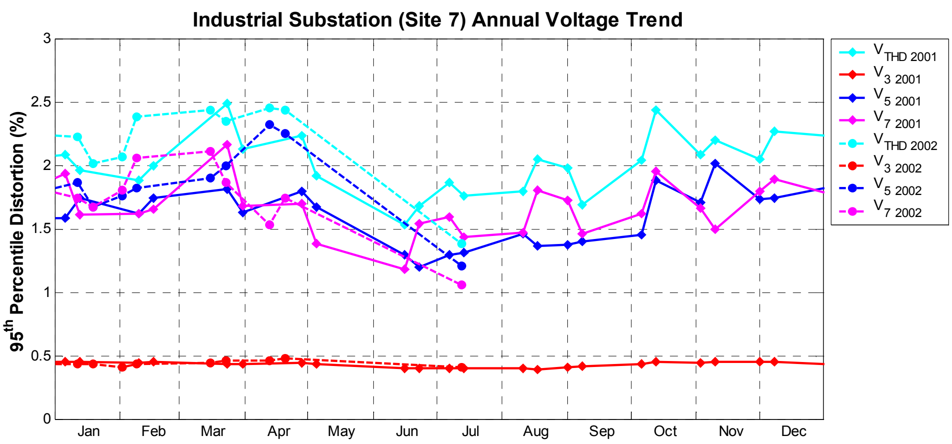

Figure C.3 Industrial substation 95^{th} percentile annual harmonic voltage trend

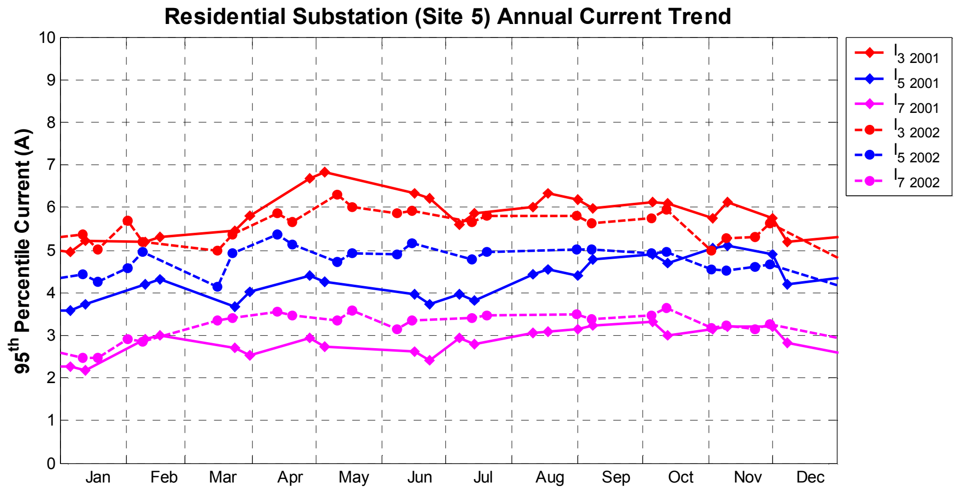

Figure C.4 Residential substation 95th percentile annual harmonic voltage trend

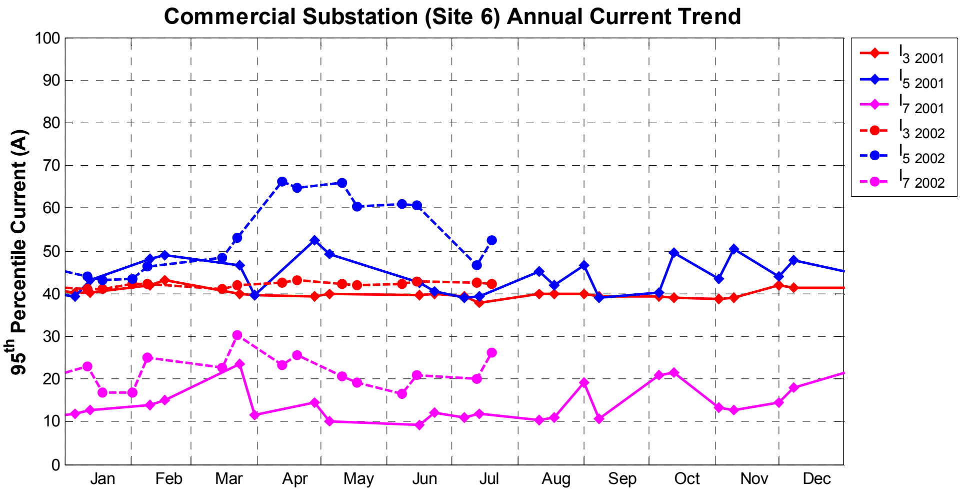

Figure C.5 Commercial substation 95th percentile annual harmonic voltage trend

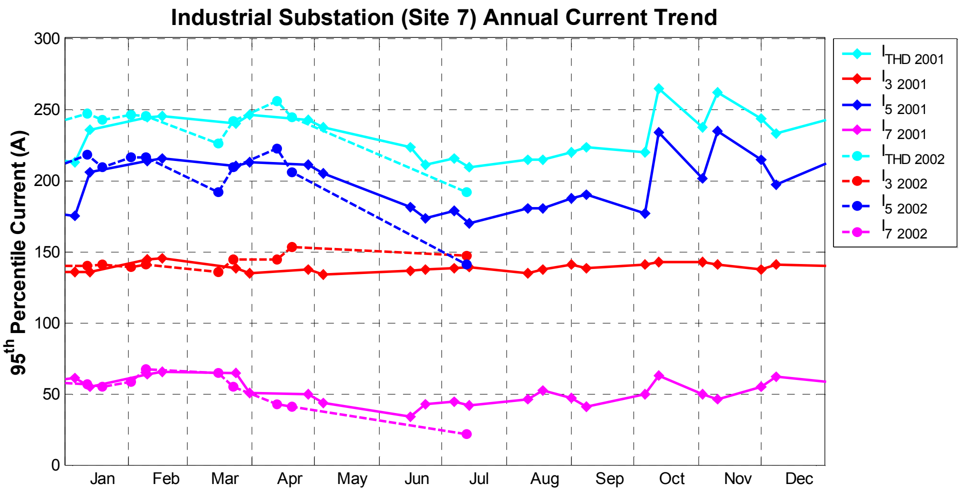

Figure C.6 Industrial substation 95th percentile annual harmonic voltage trend

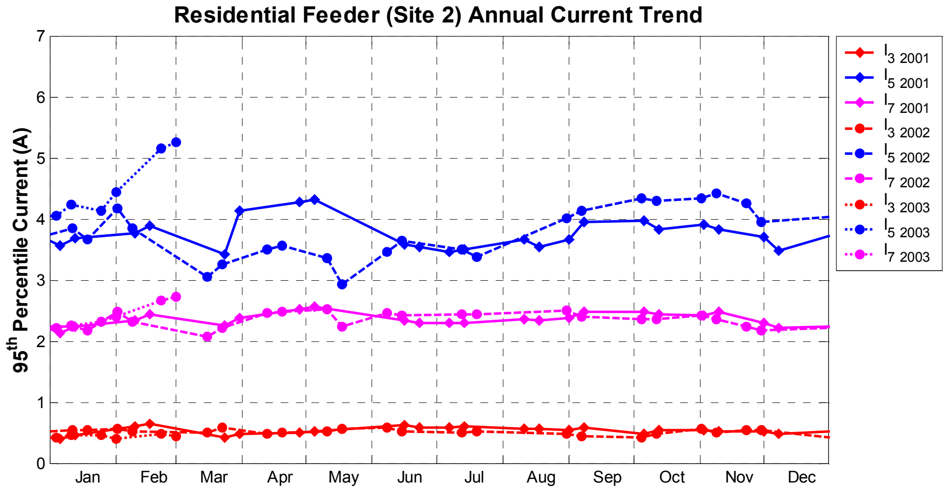

Figure C.7 Residential feeder 95th percentile annual harmonic current trend

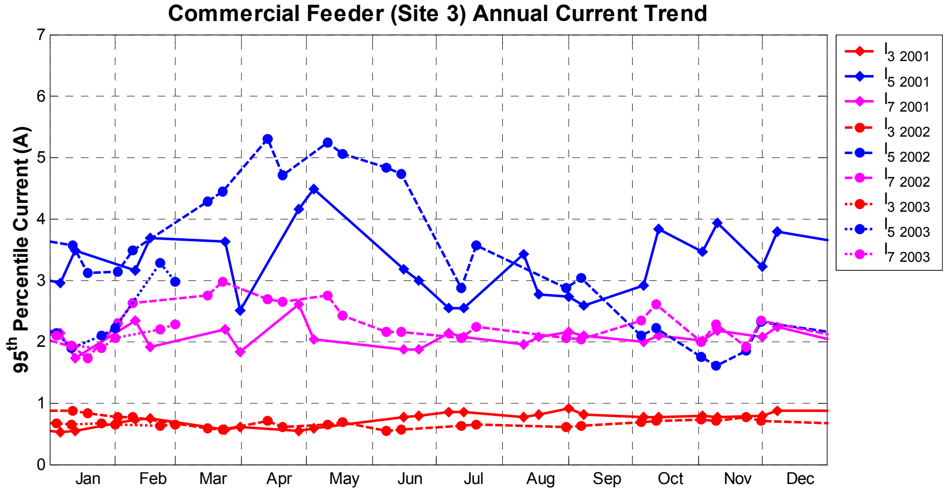

Figure C.8 Commercial feeder 95th percentile annual harmonic current trend

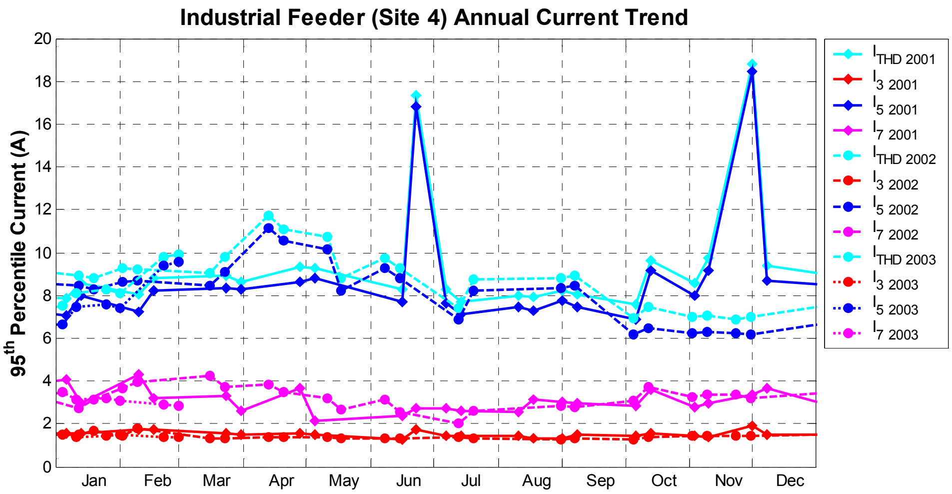

Figure C.9 Industrial feeder 95th percentile annual harmonic current trend

Appendix D

Calculation of maximum demand for *Customer A*

The following is the calculation of the maximum demand S_i for *Customer A* installation introduced in Section 7.3. Refer to Figure 7.5 for assumed data.

Real power of the drive, P_{drive} = 530kW

= 0.53pu

Complex power of the drive, S_{drive} = $P_{drive} \div pf_{drive}$

= 0.53pu÷0.7

= 0.757pu

Reactive power of the drive, Q_{drive} = $\sqrt{0.757^2 - 0.53^2}$

= 0.541pu

Total complex power, S_{load} = $\sqrt{(0.53 + 0.05)^2 + 0.541^2}$

= 0.793pu

Transformer reactive power, Q_{trans} = $(0.793)^2 \times 0.05$

= 0.031pu

Customer A maximum demand, S_i = $\sqrt{(0.53 + 0.05)^2 + (0.541 + 0.031)^2}$

= 0.815pu

Appendix E

Calculation of acceptable emissions for *Customer A*

E.1 IEC 61000-3-6 Stage 1

Assessment of *Customer A*'s installation under Stage 1 of IEC 61000-3-6 requires only a small amount of data from the customer. The data utilised in the following calculations is provided in Figure 7.5 of Chapter 7. The maximum demand of individual customer, S_i, at the PCC for *Customer A* is calculated using a base of 1MVA as 0.815pu (see appendix D). The short circuit level, S_{SC}, is 44.0pu as indicated in Figure 7.5. As the distorting load in *Customer A*'s installation contains a six pulse converter feeding a dc drive a weighting factor of 1.0 (from Table 6 in IEC 61000-3-6) is also applied to the proportion of S_i which is non-linear.

$$S_{Dwi} = 1.0 \times 0.757 \tag{E.1}$$

Thus the total load is 0.815pu as before. A customer can obtain automatic acceptance under Stage 1 of IEC 61000-3-6 if the load is of relatively small size, i.e. it satisfies equation (E.2), or if the load is under 2MVA the relative harmonic currents of the total load are less than that provided in Table 7 of IEC 61000-3-6.

$$S_i / S_{SC} \leq 0.1\% \tag{E.2}$$

For *Customer A*'s installation S_i and S_{SC} are 0.815pu and 44pu respectively. Thus using (E.2)

$$\begin{aligned} S_i / S_{SC} &= 0.851/44 \\ &= 1.85\% \end{aligned}$$

Therefore *Customer A*'s installation fails the Stage 1 test.

E.2 IEC 61000-3-6 Stage 2 – First Approximation

At saturation of the system, taking into account overload capacity and maximum utilisation factor of the 25MVA HV/MV zone substation transformer, the total power available (S_t) is 27.5MVA. The X:R ratio of the system impedance seen by *Customer A* is assumed to be 1:1. Table E.1 outlines the results from Stage 2 first approximation calculations with the recommended allowable harmonic current emission limits given relative to the PCC and the customer load in the right most columns.

Table E.1 Stage 2 first approximation results

Harmonic	α	L_{hMV}	L_{hHV}	G_{hMV+LV}	$E_{Uhi\%}$	$Z_{h(pu)}$	$E_{Ihi\,(pcc)\%}$	$E_{Ihi\,(load)\%}$
3	1	4.00%	2.00%	2.00%	0.06%	0.05	1.22%	1.50%
5	1.4	5.00%	2.00%	3.97%	0.32%	0.08	3.98%	4.89%
7	1.4	4.00%	2.00%	2.85%	0.23%	0.11	2.04%	2.51%
9	1.4	1.20%	1.00%	0.41%	0.03%	0.14	0.23%	0.28%
11	2	3.00%	1.50%	2.60%	0.45%	0.18	2.52%	3.10%
13	2	2.50%	1.50%	2.00%	0.34%	0.21	1.64%	2.02%
17	2	1.60%	1.00%	1.25%	0.21%	0.27	0.79%	0.96%
19	2	1.20%	1.00%	0.66%	0.11%	0.31	0.37%	0.46%
23	2	1.20%	0.70%	0.97%	0.17%	0.37	0.45%	0.56%
25	2	1.20%	0.70%	0.97%	0.17%	0.40	0.42%	0.51%

The above calculations were completed with a system base of 1MVA. The base current for the calculations is determined using equation (E.3).

$$\begin{aligned} I_{base} &= \frac{1MVA}{\sqrt{3}\times 11kV} \\ &= 52.5A \end{aligned} \tag{E.3}$$

The recommended allowable harmonic current emission limits in Amperes are given in Table E.2. These limits may be increased slightly if the residential loading of HV/MV zone substation transformer is significant (load curves of LV and MV are required for this).

Table E.2 Harmonic current emission limits for Stage 2 first approximation

Harmonic	E_{Ihi} (Amps)
3	0.64
5	2.09
7	1.07
9	0.12
11	1.32
13	0.86
17	0.41
19	0.20
23	0.24
25	0.22