Harmonic Impact of Photovoltaic Inverter Systems on Low and Medium Voltage Distribution Systems

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Abstract

As residential customers become more energy conscious and environmentally aware, the installation of grid connected photovoltaic solar panels for small-scale electricity generation is expected to increase. However, the issue of quality of the electrical supply is as equally important as adopting sustainable energy. This thesis proposes a method to determine the quality of electrical supply based on the acceptable level of harmonic current that can be injected from a typical grid connected residential type photovoltaic inverter system (PVIS). The acceptable number of PVISs is based on not exceeding the recommended harmonic voltage levels in medium voltage (MV–11kV) and low voltage (LV–415V) distribution systems given in standard AS/NZS 61000.3.6-2001 and its application guide HB 264-2003.

To undertake this study, an acceptable frequency domain model of a typical power system is developed, an appropriate model of a typical inverter spectrum is proposed and a method for allocating harmonic voltage distortion levels for PVIS in MV and LV systems by incorporating background distortion is suggested. The harmonic voltage distortion levels caused by the residential type PVIS are calculated based on conventional methods such as nodal analysis applied over the distribution network.

A typical residential power system is adapted from the available literature. The LV distributors of the power system were modelled based on residential load and PVIS aggregation, and MV feeders are modelled based on distribution transformer aggregation. The distributors selected for LV systems study are based on overhead open–wire conductor, aerial bundled conductor and underground cabling types and the MV system feeders are based on an open–wire overhead conductor system. Residential load for harmonic studies is modelled based on the duration of equipment usage (with typical household ratings) during the power generation (active time) of the PVIS. Active time of the PVIS is estimated from field measurement data.

Since the LV system is of multiple earth neutral (MEN) construction, an additional system study is required to investigate the effective neutral harmonic impedance. This study revealed the significance of the zero sequence impedance of the system to show the importance of representing the neutral current within the study. Consequently, the acceptable number of PVIS units is limited by triplen harmonic voltage magnitudes suggested by recommended harmonic voltage levels.

Studying the available literature revealed that the development of a harmonic current spectrum to represent a typical photovoltaic inverter's line current is required. Hence, an adequate harmonic current spectrum was developed being selected from three distinct methods. The PVIS spectrums were modelled up to 40^{th} harmonic, and an appropriate model was selected from among the three proposed models based on their compliance to recommended harmonic current emission levels, both individual and total, as suggested by standards. Examining the harmonic range up to 40^{th} revealed that recent LV distribution network harmonic studies associated with PVIS are not wide enough in harmonic range to show some important network wide harmonic issues.

Allocation of harmonic voltage distortion levels for the LV PVIS was based on the background distortion level and recommended harmonic voltage planning levels and the suggestion in standards to incorporate sufficient diversity for the MV and LV distribution systems contribution. Background harmonic voltage distortion levels were calculated based on published data related to field measurements from dedicated residential feeders in distribution systems.

This study has proposed and identified a method to assess the harmonic distortion levels in MV and LV distribution systems, and related key issues, to assist the harmonic management of these systems due to grid connected PVIS.

Statement of Originality

This is to certify that the work described in this thesis is entirely my own, except where due reference is made in the text.

No work in this thesis has been submitted for a degree to any other university or institution.

Signed

Ahmed Ahsan Latheef

December, 2006

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I would like to thank my parents for their constant support given to me throughout the time of my studies, their encouragement for me to move forward with my studies during the most depressed times is invaluable. I would also like to thank my wife and my son for their patience and understanding, when long hours were spent on studies instead of being with them.

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List of Abbreviations

PV	Photovoltaic
PVIS	Photo-Voltaic Inverter System
MV	Medium Voltage
LV	Low Voltage
THD	Total Harmonic Distortion
V_h	Harmonic voltage
V_{THD}	Voltage Total harmonic Distortion
PQ	Power Quality
I_h	Inverter Harmonic Current
h	Represents the harmonic number (Multiple of the fundamental, 50Hz)
$L_{415,h}$	Harmonic Voltage Planning Level for 415V system [10]
$L_{11,h}$	Harmonic Voltage Planning Level for 11kV system [10]
$L_{33,h}$	Harmonic Voltage Planning Level for 33kV system [10]
$L_{O,415,h}$	Distortion contribution due to existing 415V system equipment
$L_{415,PVIS,h}$	Allowable V_h contribution to PVIS for the 415V system
$L_{11,PVIS,h}$	Allowable V_h contribution to PVIS for the 11kV system
$L_{11,415,h}$	Distortion contribution due to existing 415V system equipment in 11kV system
$x_{s,tx,h}$	Impedance of the Transformer and Upstream at h^{th} harmonic
x_{tx}	Transformer impedance
α	Harmonic Summation exponent [10]
β_h	Background Harmonic allocation factor at h^{th} harmonic
GMD	Geometric Mean Distance

L_{PVIS}	Allowable distortion Limit for the PVIS
PCC	Point of Common Coupling
IEEE	Institute of Electrical and Electronics Engineers, Inc
IEC	International Electrotechnical Commission
ABC	Aerial Bundled Conductor system voltage feeder type
OH	Overhead open wire system voltage feeder type
UG	Underground system voltage feeder type
S_{INV}	Rating of the inverter
V_{INV}	Voltage at the point of grid connection of the inverter system
AAC	Aluminum Alloy Conductor
UG	Underground Cabling
ABC	Aerial Bundled Conductor
V_{BUS}	Voltage at the transformer side of a MV feeder or LV distributor
V_{MID}	Voltage at the mid-point of a MV feeder or LV distributor
V_{END}	Voltage at the end of a MV feeder or LV distributor
Z_{load}	Residential load impedance

Chapter 1

Introduction

1.1 Thesis Statement

Electrical power systems exhibit a collection of undesirable power quality behaviour such as harmonic voltage distortion because of the nonlinearity in the switching mechanisms of certain grid connected equipment. Switching equipment like inverters implemented in the front-end of energy conversions systems such as Photovoltaic Inverter Systems (PVIS) are not only responsible for distortion of the system voltage, but are also responsible for abnormal behaviour of sensitive loads, while they themselves may also be considered a sensitive load. This thesis looks at the harmonic voltage distortion levels, based on standards approved within Australia, that can be tolerated in medium and low voltage power systems exposed to a substantial amount of harmonic currents emitted from residential type solar energy systems.

1.2 Thesis Objective

As the procedure for this study, the main objective was broken down into small supporting objectives and addressed individually. The individual outcomes are then combined in addressing the main objective of the thesis.

Main Objective: The main objective of this thesis is to examine the harmonic capability of the power distribution system when a significant content of current harmonic from a large number of residential type photovoltaic inverter systems is present.

The supporting objectives are: 1) Development of representative models and 2) Analysis of results. The content breakdown of the supporting objectives are as follows:

Development of Representative Models

a. Determine a suitable method for representing the PVIS for harmonic studies.
b. Develop a method for representing the power system for harmonic studies.
c. Identify the appropriate harmonic voltage planning levels for PVIS.
d. Develop a calculation method for determining the acceptable penetration level of PVIS on the system.

Analysis of Results

a. Examine the distortion levels prior to the presence of low voltage PVIS.
b. Evaluate the harmonic impact of PVIS on LV systems.
c. Evaluate the harmonic impact of PVIS on MV systems.

1.3 Methodology

This study begins with a literature review of the state-of-art in PVIS technology, relevant power system modelling standards, and power quality analysis methods followed by the collection of chapters addressing the supporting objectives. These chapters consist of calculations completed with the aid of available computer software packages (Matlab[1] and Excel[2]). Finally, based on the results, conclusion and recommendations are provided. Additional studies contributing to the main objective include a sensitivity analysis to compare the studied harmonic current spectrum model with field measurements. This study also discusses the the available standards (from IEEE and IEC) in relevance to this study. The methodology involved in the completion of this study is given in Appendix A, Figure A.1.

1.4 Thesis Layout

This section outlines a brief summary of the remaining chapters contributing to this study.

Chapter 2: This chapter introduces the state-of-art with a literature review outlining the existing studies and methodologies in addressing the aspects related to the harmonic impact of photovoltaic inverter systems on LV and MV distribution systems. The major areas covered in this chapter are the technologies involved in photovoltaic systems, refining the characteristics of the inverter harmonic current spectrum, methodologies in evaluating distribution systems harmonic voltage issues and the viability of implementing PVISs as a sustainable energy system from an economical and technical (Power Quality) point of view.

Chapter 3: The most relevant standards (IEEE and IEC family) in addressing the implementation of grid connected residential type energy sources are discussed and the standards adopted for this study are proposed. The chapter also involves an analysis of the standards by addressing their recommended limits in the area of harmonic management in power distribution networks.

[1]Is a product of The Mathworks, Inc

[2]Excel–Microsoft®Office Excel 2003 SP1, Part of Microsoft Office Professionals Edition 2003, Copyright©1985–2003

Chapter 4: The representation of a typical PVIS's harmonic content is based on modelling data from existing spectra. This chapter proposes and implements statistical modelling techniques on the available data. As a result of these modelling techniques, a current harmonic spectrum is selected and proposed to be used in the study.

Chapter 5: A typical power distribution system is proposed for this study. The representation of the LV and the MV system characteristics for harmonic analysis is discussed.

Chapter 6: Following the selection of a proposed power distribution system for this study, the effect of residential grounding at multiple locations is investigated as a major component in the distribution system modelling. A comprehensive study on the effect of multiple earth neutral grounding in residential area is completed.

Chapter 7: Analysis of existing voltage distortion levels on the power systems is undertaken to provide a more complete analysis of the acceptable penetration levels of PVIS. This chapter proposes a method to determine the existing distortion levels in the distribution systems based on available harmonic voltage planning levels and relevant data on harmonic currents in the residential system. The outcome of this analysis was the ability to estimate harmonic voltage distortion levels for residential PVIS.

Chapter 8: Presentation of results include the outcomes from the major findings contributed from the previous chapters.

Chapter 9: The concluding chapter for this study consists of the achievements contributing towards the main objective of the study. Following the conclusion, this chapter addresses recommendation in areas where the work can be extended.

1.5 Publications Based on Work Performed for this Thesis

i. A. A. Latheef, D. A. Robinson, V. J. Gosbell, and V. Smith, "*Harmonic impact of photovoltaic inverters on low voltage distribution systems*", Cascais, Portugal: 12th International Conference on Harmonics and Quality of Power, Oct. 1–5 2006.

ii. A. A. Latheef, V. J. Gosbell, and V. Smith, "*Harmonic Impact of Residential Type Photovoltaic Inverters on 11kV Distribution System*", Melbourne, Australia: Australasian Universities Power Engineering Conference, Dec. 10–13 2006 (accepted for publication).

Chapter 2

Literature Review

2.1 Introduction

The purpose of this literature review is to present the state-of-art technology implemented in residential type solar power generation units. This literature review address two main categories, namely photovoltaic (PV) system (specifically providing an in sight to available inverter designs) and related power quality issues.

So as to conclude the understandings from this literature review, some additional issues are addressed in relation to improvement of harmonic studies with grid connected PV systems in MV and LV distribution systems.

2.2 Introduction to Solar Power

The ability to utilise free resources of energy to generate electricity is one of the major tasks for environmentally concerned research engineers. Conversion of energy from sunlight to direct current through a Photovoltaic (PV) cell has become a popular area of study and has gained attention of many engineers and researchers. The application of this free, efficient and reliable energy source is predicted to grow in years to come [16]. The large scale implementation of solar powered power systems have the potential to release the stress on overloaded power system and to contribute to green energy. With understanding of the aforementioned issues, large scale investments aim to satisfy the growing demand for sustainable energy.

Among the many large scale solar based Distributed Generation (DG) programs, the Dutch government funded project [17] can be considered as a dedicated to residential distribution project. In this project maximum utilised power from the aggregated DG with PV ratings was planned at 36MW.

Another significant programme is the Athlete's Village at the Sydney Olympic site referenced by [18] [19]. This solar village consists of approximately 665 residential homes, supplied by 1kW peak photovoltaic roof top systems. The residential PV system is connected through an inverter to an underground LV (240/415V) grid.

Based on the above examples of well established projects, it can be clearly seen that PV systems can play a major role in DG [17] especially for residential needs. For projects involving larger DG, careful planning is required by the DG planner including the PQ issues. When designing large PV systems in DG one of the perspectives of the DG planner is to assess the failures that may occur in a conventional power system which consequently accounts for reliability of the system. Based on factors such as reliability, performance, comparative costs and available technology, the planner decides if the system can be strengthened using DG or whether to replace the entire system with the required rated equipments incorporating the same bulk supply point [20]. One of the ways in reducing the bulk power supply to residential needs is to have low rated PV systems within each residential dwelling. Once a sustainable energy source is implemented as a DG running in parallel with the utility (electrical power supplier), this achieves a capacity relief from a utility point of view [16].

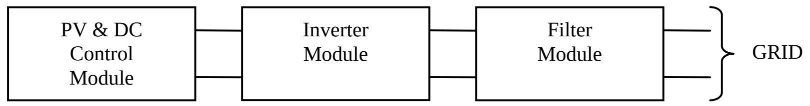

Figure 2.1 Major building blocks of a typical solar powered system, conditions for grid synchronisation is achieved from the characteristics of inverter block in combination with filter block, on fundamental frequency and the harmonic limits that can be injected to the grid

2.3 Main Systems of Solar Power Generation

Residential type solar power systems can be considered as a combination of subsystems fabricated together, dedicated to convert light energy into usable electrical energy to meet the daily requirements. The main building blocks of a residential solar powered unit, as seen in Figure 2.1, includes the photovoltaic (PV) cells converting the light into a DC power output and its control system, the inverter block where most of the switching takes place in converting the DC-AC and the filtering mechanism which is a mandatory implementation block to keep the harmonic currents within relevant standard [7] [21] limits.

This section provides information on the available technology in the market and in published literature, relating to the technical background of PV modules, the inverter system designs and required filter designs. In order to address the above mentioned areas, related case studies are revealed to incorporate practicable solutions.

PV Modules: The construction and the electrical characteristics of roof top solar panels have evolved over the past 50 years, increasing their reliability and durability [22]. The rating of the first outdoor solar panel produced in the 1950s from the Bell Laboratories was only a few watts with low efficiencies. However, the power output and efficiency improved during the 70s and 80s. By the 1980s, the power rating of solar cells reached over hundred watts range with efficiency close to ap-

Please see print copy for Figure 2.2

Figure 2.2 (Left) A mono crystalline solar panel of 175W and (Right) A polycrystalline solar panel of 165W, available ratings of solar panel can be used with manufacturers details to estimate the amount of roof area required to generate 2kW [1]

proximately 10% [22]. A typical solar panel is shown in Figure 2.2, displaying two of the most commonly used technologies, monocrystalline and polycrystalline, designed for residential use with power ratings of 175W and 165W respectively [1].

A solar panel can be modelled to represent its electrical characteristics by understanding the ‘p-n ’ junction effect. Solar cells (or PV cells) are a special form of a ‘p-n’ junction where holes are produced as the photons interact. The concept of p-n junction in solar cells behaves similarly to a diode where the current can be represented by equation (2.1), showing its relation to temperature.

$$I_d = I_D\Big(\frac{QV_{OC}}{AKT} - 1\Big) \tag{2.1}$$

where V_{OC} is the open circuit voltage, I_d represents the diode current, I_D represents the saturation current of diode, Q is the electron charge (1.6×10^{-19}), K is the Boltzmann constant, A represents a curve fitting constant and T is the temperature of the device. By understanding the concept of diode current, an electrical circuit can be modelled to represent the current behaviour of the PV modules, shown by Figure 2.3. For an ideal PV cell, the series resistance R_s=0 and the shunt R_{sh}=∞. However, for a good practical PV module parameters are approximately R_s=0.05Ω to 0.10Ω and R_{sh}=200Ω to 300Ω [2].

Please see print copy for Figure 2.3

Figure 2.3 Equivalent Circuit of a PV module showing the diode and ground leakage currents [2]

Please see print copy for Figure 2.4

Figure 2.4 The behaviour of the i-v characteristics at different illumination levels, adopted from [3]

The output power of the PV cells are influenced mainly by the amount of illumination and the temperature of the PV cells. The electrical characteristics of a PV cell can be best described by its i-v (current-voltage) characteristics. Figure 2.4, shows the behaviour of the output voltage and current for different illumination levels. Consequently, for changing meteorological conditions the output power will vary significantly. However, practical systems are designed to operate at the best possible output power (given the solar irradiance). To achieve the ability to track the maximum power, more complex control systems known as Maximum Power Point Tracking (MPPT) are implemented. The basic principle of MPPT is to detect the

Please see print copy for Figure 2.5

Figure 2.5 The characteristics of the power output due to different illumination levels related to Figure 2.4, adopted from [3]

power requirement of the load, generated power and to operate the system (DC–DC controller and the inverter) at the most feasible condition. The feasible point of operation is described by operating close to or slightly to the left of the knee point of a cell power vs voltage graph [23], as shown in Figure 2.5. The implementation of such a control system will not be in an individual block, but rather within the complete system.

Following the output from the PV modules, a DC–DC converter is required to control the variable DC to an inverter system. At times it is required to boost the voltage for MPPT.

Selecting a typical residential inverter rating: The selection of an inverter rating depends on the power requirement, available roof area for the PV modules and cost of the systems. This section addresses the selection of a typical residential inverter rating based on power requirement and available roof area.

In trying to allocate a typical rating for the PV system, publications have shown that there is no standard rating specific for residential use. However, standards [24][7] have addressed LV equipment usage based on their fundamental current magnitude and harmonic content. This led to the study of a practical project [25] incorporating many residential PVIS with different ratings to determine an average residential inverter rating. A European project revealed that a range of 1-3kW [17] was present among the residential households. Therefore, the average rating of 2kW from the study [17] was believed to be a suitable rating to represent a residential consumption. Nonetheless, projects such as [26] reveal different ratings.

Studying the available literature [18][19][6][25], the required kW for a residential dwelling was in the range 1–5kW. However, additional literature study has also revealed that a 150W inverter is an optimal rating for residential purposes [27]. It is believed that implementing such a system would significantly limit the equipment usage at times. Further to this study, a family of four has experienced 12 years of living completely off grid, utilising a PV system of 1.2kW [28]. The PV arrays served common residential equipment and in addition a microwave, air compressor and metal and woodwork equipment. With the intention of rating a PVIS for a typical power for residential use, such examples [28][27] may be considered as non-typical. One important characteristic of the residential dwellings mentioned in the above literatures is that they are specially designed for energy saving purposes. Although energy saving is the intention, a typical residential dwelling may not be designed specifically to be energy efficient. Based on the mean rating of a total of 200-400 residential installations, most of which consisted of 1-3kW inverters, from a project compiled in [17], a typical inverter rating of 2kW can be considered as sufficient for a typical residential dwelling.

Inverter Systems: The inverter is one of the most important systems that requires attention in harmonic analysis. Due to its switching mechanism causing harmonics in line current, inverters are considered as a contributor to network harmonic voltage distortion.

The most common type of inverters used to be the line-commuted inverters, due to the advance in the technology of semiconductor devices self commutated inverters are blending into PVIS [4]. The basic principle of the inverter is to switch the DC to a required AC voltage. There are a few types of inverter designs with a controllable switching scheme, namely Pulse Width Modulation (PWM) inverters and a special type of PWM called square wave inverter. The square wave inverter harmonic magnitudes can be modelled as '1/n', where 'n' is the harmonic number [29]. On the other hand, PWM uses a modulation index scheme and the harmonic components are more complex to derive. In line-commutated inverters the reference frequency is based on the frequency of the supply and are very to sensitive to distortions in the supply.

The available literature on inverter designs used in PV systems revealed that there is no specific inverter design or a rating for residential PVIS. This broadness of utilised inverter designs and ratings suggests that the selection of design is at residential preference based on the proposed usage and available space. Therefore, to understand the harmonic content of the output of the commonly accepted inverter designs and ratings, it is necessary to study available literature on practical (large scale) implementations of residential purpose PVISs. The selected two cases are:

i. The Sydney Olympic Village Case Study [18][19]

ii. The Dutch PV Suburb, Nieuwland, Amersfoort [17] [6][25][30]

The reasons for researching the above two projects are:

i. They are large scale projects defined for residential areas

ii. Their different geographical locations and the significant difference in environmental conditions would impact the required rating hence the selection of inverter designs may differ.

Studying the two cases revealed that the inverter designs include mainly self-commutated systems, however there are cases were line commutated inverters are still being utilised as central inverters. The study [4] reveals line-commutated inverters are robust, cheap, highly efficient and economical compared to self commutated inverters, however the low power factor (as low as 0.6) with significant harmonics in the line current were undesirable characteristics. In the special case of transformer-less design of a line-commutated system (as seen in Figure 2.6), the grid sees a galvanic connection (capacitor) if the filter is based on L-C-L (as for filter designs given by [31]) before the grid. It is believed that modelling a network system with such a design will need to incorporate a substantial amount of capacitance in the model, consequently shifting the resonance frequency. The case studies (i. and ii.) show

Please see print copy for Figure 2.6

Figure 2.6 (Top) A transformer-less PVIS with line-commutated inverter designed to operate as a central system, adopted from [4]. (Bottom) A transformer-less design showing the filter connected (L-C-L) to grid, model developed to study different grid conditions [5]

that other types of PVIS topologies were implemented in PVIS, one of the designs being the module integrated inverter system as seen in Figure 2.7 including the boost converter.

Please see print copy for Figure 2.7

Figure 2.7 A PVIS with boost converter, adopted from [4]

The above designs are based on the transformer-less concept but customers also favour the designs incorporating a transformer. As mentioned before, the selection of the PVIS design is based on the end user application and on the economical justifications. One of the common designs for PVIS in the H-bridge systems [6], a filter being coupled with a line frequency transformer to connect to the grid, as shown in Figure 2.8.

Please see print copy for Figure 2.8

Figure 2.8 A PVIS design incorporating a transformer at the front end, adopted from reference [6]

Alternative inverter designs for small distributed generation (one in particular for MPPT in residential PVIS) were proposed in literature [32]. This particular paper is an overview of a number of designs concepts, and suggests the functions of such an inverter [32]:

i. The conversion of power from variable dc voltage into a fixed ac voltage for stand alone systems or ac current output following the grid voltage and frequency for grid connected applications.

ii. The specified power quality requirements are met based for respective standards.

iii. Protection of distributed generated source and the utility grid from incidences such as abnormal voltage, current, frequency and temperature, and at times further protection from anti-islanding (detail in Section 2.4) and electrical isolation as required.

iv. Additional control mechanism of the distributed generators (in the case of PVIS, additional control would be the MPPT mechanism).

The literature suggests that more the requirements to be met more the components involved, hence there will be a tendency to reduce the efficiency and increase cost.

Filters: In studying the available filters implemented within the PVIS, the most common type of filters were found to be the L-C and the L-C-L combination filters [6][19][31]. It is believed that since residential purpose PVIS systems are low rated systems, passive filtering methods would be sufficient to incorporate in PVIS. Such filters (Figure 2.9) are mandatory to implement by standards [7][33][21] especially when using line-commutated inverters where the harmonics in the line currents are significant.

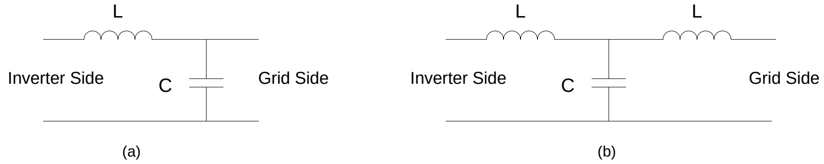

Figure 2.9 (a) an LC filter and (b) LCL filter, as required for PVIS harmonic filtering in line currents

The study on inverters and filtering techniques has revealed that with sophisticated inverter designs, even with filtering systems, the existence of line current harmonics is inevitable and requires further design enhancement.

2.4 Power Quality Issues Related to PVIS

As discussed in Section 2.3, the quality of the electrical supply can have an abnormal effect on the operation of PVIS or at times of a total failure. This abnormal effect on PVIS is caused by the dependance of PVIS on some of the electrical supply features, which are also categorised in power quality disturbances. The power quality disturbances are typically classified according to their duration and frequency content [34]. Even though this study is based on harmonic distortion of power quality, it is believed that reliability of the PVIS is significantly affected due to all power quality disturbances. Hence, for completeness of study the following major power quality disturbances are detailed.

Voltage Disturbances: Voltage disturbances occur when the utility nominal voltage is disrupted either by an increase, decrease or by a total failure of the nominal voltage since the inverter and the control system detects and compares with the nominal voltage condition at the utility [2]. For the PVIS designs mentioned in Section 2.3, especially with multistage inverters, voltage disturbances could result in an abnormal operation or a total failure of the PVIS. The standard AS/NZ 61000.3.2-2003 [24] has a time frame given in number of cycles by which the voltage needs to recover. If a total failure occurs then the inverter needs to be totally disconnected and should reconnect once the utility voltage recovers to normal condition. This is a special case and at times is referred to as “islanding.”

Islanding: ‘*Any situation where the electrical supply from an electricity distribution network is disrupted and one or more inverters maintain any form of electricity* *supply, be it stable or not, to any section of that electricity distribution network*' standard AS4777.1-2002 [35]. It is important that during an islanding process the PVIS involved are protected. At the moment of interruption the PVIS needs to disconnect from the grid until the supply voltage is totally restored. This is normally achieved by using a protection relay which detects the utility voltage and frequency for abnormalities. The available literature [36] indicates that there are two possible methods of detection, the passive method and the active method. In the passive method, the literature proposes a phase shift detection method and utilises this method to compare the phase shift in the utility line abnormal condition to that of average phase shift of the normal utility line. The active method involves the use and detection of pre-islanding reactive power of the system. During the pre-islanding condition the frequency fluctuates which corresponds to a fluctuating reactive power. This is detected and monitored for action to be taken [36].

Harmonic Distortion: The fundamental voltage distortion in distribution systems (also known as 'harmonic distortion') became one of the most investigated areas since the late 1970s or early 1980s, when power electronics was initiated within industrial plants. Since then, power electronics has been used to satisfy commercial, industrial and residential requirements in one form or the other. One of the residential level uses of power electronics with sustainable energy is solar powered systems. Because of the methodology implemented in the power electronics, network wide harmonic distortion is inevitable as partly discussed in Section 2.3. The field measurements in [37] showed that the contribution from a large building dedicated to residential use caused radical voltage distortion at the transformer bus. Residential equipment with electronic power supplies are categorised as distorting equipment, hence it is impossible to exclude network distortion due to existing equipment in harmonic studies.

In trying to understand the harmonic distortion within a distribution network, a wide range of literature is available on addressing various harmonic distortion scenarios. However, there is limited literature that has addressed the full problems of harmonic distortion caused by PVIS on the network and of the effect of a distorted network on PVIS. The case studies presented in Section 2.3 have revealed that certain inverters switch off undesirably and emit significant amount of harmonics in line currents without an accountable cause [17]. This behaviour of abnormal operation could be the result of significant harmonic distortion levels within the network, where significant number of inverters contributing harmonics to distort the utility supply are present. Some of the standards and guidelines relating to network voltage disturbance levels are standard IEC 61000-3-6-1996 [38], handbook HB264-2003 [10] and IEEE std 519-1992 [11] and, for harmonic currents emission levels these are AS 4777.2-2002 [7] and IEEE 1547-2003[21]. It is believed that even though an individual inverter satisfies the relevant standards, a significant number of inverters on a network may not satisfy the network's harmonic voltage limits. The results from a case study shows that the THD for the network's average distortion level was at 3% [17], however it also reveals that the inverters were operable at 8% THD distortion levels (maximum allowable levels based on standard EN 50 160). These studies have revealed that a complete study for determining the acceptable number of LV PVIS in LV and MV systems was believed to be an additional concept which needs to be studied, since the available literature did not address this.

Other power quality disturbances are the DC injection, sensitivity to telecontrol signals, grounding effects and audio noise. The effects of the mentioned disturbances are determined mainly by testing the manufacturers inverters [13][14].

2.5 Literature Review Summary

This literature review has provided existing PV system details, the implemented technology for the main types of PVIS, related power quality disturbances and the viability of implementing such a system from economical and reliability perspective. It is believed that the available literature lacks in addressing some issues which can be considered essential for harmonic management of distribution networks.

The available literature suggests a need for the development of a typical harmonic current spectrum model incorporating significant number of existing inverter manufacturers harmonic data. The purpose of such a model is to be utilised in distribution networks harmonic studies, where typical harmonic voltages around the network can be found which can be adopted for utility harmonic management purposes.

Most of the studies (practical cases) were based on revealing the result of a distinct number of PVISs on a given network, therefore concealing the true acceptable levels of PVIS due to proliferation of PVIS on a network. Hence, a definition for the acceptable penetration level of PVIS and an appropriate analytical method to determine the acceptable level of PVIS on distribution networks is believed to be necessary.

Chapter 3

Standards Overview

3.1 Introduction

It is understood that a standard governs both the customer and utility to coexist in a power distribution network frame on agreeable terms. During a time of increasing demand, supply reliability and quality of power, the application of standards is believed to be the decisive tool for the existence of a customer or a utility. This chapter examines the standards issued by leading organisations to regulate harmonic management within the distribution system, applicable to grid connected PVIS.

The proposed standards are related to two main groups: 1) standards related to utilities to assess the quality of power supplied to the consumers and for customers the quality of power received with conditions for utilisation of this power; and 2) standards related to manufacturers in relation to existence of harmonic currents emitted from their equipment.

3.2 Standards for Regulating Harmonic Distortion Levels in Electrical Power Systems

Among the many standards in IEEE and IEC, the most relevant standards for this study are in the area of governing the harmonic voltage distortion levels in the power systems. The two standards in this area are the IEEE std–519 ("*Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*" [11]) and the IEC 61000–3–6 ("*Assessments of Emission Limits for Distorting Loads in MV and HV Power Systems*" [38]). The details of these standards and a critical overview of some of their approaches in assessing the distortion levels within the system are discussed as follows.

3.2.1 IEEE std 519

The IEEE standards are mostly adopted by North American utilities or utilities of similar design. Standard 519 addresses multiple issues related to power quality, as for this study harmonic issues and limits are considered. This provides harmonic voltage and current distortion limits where the utility and the customers need to be obliged to meet the requirements for normal operation of the system. The voltage limits in Table 3.1 are for the "worst case" of a normal operating condition where the voltage distortion last for more than one hour, with few exceptions as indicated by the standard [11].

Please see print copy for Table 3.1

Table 3.1 Harmonic voltage limits, IEEE 519 [11]

The approach of IEEE Std 519 in harmonic management is to provide harmonic current limits for individual customers. Unlike in low voltage networks, allocation of distortion needs to be planned for medium voltage customers. On this basis, the size of the customer is defined by the ratio of the customer's I_{sc} at the PCC to maximum the load current, and the harmonic current limits are expressed as a percent of maximum load current in demand [11]. The current limits of the first row in reference [11] Table 10.3 are given in Table 3.2, where the standard specifically states that the current limits mentioned in Table 10.3 [11] should be met by all power generating equipment regardless of the I_{sc}/I_L ratio.

Please see print copy for Table 3.2

Table 3.2
Harmonic Current Distortion limits as a percent of I_L (first row in Table 10.3, IEEE std 519 [11])

Among the guidelines provided by the IEEE Std 519 for both the utility and the customer, this study adopts the harmonic voltage limits given by Table 3.1 as the harmonic voltage planning levels and current harmonic emission levels given by Table 3.2, to investigate the acceptable penetration levels of LV PVIS in distribution systems. It should be noted that the IEEE Std 519 harmonic current limits are closely related to Australian Standard AS 4777.2 [7], hence the suggested magnitudes are interchangeable for the purpose of this study.

3.2.2 IEC 61000-3-6

The IEC 61000-3-6 can be considered to have a more complex approach in network harmonic management compared to the IEEE std 519. The establishment of the IEC standard was based on two publications [39] 1)"Harmonic Producing installations in High-voltage Networks with Particular Reference to HVDC" and 2)"Equipment Producing Harmonics and Conditions Governing Their Connections to the Mains Power Supply"[40].

On 25^{th} January 2001 AS/NZS 61000.3.6:2001 [41] was published as an adaptation of the IEC 61000-3-6, superseding the AS 2279.2-1991 [42]. In 2003, a handbook was published with the name "Power Quality – Recommendation for the application of AS/NZS 61000.3.6 and AS/NZS 61000.3.7" [10] giving a very compact guide for application of the more complex standard IEC 61000.3.6. The handbook proposes test data on a case study basis, giving a strong justification for some aspects of the standard and contains typical systems details derived from field measurements. The summary of the harmonic voltage planning levels published in the handbook are given in Table 3.3. The handbook [10] will be referred to extensively in this study.

Please see print copy for Table 3.3

Table 3.3
Recommended Harmonic Voltage Planning levels for 415V, 11kV and 33kV Australian distribution Systems [10]

It is believed that one of the superior features of the IEC standard over the IEEE standard is its incorporation of compensation for time, phase and magnitude diversity within the grid connected loads (including energy systems as distorting loads). Determination of this diversity in the standard is through a statistical based formulation known as the *"summation law"*.

3.2.3 Application of Summation Law in IEC 61000-3-6

One of the key targets of standards concerned with the harmonic distortion levels in power systems is the ability to assess the net effects caused by system-wide distorting loads. The difficulty in assessing the net distortion levels lies in the allowance for phase and time magnitude diversity of these loads. IEC 61000-3-6 proposes a more hypothetical approach in addressing this issue. Otherwise a substantial amount of data and a complete system study would have been required, which at times can be considered unnecessary for the required accuracy. The IEC standard suggests the implementation of two summation laws, which are applicable based on the availability of data.

The First Summation law describes linear characteristics with the contribution from equipment-dependent diversity factors. This is believed to be a simpler form of approach (compared to Second Summation law) to implement and is mainly targeted for systems with availability of sufficient knowledge on load characteristics. First summation law in IEC 61000-3-6, to represent the harmonic voltage U_h is given by

$$U_h = U_{h0} + \sum_j k_{hj} \cdot U_{hj} \tag{3.1}$$

where U_{h0} is the background harmonic voltage (caused by j loads disconnected from the supply network) and U_{hj} is the harmonic voltage contribution from the j^{th} load. Sufficient information is required from these loads in order to determine the diversity factors, k_{hj}. The diversity factors depends on the type of equipment, harmonic order and a weighing factor of the equipment measured as the ratio of rated power to short circuit power at the PCC.

The Second Summation law given by equation (3.2), can be considered as a more general form of approach in assessing the system wide distortion levels. Unlike the First Summation law, this approach depends upon the Power law to incorporate time varying loads (i.e. distorting loads subjected to considerable time varying harmonic magnitudes and phase) in assessing the net distortion effect. The Second Summation law is a derivation based on probabilistic values reflecting existing system characteristics, making this law more applicable in many cases.

$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}} \tag{3.2}$$

where U_h is the resulting harmonic voltage of the aggregated sources, giving a probabilistic value, and U_{hi} is the i^{th} individual harmonic voltage. The summation exponent (α) depends on the degree to which the harmonic voltage is influenced to vary randomly due to phase and magnitude and the selected probabilistic value (derived based on the analysis of vast amount of harmonic data over a significant period, as detailed in the standard) that does not exceed the calculated value (or the ideal value) [38]. The most up to date values of α published in [38] are given in Table 3.4.

Please see print copy for Table 3.4

Table 3.4 Summation exponents for the application of Second Summation law [10]

3.2.4 Comparison between the IEEE std 519 and IEC 61000-3-6 on Harmonic Assessing

The reason for this comparison of the two standards is to appreciate the work involved in the standards by making critical judgments on their differences in an attempt to provide the most preferable solutions based on their proposals towards harmonic management. This comparison is based on two aspects; difference in actual magnitudes (of harmonic current emission levels and voltage distortion limits) proposed by a standard and the philosophy behind the derivation of these magnitudes.

An observable difference in relevance to the area of this study can be seen in the acceptable harmonic voltage limits between the standards, Table 3.1 and the Table 3.3, where standard 519 proposes a constant 3% distortion level for individual harmonic voltages and 5% for the total voltage harmonic distortion for voltage levels less than 69kV. Comparative results from IEC allows a higher contribution for lower harmonics and drops off significantly for higher order harmonics with a total harmonic distortion of 4.4%, 6.6% and 7.3% corresponding to 33kV, 11kV and 415V respectively. Clearly, such proposed magnitudes from a harmonic management point of view will be considered as significantly different in the standards and the decision to what can be connected to the grid will consequently be affected. The above mentioned difference in the magnitudes could be the outcome of the standard's initial philosophy in determining the acceptable harmonic voltage on the network and harmonic current emission levels, where the IEEE std 519 believes that the voltage limits (network) are the responsibility of the utility while the current limits (injected) are the customers responsibility.

The IEC standard compared to the IEEE standard compensates for the complexity by incorporating more features, by addressing a wider range of issues in allocating harmonic distortion levels and setting emission levels. One of the significant features of the IEC standard is to give an insight towards the future distortion levels by incorporating future customers in the derivation of limits and levels. In a time of ever growing customer demand for quality of power, neglecting the future customers are more likely to approach conservative results, i.e. voltage distortion limits are the crucial factor. Hence, for some critics [39] the IEC standard is believed to have a better philosophy in attempting to allocate distortion levels for customers while making customers responsible for the harmonic voltages on the system. It is understood that the background distortion is caused by existing distorting loads (existing customers), whereby the responsibility needs to be enforced. The philosophy of the IEEE std 519 tries to share this responsibility between the utility and the customer (regardless of the utility version of the IEEE standard). On this note, the IEEE standard has not addressed future customers while IEC 61000-3-6 manifests formulas that incorporate future customers to determine the system capability to cater for all customers subjected to distorting currents.

Critics of the two standards [39] suggest that even though IEC 610003-6 is more comprehensive in addressing the harmonic issues related to utility and customer interaction, this IEC 610003-6 standard relies on too many assumptions. This has been considered a drawback. However, they believe that there are no fundamental differences in these two standard's philosophies. The criteria by which a customer can be connected to the grid will be based on the compliance of harmonic voltage distortion levels in the system, the ultimate decision.

The two standards have outlined and justified to some extent their philosophies towards the issue of harmonic distortion problems by addressing the responsible parties (utility and customer). It is believed that most of the work in both standards are satisfactory, with few existing drawbacks. The existence of these drawbacks could be regarded as the readers interpretation to which party the standards favour.

3.3 Other Standards Related to Connection of Energy Sources with the Electrical Power System

This section is based on the discussion of two standards considered as applicable to the manufactured equipment in relation to this study i.e. the IEEE 1547–2003 – *"IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems"* and the AS 4777 – 2002 family – *"Grid Connection of Energy Systems via Inverters"*. The focus of this analysis will be based on the part of standard that relates to emission of harmonic currents from distributed generating systems. As these standards are related to grid connected energy systems and energy systems connected via inverters, it is vital to understand the allowable current harmonic limits from these systems, especially inverters considered as the major harmonic source within the complete energy system, as discussed in Section 2.3.

3.3.1 AS 4777–2002 Family

Note: An updated version of the standard AS 4777.2-2002, "Part 2: Inverter Requirements," was released after the implementation of this standard as required for this study. The new standard AS 4777.2-2005, "Part 2: Inverter Requirements,"[43] was not used as per the latest release. However, it is noted that the odd harmonic magnitudes proposed in Table 1, page 6 of the new standard [43] are identical to that of Table 1, page 6 of the superseded version standard AS 4777.2-2002 [7].

The standard AS 4777-2002 family was prepared between the joint Standards Australia/Standards New Zealand committee EL–041 with support from utilities, experts from the photovoltaic and inverter industry, Electricity Supply Association for Australia (ESAA) and Cooperative Research Center of Renewable Energy (ACRE) [35][7][44].

The focus on this standard will be on part two of the AS 4777 family, AS 4777.2-2002 – "*Part2: Inverter Requirements*" [7] where the Australian manufacturer of inverters for energy systems is constrained by the limits suggested in this standard. The current harmonic limits endorsed in this standard are given in Table 3.5. AS 4777.2 suggests

Please see print copy for Table 3.5

Table 3.5
Standard harmonic current limits for grid connected energy systems via inverters rated $<$10kVA, [7]

that the magnitudes of the harmonic current assigned for low order are high and high order are low with a THD up to 50^{th} harmonic given by 5%. The harmonic magnitudes in Table 3.5 are similar to the proposed magnitudes from the IEEE std 519, Table 3.2 for the customers current emission level requirements.

The application of this standard is bound by inverter ratings up to 10kVA for single phase and 30kVA for three phase. Hence, AS 4777.2 [7] can be considered as appropriate for this study as the guideline for assessing the harmonic current emission levels from residential type PVIS rated at 2kW.

3.3.2 IEEE 1547–2003 and IEEE std 929-2000

IEEE 929–2000 [33] could be considered as the foundation of the recommended practice for grid connection of PV systems established by IEEE. The development of IEEE 929 was the result of IEEE Standards Coordinating Committee 21 (SCC21) which dates back to 1981 [45]. After benefiting from many recommended practices and utility comments, SSC21 issued mandatory requirements for interconnection of all forms of Distributed Resources (DR- a more general term used in IEEE standard to address multiple types of energy systems, including PVIS) namely IEEE 1547–2003 [21]. The standard IEEE 1547 has been referred to as the single most influential standard for grid connection of distributed resources by [45] up to this date. IEEE 1547 retains guidelines for interconnection of distributed resources up to 10MVA and addresses a wide range of issues, including harmonic related issues for the system.

Some of the guidelines in IEEE 1547 related to power quality include, the DC injection into the system being limited to 0.5% of the full rated output current at the connection point and the flicker level exposes due to the interconnections being referred to limits specified by IEEE 519. Relevant to this study, harmonic emission levels are referred to IEEE 519, Table 3.2. This standard specifically refers to the harmonic injection levels to be within the levels specified, excluding any foreign contribution especially from the power system.

3.4 Chapter Summary

Standards within the IEEE and IEC in relation to this study have been reviewed. These standards cover the areas of assessing harmonic distortion levels, inverter standards and other standards related to grid connection of distributed resources (generation including PVIS). These standards have shown a significant level of similarity between the most common standardising organisations.

Some of the criticism of the IEEE std 519 standard relates to the customer being responsible for maintaining the voltage distortion limits, in addition to maintaining the current distortion limits within the standard limit. The IEC standard has a broader perspective over time on the customers emission levels, and investing to incorporate future customers is found to be preferable over the IEEE std 519. However, critics have also suggested that the two standards published by IEEE and IEC have no major differences in their philosophy towards network harmonic management, normally that the ultimate decision to connect a customer lies in the hands of utility.

Standards or the guidelines related to the main stream of this study on the LV and MV systems will be based on HB–264 [10] for assessing the networks harmonic voltage planning levels and AS 4777 – 2002 [7] for standardising the inverters harmonic current emission levels. These two standards will be frequently referred to within the study.

Chapter 4

Inverter Current Harmonic Spectrum Modelling

4.1 Introduction

The discussion in Chapter 3 was based on the most relevant standards applicable to this study with regard to harmonic management with grid connected PVIS. Among the proposed standards in Chapter 3, inverter standard AS 4777.2 [7] that recommended harmonic current emission from inverters will be used in modelling a typical harmonic current spectrum (I_h) to represent the PVIS.

This section examines the possible methods of obtaining a harmonic current spectrum (I_h) to represent the PVIS output or current injected to the grid. The purpose of modelling is not to reflect current harmonics of a theocratical system, but rather the spectrum of a practical system implemented at the front-end of a PVIS unit. This is believed to be a more realistic approach towards representing the I_h spectrum in obtaining the acceptable penetration levels of PVIS. The wide (I_h) spectrum 2^{nd}–40^{th} harmonics is used for the purpose of a detailed examination of the harmonic voltage distortion behaviour within the distribution network caused by the PVIS.

The typical inverter rating of 2kW selected for this study was based on the mean rating of 1-3kW inverters, from a project compiled in [25] as detailed in Section 2.3. For this study it is assumed that for a given distributor the PVIS units operate at their maximum power output and the failure rates as detailed in [46] and the impact of various PQ issues discussed in Section 2.4 are considered negligible, resulting in insignificant power diversity among them. Also to consider when selecting a suitable rating would be the area covered by the PV modules. Based on the 2kW proposed typical rating, the physical roof coverage needs to be found as well as the rating. A manufacturer's PV modules(available on the market) was selected to estimate the required roof-top area, as outlined below:

Model BP4170[1]: 170W (assuming this is a reasonable wattage)

Number of units: 12 units equals to 2.04kW

Dimensions [1]: 1593x790x50 (mm)

Roof area (approximately): 15 sq.m

Given that the roof area available is more than 15 sq.m, this is believed to be sufficient to supply approximately 2kW of power from 12 modules.

An additional method to model the harmonic content from inverters is to use available software packages. The process of representing inverter designs by simulation and examining the harmonic content from these inverters may lead to additional complexity. However, this method can be a preferred method in the absence of manufacturers data.

4.2 Proposed Approach for Representing I_h Spectrum

In the modelling of the harmonic current spectrum to represent the PVIS, this study considered two possible approaches. They are to adopt the standard harmonic current emission levels [7] directly to represent I_h assuming that most of the inverter manufacturers design their inverters to emit full standard emission levels or to model the spectrum based on acquired data from literature to represent a typical I_h for the study.

Adopting the standard emission levels directly from [7], presented in Table 3.5, means that the system to which the I_h spectrum is exposed will receive the full impact of the emission levels. The resulting harmonic voltage within the system due to the full impact of I_h may not reflect optimistic harmonic voltage levels within the system. However, such a representation may reveal the maximum harmonic voltages in the system due to PVIS. Since the utility experiences an aggregation of PVIS (I_h), the resultant V_h may not necessarily be within the recommended harmonic voltage planning levels [10]. On this note, adopting the standard harmonic current emission levels to represent the PVIS may produce unrealistic results.

The second approach in modelling the harmonic current spectrum to represent the PVIS was based on utilising the available data. Harmonic current emission magnitudes, typical for the types of inverters used in PVIS for the range of harmonics 2^{nd} to 40^{th} were obtained from [13], [14] and [15]. The data from [13], [14] and [15] included measurements of emissions from seven different inverter manufacturers, with inverter ratings of 0.6kW, 0.7kW, 0.8kW, 1.3kW, 2.25kW, 2.5kW, 2.8kW, 3.0kW and 3.2kW. The exact magnitudes utilised from the references are provided in Appendix C, Table C.1. The corresponding literature suggests that the data provided by the manufacturers was not obtained for extreme conditions of operation.

As for this study, the approach using data acquired from literature was selected as the means of modelling the I_h spectrum. Selecting this approach was on the basis that the resulting I_h model would be more realistic. Hence, the following studies will be based on this aforementioned basis.

4.3 Modelling Methodology

After it was decided to acquire data to model the I_h spectrum to represent the PVIS, available data from the references [13], [14] and [15] was found to be satisfactory. However, the data was found to be of different ratings from different manufacturers which required additional data preparation. For modelling purposes the data was prepared so that all the inverter spectra had the same fundamental magnitudes (fundamental magnitude of a 2kW single phase inverter). To achieve this fundamental magnitude the most appropriate method for this set of data was *"data normalisation."* Following normalisation, the data was then appropriately scaled to satisfy the rating required for the study, standardised and appropriate models were developed based on three distinct methods.

4.3.1 Data Preparation

One of the pre-modelling requirements was that the data be prepared such that it can be directly compared among the manufacturers' inverter spectra. Following this preparation, the data set had to be bound by the standard emission levels, i.e. no harmonics to exceed their respective standard emission levels [7].

The harmonic magnitude from each inverter type needs to be scaled to provide an estimated representation of a 2kW inverter. It is noted that for this study, the inverter output harmonic current magnitudes were considered. Other characteristics such as efficiency, sensitivity to interferences and reliability were ignored.

Normalising the harmonic current magnitudes from each inverter type allowed a direct comparison of the harmonic emission from each type. From the modelling perspective it was deemed acceptable that less than half the total number of inverter types may exceed the I_{THD} and/or I_h magnitude recommended limits from [35], with the existence of a particular harmonic to the rating of the inverter and the manufacturer. The reason for having such a scheme is for the model to produce current harmonic magnitudes within the recommended limits and have magnitudes slightly higher than the average inverter available on the market. The method of normalising the data set was applied based on equation (4.1)

$$\bar{I}_{i,j} = \frac{\hat{I}_{i,j}}{\hat{I}_{1,j}} \cdot \frac{S_{INV}}{V_{INV}} \begin{cases} i = & \text{2,3,..,40} \\ j = & \text{1–to total } \hat{I}_h \text{ data sets (9)} \end{cases} \tag{4.1}$$

where $\bar{I}_{i,j}$ forms the normalised "i^{th}" harmonic for a 2kW system based on individual "j^{th}" manufacturer. $\hat{I}$ gives the raw harmonic magnitude for a given "j^{th}" manufacturer with $\hat{I}_{1,j}$ being the manufacturer's inverter fundamental current.

The condition for standardisation of the model was based on the individual harmonic not exceeding the standard emission levels [7]. To perform this task the individual harmonics were "*filtered*" based on the condition given in equation (4.2)

$$\tilde{I}_{i,j} = \begin{cases} \bar{I}_{i,j} & \text{for } \bar{I}_{i,j} \leq I_{i,std} \\ I_{i,std} & \text{for } \bar{I}_{i,j} > I_{i,std} \end{cases} \tag{4.2}$$

where the $I_{i,std}$ represents the i^{th} harmonic of the standard emission levels and $\tilde{I}_{i,j}$ represents the standardised data set.

The raw data set was prepared based on the normalising technique and standardised based on the standard emission levels [7]. The prepared data set is provided in Appendix C, Table C.2.

4.3.2 Details of Modelling Methods

Following the preparation of data, three choices of modelling methods were proposed to represent an appropriate 2kW inverter spectrum. The three methods are:

i. A statistical approach using the 95^{th} percentile of the available normalised harmonic magnitudes from each inverter manufacturer

ii. The average value of the normalised harmonic magnitudes from each inverter manufacturer

iii. Selecting a suitable harmonic magnitude from the normalised harmonic magnitudes of each inverter manufacturer/spectrum

Based on the outcome from the above methods, the final model needs to satisfy the standard harmonic current emission levels [7] for both individual and the total harmonic distortion percentage. Hence, the models proposed from the three methods will be further reviewed.

4.3.3 Modelling Method Using Statistical Approach based on 95^{th} Percentile

The modelling method based on the application of statistical 95^{th} percentile allows assumptions to be made on the characteristics of available data. The assumptions made relevant to this study in addressing the 95^{th} percentile model are:

i. The raw data from the manufacturers does not contain any extreme condition data, i.e. data from a rare combination of operating conditions for a given manufacturer and rating

ii. The individual harmonic magnitude presented by each manufacturer for the given rating (Appendix C, Table C.1) is close to the mean value of a normal distribution sampled taken over the respective inverter manufacturers for the given rating

iii. The raw data provided in Appendix C, Table C.1, allows for a marginal error in the harmonic data taken from every inverter rating and manufacturer when referred to the mean magnitude, for example, errors such as measuring instrument resolution and harmonic magnitudes based on inverter operating condition

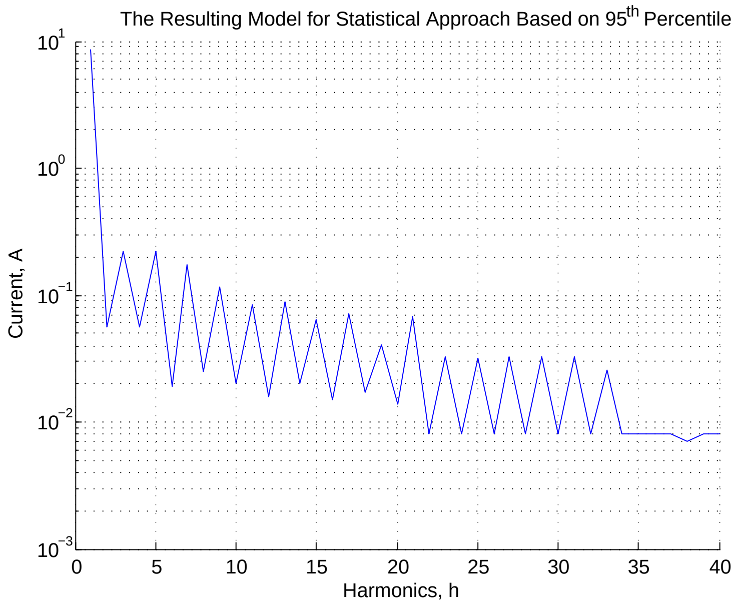

Figure 4.1 Resulting current harmonic magnitudes based on the statistical approach based on 95^{th} percentile

Based on the above assumptions that the data set could contribute a marginal error of approximately 5%, the 95^{th} percentile was found to be an appropriate method to study.

The use of existing tools such as Excel[1] and methods proposed in reference [47], was utilised to perform this analysis. The resulting model based on the statistical method of 95^{th} percentile is given in Figure 4.1.

4.3.4 Modelling Method based on Average Harmonic Magnitude

Following the statistical 95^{th} percentile method, this study proceeds to represent a modelled magnitude for a given harmonic which has the least deviation from a possible magnitude representing the harmonic current. Hence, the sum of the squares of the deviation from a possible magnitude for the harmonics based on the observed

[1]Excel–Microsoft®Office Excel 2003 SP1, Part of Microsoft Office Professionals Edition 2003, Copyright©1985–2003

manufacturers is given by equation (4.3) [48].

$$S = \sum_{j=1}^{n} (\tilde{I}_{i,j} - I_{i,m})^2; \qquad i = 2, 3, ..., 40 \tag{4.3}$$

where $I_{i,m}$ represents an arbitrary magnitude and "S" represents the sum of the squares of the deviation from $I_{i,m}$. In order to present the best possible magnitude for a given harmonic the derivative of "S" with respect to $I_{i,m}$ is equated for minimum error, given by equation (4.4),

$$\frac{\partial S}{\partial I_{i,m}} = 0 = \sum_{j=1}^{n} -2(\tilde{I}_{i,j} - I_{i,m}) = -2\left(\sum_{j=1}^{n} \tilde{I}_{i,j} - nI_{i,m}\right) \tag{4.4}$$

Having the square of the deviation minimised from the equation (4.4), it is possible to represent an acceptable magnitude for the individual harmonic. The acceptable magnitude is presented by equation (4.5) as the average value, given by $I_{i,avg}$.

$$I_{i,m} = I_{i,avg} = \frac{1}{n} \sum_{j=1}^{n} \tilde{I}_{i,j}; \qquad i = 1, 2, 3, ..., 40 \tag{4.5}$$

The resulting variation of the inverters for 3^{rd}, 5^{th} and 7^{th} harmonics and the standard deviation for the range of harmonics under study are presented in Figure 4.2. Figure 4.2 shows a relatively high standard deviation in the low order harmonic range ($2 \leq h \leq 15$) compared to $h > 15$, where the standard deviation decreases. Additional details of the standard deviation and variance are provided in Appendix C, Table C.3.

Based on the analysis, using equation (4.5), an I_h model based on averaging can be proposed. The average harmonic magnitude is presented in Figure 4.3.

4.3.5 Modelling Method Based on Selecting an Existing Harmonic Magnitude

Following the averaging method in modelling the I_h spectrum, the method of selecting an existing magnitude from the normalised data was studied. This method proposes to study the data set by observing the magnitudes of each harmonic from

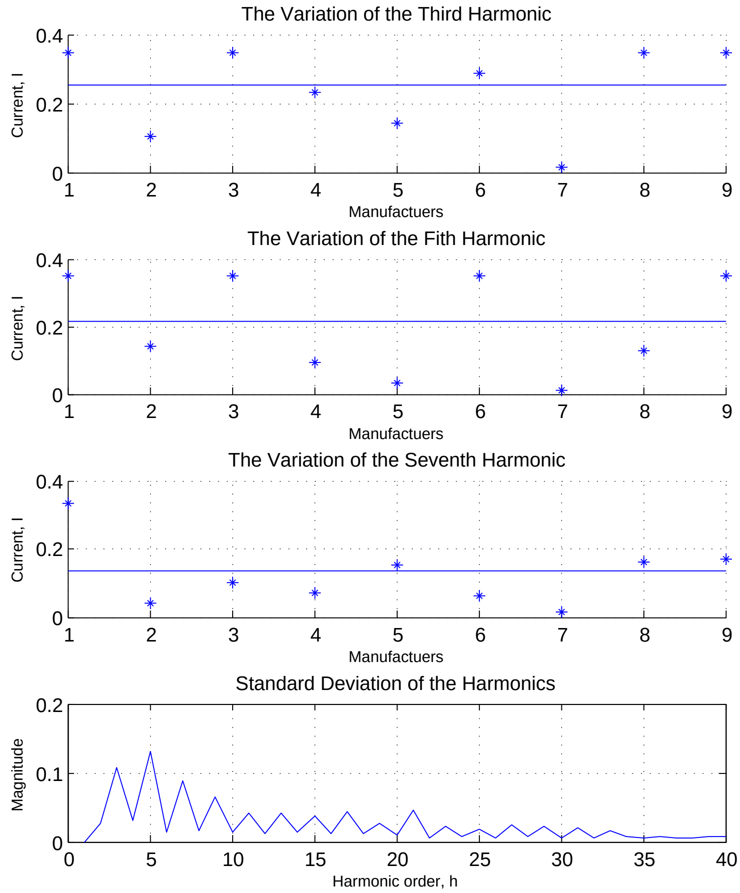

Figure 4.2 The variation in 3^{rd}, 5^{th} & 7^th harmonics and the resulting standard deviations for the observed range of harmonics in the study

all manufacturers. The highest magnitude harmonic from each manufacturer was exempted as this may lead to pessimistic results. The order of selecting the highest magnitude was from 2^{nd} highest followed by 3^{rd}, 4^{th} and 5^{th} highest harmonics until undesirable characteristics (such as significant number of zero magnitude harmonics) influence the model, from each standardised inverter spectrum.

This analysis revealed that the representative harmonics from the gradual increase in selection order of high magnitude, introduced significant amount of "*null-magnitude*" harmonics in the full spectrum. For a typical I_h spectrum model to have a null-magnitude harmonic from such a limited data set, requires all the manufacturers to exhibit null-magnitude for the same harmonic. Hence, based on selecting harmonic

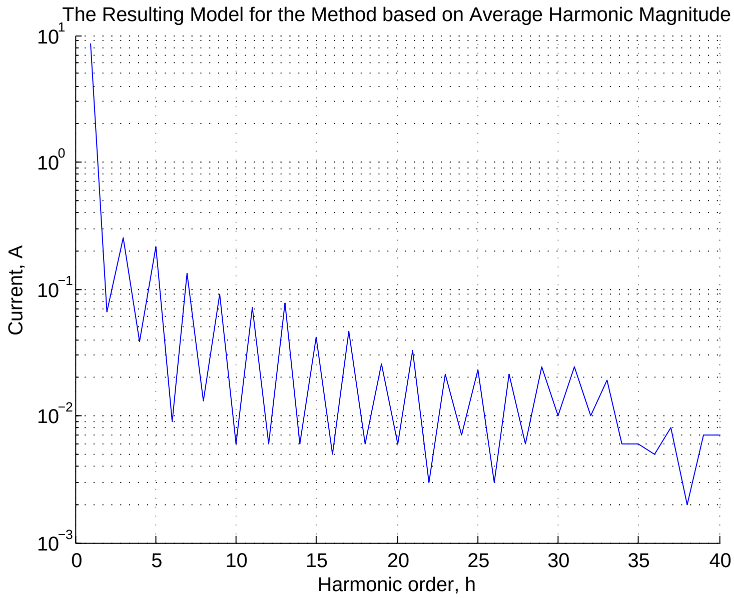

Figure 4.3 Resulting current harmonic magnitudes based on the average harmonic current magnitude among the observed manufacturers

magnitude criteria, it is believed that a significant amount of null-magnitudes may not reflect a typical I_h spectrum. The outcome of selecting distinct high order harmonics to represent the I_h spectrum is provided in Figure 4.4. Figure 4.4 shows that second highest magnitude with no null-magnitude harmonics, while beyond the third highest magnitude the null-harmonics starts to appear within the spectra. Existence of null-magnitude harmonics being an undesirable feature, this result has demonstrated that not all spectra have a common harmonic to be of null-magnitude. Hence, the second highest magnitude is preferred over the other magnitudes in representing a typical spectrum based on this method.

4.4 Proposed Model

From the observation of the proposed methods, after satisfying the individual harmonic magnitudes based on the standard emission levels, the model is required to meet the I_{THD} limit for it to become fully acceptable. Since the I_{THD} is a more

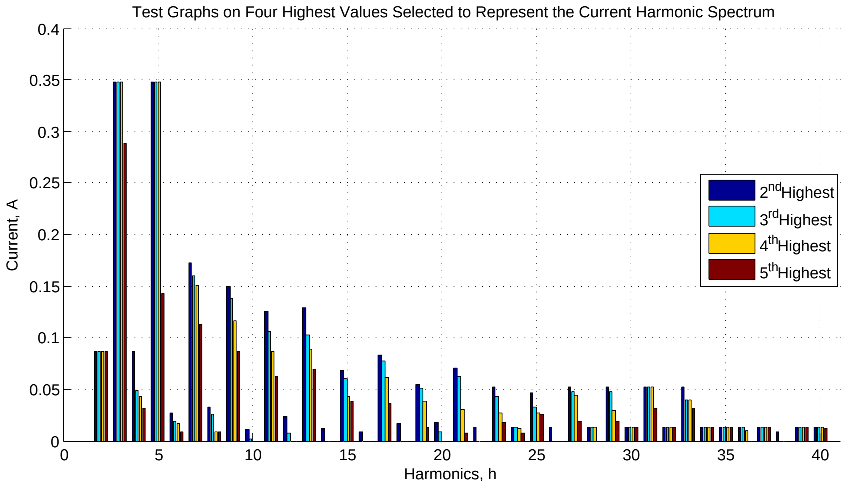

Figure 4.4 Current harmonic magnitudes based on selecting the highest magnitude method

complex term and incorporates the contribution from all harmonics, the magnitude of I_{THD} will be calculated for the modelled harmonic spectrum rather than applying the aforementioned techniques of modelling.

The I_{THD} calculated based on the modelled harmonic magnitudes was approximately 4.3%, 7.8% and 7.1% for average, 95^{th} percentile and selecting the 2^{nd} highest magnitude model respectively. The I_{THD} can be observed to be relatively low in the average model and comparably high in the 95^{th} percentile and the 2^{nd} highest magnitude model. In trying to represent the I_{THD} close to the standard limit such that the magnitudes are not too conservative, the magnitudes were adjusted such that the models are bound by the standard limit for I_{THD} of 5% [7]. Hence, the adjustment of the average model was believed to exceed its individual harmonic current limit while adjusting for I_{THD}. From the 95^{th} percentile and 2^{nd} highest magnitude methods, the model representing the second highest magnitude was believed to have the least adjustment in satisfying the I_{THD}. On this note, the most appropriate method to represent the PVIS among the studied proposals was selecting the second highest magnitude method. The selected model to represent the PVIS units harmonic current spectrum is shown in Figure 4.5, together with the unadjusted harmonic spectrum

Please see print copy for Figure 4.5

Figure 4.5 Harmonic current magnitudes of a representative 2kW inverter and recommended emission limits from [7]

and the standard current harmonic emission levels [7]. The I_h spectrum of Figure 4.5 shows that most of the low order harmonic current magnitudes from the representative inverter are well within the recommended limits. In relation to modelling, Figure 4.5 also reveals that adopting the standard harmonic limits as the magnitudes to represent the required model would have not reflected the true acceptable penetration levels of the PVIS, leading to an overly pessimistic result. Thus, the model developed using the 2^{nd} highest value from the available data was selected to represent the required PVIS model. The individual harmonic current magnitudes of the selected model are given in Table 4.1.

Harmonic, h	I_h **(Amps)**	**Harmonic** h	I_h, **(Amps)**	**Harmonic** h	I_h **(Amps)**
2	0.061	16	0.006	30	0.009
3	0.245	17	0.058	31	0.037
4	0.061	18	0.012	32	0.009
5	0.245	19	0.039	33	0.028
6	0.013	20	0.013	34	0.009
7	0.121	21	0.050	35	0.009
8	0.023	22	0.009	36	0.009
9	0.106	23	0.037	37	0.009
10	0.008	24	0.009	38	0.006
11	0.088	25	0.033	39	0.009
12	0.017	26	0.009	40	0.009
13	0.091	27	0.037	**THD**	**4.999**
14	0.008	28	0.009		
15	0.048	29	0.037		

Table 4.1
Modelled Harmonic Current Emission Spectrum of a Representative 2kW Inverter

4.5 Limitation on I$_h$ Manufacturer Data

One of the limitations was the availability of inverter manufacturers harmonic data for the I_h spectrum. It is believed that the more contributions from different manufacturers, the better representation of a "typical" I_h model (PVIS unit). In the process of modelling the I$_h$ spectrum, data was extracted from a conference publication organised by European Union (EU) PV Conference on Photovoltaic Solar Energy Conversion [13][14]. As the technology implemented in the inverter and the filter systems are advancing over time, the ability to keep a track of all I_h spectra from the major manufacturers is an impossible task. For this reason the true reflection of the I_h model of PVIS is limited in this context.

4.6 Chapter Summary

This study has proposed several methods of modelling the harmonic current spectrum of the PVIS. The proposed models were then compared to each other (with the aid of standard harmonic current requirements) on the basis of proposing an optimistic representation of a PVIS for this study.

It should be noted, that the modelling of I_h is purely based on the magnitude. An extension to this study would be to include the phase diversity of the harmonics during the aggregation of inverters for the purpose of determining the acceptable penetration level of LV PVIS. In selecting the harmonic magnitude alone and summing the harmonic magnitudes without diversity, on aggregation would mean a worst case scenario. The acceptable penetration levels of LV PVIS from this case would be a optimistic result, however introducing I_h phase diversity would mean the results may in turn be pessimistic. The study of I_h phase diversity is an additional study and can extension to this work.

Among the proposed models, selecting the 95^{th} percentile value for the typical PVIS model did not exactly reflect the inverter harmonic emissions due to the limited amount of data in this study. In addition, the use of the average value was believed to possibly lead to an underestimation of the aggregated emissions within the system. Also considered was the acceptable harmonic current (I_h) emission magnitudes from the relevant standards, however this was deemed inappropriate as it would mean that all manufactured inverters would be on the boundary of exceeding their harmonic current limits. The most appropriate method for this particular set of data among the investigated methods for determination of the representative 2kW inverter harmonic emissions was found to be in selecting the 2^{nd} highest harmonic magnitude from the normalised data, which approximates to 85^{th} percentile. The percentile approach is an improvement on selecting the maximum value (the most extreme value typically does not suitably identify the data set), but still provides a conservative (i.e. close to worst case) approach as required for this study. The selected method has three main advantages:

i) The chances of representing an existing harmonic magnitude recorded from a measuring instrument is believed to be high,

ii) Although current magnitude does not reflect the average or the 95^{th} percentile value it still maintains a relatively high value for most of the harmonics, and

iii) The model reflects all the manufacturers' inverter current harmonic behaviour.

This section has proposed to incorporate an optimistic harmonic current spectrum to represent the residential type PVIS units. The proposed model will be incorporated within the full system model as a distorting source. Chapter 5 is based on modelling the power system and the residential load where a component of the residential load represents the PVIS as a distorting source.

Chapter 5

Medium and Low Voltage System Modelling

5.1 Introduction

In Chapter 3, the relevant standards and guidelines applicable for harmonic studies involving the application of distributed generation were proposed. A selection of these standards, available data and the data modelling techniques applied in modelling a typical current harmonic spectrum to represent the PVIS units were examined in Chapter 4. Following the proposed current harmonic spectrum model in Chapter 4, this chapter attempts to represent a adequate system model including the grid connected PVIS.

This chapter outlines the detail of the relevant fundamental properties of a typical residential power distribution system and also proposes a method to define the level of acceptance of PVIS before the threshold limits are reached. The modelling of the LV and the MV system is based on two studies:

- Modelling the LV system addresses the issues of representation of residential load, characteristics of multiple earth neutral systems in rating the neutral conductor and representing the power system components such as transformers.

For the purpose of modelling some system parameters were considered negligible, this being assumed to have no impact on the acceptable penetration levels of PVIS within the range of harmonics studied. However, these assumptions are necessary to determine the system parameters when modelling.

- Modelling the MV system adopts similar modelling techniques as for the LV system. The proposed MV system is dedicated to residential distribution, hence other types of MV customers are not included in this study. The MV system is studied from an overhead open wire distribution perspective, since this gives the highest impedance compared to other available types such as aerial bundle conductor (ABC) and underground (UG) cabling type distribution feeders. Hence, MV systems having ABC or UG cabling in full or in part would be bound by the acceptable penetration level of PVIS reached by using overhead system parameters.

5.2 Selecting a Medium and Low Voltage System

The approach in selecting an acceptable or a commonly used power system model for this study was based on using one of the available systems in reference [10]. Reference [10] proposes some of the common MV/LV power distribution system characteristics widely accepted in Australia. Adopting relevant information from reference [10], the complete system to be used in this study is shown in Figure 5.1.

The system in Figure 5.1 represents a residential dedicated power distribution system, consisting of a substation rating of 25MVA (with n-1 transformer redundancy), with 7 feeders occupying a residential area consisting of 7km overhead open wire conductors and distribution transformers rated at 350kVA ($\triangle$–Y) each with two 415V distributors. For this study the proposed types of 415V distributors are overhead open wire bare conductor (OH), aerial bundled conductor (ABC) and underground (UG)

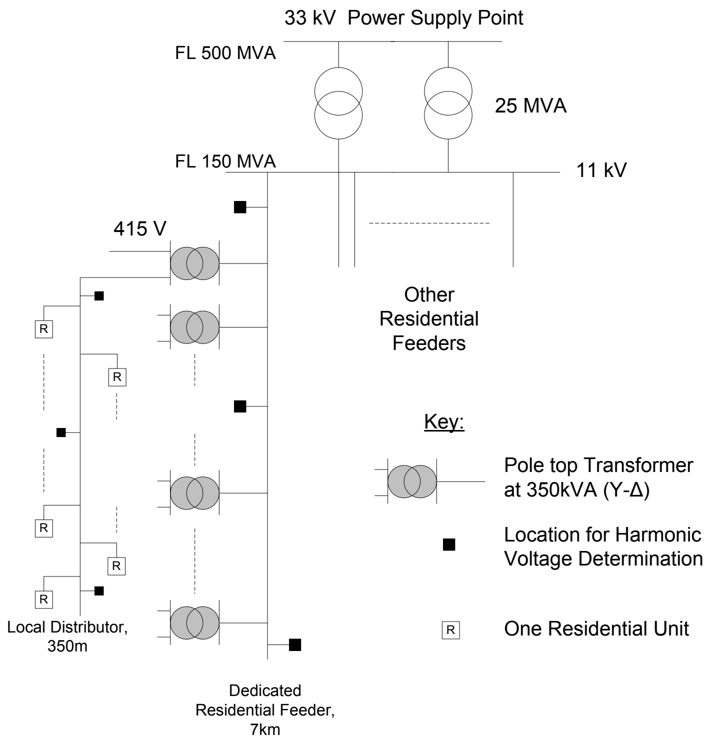

Figure 5.1 The single line diagram of the complete MV/LV system to be used in the study

cabling.

Some of the references [25] [6] [17] use residential capacitance in the complete system diagram, but in this study it is believed that the influence of residential capacitance from the residential type equipment is negligible. This concept will be further addressed in Section 5.2.5.1.

5.2.1 Transformer Details

The two distinct types of transformers used in this study are pole top transformers, also referred to as distribution transformers, and substation transformers. The physical size of the transformer largely depends on the rating of the transformer, hence being related to construction characteristics. The distribution transformers, which are of ratings approximately $<$ 400kVA for overhead distribution system are relatively small in rating and physical size compared to substation transformers. Distribution

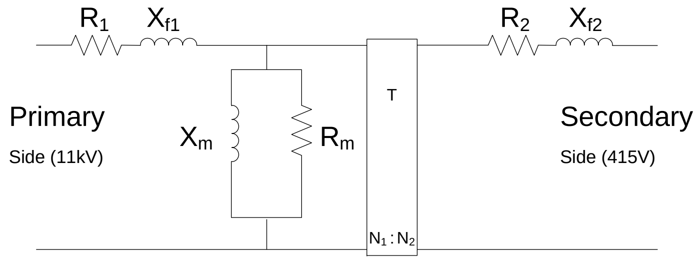

Figure 5.2 The equivalent circuit of a typical practical transformer. Ideal transformation is represented by "T" with turns ratio of N_1 and N_2 corresponding to primary and secondary side respectively.

systems with underground distributors, which have generally a lower impedance than overhead type distributors, may have higher rated transformers with pad–mounting to supply a larger customer demand. Nonetheless, the procedure for rating the transformer is based on the customer demand. On the other hand substation transformers are in the range of MVA and can be considered to have more features such as complex tap changing and cooling, amongst other features. For this study, the influence of construction features such as the cooling, tap changing, stray capacitance from transformer bushings at very high frequencies (available literature has shown that transformer capacitances becomes accountable around frequencies of approximately 5kHz [49]) and such are considered as negligible.

In trying to represent a transformer model suitable for this study, where the frequency is in the range of 100Hz to 2kHz, an equivalent representation was adopted for modification where needed from reference [12]. The equivalent representation of the transformer shown in Figure 5.2 provides some understanding of the main components. The adopted model represented in Figure 5.2 is believed to reflect a high shunt impedance (labeled as R_m and X_m) compared to the series impedance (labeled as R_1, R_2, X_{f1} and X_{f1}). Hence, the corresponding current taken in the shunt branch is minimal, provided the transformer is unsaturated. The relative magnitudes of the passive components represented in Figure 5.2 are given in Table 5.1.

Please see print copy for Table 5.1

Table 5.1
Table showing the insignificance of the typical per–unit shunt impedance of practical transformers in the range 3kVA to 250kVA [12]

Based on the aforementioned concept of high shunt impedance, the transformer can be now approximated by a series reactance for harmonic studies in the range 2^{nd} to 40^{th}. This is considered as appropriate to represent transformers in the complete system model required for this study.

5.2.2 Low Voltage System

In order to establish typical parameters for the LV system, few assumptions had to be made. The following assumptions are incorporated in the modelling of the LV system. It is believed that in making these assumptions, the accuracy of the final acceptable penetration level of this system will not be influenced.

i. The residents are tapped (connection point) directly to the distributor on an individual basis (at this stage aggregation of residential dwellings are considered negligible)

ii. The physical distance covered by the residential dwellings are considered relatively equal, hence the distance between the residential tappings on the distributor are considered relatively equal

iii. Based on the voltage drop of the distributor remaining within 0.07pu at the end of the distributor under loaded conditions, the fundamental voltage change is considered negligible for the purpose of calculations.

iv. Background distortion at LV can be considered significant to cause an impact on the penetration levels e.g. the study [37] showed the contribution from a

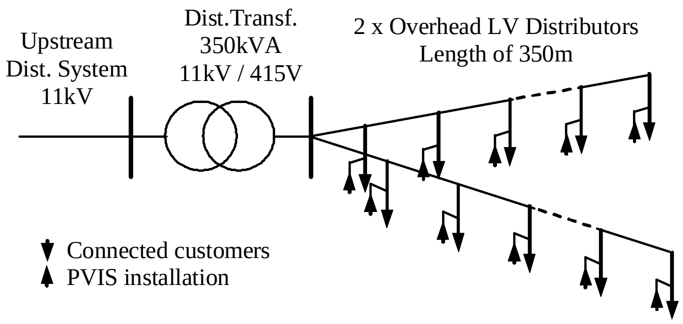

Figure 5.3 Typical LV distribution system

large building dedicated to residential use can cause radical voltage distortion at the transformer bus. Hence, background distortion is included. Details of background distortion are studied in Chapter 7, Section 7.3.3.

v. Diversity among the PVIS along the distributors has been considered insignificant, as the geographical areas covered by the two distributors are relatively small based on surface area [3]. This leads to constant sunlight intensity for all the residential loads on the studied distributors. This is true for the lower frequency harmonics but requires further investigation for the high frequency harmonics.

vi. Homogeneity is observed among the two distributors i.e. similar residential loads and PVIS characteristics.

vii. Harmonic current magnitudes from the PVIS are in proportion to the rating of the inverter system (as per Chapter 4, Section 4.3.1).

The simplified diagram of the LV system extracted from Figure 5.1 is given in Figure 5.3. Figure 5.3 shows the similar tapping feature of the residential customers on the distributors. In order to simplify the LV system calculation, the equal tapping feature and the similar load distribution character is utilised. In making use of these

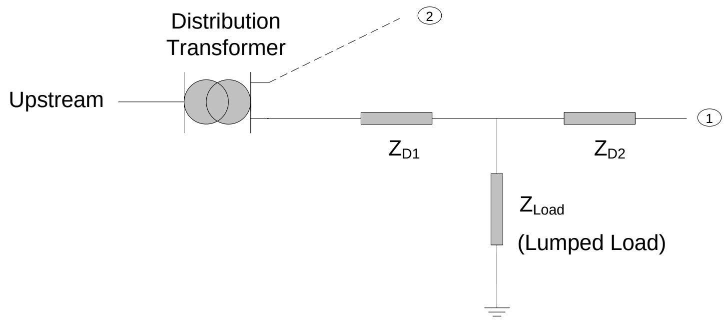

Figure 5.4 A typical method of lumping loads on the center of the distributor

features, the load on the distributor can be aggregated and presented in lump sums along the distributor.

One method is to have the lumped loads represented in the middle of the distributor as shown in Figure 5.4 and use the half length distributor to analyse the voltage along the distributor. Hence, using Figure 5.4, the voltage drop along the distributor can be estimated reasonably accurately for this study. In order to determine the fundamental voltage drop of the distributor for completeness of the study, it is also assumed that the secondary bus of the distribution transformer is kept at 1 pu (or 415V). Analysing the fundamental voltage drop along the distributor revealed that the furthest point of the distributor was within 7%. Additional details of this calculation is provided in Appendix B, Section B.3.1.

To model the LV power system in a suitable way for this study, one of the features of the model is to be able to extract the harmonic voltage along the distributor at three different points (V_{BUS}, V_{MID} and V_{END}), even though considering the fundamental voltage drop to be small. The proposed LV system model for this study, given by Figure 5.5, shows the distributor modelled with three available locations to determine the harmonic voltage, consequently lumping the residential loads at these locations. Z_{1D1} and Z_{1D2} represents the half-distributor impedances, V_{BUS}, V_{1MID}

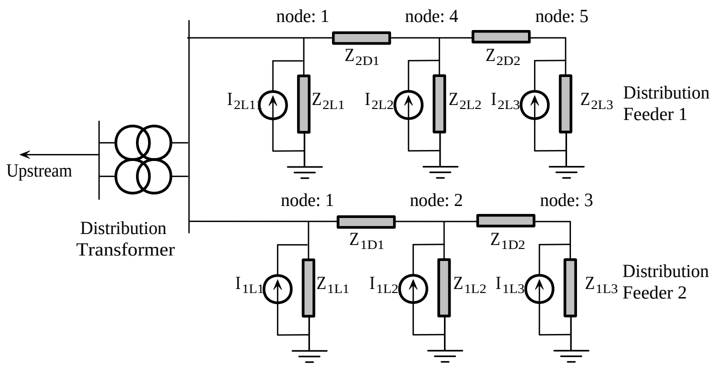

Figure 5.5 The aggregated loads on three branches, representing a typical distribution system

and V$_{1END}$ corresponds to voltage locations along the distributor and Z$_{1L1}$, Z$_{1L2}$ and Z$_{1L3}$ represents the aggregated residential loads. Aggregating the residential loads in this manner is believed to inherit errors within the calculated parameters. In trying to reduce the error of aggregation, the ratio that gives the least error was found to be when loads are aggregated in the ratio 1:2:1, corresponding to branch 1, branch 2 and branch 3 in Figure 5.5.

To determine the voltages at points along the two distributors, the conventional method of nodal analysis was applied to the circuit in Figure 5.5. The circuit in Figure 5.5 contains 5 nodes, hence the admittance matrix is of size 5x5. The nodal equation (5.1) is used to calculate the required harmonic voltages.

$$[I_{h,PVIS}]_{5\times1} = [Y_h]_{5\times5}[V_h]_{5\times1} \tag{5.1}$$

V_h is the harmonic voltage matrix representing the voltages at the monitoring points within the distributors, $I_{h,PVIS}$ is the harmonic current vector corresponding to the PVIS operating at their maximum rated current, and Y_h is the harmonic impedance matrix of the study system (including LV distributor, loads, transformer impedances and the upstream MV impedance). Each node represents the location of the aggregated, or lumped, current source models for the connected PVIS studied in Chapter 4. The resulting V_{THD} is determined by superimposing the individual harmonic voltages produce in V_h matrix. The expanded Y_h matrix is given by matrix (5.2), where Z_{st} represents the upstream and transformer impedance and other variables corresponds to Figure 5.5 directly.

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} & Y_{15} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} & Y_{25} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} & Y_{35} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} & Y_{45} \\ Y_{51} & Y_{52} & Y_{53} & Y_{54} & Y_{55} \end{bmatrix} \tag{5.2}$$

The proposed model of the LV distribution system is used in analysing the most commonly used distributor types, namely the overhead open wire bare conductor type, aerial bundled conductor type and the underground conductor type.

5.2.3 Open wire Overhead Bare Conductor type

Selecting a distributor type is normally based on geographical reasons and the economical status of a project. On this note, one the common distributor types found in residential areas of city suburbs having semi-developed areas is the overhead open wire distributor of AAC type. The parameters required for this particular overhead conductor were directly taken from the reference [50]. The parameters required are the "x_L" and the "r" per distance magnitudes corresponding to approximately $0.295\Omega km^{-1}$ and $0.266\Omega km^{-1}$ respectively. Additional calculations of open wire overhead distributors for use within the system model are provided in Appendix B, Section B.1.1.

5.2.4 Aerial Bundled Conductor type

Following the overhead conductor type distributors, the Aerial Bundled Conductor (ABC) is widely accepted in many areas of the world. ABC has a reduced impedance compared to overhead conductor, the parameters representing the distributor impedance being approximately $x_L = 0.092\Omega km^{-1}$ and $r = 0.428\Omega km^{-1}$. The impact of the mutual impedance between the bundled conductors is considered negligible for this study in ABC type distributors. The parameters for ABC type distributors were directly used from reference [50] and relevant calculations to determine the per distance absolute magnitudes are provided in Appendix B, Section B.1.1.

5.2.5 Underground Cable type

Following the OH and ABC type distributors is the underground (UG) type cabling. Though UG cabling is generally more costly than OH and ABC type distributors, there are cases where UG cabling is the preferred choice. Theses cases range from location in high natural disaster areas to populated capital cites where to use UG cabling is inevitable.

In order to model the UG cable, the parameters for fundamental impedance directly applied from reference [50] are given by approximately $x_L = 0.062\Omega km^{-1}$, $x_C = 3000\Omega km$ and $r = 0.162\Omega km^{-1}$. It is believed that data from such a cable manufacturing industry will provide a system model which is more practical and implementable. Additional calculations relating to UG cables for use in the system model are given in Appendix B, Section B.1.1.

The modelling of underground cables required for this study is based on applying the parameters to an existing model proposed by reference [12]. The model proposed by the reference [12] is based on the "pi" model. The pi model is then modified to suit this study by giving it the ability to calculate the three voltage locations as detailed in Section 5.2.2. Since the effect of capacitance in UG cabling can be more significant than for the ABC type distributors, the cable resonance frequency needs examining. The system model (based on the aforementioned parameters) has a cable resonance of above 11kHz (above 200^{th} harmonic), hence the resonant frequency has no significant impact on the harmonic analysis as required for this study. The cable

Type of Domestic Load	Electrical Characteristics
Computers	Distortive
TV	Distortive
Compact Fluorescent Lamp (CFL)	Distortive
Microwave Oven (1000W)	Distortive
Large Fridge	Distortive
Heaters (bar)	Non–Distortive
Washing Machine	Distortive
Incandescent light bulb	Non–Distortive
Audio/Video Music Player	Distortive
Air Conditioning Unit	Distortive

Table 5.2
Some of the residential equipment electrical characteristics. It should be noted that the definition of distorting equipment is relative to how much harmonic current is taken from the system in comparison to other equipment. Chapter 7 provides typical residential equipment harmonic current spectra that contributes to background distortions.

resonance was calculated based on equation (5.3).

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{5.3}$$

where f_r is the resonant frequency, C represents the cable capacitance and L represents the inductance of the cable. The representation of L and C in equation (5.3) are based on the Norton equivalent parameters of the underground cable. However, some of the literature [17] has included capacitance due to residential equipment which then in turn affects the overall resonant frequency. In such a case where the residential capacitance becomes significant, the resonant frequency was observed to be as low as approximately the 21^{st} harmonic [6] [30].

5.2.5.1 Load Characteristics and Representation

One of the complex models to derive in LV power system harmonic studies is the representation of the LV residential load. Residential loads are believed to be of high diversity in usage and are at times unpredictable in nature, unlike higher voltage customers who have an operational plan for their equipment.

As required for harmonic studies, residential loads can be divided into two main categories. They are “Distortive” loads and “Non–Distortive” loads, as shown in Table 5.2. The type of load which is of more concern in terms of harmonic voltage distortion is the distortive load. Most of the distortive loads in a residential dwelling are of the electronic-implemented power supply type. One of the accountable types of equipment of this category is the personal computer, which has a switch mode power supply (SMPS) drawing significant third harmonic. A detailed discussion on the residential distortive equipment contribution to system harmonic voltage distortions is presented in Chapter 7, and for SMPS in Section 7.4. A preliminary representation of the residential equipment from the two categories in Table 5.2 is given in Figure 5.6. Where I_h represents the harmonic current from the PVIS, I_{sys} represents

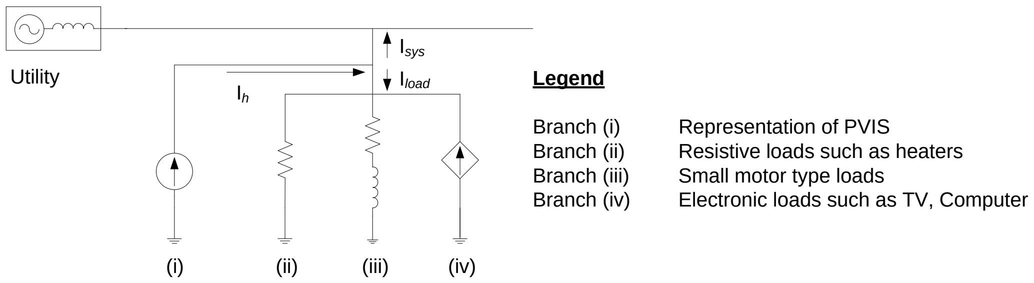

Figure 5.6 The aggregated residential loads at the distributor level

the current into the power system and I_{load} represents the current absorbed by the residential equipment.

One of the difficulties in determining the equipment category is when the operating mode of the equipment affects its current waveform. This concept is best understood with a typical example where transformer-based equipment may be considered as linear (or non distortive) provided the transformer operates without being magnetically saturated. However, at the point where the transformer starts saturating (for any given reason) the current drawn by this equipment will no longer be sinusoidal, leading the equipment category being changed to a distorting load. On the other hand, some residential equipment such as computers and resistive heaters are considered as distortive and non-distortive respectively regardless of their operating condition. It is to note that the total distortive equipment rating at a typical residential dwelling will be relatively small compared to non-distortive equipment. Therefore, a typical residential dwelling could be considered as a non-distortive unit.

Following the understanding of the categories of equipment in the residential load, the modelling of the residential load depends on making judgmental selections of equipment during the active time of PVIS. The active time of the PVIS can be considered as the time of PVIS in operational model, between approximately 10:00 am to 05:00 pm during the summer season (South-east Australia) when the days are long (see Appendix H for details of PVIS operational time). It is also believed that high rated residential equipment would impact more on the PVIS generated power. Therefore, to incorporate the loading effect of residential loads on the harmonic voltage levels within the LV distribution system a load impedance (Z_{L1}, Z_{L2}, etc.) is included in the study. The load model attempts to reflect the domestic appliances in daily use. The model was adopted on justification from [51] [52] and [53] using a passive component model with a series resistance and inductance (representing small motor type equipment), and a parallel resistor (representing heat and lighting elements), as shown in Fig. 5.7.

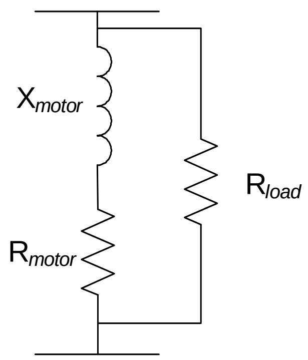

Figure 5.7 Proposed load model

The components R_{motor} and X_{motor} are determined using the locked rotor impedance as per [51] and proportioned to match the equivalent loading being applied. R_{load} is also proportioned to match the required loading assuming a residential customer load rating of 6kVA and a power factor of approximately 0.9 lagging at peak load. The proportion of the R_{load} was an extremely large impedance compared to R_{motor} and X_{motor} consequently absorbing insignificant harmonic current, hence with this understanding R_{load} was eliminated from the simulation. Skin effect, which tends to increase the harmonic impedance of resistive elements with increasing frequency, is incorporated as per recommendations in [53]. It is noted that the load impedance is relatively large compared to the power system impedance at harmonic frequencies, implying that virtually all the I_h from the inverter source flow into the system. Thus representing a residential load as a large impedance (relative to system impedance) will have a negligible effect on the acceptable penetration level of PVIS, however the load model is included for completeness. Calculations related to load modelling are provided in Appendix B, Section B.2, which shows the significance of X_{motor} and R_{motor} at fundamental frequency, resulting in extremely small fundamental current to be drawn by the load. However, this study leads to the investigation of the harmonic impedance behaviour of the load as an additional study.

Additional studies on the significance of the shunt R_{load} component in the residential load model is presented in Appendix F. The impact of the R_{load} on the system impedance with increasing load level is believed to act as a lower bounding component with increasing frequency. However, this scenario, where a substantial amount of power from the distribution transformer is taken for resistive loads at one time (from all given residential dwellings) is believed to be highly unlikely. However, for completeness of load impact within the system, an additional study was included in Appendix F.

The capacitive contribution from the residential equipment including the PVIS is considered to be insignificantly small (hence considered negligible) even when aggregated for modelling purposes. However, some of the literature [6][17] has included an aggregated capacitance parameter within the system model. Consequently, this reduces the system resonance to within the range of harmonic studied. A supportive reason for including the capacitance would be if a substantial amount of PVIS with transformer-less systems were introduced, where L-C or L-C-L type filters are present at the grid interface as discussed in Chapter 2, Section 2.3. Hence, inclusion of capacitance can be justified. Nonetheless, the mentioned literature also has addressed the drawback of these designs, as they undesirably switch off with excessive grid distortion.

5.2.5.2 Multiple Earth Neutral (MEN) Systems Characteristics

Following the understanding of the distributor types and the load model to be represented in the complete system model, a more complex concept needs to be addressed. The concept of multiple earth neutral systems in a LV distribution area. The principle of mutual impedance in overhead wires with ground return was addressed in reference [54]. Additional analysis is required for this study based on the effect of frequency on MEN systems, which leads to an understanding of the approximate neutral impedance required in the system configuration.

Due to the complexity of this work the analysis of MEN systems in LV distribution areas is addressed in Chapter 6.

5.2.6 Medium Voltage System

This section proposes a method to determine the acceptable number of LV residential type PVIS that can be connected to the grid without exceeding the MV distribution network's harmonic limits. To undertake this study a residential distribution system model was developed, which includes a residential feeder model consisting of aggregated distribution transformers represented as harmonic current sources characterised by the PVIS harmonic current spectrum, proposed in Chapter 4.

Conventional nodal analysis was used to determine the magnitudes of the individual harmonic voltages arising in the MV network due to the aggregated harmonic current emission from the grid-connected PVIS, using

$$[I_{h,aggr,PVIS}] = [Y_h][I_h] \tag{5.4}$$

where V_h represents the network wide harmonic voltage matrix, Y_h is the harmonic admittance of the system corresponding to the feeder, transformer and the upstream system impedance matrix and $I_{aggr,PVIS,h}$ represents the aggregated LV PVIS harmonic current emission.

For the purpose of calculation, the feeders are assumed to be electrically homogenous, that is, similar conductor parameters among feeders, same length feeders and each feeder comprises of similar characteristic distribution transformers. A typical medium voltage system of overhead open-wire system was adopted from reference [10] as presented in Figure 5.1. In addition to the aforementioned feeder characteristics, system wide assumptions are believed to be necessary for the calculation of the harmonic voltages around the network as follows:

i. The distribution transformers are believed to be spread out evenly along the feeder as seen in Figure 5.1.

ii. The low voltage distribution system is represented by an aggregated LV residential type PVIS.

iii. Based on the voltage drop of the feeder remaining within 0.05pu at the end of the feeder under loaded condition, fundamental voltage drop is considered negligible for the purpose of calculations (calculation is provided in Appendix B, Section B.3.2).

iv. The sun's illumination level on the MV voltage network span will be considered uneven, resulting in phase and time magnitude diversity among the PVIS on the entire network. Hence, corresponding harmonic voltages will be calculated based on related diversity factors as suggested by [10][41].

v. The harmonic current absorbed by the residential load is believed to have an insignificant impact on the MV network wide distortion levels.

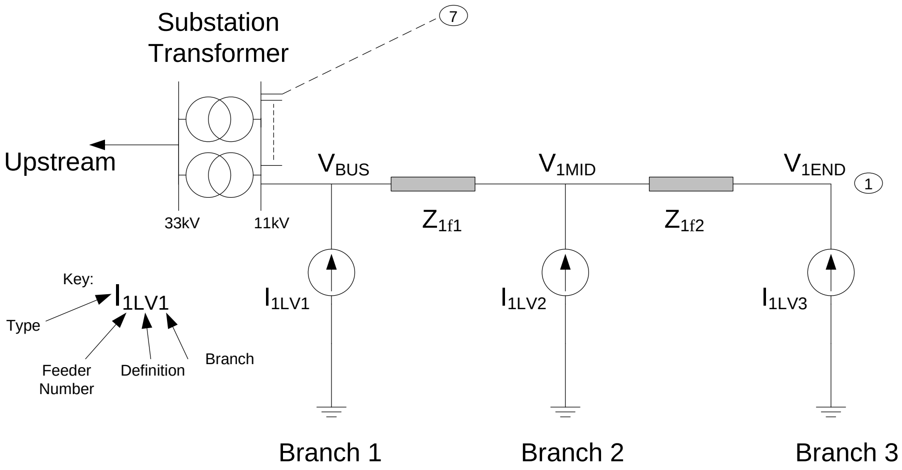

Figure 5.8 Schematic of system model including the feeder impedance and representation of the aggregated distribution transformers as harmonic current sources

On the basis of feeder homogeneity, harmonic voltage distortion levels around the network were calculated based on a lumped impedance model as shown in Figure 5.8. Where Z_{SYSh} is the transformer and upstream impedance, n_f is the total number of feeders, Z_{f1h} and Z_{f2h} corresponds to identical feeder impedances representing first and the second half of a given individual feeder respectively and I_{1LV1}, I_{1LV2} and I_{1LV3} are the lumped harmonic currents from the distribution transformers subjected to PVIS.For this study the distribution transformers per feeder are lumped at three pre–assigned locations; substation transformers busbar V_{BUS}, middle of the MV feeder V_{MID} and the end of the MV feeder V_{END}, at defined ratios of 1:2:1. The resulting harmonic admittance matrix Y_h of the system shown in Figure 5.8 is given by matrix (5.5),

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & \cdots & \vdots \\ \vdots & \vdots & Y_{33} & \cdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ Y_{n1} & \cdots & \cdots & \cdots & Y_{nn} \end{bmatrix} \tag{5.5}$$

where $n = (2\times(\text{no of feeders}) + 1)$ and V_{BUS}, V_{MID} and V_{END} are abbreviated for node 1, node 2 and node 3 respectively for a given feeder.

5.3 Determination of Acceptable Penetration Levels of PVIS

This study aims to determine the maximum penetration level of grid connected identical PVIS that may be installed based on acceptable harmonic voltage distortion levels within an LV distribution network. Penetration level (P_{level}) is defined for the purpose of this study as the ratio of the total rating of installed residential PVIS to the rating of the network service provider MV/LV distribution transformer supplying the LV distributor as follows.

$$P_{level}(\%) = \frac{n_{pvis} n_{dist} S_{INV}}{S_{TX}} \times 100\% \tag{5.6}$$

where n_{pvis} is the total number of PVIS per distributor in the LV systems, S_{TX} the distribution MV/LV transformer rating in MVA, S_{INV} the rating of the individual inverter units in MVA, and n_{dist} is the number of LV distributors connected to the distribution transformer. To determine the acceptable level of penetration the harmonic voltage distortion of the LV system is found for several values of penetration level and a comparison is made to the recommended LV and MV harmonic distortion limits [10] accordingly.

5.4 Limitation on the representation of system impedance

The ability to accurately represent a *"typical system"* using nominal characteristics, with special attention given to impedances involved in the network, are limited to the information available [10].

5.5 Chapter Summary

This chapter has proposed a model of the LV and MV system for harmonic studies in relation to a proliferation of grid-connected LV PVIS. The modelling procedure involved representation of relevant transformers, LV distributors of type overhead open wire conductor, aerial bundled conductor and underground cabling type, MV feeders of type overhead open wire and residential load representation for harmonic studies. The proliferation of PVIS and residential load was represented as aggregated lumped models, where superimposed harmonic current sources and passive components were used respectively within the system model.

Following the system modelling, the study proposes a method to determine the acceptable penetration level of PVIS in the LV system. The method of determining the acceptable penetration levels of PVIS utilises the MV/LV transformer rating as a reference and the relevant standard harmonic voltage magnitudes as the threshold limit for accepting the total power allowed to inject into the system from the PVIS.

This chapter has proposed methods and models which can predict the harmonic voltage distortion levels in LV and MV distribution system due to LV PVIS. The following chapter proposes a method for rating the neutral conductor impedance in a MEN system, thereby giving the ability to rate the neutral conductor impedance accordingly for this study.

Chapter 6

Multiple Earth Neutral Grounding in Residential Areas

6.1 Introduction

It is not a surprise to see the neutral conductor of a distribution system carrying higher current than the phase conductors, especially in harmonic analysis with zero-sequence current in the system. Neutral current generally comprises a linear load unbalance component and low order triplen harmonics arising from the magnetizing characteristics of distribution equipment, nonlinear loads and power electronics devices. Distribution systems subjected to non-linear loads (such as fluorescent lighting [55] or switch-mode power supplies in computer systems [56]) could well result in a neutral current as high as 1.73 times the phase conductor current [57]. Since residential distribution systems are of Multiple-Earth Neutral (MEN) configuration with potentially high neutral currents, it is important to understand the behaviour of the earth impedance which shares the star point neutral current from the distribution transformer.

One of the difficulties in estimating the system impedance of MEN systems with great accuracy is determining the impedance of the earth. Though the concept of impedance is well understood, the difficulty in determining a precise impedance of the earth is due to its multi-layer property which requires complex calculations. The earth's multi-layer property is a combination of unpredictable factors in terms of layer content homogeneity and geographical factors. Determining the earth impedance is complex, however understanding the behaviour of the distribution system impedances makes the work ever more challenging. As grounding is often deemed a necessity in power systems, it is important to know that there are times when grounding is not required or could be detrimental to system operation [58]. Therefore understanding the earth impedance is vital.

The impedance of overhead power lines consists of four major parts represented by (6.1) & (6.2). They are (i) the earth return impedance component ($[Z_e]$), (ii) the impedance due to the physical geometry of the conductor/cable ($[Z_g]$), (iii) impedance contributed due to internal magnetic field (internal impedance, $[Z_c]$) and (iv) admittance due to conductor contour ($[Y_g]$), [53].

$$[Z] = [Z_e] + [Z_g] + [Z_c] \tag{6.1}$$

$$[Y] = [Y_g] \tag{6.2}$$

The LV power system under study consists of a load-balanced four-wire distribution system, solidly grounded distribution transformer, segmentally grounded neutral conductor (solidly grounded in every residential unit) and the distribution feeders are structured in a bus topology. The system is used to look at the distribution of current in the neutral conductor and the "earth current" that passes through the earth impedance. The main objective of this study is to determine the effect on the neutral current due to earth impedance for the LV 4-wire power lines to assist in rating the neutral conductor impedance for harmonic studies. It is assumed that the physical distance of the phase conductors does not differ greatly within the distribution zone in the studied system and also the contribution from the earth protective conductor and skin effect is assumed negligible. Because of the complexity of this study detail analysis is beyond the scope of this thesis, hence the analysis will mostly rely on available literature.

6.2 Methodology

The fundamental concept of the earth impedance due to the overhead power lines was attempted to be solved in 1923 by Carson [54]. In order to solve the near impossible task of determining the conductivity of the actual earth, Carson [54] made certain assumptions such as replacing the actual earth by a semi-infinite solid, allowing the multi-layer property of the earth and its properties to be considered homogeneous. Carson's equations (6.3), (6.4), (6.5) and (6.6) in describing the impedance behaviour of the earth was found to be ever more complex to solve especially at the time and the limited availability of calculating tools. Nevertheless, engineers have appreciated the accuracy of Carson's work.

$$Z_s = j\omega\frac{\mu_o}{2\pi}ln\frac{2h}{r} + \omega\frac{\mu}{\pi}J_s, \quad \mu \neq \mu_o \tag{6.3}$$

$$Z_m = j\omega\frac{\mu_o}{2\pi}ln\frac{\sqrt{(h_k+h_l)^2+d^2{}_{kl}}}{\sqrt{(h_k-h_l)^2+d^2{}_{kl}}} + \omega\frac{\mu}{\pi}J_m, \; \mu = \mu_o \tag{6.4}$$

$$J_s = P_s + jQ_s = \int_0^\infty \frac{je^{-2h\lambda}}{\lambda+\sqrt{\lambda^2+j\omega\mu\sigma}}d\lambda \tag{6.5}$$

$$J_m = P_m + jQ_m = \int_0^\infty \frac{je^{-(h_k+h_l)\lambda}}{\lambda+\sqrt{\lambda^2+j\omega\mu\sigma}}cos(\lambda d_{kl})d\lambda \tag{6.6}$$

where some of the major variables are:

h, h_k, h_l - conductor height above the ground surface (physical height), the conductor configuration being shown in Figure 6.1

r - conductor radius, assumed reasonably constant throughout the conductor

d_{kl} - distance between the k^{th} conductor and the l^{th} conductor (for this study the conductor plane is horizontal, therefore d_{kl} is a horizontal distance)

Please see print copy for Figure 6.1

Figure 6.1 a) The available physical distance of the phase plane b) The complex depth and the earth return plane [8] and c) The 4-wire power system layout and their return paths

σ - is the conductivity of the earth

In light of Carson's theory, Wagner and Evans [9] showed that Carson's line (including earth impedance) could be considered as a conductor with self GMD of one unit length, located at a distance (D_{ag}, Figure 6.2) from the current carrying conductor within the earth layer. Carson's line is represented in Figure 6.2 and the corresponding impedance matrix is given by (6.7).

Please see print copy for Figure 6.2

Figure 6.2 Carson's Line, representing a unit length of an overhead power line with ground return [9]

$$\begin{bmatrix} V_{aa'} \\ V_{gg'} \end{bmatrix} = \begin{bmatrix} \bar{Z}_{aa} \bar{Z}_{ag} \\ \bar{Z}_{ag} \bar{Z}_{gg} \end{bmatrix} \begin{bmatrix} I_a \\ I_g \end{bmatrix} \tag{6.7}$$

In trying to reduce the complexity of Carson's work, Dubanton [53] [8] came up with a slightly different version to calculate the earth impedance. Dubanton introduced terms such as the (a) equivalent return distance, (b) complex depth and (c) complex ground plane. Most of the complexity in his work was in describing the conductivity of the earth at a given depth, also referred to as the *'complex depth.'* This depth is calculated for three different cases: (i) homogeneous earth case, (ii) multi-layered earth case and (iii) continuously stratified earth. Dubanton's complex calculations derive the simpler forms to represent the earth impedance given in [8]. Dubanton showed from his work that earth impedance could be calculated remarkably close to Carson's results over a wide range of frequencies, using (6.8), (6.9) and (6.10).

$$Z_s = j\omega\frac{\mu_o}{2\pi}ln\frac{2(h+p)}{r} \tag{6.8}$$

$$Z_m = j\omega\frac{\mu_o}{2\pi}ln\frac{\sqrt{(h_k+h_l+2p)^2+d^2{}_{kl}}}{\sqrt{(h_k-h_l)^2+d^2{}_{kl}}} \tag{6.9}$$

where 'p' for homogeneous earth is represented by:

$$p = \frac{1}{\sqrt{j\omega\mu_o\sigma}} \tag{6.10}$$

The system under study in Figure 6.3 represents a solidly grounded transformer i.e. ($\bar{Z}_g$) is assumed to be negligible. The self impedances are represented by $\bar{Z}_{aa}, \bar{Z}_{bb}, \bar{Z}_{cc}, \bar{Z}_{nn}$ and $\bar{Z}_{gg}$, and mutual impedances coupling with phase 'a' are $\bar{Z}_{ab}$, $\bar{Z}_{ac}$, $\bar{Z}_{an}$ and $\bar{Z}_{ag}$ with the source impedances $\bar{Z}_{as}$, $\bar{Z}_{bs}$ and $\bar{Z}_{cs}$. The primitive impedance matrix is a combination of all the coupling impedances including the contribution from the earth. All voltages are referenced to the secondary star point of the distribution transformer. The voltage matrix is given by equation (6.11).

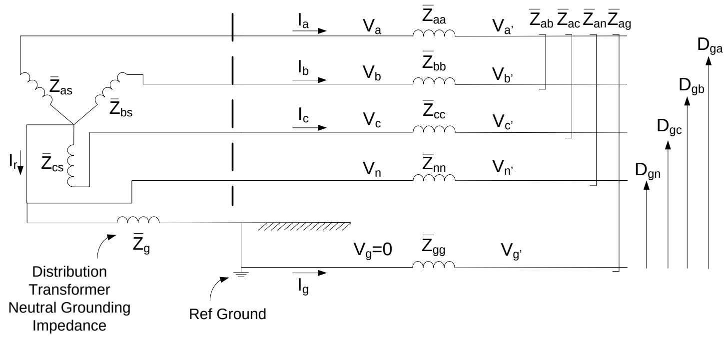

Figure 6.3 Four wire Low Voltage system under study, showing mutual impedance for phase 'a'

$$\begin{bmatrix} V_{aa'} \\ V_{bb'} \\ V_{cc'} \\ V_{nn'} \\ V_{gg'} \end{bmatrix} = \begin{bmatrix} \bar{Z}_{aa} \bar{Z}_{ab} \bar{Z}_{ac} \bar{Z}_{an} \bar{Z}_{ag} \\ \bar{Z}_{ab} \bar{Z}_{bb} \bar{Z}_{bc} \bar{Z}_{bn} \bar{Z}_{bg} \\ \bar{Z}_{ac} \bar{Z}_{bc} \bar{Z}_{cc} \bar{Z}_{cn} \bar{Z}_{cg} \\ \bar{Z}_{an} \bar{Z}_{bn} \bar{Z}_{cn} \bar{Z}_{nn} \bar{Z}_{ng} \\ \bar{Z}_{ag} \bar{Z}_{bg} \bar{Z}_{cg} \bar{Z}_{ng} \bar{Z}_{gg} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_n \\ I_g \end{bmatrix} \tag{6.11}$$

6.3 Results

In order to determine the effect of earth impedance on a 4-wire system in a harmonic study, it is best understood with the aid of sequence impedances information. Implementation of the studied system reveals that the zero-sequence impedance (influenced by triplen harmonics) exhibits approximately three times the positive or negative sequence impedance (given by Figure 6.4) of a set of 71 sq.mm bare conductors.

Since the zero-sequence impedance is a combination of phase ($\bar{Z}_{po}$), neutral ($\bar{Z}_{no}$) and earth impedance ($\bar{Z}_{go}$), this requires additional analysis on the portion that translates zero-sequence impedance into earth impedance. To be more precise, the earth impedance in the distribution network is in parallel with the neutral conductor which

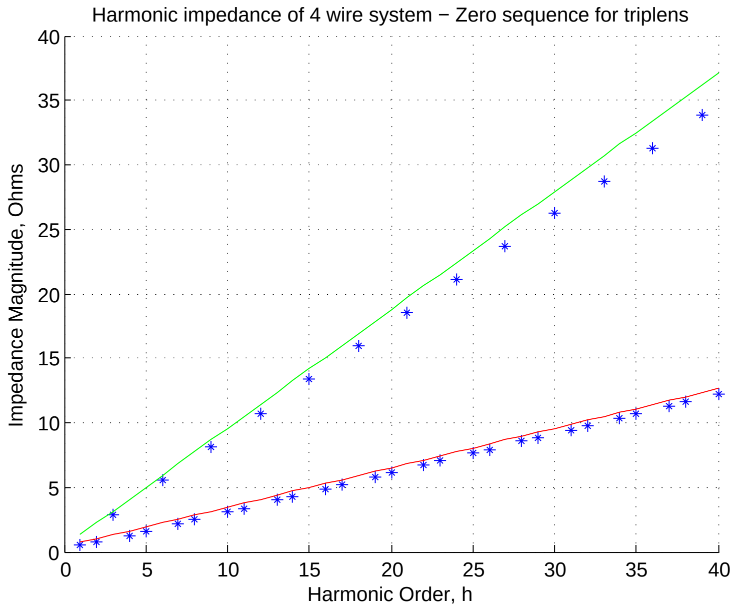

Figure 6.4 The change in zero-sequence impedance over the range of harmonics

is connected in segments (due to neutral grounding within residential units along the distributor), Figure 6.5(b).

Due to the complexity of the physical earth, studies have been conducted in determining the portion of the current that takes the ground return path, hence the main objective of this study is achieved. Reference [59] provides an equation that relates I_r (current from the neutral point of the distribution transformer (referring to Figure 6.3)) to I_n and I_g. These equations (6.12),(6.13) and (6.14) were derived based on practical data, the combination of phase and neutral impedances included in the equation making it more usable in practical situations.

$$I_r = I_n + I_g \tag{6.12}$$

$$I_n = \frac{Z_{an}}{Z_{nn}}\left(\frac{Z_{nn} - Z_{an}\mu}{Z_{nn} - Z_{an}}\right)I_r \tag{6.13}$$

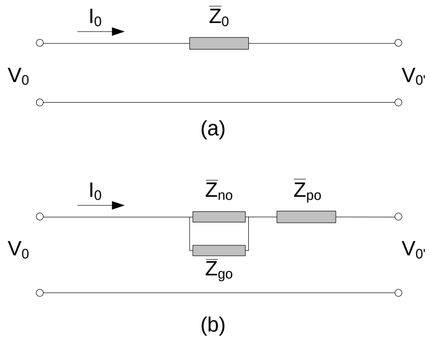

Figure 6.5 a) Zero-sequence impedance b) The earth impedance in parallel with neutral impedance

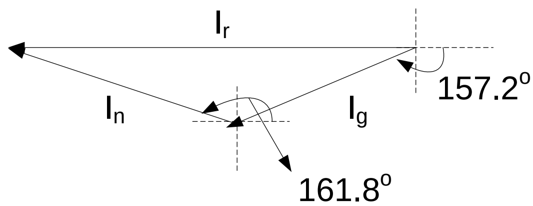

Figure 6.6 The phasor representation of the earth current and neutral current with reference to Figure 6.3

$$\mu = 1 - \left(\frac{Z_{an} - Z_{nn}}{Z_{an}}\right)^2 \frac{1}{\theta L} tanh(\theta L) \tag{6.14}$$

where μ is a factor that takes into account the number and average resistance of grounding electrodes (including terminals) along the line of length L.

From the analysis of the study presented in [59], a close relationship is shown between to the neutral and the ground current in terms of their magnitude, and the phase angle of these currents is -157.2^o for I_g and 161.8^o for I_n, as shown in Figure 6.6.

6.4 Chapter Summary

The major conclusions drawn from this study are that the influence of earth impedance in neutral grounded distribution systems is a complex combination of geographical and electrical attributes. Following the result of this study, the neutral conductor will be rated accordingly with approximately three times the phase impedance.

Secondly, the total star point current (I_r, Figure 6.3) of the distribution transformer has a substantial portion of earth return current. Therefore, to determine the neutral conductor size, it is vital to know the effective earth current.

Future work includes finding possible simpler methods to express earth impedance, and development of an accurate neutral to ground current ratio for different types of systems exhibiting geographical and electrical characteristics.

Chapter 7

Harmonic Voltage Distortion Levels for PVIS in 11kV and 415V Distribution Systems

7.1 Introduction

The representation of an inverter harmonic spectrum followed by harmonic models of the distribution network including a residential load model was presented in Chapters 4 and 5 respectively. The determination of the acceptable penetration level of PVIS however, requires the study of existing distortion levels on the distribution network due to distorting loads. The existing harmonic distortion levels in combination with relevant standards, as discussed in Chapter 3, will be used to determine an appropriate method to represent a distortion level for PVIS in both LV and MV distribution networks.

This chapter address three major issues prone to cause the system harmonic voltage levels to be exceeded due to a proliferation of PVIS. They are:

- The issue of the system's vulnerability to current harmonic spectra
- Harmonic Voltage Distortion Levels for PVIS in 415V System

  - Representing an existing distortion level for 415V system
  - Representing the upstream (11kV) system distortion in the 415V system

- Harmonic Voltage Distortion Levels for PVIS in 11kV System
  - Representing the distortion contribution in the 11kV system due to existing 415V system equipment
  - Representing the upstream (33kV) system distortion in the 11kV system

The issue of the system's vulnerability to current harmonic spectra will be addressed by proposing a method which aims to determine spectra and individual harmonics which can be considered as critical if exposed to the grid's harmonic voltage planning levels, especially upon aggregation. This study is crucial because it helps to converge the full harmonic range considered in distribution planning for harmonic analysis to only the critical spectra or individual harmonics to be investigated, and also helps to make quick judgements on determining equipment which can be harmful to the system based on their harmonic range.

A method to determine a representation for the distortion levels caused by existing 415V equipment is proposed. This method makes use of published data consisting of field measurements. Such measurements and standard guidelines will be used in determining the background distortion levels, hence, giving the ability to determine a distortion level for PVIS. The philosophy is to assume that the harmonic voltage planning level is the total allowable contribution limit from all harmonic sources both upstream and downstream depending on the point of reference.

7.2 Vulnerability of Systems to Standard Harmonic Current Spectra

This section investigates the vulnerability of the power system exposed to different harmonic spectra. In order to perform this analysis, the standard [7] harmonics were used as the inverter spectrum, providing the impact of having the inverter harmonics at the threshold levels and concurrently evaluating the potential spectrum that would influence the high penetration levels. The purpose of understanding the vulnerability of the systems exposed to standard harmonic spectra are as follows:

i. Gives the ability to estimate the limitations of harmonic spectra or an individual harmonic which can be considered critical

ii. Gives the ability to estimate the critical level of each harmonic, or the allowable level of each harmonic magnitude as a percentage of the standard value

iii. Since this study is based on the inverter standard, the vulnerability of the system would be an indication of the susceptibility of the harmonic voltage limits or planning levels [10] to standard allowable inverter harmonic limits [7]

iv Finally, the vulnerability study would provide a retrospective view of the compilation of harmonic voltage limits to account for an increase in grid connected renewable energy sources or inverter front-end systems

7.2.1 Determining Inverter Spectra for Vulnerability Study

To first determine which group of harmonic frequencies are potentially the most problematic, that is, the limiting factor on the penetration level, four types of models of 2kW inverters are initially considered based on the recommended current harmonic magnitudes in standard [7]. Three of these models are characterised by the existence of harmonics in distinct sections of the frequency spectrum and one model used the full spectrum (up to the 40^{th} harmonic). The inverter models are labelled as Low Spectrum, Medium Spectrum, High Spectrum and Full Spectrum inverter harmonic model with reference to the frequencies of the harmonics considered in each model. Each spectrum is modelled based on the maximum achievable THD without exceeding the value of 5% THD recommended in the relevant standard [7], regardless of the number of harmonics that appear in each spectrum. The characteristics of the recommended magnitudes [7] are such that the allocations of harmonic magnitudes for low order harmonics are high and high order harmonics are low. The approaches in modelling the spectra are as follows:

i. The first approach is based on the equal existence of harmonics in each spectrum (13 harmonics considered for each band) using the standard harmonic magnitudes without any alterations. This lead to a THD of $\approx 8.75\%$, $\approx 3.49\%$ and $\approx 1.29\%$ respectively for low, medium and high groups of harmonic frequencies. This method had major downfalls in optimising the spectrum. The magnitudes of the harmonics required a substantial amount of change for the spectra to satisfy the THD criteria of <5%. The low order harmonics (2^{nd}-4^{th}) needed to be reduced by $\approx 45\%$, medium order harmonics (15^{th}-27^{th}) required to be increased by $\approx 42\%$ and higher order harmonic (28^{th}–40^{th}) required an increase of $\approx 200\%$. In order to satisfy the THD, certain spectra required to increase the individual harmonics above the standard levels, hence violating the standard and as such are not acceptable.

ii To overcome the downfalls in (i.), the second approach was based on a fixed harmonic magnitude with varying harmonic number such that the maximum THD is achieved by each group of harmonics. In observing this technique, it was found that the lower order harmonics satisfies the THD with only a few individual harmonics in the spectrum. These low order harmonics revealed the significance of determining the THD for the given spectrum of harmonics. In continuing this method, a total of 5 spectra were formed that satisfies THD. Fewer harmonics in each band makes the results impractical on the basis of inverter harmonic characteristics. The THDs calculated from the 5 spectra are $\approx 4.24\%$ (spectrums 1–3), $\approx 4.97\%$ and $\approx 4.73\%$ in ascending order of harmonics.

iii. The third approach was based on both approach (i.) and (ii.) In reducing the standard harmonics (not violating the individual harmonic magnitudes) by $\approx 15\%$, three individual spectra of

   - Low Spectrum $\rightarrow 2 \leq h < 6,\ THD\ \approx 4.96\%$
   - Medium Spectrum $\rightarrow 6 \leq h < 11,\ THD\ \approx 4.97\%$
   - Low Spectrum $\rightarrow 10 \leq h \leq 40,\ THD\ \approx 4.02\%$

   was extracted, thus keeping a relatively high THD level for each band.

iv. Another approach would be to not reduce the harmonics by 15% as mentioned in part (iii) but simply let them exceed the THD

From the aforementioned methods to represent a suitable current harmonic spectrum for PVIS, the considered method for this study was choosen to be (iii) The main reason for selecting this approach was the substantially low percentage reduction in order to achieve a close required THD limit for each spectrum. The spectra modelled from the standard harmonics are shown in Figure 7.1 representing the distinct characteristics of the three spectra.

7.2.2 Determining an Effective Magnitude to Represent the Critical harmonic

In order to measure the criticality of a certain harmonic current to the corresponding voltage harmonic limit, the term *"Effective Magnitude"* will be used. The effective harmonic magnitude given by equation (7.1) is defined as the ratio of a specific

Please see print copy for Figure 7.1

Figure 7.1 The modelled harmonic spectrum from the standard current harmonic magnitudes [7] of a 2kW inverter system

harmonic order (h) by its allowable current harmonic emission level ($I_{h,\%}$) to the harmonic voltage distortion limit ($V_{h,\%}$) as a percentage. This relation looks in depth at the portion of the harmonic voltage limit to that of per unit percent of current that contributes to a given harmonic. If the effective magnitude results is a high percentage, this relates to a larger per unit voltage limit allocated to a unit harmonic current. Hence, the contribution from the harmonic source required to exceed the voltage limit is at minimal. In relation to the philosophy of the current harmonic spectrum model where the I_h is proportional to the rating of the inverter system, this would mean that few inverters can be connected to the grid before a given harmonic limit is exceeded.

$$EffectiveMagnitude_h(\%) = \frac{hI_{h,\%}}{V_{h,\%}} \tag{7.1}$$

This section has proposed a general method in identifying the critical harmonic prior to any detailed study on the penetration levels of PVIS. This method was found to be particularly useful when approaching more complex calculations involving high order harmonics.

7.3 Harmonic Voltage Distortion Levels for PVIS in the 415V System

In determining the background distortion for the LV systems, the contributing factors need to be looked at from a broad perspective. The contributing factors are:

i. Representing an existing distortion level for 415V systems

ii. Representing the upstream (11kV) system distortion

The term "Distorting Equipment" refers to as a piece of equipment which, when connected to grid (i.e. mains supply), draws a non-sinusoidal current which then has the tendency to distort the mains sinusoidal voltage waveform. Although there are many types of equipment contributing to mains distortion levels in one way or another, it is clear that some equipment harmonics stand out significantly from among the others. A collection of distorting residential types of equipment are described below, contributing to the LV harmonic distortion and its causes.

7.3.1 Representing an Existing Distortion Level For 415V Systems

Following subsection gives a generalized understanding of domestic equipment harmonic characteristic that influence the existing LV distortion. Some of the common distorting equipment found in residential premises are looked at from a harmonic point of view. Based on this understanding, an appropriate method will be proposed for determining existing distortion levels for the 415V system.

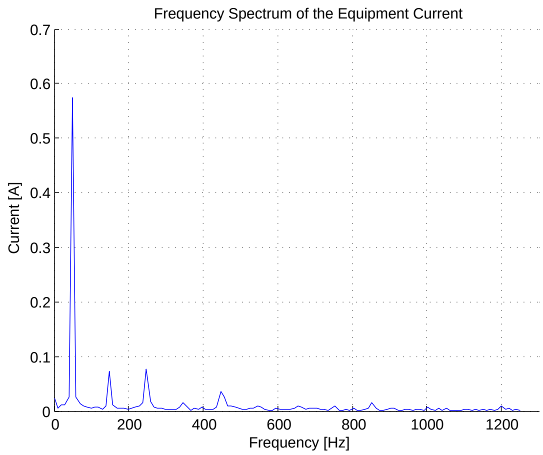

Figure 7.2 Current Harmonic Spectrum of a 36W Fluorescent Lamp

7.3.1.1 Distortion Due to existing 415V System Equipment

The determination of the exact equipment connected to a distribution transformer (over the available distributors) is a difficult task. However, it is possible to understand the most commonly used items which contribute to the voltage distortion of the 415V system. The following low voltage equipment provide an estimation of how much harmonic current is injected into the system, which then contributes to the fundamental voltage distortion.

- **Contribution from Fluorescent Lamps:** Fluorescent lamps are one of the most common forms of lighting devices used around for quite some time. The device is made up of an iron-core ballast and a lamp tube, which are responsible for the nonlinearity behaviour within systems. Reference [55] clearly shows the harmonic analysis of this device, giving the underlying current harmonic spectrum produced by this device under several equipment conditions. The harmonic current spectrum (from field measurements) of a set of two fluorescent lamp tubes at 36W are shown in Figure 7.2. The significance of this equipment is that it exhibits high magnitude odd harmonics (third harmonic

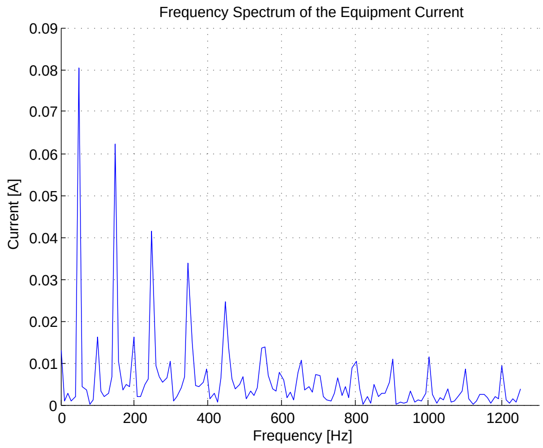

Figure 7.3 Current Harmonic Spectrum of an 11W CFL

followed by the fifth and seventh harmonic currents) and the existence of even harmonics in the current harmonic spectrum is visible at low and high frequencies.

- **Contribution from Compact Fluorescent Lamps:** Compact Fluorescent Lamps (CFL) have been introduced widely based on their distinctive characteristic of producing a high level of luminous flux compared to the conventional lighting systems (incandescent light or fluorescent lamps) for the amount of power utilised. Apart from the energy saving feature, CFL has a few drawbacks such as very low power factor (from low cost CFL) and most significantly the existence of harmonics in the current waveform . The CFL harmonic current spectrum (Figure 7.3) shows a significantly high third harmonic followed by the fifth and seven harmonics. The CFL largely contributes to similar harmonic orders in the spectrum as for fluorescent lamps. This is crucial because of the chances of these harmonics been locally additive at the PCC are high when aggregated.

- **Contribution from Switch Mode Power Supplies:** The introduction of the Switch Mode Power Supply (SMPS) brought many advantages over the lin-

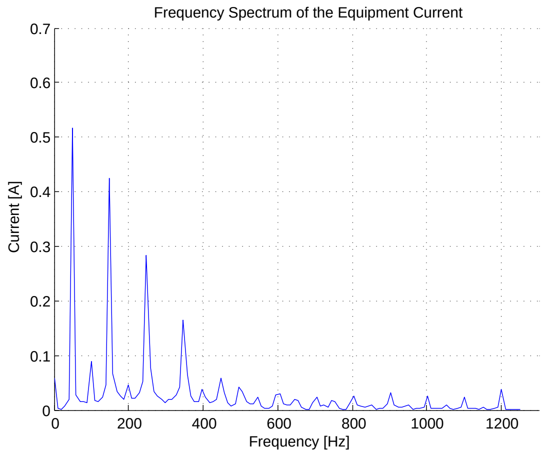

Figure 7.4 Current Harmonic Spectrum of a SMPS on a Personal Computer

ear power supply. Apart from SMPS being lightweight and physically small in size, this power supply is believed to be relatively cheap depending on the rating. The mechanism of switching the sinusoidal waveform at one voltage to the other (the switch conditions being completely on or completely off) was the basis of high efficiency in this power supply. Despite all the mentioned advantages, SMPS has the draw back of high harmonics content in its current wave from. The harmonic spectrum of SMPS (Figure 7.4) shows the visible (relatively high in magnitude) odd harmonics drawn from the mains. With the growing trend of electronic equipment use, an aggregation of such equipment in the LV distribution system is believed to cause long term problems for utilities.

- **Contribution from Microwaves Ovens:** Microwave ovens can be considered as relatively new equipment growing on the distribution system with an interesting current harmonic profile over the duration of usage. The rating of a microwave oven suitable for a typical family is considered to be a 1000W. Testing of 1000W and 1100W microwave ovens showed a steady state operation with the third harmonic current approximately 20% of the fundamental as seen in Figure 7.5. However, the peculiarity of these current harmonic profiles is the high 3^{rd} and the 5^{th} harmonics magnitude, corresponding to 50% and 20% respectively, during start-up, which could last approximately 3–5 seconds (refer to Appendix D, Figure D.1 and Figure D.2). With I_{rms} reaching approximately 4A, the combined effect of microwave ovens on the distributors during peal usage increases the chances of being the dominant cause of the mains voltage distortion of LV systems.

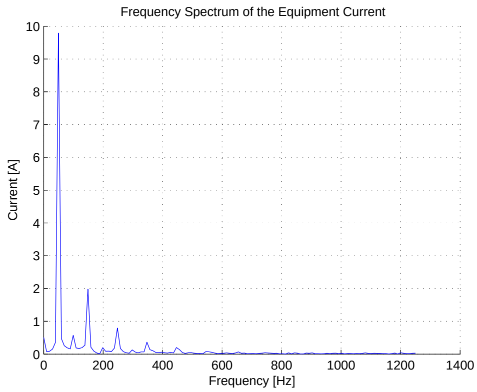

Figure 7.5 Current Harmonic Spectrum of a 1000W Microwave oven at steady state

- **Contribution from Other Domestic Items:** The harmonic contribution from other domestic equipment (such as televisions and small fridges) were found to be insignificantly small. Even so, this equipment also aggregates over the distributor hence contributing its share to the mains voltage distortion accordingly.

In determining the existing distortion in the 415V system, the difficulty lies in the large diversity among equipment usage. Clearly, the possibility of all equipment usage at one time is highly unlikely. However, there are times during a 24 hour cycle where the voltage distortion reflects high peaks within the system. Because of such diversity, to determine a value to represent the existing distortion in the 415V system

h	$L_{O,415,h}$	h	$L_{O,415,h}$
2	0.0007	22	0.0008
3	0.0026	23	0.0059
4	0.0008	24	0.0009
5	0.0052	25	0.0040
6	0.0006	26	0.0010
7	0.0060	27	0.0010
8	0.0007	28	0.0011
9	0.0023	29	0.0042
10	0.0009	30	0.0011
11	0.0069	31	0.0043
12	0.0005	32	0.0012
13	0.0069	33	0.0012
14	0.0005	34	0.0013
15	0.0009	35	0.0044
16	0.0006	36	0.0014
17	0.0058	37	0.0045
18	0.0007	38	0.0014
19	0.0049	39	0.0015
20	0.0008	40	0.0015
21	0.0008		

Table 7.1 Existing distortion $L_{O,415,h}$ levels scaled based on β_h

requires implementation of vast amount of data. Research in this area suggests, with an analysis of a significant amount of data [60], the distortion due to the harmonic current (incorporating the above mentioned equipment) on a dedicated residential feeder can be estimated by using methods such as the 95^{th} percentile which will be regarded as acceptable for this study. Typical current harmonic contributions from residential loads ($L_{O,415,h}$) can be estimated using equation (7.2) based on results from [60]

$$L_{O,415,h} = \beta_h x_{tx} h \tag{7.2}$$

where β_h is a scaling factor adopted from measurement results from actual systems ($\beta_h = 0.025$ per unit for the 5^{th} harmonic), and x_{tx} is the transformer impedance that distributes to the 415V system. The magnitudes of $L_{O,415,h}$ are given in Table 7.1.

7.3.2 Representing the Upstream (11kV) System Distortion in the 415V System

The second contributing factor is the distortion due to the upstream loading (i.e. distortion due to 11kV system). In trying to allocate an upstream distortion level, considering that the recommended planning levels (Chapter 3, Table 3.3) are reached would result in the maximum possible upstream distortion levels. For this study, considering the upstream distortion to be at the recommended planning levels would result in the least possible acceptable penetration level. In this regard, any reduction in the upstream distortion (resulting from action to mitigate the MV system distortion levels) would result in a tendency to increase the acceptable penetration levels, i.e. an improvement in the acceptable penetration levels.

7.3.3 Proposed Harmonic Voltage Distortion Levels for PVIS in the 415V System

The allocation of allowable V_h contributions from PVIS ($L_{415,PVIS,h}$) is based on the planning levels for LV systems given by Table 3.3 less the contribution from loads within the same LV distribution system and upstream. The contribution from upstream is assumed to be equal to the MV planning level as per Table 3.3. It is assumed there will be considerable diversity between the upstream and PVIS harmonic contribution, thus the “summation law” approach in accordance with [10] as detailed in Chapter 3, Section 3.2.3, is utilised. Combining the contributions from upstream ($L_{11,h}$), the LV loads ($L_{O,415,h}$) from equation (7.2) and the available LV planning level ($L_{415,h}$) using the summation law, the allowable V_h contribution from the PVIS ($L_{415,PVIS,h}$) can be determined using equation (7.3), the proposed harmonic voltage magnitudes are given in Table 7.2.

$$L_{415,PVIS,h} = \sqrt[\alpha]{L_{415,h}^{\alpha} - L_{11,h}^{\alpha} - L_{O,415,h}^{\alpha}} \tag{7.3}$$

7.4 Harmonic Voltage Distortion Levels for PVIS in the 11kV System

The harmonic voltage planning at 11kV incorporates a similar philosophy as for the 415V section of the system. The main distortion contributors for this section are:

h	$L_{415,PVIS,h}$	h	$L_{415,PVIS,h}$	h	$L_{415,PVIS,h}$
2	0.0994	15	0.1077	28	0.0872
3	0.1979	16	0.0872	29	0.3587
4	0.0394	17	0.8246	30	0.1054
5	1.0639	18	0.0872	31	0.3688
6	0.0634	19	0.5564	32	0.1054
7	0.8186	20	0.0872	33	0.1054
8	0.0614	21	0.0872	34	0.1054
9	0.2259	22	0.0872	35	0.3521
10	0.0818	23	0.6558	36	0.1054
11	1.3748	24	0.0872	37	0.3435
12	0.0624	25	0.3806	38	0.1053
13	1.2609	26	0.0872	39	0.1053
14	0.0624	27	0.0872	40	0.1053

Table 7.2 Harmonic Voltage levels in 415V systems for PVIS, reference to equation (7.3)

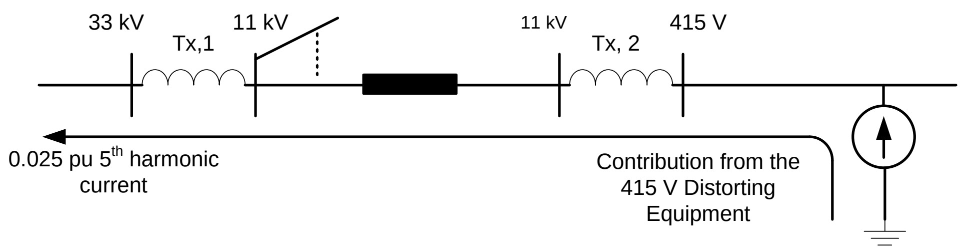

Figure 7.6 Simplified diagram of the system to show the cause of the harmonic voltage distortion levels due to 415V distorting equipment

i. Existing downstream (415V system) distorting loads

ii. The upstream (33kV system) distorting loads

Since this study is purely based on 415V residential systems, the contribution from common categories of distorting loads such as commercial and industrial loads are considered negligible for the 11kV system. Hence a simplified circuit is shown in Figure 7.6 giving a diagrammatical view of the contribution from the 415V distorting equipment within sectors of the power system under study, where Tx,1 and Tx,2 are the transformers at substation (25MVA) and distribution (350kVA) levels, respectively.

h	$L_{11,415,h}$	h	$L_{11,415,h}$
2	0.0007	22	0.0008
3	0.0026	23	0.0059
4	0.0008	24	0.0009
5	0.0052	25	0.0040
6	0.0006	26	0.0010
7	0.0060	27	0.0010
8	0.0007	28	0.0011
9	0.0023	29	0.0042
10	0.0009	30	0.0011
11	0.0069	31	0.0043
12	0.0005	32	0.0012
13	0.0069	33	0.0012
14	0.0005	34	0.0013
15	0.0009	35	0.0044
16	0.0006	36	0.0014
17	0.0058	37	0.0045
18	0.0007	38	0.0014
19	0.0049	39	0.0015
20	0.0008	40	0.0015
21	0.0008		

Table 7.3 Existing distortion $L_{11,415,h}$ levels scaled for 11kV system based on β_h

7.4.1 Representing the Distortion Contribution in the 11kV System Due to Existing 415V System Equipment

The main contribution associated with the residential distortion is considered to have originated from the 415V residential distorting loads as per previous assumptions and calculations from Section 7.3.1.1. The distorting current penetrates through to the 11kV system and is then used to determine the background distortion in the 11kV system due to the 415V existing equipment. The equation representing the harmonic contribution from the 415V system is given by equation (7.4), Table 7.3.

$$L_{11,415,h} = \beta_h x_{tx,s} h \tag{7.4}$$

where β_h is a scaling factor adopted from measurement results from actual systems ($\beta_h = 0.025$ per unit for the 5^{th} harmonic assuming that the same percentage distortion will be cause in the upstream system), and $x_{tx,s}$ is the substation transformer impedance that distributes to the 11kV system (i.e. the 25MVA transformer). For this study, it is acceptable for h in the 11kV system that their is no triplen harmonic contribution.

7.4.2 Representing Distortion in the 11kV System due to the Upstream (33kV) System

One of the factors that contributes to the allocation of distortion levels for PVIS in the 11kV system is the distortion caused by the upstream (i.e. 33kV) system. To be consistent with the 415V system, it is assumed that the upstream system is at its threshold levels defined by the harmonic voltage planning levels given in Table 3.3. This is similar to the philosophy implemented in the 415V system, providing the worst case upstream distortion levels.

7.4.3 Proposed Harmonic Voltage Distortion Levels for PVIS in 11kV System

The allocation of the allowable V_h contributions in the 11kV system from the 415V PVIS ($L_{11,PVIS,h}$) is based on a similar philosophy as the allocation of distortion levels for PVIS in the 415V System. On this note, the $L_{11,PVIS,h}$ takes into account all the possible distortions which contribute to allocating distortion levels in the 11kV system due to PVIS and is given by equation (7.5), Table 7.4.

$$L_{11,PVIS,h} = \sqrt[\alpha]{L_{11,h}^{\alpha} - L_{33,h}^{\alpha} - L_{11,415,h}^{\alpha} - L_{O,11,h}^{\alpha}} \tag{7.5}$$

Here the standard planning levels as per [10] less all the contribution from the distorting sources define a V_h planning level or a guide line for the PVIS effects in the 11kV system. On the basis that the contribution from the 11kV distorting loads are considered to be negligible, the term $L_{O,11,h}$ was not computed for this study. As for the 415V systems, the 11kV system study adopts the summation law [10] to address the issue of diversity among the distorting sources.

h	$L_{11,PVIS,h}$	h	$L_{11,PVIS,h}$	h	$L_{11,PVIS,h}$
2	0.3993	15	0.196	28	0.1245
3	1.4974	16	0.1131	29	0.4674
4	0.2292	17	1.0583	30	0.1095
5	3.1167	18	0.1245	31	0.4409
6	0.2181	19	0.8384	32	0.1095
7	2.4163	20	0.1245	33	0.1095
8	0.1984	21	0.1245	34	0.1095
9	0.5801	22	0.1245	35	0.4061
10	0.1846	23	0.8765	36	0.1095
11	2.3216	24	0.1245	37	0.3836
12	0.1285	25	0.5245	38	0.1095
13	1.7349	26	0.1245	39	0.1095
14	0.1285	27	0.1245	40	0.1095

Table 7.4 Harmonic Voltage levels in 11kV system for PVIS, referred to equation (7.5)

7.5 Limitations on Modelling the background V_{THD} distortion levels

An acceptable method of modelling the background individual V_h distortion levels was found to be inappropriate to represent the V_{THD}. The modelling of background V_{THD}, was believed to be a time consuming additional study requiring a vast amount of data.

7.6 Chapter Summary

The vulnerability study of the system to harmonic current spectra suggests a method to determine a critical harmonic from the harmonic voltage planning levels using the injection of a harmonic current spectrum into a typical grid. This study has revealed that a certain harmonic can be considered as critical due to the magnitude of the harmonic current which has the tendency to cause the corresponding harmonic voltage to reach its limit.

Following the determination of a critical harmonic in the vulnerability analysis, the study proceeds to determine the distortion level for the PVIS in the LV system. To determine a distortion level for PVIS, common residential house hold equipment harmonic current spectra were collected from practical measurements. The proposed approach involves the use of standard harmonic voltage planning levels of the power system and utilises available data on residential feeder harmonic levels to determine a distortion level for the PVIS. Certain assumptions were applied to determine a distortion level for PVIS, otherwise real-time harmonic data would have had to be extracted.

A similar concept was utilised in both LV and MV analysis to determine a distortion level for PVIS for their respective voltage levels. However, in the MV system the key concept was to use the distorting current from the LV system (generated from the distorting loads) as one of the major causes of the existing distortion and to assume there are no distorting loads in the MV system.

The proposed distortion levels for PVIS will be utilised to determine the acceptable penetration levels for PVIS in both the LV and MV system taking into account the recommended harmonic voltage limits for PVIS including the background distorting levels.

Chapter 8

Presentation of Results

8.1 Introduction

The studies presented in the previous chapters are mainly based on building a complete system and defining an appropriate methodology for the study which includes load modelling, power system representation, defining a penetration level for LV PVIS and allocation of harmonic voltages levels for PVIS including background distortion. The combination of these models in software leads to the establishment of results.

The theme of this chapter is to present and discuss the results achieved from the studies detailed in previous chapters. The results include the major outcomes of the vulnerability study of the system to standard harmonic current sources and the harmonic impact of PVIS on 415V and 11kV systems. The presentation of results are outlined as given below:

a. Results from Vulnerability of Systems to Standard Harmonic Spectra, (from Section 7.2)

b. Impact of LV PVIS on Harmonic Voltage Distortion Levels for 11kV and 415V Systems, (from Chapter 5)

i. Penetration Level of PVIS Results for 415V System, (from Section 5.2.2)

ii. Penetration Level of LV PVIS Results for 11kV System, (from Section 5.2.6)

c. Results from Additional Studies

i. Penetration Levels of LV PVIS when Shunt Load component becomes Comparable to System Impedance, (details in Appendix F)

ii. Implementation of Harmonic Voltage Limits from IEEE Std 519, (from Chapter 3, Section 3.2.1)

iii. Comparison of I_h Model with Field Measurements, (details in Appendix H)

8.2 Results from Vulnerability of Systems to Standard Harmonic Spectra, from Section 7.2

The purpose of this study is to reveal any significant characteristics of individual harmonics when calculating levels of harmonic voltages on the modelled system. The vulnerability study was conducted on four types of spectra, namely low, medium, high and full band frequencies. The critical harmonic referred to is the one that is most likely to exceed the respective harmonic voltage limit.

The critical harmonics were found to be $5^{th}, 9^{th}$ and 21^{st} for low, medium and high order frequency spectra respectively. For the full band frequency spectrum (2^{nd}-40^{th} harmonic), two models were considered, the standard model where the harmonic current spectrum is adopted from the relevant standard [7] and the harmonic current spectrum model developed from published inverter data. The results reflected similar characteristics in terms of the relevant harmonics being critical. The order of most critical harmonics in the standard model are $21^{st}, 15^{th}, 33^{rd}$ and 27^{th} and for the developed model $21^{st}, 27^{th}, 33^{rd}$ and 15^{th}, as shown in Figure 8.1. The main difference apart from the critical order is the effective magnitude (defined in Section 7.2.2) of

Please see print copy for Figure 8.1

Figure 8.1 [TOP] Three graphs represent the effective magnitude (addressed in Section 7.2.2, page 78) of selected models from the standard harmonic emission levels, and [BOTTOM] Graph represents the effective magnitude of the current harmonic spectrum from the standard [7] and the modelled spectrum

the harmonics between the two models for similar frequency spectrum. The developed inverter model gives low effective magnitude compared to the standard model, suggesting that the practical inverter system's harmonic current spectrum will have a lower tendency to exceed the V_h limit of the power system compared to the standard harmonic current spectrum. Therefore, selecting a standard harmonic spectrum to represent the inverter spectrum model as required for this study is considered to be pessimistic.

The most critical spectrum among the three developed spectra is the medium spectrum. The significance of this spectrum was the large effective magnitude corresponding to the 21^{st} harmonic which would have a tendency to reduce the penetration levels. Testing the generic (standard harmonic magnitude spectrum) and the harmonic model developed in Chapter 4, which was based on published data, also agreed with the result that the 21^{st} being the crucial harmonic when investigating the system subjected to extensive number of inverter units. Even though the medium frequency spectrum resulted as being critical, it is suggested to study the full range of harmonics in order to understand the impact of non-linear PVIS systems on the power system because of the significant difference in effective magnitude between the standard model and the developed model.

8.3 Impact of LV PVIS on Harmonic Voltage Distortion Levels for 11kV and 415V Systems, from Chapter 5

One of the major areas studied was on allocating harmonic voltage distortion limits to the PVIS. The standards related to harmonic voltage distortion provide a guideline on total harmonic voltage planning levels contributed from all equipment in the system. In order to calculate the harmonic voltage distortion limits for the PVIS, a methodical approach has been discussed in Section (7.3.3 and 7.4.3). The results of the harmonic voltage distortion limits to be used at 415V and 11kV systems as allowable harmonic voltage distortion limits for PVIS are shown in Figure 8.2. The results suggests that the allowable distortion levels are tighter for even harmonics and higher order harmonics. This agrees with the philosophy of the standards on harmonic voltage planning levels in [10]. Hence, with the appropriate background, distortion levels shown in Figure 8.2 can be utilised in determining the acceptable penetration levels for 415V and 11kV systems.

8.3.1 Penetration Level of PVIS Results for 415V System, (from Section 5.2.2

) The results presented in this section are based on the typical system characteristics discussed in Chapter 5 for the 415V system, (summarised in Table 8.1) for determining the acceptable penetration levels for PVIS.

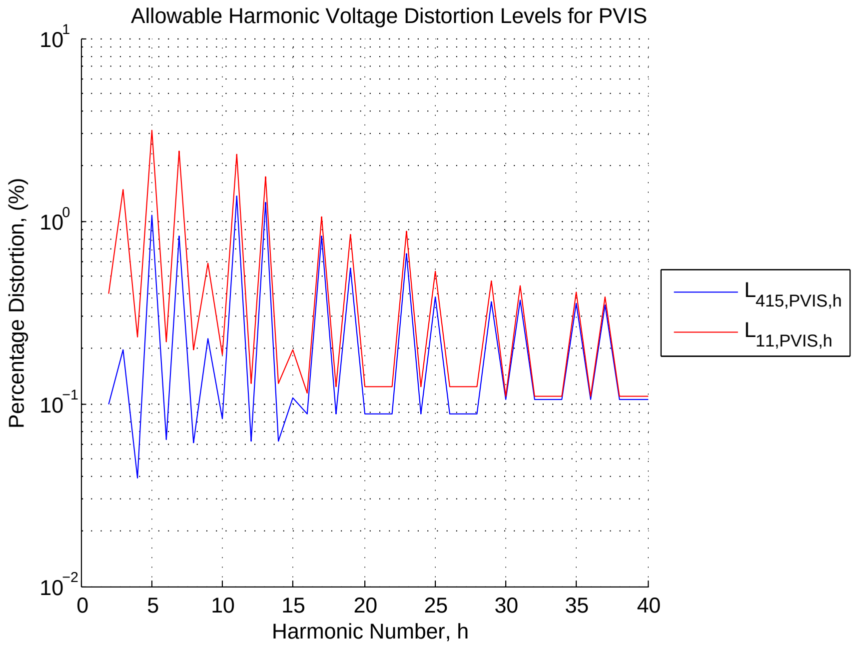

Figure 8.2 The allowable harmonic voltage distortion levels for PVIS

Total Number of Customers:	41
Transformer Loading Level:	70%
Load rating:	6kVA
Distribution Transformer Rating:	350kVA
Distribution Transformer Reactance:	5%
Distributor Length:	350m
No of Distributors:	2
Inverter Rating:	2kW

Table 8.1 LV System Parameters

The acceptable penetration level is based on two factors; V_{THD} within recommended limits and individual voltage harmonics within recommended limits. The acceptable penetration level for PVIS installations is relatively high when considering only V_{THD} but is considerably lower when based on the individual harmonic voltage levels. It was found that, with no harmonic contributions from LV loads considered, the 21^{st} harmonic exceeds the limits recommended in [10], suggesting an acceptable penetration level of approximately 9.7% for OH type distributor, as seen in Figure 8.3. These results show that it is necessary to investigate the individual voltage harmonics for significance before the acceptable penetration level can be decided.

Please see print copy for Figure 8.3

Figure 8.3 Penetration levels as a percentage of distribution transformer rating of PVIS on LV systems with limiting voltages as harmonic voltage planning levels [10] with common types of low voltage distribution feeders

When the distortion due to LV loads is included, as shown in Figure 8.4, a significant impact on the acceptable penetration levels is apparent. The acceptable penetration level of the 21^{st} harmonic is reduced to approximately 4.5% on OH, 8.6% on ABC and 10% on UG distributors, corresponding to 7, 15 and 18 PVIS units as the critical number for the LV system not to exceed its voltage harmonics at the most susceptible location at the end of the distributor. Figure 8.5 shows the penetration levels along the distributor, indicating the significance of the penetration levels from the bus location to the end of the distributor.

Additional studies were conducted on the effects of reducing the harmonic current emissions of the PVIS, i.e. reducing the I_h magnitudes. It was assumed reduction in emission levels could be achieved practically through improving filtering or inverter switching techniques. Reduction of I_h results shows that the system with the lowest impedance distributors will be allowed to have approximately 25 units of PVIS, if

Please see print copy for Figure 8.4

Figure 8.4 Penetration levels as a percentage of distribution transformer rating of PVIS in LV systems with harmonic voltage limits derived from [10] inclusive of background distortion levels ($L_{415,PVIS,h}$) with common types of low voltage distribution feeders

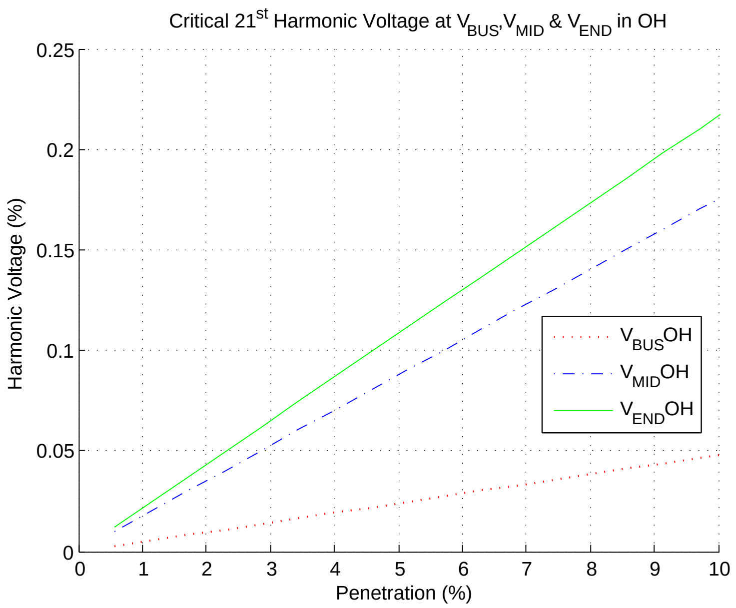

Figure 8.5 Penetration levels along the overhead type distributor

I_h Reduction (%)	OH(%)	ABC(%)	UG(%)
10	4.57	9.14	10.86
20	5.14	10.29	12.57
30	6.29	12.00	14.29
40	6.86	13.71	16.57
50	8.57	16.57	19.43

Table 8.2 The effect of I_h Reduction on Penetration Levels Based on $L_{415,PVIS,h}$

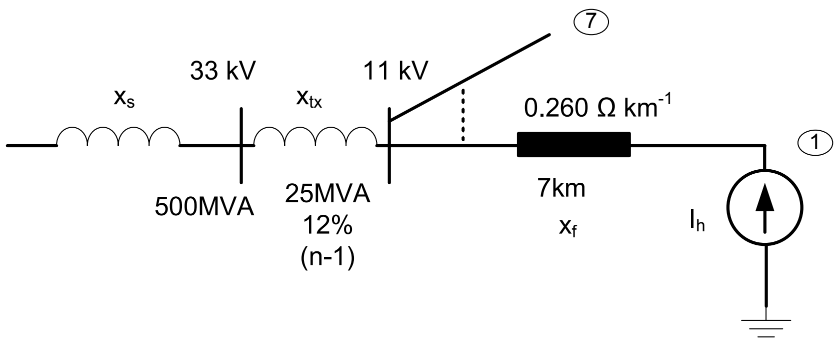

Figure 8.6 Estimating the acceptable penetration level of PVIS, based on estimated 5^{th} harmonic parameters

current harmonic emissions are reduced by 30%. The significant improvements seen over the studied distributor types are provided in Table 8.2.

Additional details on the number of PVIS units exceeding the penetration levels for harmonic voltage limits based on $L_{415,h}$ and $L_{415,PVIS,h}$ are provided in Appendix G.1.

8.3.2 Penetration Level of LV PVIS Results for 11kV System, (from Section 5.2.6

) The results of the harmonic voltage calculations using the methods and models outlined in Chapter 5, Section 5.2.6 and Chapter 7, Section 7.4 were completed using various simulation packages, based on system details given in Chapter 5, Figure 5.1 and Figure 5.8. However, a simple method for estimating the acceptable penetration levels of harmonic current sources (PVIS) is proposed by equation (8.1) based on Figure 8.6.

V_h^* Reference	Acceptable Penetration levels	
	% (units)	% (units)**
$L_{11,h}$	28(49), 34(59)	32(56), 38(67)
$L_{11,PVIS,h}$	18(32), 23(41)	20(36), 27(47)

(1) * – Harmonic voltage to compare
(2) ** – Including diversity as suggested [10][41]
(3) 40^{th},31^{st} – Format of results based on two distinct harmonics

Table 8.3
The summary of results representing the four comparison conditions in determining the acceptable penetration levels of PVIS

$$\begin{aligned}
V_{h,std} &= 5.1\% \rightarrow 5^{th} harmonic \\
I_{h,inv} &= 2.82\% \rightarrow 5^{th} harmonic \\
P_{max} &= \frac{V_{h,std}}{(x_f + x_{tx} + x_s) I_{h,inv}} \\
&= \frac{0.051}{(0.05 + 0.06 + 0.0268)0.0282} \\
&= 268\%
\end{aligned} \tag{8.1}$$

where $V_{h,std}$ is the recommended harmonic voltage planning level [10], $I_{h,inv}$ represents the modelled inverter's harmonic current magnitude, P_{max} represents the maximum acceptable penetration level based on system parameters and x_f, x_{tx} and x_s are the corresponding impedances of the system.

The derived acceptable penetration levels of PVIS exclusive of background distortion revealed a significantly higher number (a difference of approximately 17 units of PVIS) compared to inclusive of background distortion levels, as seen in Table 8.3. Hence, inclusion of background distortion is essential when determining the acceptable penetration levels of PVIS in MV systems.

The acceptable penetration level study of PVIS without diversity but including the background distortion in the MV system has shown that the 40^{th} harmonic exceeds the limits at approximately 18% acceptable penetration levels (approximately 32 PVIS units) and the limiting odd harmonic was the 31^{st} harmonic, exceeding the harmonic voltage limit at 23% acceptable penetration level (approximately 41 PVIS units), as shown in Figure 8.8. However as suggested in [10], the MV harmonic dis-

Please see print copy for Figure 8.7

Figure 8.7 Penetration levels of LV PVIS as a percentage of distribution transformer rating on MV system with limiting voltages as harmonic voltage planning levels [10] on long overhead open wire distribution feeders

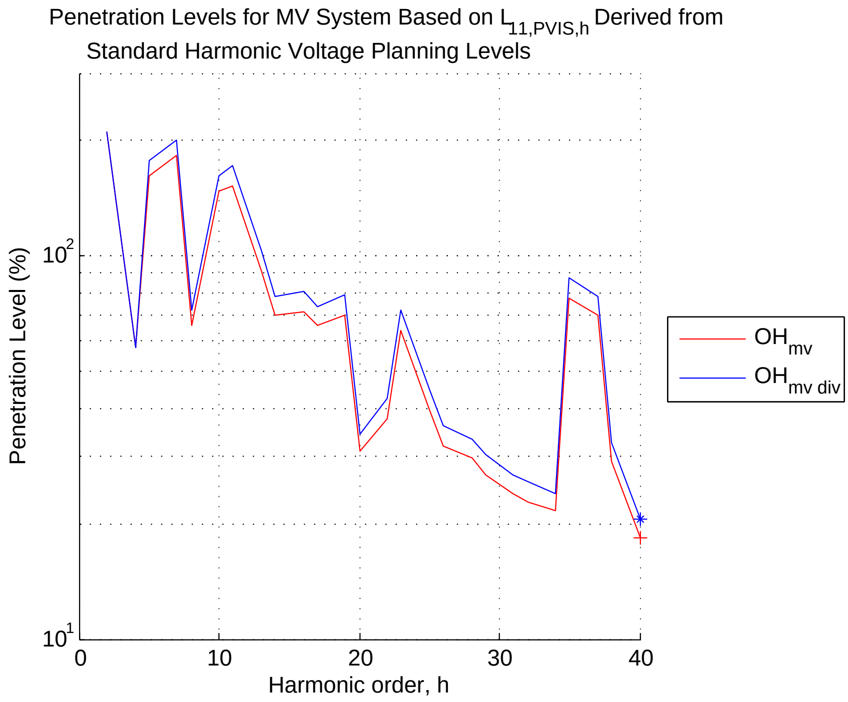

Figure 8.8 Penetration levels of LV PVIS as a percentage of distribution transformer rating on MV system with limiting voltages as harmonic voltage limits given by Chapter 7, Table 7.4 on long overhead open wire distribution feeders

tortion levels are better expressed with phase and time magnitude diversity among the distortion contributors. The acceptable penetration level study of PVIS with diversity including the background distortion in MV system has shown that the 40^{th} harmonic exceeds the limits at approximately 20% acceptable penetration levels (approximately 36 PVIS units), and the limiting odd harmonic was the 31^{st} harmonic, exceeding the harmonic voltage limit at 27% acceptable penetration level (approximately 47 PVIS units), as shown in Figure 8.8. Individual harmonic magnitudes corresponding to the number of acceptable PVIS units are provided as additional detail in Appendix G, Table G.4.

Additional studies were conducted on the effects of reducing the harmonic emissions of the PVIS, i.e. reducing the I_h magnitudes. It was assumed this could be achieved through improving filtering or inverter switching techniques. For a reduction of I_h

I_h Reduction (%)	$L_{11,h}$ Based		$L_{11,PVIS,h}$ Based	
	I_h	I_h^*	I_h	I_h^*
10	37(31)	42(35)	26(20)	29(32)
20	42(35)	47(40)	29(22)	33(25)
30	48(40)	54(45)	33(26)	38(29)
40	56(47)	63(53)	39(30)	44(34)
50	67(56)	76(63)	47(36)	53(41)

(1) * – Including Diversity among the Distortive Sources [10][41]
(2) $31^{st}(40^{th})$ – Results based on two distinct harmonics

Table 8.4 The effect of I_h Reduction on Penetration Levels (%)

by 30% the results showed that for the 40^{th} harmonic, the limits were exceeded at approximately 29% acceptable penetration levels (approximately 51 PVIS units), and the limiting odd harmonic was the 31^{st} harmonic, exceeding the harmonic voltage limit at 38% acceptable penetration level (approximately 67 PVIS units) with inclusion of background and appropriate diversity as given by Table 8.4.

Overall results of the study illustrated that a reduction by 30% in the line current of the PVIS can significantly decrease the harmonic voltage distortion levels in medium voltage systems. However, the acceptable penetration levels of PVIS are significantly influenced by the background distortion levels contributing to the medium voltage system distortion.

8.4 Results from Additional Studies

The following sections will review the major findings from additional studies. Additional studies are used as an extension to this work, which helps to broaden the understanding of the main stream study. The additional studies are related to studies detailed in Appendix F, Chapter 3, Section 3.2.1 and Appendix H.

8.4.1 Study 1: Penetration Levels of LV PVIS when Shunt Load Component "R_{load}" becomes Significant Relative to System Impedance, (Appendix F

) Additional studies, looked at from the penetration of PVIS point of view, were based on the effect where the shunt impedance in the load model becomes comparable to system impedance. The results shown in Table F.1 suggests that the change in loading level shifts the critical harmonic from mid-spectrum to a low spectrum harmonic. On observation, at approximately 40% loading level of the LV system, the critical harmonic changes from 21^{st} (as before) to 3^{rd} followed by 4^{th} harmonic due to the change in loading level. Comprehensive details of this study are available in Appendix F.

8.4.2 Study 2: Implementation of Harmonic Voltage Limits from IEEE Std 519, Chapter 3, (Section 3.2.1)

An additional study was conducted using the IEEE std 519 [11] harmonic voltage limits to determine the penetration levels of the PVIS. A similar philosophy applied to the IEC standard [38] was conducted for the IEEE standard to determine the penetration levels of the PVIS. The proposed method for determining the background distortion is not applicable to systems where several upstream voltage levels share the same harmonic voltage planning levels. Hence there is a difference in harmonic management approach between the two standards IEC [38] [10] and IEEE Std [11]. The ability to determine the background distortion levels in IEEE Std 519 [11] implemented system requires additional studies, which were not performed as it is beyond the scope of present work.

In the application of the IEEE standard as the harmonic voltage limit, the selected current emission levels based on the standard AS 4777.2 [7]. The reason for selecting the AS standard as the current emission level was based on the understanding that the current limits suggested by the IEEE standards [21], [33] and [11] are believed to

Please see print copy for Figure 8.9

Figure 8.9 Penetration levels of PVIS on 415V systems with harmonic voltage limits derived from IEEE std 519 [11].

be very closely related to the AS standard [7]. On this note, the results for the penetration levels of PVIS on LV systems are presented in Figure 8.9. The significance of this result is the THD limit being the critical factor and overall penetration levels for individual harmonics are observed to be higher than the IEC standards results. This is due to the proposed limits of 3$\%$ for I_h and 5$\%$ for THD. The harmonics which showed comparatively low acceptable penetration levels of PVIS within the spectrum are 21^{st}, 27^{th} and 33^{rd}. Therefore, these harmonics can be considered as in need of special attention when planning harmonic management in distribution systems exposed to a substantial amount of PVIS.

8.4.3 Study 3: Comparison of I_h Model with Field Measurements, Appendix H

As apart of sensitivity study, field measurements from a 30kW solar panel were used to monitor the behaviour of the harmonic current injected into the system. The monitored current was compared with the standard harmonic current emission levels [7] and model developed in Chapter 4. Additional details regarding the current harmonic

Please see print copy for Figure 8.10

Figure 8.10 Comparison of the standard [7], field measurement and developed model

spectrum from the field measurements are given in Appendix H.

The current harmonic spectrum of the field measurement is presented in Figure 8.10. On observation of the measured harmonic spectrum and the modelled harmonic spectrum, the 10^{th}–22^{nd} harmonics can be considered as reasonably similar in magnitude. However, Figure 8.10 reveals that some harmonics exceed the current harmonic standard emission levels [7] as discussed in Section 3.3.1. The harmonics which exceed are the 3^{rd}–9^{th} and 23^{rd}–27^{th}, which is undesirable and requires special attention for particular field applications.

Through observation of Figure 8.10, the model meets closely with the measured current harmonic magnitudes around mid–harmonic ranges (around the 20^{th} harmonic). A similar range of harmonics can be observed from Figure 8.1, which represents the critical harmonic range in exceeding the voltage harmonic limits of the system. Therefore, the model can be considered to meet closely with the critical harmonics from this measured current harmonic spectrum.

8.5 Chapter Summary

The study based on determining the most critical harmonic (or a range of harmonics) with the standard harmonic voltage planning levels revealed that the most critical harmonics are around the mid-range (around 20^{th} harmonic). Among the mid-range harmonics, the 21^{st} harmonic exceeded with the greatest magnitude, hence being the most critical harmonic amongst all investigated. Following the study on the standard current harmonic emission levels, this study continued to expose the system to the modelled current harmonic spectrum. The results revealed were similar both in critical harmonic range and on an individual harmonic basis.

Overall results from the penetration levels of PVIS on 415V systems illustrated that a particular harmonic (21^{st}) has the tendency to exceed the acceptable voltage harmonic limits on LV systems, rather than overall V_{THD}, regardless of the distributor type. However, the distributor type used on LV systems has a significant effect on the acceptable penetration levels due to the large variation in harmonic impedance. When comparing the common distributor types, UG was found to be the distributor type which allowed the highest acceptable penetration of PVIS based on harmonic voltage levels.

Overall results from the penetration levels of 11kV system study illustrated that particular harmonics (namely, 31^{st} and 40^{th}) have the tendency to exceed the acceptable voltage harmonic limits on 11kV system. Therefore, these can be considered as critical harmonics when considering the acceptable penetration levels of residential type PVIS.

Additional studies on the load type showed that the shunt component has a significant effect on the penetration levels, especially when determining the critical harmonic. This is due to the shunt resistive component limiting the total impedance of the system (total impedance includes the upstream, transformer, distributors and the load).

A further investigation was conducted using the IEEE Std 519 [11] to determine the acceptable penetration levels of PVIS with the possibility of the standard been implemented in a distribution network. The results revealed significantly high penetration levels for overall individual harmonics and THD compared to the IEC standard. The critical factor was observed to be THD with the IEEE standard [11].

The investigation which compared the current harmonic model with field measurement showed significant similarity in the mid-range (around 20^{th}) harmonics. Accepting the marginal errors involved in the field measurements and the modelling technique, the developed model was considered as acceptable for this study.

Chapter 9

Conclusions and Recommendations for Future Work

9.1 Introduction

The literature review given in Chapter 2 has shown that, though specific case studies on residential districts subjected to photovoltaic systems are available as publications, a harmonic study specific to the proliferation of LV PVIS investigating the acceptable penetration level of PVIS is required. The contribution from such studies is important in the harmonic management of the power system.

This study has adopted typical models from available literature and modified these models (where necessary) to meet the requirements for this study. The proposed models for the system studies included development of power systems representation, representation of a typical residential load during the operating hours of PVIS and a model to represent the harmonic current spectrum of the inverter. These models have been found to be reasonably accurate for harmonic study purposes based on simple calculations and revealed by relevant literature, where marginal errors (applicable to certain calculations) appear to be insignificant in the overall results.

The low voltage systems (415V system) modelled for this study were based on the three most common distribution feeder types, overhead open wire systems, aerial bundled systems and underground systems. The medium voltage system (11kV system) model comprises seven residential feeders of overhead type open wire systems, where by reflecting the highest impedance among the three most common distribution feeder types, and a substation transformer (with n-1 redundancy).

In order to represent a practical current harmonic spectrum for the inverter system, several spectra from existing inverters have been considered from available literature. In modelling the current harmonic spectrum suitable for this study, statistical methods in conjunction with the existing spectra were utilised. A current harmonic model which is believed to be a pessimistic model has been proposed. Comparing the modelled spectrum with field measurements confirmed the validity of the model.

9.2 Penetration levels of residential type photovoltaic systems on 415V Systems

The acceptable penetration levels of residential type photovoltaic inverter systems in 415V systems were found to be more restricted by individual harmonics than THD. Therefore, the results for individual harmonics are considered to be of more concern than for THD. The conclusion presented below is based on the study detailed in Chapter 5, Section 5.2.2.

The acceptable penetration levels of residential photovoltaic inverter systems connected to the power system has been shown to be approximately 5%, 9% and 10% for overhead open wire, aerial bundled and underground type distribution feeders, respectively. With the possibility of better filtering, I_h could be reduced by 30% giving acceptable penetration levels of photovoltaic installations of approximately 6%, 12% and 14% for overhead conductor, aerial bundled conductors and underground cabling of LV distribution feeder types, respectively. Correspondingly, the acceptable penetration levels for such a reduction in I_h leads to a distribution of approximately 22kW, 42kW and 50kW of power along their respective LV systems. The results are based on the inclusion of significant contributions from background distortion from both upstream and LV system distorting loads.

9.3 Penetration levels of residential type photovoltaic systems on 11kV Systems

From the knowledge of 415V system results on penetration levels of photovoltaic systems, a typical 11kV system was studied based on the worst case distribution feeder type i.e. overhead open wire system, detailed in Chapter 5, Section 5.2.6.

The possibilities of implementing a customer level mitigation technique such as better harmonic filtering was studied on an overhead open wire feeder system to understand the impact of acceptable penetration levels of residential type photovoltaic inverter systems in medium voltage distribution systems.

To allow the calculation to be performed, a medium voltage distribution system was modelled and sufficient background distortion level was derived. This model was based on the aggregation of distribution transformers represented as superimposed harmonic current sources for frequency domain calculation.

The acceptable penetration levels from the residential type photovoltaic systems injecting their full rated current in the LV system was shown to be approximately 21% for the most significant even harmonic (40^{th}) and 27% for the most significant odd harmonic (31^{st}) corresponding to approximately 72kW and 94kW of total power subjected from PVIS, respectively. The study also considered the possibility of better filtering at the customer level. Provided the filters were capable of reducing the current harmonic magnitude by 30%, the acceptable penetration levels of residential type photovoltaic systems reached 29% for the 40^{th} harmonic and 38% for the 31^{st}

harmonic corresponding to approximately 100kW and 133kW of power, respectively.

The results are based on the inclusion of reasonable contributions from background distortion from both upstream and downstream systems and considering a significant amount of diversity among the individual systems over the network.

9.4 Additional Studies

Study 1, Results in Section 8.4.1: An additional study was conducted to investigate the effect of the significance of the shunt component impedance (R_{load}) in the load model relative to the system impedance. The acceptable penetration levels of LV PVIS was based on the IEC standard harmonic voltage limits. The results from this study revealed that the acceptable penetration level of LV PVIS was based on an individual harmonic rather than the THD. The results provided in Section 8.4.1 and in Appendix F also revealed that for changing loading level of the transformer, the critical harmonic that limits the penetration level also changed accordingly. This indicates that the critical component (individual harmonic, namely 21^{st}) is no longer a constant for all transformer loading levels as observed when the load impedance was insignificant relative to the system impedance from the previous studies, Section 9.2 and 9.3.

Study 2, Results in Section 8.4.2: An additional study was based on the IEEE standard as a guide on harmonic voltage levels in distribution systems. The acceptable penetration levels of residential photovoltaic systems observed was substantially higher with the IEEE standard limits compared to IEC recommended standard harmonic voltage limits. The high penetration levels of PVIS observed using the IEEE standard indicates that the harmonic voltage limits proposed are more lenient in comparison to the more restricted limits from the IEC. The harmonic voltage spectrum observed with the application of the IEEE standard had a significant difference in shape to that of IEC standard. Consequently, the critical component responsible for limiting the acceptable penetration levels of residential type photovoltaic inverter systems was found to be the THD for the IEEE standard and an individual harmonic for the IEC standard.

Study 3, Results in Section 8.4.3: For the purpose of comparing the developed model, field measurement data from an installed PVIS was obtained. The comparison results revealed a difference in magnitude of some harmonics between the developed model and field measurement. This difference could be due to the difference in inverter manufacture (implemented inverter technology) and/or the characteristics of the measuring instrument used to monitor the reading. However, the comparison results between the mentioned spectra revealed a close magnitude within the mid-harmonic range described in Section 8.4.3, which also includes the critical harmonic (21^{st}). This result has shown that the developed model (with the methodology in obtaining the model) is reasonable to represent a typical harmonic current spectrum from a PVIS for practical purposes.

9.5 Recommendations for Future Work

This study has proposed methods, models and results for medium and low voltage distribution systems. A proposed expansion for this work will be the analysis of the harmonic impact caused in the high voltage system due to the proliferation of residential type distribution feeders in the low voltage system exposed to such renewable sources. In this study it will be vital to include large distorting loads on the network, incorporated in the existing distortion levels. Hence, the background harmonic distortion levels will need to accommodate and aggregate a variety of harmonic spectra.

This study has implemented power distribution systems only of residential type. With the growing trend of distortion levels caused by various equipment, an area to expand this work is to incorporate the distortion levels in the power distribution network due to residential, commercial and industrial loads.

In the development of the inverter current harmonic spectrum, the available data from existing inverters were restricted to a few inverter manufacturers in the market. It is highly recommended to expand the study to include additional harmonic current spectra available in the market, which is assumed to result in a more accurate spectrum model.

Some of the available standards (namely IEC and IEEE studied standards) have suggested distortion limits and emission levels which are believed to have been released for use prior to the increase of sustainable energy sources (such as PVIS) on the network. Such limits and levels may not have fully accommodated the distortion levels caused due to PVIS. As a result, the distribution network will experience significantly low acceptable penetration levels of LV PVIS. From a standard point of view, it is important to include the distortion levels caused by PVIS when proposing distortion levels and emission levels to be used as a guideline. Hence, with the growing concern about network wide harmonic voltage limits being exceeded, the standards committees dealing with these limits need to consider the full impact of distortion caused by distributed generation.

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Appendix A

Methodology

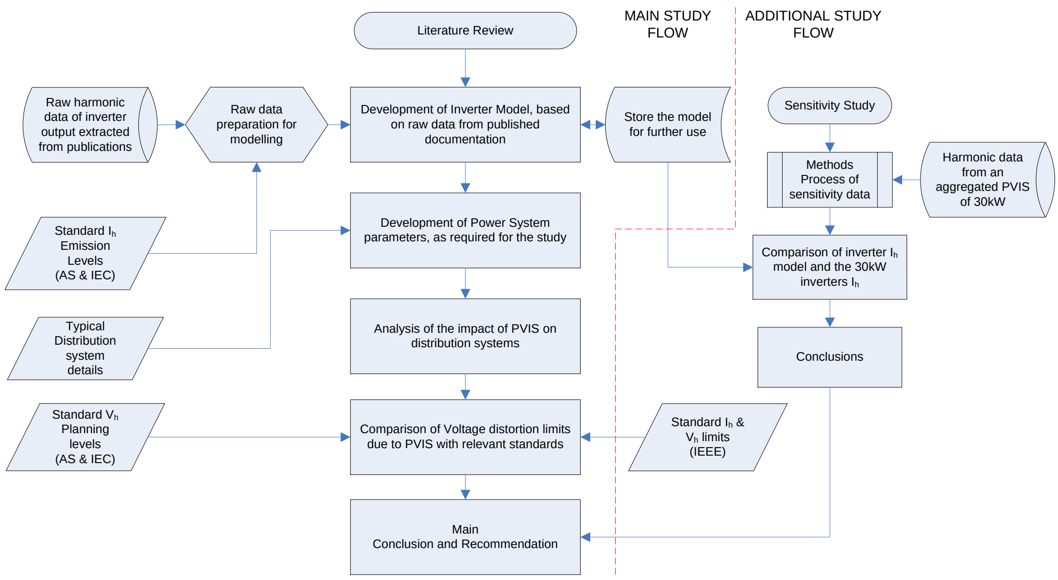

Figure A.1 A comprehensive understanding of the major building blocks in achieving the main objective of this study

Appendix B

Related Calculations

B.1 Distributor Parameter Calculations

The calculation given below indicates the absolute per unit length impedance parameters based on the conversion of the percentage impedance magnitudes from reference [50]. The LV distributors and MV feeders are calculated separately.

B.1.1 LV Distributor Parameters

Conductor Reference for OH [50]:

Code (E44), 415V, 3–ϕ, 7/1.73–7.4.5, AAC, Cu.EQU 0.1.

Given:

S_{base} = 100MVA, V_{base} = 415V $\rightarrow$ Z_{base} = 1.72×10^{-3} Ω, r = 15435.6% and x = 17142.34%.

$$\begin{aligned} r &= \frac{15435.6}{100} \times 1.72 \times 10^{-3} \rightarrow 0.266\Omega km^{-1} \\ x &= \frac{17142.34}{100} \times 1.72 \times 10^{-3} \rightarrow 0.295\Omega km^{-1} \end{aligned} \tag{B.1}$$

Conductor Reference for ABC [50]:

Code (E47), 415V, 3–ϕ, 95 sq.mm ABC, Cu.EQU 0.1.

Given:

S$_{base}$ = 100MVA, V$_{base}$ = 415V $\rightarrow$ Z$_{base}$ = 1.72$\times 10^{-3}$ Ω, r = 2487% and x = 5331.25%.

$$r = \frac{2487}{100} \times 1.72 \times 10^{-3} \rightarrow 0.4284 \Omega km^{-1}$$
$$x = \frac{5331.25}{100} \times 1.72 \times 10^{-3} \rightarrow 0.0918 \Omega km^{-1} \quad \text{(B.2)}$$

Conductor Reference for UG [50]:

Code (T54), 415V, 3–ϕ, 240 sq.mm 4 cores XLPE

Given:

S$_{base}$ = 100MVA, V$_{base}$ = 415V $\rightarrow$ Z$_{base}$ = 1.72$\times 10^{-3}$ Ω, r = 6406% and x = 3600%.

$$r = \frac{6406}{100} \times 1.72 \times 10^{-3} \rightarrow 0.162 \Omega km^{-1}$$
$$x = \frac{3600}{100} \times 1.72 \times 10^{-3} \rightarrow 0.062 \Omega km^{-1} \quad \text{(B.3)}$$

B.1.2 MV Feeders Parameters

Conductor Reference [50]:

Code (A44), 11kV, 3–ϕ, 7/1.73–7.4.5, AAC, Cu.EQU 0.1.

Given:

S$_{base}$ = 100MVA, V$_{base}$ = 11kV $\rightarrow$ Z$_{base}$ = 1.21 Ω, r = 26.033% and x = 30.136%.

$$r = \frac{26.033}{100} \times 1.21 \rightarrow 0.315\Omega km^{-1}$$
$$x = \frac{30.136}{100} \times 1.21 \rightarrow 0.365\Omega km^{-1}$$

(B.4)

B.2 Load Parameter Related Calculations

Shorthand calculation for domestic load modelling based on typical load requirements:

The proposed model is based on Figure 5.7, where the parameters are given by R_{motor} and X_{motor} and are determined using the locked rotor impedance as per [51] and proportioned to match to the equivalent loading being applied. R_{load} is also proportioned to match the required loading assuming a residential customer load rating of 6kVA and a power factor of approximately 0.9 lagging at peak load. The proportion of the R_{load} was an extremely large impedance compared to R_{motor} and X_{motor} consequently absorbing insignificant harmonic current, hence with this understanding R_{load} was eliminated from the simulation. Skin effect, which tends to increase the harmonic impedance of resistive elements with increasing frequency, is incorporated as per recommendations in [53].

– Typical load consumption: 6kVA

– Typical load pf ($\cos\phi$): 0.9

$$P_{total} = 0.9 \times 6kVA$$
$$P_{total} = 5.4kW$$
$$Q_{total} = \sin(\arccos 0.9) \times 6kVA$$
$$Q_{total} = 2.615kVAr$$

(B.5)

– Provided that motor type loads are rated relatively high compared other loads in the residential dwelling, the Q_{motor} is given by:

$$Q_{total} = Q_{motor} \tag{B.6}$$

– Typical locked rotor condition $\cos\phi$ [51]:

$$\begin{aligned} \cos\phi &= 0.32 \\ \phi &= 71.34^o \\ \tan\phi &= 2.91 \end{aligned} \tag{B.7}$$

– Therefore, for motor details

$$\begin{aligned} P_{motor} &= \frac{2.615k}{2.91} \\ P_{motor} &= 883.24W \\ Q_{motor} &= 2.615kVAr \end{aligned} \tag{B.8}$$

– Power assigned for lighting/heating ($P_{L/H}$) purposes:

$$\begin{aligned} P_{L/H} &= 5400 - 883.24 \\ P_{L/H} &= 4.52kW \end{aligned} \tag{B.9}$$

–Motor type details satisfying the suggestion in [51]:

$$\begin{aligned} Q_{motor} &= 3.615kVar \\ P_{motor} &= 883.24kW \\ S_{motor} &= 2.76kVA \end{aligned} \tag{B.10}$$

From reference to [51]

$$X_1 = \frac{V^2}{S_{start}}$$
$$R_1 = \frac{X_1}{3}$$
$$R = \sqrt{h} R_1$$

(B.11)

–Applying the above mentioned equations, the motor parameters can be determined as:

$$X_{motor} = \frac{V^2}{S_{start}}$$
$$R_1 = \frac{X_1}{3}$$
$$R_{motor} = \sqrt{h} R_1$$

(B.12)

where X_{motor} and R_{motor} are the motor representation in Figure 5.7.

Hence, the parameters for the load model represented in Figure 5.7 are given by the following equations. The base values for the per–unit calculations are S_{base} of 100MVA, V_{base} of 415V leading to Z_{base} of 0.0069Ω.

$$X_{motor} = 20.8\Omega (3020 pu)$$
$$R_{motor} = 6.93\Omega (1000 pu)$$
$$R_{L/H} = 12.7\Omega (1840 pu)$$

(B.13)

Following the determination of the individual parameters, the load needs to be placed accordingly (aggregated) in the system model. This aggregation depends on the loading level of the distribution transformer. The conclusion from this study is to consider the residential load impedance to be significantly high at fundamental frequency, hence the current drawn by the load is at a minimum. Therefore, for the purpose of harmonic voltage calculations required for this study, the residential load will have a minimal impact on the system harmonic voltage levels.

B.3 Example of Voltage Drop Calculation

B.3.1 Voltage Drop Across a LV Distributor

The voltage drop calculation example presented below is one of the ways in estimating the change in voltage at the end of a distributor exposed to approximately equally distributed loads. Figure B.1 represents a typical distribution system. The

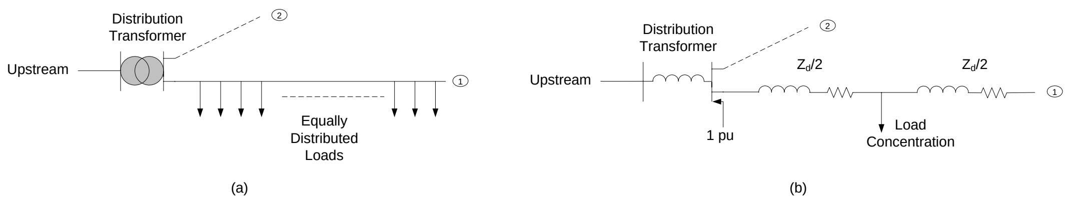

Figure B.1 (a) A typical LV distribution system and (b) Shows the impedance diagram of Figure (a)

system consists of a 350kVA transformer with two overhead open wire distributors of AAC type. For the calculation in the pu system, S_{base} was selected as 350kVA and the corresponding V_{base} at 415V resulting a Z_{base} of approximately 0.49Ω. The parameters for an AAC type conductor are approximately $x = 0.295\Omega km^{-1}$ and $r = 0.266\Omega km^{-1}$ and the distributors are 350m in length. The voltage drop estimated at the end of the distributors for a full load scenario is given by the following calculation.

$$
\begin{aligned}
V_{drop} &= \frac{1}{2} \times \frac{1}{2}\Big(\frac{(0.266 + j0.295)0.35}{0.49}\Big) \\
V_{drop} &= \frac{1}{2} \times \frac{1}{2}(0.19 + j0.21) \\
V_{drop} &= 0.07pu \qquad \text{(B.14)}
\end{aligned}
$$

The voltage drop at the end of the distributor in a worst case scenario shows approximately 7% drop from the sending end voltage. Typically, the voltage drop of such a system given in Figure B.1 is believed to be in the range of 5%–7%.

B.3.2 Voltage Drop Across an MV Feeder

Estimating the voltage drop at the end of the feeder, a similar concept is introduced as for LV distributors. For the calculation in the pu system, S_{base} was selected as 25MVA and the corresponding V_{base} at 11kV resulting a Z_{base} of approximately 4.84Ω. The parameters for an AAC type distributor are approximately $x = 0.365\Omega km^{-1}$ and $r = 0.315\Omega km^{-1}$ from Section B.1.2 and the feeders are 7km in length. The voltage drop estimated at the end of the distributors for a full load (worst case) scenario is given by the following calculation.

$$
\begin{aligned}
V_{drop} &= \frac{1}{7} \times \frac{1}{2}\Big(\frac{(0.315 + j0.365)7}{4.84}\Big) \\
V_{drop} &= \frac{1}{7} \times \frac{1}{2}(0.46 + j0.53) \\
V_{drop} &= 0.05pu \qquad \text{(B.15)}
\end{aligned}
$$

The voltage drop at the highest impedance location (end of the feeder) is approximately 5%. This is acceptable to be used in this study, hence the conductor was selected for MV feeder calculations.

B.4 Substation Transformer Impedance Calculation

S_{base} = 25MVA, V_{base} = 33kV

$$
\begin{aligned}
I_{pu} &= \frac{FL}{S_{base}} \\
I_{pu} &= \frac{500M}{25M} \\
I_{pu} &= 20pu
\end{aligned}
\tag{B.16}
$$

A fault on the primary bus of the substation draws approximately 20pu of fault current. Leading to estimate the upstream impedance to approximately 0.05 pu for the system. Since the secondary fault level is available (150MVA leading to approximately 6pu of fault current), using this fault level the transformer impedance can be determined,

$$
\begin{aligned}
\frac{1}{6} &= 0.05 + x_t \\
x_t &= 0.12
\end{aligned}
\tag{B.17}
$$

The results have shown that the transformer impedance is approximately 12% on its own base. This is considered to be an acceptable impedance for a substation level transformer.

B.5 Underground Cable Model

Figure B.2 shows the adopted underground cable model for harmonic studies applied to fulfil the requirements of being able to calculate three voltage points along a given distributor. The calculation below gives details of the capacitance of the cable presented at the three lumped branch locations given in Figure 5.5. Given that:

$$X_C = \frac{3000\Omega km}{0.35km}$$

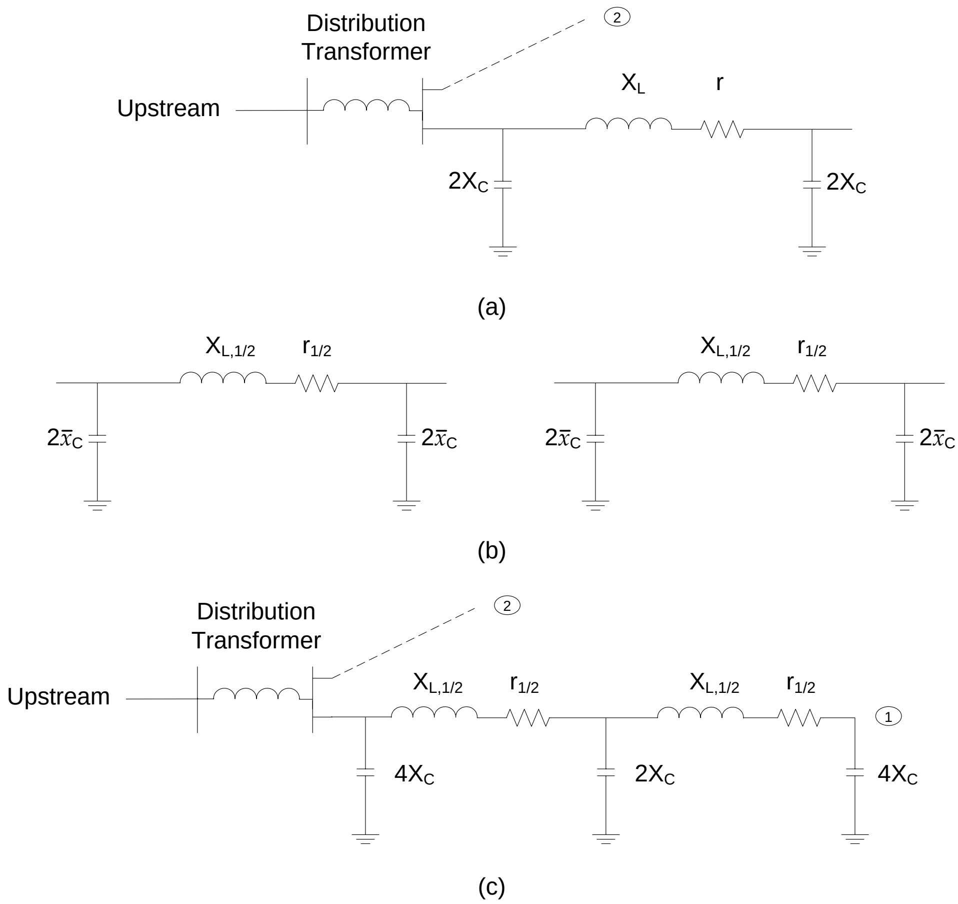

Figure B.2 (a) Adopted model to represent the UG cable (b) The selected UG model is modified to allow an accessible mid-point on the cable for harmonic voltage calculation (c) The proposed model for the UG cable to be used in this study and

$$\overline{x}_C = \frac{3000\Omega km}{(0.35/2)km}$$
$$\overline{x}_C = 2\frac{3000\Omega km}{0.35km}$$

Therefore,

$$\overline{x}_C = 2X_C$$

It is worth noting that, if the residential dwelling exhibits a substantial amount of capacitance from its low voltage equipment then the equipment capacitance needs to be aggregated and placed in the model accordingly. Based on the available literature, [25], [6] and [17] has shown that some LV networks reflect significant capacitance. Hence, the capacitive impedance needs to be accounted for in harmonic studies.

Appendix C

Inverter Data

C.1 Raw Data from Literature

Please see print copy for Table C.1

Table C.1 Raw Data from [13], [14] and [15] as published

C.2 Normalised Data, $\bar{I}_{i,j}$

Please see print copy for Table C.2

Table C.2 All inverter harmonic currents rated to 2kW and standardised to [7] , $\bar{I}_{i,j}$

C.3 Additional Results Related to Section 4.3.4

h	Variance	Standard Deviation	h	Variance	Standard Deviation
2	0.009	0.093	22	0.000	0.015
3	1.627	1.275	23	0.001	0.028
4	0.003	0.058	24	0.001	0.027
5	4.201	2.050	25	0.000	0.019
6	0.000	0.013	26	0.000	0.012
7	0.007	0.084	27	0.002	0.039
8	0.000	0.016	28	0.004	0.059
9	0.004	0.067	29	0.001	0.027
10	0.004	0.061	30	0.003	0.057
11	0.002	0.043	31	0.002	0.047
12	0.000	0.010	32	0.000	0.017
13	0.002	0.049	33	0.003	0.052
14	0.000	0.013	34	0.001	0.027
15	0.001	0.038	35	0.001	0.035
16	0.000	0.012	36	0.000	0.019
17	0.002	0.044	37	0.002	0.042
18	0.000	0.015	38	0.000	0.010
19	0.001	0.027	39	0.001	0.026
20	0.000	0.009	40	0.001	0.034
21	0.005	0.067			

Table C.3
Shows the variation and the standard deviation for the observed harmonics related to Figure 4.2 Section 4.3.4, Modelling Method based on Average Harmonic Magnitude

h	Averaging Model	95^{th} percentile Model	2^{nd} Highest Model	h	Average Model	95^{th} percentile Model	2^{nd} Highest Model
1	8.696	8.696	8.696	22	0.003	0.013	0.013
2	0.066	0.087	0.087	23	0.021	0.052	0.052
3	0.251	0.348	0.348	24	0.007	0.013	0.013
4	0.038	0.087	0.087	25	0.023	0.050	0.046
5	0.214	0.348	0.348	26	0.003	0.013	0.013
6	0.009	0.030	0.019	27	0.021	0.052	0.052
7	0.134	0.269	0.172	28	0.006	0.013	0.013
8	0.013	0.040	0.033	29	0.024	0.052	0.052
9	0.092	0.180	0.150	30	0.010	0.013	0.013
10	0.006	0.031	0.011	31	0.024	0.052	0.052
11	0.072	0.130	0.125	32	0.010	0.013	0.013
12	0.006	0.025	0.024	33	0.019	0.040	0.040
13	0.078	0.138	0.129	34	0.006	0.013	0.013
14	0.006	0.031	0.012	35	0.006	0.013	0.013
15	0.042	0.101	0.068	36	0.005	0.013	0.013
16	0.005	0.023	0.009	37	0.008	0.013	0.013
17	0.046	0.111	0.083	38	0.002	0.011	0.009
18	0.006	0.027	0.017	39	0.007	0.013	0.013
19	0.026	0.064	0.055	40	0.007	0.013	0.013
20	0.006	0.022	0.018	THD	4.629	7.795	7.094
21	0.033	0.107	0.071				

Table C.4
The I_h magnitudes produced by three analysed methods, without THD adjustment

Appendix D

Domestic Equipment Contribution to LV System Distortion

Current Waveform Distortion of a 1000W Microwave During Startup

The current harmonic spectrum of a 1000W microwave in Figure D.2 shows the significance of the harmonic magnitudes during the start up procedure which could last approximately 3–5 seconds. The starting current wave seen in Figure D.1 shows the severity of the wave distortion. The magnitude of the current harmonics of the equipment when compared to other domestic items was found to be significantly higher, even though the duration of the operating time is comparatively short when compared to other domestic equipment. However, if the highly unlikely were to happen (when a significantly large number of users at a particular time were to operate the item), the distortion of the LV system will be dominated by this item due to its high current harmonic magnitude. The data shown below was measured using a Fluke 129 analyser, with a microwave rating of 1000W at high power level heating a glass of water.

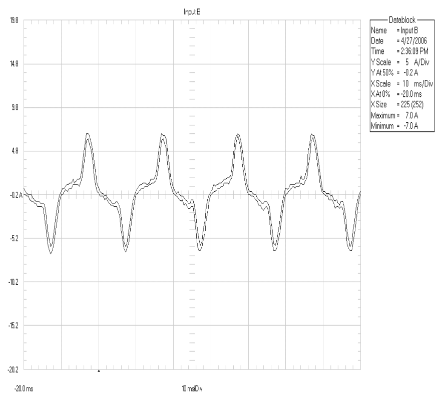

Figure D.1 Current Wave Form of a 1000W Microwave at start up

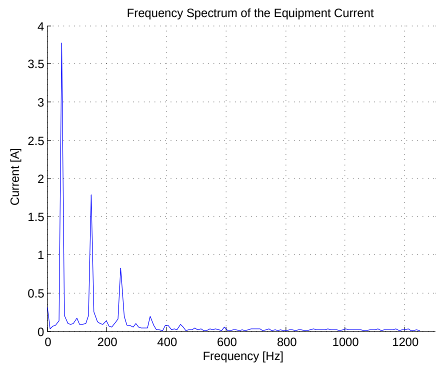

Figure D.2 Current Harmonic Spectrum of a 1000W Microwave at start up

Harmonic Spectrum of a Television Set

The Figure D.3 shows the harmonic spectrum of a television set. The harmonic magnitudes are comparatively low and the equipment can be considered as a low power rated equipment. Therefore, the contribution from this equipment to the main LV system distortion would be significantly low.

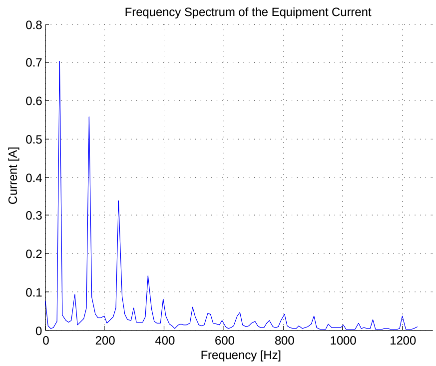

Figure D.3 Current Harmonic Spectrum of TV

Appendix E

Harmonic Spectra for Vulnerability study

Please see print copy for Table E.1

Table E.1
Categorised three harmonic spectra from the standard [7] satisfying the total harmonic distortion condition of 5%. The I_h is reduced by 15% for use in the system vulnerability to harmonic spectra study.

Appendix F

Additional Study on the Significance of the Shunt Component in Residential Load Model

F.1 Introduction

To incorporate the loading effect on the harmonic voltage levels within the LV distribution system, a load model was developed for the study. A typical residential type load model incorporated in this study attempts to reflect the domestic appliances in daily usage. The domestic appliances are categorized into two parts - collectively the appliances with small motors corresponds to motor type loads (represented by R_m and X_m) [51] and heating/ligthing corresponds to resistive type loads ($R_{L/H}$). The components used in the model were selected as passive elements, this being justified based on the references [51] [53]. The model is shown in Figure 5.7. The case presented in this study is based on where the shunt component in the load model referred to as the R_{load} becomes significant comparable to system impedance.

Based on typical residential premises, a peak power load rating of 6kVA at 0.9 pf lagging was selected. Using the peak power the load model elements was calculated in accordance with reference [51] on a 70% loaded transformer. The combined impedance of the two categories representing the load model are plotted over the frequency range, as shown in Figure F.1. The effective load impedance is comparable to system impedance, especially at high frequencies which will be accounted for in the determination of the voltage harmonics leading to penetration levels.

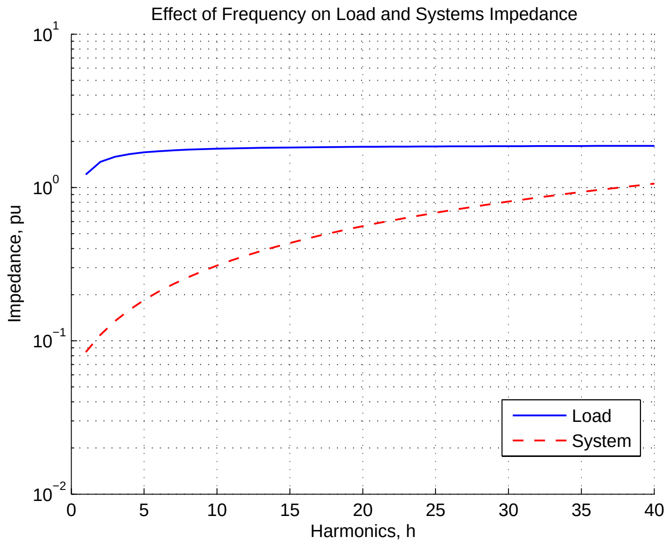

Figure F.1 Changing impedance of system and load against frequency

F.2 Results

The results of a typical harmonic voltage calculation using conventional methods and system models described in Chapter 5 were completed using a combination of tools such as MATLAB. A typical system consisting of approximately 41 residential houses was connected to a system transformer rated at 350kVA, leading to a loading level of approximately 70%.

Effectively, the loading level (total number of residential units) has even greater impact on the total impedance of the load relative to power system impedance. The variation of load impedance is plotted over loading level for 3^{rd}, 5^{th} and 21^{st} harmonic in Figure F.2. Clearly, the high loading level of the distribution transformer will result in a greater impact on the harmonic voltage at the far end of the distributor compared to low loading levels, consequently affecting the acceptable penetration levels of PVIS.

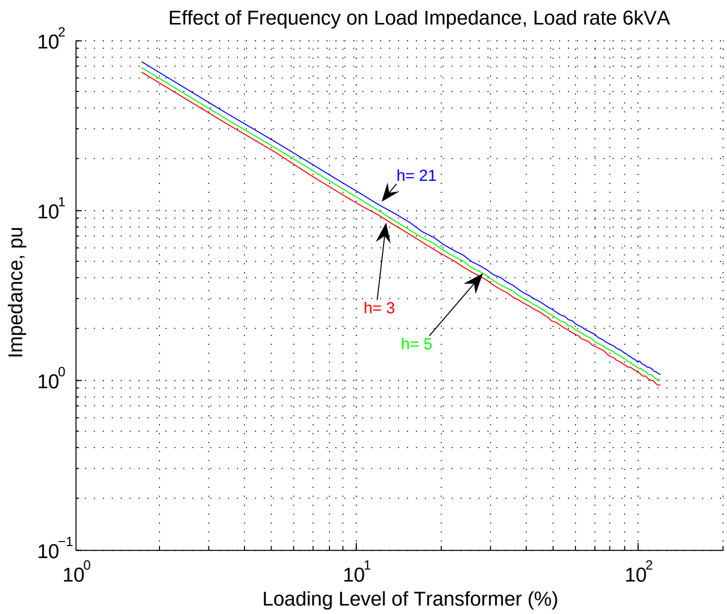

Figure F.2 Changing impedance of the load over loading level of the transformer

The acceptable penetration level is based on two factors; V_{THD} within recommended limits, and individual voltage harmonics within recommended limits. The acceptable penetration level for PVIS installations is relatively high when considering only V_{THD}, however is considerably lower when based on the individual harmonic voltage levels. The harmonic determining the acceptable penetration levels of PVIS was 21^{st} harmonic based on the standard harmonic planning levels [10]. However, it was found that the individual harmonic determining the acceptable penetration level of the PVIS changed when the harmonic voltage limit ($L_{415,PVIS,h}$) was incorporated as the threshold. The significance change in the limiting harmonics was observed at the 40% loading level, Table F.1, with a minor change of the individual harmonic

Loading Level (%)	h* OH,ABC,UG			Penetration Levels* OH,ABC,UG			h** OH,ABC,UG			Penetration Levels** OH,ABC,UG		
0	21	21	21	8	18	21	21	21	21	3	7	9
10	21	21	21	15	25	28	21	21	21	7	11	13
20	21	21	21	22	32	35	21	21	21	10	14	15
30	21	21	21	30	39	42	21	21	21	13	17	18
40	21	21	21	37	46	50	21	21	21	16	20	22
50	21	21	21	45	54	57	3	21	21	19	23	25
60	21	21	21	52	62	65	4	21	21	21	26	28
70	21	21	21	59	69	72	4	4	4	22	29	31
80	21	21	21	67	77	79	4	4	4	23	30	32
90	21	21	21	75	85	87	4	4	4	25	31	33
100	21	21	21	83	93	94	4	4	4	26	32	35

*– Penetration Level of PVIS in the system based on $L_{415,h}$

**– Penetration Level of PVIS in the system based on $L_{415,PVIS,h}$

Table F.1
Shows the harmonics which limit the acceptable penetration levels of PVIS for different system loading levels, subjected to the emission of the current harmonic spectrum modelled in Chapter 4

based on the distributor type.

With the significant change in the system impedance, the acceptable penetration levels of PVIS were found to increase significantly. The increase in loading levels from 10% to 50% increased the acceptable penetration levels from approximately 7% to 19% on the highest impedance distribution feeder, overhead open wire conductor type.

F.3 Conclusion

The presented case study has highlighted the behaviour of low voltage distribution network harmonic voltage levels caused by the significance of the shunt component in the load model.

The comparable load impedance (aggregated) with respect to the systems impedance indicats that the harmonic current absorbed by the shunt impedance will be significant. Consequently, such an effect in this presented system is an undesirable effect. Hence for such a case at low voltage, the distribution network requires implementation of mitigation techniques or otherwise.

Appendix G

Additional details on Acceptable Penetration Levels

G.1 Additional Details related to 415V system

Please see print copy for Table G.1

Table G.1
Shows the maximum number of units that can be connected to 415V system with OH, ABC and UG distribution type feeders before exceeding the voltage planning levels given in [10] Table 3.3 for individual harmonics

Harmonic h	PVIS Units OH	PVIS Units ABC	PVIS Units UG	Harmonic h	PVIS Units OH	PVIS Units ABC	PVIS Units UG
2	125	174	202	22	67	103	109
3	23	37	52	23	123	191	198
4	25	36	40	24	34	69	82
5	138	211	222	25	74	112	118
6	69	134	165	26	57	87	92
7	154	240	248	27	8	15	18
8	52	78	83	28	53	80	85
9	21	40	49	29	53	80	84
10	166	262	268	30	33	67	79
11	232	375	374	31	51	77	81
12	27	53	64	32	56	85	90
13	172	272	277	33	10	20	24
14	87	133	139	34	53	80	85
15	13	26	31	35	176	280	284
16	142	223	229	36	28	56	66
17	132	206	213	37	162	256	261
18	34	69	82	38	71	109	115
19	119	185	192	39	26	52	61
20	55	83	88	40	45	68	72
21	8	15	17				

Table G.2
Shows the maximum number of units that can be connected to 415V system with OH, ABC and UG distribution type feeders before exceeding the voltage limits incorporating background distortion levels given in Table 7.2 for individual harmonics

G.2 Additional Details related to 11kV system

Please see print copy for Table G.3

Table G.3
Shows the maximum number of units that can be connected within the 415V systems before exceeding the 11kV system's harmonic voltage planning levels given in [10] Table 3.3 for individual harmonics

Harmonic h	Without Diversity	With Diversity	Harmonic h	Without Diversity	With Diversity
2	368	368	22	66	74
4	100	100	23	112	126
5	282	311	25	69	78
7	319	352	26	56	63
8	115	126	28	52	58
10	258	284	29	47	53
11	265	300	31	41	47
13	160	180	32	40	45
14	122	137	34	38	42
16	125	141	35	136	153
17	115	129	37	122	137
19	122	138	38	51	57
20	54	60	40	32	36

Table G.4

Shows the acceptable penetration level of PVIS units in 11kV system before exceeding the voltage limits given in Chapter 7, Table 7.4 for individual harmonics

Appendix H

Harmonic Current Spectrum Field Measurements

H.1 Introduction

The presented study is based on analysing the harmonic currents generated from a series of roof top solar panels. A series of solar panel modules totaling up to approximately 30kW of power was fed through a suitably rated inverter system to an office building (also commonly categorized as commercial load) in shaping their peak power demand.

H.2 Measuring Instrument

The instrument used for measuring harmonic data on the solar panels was a "Hioki 3196 Power Quality Analyser" as seen in Figure H.1. Further details on this instrument can be obtained from reference [61].

Please see print copy for Figure H.1

Figure H.1 Hioki 3196, used for power quality analysis

H.3 Acquired Graphs from the Measurements

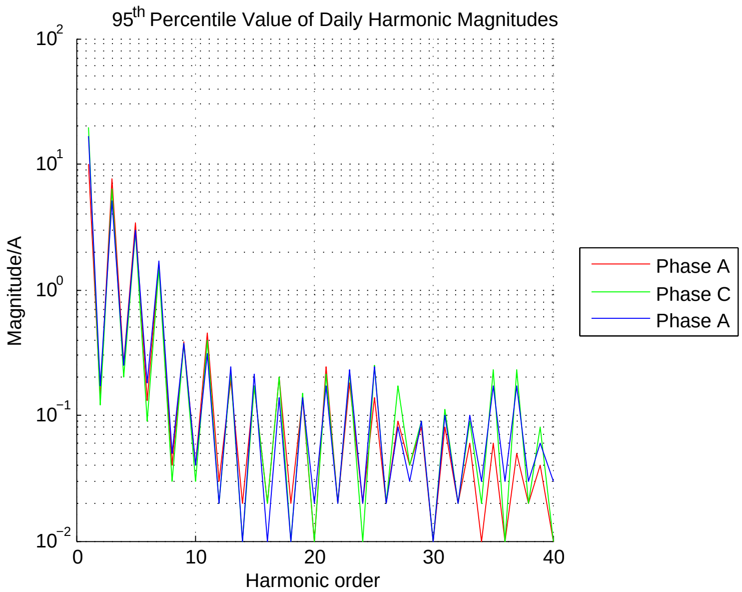

Figure H.2 The daily 95^{th} percentile value of harmonic current for phases A, B and C

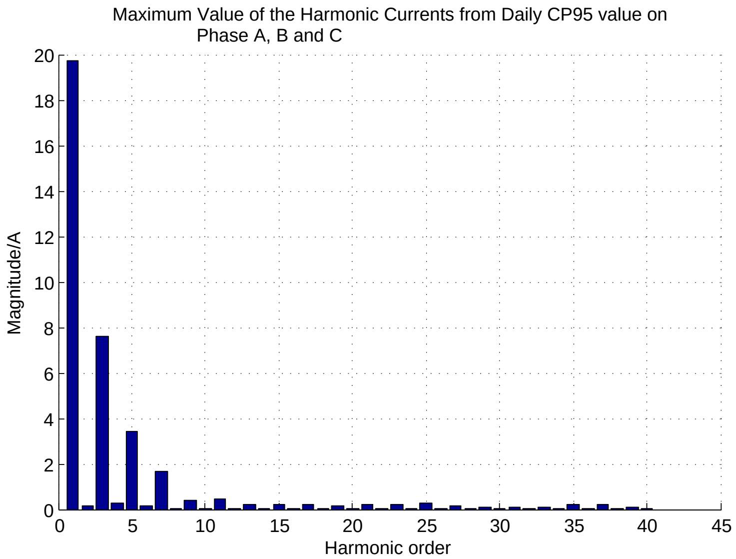

Figure H.3 The maximum I_h of the daily 95^{th} percentile value for harmonic current from phases A, B and C

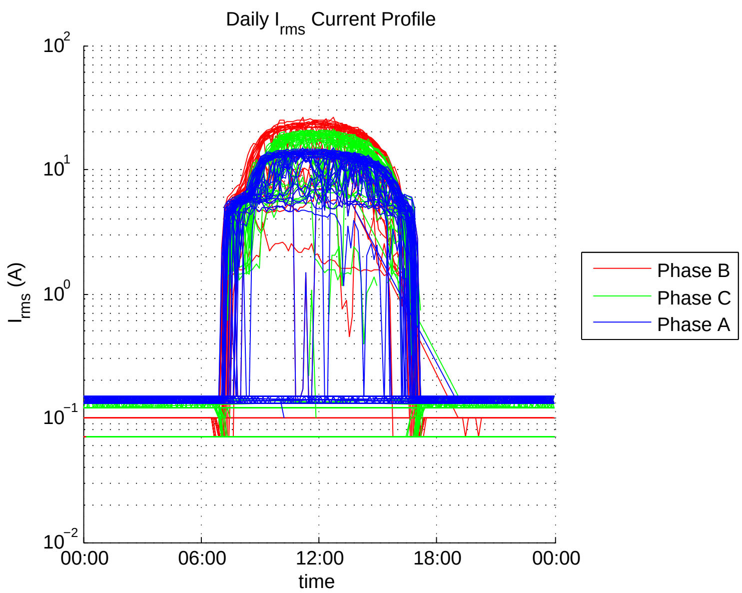

Figure H.4 The rms value of the current in phase A, B and C taken over the period of monitoring

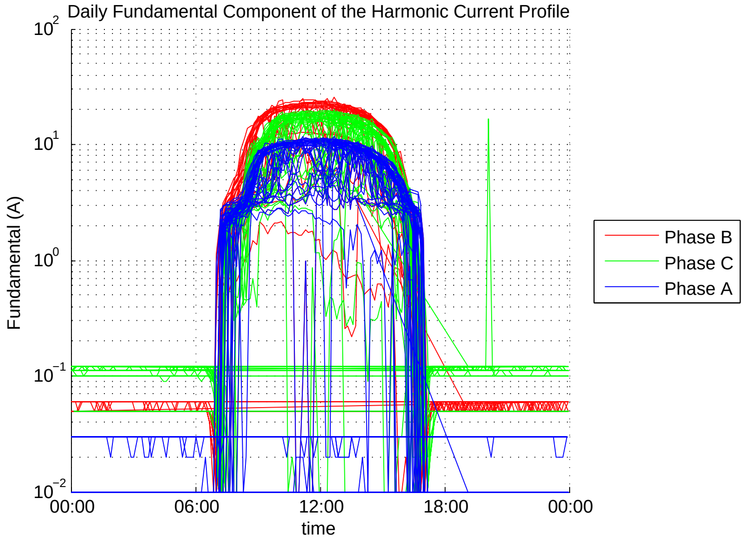

Figure H.5 The fundamental current magnitude in phase A, B and C taken over the period of monitoring

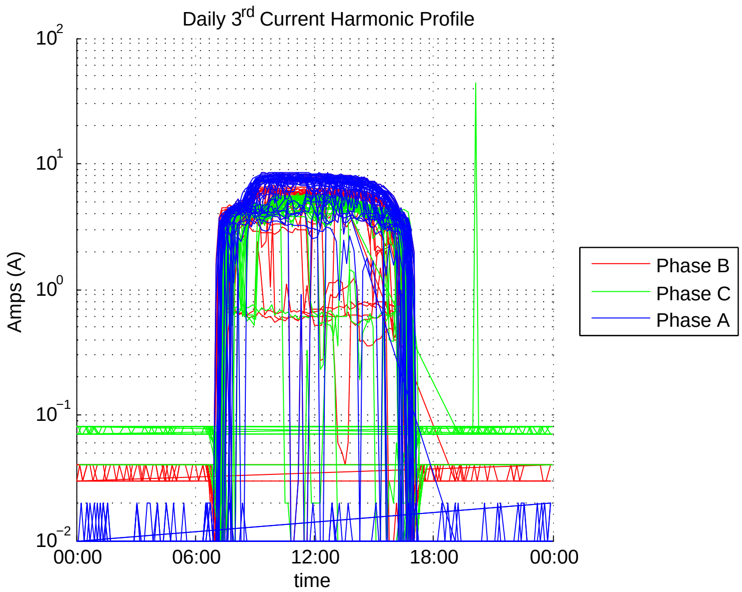

Figure H.6 The third harmonic current magnitude in phase A, B and C taken over the period of monitoring

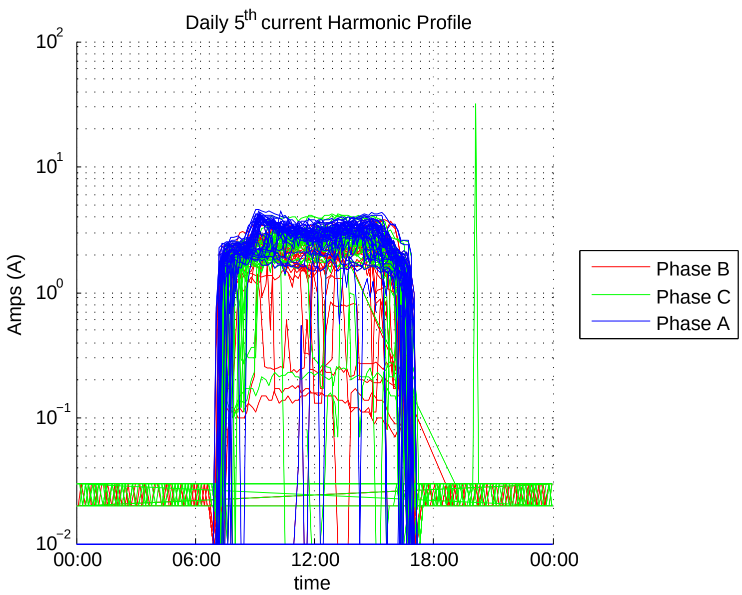

Figure H.7 The fifth harmonic current magnitude in phase A, B and C taken over the period of monitoring

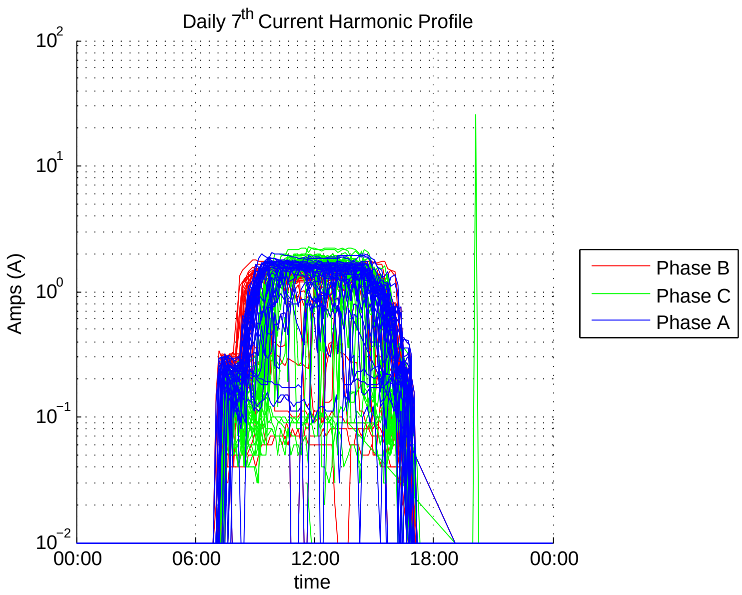

Figure H.8 The seventh harmonic current magnitude in phase A, B and C taken over the period of monitoring