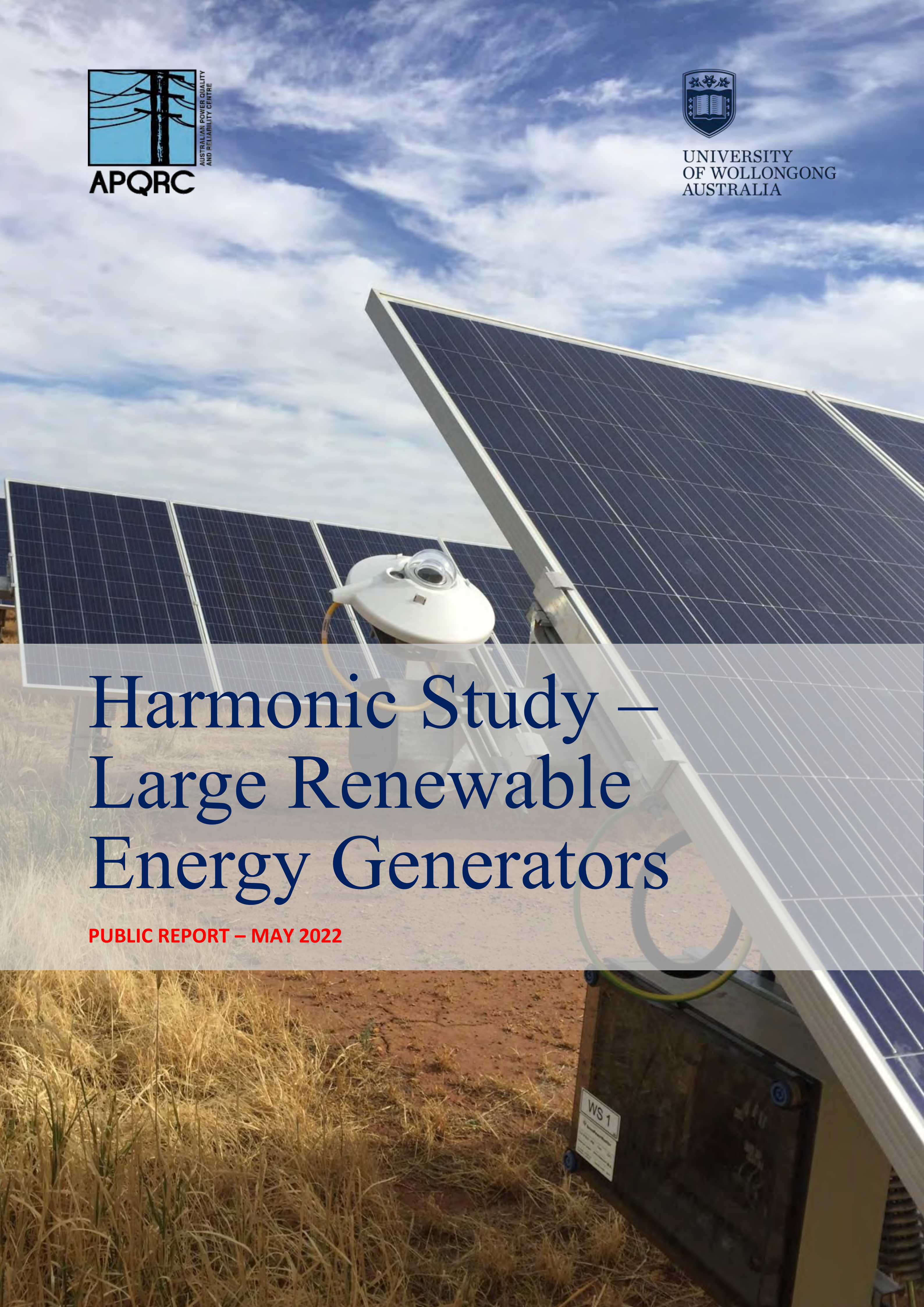


APQRC
AUSTRALIAN POWER QUALITY AND RELIABILITY CENTRE

UNIVERSITY
OF WOLLONGONG
AUSTRALIA

Harmonic Study – Large Renewable Energy Generators

PUBLIC REPORT – MAY 2022

This project received funding from the Australian Renewable Energy Agency (ARENA) as part of ARENA's Advancing Renewables Program.

UNIVERSITY
OF WOLLONGONG
AUSTRALIA

Project Lead

The University of Wollongong is the lead organisation responsible for delivery of this project

Project Partners

Edify
ElectraNet
Endeavour Energy
essential energy
NEOEN
res power for good
Transgrid
Vestas

List of symbols & Abbreviations

Ω	Ohms
ω	Angular frequency
ψ	Phase shift between waveforms
A	Ampere
AC	Alternating current
AEMO	Australian energy market operator
APQRC	Australian power quality & reliability centre
ARENA	Australian renewable energy agency
AS/NZS	Australian standards/New Zealand standards
CG	Collector group
DC	Direct current
DG	Distributed generation
DNSP	Distribution network service provider
EHV	Extra high voltage
EMC	Electromagnetic compatibility
EMT	Electromagnetic transient
ENA	Energy Networks Australia
h	Harmonic order
HV	High voltage
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
IBR	Inverter-based resources
IEC	International electrotechnical commission
IEEE	Institute of electrical and electronics engineers
IGBT	Insulated-gate bipolar transistor
ISP	Integrated system plan
LCC	Line-commutated converters
LV	Low voltage
MATLAB	Matrix laboratory software
MV	Medium voltage
NEM	National electricity market
NER	National electricity rules
NSP	Network service provider
OEM	Original equipment manufacturer
OWF	Offshore windfarm

PCC	Point of common coupling
PFC	Power factor correction
PE	Power electronics
PQ	Power quality
PV	Photovoltaic
R	Resistance
REG	Renewable energy generator
REZ	Renewable energy zone
RMS	Root-mean square
SCR	Short-circuit ratio
STATCOM	Static synchronous compensator
THD	Total harmonic distortion
TNSP	Transmission network service provider
TR	Technical report
TSO	Transmission system operator
VSC	Voltage source converter
V	Voltage
VA	Volt-ampere
VAr	Volt-ampere reactive
VT	Voltage transformer
W	Watts
WTG	Wind turbine generator
X	Reactance
Z	Impedance
ZS	Zone substation

Executive Summary

Harmonic distortion is periodic (repetitive) variation to the shape of the nominally sinusoidal 50 Hz electricity supply waveform. The mathematical Fourier series theorem states that any waveform can be represented as the summation of a number of sine or cosine waveforms. In the case of a waveform with harmonic distortion, the waveform can be represented by a fundamental component in addition to a number of other waveforms whose frequencies are multiples of the fundamental frequency. For example, the third harmonic has a frequency of 150 Hz or three times the fundamental frequency of 50 Hz. A major source of harmonic distortion of voltage waveforms in the electricity supply is the interaction between harmonic currents emitted by non-linear loads or generators and the electricity supply network impedance. Inverters used by renewable energy generators such as solar farms and some wind farms are non-linear devices and will intrinsically produce some level of harmonic distortion. Harmonic distortion is undesirable as it increases losses within the power system and customer installations and can interfere with the propoer operation of some equipment. It also leads to increased ageing of insulation and in some cases may cause catastrophic failure of some components. As a general principle, Network Service Providers (NSPs) are responsible for managing harmonic voltage distortion within bounds that ensure safe and reliable operation of equipment connected to electricity supply networks. One of the methods used by NSPs to manage voltage distortion is to allocate emission limits to large customers (loads and/or generators). Under this management philosophy it is then the responsibility of the customer (load or generator) to ensure that their plant does not exceed the allocated emission limit.

There is considerable evidence to suggest that the existing methodologies used by NSPs to maintain appropriate harmonic distortion levels are not fit for purpose, difficult to implement and/or may result in inefficient use of the capability of the power system to absorb some level of harmonic distortion. This report provides an overview of the Investigation of the Impact and Management of Harmonic Distortion for Large Renewable Generators project led by the University of Wollongong and supported by ARENA. Other project partners were Endeavour Energy, TransGrid, Essential Energy, ElectraNet, Neoen, RES Group, Edify and Vestas. These project partners include a diverse range of Renewable Energy Generator (REG) stakeholders. The primary aim of this project was to develop a clear framework for managing harmonic distortion that meets the needs of a changing electricity supply sector and removes technical, financial and administrative barriers to the uptake of renewable energy generation. These aims were achieved through an extensive literature review, collaboration with industry partners and research activities.

Review of Impact of REG on Network Harmonic Distortion Levels

An initial project task was to investigate long-term power quality monitoring projects that included data prior to, and post integration of significant volumes of large REG plants in order to assess the impact of large volumes of REG on network harmonic distortion levels. Data reviewed within Australia showed harmonic voltage distortion levels to be steady or possibly reducing in recent years. This reduction was attributed to reduced emissions from new technologies and strict harmonic management processes (i.e. harmonic emission limit allocation and mitigation). Studies internationally showed varying experiences, some with increasing distortion levels and others with a reduction of distortion as REG connections increased. Regardless of power system distortion increasing or decreasing, the outcomes indicate that REG plants are capable of having significant impacts on harmonic distortion levels. Thus, the impacts must be carefully assessed to ensure the approach to managing power system distortion results in efficient and fair outcomes for all customers.

Evaluation of Harmonic Emission Allocation Methodologies

Many different methodologies to calculate harmonic emission allocations are in use internationally. The method defined by the International Electrotechnical Commission (IEC) is the most commonly used within Australia and as such was the focus of the majority of the studies undertaken within this project. However, both qualitative and quantitative reviews have been completed for a number of other allocation methodologies in order to assess their advantages and disadvantages and applicability in a scenario of ongoing increasing REG penetration. The outcomes of these reviews indicate that of all present allocation methodologies the IEC methodology, whilst more complex to apply and affected by issues such as long line effects, varying network harmonic impedance and uncertainty, appears to be the most appropriate approach for Australian power systems. Other international methodologies were found to include assumptions and processes that commonly resulted in harmonic voltage limits being exceeded in many scenarios. A number of proposed revisions to the IEC emission limit allocation process were developed for this project to address some of the shortcomings identified with the methodology. Further work is necessary to verify the outcomes and confirm their suitability.

Investigation of Diversity in Harmonic Emissions from REG Plant

A requirement prior to a new installation connecting to the network is to meet pre-connection compliance assessment, also known as R1 compliance. This essentially requires the proponent to develop a harmonic model of their plant, incorporate the model with the power system model and estimate the harmonic emissions of the plant when operational. If the model suggests the plant will not comply with allocated emission limits, a mitigation solution must be designed prior to the connection being accepted. A review of existing literature, discussion with industry stakeholders and the experience of the research team confirmed that a number of the processes implemented within Australia to assess pre-connection compliance are not able to accurately represent post-connection measurements and may result in harmonic mitigation being required due to highly conservative assumptions being implemented. Mitigation generally takes the form of passive harmonic filters which are costly and capable of making the process of managing power system harmonics more complex. The research activities undertaken in this project have identified potential flaws in the existing methodologies implemented in developing harmonic models for present-day power electronic devices. Further, it has been identified that the representation of the power system is capable of having a significant impact on the response of power electronic devices and on the outcome of the studies in general.

One of the factors identified as having a significant impact on compliance assessment is the approach to determining how multiple harmonic sources interact with each other, i.e. aggregation of multiple harmonic sources. For traditional loads, diversity in both phase angle and time in emissions is accounted for in IEC documents using a process known as the summation (or alpha) law. While it is accepted that diversity exists across emissions from individual loads, the present approach in the case of REG, where multiple of the same type of inverter is commonly used, has been to ignore diversity and arithmetically sum emissions. This approach has been reviewed and was found to be highly pessimistic resulting in significant over-estimation of harmonic emissions. While this initial study indicated that diversity should be considered within REG plants, further work is necessary to analyse interactions across different REG plants and various technologies to investigate more appropriate means of estimating harmonic source aggregation. Significant effort is required to improve the understanding of these impacts and their sensitivities not just in an Australian context but internationally.

Modelling to Evaluate the Impact of High Penetration of REG on Network Harmonic Distortion

A number of modelling studies were undertaken to investigate the impacts of high penetration of REG within geographically large networks. Specifically, the studies leveraged industry provided data to estimate harmonic emissions within a proposed Renewable Energy Zone (REZ) as more REGs continue to connect. The outcomes of the modelling activities were extended to review and compare approaches to mitigation of harmonic emissions. The findings of these studies identified that harmonic emissions were generally most problematic in areas distant to the harmonic sources due to the impacts of remote resonance. This is a significant outcome as the present methodology for assessment of connections only focusses on the point of connection and does not consider impacts on the wider network. Further, it was found that the most efficient approach to harmonic mitigation in such circumstances is to apply mitigation at the point at which resonance occurs, not at the connection point of the plants that are emitting harmonic emissions. A simple example was presented finding that the revised methodology was capable of reducing the required rating of the harmonic filter by 98 %. The outcomes of this study challenge a number of the traditional processes for the management of harmonic distortion. The outcomes indicate that alternative approaches are capable of significantly reducing costs for proponents and simplifying the process of managing harmonic emissions in general for NSPs. However, it is unclear how this proposed methodology can be integrated into present technical and regulatory frameworks and further work is necessary to better understand the implications of practical application.

Key Outcomes

The key outcomes of this project identify that a number of the existing practices for the management of harmonic distortion within electricity supply networks, particularly with respect to increasing proliferation of large REG are leading to inefficient harmonic emission limit allocation, potentially increasing investment requirements from proponents and making the management of power system distortion in general more complex than is necessary. The following is a summary of the key outcomes of this project:

- With respect to the impact of increasing penetration of REG on harmonic distortion in electricity networks and review of Australian and international literature on this subject indicates that **the impact is highly varied** with harmonic distortion in some networks increasing as the number of REG plants increase while in other network distortion levels appear to be decreasing as the number of REG plants increases.

- An assessment of a range of the most common methodologies for determining an emissions allocation for harmonic distortion has shown that while subject to a range of limitations that require addressing, **the IEC methodology** appears to remain the most valid approach for Australian networks, although challenges have been investigated with its application in networks with long feeders and high levels of REG penetration and uncertainty.

- A case study has indicated that **diversity exists for all harmonic orders between the harmonic emissions from identical inverters** within a wind farm. This challenges the conservative approach of arithmetically summating emissions which is presently applied with important consequences for pre-connection compliance assessment.

- Outcomes of modelling undertaken to investigate the impact of increasing REG penetration into a proposed renewable energy zone **challenges the efficiency and efficacy of the present methods of assessing impact and implementing mitigation**. These preliminary studies indicate that an **approach which is network focussed as opposed to plant focussed** will be better able to detect areas where harmonic distortion levels are problematic and also provide more efficient and targeted mitigation.

- A preliminary assessment of the challenges related to pre- and post-connection compliance assessment has identified that significant work is required to **develop prescriptive and technically robust methodologies for network and plant modelling as well as assessment of compliance through the use of field measurements.**

Table of Contents

1 Introduction

1.1 PROJECT BACKGROUND

One of the major sources of harmonic distortion of voltage waveforms in the electricity supply is the interaction between the harmonic currents emitted by non-linear loads or generators and the electricity supply network impedance. Inverters used by renewable energy generators such as solar farms and some wind farms are non-linear devices and will intrinsically produce some level of harmonic distortion [1-4]. There are a range of undesirable effects that can arise from harmonic distortion including equipment damage and in extreme cases failure. Management of harmonic distortion is becoming increasingly difficult with increasing penetration on inverter based generation [5, 6].

The National Electricity Rules (NER) impose a set of requirements for network service providers (NSPs) and network customers (large loads and generators) to manage harmonic distortion. However, in many cases these requirements are complicated, difficult to interpret and are not implemented uniformly across NSPs. Using the methods prescribed in the NER, as a general principle NSPs are responsible for managing harmonic voltage distortion within bounds that ensure safe and reliable operation of equipment connected to electricity supply networks. In order to limit voltage distortion, the NSP is required to provide an emission allocation, which is documented in the connection agreement, to the proponent of the connecting plant. It is then the responsibility of the proponent to ensure that the harmonic emissions of their plant do not exceed the emission allocation.

Under present requirements for management of harmonic distortion, network operators and renewable generator proponents are investing significant resources in managing harmonic emissions that are allocated using a methodology that is complex, requires significant volumes of data including sophisticated understanding of present and future network characteristics and which may not be fit for purpose or technically robust. The difficulties in applying and uncertainties associated with the use of this methodology is creating significant and meaningful technical, financial and administrative barriers to the deployment of renewable energy generation into the National Electricity Market (NEM).

1.2 PROJECT SCOPE

The primary aim of this project was to develop a clear framework for managing harmonic distortion that meets the needs of a changing electricity supply sector and removes technical, financial and administrative barriers to the uptake of renewable energy generation (REG). Through investigation of alternate methods for management of harmonic distortion levels and the potential identification of an emission allocation methodology which is easier to apply while remaining technically robust, this project sought to reduce technical, administrative and financial barriers to renewable energy integration. Specifically, the outcomes of this project aimed to achieve the following:

- Reduction in the costs of deployment of large-scale renewable energy through reducing the cost of studies related to the management of harmonic distortion.
- Better understanding of the harmonic performance of large-scale REGs and the networks to which they are connected in order to ensure that costly mitigation of harmonic emissions is only undertaken if absolutely necessary.
- Reduction of the administrative barriers which exist due to the uncertainty related to harmonic management. At present, there are significant knowledge gaps with regard to the overall impact on harmonic distortion due to high penetration of large-scale REGs. These knowledge gaps often manifest as a reticence on the part of network operators to connect such generators.
- An increase in the skills, knowledge and capacity related to renewable energy technologies. The outcomes of the project will fill knowledge gaps and contribute to changes to standards, regulations and/or the methods used by renewable energy proponents and network operators when managing harmonic distortion.

The key objectives of the project were to provide:

- Identification and/or development of technically robust methodologies with limited complexity and modest data requirements that can be used to allocate harmonic emissions.
- Increased confidence in harmonic distortion emission allocation methodologies and ultimately the level of emission allocated.
- Identification of the actual likely harmonic distortion emissions from large renewable energy generators.
- Preliminary steps toward improved methods of harmonic emission compliance assessment to provide certainty as to performance and also ensures that mitigation equipment is only installed after determination of any exceedance of emission allocation is made using technically robust methods.

1.3 PROJECT PARTICIPANTS

The project was led by the University of Wollongong in conjunction with a number of NSPs and renewable energy proponents. The project partners are shown in Table 1.1.

Table 1.1 – Project Participants

Organisation	Role
Endeavour Energy	Distribution NSP
Essential Energy	Distribution NSP
TransGrid	Transmission NSP
ElectraNet	Transmission NSP
Neoen	A large renewable energy developer
Edify Energy	A large renewable energy developer
RES Group	A large renewable energy developer
Vestas	A large renewable energy developer and technology vendor

Each of the project partners listed in Table 1.1 was represented on the project control group (PCG) which provided high level project oversight and was tasked with ensuring that the project remained on time, on budget and on scope. This PCG met on a quarterly basis. In addition to representation of the PCG, project partners also provided the following to the project on and ad-hoc basis:

- Data including network data, plant data and field measurements
- Technical advice
- Review of all project outputs

1.4 CONTENTS AND LAYOUT OF THIS REPORT

This report provides a complete overview of the project activities, findings and recommendations and is a revised amalgamation of the two milestone reports submitted throughout the life of the project. The layout of the remainder of this report is as follows:

- *Section 2* of this report contains a wide-ranging literature review that identifies the current state-of-the-art with respect to the management of harmonic distortion in the context of large REGs. The literature review examines state-of-the-art for the following topics:
    - Methods of modelling renewable energy farms
    - Impact of renewable energy farms on harmonic distortion magnitudes in electricity networks
    - Methods of undertaking allocation of harmonic distortion emissions

  - Methods of aggregating harmonics from a number of inverters at solar farms
- *Section 3* of this report comprises of an evaluation of the efficiency, efficacy and technical robustness of various Australian and international methods of allocating harmonic emissions to renewable energy generators. Case study models are also developed and used as inputs for assessment and comparison of each allocation strategy/method.
- *Section 4* provides a detailed investigation of the applicability of existing practices related to the aggregation of multiple harmonic sources using a case study. The case study and outcomes are based on field measurements from a large REG during normal operation.
- *Section 5* is an account of a large modelling study that was undertaken to forecast harmonic emissions in wide area networks with high penetration of renewable energy sources. The study also investigated revised methodologies for appropriate mitigation strategies based on the findings.
- *Section 6* discusses the difficulties in the application of methods for determining harmonic emission compliance of large renewable energy generators including commonly implemented modelling applications.
- *Section 7* details the findings and recommendations based on the outcomes of the project.

1.5 DETAILS OF KNOWLEDGE SHARING

The following are publicly available knowledge sharing outputs related to this project:

- *International Conference Publication and Presentation (accepted, to be presented)*: J. David, D. Robinson, S. Elphick "Aggregation of multiple inverter-based harmonic sources within a renewable energy generation plant", *IEEE International Conference on Harmonics and Quality of Power (ICHQP)*, Paper 93, Naples, May/June 2022
- *Journal Paper (in draft):* J. David, D. Robinson, V. Gosbell, S. Elphick, "Optimal harmonic mitigation strategies in networks with remote resonance", to be submitted to *IEEE Power Delivery*, 2022.
- *Journal Paper (in draft)*: J. David, D. Robinson, V. Gosbell, S. Elphick, "Revised application of IEC 61000-3-6 to systems with high uncertainty", to be submitted to *IEEE Power Delivery*, 2022.
- *International Conference Publication and Presentation*: T. Vu, D. Robinson, "Strategic Harmonic Planning and Management Framework for Transmission Systems", *CIGRE 2022 Kyoto Symposium*, Japan, 3-8 April 2022, Paper C000076
- *International Conference Publication and Presentation*: J. David, D. Robinson, S. Elphick, G. Drury, "Statistical impacts of renewable energy generation on power system harmonic distortion", *CIGRE 2022 Kyoto Symposium*, Japan, 3-8 April 2022, Paper C000033
- *International Conference Publication and Presentation*: J. David, A. Kazemi, S. Elphick, D. Robinson, "Challenges with harmonic emission compliance assessment of inverter-based resources – an international review", *CIGRE 2022 Kyoto Symposium*, Japan, 3-8 April 2022, Paper C000003
- *CEC Large-Scale Solar Forum Presentation:* Optimised harmonic mitigation of renewable energy generation, J. David, 19th May 2022.
- *TNSP PQ Forum Presentation*: ARENA Harmonic Management Project Update, Jason David, 24th February 2022.
- *DNSP PQ Forum Presentation*: ARENA Harmonic Management Project Update, Jason David, 17th February 2022.
- *Engineers Australia Presentation*: CPD Online - Network connection studies for large renewable energy generators, Engineers Australia, Jason David, 9th February 2022.
- *Milestone Project Report*: Harmonic Study – Large Renewable Energy Generators – Milestone 1 Report, *University of Wollongong*, November 2020

- *Milestone Project Report*: Harmonic Study – Large Renewable Energy Generators – Project Report, *University of Wollongong*, April 2022
- Article in the University of Wollongong *Faculty of Engineering and Information Science Newsletter.*
- Article in the *Power Quality Compliance Audit Newsletter* distributed by the Australian Power Quality and Reliability Centre and distributed to Australian electricity network service providers.

2 Literature Review

2.1 INTRODUCTION

This literature review provides a review of the state-of-the-art of harmonic modelling, management and allocation, with a particular focus on inverter based renewable energy generators (REGs). The topic has received considerable attention in recent years due to the increasing numbers of REGs. The literature review begins with an introduction to harmonic distortion (causes and impacts) and then provides a comprehensive review of monitored harmonic distortion levels from international power systems containing significant inverter based renewable energy generators (REG). The immediate impacts on distortion levels that have been observed due to the commissioning of large REGs is provided, with case studies and industry insights being presented. Following this, analysis of ongoing system, network or multiple network PQ monitoring data is undertaken to ascertain the developing and long-term trends of harmonic distortion that networks may experience due to the increased connection rates of REG.

Existing harmonic allocation and management techniques are qualitatively reviewed, considering the suitability of the methods for Australian conditions with the expected levels of REG penetration in the future. Processes of harmonic modelling and aggregation of sources are then briefly introduced, identifying the suitable modelling methods available to undertake a pragmatic allocation process, including a critical review of such approaches.

2.2 HARMONIC DISTORTION

2.2.1 Definition

Harmonic distortion may be defined as a periodic change in the waveform shape from an ideal sinusoidal [7, 8]. Harmonic distortion is generally considered to be a steady state characteristic, although levels (waveform shape) are likely to vary over time. It can be shown that any periodic waveform is able to be accurately constructed using the sum of a series of sine waves (at frequencies of integer multiples of a fundamental) [9]. This summation can be written as (1):

$$A_{total} = A_1 \cdot \sin(\omega + \psi_1) + A_2 \cdot \sin(h_2 \cdot \omega + \psi_2) + \cdots + A_n \cdot \sin\,(h_n \cdot \omega + \psi_n) \qquad (1)$$

Where

A is the peak value of the sine wave magnitude
ω is the angular frequency of the fundamental (nominally 50 Hz in Australia)
h_n is the harmonic order of integer n
ψ_n is the phase shift of the sine wave at angular frequency $h_n \cdot \omega$
A_{total} is the resulting distorted waveform.

Figure 2-1 shows an example of a distorted waveform, illustrated in blue, which is comprised of three (fundamental plus harmonic) waveforms. The magnitude, frequency and phase parameters for each components of the waveform in Figure 2-1 are provided in Table 2.1.

Table 2.1 – Parameters for example waveforms in Figure 2-1

Waveform	Peak Amplitude (pu)	Frequency (Hz)	Phase Shift (°)
Fundamental	1	50	0
3rd harmonic	0.1	150	0
7th harmonic	0.05	350	0

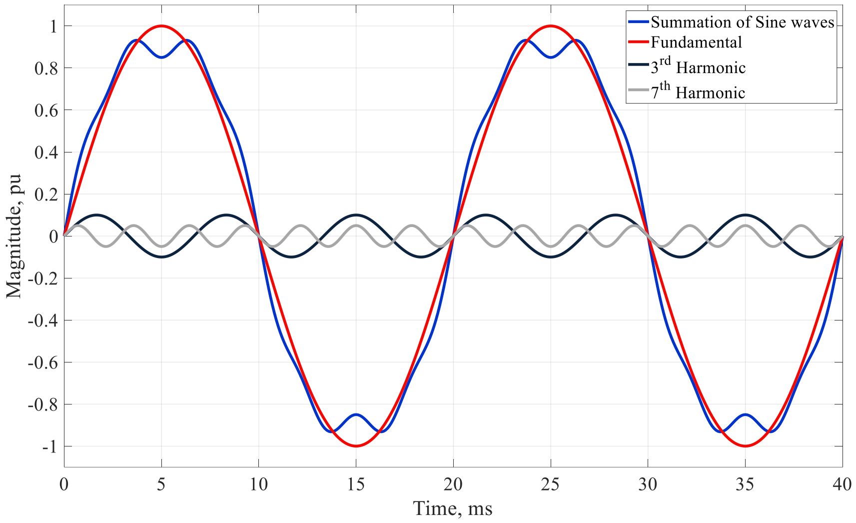


Figure 2-1 – Example distorted waveform with individual harmonic components

2.2.2 Causes of harmonic distortion in power systems

The most common cause of harmonic distortion is the presence of non-linear loads. Non-linear loads are those that draw currents which include frequency components in addition to the 50 Hz fundamental frequency and which are not sinusoidal in shape. Any non-linear current waveform can be mathematically described by (1) as a collection of sinusoidal signals with individual magnitude, integer multiple frequencies, and phase shifts. Networks inherently possesses frequency dependent impedance that interacts with distorted current giving rise to harmonic voltage. Examples of non-linear loads or installations within the transmission and distribution system include (but are not limited to):

- Inverter based REGs, such as some wind turbine technologies and solar PV
- Battery storage installations
- STATCOMs and SVCs
- HVDC connections
- Arc furnaces and other smelters
- Power electronic based appliances

Due to the increasing number of non-linear loads being connected at large scales to international networks, it has been identified that a comprehensive review of how the devices interact with the network with respect to harmonics and pragmatic harmonic distortion management processes should be performed [10-12]. Studies such as those presented in [5, 6] indicate that Australia is likely to experience significant impacts from renewable based generation penetration due to the physical structure of the grid, i.e. long feeders, areas of low system strength, and high levels of inverter based renewable energy sources. Appropriate (technical and cost) mitigation for these impacts, or alternative approaches to harmonic management, will be required in the near future.

2.2.3 Impact of harmonic distortion

The impact of harmonic distortion within networks is a well-researched topic. The most significant concerns include:

- Increased losses, i.e. increased heating of transformer windings, rotating machinery windings, lines and capacitor banks, and within customer appliances.
- Reduction in the effective life time of equipment.
- Negative torque in rotating machines which leads to additional heating increasing losses and potentially reduction in rated lifespan.

- Maloperation of network protection and signalling systems.
- Malfunction of power-electronic controllers and harmonic instability.

Each identified impact increases costs and risk to connected customers, generators and the network service provider (NSP). Therefore, harmonic distortion needs to be managed in a pragmatic manner that does not over-burden connecting customers. This is achieved by designing equipment to have immunity to harmonic distortion while also limiting the magnitude of distortion present in networks to levels below equipment immunity levels.

2.3 IMPACT OF RENEWABLE ENERGY GENERATORS ON HARMONIC DISTORTION

Large REG that connect to the network via power electronic interfaces are a source of harmonic emissions [3, 10, 12-14]. Given that REGs are often connected to weak areas of the network (mainly due to the geographic location of renewable energy resources and/or the geographic area required) the impact such installations have on harmonic distortion levels may be significant, especially where high penetrations exist. Further, auxiliary components (

e.g. passive harmonic filters) and long underground reticulation cable networks of these installations are capable of altering the impedance of the network at the point of connection [14], subsequently impacting the overall distortion within the network.

There have been many research and industry supported studies investigating the impact of REGs on harmonic distortion levels. Activities undertaken in these studies include monitoring and/or detailed modelling of the installation and network, followed by analysis or deterministic studies to identify the impact of individual installations on the network at the point of common coupling (PCC) [15-20]. While these studies predominately examine the impact of individual sites, there are also multiple long-term power quality (PQ) monitoring programs undertaken by network service providers (NSPs) that capture the impact of the rapid increase of REG connections. Using these studies, it possible to review the impact that REG connections are having on system wide network performance and trends of distortion levels over time. To appropriately manage harmonics in networks with high penetration levels of REGs, it is important to first understand the potential impacts of such installations.

2.3.1 Generator technologies

The power electronic interface by which REGs typically connect to the network vary depending on the energy source and topology used by the manufacturer. Some of the more typical generator technologies in use are included in Figure 2-2 – Figure 2-5.

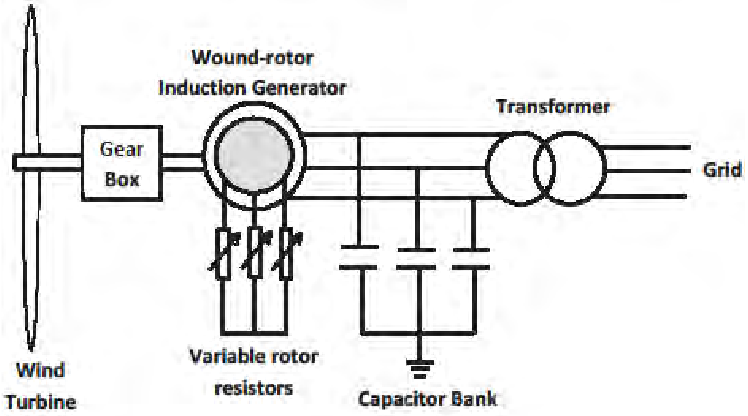


Figure 2-2 – Type-II Wind Turbine Generator

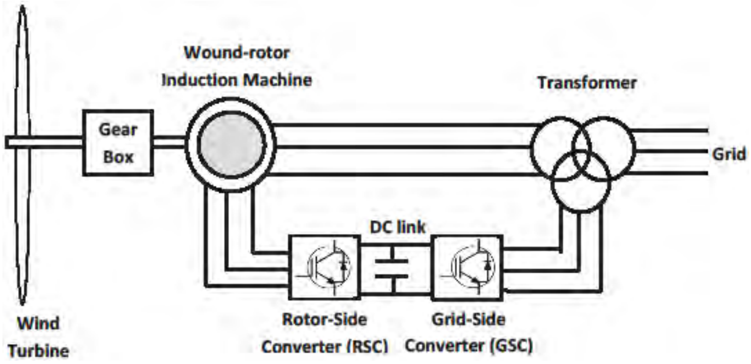


Figure 2-3 – Type-III Wind Turbine Generator

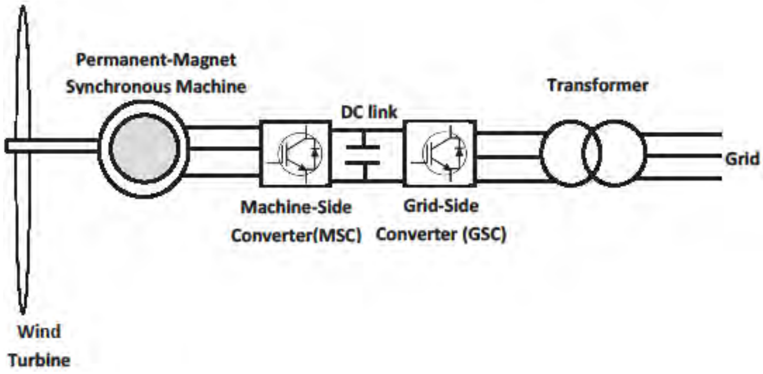


Figure 2-4 – Type-IV Wind Turbine Generator

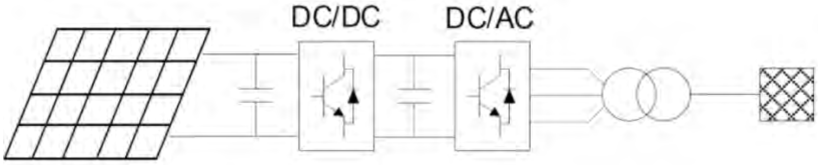


Figure 2-5 – Solar PV Generator Inverter [2]

Older generation wind farms are most likely to contain wind turbine generators (WTG) of Type-I (same as Type-II without variable resistor component) or Type-II topologies (refer to Figure 2-2). Type-I and Type-II wind turbines do not use power electronic switching components and thus do not inherently emit steady-state harmonic current to the network [21]. Instead, these devices present as a complex impedance, capable of impacting the network impedance and subsequent harmonic distortion levels.

Type-III and Type-IV wind turbines incorporate active switching components, thereby introducing harmonic distortion. Type-III WTGs are known to emit both harmonic and interharmonic emissions due to the operation of converters on the grid and rotor side. Emissions characteristically include higher order harmonics due to the air-gap flux present between stator and rotor windings not being perfectly sinusoidal [22].

Type-IV WTGs employ back-to-back converters, decoupling the generator from the network. Harmonic emissions of Type-IV generators are mostly due to switching frequency sideband emissions (high order), AC/DC cross-modulation, and the non-ideal nature of switching components (e.g. dead-time) [2]. Generally, low-order harmonic emissions of Type-IV WTGs are relatively low, although shifting resonance frequencies resulting from long underground cables and reactive power support equipment are a common concern.

Harmonic emissions of PV inverters are similarly due to the non-linear operation of the power electronics (PE). Emissions are capable of varying significantly due to changing conditions of the network and the operational state of the device itself [23, 24]. These impacts are difficult to ascertain and thus a generalised emission spectrum for individual PE devices is generally not practical. If a network operator or proponent is required to develop an understanding of how an installation will interact with the network (with regards to harmonic emission levels), modelling data is required to be supplied by the original equipment manufacturer (OEM). However, the data is often limited and the process undertaken to collect the data is not always consistent, this topic is discussed in further detail in Section 6.

2.3.2 Management of harmonics

Tools to manage harmonic emissions have existed for decades, however, it has become apparent that networks with high penetration of REGs require special attention. The unique challenges include evaluation of emission of harmonic orders that are not generally associated with other loads and higher frequency harmonic orders, difficulty related to harmonic modelling, requirement for mitigation equipment and its impact on network impedance and difficulties applying existing allocation and compliance assessment methodologies.

Management of harmonics is achieved through a number of mechanisms, however for MV and HV customer connections, in principle, the process relies on dividing up (allocating) the total harmonic emissions able to be absorbed by the network without resulting in harmonic distortion magnitudes exceeding specified planning levels. The development of harmonic voltage planning levels was based on the measured emissions and characteristic harmonics of the predominant emitting technologies at the time of standards development, e.g. the experiences shared in [25] relates the proliferation of DC rail throughout the second world war to the development of the first known network standard to manage power system harmonic distortion in 1952 [25, 26]. A revision to these standards were published in the UK in 1967 and revised in 1976 [27] which were the initial iterations of what is referred to Engineering Recommendation G5/5 [28]. For example, the characteristic harmonic spectrum of a three-phase LCC six-pulse inductor filtered rectifier under balanced and ideal conditions can be calculated with reasonable accuracy using (2) [29].

$$I_h/I_1 = 1/h \tag{2}$$

Where

I_h is the harmonic current in p.u. at order h

I_1 is the fundamental current in p.u.

h is the harmonic order sequence of $h = 6k \pm 1 \qquad k = 1, 2, 3 \ldots$

The harmonic spectrum of the resulting current emissions is shown in Figure 2-6. The characteristic harmonics for such devices are odd orders not divisible by 3 (i.e. exclude even orders and “triplen” harmonics).

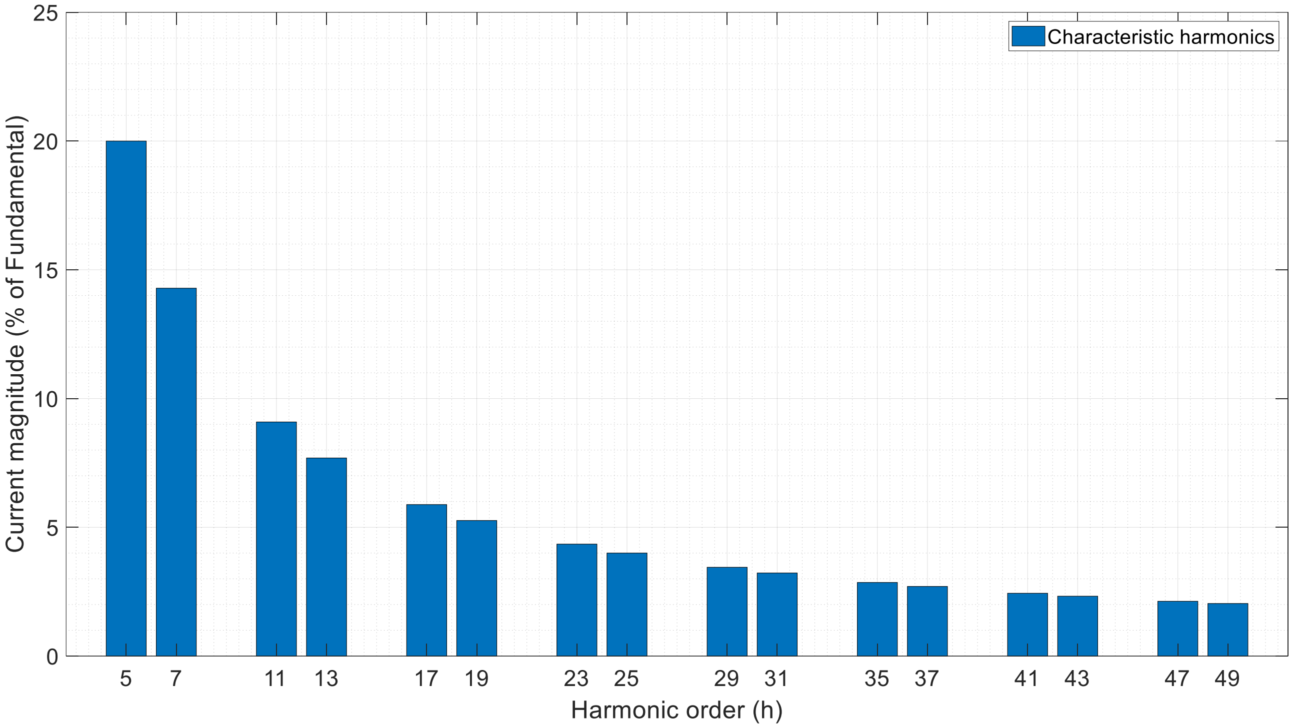


Figure 2-6 - Characteristic harmonic spectrum of six-pulse Rectifier

The impact of developing planning levels and allocating harmonic emission limits based on specific equipment characteristic harmonic emissions is reviewed in more detail in later sections. However, it has been presented here as it is identified in [2, 4, 30, 31] that typical power electronic (PE) interfaces of REGs are capable of emitting harmonic orders that do not follow the characteristics of (2), i.e. the harmonic emissions of inverter based REG plants does not follow that of traditional large PE equipment and will emit even order and triplen harmonics. It is identified in [2, 31-35] that a number of network and operational conditions may lead to a considerable increase of non-characteristic emissions from REGs. For example, unbalance in phase voltages and network impedances are capable of introducing a 2nd order harmonic ripple in the DC-side voltage of power converters which subsequently leads to increased emission of 3rd harmonic on the AC side. Further, emissions of non-characteristic harmonics have been attributed to network asymmetry and non-ideal switching within inverters (e.g. IGBT dead-time) [31, 34].

A number of case studies have identified an increase in the magnitude of non-characteristic harmonic orders in electricity supply networks due to the connection of utility-scale REGs. For example, [36] identifies an increase in harmonic levels for low order characteristic harmonics over a one year period, in addition, increases in the 2nd, 4th and 8th harmonic orders were also detected. The authors attributed this to connection of new network equipment such as long HVAC cable networks, inherent to wind farms, subsequently shifting electricity network resonant frequencies lower, explained in further detail in Section 2.3.4.

The study presented in [37] reviews a scenario where HVDC and REG (windfarms) are both connected to an onshore transmission system electrically close to one another. The study identifies an increase in the magnitudes of 4th, 7th and 17th harmonic orders. This increase is predominantly attributed to the long reticulation and grid interfacing HV cable connecting the windfarm to the network. The outcomes suggest interactions between various PE devices within the vicinity of each other are capable of having significant effects on harmonic emission levels, including amplified characteristic and non-characteristic harmonic orders.

Numerous studies detail harmonic measurements being undertaken for a range of REG converter types and rated capacities. In [19, 38] long-term measurements of windfarms were analysed and notable changes to emissions at characteristic, low-order harmonics and interharmonics (non-integer) were identified. Whilst the analysis within [19] employs debatable approaches to harmonic source detection [39, 40], the changes detected using long-term trends in [19, 38, 41] confirm that REG installations are capable of having significant impacts on harmonic distortion levels. The analysis of [38] also highlights the importance of pragmatically managing non-characteristic and interharmonic orders, likely requiring a re-evaluation of planning levels.

Some case studies, based on actual measurements of existing wind turbines are provided in [38]. Further to confirming increased harmonic distortion being measured for characteristic and non-characteristic harmonic orders, the study investigates the impact of renewable generation replacing conventional thermal-based generation, thereby removing synchronous generators from the network. In such scenarios, the low-impedance characteristic of the generators is removed and thus impacts the harmonic voltage emission levels. Analysis of the resulting system impedance shows that in some scenarios this may increase harmonic impedance for lower frequencies, but decrease the impedance for higher frequencies, as shown in Figure 2-7.

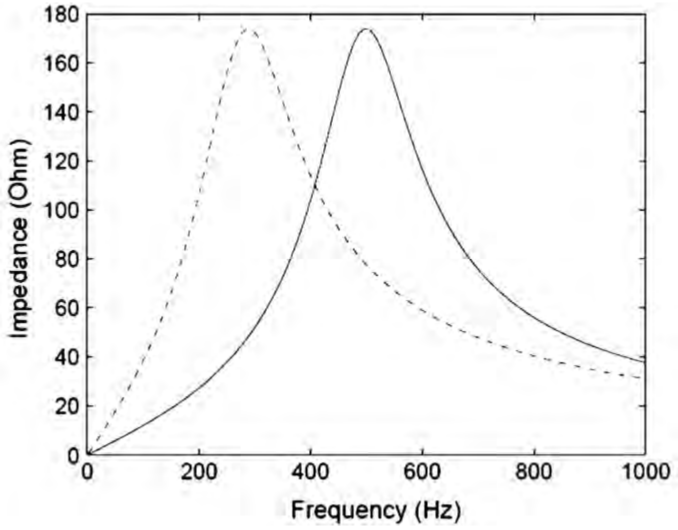


Figure 2-7 - Network harmonic impedance for a strong (solid line) and weak (dashed line) network from [38]

The outcome demonstrated in Figure 2-7 emphasises another aspect of the impact of REG on network impedance. With reduced synchronous generation connected, network harmonic resonant frequencies may shift to lower, more problematic values, including non-characteristic and interharmonic orders [38]. Such outcomes are challenging when combined with the ongoing connection of PE devices, emitting characteristic, non-characteristic and interharmonic orders.

Extensive testing, measurement and analysis of the harmonic emissions of PV inverters, solar farms and utility scale PE devices is provided in [23, 32]. Both publications identify not only the potential for increased harmonic emissions due to the connection of such components but also the dependency of emissions on network conditions such as background distortion and network harmonic impedance. It is an important finding that the harmonic emissions of many present-day, non-linear devices are dependent on a range of network and operational conditions. Whilst this outcome may have little bearing on the process of harmonic allocation and management, it is inherently important when undertaking compliance assessment and thus should be noted.

As previously discussed, non-characteristic and interharmonic orders were once considered inconsequential as the emission levels of characteristic harmonic orders dominated the spectrum. Recent experiences of NSPs and proponents internationally suggest emissions of these once inconsequential harmonic orders are likely to increase due to the continued connection of REGs. When combined with shifting resonant frequencies, the outcome may be that planning levels are exceeded or the management of harmonics become more difficult. It is apparent that the harmonic impact of all non-linear devices need to be treated with due consideration. The existing literature identifies the unique challenges of REG integration due to inherent componentry and potential for increased harmonic emission levels, including non-characteristic orders. The impact of increased emissions for all harmonic orders may be exacerbated due to the connection of reactive power support or passive filtering components and their interaction with network harmonic resonant points. This is explored further in the following section.

2.3.3 Passive harmonic filtering and reactive plant

Reactive power support, e.g. power factor correction (PFC) capacitors, and passive harmonic filtering are used within REG installations to address issues related to power-factor correction, reactive power/voltage support, and power quality including harmonic distortion [42]. The circuit topology of a single tuned shunt harmonic filter is shown in Figure 2-8, which provides a low impedance path for the harmonic current at the tuned harmonic frequency. Dedicated resistor banks (as shown) may also be included in the design of passive filtering if resonance damping is an objective.

Figure 2-8 - Passive harmonic filter

Whilst passive harmonic filtering is relatively simple to implement and cost effective for proponents attempting to address harmonic emission compliance concerns, connection of passive filters to the network is capable of introducing and/or shifting network resonant frequencies to lower values [42-44]. Harmonic resonance presents a challenge for NSPs as coincidence of network resonant frequencies with harmonic sources can result in amplification of harmonic currents or voltages. The design and implementation of passive harmonic filters is sensitive to network operating conditions, ambient/operating temperature, and parameter variation effects due to component tolerances and deterioration [42]. Such factors are also capable of shifting network resonant frequencies. The use of passive filters also increase losses within the installation and the network [43].

Continued connection of passive filters (and reactive power support equipment in general) is capable of leading to multiple network resonant points occurring at lower frequencies [2, 45, 46] which further complicates the management of harmonic distortion. For example, a simple two bus network that is supplied by an upstream source with a fault level of 500 MVA, is shown in Figure 2-9.

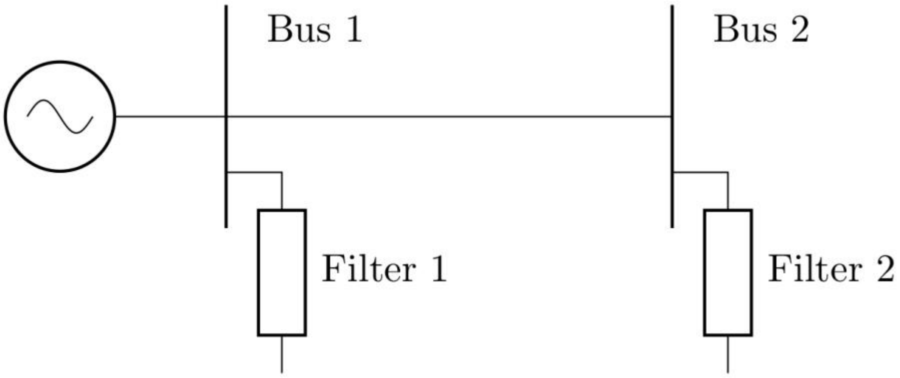


Figure 2-9 - Simple two bus system

An existing installation at bus 1 has a passive filter installed in order to meet allocated emission limits at the 5th harmonic order. Pre-connection studies for bus 2 find that mitigation is required for the installation to meet compliance at the 11th harmonic order. Another passive filter is designed and connected to address 11th order harmonic emissions. The connection of the second filter will introduce a resonance between that of the original filter and the tuned frequency of the new filter. This can be seen by comparing the harmonic impedances of the network, as seen by bus 1, for both scenarios, as shown in Figure 2-10.

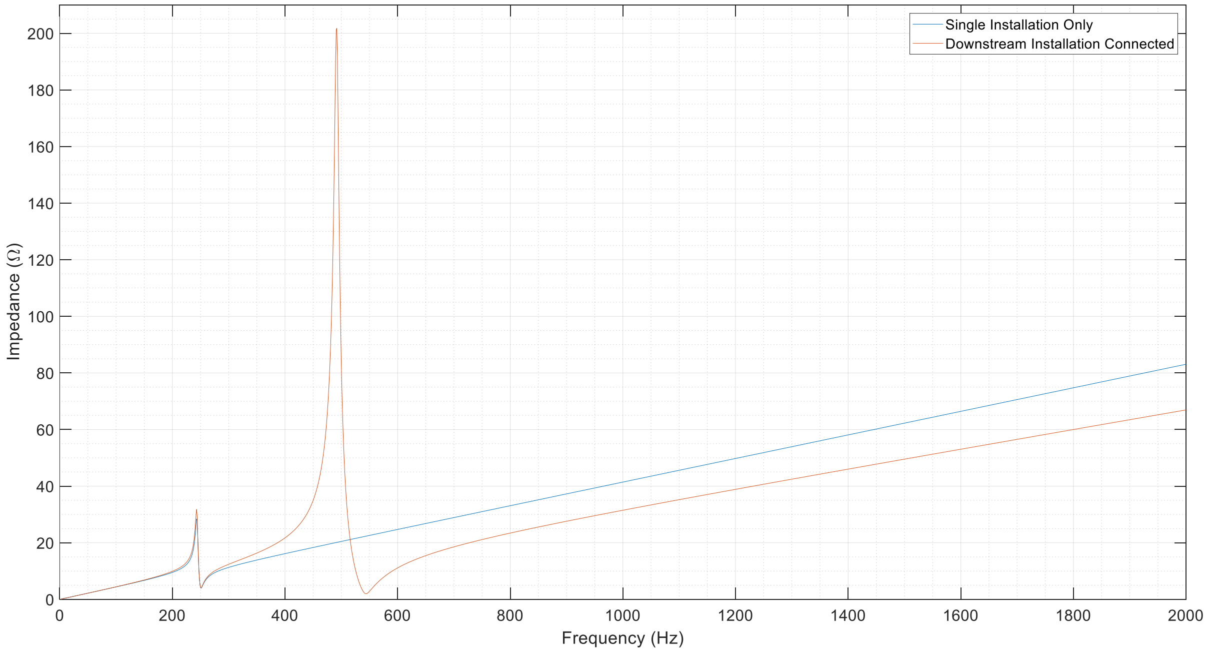


Figure 2-10 – Harmonic impedance comparison when viewed from Bus 1 for evolving network with passive filtering

Whilst the designed filters may continue to mitigate emissions at the harmonic order for which they are designed, the resonance introduced by the second filter may correspond to a frequency at which significant emissions exist for the first installation. Due to the impedance of the network prior to the connection of the second installation, emissions which may not have been a concern may become problematic once the second installation is connected.

The present emission allocation process applied in Australian combined with conservative harmonic management strategies (e.g. planning levels, use of multiple network scenarios which do not reflect normal operation and impacts of long line impedances) applied by NSPs is resulting in passive filters being required for many large REG installations. This is discussed further in Section 3, however it should be noted that due to the concerns related to shifting and/or multiple network resonant frequencies, and increased network losses, it is in the interest of both NSPs and REG proponents that the installation of passive components for filtering and reactive compensation be carefully considered [46].

2.3.4 Impact of underground and submarine cable

There exists a number of case studies and reports in which the inherent capacitance of cables, often used for reticulation networks within large REG plants, has been reported to have a significant impact on network resonant frequencies [13, 14, 36]. Capacitance exists between conductors and also the conductor and outer layers of the cable (e.g. semi-conductor layer, insulation, sheath armour, etc.)[47, 48]. Equation (3).[1] provides a simple estimation of the first harmonic resonance frequency due to the connection of a capacitive component to the system [36].

---

[1] It should be noted that (3) omits the impact of network capacitance and should be used as a general guide only.

$$h_r = \sqrt{\frac{X_C}{X_S}} = \sqrt{\frac{MVA_S}{MVA_C}} \qquad (3)$$

Where

h_r is the resonant harmonic order

X_C is the capacitive reactance being connected

X_{SC} is the inductive reactance of the of the transmission system at the PCC

MVA_s is the system short-circuit power at the PCC

MVA_c is the reactive power produced by the capacitive component

Inspection of (3) identifies that the resulting resonant frequency is inversely proportional to the ratio of the fault level of the network at the PCC and the reactive component of the connecting cable, i.e. the frequency shift is greater for weak networks. A simple graphical representation of this impact for a nominally strong and weak network is shown in Figure 2-11 in which the estimated harmonic resonance is calculated using (3) for a strong and weak network, $MVA_S = 1000\ MVA$ and $MVA_S = 250\ MVA$ respectively.

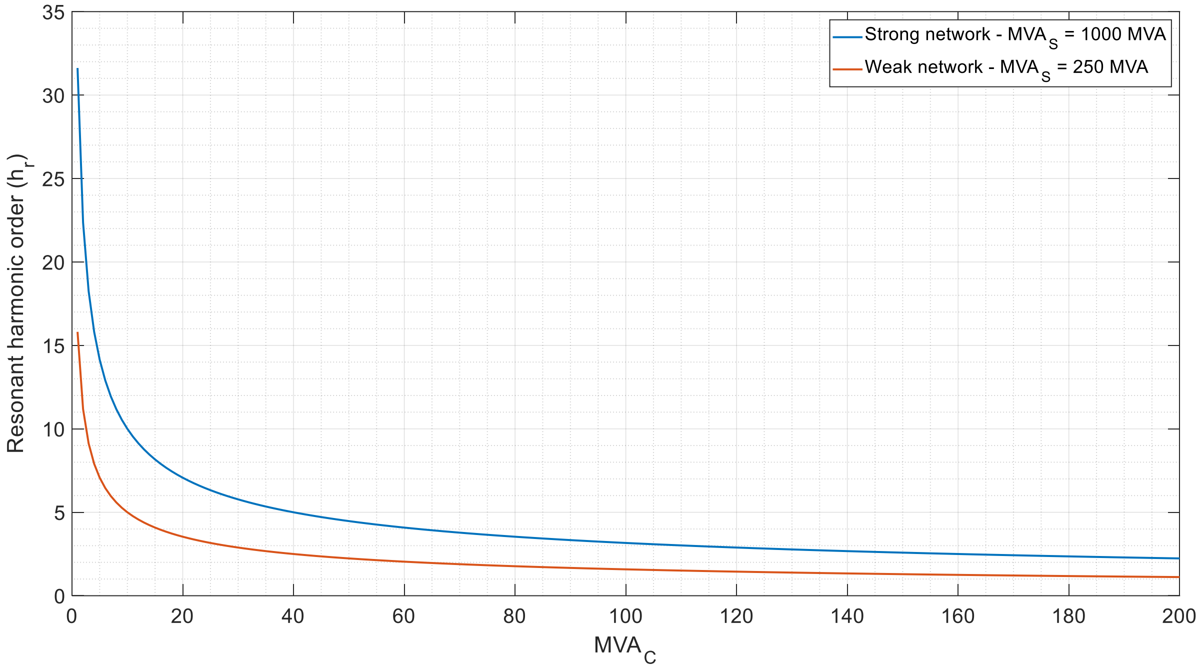


Figure 2-11 - Estimated resonant frequency for varying capacitive connections. Strong network ($\boldsymbol{MVA_S = 1000\ MVA}$ (blue)), weak network ($\boldsymbol{MVA_S = 250\ MVA}$ (orange))

It can be seen in Figure 2-11 that the harmonic order which corresponds to the resonant frequency is significantly impacted by the increasing connection of capacitive MVA for both networks. However, the impact on the weaker network may be of more concern as the resonant frequency falls to a lower value potentially aligning with harmonic orders that are more likely to have higher levels of existing background distortion.

The impacts on resonant frequency due to the connection of long reticulation and feeder cables within large REG installations have been identified and reported by the Irish, Dutch and German TNSPs that have continued (and are expected to continue) to connect large amounts of wind power plants [44, 49].

The impact of reticulation network capacitance is typically less for large PV plants due to the shorter lengths of cable required. However, the connection of such installations to weak areas of the network, including any passive filtering or reactive plant needs to be considered with care in reference to the same concern of shifting network resonant frequencies as per (3).

2.4 LONG-TERM POWER QUALITY MONITORING CAMPAIGNS RELATED TO RENEWABLE GENERATION

The ongoing concern related to the impact of REG connections on power quality is evidenced by the number of large, industry supported, research projects undertaken in recent years. These studies have focussed on reviewing and estimating the impacts of high penetration levels of REG connections on the operational capability of electricity networks, including the impacts on power quality, principally, harmonic distortion [3, 4, 10, 13, 36, 50, 51]. The majority of such projects explicitly state that there is an increased likelihood for increased harmonic voltage levels due to the connection of REG.

A review of international PQ monitoring campaigns has been completed in order to develop an understanding of the experiences of NSPs both nationally and internationally. Where available, network measurements were collated to determine historical harmonic distortion trends. Where data is available before the connection of REG, trends can be used to empirically identify the impact of REG as it is connected.

2.4.1 Australia

In 2002 the Australian Power Quality & Reliability Centre (APQRC) began a long-term survey in which various power quality characteristics were audited across participating networks and appropriate indices were developed to benchmark performance. Due to the ongoing status of the study, the project is now capable of identifying PQ trends for Australian network operators that participate in the program.

Reporting in [52] identifies a near linear increase of voltage THD throughout the years of 2002-2006 and shows the level of THD almost doubling within the four year period. A second study, presented in [53] found that harmonics across the MV and LV networks had slightly decreased over the period of interest (prior to 2017). The earlier study would not have captured the recent sharp rise in large-scale REG connections, however the latter does to an extent.

It is suggested in [53] that the small decrease in harmonic emission levels may be attributed to technology changes in small domestic non-linear devices (e.g. consumer electronics and air conditioning) subsequently lowering the level of harmonic current emissions along with more informed use of harmonic allocation and management techniques. The impact of harmonic phase cancellation and altered network impedance may also contribute to this small reduction in harmonic voltage levels.

2.4.2 The Netherlands

Perhaps the most transparent and accessible PQ monitoring campaign has been undertaken by a committee of network operators within the Netherlands, known collectively as Netbeheer Nederland (directly translates to: *Grid management in The Netherlands*). The measurement program includes PQ measurements from 2013 onwards and encompasses data for all voltage levels from LV to EHV [54]. For substations where monitoring devices are installed, the weekly average THD for individual phases is reported (among other PQ characteristics) and compiled into quarterly reports. This large scale, long term monitoring program allows investigation of the impact of REG by observation of trends in disturbance levels over time. Given that data is available prior to the proliferation of REG, if all other factors were to remain constant, movement in disturbance levels attributable to connection of REG may be identified.

The format and availability of data provided in [54] restricted the number of substations able to be reviewed. To develop an understanding of the impact of large REGs on the trend of harmonic levels within the Dutch electricity distribution networks, specific areas were targeted based on the proximity to recently commissioned REGs. For the selected areas, THD levels were collated and analysed. Using this data, an average harmonic trend was developed over the available time range. Results and analysis for the areas investigated (Eemshaven, Westermeerdijk, Eneco Luchterduinen and Borssele Stages I & II) are provided below.

2.4.2.1 EEMSHAVEN

The transmission infrastructure in Eemshaven is vital to a number of sub-networks as it provides key links between transmission networks in The Netherlands, Norway, Denmark and the 600 MW Gemini Wind Farm. The area has a total supply capacity of approximately 8 GW [55].

The Gemini wind farm was commissioned in 2017 and is located 85 km off the northern coast of The Netherlands and connects directly to the TenneT network at Eemshaven [56]. Although not specifically identified in official documentation, there is indirect reference to the use of a STATCOM [57] and passive filtering [56] within the onshore substation for the purposes of harmonic mitigation. The STATCOM being able to provide reactive power support and, in some cases, act as an active harmonic filter [58, 59]. Processed THD data for the Eemshaven substation is available from 2014 onward. Figure 2-12 shows the trend of THD levels over time. The yellow line on the graph indicates the commissioning date of the Gemini Wind Farm.

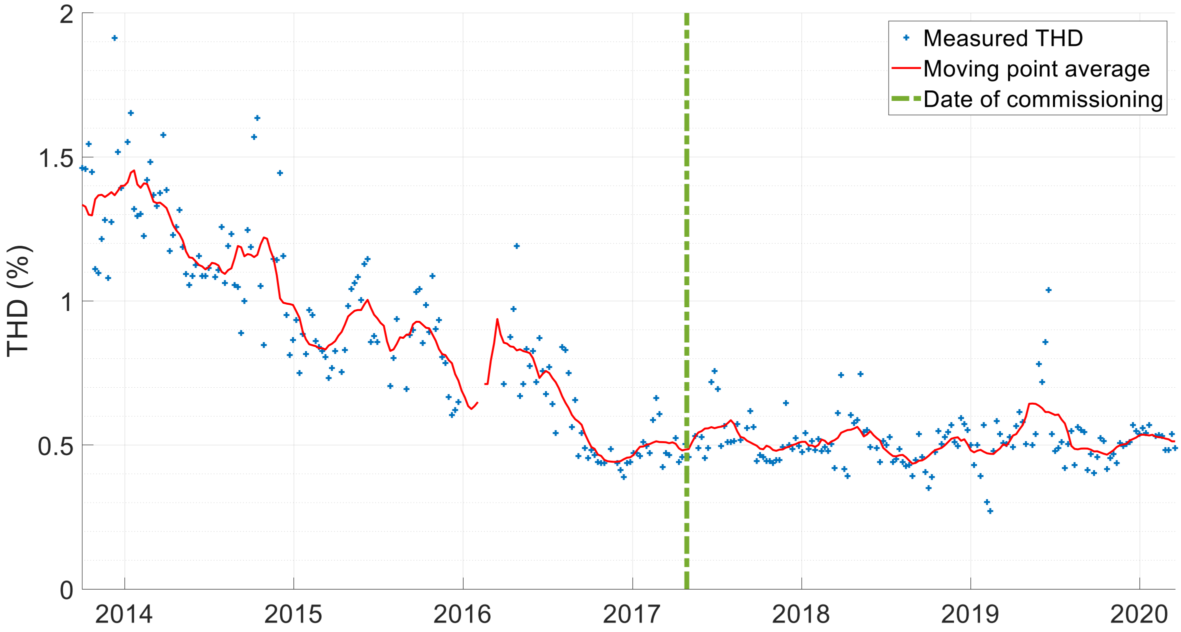


Figure 2-12 - THD of Eemshaven with moving average

Based on the data provided, a continued reduction in THD levels at Eemshaven is observed. Correlating the data with the project timeline for the Gemini wind farm, provided in [60], suggests that increased investment in transmission infrastructure, including potential harmonic mitigation strategies, may have been a contributing factor to a long-term reduction in voltage THD levels [55-57, 60].

2.4.2.2 WESTERMEERDIJK

The Westermeerwind wind farm, considered a ‘near-shore’ wind farm, is located on the IJsselmeer, the largest lake in The Netherlands and has a nameplate rating of 144 MW [61]. A number of upgrades were made to the existing transmission infrastructure to accommodate this installation, including an onshore transformer and switching station prior to commissioning of the wind farm in June 2016. Measurements prior to the installation of the windfarm are not available. Instead, data was collected and processed for the nearby Vollenhove substation. This data is shown in shown in Figure 2-13 with the yellow line again indicating the date of windfarm commissioning. The Vollenhove substation is located approximately 25 km from the Westermeerwind wind farm and data was available throughout the construction and commissioning process (although not for the entirety of 2018).

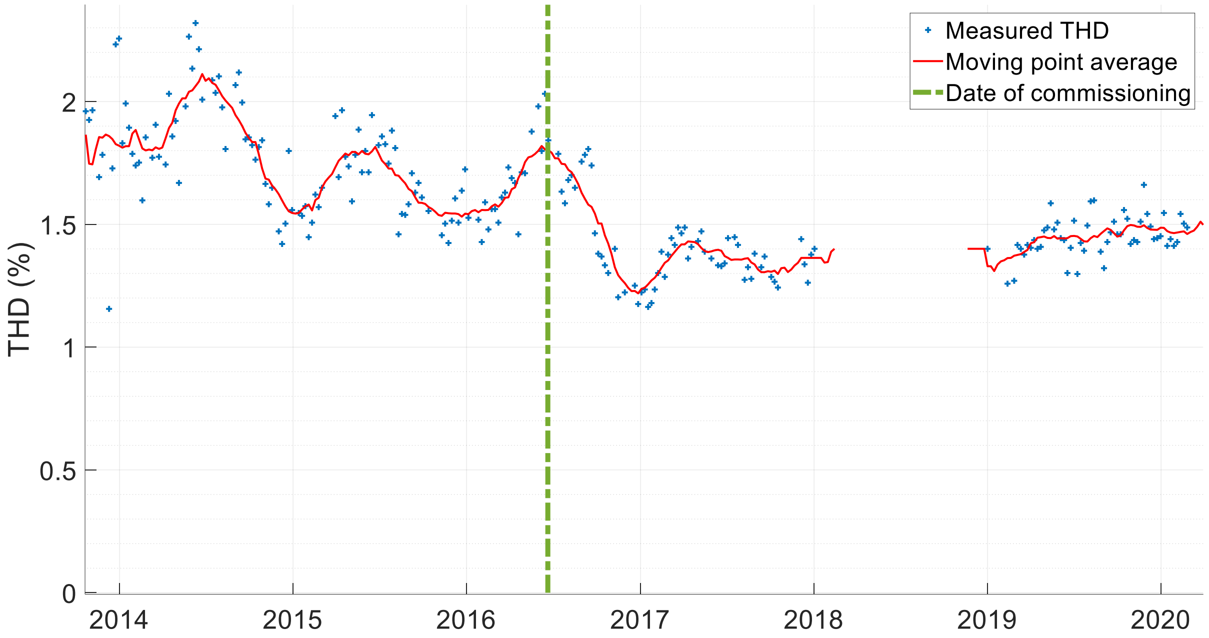


Figure 2-13 - THD of Vollenhove with moving average

From the time of commissioning of the Westermeerwind wind farm, a continued reduction of THD can be observed, noting the seasonal peaks during summer months which appear to be dampened post-commissioning. Minimal information was available regarding the cause of reduction in voltage THD, however, it could be due to one or more of the following:

- Transmission infrastructure investment;
- Installation of harmonic mitigation, reducing background distortion as well as plant emissions;
- Increased phase cancellation (diversity); or
- Connection of passive components (capacitive cable elements, transformers, etc.) shifting resonance away from background harmonic orders.

Without detailed information regarding the network, it is difficult to identify precisely the degree of impact that each of the above is having on the harmonic distortion levels in the network surrounding Vollenhove. Other network modifications not made publicly available in the Vollenhove area may also contribute to this decrease in THD. To further investigate the impact the Westermeerwind wind farm may have had on the harmonic distortion levels around Vollenhove, the available data for the commissioned Westermeerdijk substation was overlayed with that of the Vollenhove substation, as shown in Figure 2-14.

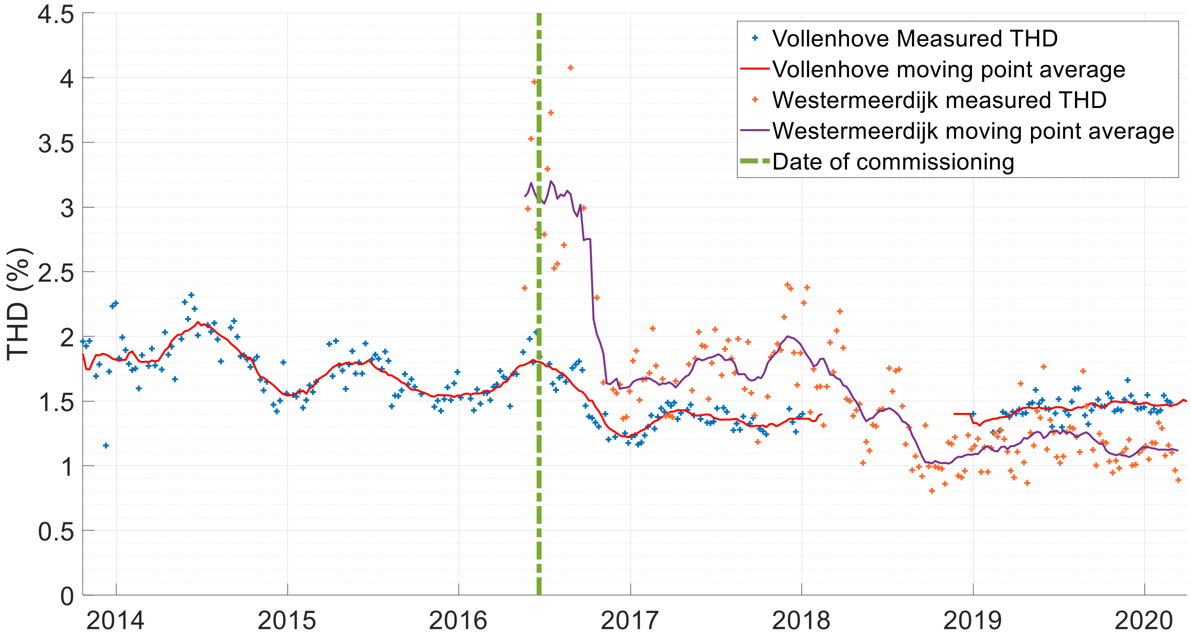


Figure 2-14 - Vollenhove THD data with Westermeerdijk THD overlayed

The data presented in Figure 2-14 identifies the Vollenhove substation to be somewhat representative of the area near the Westermeerwind wind farm. Further, a comparative 'spike' in THD levels can be detected in both data sets during the period following commissioning. This spike aligns with existing seasonal peaks and follows a similar trend of the Vollenhove substation. This is to be expected as commissioning tests can take months to complete and may include modifications to components such as park and inverter controllers, subsequently impacting harmonic emissions (reviewed in later sections). The data following this period for both data sets suggest the overall THD settles at a lower level than prior to windfarm connection.

Whilst it is difficult to make any confident suggestion with respect to the measured impact the Westermeerwind wind farm has had on the local THD levels, a demonstrable reduction in THD is shown, the cause of which can only be postulated.

2.4.2.3 ENECO LUCHTERDUINEN

The Eneco Luchterduinen wind farm was commissioned in September 2015 [62] and has a nameplate capacity of 129 MW. The wind farm is connected to the TenneT network in Sassenheim via a 25 km submarine cable along with an 8 km underground cable [63]. Data for the Sassenheim substation is available from July 2015 onwards and is shown in Figure 2-15 (the yellow line indicates the date of commissioning of the Eneco Luchterduinen wind farm). Similar to the case of the Westermeerdijk wind farm, Figure 2-15 shows seasonal trends, which are again dampened after the wind farm is connected. However, the seasonal peaks measured at Sassenheim substation align with winter months rather than summer peaks as at Vollenhove. The cause of these peaks is difficult to identify from the available data.

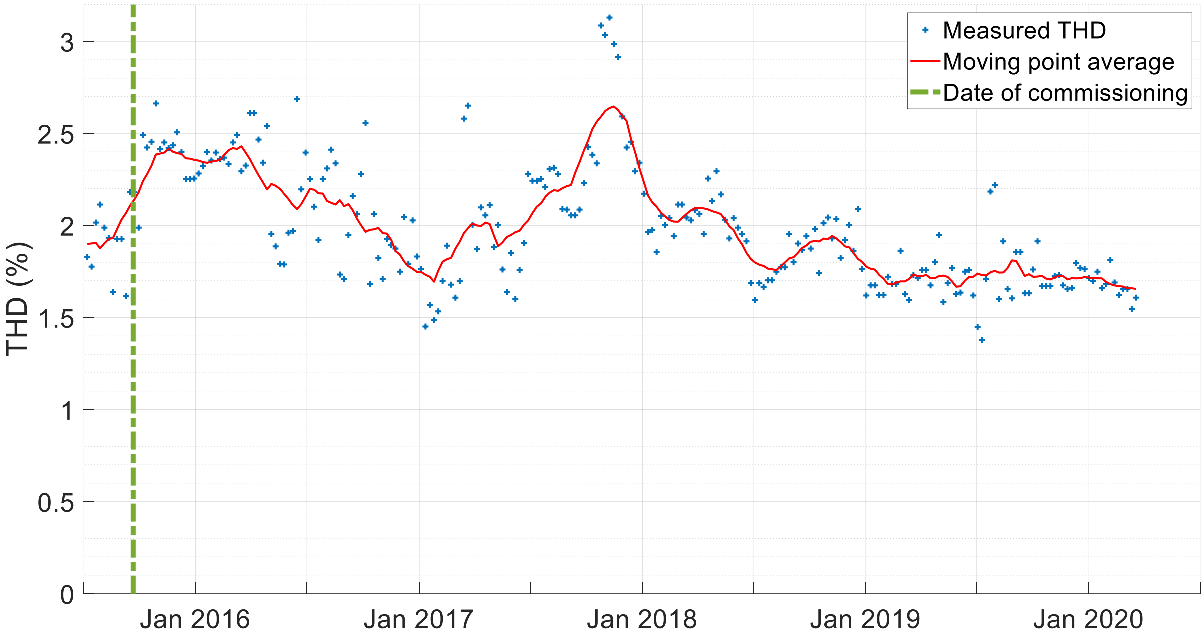


Figure 2-15 - THD of Sassenheim with moving average

2.4.2.4 BORSSELE STAGES I & II

The Borssele windfarm consists of four stages, with total anticipated capacity of approximately 1.4 GW. Stages I & II of the project, expected to be commissioned during 2020, consists of 750 MW and connects to the network within the town of Borssele [64], on the western coast of The Netherlands. Construction of an onshore substation was undertaken and partially commissioned in 2019 to accommodate for the increased generation in the area [65, 66]. THD data was compiled and a historical trend for the Borssele area is shown in Figure 2-16.

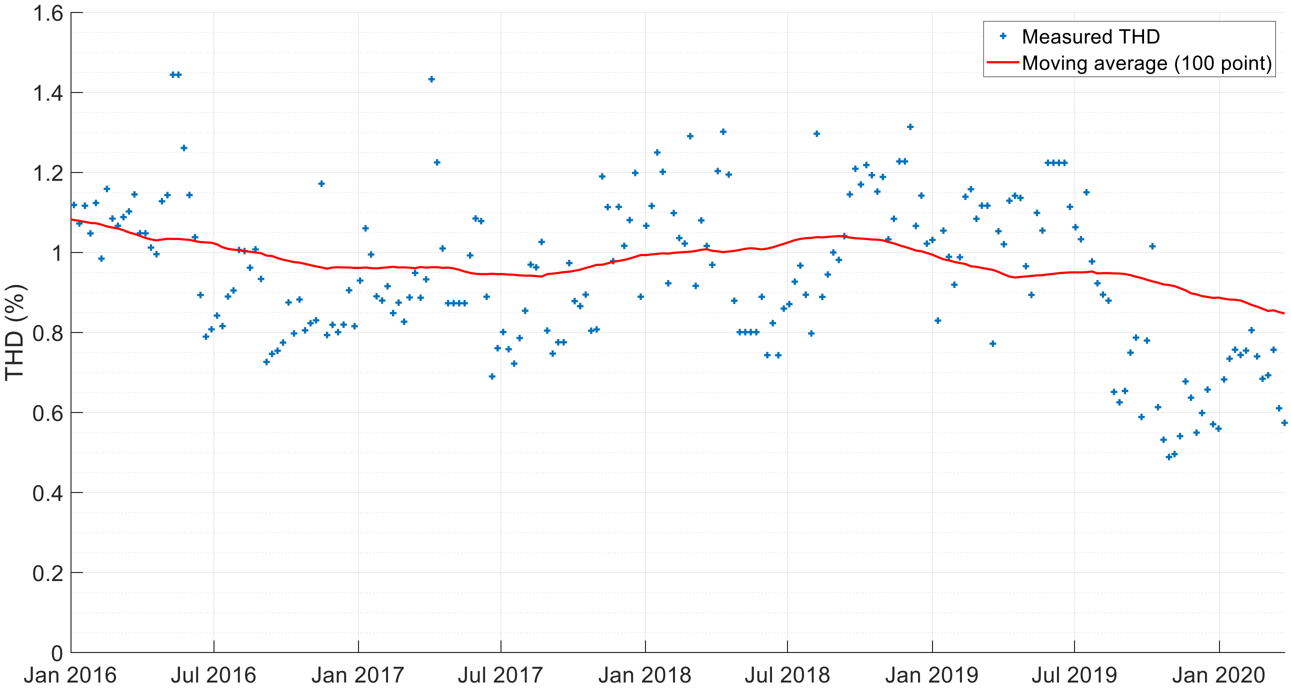


Figure 2-16 - THD of Borssele with moving average

Similar to results previously shown, a downward trend for THD is noticed for Borssele although the wind farm is yet to be fully connected and commissioned. Whilst exact commissioning dates for the onshore substation at Borssele are not available, it is identified in [66] that the station was partially active in 2019. Review of the data for 2019 only is shown in Figure 2-17.

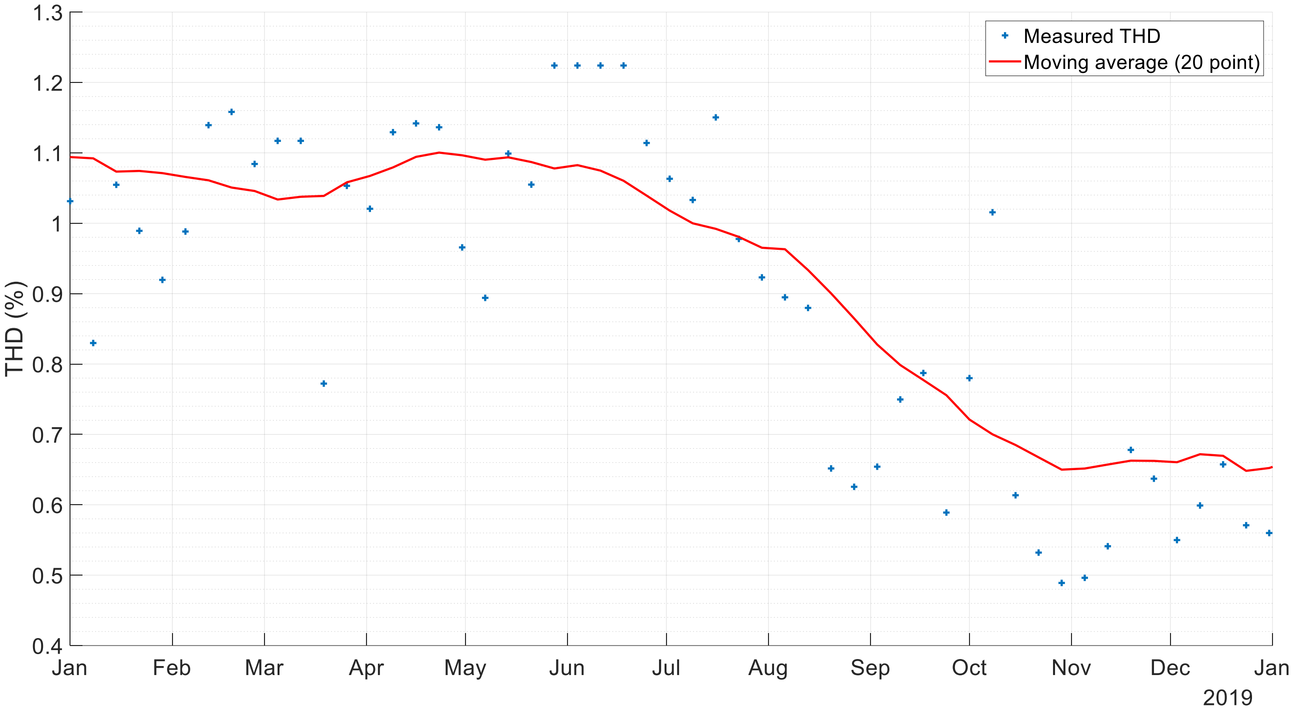


Figure 2-17 - THD of Borssele (2019) with moving average

Figure 2-17 shows a significant decrease of THD for the second half of 2019, however this could simply align with inherent seasonal trends such as those that have been detected for substations already reviewed. It would be prudent to continue collecting and analysing the THD levels of Borssele during the commissioning process of the anticipated windfarms. Without specific details related to the changes or investment made within the network, it is difficult to provide detailed insight into the impact the REG plants are having on the harmonic distortion levels. It is important however to note that the reviewed substations have not experienced an increased level of THD.

2.4.3 TenneT harmonic management

The process for harmonic allocation and management implemented by the Dutch transmission system operator (TSO), TenneT, for large offshore wind farms (OWFs) is summarised in [67]. Whilst the specifics of allocation will be reviewed in Section 3, the document identifies the responsibilities of both parties (i.e. proponent and TSO) with regards to the management of harmonic distortion. It is clearly stated in [67] that it is the responsibility of the proponent to ensure harmonic current emissions are below allocated limits (provided by TenneT) whilst mitigation of any adverse impacts due to the connection of the offshore wind farm (OWF) (e.g. harmonic resonance) is the responsibility of TenneT.

The division of responsibilities in such a manner requires the TSO to ensure the transmission infrastructure is capable of accommodating the expected level of asynchronous generator penetration. Whilst it is unknown whether such investment has been the standard operating practice of TenneT, the data reviewed in Section 2.4.2 shows that areas with newly commissioned OWFs have experienced a decrease of THD over the period of which data was available. The reduction in THD may be the result of active/passive filtering and the potential for OWFs to operate as a harmonic sink at particular frequencies.

It is difficult to provide definitive analysis of the harmonic trends developed in the figures above without more detailed information regarding commissioning dates, topology and components of supporting infrastructure. However, a key insight is that harmonic levels may be managed in areas with high levels of REG penetration through targeted investment in transmission infrastructure and careful application of harmonic allocation and management strategies. However, investment in infrastructure can be expensive and existing assets should be used to their full potential (e.g. in preparing for renewable energy zones as in [6]) before any upgrades are considered.

2.4.4 MIGRATE Project

The MIGRATE (Massive InteGRATion of power Electronic devices) project developed a range of work packages that address a number of the key technical challenges related to integrating non-linear devices into electricity transmission and distribution networks on a large scale. One of these packages included a detailed audit of existing PQ phenomena within European transmission systems [44]. The experiences of each TNSP, as summarised below, vary based on the size and strength of the network and the level of REG penetration; existing and expected. The project audit requested each participating TNSP to respond to a brief survey which included identification of the PQ phenomenon of most concern at present and anticipated in the future. A brief overview of the outcomes is provided below.

2.4.4.1 TENNET

Whilst some of the experiences of TenneT have been reviewed in detail in Section 2.4.2, they also participated in the survey for the MIGRATE project, in which they identified that the PQ phenomena of most concern was harmonics. As previously discussed, TenneT anticipates a significant level of OWF penetration driven by Germany and The Netherlands setting ambitious goals for renewable energy generation and already exceeding planned penetration levels [68]. Further, the proposed North Sea Wind Power Hub is expected to connect up to 36 GW of offshore wind power that will feed the Danish, Dutch and German networks [49].

Based on information provided in [44], the biggest challenge related to PQ being experienced by TenneT is shifting resonant frequencies due to the connection of long AC cables (as discussed in Section 2.3.4), with the primary concern being an increase in non-characteristic and interharmonic emission levels. Such impacts have also been shown to cause harmonic stability concerns, such as interaction between PE controllers and background distortion and/or system resonances leading to maloperation or increased harmonic emissions [13, 44].

2.4.4.2 ELEKTRO-SLOVENIJA (ELES)

ELES is a state owned and operated TSO responsible for the operation of the Slovenian power system. ELES identified their PQ phenomena of most concern as flicker, due to operation of multiple arc furnaces. Harmonic voltage levels over the years of available data (2009-2016) show a minor decrease in THD. This has been attributed to one or both of the following [44]:

- The ongoing strengthening of the transmission network
- Improved switching technologies

Although the voltage of some individual harmonic orders are increasing marginally, the Slovenian network remains considerably below the planning levels specified in [69].

2.4.4.3 ELERING

The Estonian TNSP, Elering, operates a relatively small network compared to some of its surrounding countries. The network has comparatively lower fault levels and has experienced similar connection rates of PE devices as many of the larger TSOs within Europe. This has manifested as a general increase in harmonic voltage levels with the weaker areas of the network exhibiting the largest increase [44]. There are reports of some areas exceeding planning levels. The country is also anticipating a continued uptake of offshore wind farms in the near future.

2.4.4.4 EIRGRID

The Irish TNSP, EirGrid, has identified the PQ phenomena of most concern as increasing harmonic distortion levels due to the impact of large wind farms, similar to that of TenneT. EirGrid, performed an empirical investigation of PQ trends within their network [36, 44], the study examined harmonic voltage trends within the Irish transmission system over 12 months and found the following:

- A reduction in magnitudes of triplen harmonic orders and orders above the 13th harmonic
- A significant increase for characteristic harmonic orders, particularly the 5th harmonic with a 24% increase over a single year. These trends were attributed to the significant increase in the level of penetration of wind farms and the associated underground/submarine cable reticulation networks (as per Section 2.3.4).

EirGrid introduced a revised harmonic allocation methodology in 2015 [70] which implements a headroom approach (details and review provided in Section 2.5.4). Whilst such a method is capable of positively impacting the harmonic management process, no studies have been found that provide insight into the effect on harmonic levels this change has brought.

2.5 METHODS OF UNDERTAKING ALLOCATION OF HARMONIC DISTORTION EMISSIONS

There exists a range of harmonic emission limit allocation procedures, the most prominent being the IEC [71] and IEEE [72] methods. There are also a number of procedures that are more specific to the network in which they are applied but have adapted parts of the IEC or IEEE methodologies, e.g. [70, 73]. Whilst some allocation methodologies are better suited for particular networks, a comprehensive and critical review of the available, unique approaches has been completed. The aim of this review is to identify the fundamental theories and inherent difficulties of each process with particular focus on uncertainties and the impacts related to allocation of harmonic emission limits in the presences of significant volumes of REG.

A concise and critical qualitative review of the IEEE method is provided in [74] which encapsulates the historical evolution of harmonic management and the ongoing difficulties and challenges related to the allocation of emission limits (for all prominent methods). The earliest application of limiting harmonic emissions can be dated back to 1913 [75]. Considering the number of distorting installations at this point in time, the allocation and emission assessment, is comparatively simple to apply and enforce. Since 1913 however, the number of distorting installations has increased in an exponential manner, requiring the management process to become more complex. As stated in [74], the experience and understanding of power engineers implementing harmonic allocation procedures has not always moved in lock-step with the level of distorting connections present or the technology of non-linear devices. As such, in many cases the methodologies presented in [71, 72] have been implemented as requirements, or law in the case of [76] in Australia. It is well documented and acknowledged by the IEC that the processes specified in these documents are intended to be guiding principles and should only be applied with sound engineering judgement as opposed to being considered a normative process [74, 77-79].

Although the objective is the same, the technical approach of allocating emission limits to a customer connecting to a transmission or a distribution network can be very different. This is due to how the networks are designed and operate and the impact this has on harmonic distortion and propagation. This project has a focus on addressing issues that are identified with allocation in transmission and sub-transmission systems, which often consist of meshed-network topologies.

To gain insight into the allocation methods that are in use internationally, a comprehensive analysis of a number of network and country standards has been completed. This revealed that whilst there exists a large range of allocation processes and methodologies, they can be grouped into two specific categories based on their alignment with the distinctive IEEE and IEC approaches. These have been given the terms:

- Fixed harmonic allocation methodologies (IEEE/related methods), and
- Network forecast methodologies (IEC/related methods)

A fundamental difference exists between the two processes, as discussed in [80, 81]. Fixed allocation methods, such as the IEEE method, allocate emission limits to connecting installations independent of the state of the network (existing or expected). The fundamental philosophy being that the assumptions made during the development of the allocation method will result in the harmonic voltage levels being below or reaching required limits if all customers are meeting their relative emission allocations. In the event that the system exceeds harmonic voltage limits, it is the responsibility of the NSP to implement mitigation. In contrast, network forecast methods, such as the IEC method, allocate harmonic emission limits on a pro-rata basis of the agreed power of the connection and the total agreed power of all connections (existing and future) within the system. This approach attempts to implement engineering judgement of the future to ensure planning levels are never exceeded if all customers are meeting their allocated emission limits. These two allocation methodologies are reviewed in detail below, with particular focus on their application in relation to increasing REG penetration levels and uncertainty.

2.5.1 Fixed harmonic allocation methodologies

Fixed allocation methods allocate a predetermined percentage value of harmonic voltage or current based on simple details related to the connection request. The simplest approach to fixed allocation can be found in [82, 83] which are applied in Finland and Brazil respectively. A discrete harmonic voltage is allocated to the connecting customer based solely on the connecting voltage level of the installation, i.e. allocation is independent of the agreed power and Short Circuit Ratio (SCR) of the installation. Fixed allocation methodologies such as those found in [72, 73, 84] (IEEE, Hydro-Quebec & France respectively) allocate a discrete emission limit to the installation based on the SCR at the PCC. This is done via a lookup table an example of which is shown in Table 2.2 [72].

Table 2.2 - IEEE harmonic current allocation ($\mathbf{0.12} \le \boldsymbol{V_{nominal}} \le \mathbf{69}\ \boldsymbol{kV}$ *[72]*

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)						
$^{I_{SC}}/_{I_L}$	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

The method in [73] uses a similar table however linear interpolation is used to scale the harmonic emission limit based on the actual SCR of the installation. Some of the fixed allocation methods use scaling factors and equations to define the final harmonic emission limit [84, 85]. For example, the process in [85] uses (4) to allocate harmonic current emission limits to connecting installations.

$$\frac{I_v}{I_A} \le \frac{p_v}{1000} \cdot \sqrt{\frac{S_{kV}}{S_A}} \tag{4}$$

Where

I_v is the harmonic current in A

I_A is the nominal operating current of the installation in A

p_v is a proportionality factor based on the compatibility levels for the harmonic order of interest (h) and the impact of harmonic interaction across different voltage levels, given in [85]

S_{kV} is the short-circuit power of the network at the PCC

S_A is the nominal power of the installation

The approach in [85] removes the need for a lookup table as the resulting harmonic emission limit for all orders are calculated. However, the allocation is still considered as fixed as the variables of (4) are not impacted by the consideration of future forecasts, but instead use fixed scaling factors such as p_v. Conservative assumptions and scaling factors are introduced to allow for uncertainty, e.g. diversity of emissions, varying network characteristics and resonance.

The fixed allocation processes prioritise simplicity of application over detailed assessment of allocation limits. The process by which this is achieved is by developing a number of conservative assumptions about the range of networks to which they are being applied [74, 81, 86]. These assumptions are implemented to account for impacts such as resonance or reduced diversity of emission [87]. However, these assumptions are also capable of leading to overly conservative allocation limits. Further, if the network parameters to which the process is being applied significantly differ from the characteristics assumed in the development of the allocation process, harmonic voltage limits may be exceeded. This is evident in [74, 86-89] where the resulting allocated emission limits are seen to be entirely location dependent, resulting in final emissions capable of over or under-utilising the harmonic absorption capacity of the network. This suggests that the assumptions made to define the harmonic emission limits are not suitable in all scenarios and thus cannot be confidently applied when the underlying assumptions and calculations are not well known [74] or not applicable to the network to which the method is being applied.

With the added uncertainty of future REG penetration levels, a review of the above assumptions is required. If the fundamental process of the approach were to remain it is most likely that more conservative assumptions would be required to ensure harmonic voltage emissions remain below defined limits for all likely scenarios. Increasing conservatism of the allocation process is capable of decreasing the efficient use of the absorption capacity of many networks to which the process is applied. Many of the fixed allocation methodologies also apply increased restrictions on generating plants (including REG) based on the principle that generating installations emissions should be similar to those of large synchronous generators, i.e. present as a low harmonic impedance with minimal harmonic current injection. Such principles do not hold for REG such as solar PV and wind that are a harmonic source, similar to loads.

Fixed allocation method advantages and disadvantages that have been identified are as follows.

ADVANTAGES

- Simplicity of implementation (i.e. basic calculations)
- Minimal input data requirements

DISADVANTAGES

- Underlying assumptions not designed to be applied to all network types
- Assumptions can be shown to be overly conservative in general but also capable of exceeding planning levels in some cases
- Increased uncertainty of REG exacerbates issues related to conservative assumptions

2.5.2 Network forecast methodologies

The most frequently applied network forecast methodology is the IEC method [71]. This allocation process requires the network operator to define harmonic voltage planning levels, described as internal objectives for the operator. These planning levels should be less than or equal to the defined compatibility levels (also given in [71]). As customers begin to connect to the network, they are allocated a portion of the planning levels based on the relative size of the proposed installation (S_i) and the peak forecast of connected loads at the PCC allowing for diversity (S_t). Similar to many other allocation methodologies, if an installation is sufficiently small relative to the strength of the network at the PCC (i.e. $SCR \geq 500$), connection may be accepted without any further considerations. If the installation does not meet this requirement, harmonic emission limits are allocated using (5), assuming all loads are connecting to the same PCC.

$$E_{Uhi} = G_{h,MV} \cdot \left(\frac{S_i}{S_t}\right)^{1/\alpha} \tag{5}$$

Where

E_{Uhi} is the allocated harmonic voltage provided by the network operator to the connecting installation.

$G_{h,MV}$ is the global contribution of harmonic voltage emissions allowable at the PCC from MV installations

S_i is the agreed power of the installation under consideration

S_t is the aggregate agreed power of all existing and projected connected installations

α is the summation exponent to allow for diversity of emissions between harmonic sources. Relevant values are given in [71]

There exists some contention with respect to the definition and therefore assessment of compliance for E_{Uhi} as the actual harmonic voltage due to the connection of the installation is entirely dependent on the level of harmonic voltage distortion and operating state of the network [90]. This is discussed in further detail in Section 6. For the purposes of this project, E_{Uhi} is defined as the decremental harmonic voltage magnitude when the installation is disconnected from the network with background harmonic magnitude at the planning level, i.e. from a compliance assessment standpoint;

$$E_{Uhi} = L_h - V_s$$

Where

L_h is the harmonic voltage planning level

V_s is the harmonic voltage due to all other plants other than i

Equation (5) allocates a harmonic voltage to the installation which can also be converted into a current using the harmonic impedance of the network at the PCC. In the scenario that:

- Aggregated agreed power of all connected installations are equal to S_t, i.e. network is fully loaded;
- All installations have received an allocation using (5); and
- All installations are emitting their allocated limits

the allocated harmonic emissions will effectively reach planning levels (also taking into account diversity and 95th percentile measurement). This is the ideal scenario as all customers receive a fair allocation, commensurate with their agreed power and the capability of the network to absorb harmonic emissions is fully utilised (with a small buffer remaining between the planning and compatibility levels). The reality however is that this scenario is unlikely due to a number of factors [91] and the application of the Australian Standard [76] is becoming increasingly difficult due to uncertainty. The following subsections identify some of these difficulties.

2.5.3 Impact of REG penetration level uncertainty on harmonic allocation

Uncertainty exists with respect to the connection rates of REG and the impact this has on harmonic emissions within networks [92]. During the planning phase of a new or upgraded network area, it is necessary to estimate the peak load forecast (S_t) which, in itself is prone to uncertainty and can result in significant financial impacts when estimated peak loads are not realised [93]. The degree of uncertainty and therefore possibility for inaccurate estimates is exacerbated when considering the connection of REG. For example, a network planner may expect a particular area of a network is likely to connect large amounts of REG and plan accordingly. The final level of penetration of REG may be far more (or less) than expected, resulting in the harmonic absorption capabilities of the network being inefficiently utilised.

A practical approach under these circumstances could be for a network operator to allow for levels of REG to be incorporated into S_t based on certain, probable and uncertain connections. A comparative infographic is shown in Figure 2-18 where;

(a) represents the present-day approach i.e. generation is not planned for and thus the system will reach planning levels prior to the thermal capacity of the system being fully utilised. This results in under-utilisation of the system harmonic absorption capacity.

(b) Represents a situation where the NSP accounts for REG connections that are certain ahead of time and thus apportions this into the harmonic management process with;

$$S_t = S_c + S_G$$

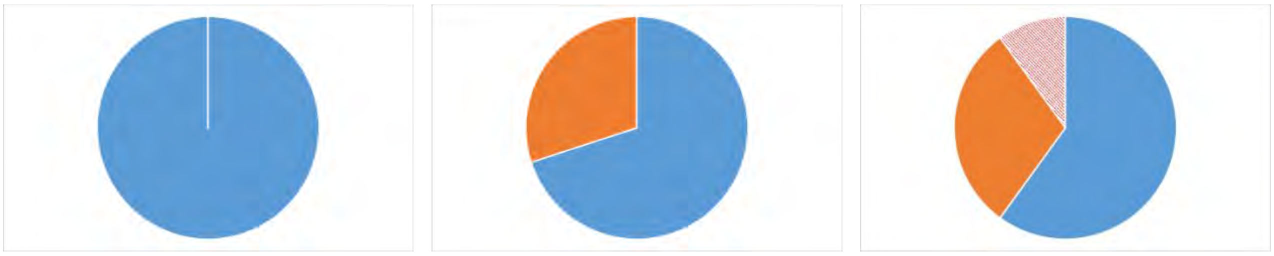
Where;

S_c is the sum of the agreed power for all expected standard consuming installations

S_G is the sum of the agreed power for all expected generator installations

Such a scenario, whilst ideal is unlikely in many cases given the uncertainty of generator connections and expected penetration levels for some networks.

(c) This represents perhaps the most likely scenario in which there is a level of uncertain REG connections to be accounted for, providing a buffer for uncertain generators although reducing the total level of allocated distortion. The way in which uncertain REG installations are apportioned can vary depending on the level of uncertainty.



(a) *Certain REG apportioned* (b) *REG considered as part of* S_t (c) *Certain and uncertain REG apportioned*

Figure 2-18 - Blue – Peak forecast load, Orange – Certain REG, Red hatch – Uncertain REG

A number of approaches to mitigate the impact of the uncertainty of REG penetration levels have been suggested in recent years. One of the more basic considerations was included in the 2008 revision of the IEC method (adopted by Standards Australia in [71]), where it is suggested that the agreed power of distributed generation is to be included into the value of S_t however it also states that a more detailed consideration is required to better understand the contribution of the generator to both the system supply capacity and fault level. The idea of including REG agreed power in S_t is extended in [11, 94] which suggests an updated definition of S_t to include expected REG, i.e.:

$$S_t = \lambda_c S_c + \lambda_p S_p \qquad (6)$$

Where

Subscript c identifies the variables related to consuming installations (conventional loads)

Subscript p identifies the variables related to generating installations (generators)

λ_c is a scaling factor applied to standard consuming loads

λ_p is a scaling factor applied to generating connections

This approach can augment the IEC method which otherwise remains as defined by (5). The values for each parameter are network specific, so incorrect assumptions are capable of excessively strict allocations to connections that eventuate in favour for those that do not.

A related approach has been presented in [67] specifically for the allocation of offshore windfarms in the Netherlands and Germany. Investigation of the defined harmonic allocation limits provided in [67] finds that the limits have been halved in comparison to the limits found using the existing IEC method. Such a reduction in allocated limits is akin to the use of (6) with;

$$S_c = S_p$$

and

$$\lambda_c = \lambda_p = 1$$

Whilst such an approach may be acceptable in unique cases, the scenario in which it is applied in [67] is for an offshore platform, i.e. a system with minimal consuming load. Therefore, the level of generated power is likely to far exceed the level of consuming power, i.e. $S_c \ll S_p$, needlessly limiting the harmonic emissions of the generators.

The IEEE method directly addresses REG within the document by stating that generating installations are to have minimal impact on the distortion of the network and thus are limited to the lowest allowable harmonic emission limit, regardless of SCR. This approach, whilst ensuring minimal impact of REG installations, is highly conservative and likely to result in substantial increase to costs related to mitigation.

Other methods to mitigate the impact of uncertainties related to REG have been briefly investigated in [92], however, their practical implementation and impacts are yet to be adequately researched. This will be investigated in detail later in this report.

2.5.4 Uncertainty related to previous harmonic allocations

Another difficulty related to the IEC approach to emission allocation is the uncertainty of previous allocations. The practical implementation of (5) is predicated on all installations within a network being allocated using the same methodology [11]. Historically, the IEC approach has been introduced to many existing networks with existing customers, each potentially with a connection contract that already defines their harmonic emission limits which were allocated using a predecessor to the latest IEC approach. Recent updates to existing allocation methodologies [28, 70] and suggestions in [11] address this uncertainty in slightly different ways by implementing what is colloquially known as the "headroom approach". Both variations determine the level of distortion present on the network at a point in time and then allocate a portion of the remaining headroom to the connecting installation, this approach is illustrated graphically in Figure 2-19.

Figure 2-19 - Distortion limits illustration including background levels and available headroom [70]

Whilst both implementations of the headroom approach are capable of adequately addressing the uncertainty of previous allocations, networks implementing these approaches are susceptible to further difficulties as described below.

2.5.4.1 DIFFICULTIES IN THE APPLICATION OF EXISTING HEADROOM APPROACHES

The process in [28] is concerned with both calculating harmonic allocations and harmonic management in general. The approach is a three-stage process where a connecting installation must provide adequate evidence that connecting equipment is capable of meeting harmonic emissions compliance at one of the relevant stages. Progression through the stages increases the data required and complexity of the process.

- Stage 1 - Includes four sub-stages, relevant to LV connections only
- Stage 2 - Includes three sub-stages, relevant to MV connections and LV connections that fail Stage 1
- Stage 3 - Implements the headroom approach for all connections failing to meet the requirements of Stage 1 and 2

Both Stages 1 and 2 do not allocate harmonic emission limits but instead make a number of pessimistic assumptions to allow simple studies for installations that are unlikely to have a large impact on harmonic voltage levels and network impedance. The installation is considered to have passed if any of the relevant studies suggest the network will not exceed planning levels post-connection or if the connecting equipment meets a number of international standards related to harmonic emissions e.g. [95, 96].

An installation will progress to a Stage 3 allocation for two reasons, the background harmonic voltage levels are above 75% of the planning levels or the identified harmonic current emissions from the new installation cannot meet the requirements of Stage 1 and 2 (based on pessimistic assumptions regarding the network impedance). In the event that the background harmonic voltage levels are approaching planning levels and a connection requires an emission allocation, this is completed by determining the available headroom at the PCC (or any bus of interest within the network) by using (7).

$$V_{h,HR,PCC} = \left(L_{h,MV}^{\alpha} - V_{h,BG,PCC}^{\alpha}\right)^{\frac{1}{\alpha}} \tag{7}$$

Where

L_{MV} is the planning level at the PCC

$V_{h,BG,PCC}$ is the background harmonic voltage level at the PCC

α is the diversity factor, as defined in [71]

This process is also completed for any bus of interest in the network and the minimum available headroom is apportioned to the connecting installation based on voltage level. If $V_{nom} \leq 132\ kV$, the installation is allocated 50 % of the remaining headroom. If $V_{nom} > 132\ kV$ the allocation is scaled based on the agreed power of the installation and the connecting voltage level. The scaling process is given in [28].

Using this approach, it can be shown that no installation ever receives the remaining headroom and therefore the allocated harmonic emission levels should never exceed planning levels, provided all installations are meeting their allocated emission limit. However, for networks operating at or below 132 kV, installations receive 50 % of the remaining headroom regardless of the agreed power. This approach can be shown to be disproportionately biased toward early connections, omitting the objective of fair emission limit allocation in [71]. This is shown graphically in Figure 2-20, in which the harmonic voltage profile of a network evolves over time due to continued connections.

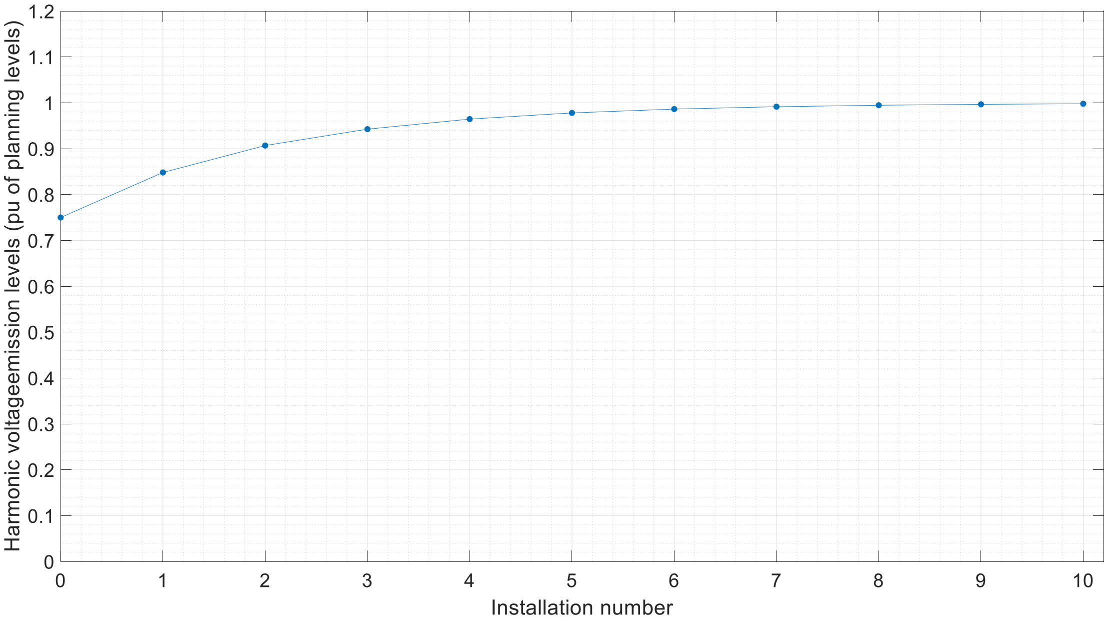


Figure 2-20 - Harmonic voltage growth profile

As shown in Figure 2-20, the background harmonic emission level is at 75 % of the planning level at which point a new connection is allocated 50 % of the remaining headroom (determined by (7)), regardless of its agreed connection capacity. Due to allowance for diversity, the expected emissions from the new plant increase the background harmonic distortion to 85 % of the planning levels, and the next installation receives an allocation of 50 % of the remaining headroom and so on. Whilst the remaining headroom is never fully allocated, unrealistic restrictions are imposed on installations solely based on the point in time at which the connection request occurs. The process is also capable of being too lenient on earlier installations. For these reasons it can be shown that the harmonic allocation approach given in [28] may be capable of efficient usage of the power system harmonic absorption capacity and ensuring that planning limits are not exceeded but is not capable of fair allocation across all customers, a key objective of the IEC methodology.

Recent alterations made by the Irish TSO, EirGrid, given in [70], to the IEC method introduce a requirement for monitoring prior to emission limits being calculated. The first step is to determine the background harmonic voltage level at the PCC. The background harmonic voltage levels (V_{BG}) are then used to determine the available headroom at each harmonic frequency at the node under study using equation (8).

$$V_{headroom} = \left(L_h^{\alpha} - V_{h,BG}^{\alpha}\right)^{\frac{1}{\alpha}} \tag{8}$$

Where;

$V_{headroom}$ is the harmonic voltage headroom at the location of interest within the network

L_h is the harmonic voltage planning level

$V_{h,BG}$ is the measured background harmonic voltage distortion at the location of interest

α is the summation exponent as defined in [69]

A portion (25 %) of the available headroom ($V_{h,remaining}$) is retained as a conservative measure to ensure planning levels are not exceeded for any connecting installations when meeting their allocated levels. The remaining headroom available for allocation is therefore;

$$V_{h,remaining} = V_{headroom} \cdot (1 - 0.25)$$

Allocation of the harmonic voltage distortion limit is then completed by apportioning the remaining headroom available on a ‘MW pro-rata basis’, i.e. following a modified Stage 2 allocation of [71] using (9).

$$E_{Uhi} = V_{h,remaining} \cdot \left(\frac{S_i}{S_t}\right)^{\frac{1}{\alpha}} \quad (9)$$

Whilst such an approach is able to pragmatically allocate the remaining headroom and removes the difficulty introduced in the approach presented in [28], ambiguities in the description of the process are capable of resulting in disproportionately conservative harmonic emission limits. The explanation of the allocation method in [70] suggests that harmonic monitoring and calculation of remaining headroom (including planning margin allowance) is performed for every connecting installation. However, the division of available headroom as shown in Figure 2-19 (from [70], noting $S_n > S_2 > S_1$) suggests that the background harmonic voltage levels are measured once and the remaining headroom is apportioned to n customers, with the final allocated harmonic distortion limits reaching 0.75 pu of L_{MV}.

The impact of this discrepancy can be shown by considering two scenarios:

1. Remaining headroom of the system is monitored and calculated for every connecting installation
2. Headroom is calculated once and apportioned to the remaining installations using (9)

The result of both scenarios is shown in Figure 2-21 in which it can be seen that Scenario 1 results in a conservative use of the network harmonic absorption capacity whilst Scenario 2 meets the expected planning level once all installations are connected. The conservative result for Scenario 1 is due to the repeated calculation of available headroom including planning margin for every connection, reducing the total allocated emission limits.

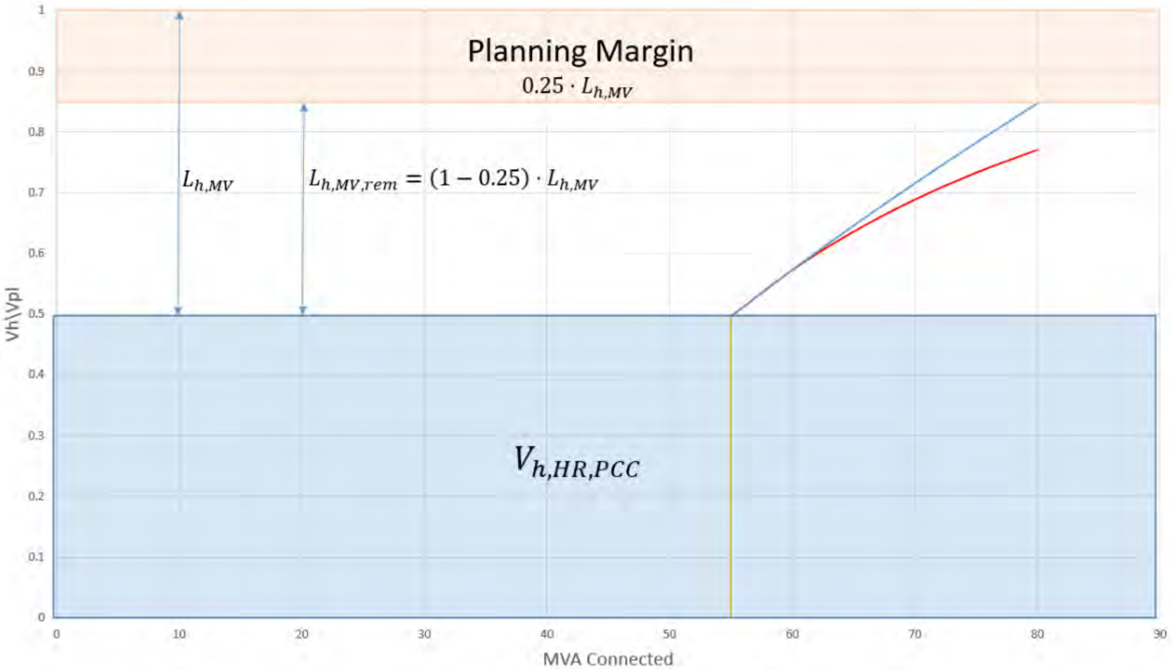


Figure 2-21 - EirGrid allocation example with existing harmonic sources, $S_{connected} = 55\ MVA$ *(yellow),* V_h/V_{PL} *– Scenario 1 (red),* V_h/V_{PL} *– Scenario 2 (blue)*

Clarification of these ambiguities would serve to improve the application of the process in [70].

2.5.5 Uncertainty of REG connection location and concentration

A number of proposed updates to the existing IEC method have been published since its inception in 1996. These updates have been provided to address a number of issues and have had varying levels of impact on the allocation process in Australia.

The revised methods presented in [97-100] define a process which reduces the disparity of allocated emissions for connections of similar agreed power connecting to positions on the network with significant differences in fault levels (e.g. sending/receiving ends of long feeders). The methods determine the position on the network that will reach planning levels first and implement a scaling factor to the equation and allocate emission limits on a pro-rata basis to all connections.

It is identified in [78, 98, 99, 101] that such an approach requires an unrealistic knowledge of future loading that exposes the process to significant impacts of uncertainty. This is addressed in [98, 99] by providing a simplified process to determine the weakest feeder in the system. However, the method adopts the assumption that all connections are evenly distributed along the feeders. It can be shown that such an assumption is too general and can lead to incorrect calculations of where the system will reach planning levels first. This is an important factor as REG connections commonly occur in geographically remote locations [6, 70].

Another proposed method, known as the voltage droop method [78, 101], addresses network uncertainty with a pragmatic process that significantly reduces the data required. This method has been well received and is incorporated into Australian industry guiding practices [102] and IEC revisions currently underway [11]. There exists limitations to the method however when the presence of REG is taken into account [102]. Further, the voltage droop method can be shown to consistently allocate more conservative limits than the standard IEC method [78], already one of the more strict allocation procedures based on a simple study presented in [103]. Although one must take into the account the impact of different network characteristics when comparing allocation methodologies [81, 88, 103]. As such, widespread application of the Voltage Droop method may lead to disproportionately stringent emission limits being applied.

Whilst a significant amount of work has already been completed in relation to the practical application of the IEC method, there remains a number of significant issues. As identified, the proposed methods introduced to address the significant level of data required for strict application of the IEC method can in turn be too general, omitting considerable impacts of concentrated loads. Further concern related to the application of the voltage droop method, i.e. overly stringent limits being applied, and concern of REG have also been identified.

2.5.6 Uncertainty of future harmonic impedance of Networks

Significant difficulties have been identified by the Australian Energy Market Operator (AEMO) and other industry bodies, both nationally and internationally with regard to the changing impedance of future electricity networks. Following the significant increase in renewable energy generators, Australia is expected to begin retiring its aging fleet of synchronous generators. AEMO anticipates 63 % of existing synchronous generation to be lost from the NEM by 2040 [6]. This poses a difficulty as synchronous generators provide a low impedance path for harmonic currents, reducing the voltage distortion of the network in the area. Studies provided in [3, 4, 13] identify a range of complications being introduced in networks with high levels of REG penetration. The most concerning in relation to this project is the increase of harmonic impedance and reduction in network absorption capacity due to the retirement of synchronous generators.

Mitigation via connection of network strengthening devices such as synchronous condensers, that provide similar characteristics as a synchronous generator, is expensive and only considered if the condenser is required to solve other higher-profile issues, e.g. voltage stability or reactive power support. Another potential solution could be the use of harmonic filters however, as previously discussed, continued connection of filters is capable of shifting resonant frequencies to problematic values and may ultimately amplify emissions of other installations.

The uncertainty and related concerns introduced by the variation of network impedance highlights the importance of a pragmatic and robust harmonic allocation methodology that understands and suitably considers such variation. A comprehensive logistical and quantitative review is required to develop an understanding of the efficacy of identified allocation methods in a range of network variations and scenarios.

2.6 METHODS OF MODELLING RENEWABLE ENERGY GENERATORS

The scope of this project does not include the validation of component modelling in the frequency domain as this has been adequately detailed previously [104-107] and is generally well accepted. However, studies have identified the difficulty of balancing time and cost with the accuracy of contemporary harmonic modelling methods [12, 23]. Indeed, the work required to perform pre-connection harmonic emissions compliance studies should be commensurate to the risk of operating a power system with increased distortion levels. Therefore, a practical approach is necessary whilst maintaining a level of accuracy that is capable of identifying impacts on harmonics levels without introducing unfairly conservative assumptions.

There are at present no agreed guidelines for establishing generic models of combined harmonic producing equipment and thus requests for information related to the interaction of components with the system beyond the fundamental frequency are often not fulfilled. Modelling systems and components at the fundamental frequency, whilst a necessary exercise and very well understood, is typically insufficient for harmonic investigations [9, 46, 105]. In-lieu of detailed, accurate data, development of assumptions or estimation methods and perform sensitivity tests to ascertain the impact of these inaccuracies is necessary. Increased attention to detail, research and collaboration is required around harmonic modelling and management processes to ensure power systems with increased power electronic interfaced generation are capable of continuing to operate uninterrupted and satisfactorily [4, 10, 12, 13].

The following outlines the challenges related to harmonic modelling within an Australian context based on the discrepancy between state-of-the-art presented in literature and commonly employed practices.

2.6.1 Plant-level modelling

Once a preliminary design of a REG plant is available, a harmonic model can be established to estimate the expected harmonic emissions. Similar to individual device modelling, plant modelling has recently become more complex and detailed and may include:

- Site layout such as converter, transformer and cable topology (types and lengths)
- Individual generation or harmonic producing devices
- Reactive plant or planned harmonic filtering
- Other relevant plant and station loads

Studies have shown that it is important to accurately represent the entire installation in order to capture the interaction between both passive and active components and the existing network [6, 50, 108-110].

The alternative to a detailed approach containing representation of individual converter operation, control system interaction, etc., is the relevant aggregation of devices or entire plants to a simplified model. Studies presented in [108, 110, 111] review processes that reduce parts of, or entire installations, to a simplified representation. However, results were only suitable for preliminary, exploratory studies, or to investigate harmonic impacts in large transmission systems with scenarios of limited information regarding specific installations.

Impacts and sensitivities of the electrical layout of an installation vary based on the size of the installation and harmonic characteristics of the network at the PCC. Due to the ongoing improvements of available software and continued increase of power electronic interfaced generation, it is suggested that all available and pertinent information needs to be considered for such studies, including further considerations provided in sections 2.6.2-2.6.3.

2.6.2 Transformers

Power transformers are largely inductive, however any harmonic calculations beyond the simplest form need to also accurately model the frequency dependent resistance [106, 107]. Frequency dependent resistance in transformers capture the impact of eddy current losses, excitation current and skin effect [112, 113]. Omission of this component is capable of over-estimating the final emissions as the damping effect of the transformer resistance is disregarded or underestimated. The impact is more significant in plants where the impedance is dominated by the transformer. Five modelling processes to estimate the frequency dependent resistance were reviewed in [2] which finds considerable variation between the methods and with measured values in some scenarios.

Further, the contribution of transformer excitation current is capable of impacting harmonic emissions [114]. This is often neglected in pre-connection compliance assessment, as the excitation current is generally 1 – 2 % of rated current, with the dominate harmonic order being the 3rd (≈ 40 % of excitation current)

[115]. Neglecting excitation current remains an acceptable approach while the transformer operates within its linear region. However, increased fundamental voltage levels are capable of saturating the transformer and increasing the excitation current. This in turn increases the harmonic current drawn by the transformer [116]. The impact of physical characteristics on the knee-point voltage level of transformers generally result in transformers of lower quality having a lower knee-point voltage and are thus more likely to saturate at lower fundamental voltage magnitudes [117]. Careful consideration by the network operator should be given to the possibility of transformer saturation occurring whilst the network operates within reasonable limits.

2.6.3 Power electronics

Harmonic modelling of power electronic devices has evolved over time due to increased complexity of design and the need for more accurate harmonic emissions studies [12, 23]. The level of accuracy of the PE harmonic model is directly correlated with difficulty and time required to develop and validate such models. It has been identified in previous studies [2, 23] that no ‘generalised’ harmonic modelling or assumptions can be made regarding present technology. It therefore requires the equipment manufacturer to provide detailed modelling data to allow accurate harmonic emissions studies to proceed. The appropriateness of the modelling approach must be carefully considered, including impacts of the external network.

Traditional modelling of PE devices was simplified to constant current sources. This was due to the simplicity of the technology and minimal interaction occurring between devices and the network [118]. As suggested in [118, 119] the passive components of more recent PE devices (e.g. voltage source converters (VSC)) and the response of controllers to network conditions are capable of significantly impacting the harmonic impedance and current emissions of the device, thereby altering the impedance at the PCC and resulting harmonic emission levels. Such impacts are not captured when modelling the device as a simple harmonic current source. The simple current source approach to modelling is also capable of leading to improper harmonic mitigation design [45] and is therefore not suitable for harmonic emissions studies of large asynchronous generators.

A Norton/Thévenin equivalent model has become the most common modelling technique for PE devices which represents the device in the harmonic domain using;

- a voltage source in series with an impedance, known as a Thévenin equivalent model or
- a current source with a parallel admittance, a Norton equivalent model.

The current source component represents the harmonic current emissions due to the closed-loop controller and non-linear operation of the device. The parallel admittance is representative of both physical hardware (e.g. grid-tie filter) and impacts introduced due to responses of the closed-loop controller [33, 120].

Processes to develop Norton/Thévenin equivalent models are described in [24, 121]. The models provided by equipment manufacturers to represent the harmonic emissions of the PE devices are based on a range of specified network conditions. However, in [121] the onus is left to manufacturers to determine and identify the network conditions under which the models are to be defined. It is stated in [23, 24, 121] that the components of the Norton/Thévenin equivalent model are capable of varying significantly due to changing network conditions.

Inaccuracies in models may be introduced based on the simplified data provided by equipment manufacturers. It is most common for harmonic models of PE devices to be developed based on a single network operating scenario. Such a definition entirely removes the impacts of external conditions and is capable of under or over-estimating final harmonic emissions. Possible updates to the existing methodology could require the manufacturer to provide the proponent with a number of harmonic models referencing the network conditions for which they are valid. The harmonic emissions study would then be performed for all network conditions defined and the relevant harmonic model for the PE devices would be selected based on the scenario under consideration. A graphical interpretation of this is shown in Figure 2-22. Such an update to current practices is capable of increasing computational time to complete however, a simple programmatic tool would allow for autonomous execution, reducing human interaction and subsequently time required.

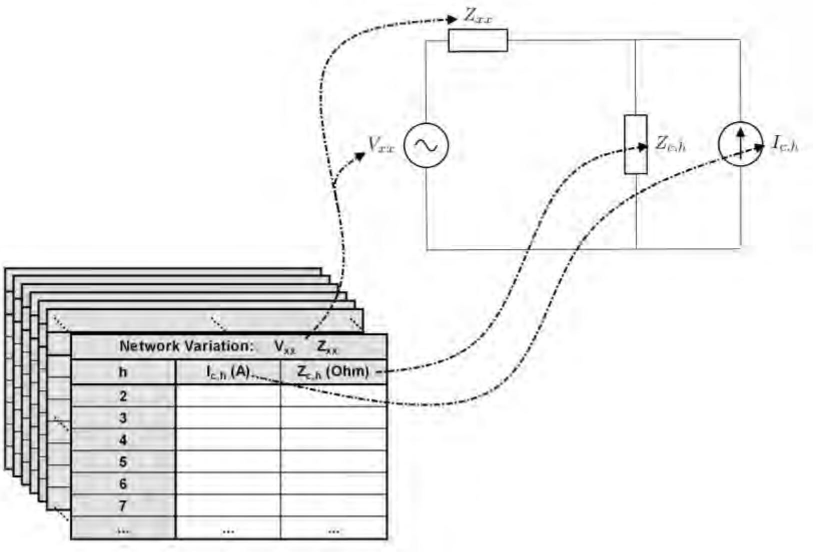


Figure 2-22 - Multiple harmonic models defined based on network conditions

2.7 AGGREGATING HARMONICS FROM MULTIPLE INVERTERS WITHIN REG INSTALLATIONS

Harmonic source representation is often a difficult modelling process. This is particularly true for networks that have a wide range of varying non-linear loads connected from LV to MV/HV. As with harmonic allocation and modelling, the calculation of the interaction between sources was simpler to determine when there were limited distorting loads present on the network. With the continued propagation of REG and non-linear devices, harmonic emissions diversity and interaction are becoming more difficult to estimate. Accurate assessment of the total overall emissions of a plant (whether it be a load or generator) is important as this value is an input to the pre-compliance modelling process and ultimately impacts the entire pre-connection harmonic management process, i.e. from allocation to compliance assessment.

There is significant conjecture with respect to how harmonic emissions from identical non-linear devices that operate within a single installation should be aggregated. Due to similarities and symmetry of design, it may be reasonable to suggest that two identical devices operating within close proximity of each other are likely to emit harmonic currents with very little diversity in phase angle or time of emission and thus should add arithmetically. Studies investigating such phenomena suggest however that such an assumption may be pessimistic, particularly for higher order harmonics. Incorrect assumptions regarding the aggregation of harmonic emissions in such a scenario is capable of leading to further error in evaluation of the impact of the plant.

This section will present a review of some of the state-of-the-art studies that have been completed to investigate aggregation of harmonic emission from REGs and present the level of understanding the industry currently possesses. First, the summation law will be presented after which studies that challenge the use of the law in its present form will be reviewed.

2.7.1 The Summation Law

The development and use of the summation law in its present form has a considerable history, with the first consideration of non-arithmetic summation to take into account diversity in harmonic emissions being presented in [122] in 1967 [81]. The document identified that harmonic sources that are not consistently online or emitting harmonic currents in a continuous manner should be allowed to emit higher currents. Further developments were then made in [123, 124] with these studies identifying use of arithmetic summation to estimate overall harmonic emissions to be pessimistic. The studies also presented equations which could be used to account for diversity. Further progress continued throughout the 70s [125] and 80s [126] to reach the state of the summation law as it is presented in [71] and shown in (10).

$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}} \tag{10}$$

Where

U_h is the resulting harmonic voltage or current magnitude for harmonic order h (probabilistic value)

U_{hi} is the harmonic voltage or current magnitude of order h due to harmonic source i

α is the diversity exponent that accounts for statistical variation of phase angle and magnitude, values given in Table 2.3

Table 2.3 - Recommended values of α

Harmonic Order	α
$h < 5$	1
$5 \leq h \leq 10$	1.4
$h > 10$	2

Recommended values for α are given in [71] with little reference or suggestion as to how they have been determined. Application notes are also provided in the standard that state the values of α are to be revised if more is known about the emissions of the devices under study. This has led to NSPs suggesting that α should be given a value of 1 for identical devices within close proximity of each other for all harmonic orders. It is not clear where this suggestion originated however it has been identified to lead to pessimistic emission allocations and ill-designed mitigation solutions [2]. A collection of studies is provided below that investigate the validity of assuming no diversity in harmonic emissions from asynchronous generators for all harmonic orders.

2.7.2 Prevailing phase angle

To account for phase angle diversity, an approach is provided in [127, 128] in which the sum of phasor quantities is compared with the arithmetic sum of the phasors, given in (11).

$$PR_{agg,h} = \frac{|\sum_{i=1}^{n} \underline{Y}_{H,h,i}|}{\sum_{i=1}^{n} |\underline{Y}_{H,h,i}|} \tag{11}$$

Where

$PR_{agg,h}$ is the calculated prevailing ratio

$\underline{Y}_{H,h,i}$ is the phasor quantity (harmonic current or voltage) of harmonic order h, of measurement iteration i

This allows for a simple understanding of how one or more harmonic sources interact with the network. The outcome of (11) provides a statistical comparison of phase angle measurements, the result providing an indication of the possible range of phase angles that were measured. For example, in [127] a set of prevalence classes were developed, i.e. a $PR_{agg,h} \geq 0.89$ is defined as an acceptable level of certainty for harmonic phase angle between sources. Whereas $0.8 \leq PR < 0.89$ suggests more variation with the possibility of identifying a tendency of phase angle is possible. For $PR < 0.8$ very low prevalence of phase angle is detected and a large range of phase angles is likely. A graphical comparison of varying levels of $PR_{agg,h}$, from [128] are shown in Figure 2-23.

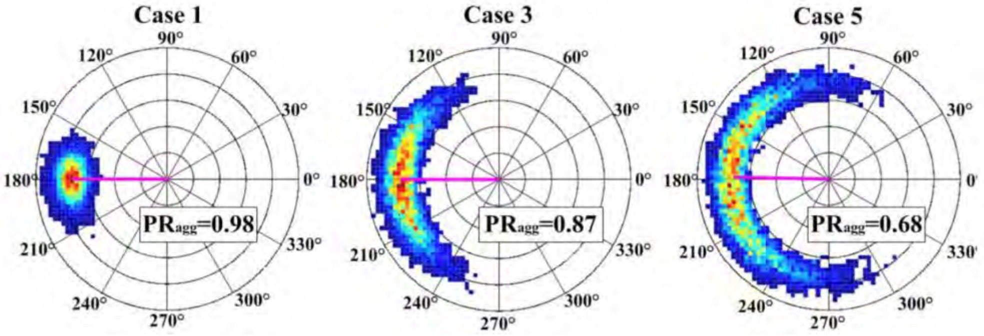


Figure 2-23 – Comparison of varying levels of $\boldsymbol{PR_{agg,h}}$ *[128]*

It is suggested in [2] that TenneT is implementing the requirement of prevailing phase angle ratios to be included in HVDC modelling for connection to the German transmission network. However, it is also identified within the same document that the accurate representation of phase angles requires detailed discussion with equipment manufacturers.

2.7.3 Validity of zero diversity within REG plants

The use of the summation law is referred to in many Australian standards referencing the calculation of long-term PQ trends. Often, the use of the summation law and subsequent coefficients (as defined in Table 2.3) defined are presented with the caveat that updated values of α are to be used if it is known that harmonic orders are likely to have reduced diversity of phase angle, thus leading to increased voltage or current magnitude.

The desktop study presented in [129] undertook a comparison of emission calculations using the second summation law as defined in [71], compared with calculated emissions aggregated within a simulation platform. It is not clear whether the study takes into account possible differences in phase angle of emissions between each generator or the study is simply focused on the impact of phase cancellation introduced due to network equipment (e.g. long underground cable). Regardless, the outcomes suggest that the use of the summation law for full power output of Type-IV windfarms with a value of α that is too low, results in estimated emissions being too high. Another finding however is that the value of α as shown in Table 2.4 is too high for Type-IV wind turbines at partial rated power output and Type-III wind turbines for higher order harmonics. The findings, although undertaken in a simplified study, should prompt caution when applying the currently defined values of α or using a value of $\alpha = 1$ for all harmonic orders.

Measurements are carried out in [130] of two identical wind turbines (type undefined). The analysis aggregates the relative phase angle between the two turbines and develops a statistical relationship for the emissions of both generators. The findings, although for a very specific condition, finds the suggestion of setting $\alpha = 1$ for all harmonic orders to be far too pessimistic and removes the likely phase cancellation for higher order harmonics.

Measurements are outlined in [131, 132] for wind farms of varying sizes that support the previous findings, i.e. lower frequency and characteristic orders tend to have a lower degree of phase angle diversity, thus reducing the value of α that should be applied, and non-characteristic and higher harmonic orders tend to vary in phase angle somewhat stochastically and by a large degree. The literature indicates that use of an α value of 1 for all identical generators and harmonic orders within an installation should be revised. Where revisions have been developed, the most commonly implemented approach is the use of the prevailing phase angle to aggregate harmonic sources.

2.7.4 Interaction of background levels with individual customers

The studies identified in Section 2.7.3 present inaccuracies of the application of the summation law within a single installation with multiple harmonic sources. There are also questions with respect to the validity of the summation law for REG within plants and their probabilistic contribution to network harmonic voltage levels, i.e. diversity between REG plants and existing network harmonic sources.

The study presented in [133] aggregated harmonic sources within a distribution substation with multiple distorting loads present. The system comprises of traction loads (e.g. electrified rail) and two 75 MW PV plants. The study finds that aggregating low-order characteristic harmonic orders at the substation using summation law exponent values in Table 2.3 is insufficient. Focussing on the 5th and 7th harmonic orders existing at the zone substation with all connections operating, the study determines both orders are capable of 360° phase angle variation throughout the measurement period. Use of (11) for such data results in a very low value of $PR_{agg,h}$ and significant levels of diversity can be reasonably expected. Thus, the use of the summation law in its present form is insufficient to estimate the interaction of all installations on the harmonic voltage.

Another study presented in [134] suggests the use of the summation law to be the best-guess in the scenario where minimal information is known regarding the harmonic sources. It was found the summation method was able to better estimate harmonic emission compared to the calculation using complex phasors, when compared with actual measured values. The study focused on MV distribution networks and the subsequent impact of LV harmonic aggregation. However, it confirms the validity of the summation law in the general case, i.e. with minimal penetration of REG.

2.8 SUMMARY

The generalised deleterious effects of harmonic distortion on power system components and customer installations is well understood. The presence of harmonic distortion is due to the connection of non-linear devices such as arc furnaces, solar/wind/battery inverters, HVDC links, or power electronics in general. The impacts of harmonic distortion are wide-ranging, most prominently, harmonics introduce increased losses within the system and are also capable of interacting with power electronic controller components. A pragmatic approach to managing power system harmonic distortion levels is therefore a necessary practice in maintaining a power system that is fit for purpose.

There exists a range of technology types that connect REGs to the network, each with unique topologies and controller strategies, however, the literature reviewed suggests that it is common for PV and Type III and IV WTGs to emit non-characteristic and interharmonic orders. Further, the impacts of a range of factors on harmonic emission levels lead to generalised harmonic models being unable to be defined.

Equipment such as long cables, transformers and passive harmonic filters, commonly forming part of REG plants, are capable of interacting with existing harmonic sources within the network with the outcome being the shifting of harmonic resonant frequencies. A number of case studies provide detailed accounts of international TNSPs with large volumes of renewable generation in their networks, particularly wind.

A review of available long-term power quality monitoring data has been undertaken in order to ascertain the impact of increased REG penetration of harmonic distortion levels. The outcome of this review identified that the experience of NSPs internationally varied widely. Some studies found a number increasing harmonic emissions in lockstep with renewable generation connections whilst others have detected a reduction in overall distortion. Such experiences of decreased distortion levels have been postulated within the reviewed literature to be attributed to one or more of the following:

- Improved harmonic management processes
- Increased investment in transmission infrastructure
- Improved technologies related to REG connections

Other possible mechanisms for reduced network harmonic distortion levels include phase cancellation or installations operating as a harmonic sink at particular frequencies. Of most importance is that REG technologies are capable of significantly impacting harmonic emission levels and pragmatic approaches to ensuring appropriate levels are maintained without over constraining customers is prudent.

Harmonic allocation and management was shown to vary significantly between countries and network operators. This literature review analysed a significant number of network and country standards with relation to technical performance and power quality. The qualitative review identifies the similarities and differences between the most commonly implemented methodologies. An important objective of the allocation process is maintaining harmonic voltage distortion below predefined levels. However, the review also shows that an overly conservative use of the network absorption capacity increases the likelihood of expensive mitigation being required and potentially impacting the harmonic resonant frequencies of the system due to the connection of passive filtering.

The harmonic allocation methods identified in this chapter were collated based on the fundamental process used to calculate emission limits for connecting customers i.e. fixed harmonic allocation methodologies and network forecast methodologies. Fixed allocation methodologies were found to implement assumptions that are too general to maintain acceptable applicability across a range of network types. Whereas network forecast methods were found to be capable of overly conservative allocations due to the impact of future uncertainties. Whilst some updates have been proposed or implemented by NSPs internationally, such processes are shown to remain insufficient for uncertainties related to REG penetration levels, concentration and future system harmonic impedance. A targeted and detailed review of the implementation and update of harmonic management processes was a key task of this project and is presented in Sections 3, 5 and 6.

The harmonic modelling of PE devices has evolved over time although impacts of internal and external factors are yet to be adequately captured in harmonic domain modelling practices. Further, the continued propagation of REG and non-linear devices to the network has increased the complexity of determining a statistical representation of harmonic sources and subsequent interactions that accurately represent that which is observed in practice in networks. Currently implemented assumptions of reduced (or no) diversity between identical devices has been suggested to be pessimistic, particularly at higher harmonic orders. The outcomes suggest that a targeted campaign of measurements and detailed analysis is required to better understand the applicability of existing methods and inform improved practices. This activity was undertaken as part of this project and is detailed in Section 4 of this report.

Difficulties and challenges related to harmonic modelling for the purposes of compliance assessment remain elusive and difficult to address. There remains a significant level of research and experience to be gained before confident decisions can be made. Previous studies identify the need for detailed studies to be undertaken due to the impacting factors that are capable of introducing significant error. A more complete assessment of the challenges of compliance assessment in the presence of REG is provided in Section 6 of this report.

3 Comparison of Harmonic Emission Allocation and Management Strategies

This project is concerned with the pragmatic management of harmonic distortion within networks due to the ongoing proliferation of REG connections. The literature review provided in Section 2 identified a number of difficulties that currently exist with harmonic emission allocation methodologies as they are presently applied. This section of the report is concerned with comparing the most widely used harmonic emission allocation strategies to evaluate their strengths and weakness with particular emphasis on Australian conditions and REG connections. In the first instance, in order to compare methodologies models are needed to be developed that;

a) Represent Australian network conditions
b) Accurately represent all components in the harmonic domain
c) Allow for easy modification and updates
d) Are capable of fast computation

With the above requirements as a basis for comparison, existing models and simulation platforms were used to determine the most practical approach to developing representative network models that could be used to provide a comparison of harmonic emission allocation methodologies. It should be noted here that there is no requirement for detailed harmonic models of REG installations. Instead, the study simply assumes that all connections (REG and standard consuming loads) are represented by equivalent current sources with inconsequential impedance[2]. This is effectively the worst-case scenario for the network (omitting impacts of resonance) as the removal of impedance disregards any harmonic current absorbed by the installation. Impacts of existing and future connections on the network harmonic impedance are investigated in further detail in Section 5 of this report.

3.1 EXISTING BENCHMARK MODELS

Benchmark models are a useful tool to allow the development of processes on a system that is indicative of existing networks relevant to the study. A comprehensive search of existing benchmark models was undertaken to determine appropriate existing models that have been used to complete similar studies.

3.1.1 IEC 61000.3.6:1996 Model for long feeder allocation

A benchmark model developed by the IEC is presented in [76] and shown in Figure 3-1. The purpose of this model is to investigate the impacts of long feeders on the IEC allocation process. The report provides little detail regarding how the model was developed, referencing a UNIPEDE report on EMC coordination for further information. The model is homogenous (i.e. all feeders are identical and evenly distributed) and fault level ratio from sending to receiving end of the feeders is 6:1. It should be noted that the assumption of homogeneity is capable of introducing errors in the allocation process due to uncertainty [97, 102].

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[2] Such a model is not suitable for compliance assessment, for reasons identified in Section 2.6 such as interaction of installation impedances on resonant frequencies, PE response to network events etc.

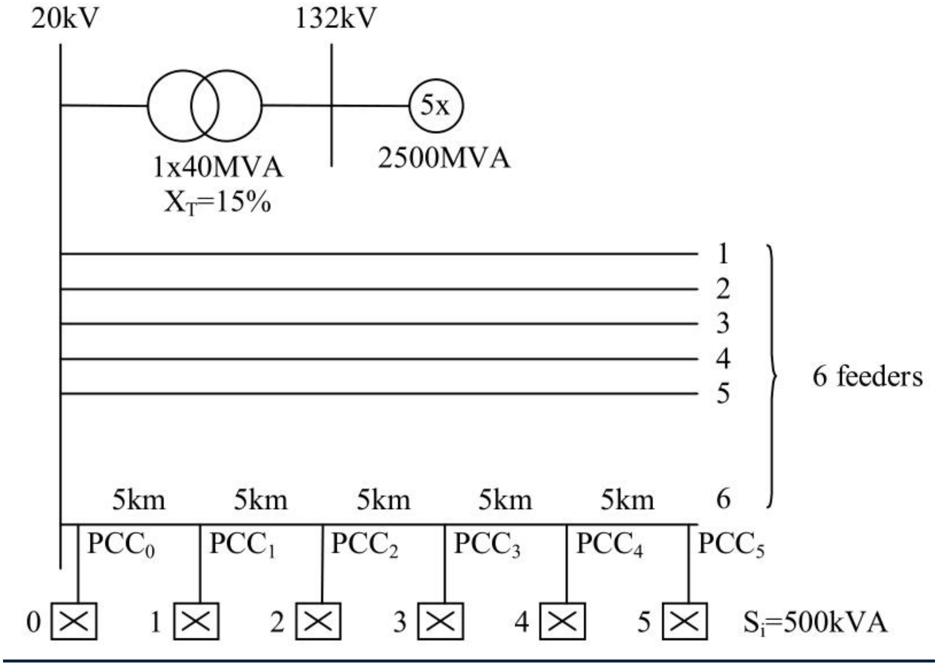

Figure 3-1 – IEC homogenous benchmark model for allocation in systems with long feeders

3.1.2 Energy Networks Association PQ Guidelines – Harmonics

Two network models were developed initially for Standards Australia to assist in the application of the IEC allocation methodology [76, 100]. This application guide was then revised and extended in 2013 [102]. The revision included a total of six models, all of which ranged from EHV to LV, an example model is shown in Figure 3-2. The models were developed based on Australian industry feedback and represent a number of network types, voltage levels and fault level ratios.

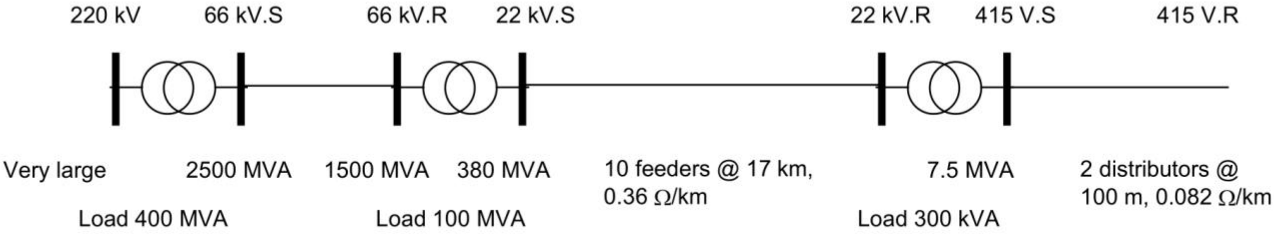

Figure 3-2 – Example system model provided in [102]

All system models presented in [102] are homogenous (noting that load distribution is not defined in the document). However, based on the approach undertaken to develop the models and the purposes for which they were developed, it has been ascertained these models are the most suitable for this project. Impacts related to the assumption of homogeneity were investigated in detail in [135] to ensure the impacts were well understood.

3.2 SIMULATION PLATFORM

The choice of simulation platform to develop and compare allocation methodologies was MATLAB due to the availability and capabilities of the software. A suite of MATLAB algorithms have been written to implement the identified models with the ability to simply change components, network types, allocation processes and quickly present and compare outcomes. Validation of the outcomes have been confirmed by comparing results in a PowerFactory simulation model which found suitable agreement with MATLAB calculations.

3.3 HARMONIC EMISSION LIMIT ALLOCATION COMPARISON

This section presents a numerical comparison of some of the harmonic allocation procedures reviewed in Section 2.5. The purpose is to present the fundamental difference in outcomes of some of the more commonly used allocation methods when applied to the same networks. This includes evaluation of where the methods are capable of either being too conservative or lead to exceeding predefined voltage limits. Sensitivity analysis was undertaken to determine the impact of feeder lengths and the presence of REG, i.e. uncertainties presented in Sections 2.5.3 and 2.5.5.

Firstly, the practical implementation of each allocation methods is outlined using a simplified network model. The network scenarios are then defined and each allocation method used to calculate emission limits with the results compared.

3.3.1 Australian standards/NER

The NER [136] refers to the use of the 2001 version of the Australian clone of IEC technical report 61000-3-6 [76] for management of harmonics in Schedule 5.1.6, stating that:

> *'The Network Service Provider must allocate emission limits no more onerous than the lesser of the acceptance levels determined in accordance with either of the stage 1 or the stage 2 evaluation procedures defined in AS/NZS 61000.3.6:2001 IEC standards'*

It is important to note here that the 2001 version of the technical report that has since been updated [137].

AS/NZS 61000.3.6 prescribes a 3-stage approach to connection of distorting load:

- Stage 1 is only considered for relatively small loads
- Stage 2 is the most commonly implemented methodology for harmonic allocation [97]
- Stage 3 allows for connection at the discretion of the NSP even if emission limits cannot be met and is rarely implemented

Given the fact that stages 1 and 3 are rarely applied, only the Stage 2 methodology is examined in detail.

3.3.1.1 STAGE 2 ALLOCATION – SIMPLE NETWORK

The network model in Figure 3-3 which is a reduced example of the network model presented in [102] has been used to illustrate the outcomes of various emission allocation methodologies. For the purposes of this study, S_t = 10 MVA, and $S_1 = S_2 = \ldots = S_n$ = 2.5 MVA, The fault level at the 22 kV Zone Substation (ZS) point of connection is 380 MVA with the transformer as the dominant impedance. The transformer impedance has been assumed to be purely reactive as reactance values are generally much large than resistance and as such the resistance has lower impact on outcomes. For the purposes of this study, the 5th harmonic has been selected as the order for which an allocation is to be calculated.

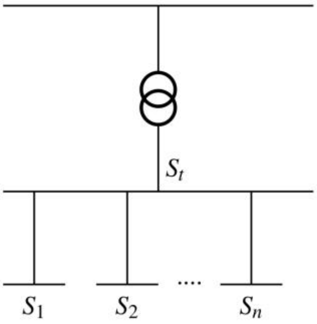

Figure 3-3 – Example Short Feeder Network to Demonstrate Harmonic Allocations

The connecting installation, S_i, receives an allocated harmonic voltage emission limit using (5) as follows (where h = 5 and α = 1.4);

$$
\begin{aligned}
E_{Uhi} &= \mathrm{G}_{h,MV} \cdot \left(\frac{S_i}{S_t}\right)^{\frac{1}{\alpha}} \\
&= 1\,pu \cdot \left(\frac{2.5}{10}\right)^{\frac{1}{1.4}} \\
&= 0.371\,pu
\end{aligned}
$$

Where E_{Uhi} is expressed in per unit of $G_{h,MV}$. From [102] $G_{h,MV}$ can be derived from the suggested planning level for 22 kV and the upstream contribution.

$$
\begin{aligned}
G_{h,MV} &= \sqrt[\alpha]{{L_{MVh}}^{\alpha} - {L_{USh}}^{\alpha}} \\
&= \sqrt[1.4]{0.051^{1.4} - 0.028^{1.4}} \\
&= 0.034\,pu
\end{aligned}
$$

Thus $E_{Uhi} = 0.034 \times 0.371 = 0.0126$ pu on 22 kV, 1 MVA base. The allocated voltage limit (expressed as per unit of relevant limit) can be transformed to a current emission limit for the purpose of compliance assessment using (12).

$$
E_{Ihi} = \frac{E_{Uhi}}{\mathrm{x}_{hi}} \tag{12}
$$

For the scenario above this would result in a 5th harmonic current emission limit of 0.0126 / (5 × 2.5/380) = 0.383 pu with a 22 kV and connection agreed power (2.5 MVA) base. Loads or generators subsequently connected for this scenario would receive allocations as per (5) and (12). Once the system reaches capacity (i.e. $\sum_{i=1}^{n} S_i = S_t$) and all connections are meeting their 95th percentile allocated emission limits, the system would theoretically reach planning levels.

This is certainly the simplest application of the IEC method and remains a valid process for the scenario in which the PCC of all connections are the same point on the network. There have been a number of variations and modifications to the IEC method since its first inclusion in the technical report in 1996. These modifications, as discussed in Sections 2.5.4 and 2.5.5 have been developed to extend the application of the IEC method to systems that contain feeders with significant variation in fault levels between the sending and receiving ends of feeders.

3.3.1.2 STAGE 2 ALLOCATION – LONG FEEDER

The application of (5) in a system with multiple connections that are distributed along a feeder with a considerable reduction in fault level between the sending and receiving end results in a significantly reduced harmonic current emission limit for the connections at the end of the feeder. Consider for example if the network shown in Figure 3-3 was modified such that load S_2 was connected at the end of a feeder 17 km in length with a reactance of j0.35Ω/km at fundamental frequency. Both S_1 and S_2 are of equal size (2.5 MVA), S_1 connects to the ZS busbar, as in the previous example, and S_2 connects at the end of the feeder. Based on this data, both will receive the same allocated harmonic voltage limit but S_2 receives an allocated current emission limit 18% of S_1 due to the difference in impedance (x_{hi}) at the point of connection.

To alleviate the variation between allocations at different locations along feeders, a suggestion is made in Appendix B of [71] to allocate a constant harmonic VA to loads of the same agreed power, regardless of their position on the network. This is achieved by using (13) to calculate harmonic current emission limits.

$$
E_{Ihi} = \frac{A_h \cdot S_i^{1/\alpha}}{\sqrt{\mathrm{x}_{hi}}} \tag{13}
$$

Where

A_h is the allocation constant calculated by determining the maximum harmonic voltage in the network with assumed future loading and reference current source

S_i is the agreed power of installation i

x_{hi} is the impedance of the system at harmonic order h at the PCC of installation i

The use of (13) for the previous example results in S_2 receiving a current emission limit allocation that is 41.5 % of S_1, a marked increase and strikes a reasonable compromise between suitable use of the harmonic absorption capability of the system and fair allocation limits for all connections based on their position on the network.

It should be noted here that considerable errors may be introduced to this approach due to uncertainties of load concentration and position of connections on the network. This was investigated in detail in [135] with the finding being that assumptions based on the final distribution of connections of a network may lead to planning levels being exceeded in many scenarios. A study was undertaken that proposed a revised methodology in the determination of the allocation constant, A_h for a network with high uncertainty and compared the resulting outcomes with ideal and existing practices. The study compared the final emission levels for a large number of scenarios based on existing, ideal and proposed methodologies, including the Voltage Droop method presented in [101, 138]. A statistical representation of the outcomes are shown in Figure 3-4 in which;

- The outer box represents the 5th-95th percentile values
- The minimum and maximum values are indicated by the black line extended from each box
- The median value is indicated by the dashed line within the box

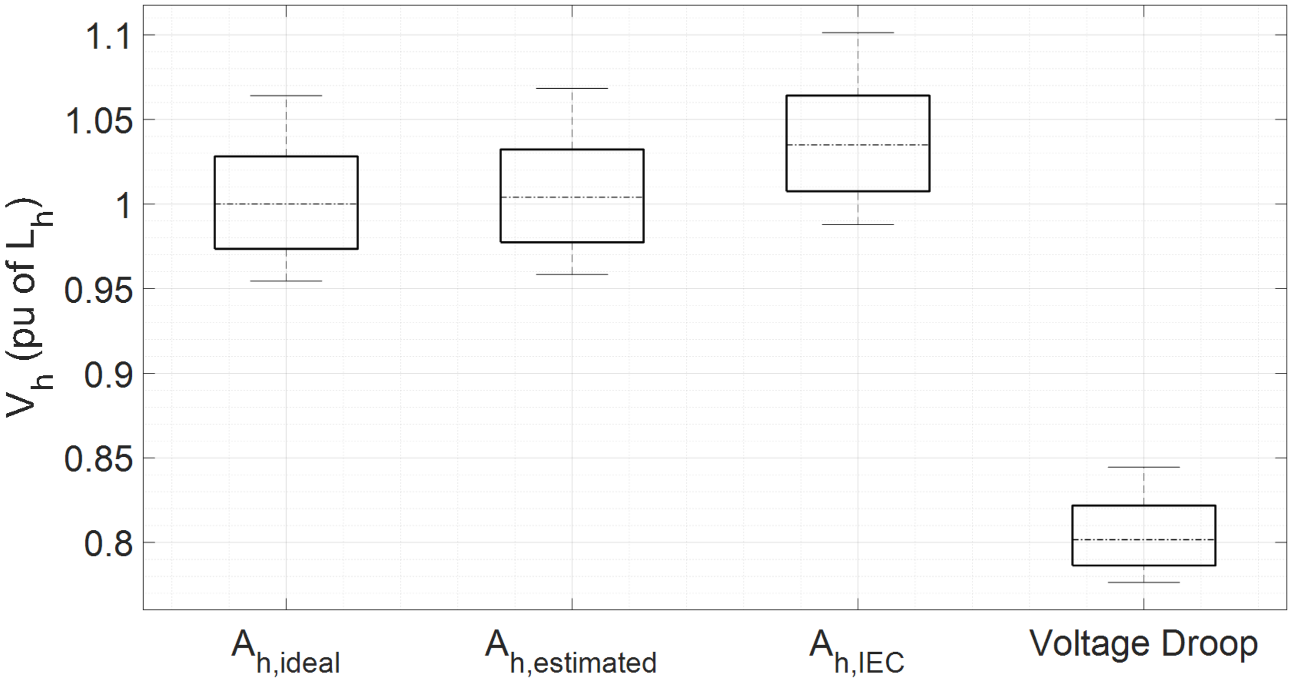

Figure 3-4 – Comparative harmonic voltage results when allocating with and without uncertainty ($A_{h,IEC}$ ans $A_{h,ideal}$ respectively), results also compared with Voltage Droop method

The outcomes of the study identify a revised approach to estimating the expected loading of the network, improving harmonic voltage levels for networks with high levels of uncertainty.

3.3.1.3 STAGE 2 ALLOCATION – DISTRIBUTED GENERATION

As discussed, the treatment of REG is not sufficiently addressed in existing methodologies. This places the onus on NSPs to determine the level of impact REG is likely to have on systems and plan appropriately. Consider for example, the scenario provided in Section 3.3.1.1 in which the connecting installation is a REG connection. If the NSP has knowledge about this connection, the values of S_p and λ_p (as defined in (6)) may be appropriately accounted for and the method continues to be valid and confidently applied. However, if the level of future REG penetration is unknown, the approach identified in [11] is one possible way to attempt to mitigate the impact of uncertain REG penetration levels.

For example, if the connection of Section 3.3.1.1 was a generator as opposed to a conventional load and the NSP had decided to implement a harmonic allocation policy that accounts for REG, i.e. implementing (6) to estimate S_t. The magnitude and uncertainty coefficient for generating installations may be reasonably set to:

- $S_p = 4\ MVA$
- $\lambda_p = 0.7$

Note that these values are somewhat arbitrary (within reasonable limits) as the selection of S_p and λ_p are based on conditions specific to the network and are to be determined on a case by case basis [11]. Given these values, one can implement the updated approach of the IEC method by calculating an updated value of S_t using (6) and calculating the harmonic emission limits using (5), i.e.;

$$\begin{aligned} S_t &= \lambda_c S_c + \lambda_p S_p \\ &= 1 \cdot 10\ MVA + 0.7 \cdot 4\ MVA \\ &= 12.8\ MVA \\ E_{Uhi} &= G_{h,MV} \cdot \left(\frac{S_i}{S_t}\right)^{\frac{1}{\alpha}} \\ &= 1\ pu \cdot \left(\frac{2.5}{12.8}\right)^{\frac{1}{1.4}} \\ &= 0.311\ pu \\ E_{Ihi} &= 0.375\ pu \end{aligned}$$

It can be seen that the inclusion of REG reduces the relative harmonic voltage emission that the installation is able to contribute to the system as compared with the results of Section 3.3.1.1. The connection in this example receives a voltage emission limit allocation equal to 84 % when compared to the scenario in which REG is not accounted for. This is due to the inclusion of S_p into the calculation of S_t. The approach attempts to mitigate the impacts of uncertain REG penetration by constraining the emissions of all connecting plants. It should be noted that such an approach may only be implemented in greenfield sites, i.e. accounting for REG may not be retrospectively considered in networks that have distorting installations already connected.

There is scope in this approach to include connections that are certain with a $\lambda = 1$ and for all uncertain installations with a $\lambda < 1$. The fundamental philosophy behind this is to give priority to connections that are definite whilst still accounting for connections that may eventuate but are not certain. Such an approach has merits in its simplicity, but it is too premature to determine the efficacy of its economic use of the harmonic absorption capability of the network.

3.3.2 IEEE standards

The IEEE method, as previously discussed, is a simpler emission allocation methodology that assigns a harmonic current emission limit based on the SCR (ratio of fault level to connection power) of the installation at the PCC.

3.3.2.1 IEEE ALLOCATION – SIMPLE NETWORK

For the connection request in Section 3.3.1.1, the SCR is calculated as;

$$\begin{aligned} SCR &= \frac{S_{FL}}{S_i} \\ &= \frac{380\ MVA}{2.5\ MVA} \\ &= 152 \end{aligned}$$

For the scenario in which the connection is a standard load, this results in a 5th harmonic current emission limit of 12 % of the installation rated current. Converting this to an allowable harmonic voltage contribution using the system impedance results in 0.004 pu. This allocation is 27 % of the calculated IEC method. This result agrees with the qualitative review of the IEEE methodology that stated that the IEEE method implements conservative assumptions to ensure voltage limits are not exceeded across many different network scenarios and topologies.

3.3.2.2 IEEE ALLOCATION – LONG FEEDER

As with Section 3.3.1.2, consider the same connection now connecting at the end of a long feeder. The approach is not altered in any way, but the SCR of the connection is revised to 26.2. This results in a harmonic current allocation of 7 % of the installation rated current. This is a 40 % reduction compared to the allocation if the connection was made at the ZS busbar and 90.7 % of the IEC allocation at the same PCC when allocating constant harmonic voltage. However, if the IEC harmonic VA methodology, as in Section 3.3.1.2, is applied the IEEE allocation is 41.2 % of the IEC method, maintaining the relative conservative nature of the IEEE methodology.

3.3.2.3 IEEE ALLOCATION – DISTRIBUTED GENERATOR

The IEEE guidelines are definitive with respect to the treatment of generating installations. The IEEE standard states that all generator installations are limited to the emission limits identified for the lowest short-circuit ratio. For the example presented in Section 3.3.2.1, if the requesting connection were a generator, this would reduce the emission limit to 4 % of the installation rated current, just 9 % of the IEC allocation for the same scenario (assuming REG is treated identical to consuming loads).

A simple comparison of the allocation for 5th harmonic emission for each method for all scenarios is presented in Figure 3-5. As previously discussed, the IEEE method is found to be consistently more conservative (i.e. result in lower emission allocations) than the IEC method. It is worth repeating here that the value of the allocation using the revised IEC method to address REG was developed using indicative values. Such outcomes are wholly dependent on the network to which the allocation is applied and decisions made by the NSP.

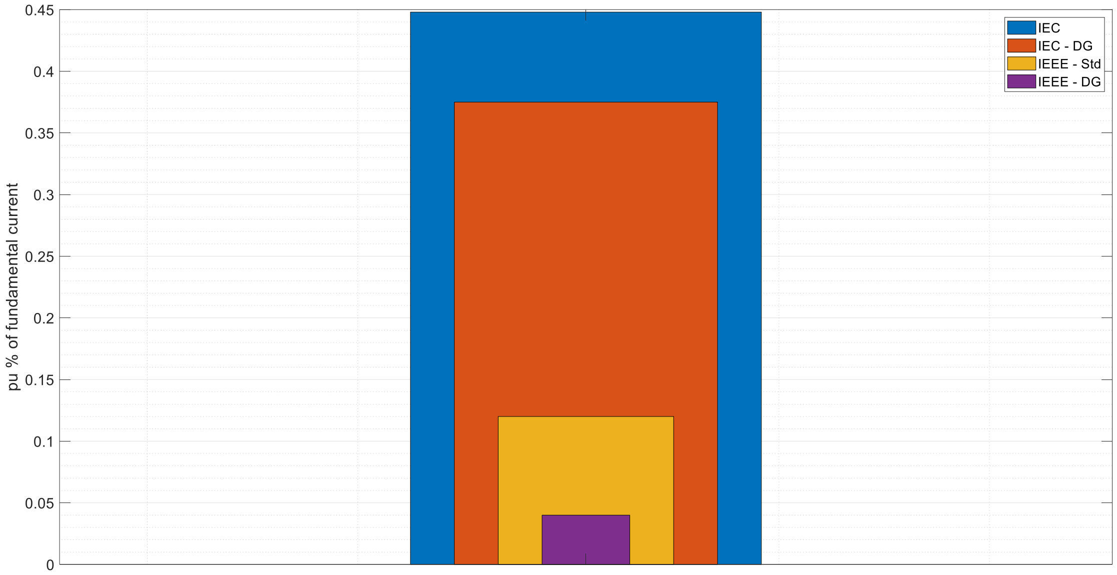

Figure 3-5 – Comparison of IEC and IEEE harmonic allocations with and without renewable energy generation

3.3.3 Other International Methods

A probabilistic study has been conducted to compare the allocations for the 5th order harmonic using the IEC with a range of other methodologies applied internationally and defined in [72, 73, 84, 85] (i.e. applied within the US, parts of Canada, France and other parts of Europe respectively). The study utilised a model adapted from Figure 3-2 to compare the outcomes for multiple allocation methodologies in networks with long lines (REG was not considered in this study). In order to account for variations of allocation limits due to connection location on the network, randomly defined scenarios were created, emission limits calculated and the resulting maximum expected distortion on the network was determined. It is important to note that the results were compared against planning levels (or network harmonic voltage limits) as defined in each relevant document. Statistical representation of the results is shown in Figure 3-6 where the box encloses the inter-quartile range (i.e. 25th – 75th percentiles) of harmonic voltage levels with the extending lines indicating minimum and maximum values, the horizontal dashed line represents the median value.

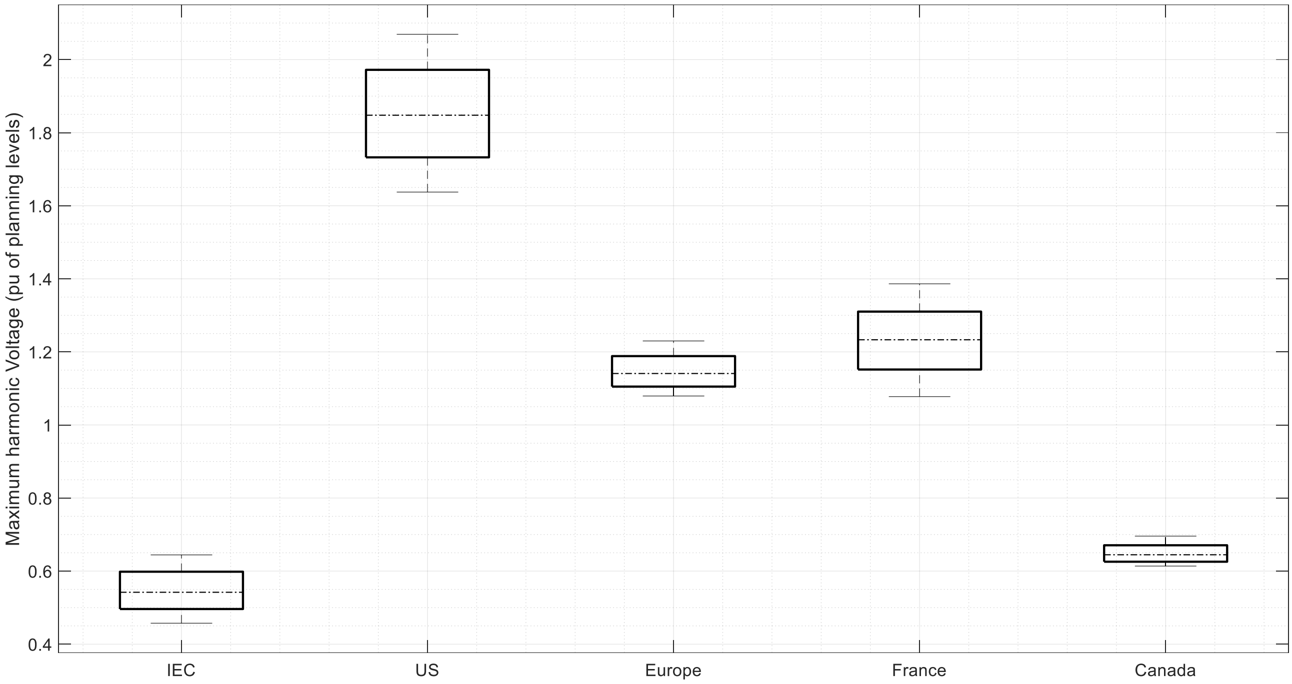

Figure 3-6 - International allocation comparison

One of the interesting findings in this study is the consistent exceedance of network voltage levels for the IEEE and other fixed allocation methodologies, given the comparatively conservative outcomes of Section 3.3.2. This was found to be due to the comparatively lower planning levels for lower order harmonics specified in these standards compared to the IEC by [72], i.e. the comparatively reduced emission limits found in Section 3.3.2 result in IEEE harmonic voltage limits being consistently exceeded once the network is fully loaded. This outcome confirms the finding of the literature review that such methodologies are generally not appropriate for networks that do not adhere to the assumptions that were used in the development of the method.

Further, the IEC methodology consistently resulted in maximum network harmonic emissions falling below planning levels due to the assumptions related to the final state of the network, identifying the impact of uncertainty on the methodology. Whilst the results in Figure 3-6 fall within approximately 20 % of planning levels, increased penetration of REG is capable of significantly impacting network uncertainty and related effects.

3.4 SUMMARY

A numerical comparison of some of the qualitatively reviewed harmonic allocation processes has been provided, notably the IEEE and IEC methods. This includes derivations of the IEC method used to account for long feeders and REG connections. The study exemplifies the uncertainty related to the IEC method and how outcomes are capable of being significantly impacted by future uncertainties such as REG penetration, concentration and system loading variation. Further, suggested approaches to integrate REG have been shown to be theoretically sound but further constrain connecting installations. The full implications of such solutions are yet to be well understood due to the lack of experience by the industry in its application.

The IEEE method was also applied to a simple system. The results highlight the simplicity of the method but also its conservativeness. An example was provided in which the IEEE method is applied to a single long feeder. This results in the connecting installation receiving an allocated emission limit equal to 41 % of the IEC method allocated in the same scenario. Written caveats in the IEEE method also suggest generating installations are to receive the lowest allowable allocation limit, regardless of the SCR of the installation. This results in the IEEE method allocating only 9 % of the IEC method when considering this REG example.

A full system comparative study was undertaken in which the resulting harmonic voltage of a multi-feeder system is calculated for a range of allocation procedures once the system reaches capacity. This study found the IEC method to be reasonably conservative whilst the fixed allocation methodologies consistently resulted in system harmonic voltage limits being exceeded. The study shows that fixed allocation methodologies are suitable for limited system types and topologies with very little guidance regarding when the method is unsuitable. These simple examples identify and confirm some of the findings identified in the literature review. Given the consistent capability of the fixed allocation methodologies to result in harmonic voltage levels exceeding predefined limits, it is suggested that they should only be used with due care and understanding of the implications.

4 Investigation of the Applicability of the Summation Law within Renewable Energy Farms

4.1 INTRODUCTION

This section of the report details work undertaken to investigate how emissions from multiple identical harmonic sources within a single renewable energy generator (REG) plant should be aggregated. Presently, common practice when undertaking harmonic analysis of REG plants is to assume that the harmonic emissions of identical equipment, e.g. wind/solar PV inverters, have no significant diversity for all harmonic orders, i.e. the emissions at each harmonic order should add arithmetically. This assumption has significant implications for harmonic emission limit allocation, compliance assessment and mitigation design/implementation. Disregarding the possibility of harmonic emission diversity is capable of significantly overestimating the magnitude of emissions, leading to significantly increased costs and potentially unnecessary or oversized mitigation equipment being installed. This section presents the findings of an empirical study, investigating the aggregation of multiple identical Inverter Based Resources (IBR) by analysing measurements of such devices.

Harmonic source aggregation is defined in AS/NZS 61000.3.6 [76] to allow a generalised approach to estimating the interaction between multiple or aggregated harmonic sources. The statistical calculation is shown in (14), noting the process may be used for voltage and current interchangeably.

$$U_h = \sqrt[\alpha]{\sum U_{h,i}^{\alpha}} \tag{14}$$

Where;

U_h is a probabilistic estimation of harmonic emissions based on the interaction between harmonic sources

$U_{h,i}$ is the individual harmonic emission of each source under assessment

α is the summation exponent that takes into account the (time, magnitude and phase) diversity that is anticipated to exist between harmonic sources

The final values of α selected for application in AS/NZS 61000.3.6 are reproduced in Table 4.1 for ease of reference.

Table 4.1 - Values of α as per [76]

h	α
$h < 5$	1
$5 \leq h \leq 10$	1.4
$h > 10$	2

The use of (14) with the values of α as shown in Table 4.1 effectively reduces the aggregated emissions for harmonic orders 5 and above. However, Note 1 of Table 4.1 in [76] states that the provided values of α are to be used when specific detail is not known regarding the individual harmonic sources. This has led to many studies undertaken within Australia assuming that $\alpha = 1$ for all harmonic orders when aggregating identical harmonic sources, such as a solar PV or wind turbine inverter within a REG plant. The justification for this approach being that REGs generally consist of multiple, identical harmonic sources that are generally operating in the same state (e.g. they are all exposed to the same solar irradiance or wind conditions), thus it is likely that the emissions add arithmetically. A number of studies have been undertaken to further investigate this assumption [4, 139-141]. Each of the existing studies present different, inconclusive outcomes, are based on minimal datasets or do not adequately represent Australian industry experience. As such, a focused review with an Australian context has been undertaken in this section.

The original project plan identified the use of detailed REG farm models to undertake this task, however, based on the inaccuracies that currently exist with IBR harmonic modelling procedures [142-144] a revised approach has been undertaken. The approach instead focused on actual site measurements collected from a

REG plant connected to the NEM. As such, the results presented here can be considered to be a case study. The advantage of this revised approach is that observed impacts may be reported on, rather than hypothesised. However, an added challenge is introduced, that being identification of impacts due to external sources. This is addressed and discussed in later sections.

A description of the measurement and plant layout is first provided with a verification of the measurements and analysis described. A direct comparison of arithmetic summation and use of the summation law as it appears in AS/NZS 61000.3.6 (adapted from IEC TR 61000.3.6) is presented. Finally, values of α that result in an accurate aggregation of the measured currents determined using empirical methods are presented for each harmonic order.

4.2 MEASUREMENT DESCRIPTION

Measurements have been taken within a REG plant to ascertain the level of diversity of individual harmonic orders between multiple, identical harmonic sources. The case study plant consists of several feeders, each with multiple, identical inverter-based generators connected. The harmonic emissions analysed were taken from a single case-study feeder containing eight identical generators as shown in Figure 4-1. Measurements at each of the generator terminals and at the connection point of the collector cable to the reticulation bus were analysed.

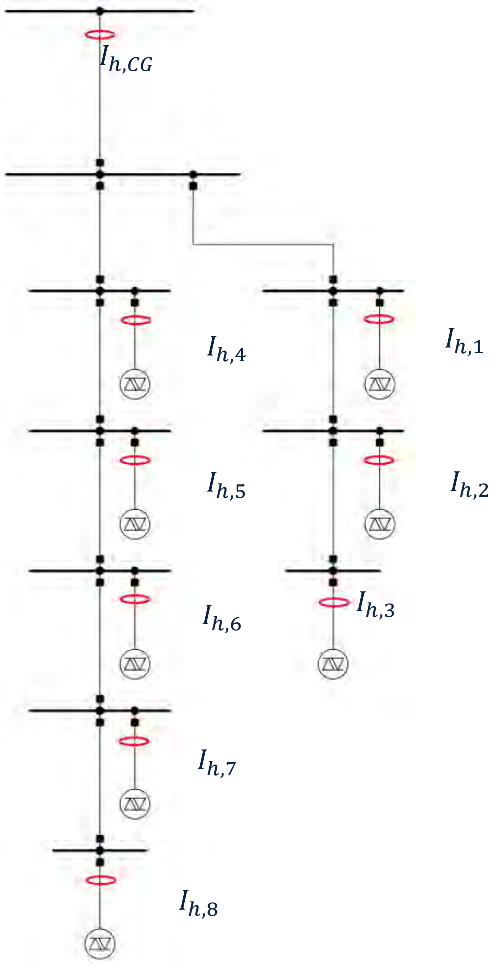

Figure 4-1 – REG plant collector cable and reticulation bus harmonic measurement points

Not shown in Figure 4-1 are the inverter transformers that step generator connection voltage up to the collector voltage of 33 kV. The individual generator harmonic current measurements were taken at the low voltage terminals and have been scaled based on the turns ratio of the inverter transformer so as to allow a direct comparison between the aggregation of individual emissions and harmonic current measured through the collector cable.

The measurements were restricted to harmonic current magnitudes (i.e. phase angle data was not collected) only and were recorded by power quality monitoring instruments[3] using 10 min intervals.

4.2.1 Process

Evaluation of diversity in harmonic emissions was considered by comparing the summation of individually measured harmonic currents from the generators with the total measured harmonic current through the collector cable using (15).

$$I_{h,CG,calculated} = \left(\sum_{i=1}^{8} I_{h,i}^{\alpha}\right)^{1/\alpha} \tag{15}$$

Where;

$I_{h,i}$ is the harmonic current of order h from generator i,

α represents the diversity of the harmonic summation ($\alpha = 1$ representing no diversity), and

$I_{h,CG,calculated}$ is the calculated collector harmonic current of order h.

In this process the time diversity associated with the α exponent is initially disregarded, i.e. the measured values of harmonic currents from each generator at each time interval are summated by direct addition and, for comparison, in accordance with the summation law as defined by (15). The time diversity component is then considered by taking the 95th and 99th percentile values of the resulting summated currents over the measurement period.

The resulting 95th and 99th percentile values of the calculated collector harmonic current (the summation of the harmonic currents from each generator) is compared to the measured 95th and 99th percentile values of collector current for the same measurement period. A comparison of the result with α as per Table 4.1 is made, and additionally a more suitable value of α (where relevant) is established to illustrate the empirically calculated diversity.

4.2.2 Verification of measurements and analysis program

In order to perform analysis on large volumes of data, across the frequency range and time period of interest, scripts and automated programs were written to aggregate and compare calculated values against the values measured through the collector cable. Prior to undertaking analysis, the measurements, calculation process and all developed tools were verified to ensure processes were working as expected. This verification was completed by comparing the arithmetic aggregation of the fundamental current with the measured current through the collector cable. It is fair to expect that the relative phase angle at the fundamental frequency between individual WTGs will be $\theta \approx 0°$ and thus the total measured fundamental current should be approximately equal to (15) with $\alpha = 1$. The comparison of measured and calculated fundamental current values for all three phases is shown in Figure 4-2 (time-series) and Figure 4-3 (scatter).

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[3] All class A instruments [145] *Australian/New Zealand Standard, Electromagnetic Compatibility (EMC) –Part 4-30: Testing and Measurement Techniques – Power Quality Measurement Methods,* Standards Australia AS/NZS 61000.4.30-2012, 2012.

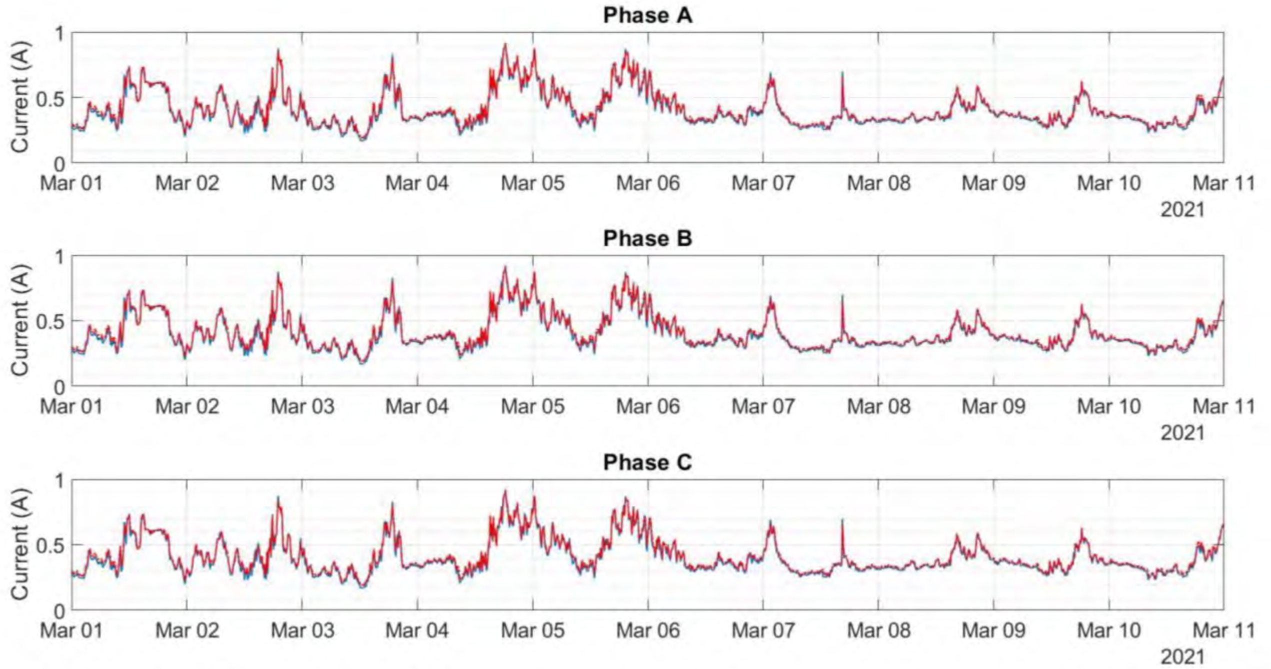

Figure 4-2 – Time-series comparison of measured (red) and calculated (blue) fundamental current values

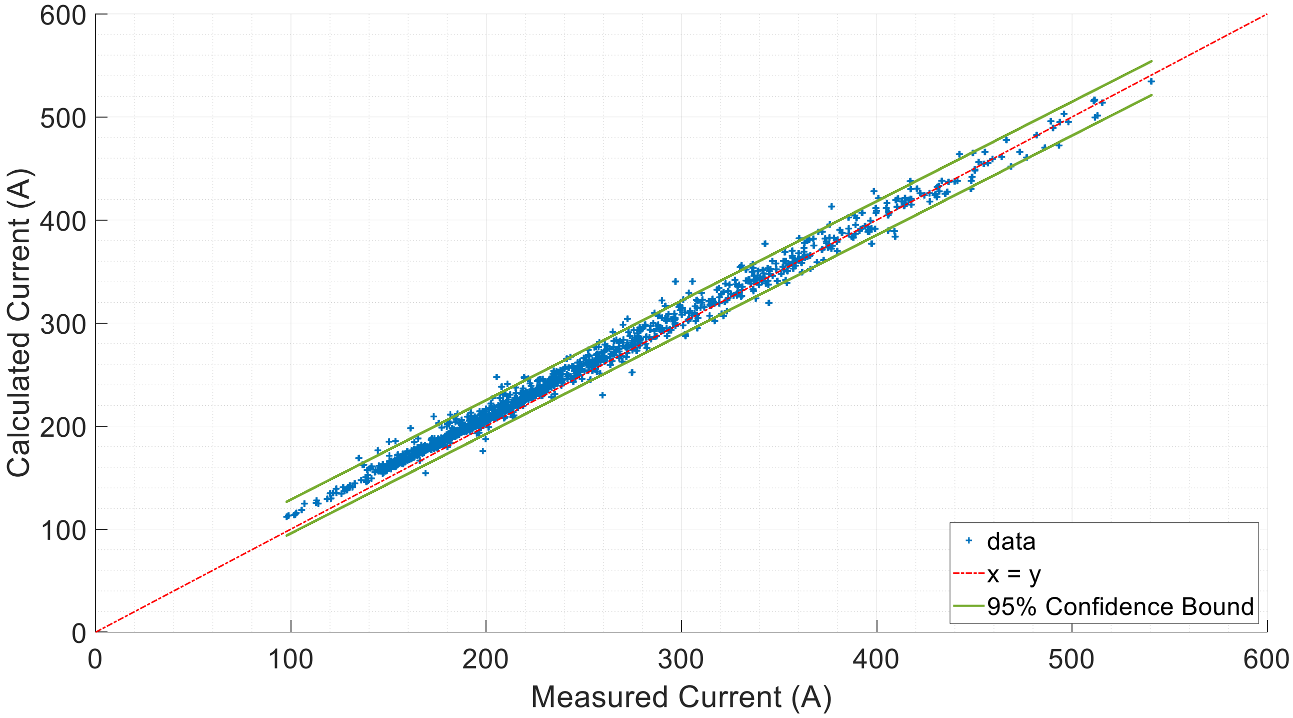

Figure 4-3 – Scatter comparison of measured and calculated fundamental current values

The comparison between the two value sets shows very good alignment between the measured and calculated fundamental current values, confirming the dataset to be valid and that the developed tools provide the expected outcomes. This is further exemplified by the linear series plot (i.e. $x = y$) which shows that outcomes lie within the 95 % confidence bounds of the scattered data.

It should be noted that summation using (15) assumes passive components (i.e. collector cable and reticulation transformers) have no impact on the diversity of the harmonic emissions. A sensitivity study was undertaken and found this assumption to remain valid for harmonic orders for which harmonic resonance was not a factor, i.e. modelling of the plant found resonance at the collector bus to occur at the 30th harmonic order. No discernible harmonic emission measurements were recorded at this order.

The following sections investigate the level of diversity which exists between individual harmonic sources, identify scenarios by which this diversity may be estimated (and scenarios where it may not) and explore potential processes to further the analysis beyond the case study presented here. As discussed in the introduction, the importance of this study is the fact that present-day methodology will commonly not consider diversity within a plant between harmonic sources. This represents the worst-case scenario with the very real possibility of considerable over-estimation of the aggregated harmonic contribution.

4.2.2.1 CONSIDERATION OF MEASUREMENTS BELOW MINIMUM THRESHOLD

The accuracy of the measured current values used is dependent on the components of the measurement setup. For the purposes of the study, it was necessary to determine a minimum measurement threshold below which, measurement accuracy could not be guaranteed. Given the uncertainty associated with measurements below the minimum accuracy threshold they were omitted from further consideration. Specific details regarding voltage/current transducers and the remainder of the measurement setup was not available. As such, reasonable values of nominal current, I_{nom}, were assumed based on the measured fundamental current data, and the values in Table 1 of IEC TR 61000-4-7:2012 [146] were used to determine the minimum threshold. Minimum threshold values for all meters used to capture data for analysis were calculated.

For the Collector Group meter (CG in Figure 4-4), the minimum threshold was calculated as 0.15 A, whilst 3 mA was the threshold calculated for the generator terminal meters. An important outcome of this evaluation is that for many harmonic orders, the aggregated current of the individual generators (i.e. (15)) results in harmonic current emissions above 0.15 A, whilst the CG meter does not register emissions above this calculated minimum measurement threshold. Thus, in such a circumstance, one may confirm that diversity exists, however, the magnitude of error is unable to be determined as the measured collector current is uncertain. Where possible, analysis has been performed with this understanding of uncertainty noted. For example, the measured current through the collector cable for $h = 4$ is shown in Figure 4-5, along with the arithmetic summation of the individual generator currents. The minimum measurement threshold for the CG meter is also shown and it can be seen that the measured values are below the minimum measurement threshold for all data. This may indicate significant cancellation of 4th harmonic emissions, but the level of uncertainty is too high to make this conclusion with any degree of confidence.

As discussed above, in order to ensure analysis is undertaken on valid measurements, data points that were below the minimum threshold have been removed. As a consequence, many harmonic orders did not register a single measurement above the minimum threshold of the CG meter for the entire measurement period.

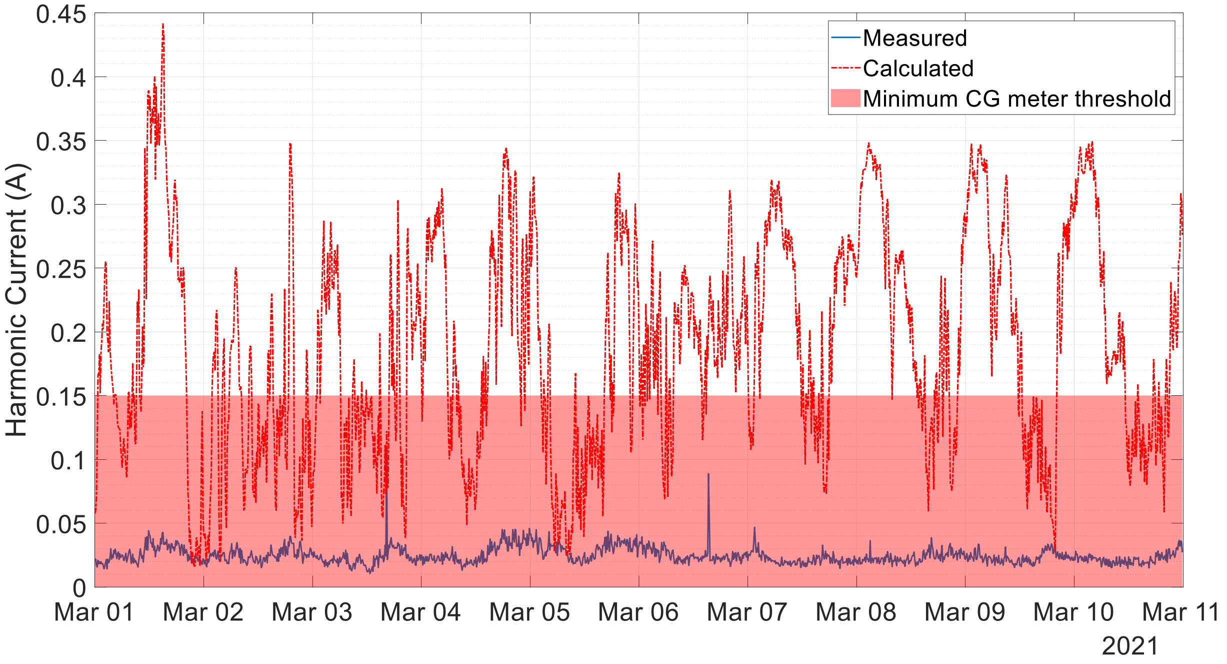

Figure 4-5 - Identification of disparity between (15) and CG measurements for the 4th harmonic

As can be seen in Figure 4-6, there are significant periods for which the aggregated current emissions are expected to exceed the minimum measurement threshold whilst the actual measured current does not exceed this threshold for the entire measurement period. This comparison suggests a high degree of diversity between the harmonic sources for the measurement period. A bar graph was developed, as shown in Figure 4-7, that identifies for each harmonic order the:

a) Percentage of measurements that fall below the collector group minimum measurement threshold (blue bar), and

b) Proportion of a) for which the aggregate of individual emission measurements (i.e. (15)) exceed collector group minimum measurement threshold (red bar)

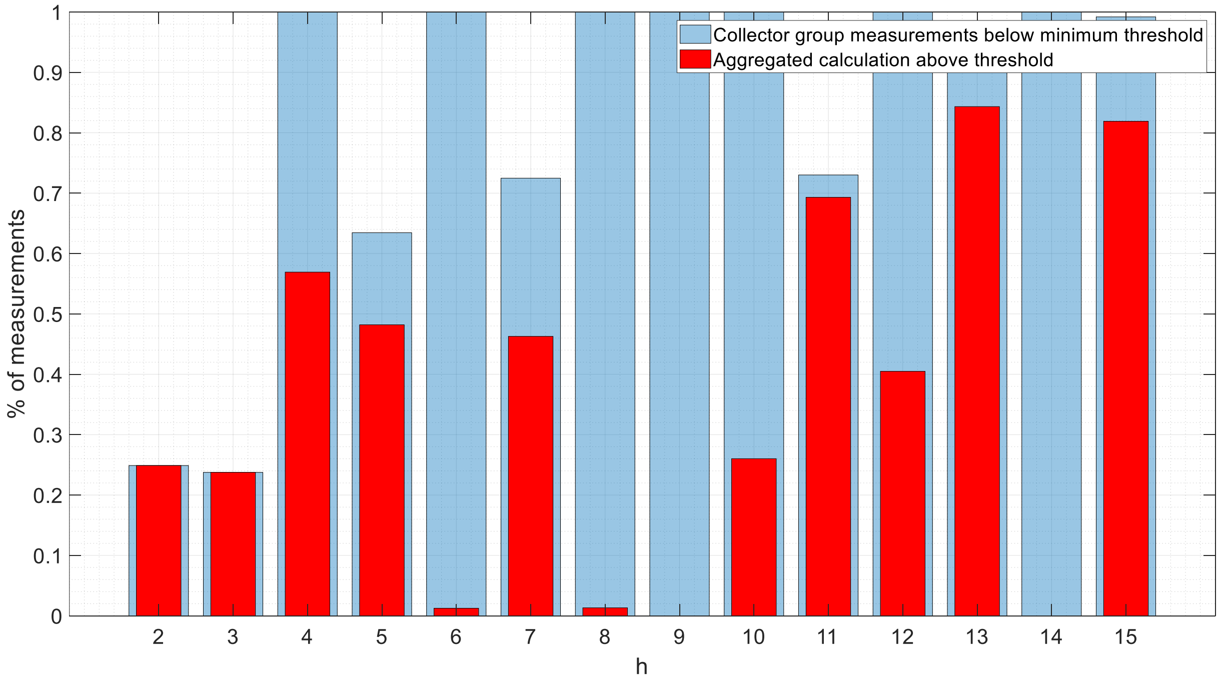

Figure 4-7 - Percentage of measurements below minimum threshold and aggregation above measurement threshold

It should be noted that for harmonic orders above the 15th, all measurements were below the collector group measurement threshold and (15) did not exceed the threshold value, i.e. results were identical to those seen for the 9th and 14th harmonic orders shown in Figure 4-7. As such, results for harmonic orders above the 15th have been omitted from further analysis.

Based on the data presented in Figure 4-7, the following may be surmised:

- All even harmonic orders above the 2nd order, and most non-characteristic orders do not register a measurement through the collector group that exceeds the minimum measurement threshold for the entire period.
- The percentage of measurements below the minimum measurement threshold for odd harmonic orders increases with frequency.

These outcomes suggest that diversity between harmonic sources is more pronounced for non-characteristic orders and the degree of diversity increases with frequency.

Figure 4-7 shows that for 2nd and 3rd harmonic the arithmetic sum of individual generator measurements results in values above the minimum collector group measurement threshold however the values collected by the collector group meter are all below the minimum measurement threshold. This suggests that ignoring diversity in individual emissions leads to consistent over-estimation of harmonic emissions. For 4th harmonic, aggregation of the individual generator measurements exceed the minimum collector measurement threshold for 57 % of the total measurements whilst this value is 50 % for 5th harmonic. A significant percentage of measurements fall below the minimum threshold for characteristic harmonic orders, whilst aggregation of emissions from individual inverters result in considerably larger values. These outcomes suggest that diversity exists for significant periods of time between the harmonic sources for all of these orders.

The percentage of valid measurements across phases for the entire measurement period and for harmonic orders with discernible measured current through the collector group is provided in Table 4.2.

Table 4.2 - Percentage of valid measurements through collector group meter

h	**% of valid measurements**
1	100
2	75
3	76
5	37
7	28
11	27
13	6
15	0.8

Given the comparatively low percentage of measurements available for $h = 15$, it has also been removed from further analysis.

Based on the analysed data, it may be surmised that arithmetic summation of individual emissions, which equate to use of (15) with $\alpha = 1$, regularly over-estimates aggregated emissions in conditions where emissions are below the CG meter measurement threshold. Further, such scenarios exist for significant periods of time for all harmonic orders, i.e. a large proportion of the analysed data suggests diversity to exist between harmonic sources for all harmonic orders. These findings challenge the present practice of arithmetically summating harmonic emissions from multiple instances of the same equipment with a REG. Ignoring diversity results in increased emission values which in turn increases the likelihood of non-compliance during pre-connection compliance. Pre-connection non-compliance may necessitate mitigation which most often takes the form of harmonic filters which are both expensive and have uncertain impacts on the broader network.

4.3 ESTIMATION ERROR

The analysis process presented in Section 4.2.1 (i.e. comparison of measured CG meter current with aggregated emissions calculated using (15) with an α value of 1) was implemented for frequencies above the fundamental to investigate the impacts of diversity and potential error introduced when aggregating harmonic sources. Example results are shown for 3rd and 5th harmonic are shown in Figure 4-8 and Figure 4-9 respectively.

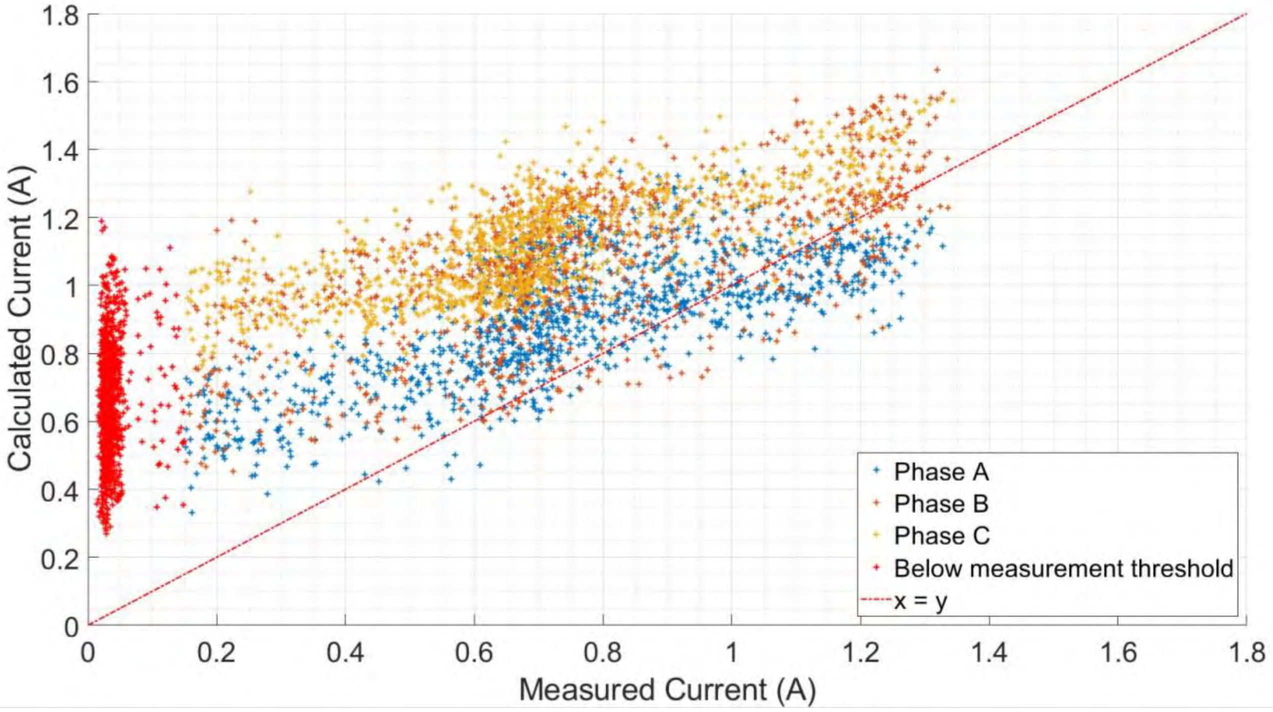

Figure 4-8 – Comparison of measured and calculated current values for h = 3

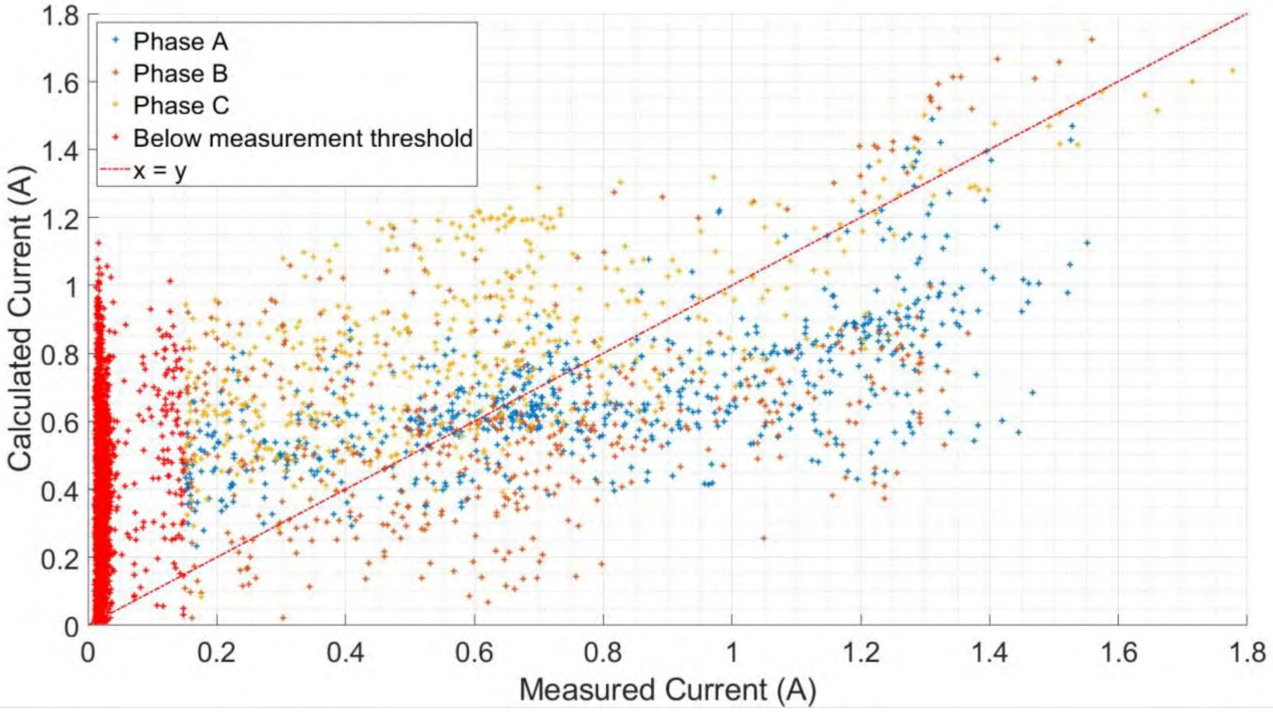

Figure 4-9 - Comparison of measured and calculated current values for h = 5

The following provides a summary of the results shown in Figure 4-8 and Figure 4-9:

- The correlation between measured and calculated current was much better for the fundamental current than is observed for harmonic currents.
- There is a significant number of instances where currents are below the threshold of measurement for the collector current in spite of there being measurable values for each individual source. This suggests a high level of diversity, i.e. in some cases there is almost complete cancellation in emissions.
- There is rarely strong correlation between measured and calculated values indicating that some degree of diversity exists.

Similar outcomes to those detailed above exist for all harmonic orders assessed. Thus, arithmetic aggregation of harmonic current emissions does not appear to be a suitable approach to determine the summated emission of individual generators of the same type. The magnitude of error of using (15) with α = 1 has been investigated to understand the sensitivity of the analysed dataset. The error for each valid measurement point was calculated using (16) and the results collated, shown as a boxplot in Figure 4-10.

$$err_h = \frac{I_{h,calculated} - I_{h,measured}}{I_{h,calculated}} \times 100\ \% \tag{16}$$

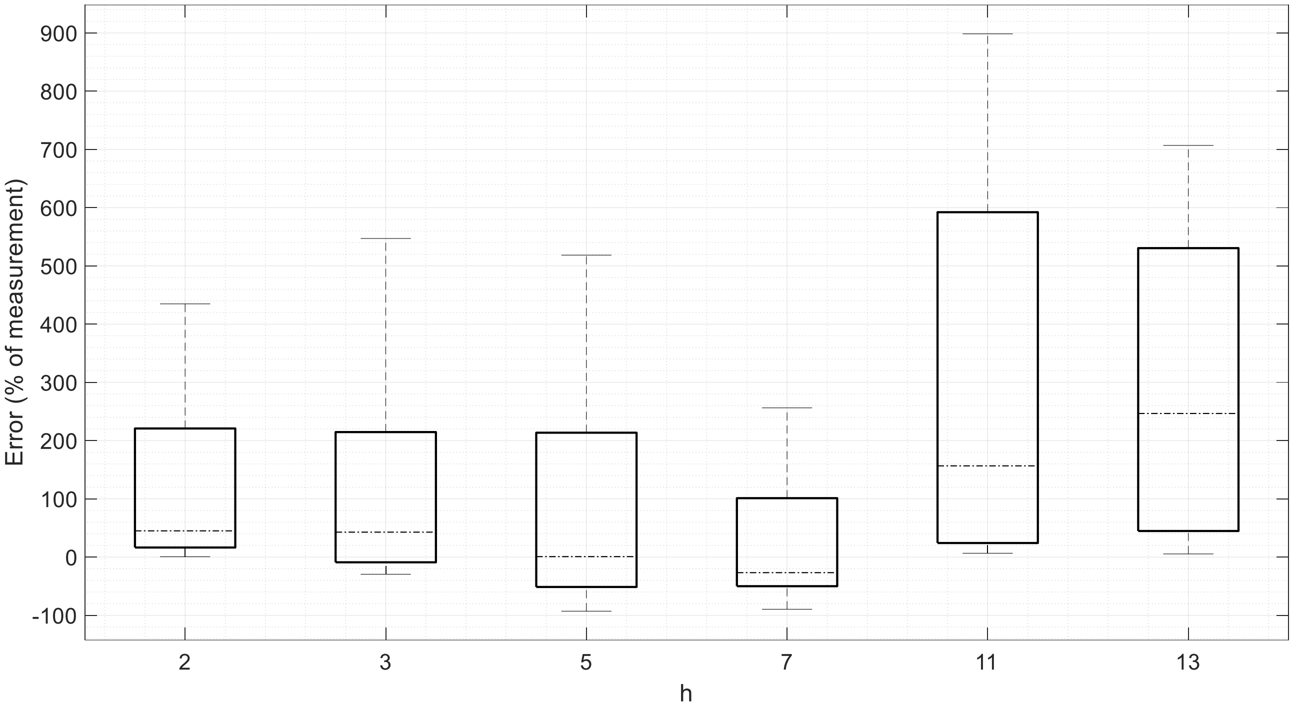

Figure 4-10 - Boxplot of error detected for harmonic orders with measurable harmonic emissions through collector group

These box and whisker plots provide a statistical representation of the calculated error for all measurement points. The whiskers represent the minimum and maximum values recorded across all data points whilst the box encloses data points recorded above the 5th percentile and below the 95th percentile of values, with the horizontal dashed bar identifying the median value for the given harmonic order.

Based on the calculated error for each harmonic order for which measurable harmonic emissions through the collector group exist, it can be seen that the possible error has a large range, which generally increases with frequency. Thus, it may be suggested that phase-angle diversity exists for all harmonic orders, however, the magnitude of diversity is higher at higher frequencies. This tends to agree with traditional approaches with respect to the aggregation of harmonic currents and is partially the reason that summation laws are applied in AS/NZS 61000.3.6.

As can be seen in Figure 4-9 for the 5th harmonic order and Figure 4-10 for the 3rd, 5th and 7th harmonic orders, there are scenarios in which the calculation of (15) using α = 1 underestimates the measured collector harmonic current. This may appear to be somewhat counter-intuitive, given the calculation has assumed a worst-possible case, i.e. no diversity existing between all harmonic sources. Further data and analysis is required to understand the likely cause of these outcomes, although it is hypothesised that emission from other sources (e.g. transformer excitation current and other harmonic sources within the wider REG plant) which will not be measured by the individual meters are impacting the total measured current.

4.3.1 Error of the 95th percentile measured value

Another further study was undertaken to determine the error of the method of aggregation when calculating the maximum harmonic emissions for $\alpha = 1$ (present-day practice) and the α values as per AS/NZS 61000.3.6 [76], shown in Table 4.1.

Given the summation law, as is presented in [76], is intended to account for diversity in both phase angle and time of emission, aggregated 95th percentile values for 1 week of measurements have been compared against the measured current through the collector group for all harmonic orders with valid measurements, (i.e. above the minimum measurement threshold). This study assesses the suitability of aggregation processes when applied as per the methodology that is implemented during the post-connection compliance stage, i.e. compliance is assessed based on a 95th percentile measurement rather than instantaneous values. The results are provided in Table 4.3 as a percentage of the measured weekly 95th percentile value.

Table 4.3 - Comparison of 95th percentile aggregated values as a percentage of measured values

h	95th percentile value $\alpha = 1$			95th percentile value α as per Table 4.1		
	Phase a	**Phase b**	**Phase c**	**Phase a**	**Phase b**	**Phase c**
1	100.0	100.0	100.0	100.0	100.0	100.0
2	23.3	46.7	26.0	23.3	46.7	26.0
3	4.5	6.2	31.2	4.5	6.2	31.2
5	-23.9	-26.8	7.7	-56.6	-58.4	-40.2
7	-36.0	-42.2	-36.7	-62.7	-66.7	-62.9
11	75.7	30.7	107.1	-31.4	-49.1	-22.2
13	435.0	791.5	169.3	99.7	241.7	2.4

It can be seen that the use of aggregation in both forms is capable of both under and over-estimating the measured weekly 95th percentile values. Generally speaking, the magnitude of error increases with frequency. For the cases of 5th and 7th harmonic the 95th percentile values measured through the collector group are consistently under-estimated using (15) for all values of α considered (neglecting phase C 5th harmonic). As previously discussed, it is postulated that this is due to emissions from other harmonic sources which are not being measured by the meters which are installed. A more complete data set is required to adequately determine this, i.e. phase angle data required.

As can be seen, the values of α assessed are capable of introducing considerable error in determining the maximum harmonic current emissions. For the 3rd harmonic order, a summation exponent of $\alpha = 1$ suggests relatively accurate estimates may be made. The validity of this outcome is to be further reviewed in the following section. Most other harmonic orders have a considerable error, with particular reference to $h = 10, 12$ in which the use of (15) results in significant over-estimation of the measured maximum harmonic emissions, regardless of the value of α. Higher frequency harmonic orders (e.g. $h > 20$) are consistently over-estimated when using (15). The degree of error is increased when following the use of α values as per the AS/NZS 61000.3.6. The causes for this error are investigated further in the following section.

4.4 DETERMINING ACCURATE VALUE OF α FOR ALL MEASUREMENTS

To further this investigation, the appropriate value of α was calculated for the 5th harmonic, using a-phase (only) measurements. This calculation was completed by determining the value for α for which the aggregation of the individual generator measurements accurately represented the measured current through the collector group. An iterative program was developed in which an appropriate value of α was found that was able to estimate the measured current through the collector group to within a ± 0.5 % margin of error. In the event that this margin of error could not be achieved, a value of $\alpha = \infty$ was assigned and data was omitted from further consideration. As per the process in Section 4.2.1 the time diversity component of α has been disregarded for this investigation.

A statistical representation was used to determine the distribution across the range of possible values. To include all data, the value of α was calculated for all phases (a, b, and c), with the results divided into bins and provided in the histogram below, Figure 4-12.

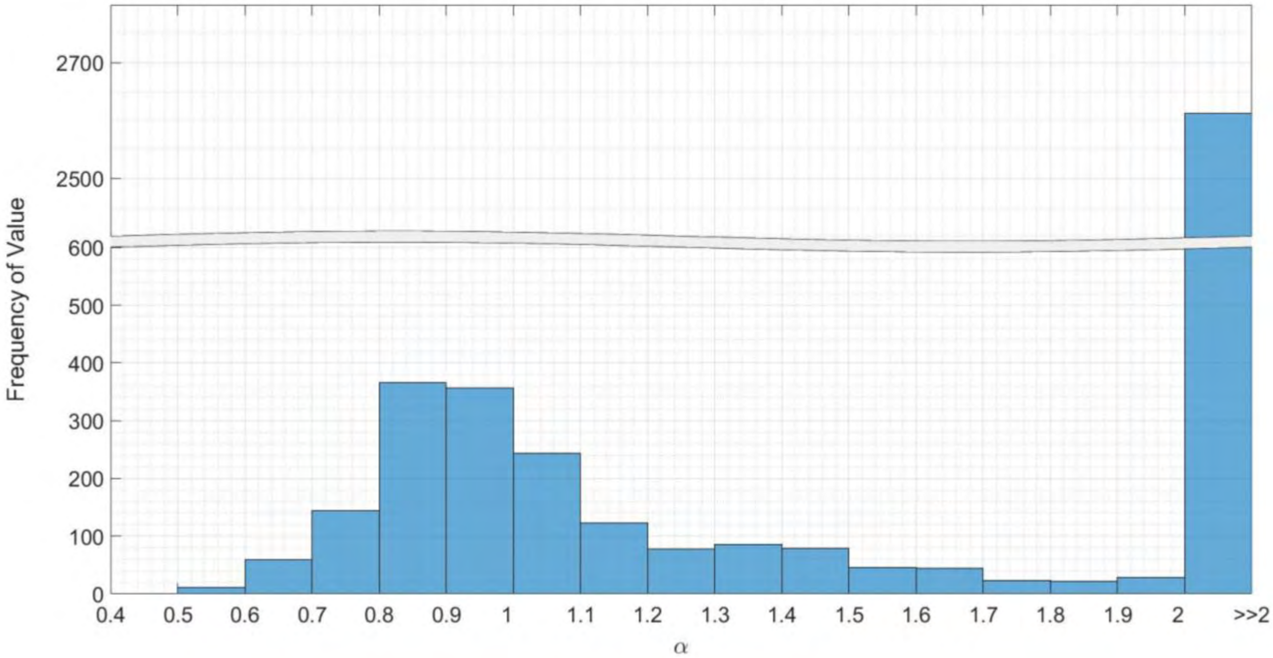

Figure 4-11 – Histogram of calculated α values for h = 5

As can be seen in Figure 4-12, for the majority of cases an α value of greater than 2 is required to provide a value for the summation of individual sources which matches that measured by the CG meter. This confirms that diversity commonly occurs between the individual harmonic sources at the 5th harmonic.

This study was then extended to include all harmonic orders for which valid measurements through the collector group were available, i.e. $h = 2, 3, 5, 7, 11$ and 13. The results are shown in Figure 4-13 and Figure 4-14. Figure 4-13 can be regarded as a 3-dimensional histogram including all considered harmonic orders and Figure 4-14 as a heat map representation of the same data. It should be noted that for all harmonic orders, scenarios in which the identified value was calculated to be above 2 have been omitted in these figures in order to show results for $\alpha < 2$ with more clarity.

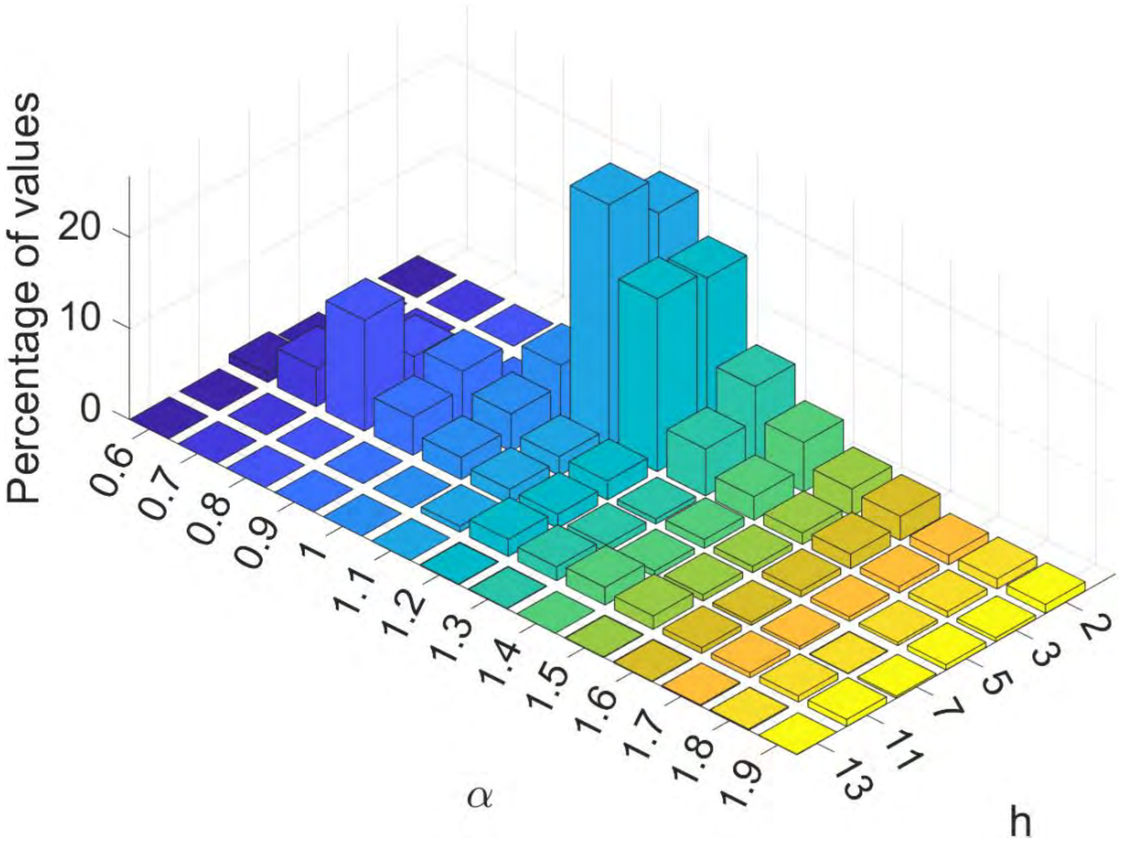

Figure 4-12 – 3-dimensional histogram of calculated α values for harmonic orders

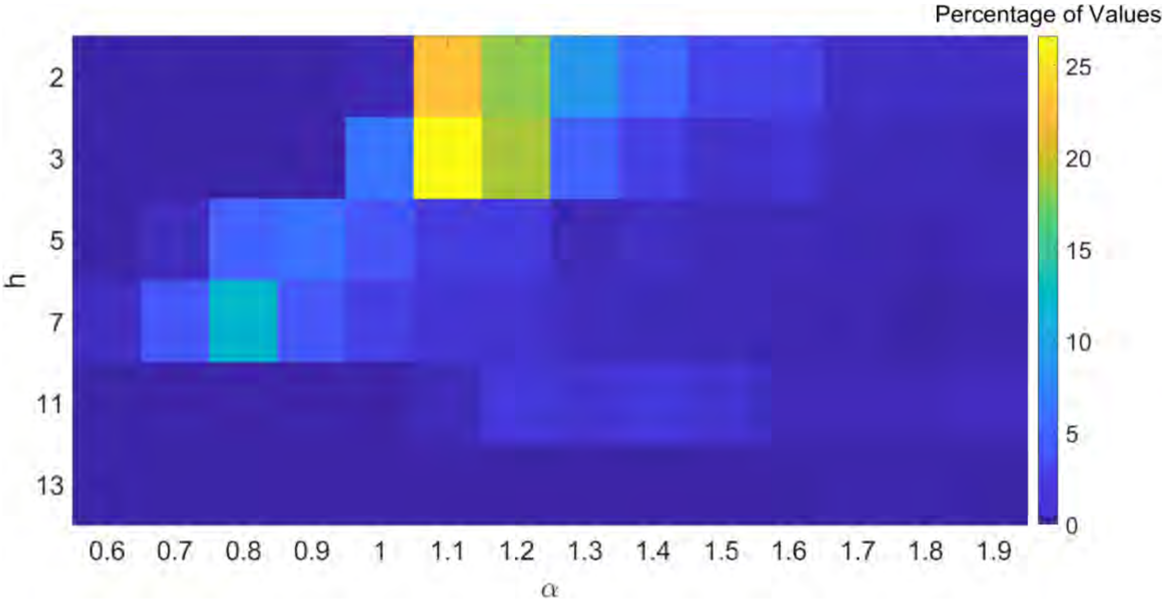

Figure 4-13 – Heat map representation of results

An important outcome evident from the above figures is that a significant number of measurements for 5th and 7th harmonic result in an expected $\alpha < 1$. This result suggests that the measured harmonic current through the collector group is greater than the arithmetic summation of the emissions from the individual generators. As previously discussed in Section 4.3, this may be due to the presence of other harmonic sources that are not represented or captured by the measurements of the individual generators. However, more measurements and analysis are required to investigate this.

4.5 SUMMARY

Power quality data collected within a REG has been reviewed in order to investigate the potential diversity between individual harmonic sources within a REG plant. In general, the analysis found diversity in emissions to exist between identical harmonic sources (generators) within the REG plant studied, at all harmonic orders, and for considerable intervals of the measurement period. It should be noted here that this study has not been provided to suggest updated values of α to be used when undertaking harmonic emissions assessment, allocation or any other study. Rather, the study simply identifies the possible range of values throughout the measurement period if aggregation using the summation law were to be used. The outcomes finding that the methodology of calculation to be unable to accurately capture the interaction between multiple inverters for the majority of the measurement period. Further, potential impacts that the variation of operational conditions on the appropriate harmonic source representation may lead to increased diversity to be detected.

The present practice of assuming no diversity between such sources for the purposes of undertaking harmonic modelling and pre-connection compliance assessment studies is capable of leading to significant error. The implications of this error include requirement for harmonic mitigation to be installed that is not required once commissioning of the plant is complete as well as inappropriately designed mitigation, resulting in increased costs for the proponent. However, it should be noted that while this case study provides some evidence that present methods of aggregating harmonic emissions from identical individual sources in pessimistic much more data is required to comprehensively understand the likely interactions and impacts across many REG plants and technology types. It is recommended that further measurements and investigations be undertaken in similar plants to determine the sensitivity of these values to a range of network and topological variations. Future work should include:

- More complete modelling and monitoring of all PE devices within the plant.
- Measurement campaigns with different technologies, network conditions and operational scenarios.
- Longer measurement campaigns.

5 Investigation of the Impact of High Penetration of Large Renewable Energy Generators on Network Harmonic Distortion Magnitudes

5.1 INTRODUCTION

This section of the report has been developed to collate various data sources in order to facilitate a generalised study that provides a broad understanding of how harmonic emissions are likely to evolve in Renewable Energy Generator (REG) rich networks. Further, an alternative approach to the efficient management of harmonic distortion levels has been developed that simplifies the management process and reduces the level of harmonic mitigation that is required throughout the network. These findings are important as present-day methodologies for management of harmonic distortion are often leading to harmonic mitigation being required by REG proponents, with the outcome often being the installation of expensive passive filtering. As discussed in [142], ongoing connection of such filters leads to shifting resonant frequencies within the network, further complicating the management of harmonic distortion levels.

This section utilises network model information that is representative of an Australian sub-transmission network. Harmonic domain models of prospective REG plants were developed and connected to the system model in order to evaluate the impact of increasing REG penetration on network harmonic distortion levels. All components that have been modelled have been acquired from industry sources and thus remain confidential and have been anonymised for the purposes of this report.

Two studies are provided in this section. The first implements and investigates the harmonic management of a simple radial network using data from the available network model. The study considers the management processes that are defined in Australian Standard AS/NZS 61000.3.6 [76], identifies some of the key misinterpretations of the allocation methodology and investigates revised processes aimed at simplifying the management of harmonic distortion in particular scenarios. The second study seeks to validate the findings of the first study in a much more detailed network that is more representative of the topologies of the Australian networks that large amounts of REG are expected to connect to in the near future. It should be noted that the following studies are not intended to be accurate estimations of specific networks or REG plants, rather they provide generalised insight designed to highlight the key findings and proposed solutions.

5.2 DATA

Various data sources were leveraged for this study in order to ensure each component was represented appropriately in the harmonic domain according to existing common practice. The base network data was provided by a NSP whilst the models used to represent REG power electronics in the harmonic domain were gathered from OEM datasheets provided to enable pre-connection harmonic emission studies to take place. A description and process of validation for each modelling component is provided in the following sections.

5.2.1 Network Model

The network model used in these studies was provided by a NSP and represents an Australian sub-transmission network. The area is supplied by a single connection, represented by an external network element at 132 kV. The network contains representation of all system components down to distribution voltages at which point, down-stream connections are represented by lumped loads. This network model was selected as it contains a wide range of fault levels consistent with those found in rural/remote Australian networks (where many REGs are connecting). It is also a model of an area that has been identified by AEMO as a Renewable Energy Zone (REZ) [6]. As such, it is expected that high levels of REG will be connected to this network in the next 20 years. The data available in the model was used for both studies, as described below.

5.2.1.1 SIMPLIFIED NETWORK STUDY

For the simplified study, results of which are presented in Section 5.4, a portion of the network model was isolated and its complexity reduced. This simplified the analysis process that was then able to be extended to the second, more complex network study. A single line diagram of the network used in the simplified network study is shown in Figure 5-1. The nominal voltage of the network is 66 kV, all feeders have identical impedance per km characteristics which were obtained from the full network model. Components such as feeder lengths and network topology were also obtained from the full network model.

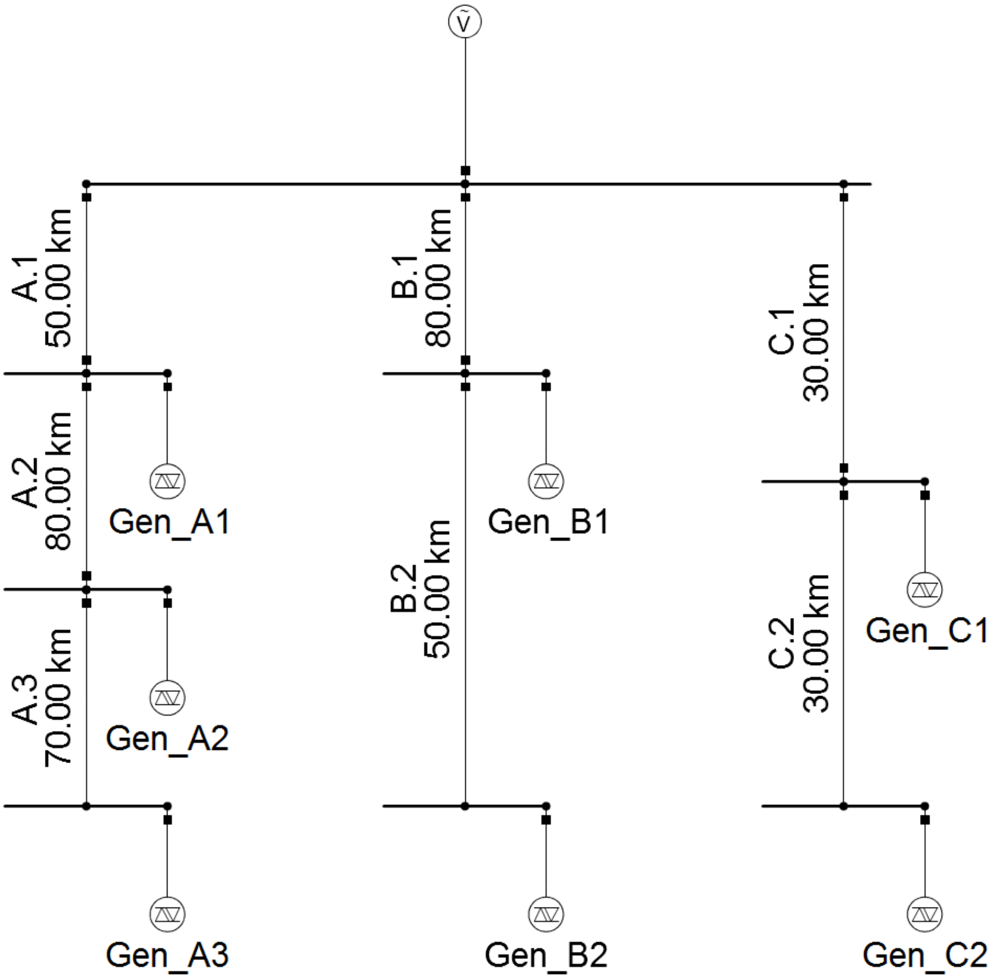

Figure 5-1 - Single line diagram of simplified model used for study

The study placed a generator connection at each busbar with the agreed power of each connection determined based on the nominal transformer rating at each connection point in the full network model. Using this methodology, the agreed power of each generator connection is provided in Table 5.1.

Table 5.1 - Plant agreed power

Plant Name	P_{nom} (MW)
Gen_A1	30
Gen_A2	4.2
Gen_A3	13
Gen_B1	4.2
Gen_B2	13
Gen_C1	8
Gen_C2	13

A key assumption of the study is that the REG connections are the only source of harmonic emissions considered, i.e. loads are assumed to have negligible impact on the emission levels of the network. This assumption has been implemented to maintain a simple, focused analysis on the interaction and management of harmonic emissions between multiple REG sources across the network. Future studies may replace these assumptions with real/expected loading data.

5.2.1.2 FULL NETWORK STUDY

As discussed above, the full network study utilises the entire sub-transmission network. The purpose of the full network study was to expand the findings of the first, simplified study to validate and further investigate the outcomes. Where necessary, network augmentation such as upgraded/added transformers and conductors were implemented to maintain appropriate fundamental voltage levels. It should be noted that the study did not consider the impact of high penetration of REG on the operation of the network, e.g. operational stability, demand/generation balance etc.

In order to inform the size and location of REG plants across different areas of the network, a definition for strong, normal and weak fault levels was created and each busbar within the network was assigned a strength characteristic. The definition was based on the fault level of each busbar when compared to the rest of the network. The fault level definitions that were developed are provided in Table 5.2 based on the three-phase (bolted) short circuit fault level.

Table 5.2 - Definition to characterise relative strength of busbars

Definition	Maximum Fault Level (MVA)	Minimum Fault Level (MVA)
Strong	∞	500
Normal	500	200
Weak	200	50

The busbars with a fault level lower than 50 MVA were considered too weak to allow any significant volume of REG to connect and thus have been omitted from having REG connections. These busbar strength definitions were used to apportion a ratio of REG across the network for each stage, as described in Section 5.3.2.

The network was also split into 5 zones based on the layout and interconnection with other zones to allow for simpler reference to network areas and labelling of components. These zones are shown graphically in Figure 5-2 and a qualitative description of each zone is provided below.

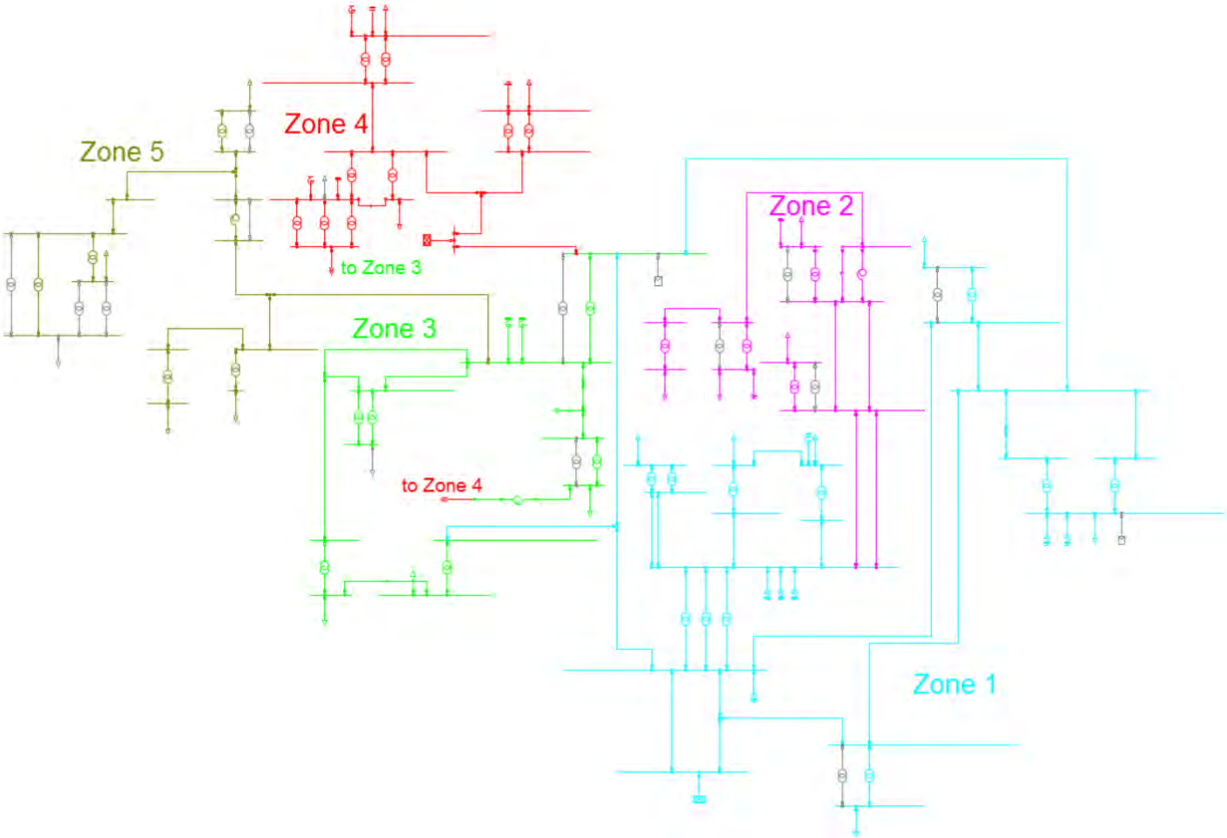

Figure 5-2 - Base network used for study

ZONE 1

Zone 1 is the strongest zone being supplied directly from the upstream network. This network zone is predominantly 132 and 66 kV nominal voltage and almost all busbars meet either the strong or normal network strength definition. As such, Zone 1 may be expected to be able to host the largest amount of REG throughout the study.

ZONE 2

Zone 2 is supplied directly from the Zone 1 substation via a relatively short (~4 km) double circuit feeder although the total line length from the Zone 1 interconnection to the final bus within Zone 2 is 156 km, as such, the fault level within Zone 2 has a considerable range of approximately 450 MVA (i.e. the difference between the fault level at the strongest and weakest buses).

ZONE 3

Zone 3 is meshed with Zone 1 via three separate interconnections, with the strongest busbar within Zone 3 closing a ring circuit of Zone 1. The zone is primarily 132 and 66 kV nominal voltage although most busbars (beyond that which closes the ring network of Zone 1) are defined as weak. The low fault level of the zone is due to the long line lengths between substations, noting that the geographical location of the area would be considered to be remote.

ZONE 4

Zone 4 is meshed with Zone 3 at two voltage levels. The first is fed directly from the strongest busbar of Zone 3 via approximately 100 km of line, which feeds a tee point splitting the supply to separate substations. The other interconnection of the two zones occurs at 22 kV, noting that this is the 22 kV busbar of the substation in Zone 4 that is alternately supplied by the 100 km tee off line previously mentioned. Given the comparatively low fault levels of Zone 3 through which this zone is supplied, the majority of Zone 4 is defined as weak and is predominantly 132 kV nominal voltage with 22 and 11 kV nominal voltages available on the LV side of a number of substations.

ZONE 5

Zone 5 is supplied directly from Zone 3 via approximately 170 km of line, including a 1:1 auto-transformer used for voltage control for a weak section of the zone. As will become obvious throughout the study, this is the area that experiences the most difficulty with respect to harmonic emission non-compliance which is subsequently attributed to long line effects introducing remote resonance phenomena.

The model used was benchmarked against existing (confidential) sources to ensure the data accurately represents the network using appropriate harmonic modelling methodologies (e.g. [2]). Included within the model was indicative loading of the network. A number of challenges have been identified regarding the appropriate harmonic domain representation of loads and their impacts on damping [2]. Due to lack of information, the load is modelled as a simple resistive/inductive component.

5.2.2 REG Plant Model

REG plant models were developed using confidential data sources provided to the research team. The modelling of REG plants followed common industry practice, with individual inverters represented as Norton equivalent models, i.e. a current source with parallel impedance, as described in detail in [142]. The models utilised in this project were provided by device manufacturers and are identical to those used to undertake pre-connection harmonic emissions studies. Whilst there is ongoing contention with respect to the validity of such modelling practice (discussed further in Section 6), this study is not focused on providing a high accuracy forecast of emission levels, rather, it is an informative study to estimate the interactions within a remote network with high penetration of REG and capable of identifying the challenges of, and possible solutions for harmonic management in high REG penetration networks. Thus, it is important for plant models to include both harmonic current emissions and a shunt impedance to account for the potential impact that the plant has on the network impedance.

A total of three individual inverter harmonic models were used to represent each of the REG plants in the study. It is noted that it is highly unlikely for a network to contain a high penetration of REG plants with a limited number of inverter types. However, the use of a restricted number of inverter models results in a pessimistic estimation as there will be less diversity across the emission spectra between each REG plant. The three models used in the study represent;

- A 4.2 MW wind turbine generator connected at 33 kV
- A 3 MW solar PV inverter connected at 11 kV
- A 3 MW solar PV inverter connected at 22 kV

Individual REG plants were modelled in the harmonic domain on the LV side of the grid-connecting transformers. This modelling was completed by defining the required number of parallel inverter units to reach the determined nominal MW capacity of the connecting plant. Data for the grid-connected transformer was also obtained from previous industry commissioned studies. Impacts of transformer excitation current were omitted from this study, so too was the impact of the collector impedance present within the REG plant. Whilst there have been studies that identify the collector network to be able to introduce considerable impacts, as discussed in [142], such impacts are case specific and cannot be assumed. A sensitivity study which was undertaken to determine the sensitivity of these assumption is provided in the following section.

5.2.2.1 SENSITIVITY OF COLLECTOR NETWORK MODELLING

Comparison of simulated harmonic voltages when omitting modelling of the collector network was undertaken through the use of a harmonic model of an existing 300 MW REG. Harmonic voltage distortion values were compared with the collector network fully modelled and for the scenario in which all inverters were connected directly to the LV winding of the grid-interfacing transformer.

The results of both scenarios are shown in Figure 5-3. It can be seen the maximum difference between the two scenarios occurs at the 13th harmonic order with little difference between outcomes for other harmonic orders. Investigation of the frequency sweep at the PCC with the collector network identifies a resonance occurring at the 13th harmonic order. Given the relatively small impact and the generalised nature of this study and its outcomes, omission of the collector network was considered to be a reasonable assumption.

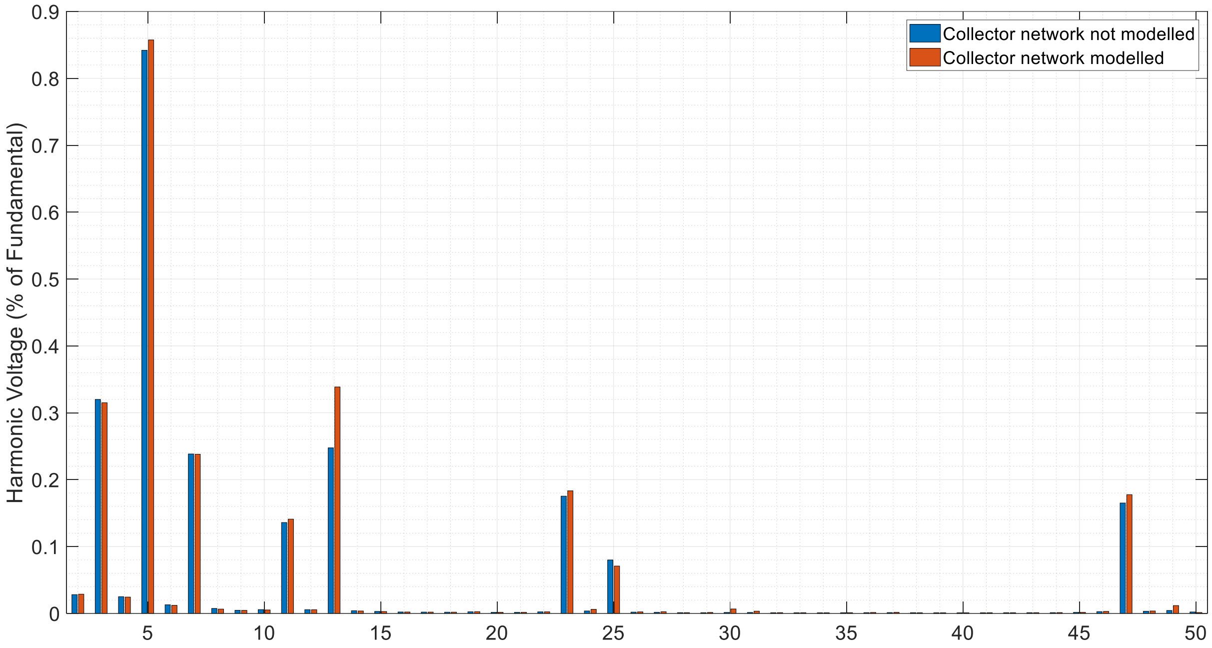

Figure 5-3 - Comparison of emission levels with and without REG collector network modelled

5.3 STUDY METHODOLOGY

The methodology by which the studies were undertaken are described in detail below.

5.3.1 Simplified Network Study

The aim of the simplified network study was to consider and investigate the existing practices implemented in networks with respect to harmonic distortion management. This included both the planning (allocation) and compliance assessment (measurement) stages. The purpose of undertaking this study on a simplified model was to simplify the analysis process, enabling assessment of interactions occurring between a reduced number of plants. The outcomes of this study highlight some of the identified issues in [90, 142] and investigate possible modifications to address them.

As discussed in [90], a major misinterpretation of [76] is the definition of the harmonic current emission limit and how compliance is assessed. The misinterpretation is related to the impact that network harmonic levels and impedance have on the measured current of a plant, i.e. a plant may be assessed as non-compliant, solely due to the natural variation of background harmonic emissions and impedance of the network at the PCC. For the purposes of this study, it has been decided to implement the more commonly used definition, i.e. the impacts of the external network as further connections are made was disregarded.

5.3.1.1 STUDY 1

This study was undertaken to confirm the program and modelling processes to be utilised for the remainder of the study, it also provides a benchmark against which impacts of assumptions and other considerations implemented in the following studies may be compared.

A defined network in which all specifics are known (i.e. no uncertainty) and line capacitance[4], is neglected was first used to determine the 'optimum' current emission limits for all plants connecting to the network. Harmonic emission levels were then calculated and compared with planning levels (as per [147]). The program, calculations and modelling process were considered to be validated provided the network reached planning levels once all connections were simultaneously present and meeting their allocated emission limits.

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[4] Following assumptions provided in IEC TR 61000.3.6:2008

5.3.1.2 STUDY 2

The second study simply compared the outcomes of the first study with results when long-line capacitance and resistance were accounted for. The examples and discussion presented in the IEC technical report [76] make the assumption of considering inductive line reactance only, noting the excerpt from the technical report;

> *"In the case where the system response is dominated by resonance caused by cables or shunt capacitors, the method provided in this annex is not appropriate for the harmonic frequency at which the resonance occurs."*

Study 2 provides an example of how appropriate representation of the line may affect the outcomes of the allocation.

5.3.1.3 STUDY 3

The third study removed certainty of the final state of the network and instead calculated the emission limit allocations following the example application provided in Appendix I of IEC TR 61000.3.6:2001. The example provides a practical implementation of the allocation methodology by which it assumes that feeder loading is uniformly distributed. All connections were allocated an emission limit assuming the network connections to be uniformly distributed and network distortion was calculated again assuming that all plants were meeting their allocated emission limit.

This study was split into two parts as follows;

a) Inductive line model

b) Full line model (i.e. RLC components accounted for)

The outcomes provide an identification of how uncertainty impacts the practical implementation of the allocation approach when little is known about the final state of the network. This is a worked example of the issues identified in [92, 142].

5.3.1.4 STUDY 4

The fourth study removed the assumption that all connections were meeting their allocated emission limit and instead used a simplified harmonic model of a REG inverter, scaled to match the agreed power of each REG plant connection, as discussed in Section 5.2.2. Whilst concerns have been raised in regards to the use of such data to represent large REG plants, it provides some consideration with respect to the impact of such plants on the harmonic impedance of the network as per [2, 14, 148]. Further, many of the findings of the study are insensitive to the specific harmonic model that is used, this is discussed in more detail in the analysis section.

5.3.1.5 OPTIMISED MITIGATION STUDY

The outcomes of Study 4 were further expanded by considering the mitigation of a single harmonic order throughout the network (noting there were numerous harmonic orders that exceeded network planning levels). In the event that a plant was found to exceed its allocated emission limit, a harmonic filter was connected directly at the terminals of the PCC of the plant to reduce the harmonic current emitted into the network. All filters were of the same topology (i.e. single tuned filter at the harmonic order of concern with a quality factor of 50, matching guidance values provided in [46]) and the rated reactive power was scaled so that each plant met its allocated emission limit. It is important to note that each filter was designed individually, i.e. each filter was designed with all other filters switched off. This is to represent existing connection study practices which do not require a detailed passive representation of plants 'behind the meter'.

A revision to the existing approach was then considered, in which mitigation was instead connected directly to the point of the network where the harmonic voltage magnitude was highest. The required filter sizes and their impact on the network harmonic impedance were reviewed and compared between the two approaches to mitigation.

5.3.2 Full Network Study

Given the size and complexity of the full network considered, only the findings of the optimised mitigation study were further investigated i.e. rather than undertaking comparative allocation and harmonic emissions studies, the revised approach to mitigation was implemented to ascertain the mitigation requirement for the step change scenario, defined by AEMO [6]. The ISP [6] identifies the modelled area to be a Renewable Energy Zone (REZ), and as such there is an expectation that a considerable volume of REG will be connected in the next 20 years. The full network study was undertaken in stages, with 500 MW of REG being connected to the network per stage for a total of 8 stages. Determination of the location and rated capacity for each stage was subject to a number of constraints and followed a partially formulaic process, as discussed below.

Firstly, REG plants were distributed across areas of the network using a ratio of 60/25/15% across the strong/normal/weak busbars respectively (equating to 300/125/75 MW per stage). A commonly used metric of the capability of the network to connect REG plants, as defined in [13, 50] is the short-circuit ratio (SCR) of asynchronous generation, i.e.

$$SCR_{AG} = \frac{\sum P_{i,nom}}{S_{fault}} \tag{17}$$

Where;

SCR_{AG} is the short-circuit ratio of asynchronous generation in the area.

$\sum P_{i,nom}$ is the aggregate agreed power of all asynchronous generation connected at the point of study.

S_{fault} is the three-phase fault level at the point of study.

This simple metric is a good indication of whether issues such as system stability may be of concern due to the connection of REG. For each stage of connections, a minimum allowable SCR was defined to ensure that;

- REG was not concentrated to particular areas of the network and,
- System stability would not be of major concern

For example, a minimum SCR of 3 was implemented for stage 8 to avoid possible impacts of reduced available fault level and controller interactions due to required minimum short-circuit ratios of PE converter controllers [13, 50, 149].

At the completion of each stage, harmonic voltage emission levels were calculated across the network and resulting distortion levels were compared against suggested harmonic voltage planning levels as per [102]. In the event that a busbar (or busbars) were exceeding planning levels, network-based mitigation options were considered. Once mitigating solutions were designed and installed, harmonic emissions were again determined, the stage was only considered complete once all busbars within the system were below the defined harmonic voltage planning levels.

It should be noted that this part of the study deviates significantly from present-day practice in two key areas:

- Firstly, the connecting plants are not allocated a harmonic current emission limit, instead, all plants are able to connect preliminarily.
- Secondly, mitigation is investigated at the location of non-compliance, not at the PCC of the offending plant(s).

This approach has a large impact on the appropriate mitigation strategy and ultimately changes the process of harmonic management. The impacts and logistics of this are analysed and discussed in detail in Section 5.7.

5.4 RESULTS – SIMPLIFIED NETWORK STUDY

5.4.1 Study 1

Study 1 follows the 'ideal' allocation methodology provided in [76] in which, the harmonic voltage levels reach the planning levels at the weakest busbar once all connections are emitting their allocation emission limits. The study identifies busbar A_3 to be the weakest point of the network. This is due to the study only considering inductive reactance of the network lines, thus the largest impedance occurs at the end of the longest feeder. All connections are known ahead of time and thus the optimal value of A_h which is the allocation constant can be calculated based on the harmonic voltage response of the network under study [71]. It is noted that such detail is generally not known during practical implementation. The result of this scenario is that busbar A_3 reaches planning levels at all harmonic orders once all connections are emitting their allocated emission limit, shown in Figure 5-4.

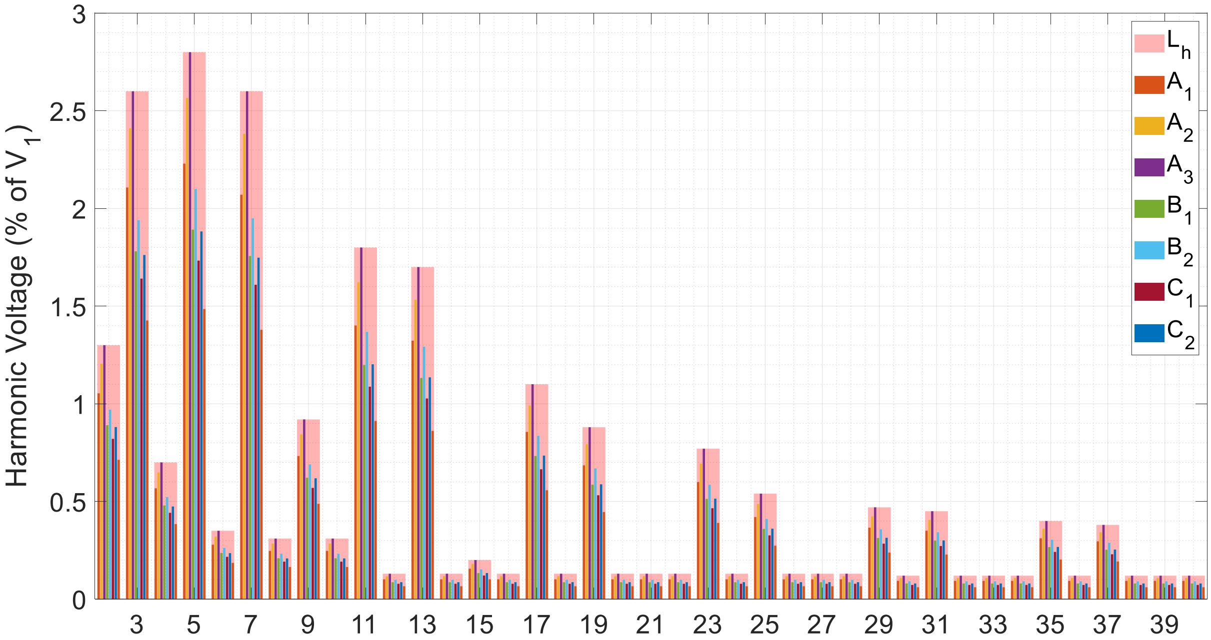

Figure 5-4 - Harmonic voltage distortion at each busbar, study 1(L_h is the harmonic voltage planning level, A_1, B_1, C_1 etc. are network busbars as shown in Figure 5-1

The outcome of the system reaching planning levels for all harmonic orders at the expected point of the network verifies that the model, calculation and allocation program are operating as expected and are fit for purpose for the remainder of the studies.

5.4.2 Study 2

Study 2 updates the line model that was used in Study 1 to include capacitance and resistance data provided. The inclusion of line capacitance introduces resonances across the network, as shown in Figure 5-5 as an example for 2 busbars within the network.

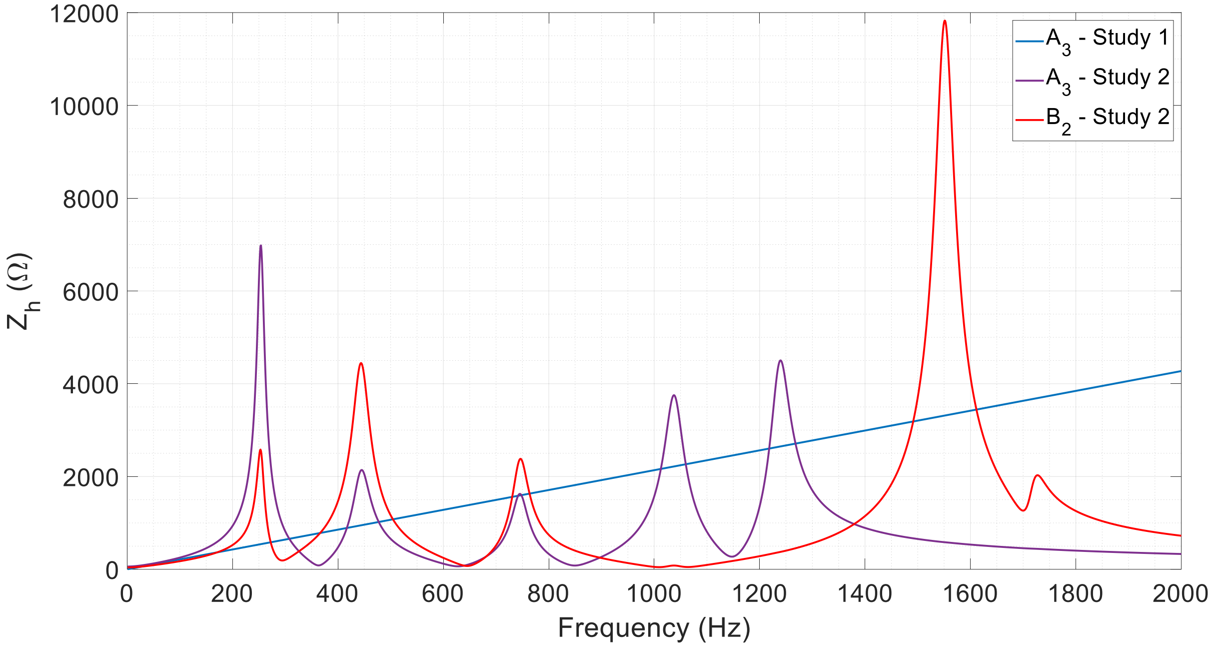

Figure 5-5 - Frequency sweep comparisons

It is important to note that due to long line capacitance, it is no longer suitable to assume that the harmonic impedance will be the highest at the end of the longest feeder. It can be seen in Figure 5-5 that the impedance is larger at bus B_2 at the second and third resonant points. This result greatly affects the implementation and complexity of the allocation procedure in [76] and for networks in which long-line effects are present, the procedure must be very carefully considered. The resulting harmonic voltage distortion at each busbar is shown in Figure 5-6 for the same harmonic source currents as applied in Study 1.

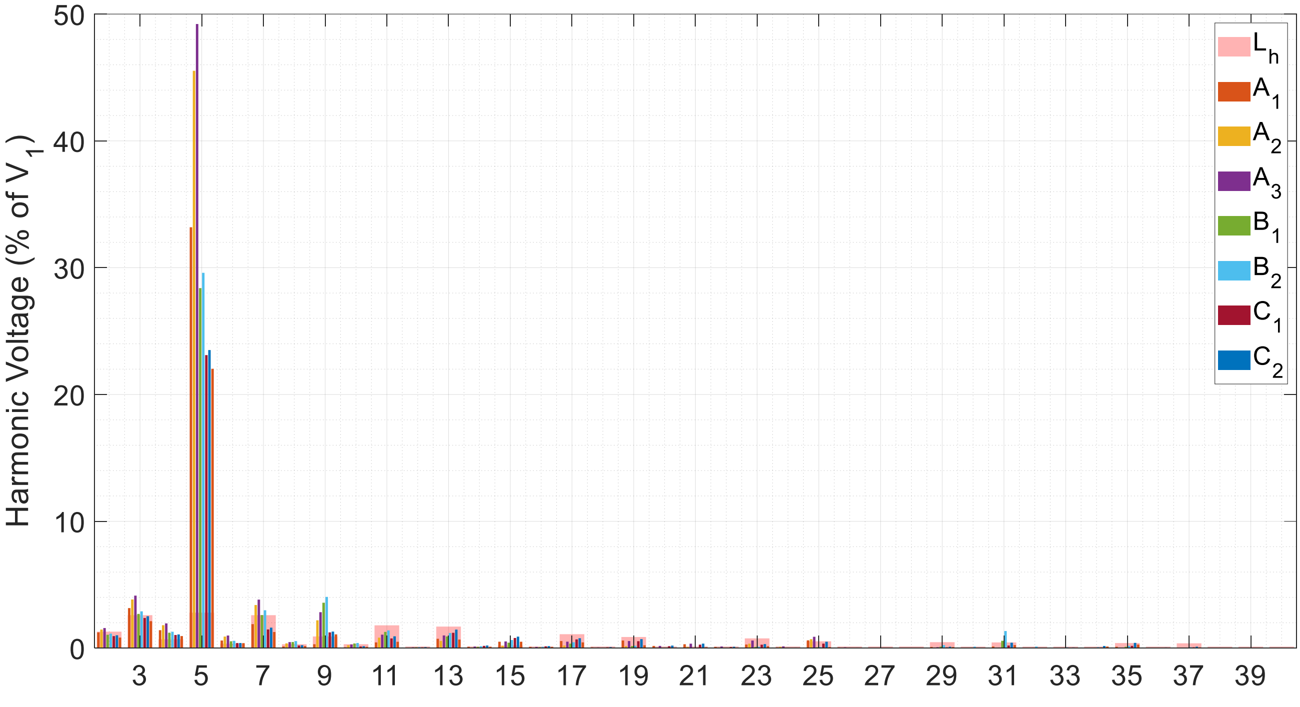

Figure 5-6 - Harmonic voltage distortion, study 2

It can be seen that the resonance at the 5th order harmonic, shown in Figure 5-5, clearly results in increased 5th harmonic voltage magnitudes. The outcome is that while all connections are meeting their allocated harmonic current emission limits, as calculated in the ideal allocation scenario in Section 5.4.1, the harmonic voltage magnitudes are exceeding the planning levels at a number of busbars for multiple harmonic orders.

The results of this study show that incorrectly assuming line capacitance to be negligible may lead to significant increases in the harmonic voltage magnitudes. Further, if a NSP were to investigate the emissions to determine the offending plant(s), current emissions of all customers are found to be considered compliant based on existing definitions.

The primary outcome of this study is that accounting for line capacitance in the allocation process is an important consideration for networks with long lines. However, further studies will show that uncertainty and future plant shunt impedance are also both capable of significantly impacting the frequency response of the network. Consequently, development of an efficient and effective allocation for connections accounting for these impacts becomes more challenging, as discussed below.

5.4.3 Study 3

5.4.3.1 STUDY 3A) INDUCTIVE LINE MODEL

The third study removed certainty from the allocation process, replacing knowledge regarding the final state of the system with the assumption that connections are uniformly distributed along each feeder, as per the suggested application in [76]. This assumption is generally accepted for practical applications given the stochastic nature of evolving networks.

A comparison of the allocated emission limits for a representative installation, in this case GEN B_2 as shown in Figure 5-1, with the limits calculated when the final state of the network is certain, i.e. Study 1 and 2, is shown in Figure 5-7.

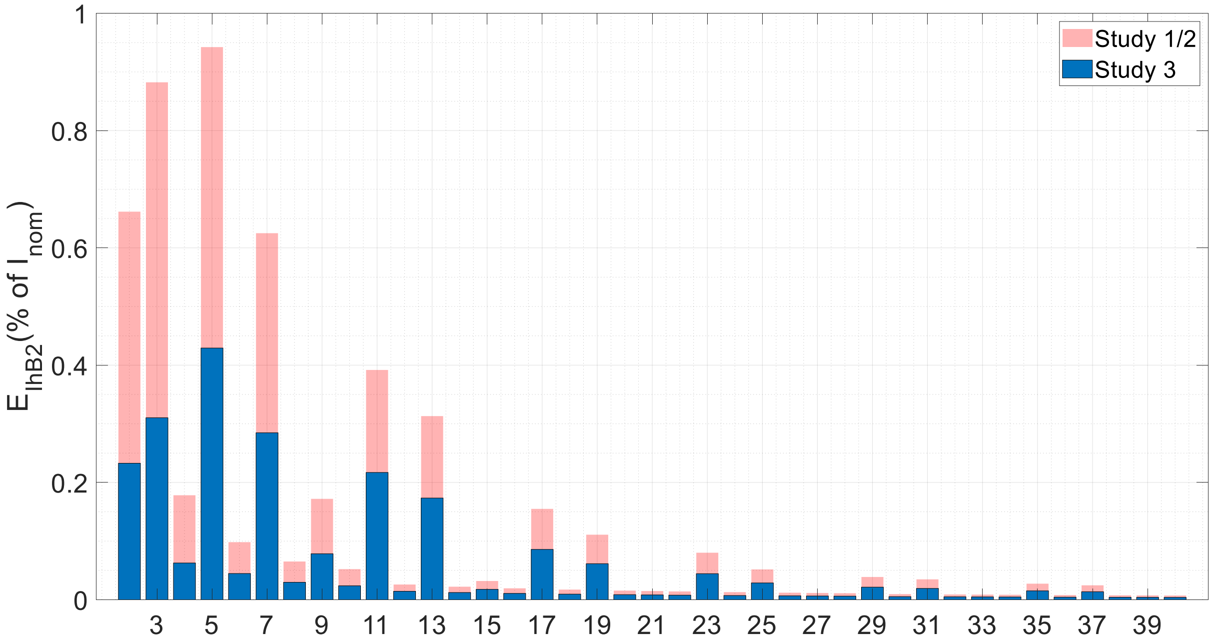

Figure 5-7 - Comparison harmonic emission limits (E_{IhB2}) for connection B_2

As can be seen, the allocated harmonic emission limits are significantly lower when the final state of the system is not known. This is to be expected and what may be termed as inefficiencies (given the allocation of Study 1 is the optimal allocation) may simply be considered as conservative assumptions to allow a safety margin for an unknown system, as discussed in Section 2.5. Further, it must be kept in mind that this is an individual sample case and the impacts of uncertainty may be more or less pronounced for different networks. The harmonic voltages calculated by Study 3a with all plants emitting their allocated emission limit is shown in Figure 5-8.

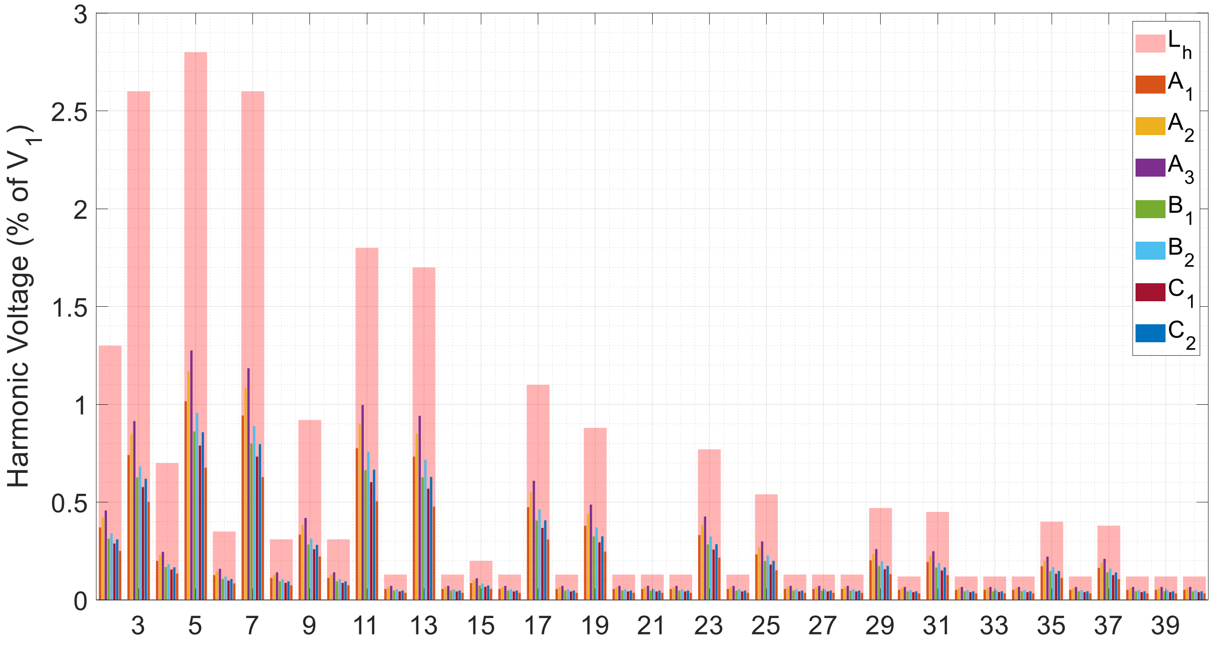

Figure 5-8 - Harmonic voltages at each busbar for Study 3.a with inductive reactance modelled lines

As expected, there is a significant reduction in harmonic voltage distortion across the network. Compared with the outcomes of the first study in which the network harmonic voltage magnitudes reached planning levels, voltage levels only reach 35 – 55 % of the planning levels across the harmonic orders considered in this study. This shows that uncertainty can have a large impact on the appropriateness of the harmonic allocation procedure implemented in [71].

5.4.3.2 STUDY 3B) FULL LINE MODEL

Study 3b) provides a comparison with Study 3a when line capacitance and resistance are accounted for. The resulting harmonic voltage distortion with the full line model in place is provided in Figure 5-9.

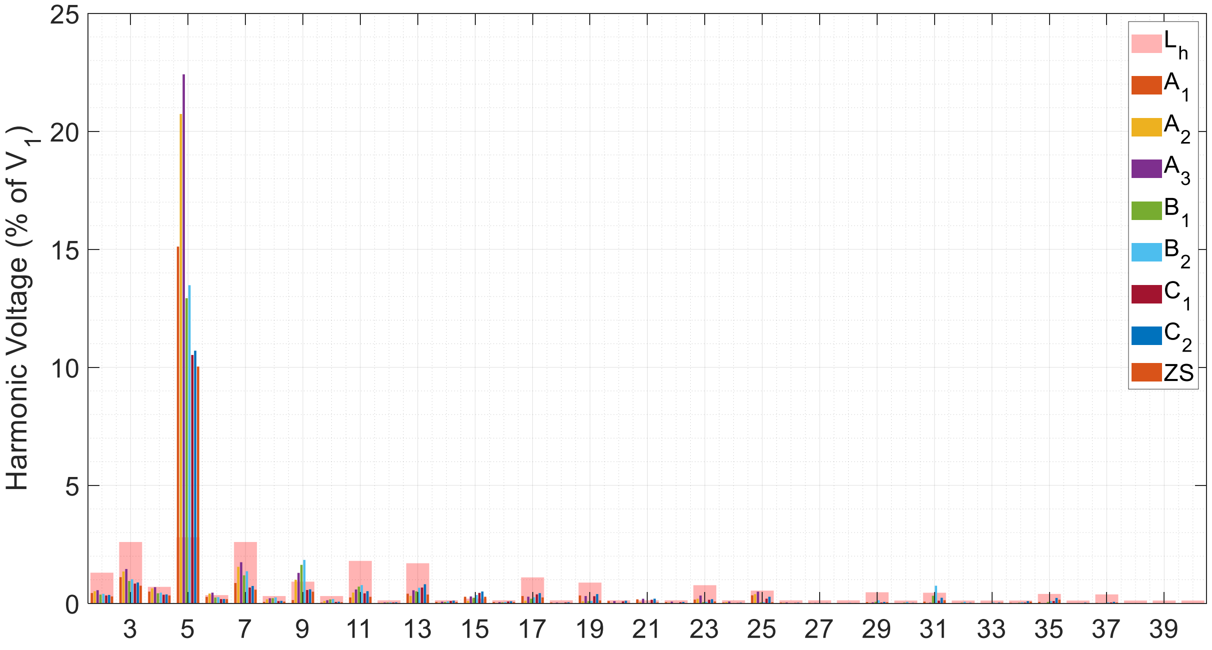

Figure 5-9 - Harmonic voltage, Study 3.b with capacitance and resistance included in line model

As seen in the figure, the inclusion of the capacitive component of the line again results in a significant amplification at the 5th harmonic order for all busbars and for the 9th harmonic order on the B feeder.

However, compared to the results of Study 2, the level of non-compliance is approximately half, due to the impacts of uncertainty on the allocated emission limit.

Thus, the consideration of uncertainty of the future state of the network in the harmonic emission limit allocation process is capable of both over and under-estimating final voltage distortion levels. A reasonable suggestion would be to allow for resonances in the allocation process, at least addressing the outcomes seen in Figure 5-9, i.e. amplification of harmonic voltages. However, such an approach would greatly reduce the harmonic emission limits allocated to connecting plants at these resonant frequencies.

5.4.4 Study 4

Study 4 removes the assumption that all connections are meeting their allocated emission limit and instead uses a simplified harmonic model of REG inverters including a Norton impedance. When replacing the plant model with a simplified Norton model, impacts of plant shunt impedance are considered. The network harmonic voltage distortion magnitudes obtained for this study is shown in Figure 5-10.

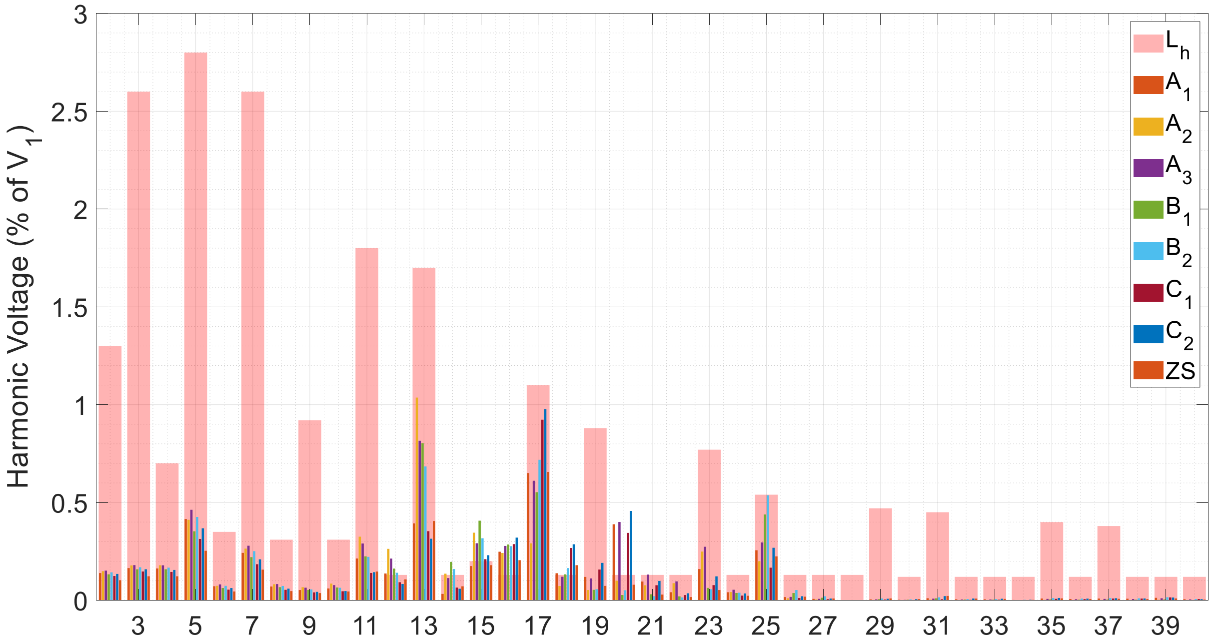

Figure 5-10 - Network Voltage distortion at each busbar with Norton equivalent sources representing connections

The alignment of increased non-characteristic harmonic emissions, i.e. harmonic orders that are not $6k \pm 1$ for $k = 1, 2, 3 \ldots$ (from present-day VSC converters [142]) with remote resonances and lower voltage planning levels lead to harmonic voltage planning levels being exceeded for non-characteristic harmonic orders. It should be noted that such outcomes align with industry experiences in relation to pre-connection compliance assessment studies, resulting in harmonic mitigation being increasingly necessary for non-characteristic harmonic orders.

The harmonic emissions for each connection were compared with allocated emission limits, as defined in Study 3 (i.e. allocation constant method with uncertain final network state). All plants were found to be non-compliant with voltage planning levels for one or more harmonic orders, an example is shown in Figure 5-11 for GEN B_1

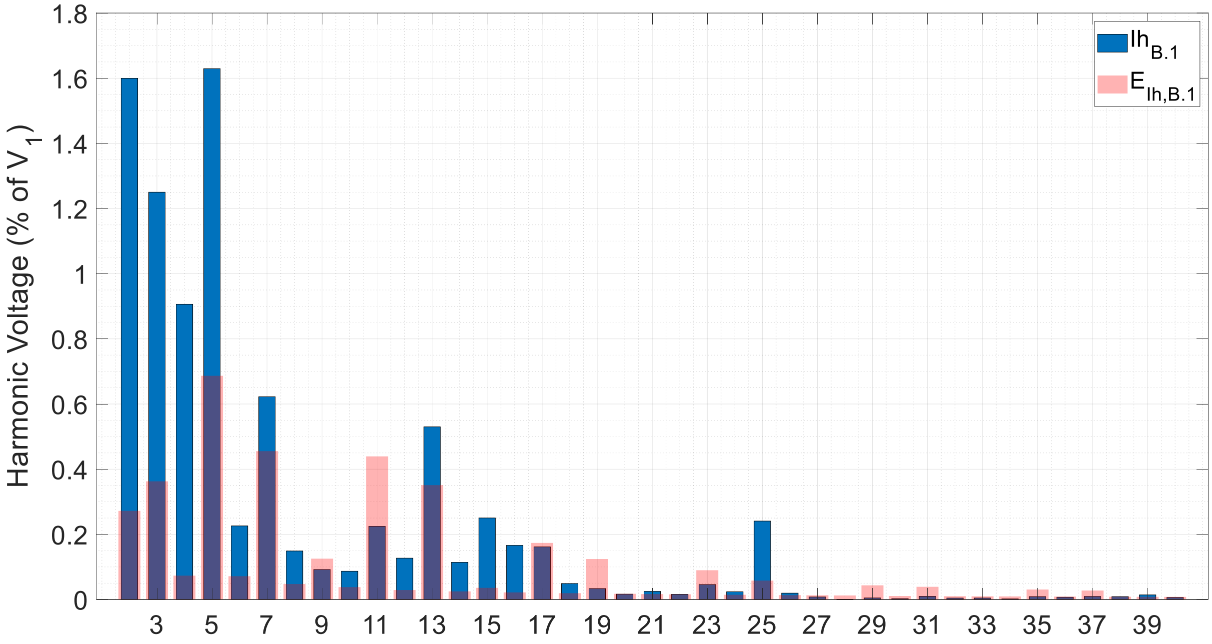

Figure 5-11 - Harmonic current emissions and allocated limits for plant B.1, Study 4

Figure 5-11 shows GEN B_1 to be non-compliant for multiple harmonic orders, and this was found to be representative of many of the plants. However, when compared with the voltage distortion in Figure 5-10 non-compliance is restricted to $h = 12, 14, 15, 16, 18, 20$. The cause and mitigation of this non-compliance is discussed in the following section.

5.4.4.1 PRELIMINARY HARMONIC MITIGATION STUDY

Rather than investigating a harmonic mitigation solution for each individual plant, a strategy for mitigation of a single harmonic order was investigated for all plants. Based on the results in Figure 5-10, $h = 12$ is the lowest harmonic order that exceeds its harmonic voltage planning levels. Thus, harmonic current emissions at $h = 12$ were filtered for all plants individually, i.e. filtering was designed to reduce current emissions at PCC of the plant under investigation whilst all others were switched off. Whilst it would be advantageous for all plants to be connected during the filter design for each plant, this is not representative of a real-world scenario. Based on experience, it is unlikely that a detailed model of existing plants would be available to be included in such studies. Further, it is not possible to estimate future network connections and their impact on the system harmonic impedance.

The filter design for each plant in this study was completed by connecting a harmonic filter (single tuned filter, $f_{res} = 600\ Hz$, Quality Factor = 50, following guidance values of [46]) at the PCC of the plant and determining the reactive rating, Q_{filt} requried to reduce emissions to meet allocated emission levels at the PCC of the plant. The required filter size for each plant is provided in Table 5.3.

Table 5.3 - Required filter size by plant to meet allocated emission limits

Plant	$Q_{filter}\ (kVAr)$
A.1	190
A.2	70
A.3	280
B.1	40
B.2	120
C.1	32.5
C.2	27.5

With the designed filters connected at the PCC of each plant, harmonic emissions were calculated across the network and are shown in Figure 5-12.

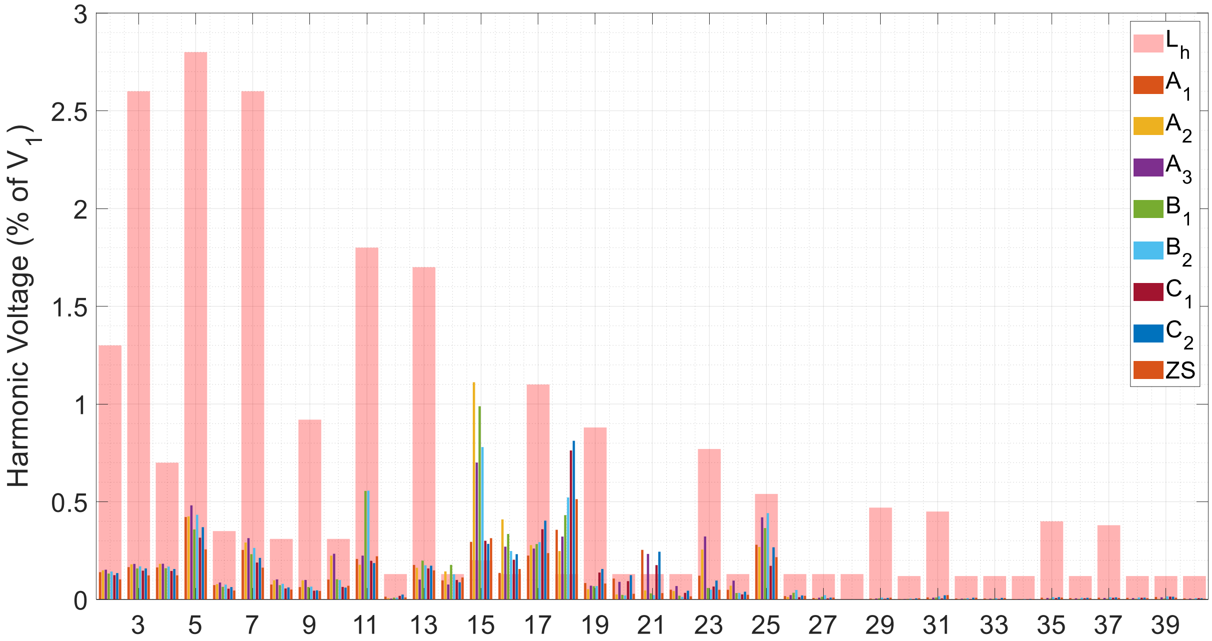

Figure 5-12 - Network Voltage distortion with filtering connected directly at PCC of plant

As can be seen, the 12th harmonic order is now significantly lower than the harmonic voltage planning levels across the network. This is due to the harmonic impedance at each terminal connecting its own individual harmonic filter to sink the current, limiting the voltage rise. It should also be noted that the connection of the filters across the network lead to an amplification for a number of other higher order harmonics, e.g. if a comparison is made of the 15th order harmonic emissions in Figure 5-10 with those in Figure 5-12, an increase of 250 % is observed at busbar B_1 with all plant filters connected and operating. This indicates that a piecemeal approach to harmonic management is capable of leading to resonances and amplifications at other harmonic orders.

It should be noted that there were many lower harmonic orders for which all plant emissions were non-compliant, however these did not result in voltage distortion exceeding planning levels. Thus, plant shunt impedance is an important consideration in determining both compliance and the appropriate emission limit allocations.

5.4.5 Optimised Mitigation Study

An alternative mitigation methodology has been investigated in which mitigation is implemented at the point of the network where harmonic distortion levels are likely to reach planning levels first, i.e. a network-centric (as opposed to plant-centric) solution is proposed with the aim of minimising the number of filters being installed and to optimise the size of the required filter. Harmonic emissions at the 12th order have again been investigated to enable a direct comparison with Study 4.

All installations are connected and emitting harmonic emissions as previously, without any mitigation considered. A frequency scan was conducted and identified that the largest harmonic impedance for the 12th order occurred at busbar A.2. Thus, this is the point of the network at which harmonic voltage is the largest. Subsequently, a harmonic filter was connected to this busbar and sized such that all busbars remained at, or below planning levels for the 12th harmonic order. The resulting filter size required was 20 kVAr, (noting that the sum total for the PCC filter solution, provided in Table 5.3 was 760 kVAr). The centralised filter option results in 98 % less reactive power being connected to the network.

Harmonic emissions for 3 scenarios (i.e. no filtering, existing mitigation methodology and proposed methodology) are compared at the B.1 busbar (provided as an example) as shown in Figure 5-13.

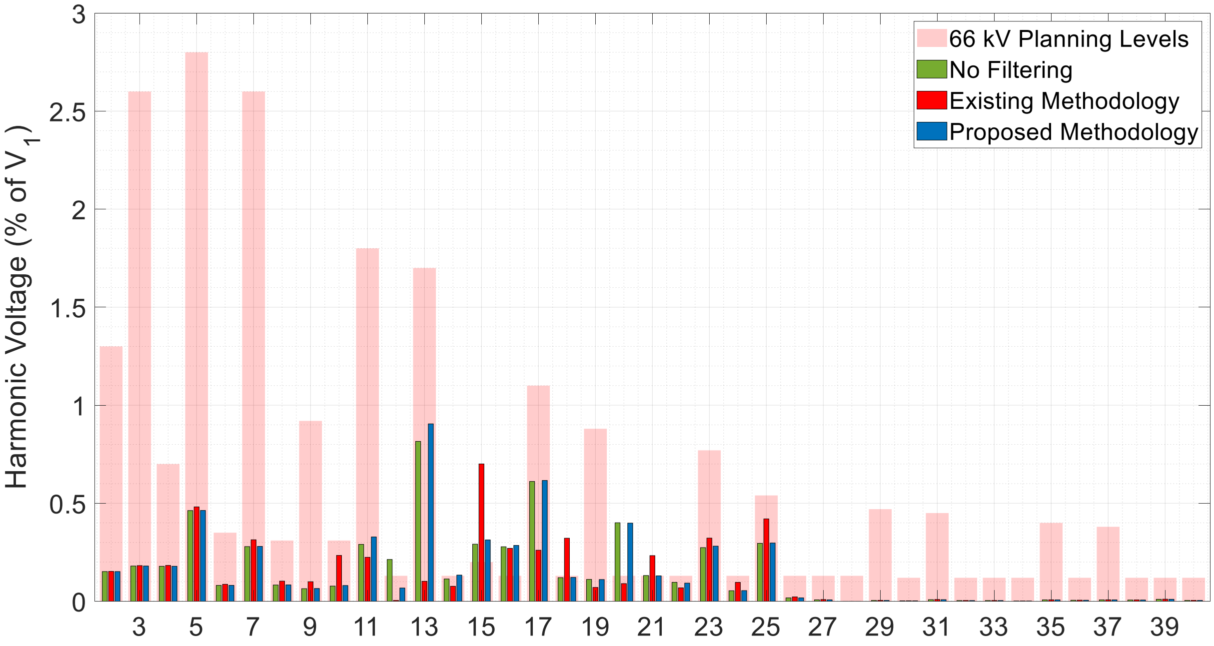

Figure 5-13 - Comparison of mitigation methodologies at busbar B.1

As can be seen, the existing mitigation methodology, whilst effective at the 12th harmonic order, leads to substantial amplification of other harmonic orders, which is likely to lead to NSPs being required to implement solutions to ensure harmonic voltage distortion is maintained below planning levels. Whereas the proposed methodology, whilst minimising the reactive rated reactive power being connected to the network, also maintains a localised impact at the harmonic order of interest and has minimal impacts on the wider harmonic spectrum.

5.5 SIMPLIFIED STUDY ANALYSIS

A further comparative study was undertaken to compare the outcomes identified in Sections 5.4.4 and 5.4.5. Specifically, the required VAr rating of a filter was considered when:

a) Connected at the PCC of a harmonic emitting plant (Study 4)

b) Connected at the point of concern within the network (Optimised mitigation study)

In order to compare the two options, a) was completed first for a proposed plant. The filter was designed as per Section 5.4.4 so the harmonic current flowing from the plant resulted in compliance for the plant. The subsequent change in harmonic voltage (ΔV_h) at the point of the network at which distortion levels were being managed was then calculated due to the connection of the filter. The comparative study b), followed the same process with the filter connected at the point of concern on the network and was rated to achieve the same ΔV_h as a).

The study found that when comparing the two options, the required rating of the filter when connected directly at the point of concern was equal to:

$$Q_{res} = Q_{PCC} \cdot \frac{Z_{hPCC}}{Z_{hres}} \qquad (18)$$

Where,

Q_{PCC} is the rating of the filter when connected at the PCC of the harmonic source.

Z_{hres} is the impedance at the point of concern (i.e. largest impedance within the network for harmonic order h)

Z_{hPCC} is the harmonic impedance at the PCC of the harmonic source

In conditions of resonance, one may identify the efficiencies of connecting a filter directly at the point of the network at which resonance occurs (i.e. where $Z_{hres} \gg Z_{hPCC}$) . Of course, other factors require consideration when connecting passive filtering, such as installation and capital costs and the capability of the network infrastructure to connect passive plants, e.g. location on network at which resonance occurs may be remote to substation, making the installation of filters difficult/more expensive.

A further study found that the value of Q_{res} may be calculated for any position along the feeder of concern, replacing Z_{hres} with the impedance of the network at the point at which the filter is to be connected. As the connection of the filter moves further from the point of concern, the required VAr rating will increase, however, the solution remains more efficient than mitigation within individual plants, in reference to VAr ratings. Thus, the optimised location and size of a harmonic filter may be determined based on;

- Required VAr
- Position within the network at which a harmonic filter is suitable
- Cost ($/VAr) of the filter

Careful consideration needs to be given to the possibility that optimising the cost of the filter may subsequently lead to shifting resonant frequencies across the network. Such consideration requires further studies and collaboration with stakeholders to adequately understand and determine sensitivity.

5.5.1 Outcomes

Whilst the example used in this section is somewhat limited in its application, i.e. single, simplified network, single simplified harmonic model etc., it encapsulates the broader insights that have been gained, such as, the fact that harmonic mitigation is most effective and efficient when connected to the point of the network at which harmonic distortion is the highest as opposed to at individual plants. Also, filtering connected to the PCC of installations is capable of leading to complications due to shifting resonances.

It must be stated that a network-centric mitigation philosophy is a considerable deviation from existing harmonic management practice, i.e. the fundamental theory of limiting harmonic currents from individual plants is abandoned in favour of managing system harmonic resonance. In this preliminary state, it is suggested such a process is only suitable for networks in which resonances are, or may become a concern, further research is required to consider different network types and sensitivities, e.g. strong/weak meshed networks.

Further, it can be shown that the proposed approach would be most beneficial when implemented as the system is nearing its thermal loading capacity. It is currently unclear whether such a deviation from existing practice is amenable to the industry and relevant regulators, i.e. allowing connections to be made preliminarily with network-led mitigation being installed as the network continues to evolve and connect installations.

5.6 RESULTS – FULL NETWORK STUDY

As stated in Section 5.3.2, the full network study was used to validate and further investigate the findings of the simplified network study. The full network study involved connection of distorting installations to the full network model, calculating harmonic emissions across the network, identifying areas at which distortion levels exceed the harmonic voltage planning levels and investigating appropriate harmonic mitigation solutions. As previously discussed, generation was connected in 500 MW stages and spread across all areas of the network based on the relative strength.

The simulation for each stage was executed and the results collated. Harmonic emission levels at all busbars were compared against harmonic voltage planning levels. An example of this for the results of Stage 1 (as discussed in Section 5.3.2), prior to implementing any harmonic filtering, is provided in Figure 5-14. It can be seen that the 4th harmonic order is non-compliant at the Z5.02 66 kV and Z5.04 66 kV busbars, noting that both busbars are supplied from an upstream tee point. It should also be noted that neither busbar has REG connected, and the length of line between these busbars and the nearest REG plant is approximately 200 km.

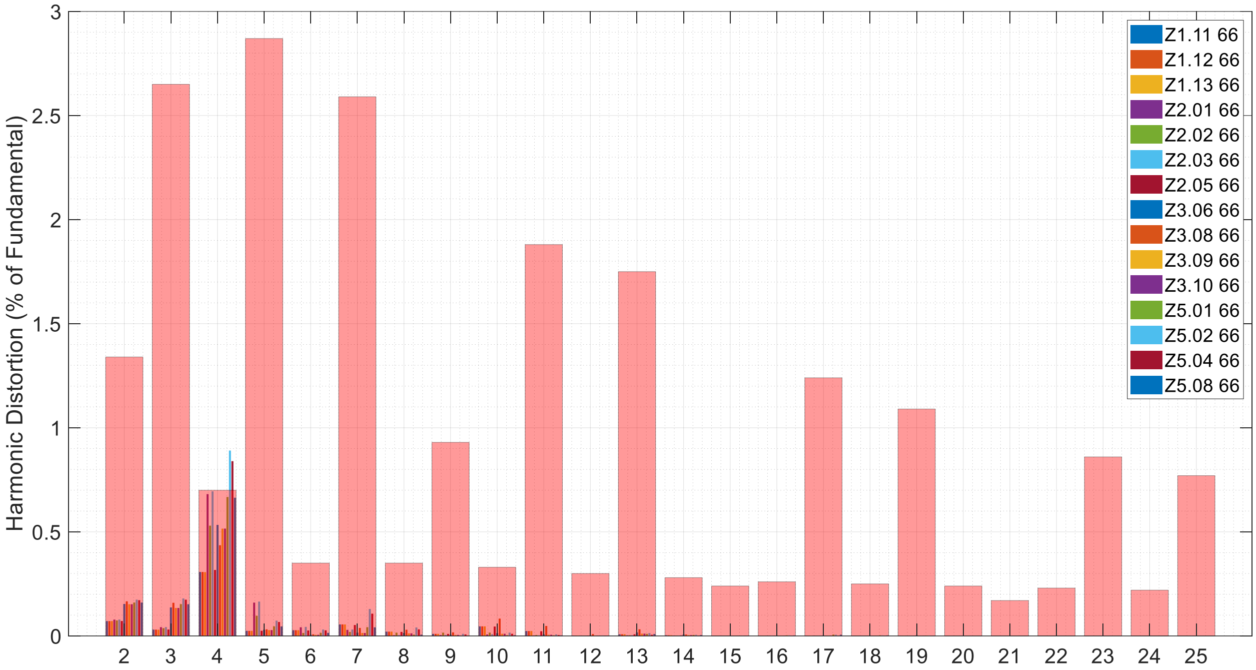

Figure 5-14 - Stage 1 results, 66 kV (pre-mitigation)

To investigate the cause of non-compliance occurring at a point that is remote from sources of distortion, firstly the system impedance at the areas of concern were investigated, as shown in Figure 5-15.

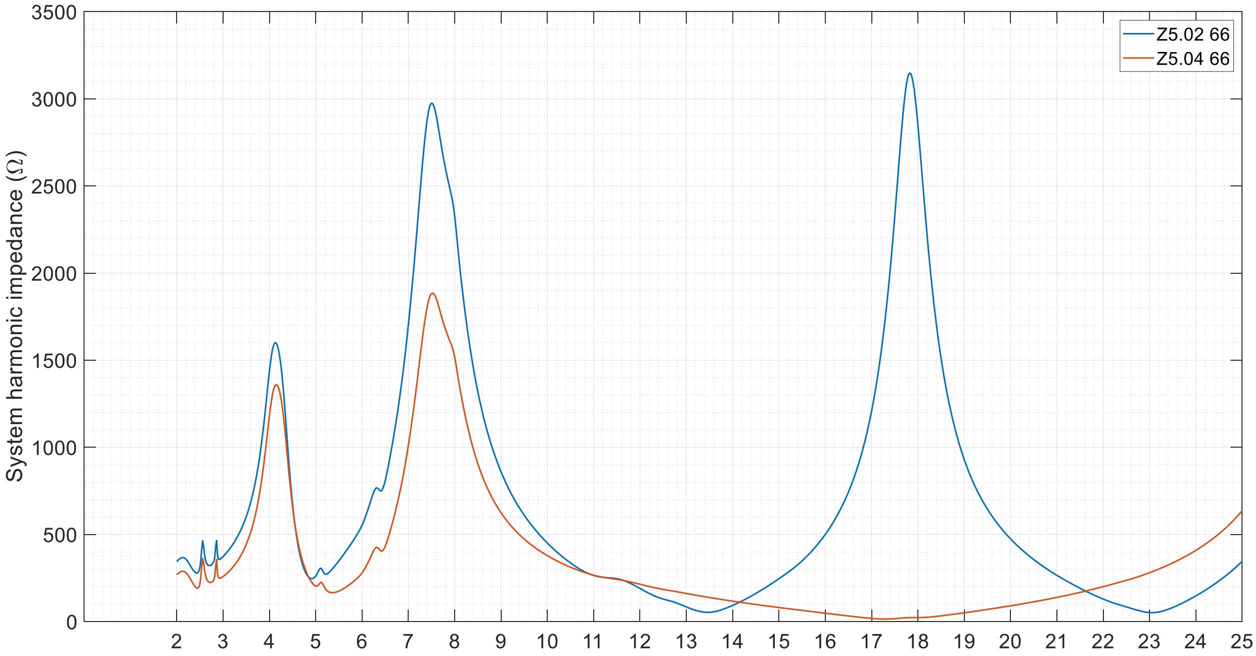

Figure 5-15 - Frequency sweep at points of concern

As can be seen, harmonic resonance occurs close to the 4th harmonic order. Resonance results in an amplification of harmonic voltage distortion due to the large impedance interacting with the harmonic sources on the network. As both busbars are fed from the same supply point, causes for this resonance were investigated upstream. It was found that detuning an upstream 6 MVAr capacitor bank, connected to Z1.11 66 kV busbar, was able to mitigate emission levels to within planning levels, as shown in Figure 5-16. An annotated single line diagram of the relevant network areas is provided in Figure 5-17.

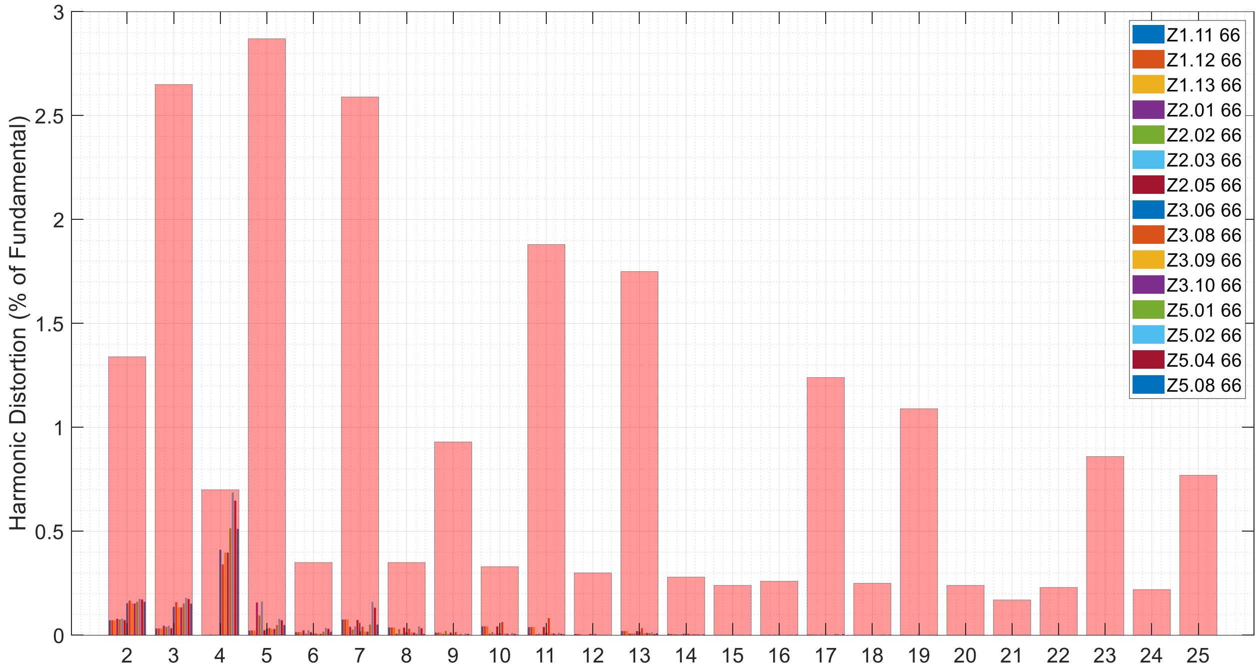

Figure 5-16 - Stage 1 results, 66 kV (post-mitigation)

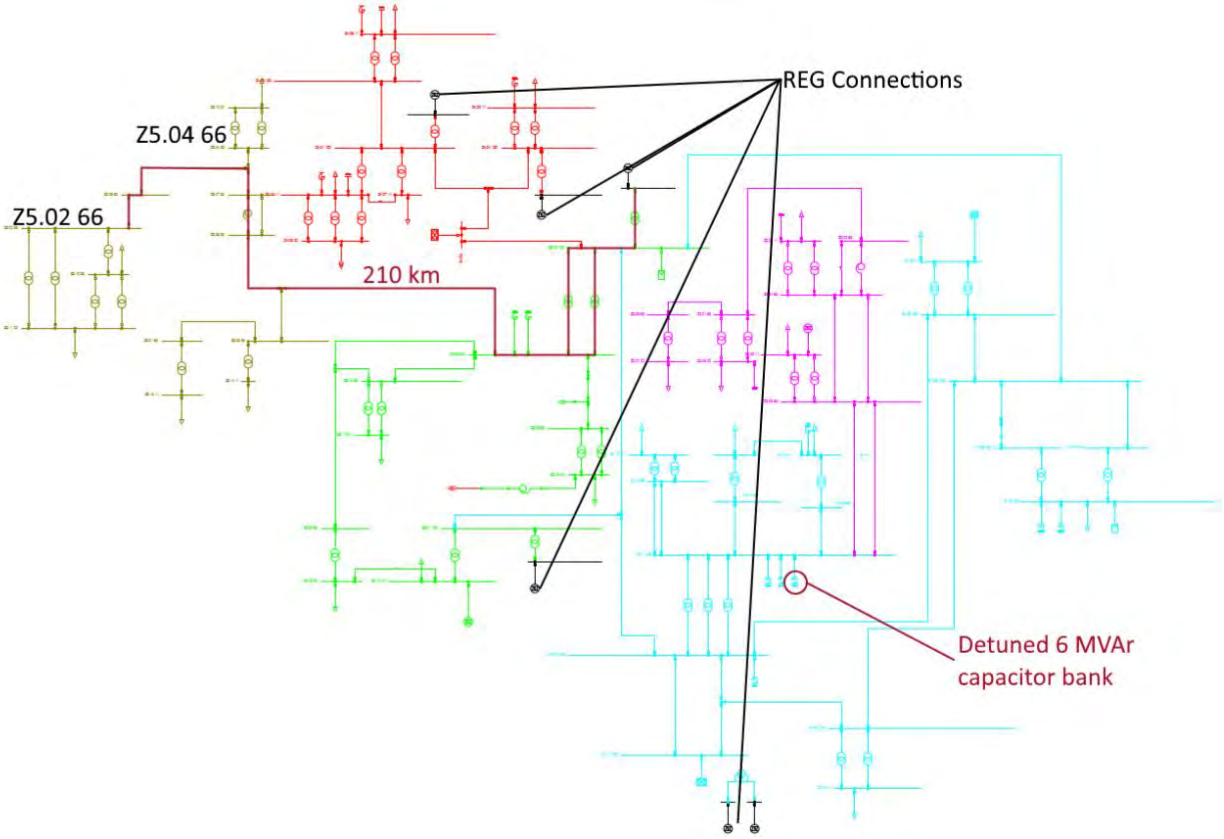

Figure 5-17 – Annotated network SLD, identifying REG connections, locations of non-compliance and mitigation implemented

Once mitigation solutions were found for each stage, simulations were re-executed to ensure the selected approach to mitigation did not introduce any further instances of non-compliance in other areas of the network. Once system-wide compliance was achieved, the next stage was implemented, simulations executed and where required, mitigation solutions investigated and implemented. Whilst Stage 1 was mitigated through modification of an existing reactive plant, some stages required additional or modification to harmonic filtering. A summary of the mitigation solutions implemented in this study for each stage is provided in Table 5.4.

Table 5.4 - High-level stage outcomes mitigation implemented

	Pre-mitigation		**Mitigation implemented**		
Stage #	**Location(s) of non-compliance**	**Harmonic order(s)**	**Solution implemented**	**Location**	**Capacity[5] (MVAr)**
1	Z5.02 66 Z5.04 66	4	Capacitor bank detuned	Z1.11 66	6
2	Z5.02 66 Z5.03 66	8	Harmonic filter added	Z5.02 66	0.05
3	Total of 22 busbars non-compliant	4, 8	Stage 2 filter updated - Capacitor bank detuned	Z5.02 66 - Z4.10 11	1 - 8
4	Z5.02 66 Z5.03 66	8	Harmonic filter added	Z5.02 66	0.1
5	Total of 26 busbars non-compliant	4, 8	Capacitor bank detuned	Z3.09 66	8
6	Z5.03 66	10	Harmonic filter added	Z5.03 66	0.05
7	N/A	-	None required	-	-
8	N/A	-	None required	-	-

Neglecting Stages 3 and 5, it can be seen that non-compliance is restricted to three busbars in Zone 5, all within relatively small geographical and electrical distance of each other. Further, the harmonic orders for which non-compliance is detected are restricted to non-characteristic, even harmonic orders. Based on the outcomes of the study, it can be seen that the management of distortion throughout the network can be achieved by;

- Leveraging existing assets (e.g. detuning capacitor banks).
- Adding/modifying harmonic filtering efficiently, rather than connected at the PCC of REG plants.

Further, the final two stages require no mitigation to manage distortion levels. Investigation of the frequency response of the network at one of the problematic busbars (Z5.03 66) finds that the solutions implemented throughout the staged process subsequently addresses the resonance at the 4th order that existed prior to the connection of Stage 1. As previously mentioned, this resonance aligns with a non-characteristic harmonic order that has a comparatively lower harmonic voltage planning level. Thus, the increased penetration of distorting loads that emit non-characteristic harmonic currents (albeit relatively small) lead to non-compliance. This outcome supports the findings of Section 5.4, i.e. addressing network resonances significantly improves the efficiency and effectiveness of the implemented mitigation solution.

A comparison of the network harmonic impedance prior to stage 1 and after stage 8 is shown in Figure 5-18. The harmonic voltage levels for the 66 kV busbars after stage 8 connections, including mitigation, are shown in Figure 5-19.

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[5] Capacity refers to size of reactive plant added or modified in the solution implemented, i.e. for existing plants, the capacity is the rated reactive power of the capacitor already connected to the network.

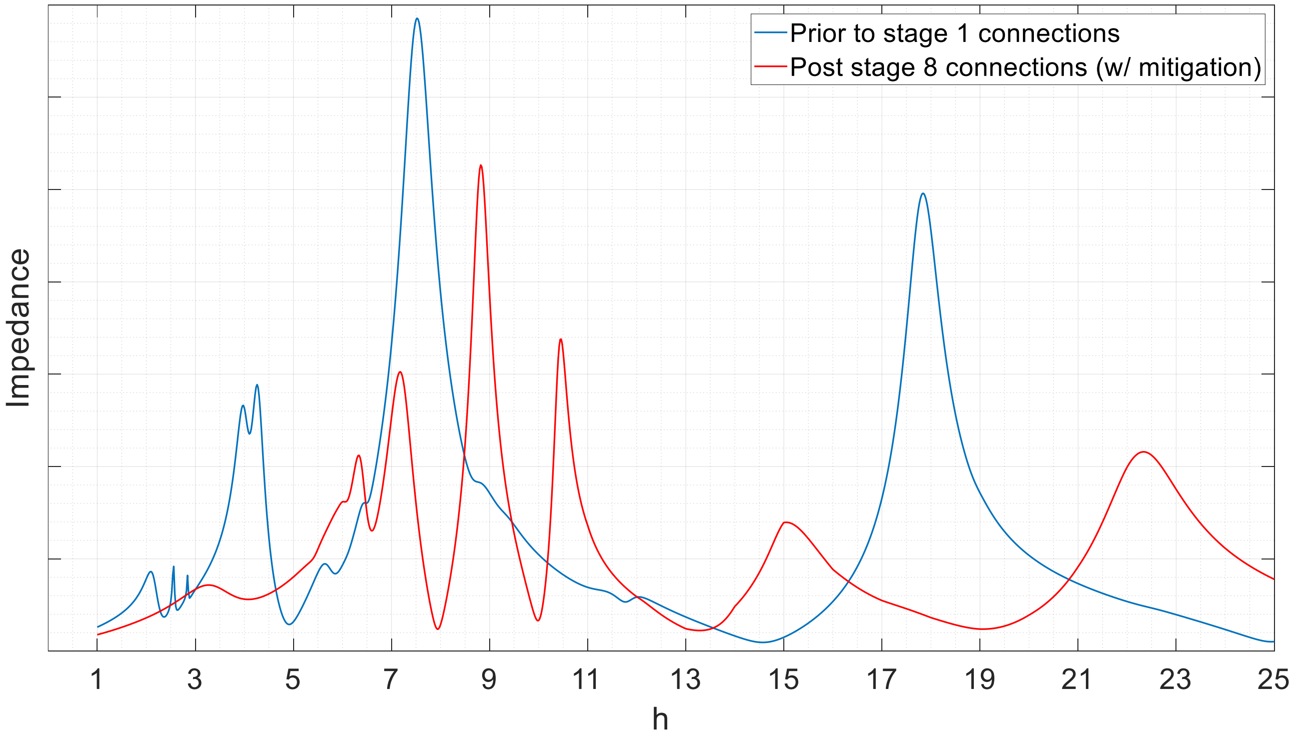


Figure 5-18 - Comparative frequency response at busbar Z5.03 66

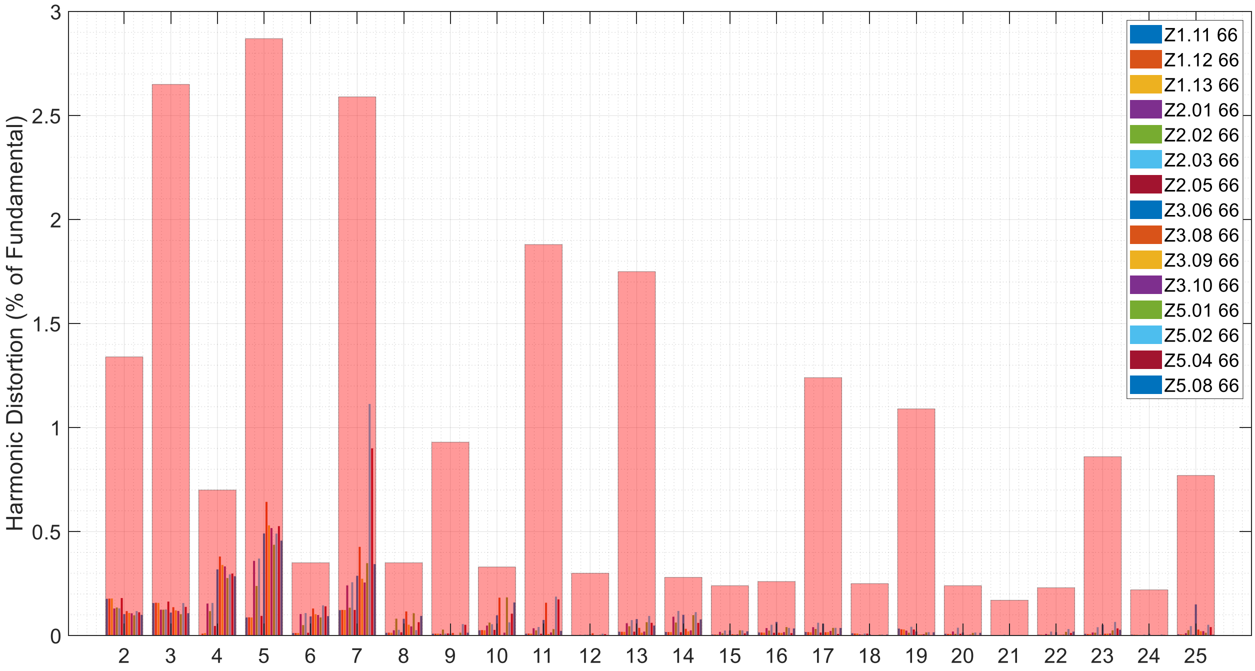


Figure 5-19 - Stage 8 harmonic voltage distortion levels (66 kV busbars only)

As can be seen, there remains a considerable amount of headroom available after Stage 8. It is previously mentioned that the study may be considered somewhat pessimistic due to the minimal number of IBR harmonic models being used to represent REG plants. It is suggested therefore that the implementation of a network-led mitigation approach allows high levels of REG penetration whilst accounting for existing (and anticipated) distorting loads.

The implemented approach to manage harmonic distortion levels resulted in a total of 23.2 MVAr of reactive plant being required across the network, the majority of which consisted of simply detuning existing capacitor banks and 1.15 MVAr of new harmonic filtering being required.

5.6.1 Impact of background emissions

The previous study did not consider any background harmonic voltage levels, instead it focused solely on the interaction and mitigation of REG harmonic emissions. Measurements were available for busbars Z1.01 132 and Z3.06 66 which allowed calculation of 95th percentile harmonic voltage levels for a recent period of time. A simple addition of the harmonic voltage levels for stage 8 with the background emissions was completed and found headroom to still be available in both areas, as shown in Figure 5-20 and Figure 5-21.

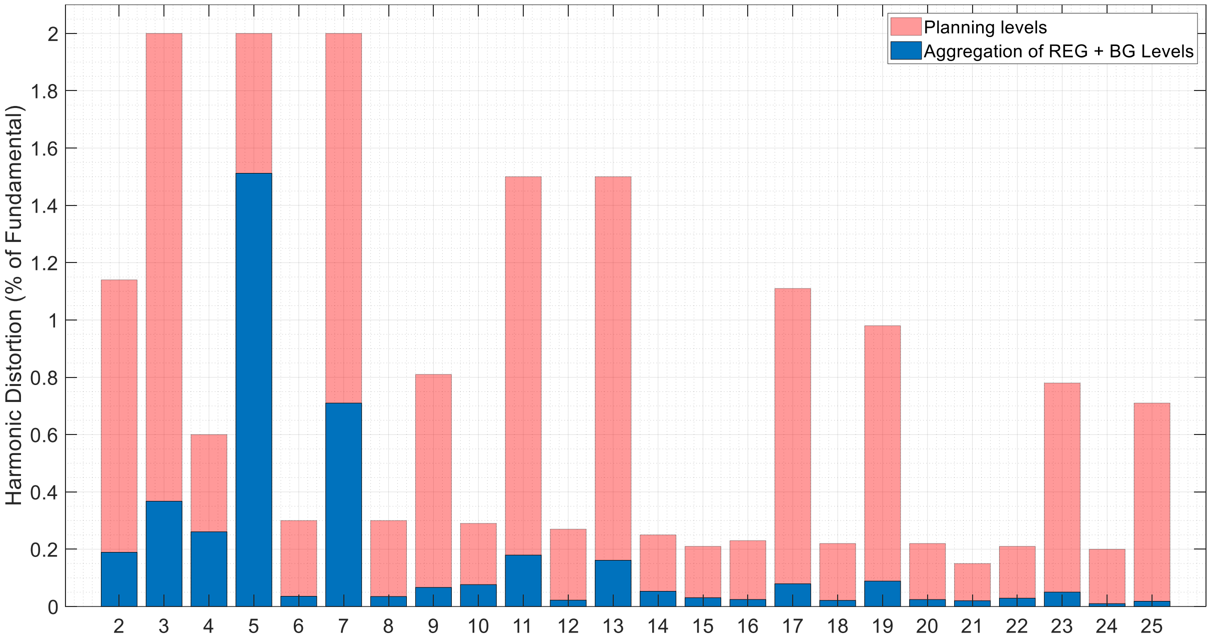


Figure 5-20 - Aggregation of background emission levels and calculated REG emissions – Z1.01 132

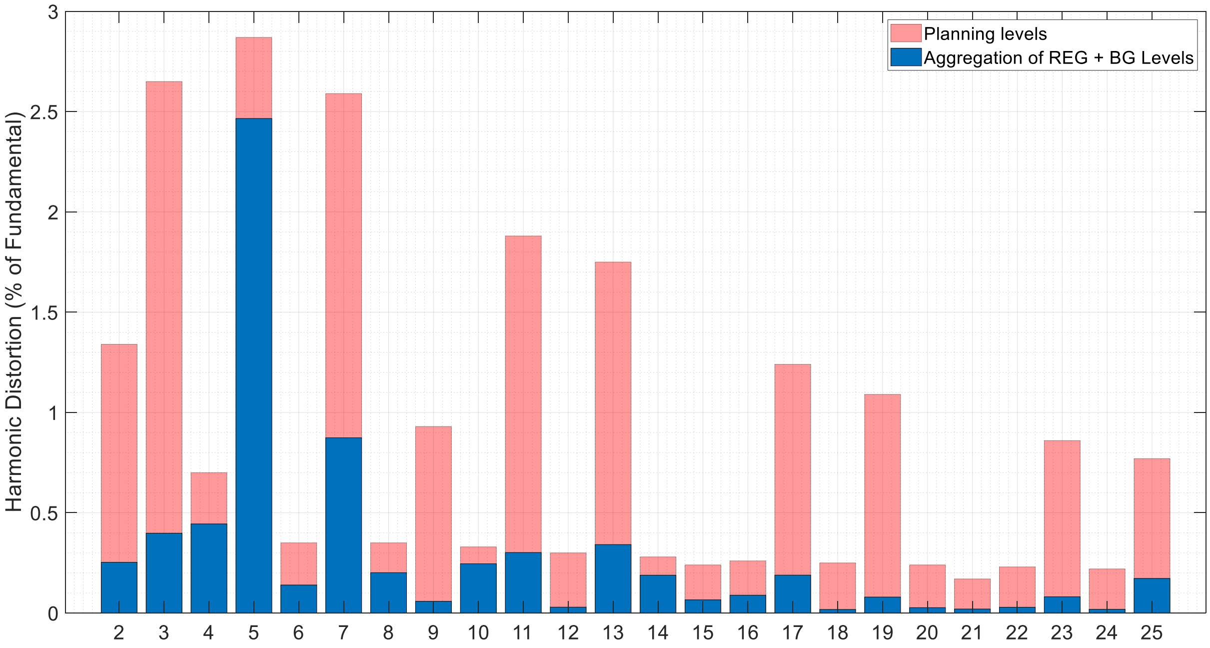


Figure 5-21 - Aggregation of background emission levels and expected REG emissions – Z3.06 66

The minimum amount of headroom available occurs for a non-characteristic harmonic order ($h = 10$) occurring at busbar Z3.06 66. Consideration of background harmonic voltage levels at two busbars shows planning levels are most likely to be reached at non-characteristic orders, similar to the base study. It should be noted that a frequency sweep was conducted at these busbars which found that there was no resonance at the order for which there is the least headroom available. Increased emissions and low planning levels are the cause for minimal headroom being available.

5.7 FULL NETWORK STUDY ANALYSIS

Based on the results of the full network study, some important insights may be surmised that may have weighting on appropriate harmonic distortion management processes. One of the key outcomes is that non-compliance was restricted to non-characteristic harmonic orders (i.e. $h \neq 6k \pm 1$ for $k = 1, 2, 3 \ldots$). It is hypothesised that the reason for this is multi-faceted and may be due to one or more of the following:

- System harmonic impedance resonance.
- Harmonic voltage planning levels being comparatively lower for these harmonic orders.
- Increased non-characteristic harmonic emissions from REG plants.

Often, in weak networks with long lines and/or reactive power support, resonances will be shifted to lower frequencies due to the increased capacitance within the network. NSPs may install a detuning reactor in order to shift the resonance to an order for which there are lower or no emissions present (e.g. non-characteristic, even and inter-harmonic frequencies). With the introduction of significantly more REG plants which are known to emit non-characteristic orders [2, 31], the alignment of resonances with these emissions results in amplification at the point of resonance and thus harmonic voltage planning levels are exceeded.

This alignment of resonance and non-characteristic harmonic current emissions is compounded by the comparatively lower harmonic voltage planning levels for even order harmonics. It is discussed in the literature review of this project and [81] that the harmonic voltage planning levels defined in [137] 'prioritise' characteristic harmonic orders, i.e. characteristic harmonic orders are given higher magnitudes in the recommended planning levels. As discussed in [81], this approach is based on measurements that were undertaken at a time in which line-commutated converters (LCC) were prevalent and their harmonic spectra known to be dominated by characteristic orders. As such, non-characteristic orders have been given lower allowable emission levels. Further, concern of the deleterious effects introduced by even order harmonic emissions, such as saturating transformers and iron-core reactors due to the inherent DC component must be given due consideration. It is noted that other harmonic management practices such as [72] implement uniform emission limits regardless of harmonic order.

5.7.1 Location of harmonic mitigation

The process of mitigation presented in Section 5.4 added or modified a total of 23.2 MVAr of reactive plant to manage the harmonic emissions of 4 GW of renewable generators, i.e. total mitigation ≈ 0.6 % of nominal generator capacity. It is known through extensive industry interaction that harmonic mitigation for an individual generator is capable of being rated ≤ 20 % of the nominal generation capacity when being applied directly at the PCC of connecting plants.

A sensitivity study was undertaken to determine the required harmonic mitigation if the distorting plants were required to install passive filters within their installation as opposed to a network-led solution being connected in the area of concern. The mitigation implemented for Stage 2 (Table 5.4, 50 kVAr filter) of the base study was compared against three approaches in which mitigation is individually managed by the REG proponents;

a) All REG plants in the network required to mitigate offending harmonic emissions.

b) Limited number of plants within a restricted region required to mitigate emissions.

c) Single REG plant closest to the point of the network at which non-compliance occurs required to install filter.

The rated capacity of the mitigation was increased across all plants uniformly for each scenario until emission levels for the offending harmonic order reached the same value when considering the mitigation solution implemented in the base study, similar to the process discussed Section 5.5.

The sensitivity study found the aggregate required filter rating for *a)* to be 7.65 MVAr whilst *b)* required 4.2 MVAr. The rated capacity of the filter for *c)* was 1.5 MVAr, noting that this particular plant is 160 km from the busbar at which emission levels are being managed.

Whilst *c)* may present as the best option in the event that mitigation is restricted to the responsibility of proponents, it creates inequality as many of the connected plants are contributing to the emission levels at the point of concern. However, spreading the responsibility across those within a limited vicinity or requiring all plants to install filtering to manage emission levels at the remote area significantly increases the required capacity of the filter. These outcomes confirm the findings of Section 5.4 on a much wider and complex network being that; harmonic mitigation is most effective and efficient when connected closest to the point of the network at which harmonic emissions are the highest.

It is noted here that the Australian Standard for managing harmonic distortion levels within networks containing long feeders, provided in Appendix B of [137] aims to manage harmonic emission levels at the point of the network which is expected to reach planning levels first. For the study presented here, this would be Z5.02 66 or Z5.04 66. This is implemented by ensuring harmonic current emissions of connecting plants across the network are limited to ensure that the remote point of the network maintains appropriate distortion levels. The study undertaken in this section, suggests this to be an impractical and inefficient harmonic management methodology. This investigation of harmonic filtering location sensitivity identifies that addressing harmonic emissions at the remote area(s) of the network at which planning levels are exceeded (or approaching levels of concern) may be a much more practical process resulting in reduced reactive power being required, reducing costs and simpler application and management of harmonic distortion in general.

5.7.2 Challenges of Network-Led Harmonic Mitigation Solutions

It must be noted that the above suggestions of implementing network-led solutions to mitigate harmonic distortion is a considerable departure from present-day practice and as such would present a number of challenges to implement. Beyond the ‘traditionalism’ and regulatory inertia that is to be overcome, some of the key challenges to be addressed have been identified by the research team and are discussed below (note; this is not intended to be an exhaustive list of potential issues).

5.7.2.1 APPORTIONMENT OF FINANCIAL AND OPERATIONAL RESPONSIBILITY

The proposed alternative approach to harmonic management suggests that mitigation be a network-led solution, i.e. external to any installation connected to the network. Thus, implying that the reactive plant and related components are owned and operated by the NSP. However, as the proponents of REGs would no longer be required to install individual filtering, assigning financial responsibility to plants that emit harmonic orders which interact with problematic frequencies (e.g. resonances) is to be considered. It should be noted that, given the costs would be shared across multiple plants and the required rating for filtering is significantly less, it is most likely to remain a far less expensive option for proponents compared to existing practice. A number of factors may be required to apportion responsibility to the level of distortion across the network such as;

1. Proximal influence
2. Magnitude of harmonic current emissions

The first consideration may assign an increased responsibility to the installations that are electrically closer to the point of concern whilst still accounting for impacts of resonance. The second consideration accounts for the comparative amount of harmonic current an individual plant is contributing.

To develop a ratio based on the proximal influence of a generating plant, a reference harmonic current source may be connected to the bus at which mitigation is necessary, the harmonic voltage resulting from this reference current is calculated, given the symbol $V_{h,ref}$. Next, the same reference current source is connected at the PCC of each of the REG plants to be assigned responsible for the mitigating equipment and the resulting harmonic voltage at the busbar of concern is calculated due to the injected reference current source at each PCC, given the symbol V_{hi}. A ratio based on location of connection may then be determined for each REG plant using (19).

$$k = \frac{V_{hi}}{V_{h,ref}} \tag{19}$$

Where –

V_{hi} is the harmonic voltage at the busbar where the mitigation is being installed due to the reference current connected at the PCC of the connected generator.

$V_{h,ref}$ is the harmonic voltage at the busbar at which mitigation is being installed with the reference current connected directly at this point.

A secondary scaling value may be used that accounts for the amount of current that the plant is expected to inject into the system. This value is introduced to avoid circumstances in which a plant that is not emitting harmonic current for which the mitigation has been designed being financially responsible for the mitigation of harmonic distortion to which it is not contributing. The value of the magnitude of current emissions may be scaled based on the expected harmonic current that is to be absorbed by the harmonic filter so that all contributing installations may appropriately contribute, e.g. (20).

$$m = \frac{I_{hi}}{I_{h,filter}} \tag{20}$$

Where –

I_{hi} is the harmonic current of installation i.

$I_{h,filter}$ is the expected harmonic current to be sinked by the proposed filter.

Undertaking this approach would lead to an apportioning of financial contributions across distorting installations by implementing (21).

$$E_{fi} = C_{filt} \cdot m \cdot k \tag{21}$$

Where;

E_{fi} is the allocated proportion of the total cost of the filter to customer i.

C_{filt} is the total cost of the filter.

This approach needs to be formulated and tested with more detail to ensure the approach is equitable. It would be appropriate to consider impacts of REG plants on system impedance at the point of concern to ensure connecting plants do not further exacerbate existing resonances. Maintaining a detailed harmonic model of the system, including detailed representation of network connections is an inherent requirement for this, and a challenge to be addressed in the implementation of the revised approach as such detail is commonly not available to NSPs.

Advantages to proponents of the proposed alternative approach to harmonic management are that the cost of harmonic management is greatly reduced and there is no requirement to engage external consultancy services to undertake and/or analyse detailed harmonic emissions studies. Advantages for the NSP is the reduced amount of reactive plant connected across the network resulting in the management of resonant frequencies and harmonics in general becoming much easier. However, it is noted that the approach does increase the responsibility of the NSP.

5.7.2.2 IDENTIFICATION OF NETWORK AREAS OF CONCERN

Another challenge that is yet to be considered in detail is the determination of a process for NSPs to identify the position(s) of the network that are of most concern. In the examples provided previously, it was assumed that the model was absolutely accurate and representative of the network and connecting installations. This enabled identification of the position(s) within the network at which harmonic distortion was of most concern, availability of the data required for these calculations may be difficult to obtain due to variation and dependency of customer type, location and design.

These concerns may be overcome in time with the ongoing connection of REG plants, as each is required to have relevant PQ monitoring installed. However, as identified in the study it is not the PCC of the plants that are of significant concern but rather remote areas with resonance that will pose a significant challenge. Regardless, the availability of data may be incorporated with detailed network modelling to identify areas of the network which may require monitoring or mitigation to be considered.

Another related challenge that may not be clear in the provided examples is the determination of when harmonic emissions are to be addressed. The studies presented in this report simply take snapshots after each stage at which a further 500 MW of generation has been connected. It would be assumed that a more consistent review of existing emission levels along with estimating harmonic emissions from proposed plants would dictate the need for mitigation as appropriate.

5.7.2.3 EXISTING AND FUTURE DISTORTING INSTALLATIONS AND ALLOCATED EMISSION LIMITS

The proposed approach is a significant departure from present-day practice related to harmonic emissions management. Existing methodologies attempt to manage distortion levels by applying current emission limits to installations as they connect with the aim of reaching harmonic voltage planning levels once the system is fully loaded. Such an approach introduces many difficulties, which have been explored in previous sections of this report. A difficulty in the implementation of the proposed approach is the reasonable and equitable management of existing connections.

Similarly, a reasonable approach needs to be determined for the consideration of future connections that contribute to the emissions for which mitigation is already existing within the network. Some pertinent questions that may require review are;

- Is it appropriate to simply apportion costs to a new distorting installation for mitigation that is already installed and paid for? For example, following the process discussed in Section 5.7.2.1.
- If not, how is one to implement a harmonic management strategy that does not require mitigation to be installed after every connection?

It would be suggested that in the event that mitigation is installed, it is designed to not only mitigate the emissions of existing plants but to account for some future installations also. Anecdotal evidence suggests that expenses related to the installation of harmonic mitigation are less sensitive to size and more aligned with costs for civil works, e.g. installing a 1.5 MVAr filter to account for future installations rather than a 1 MVAr filter to address the emissions of only present day connections would not greatly increase costs and provide the NSP a solution to the above questions. A framework may be a reasonable approach that requires every connecting plant that impacts harmonic distortion throughout the network (including emission of harmonic distortion and impacts on harmonic impedance) are required to pay a ‘flagfall’ fee which is used by the NSP to maintain network distortion levels for all customers.

5.8 SUMMARY

This section presented a number of studies to examine the difficulties and inefficiencies of existing harmonic management processes implemented within Australia. Firstly, the outcomes identified, through a simplified network study, that existing harmonic emission limit allocation methodologies are capable of leading to network distortion levels exceeding harmonic voltage planning levels. This is due to:

- Uncertainty of the final state of the network,
- Impact of plant shunt impedance on the network frequency response and
- Inappropriate/incomplete definitions with respect to the emission assessment of distorting plants.

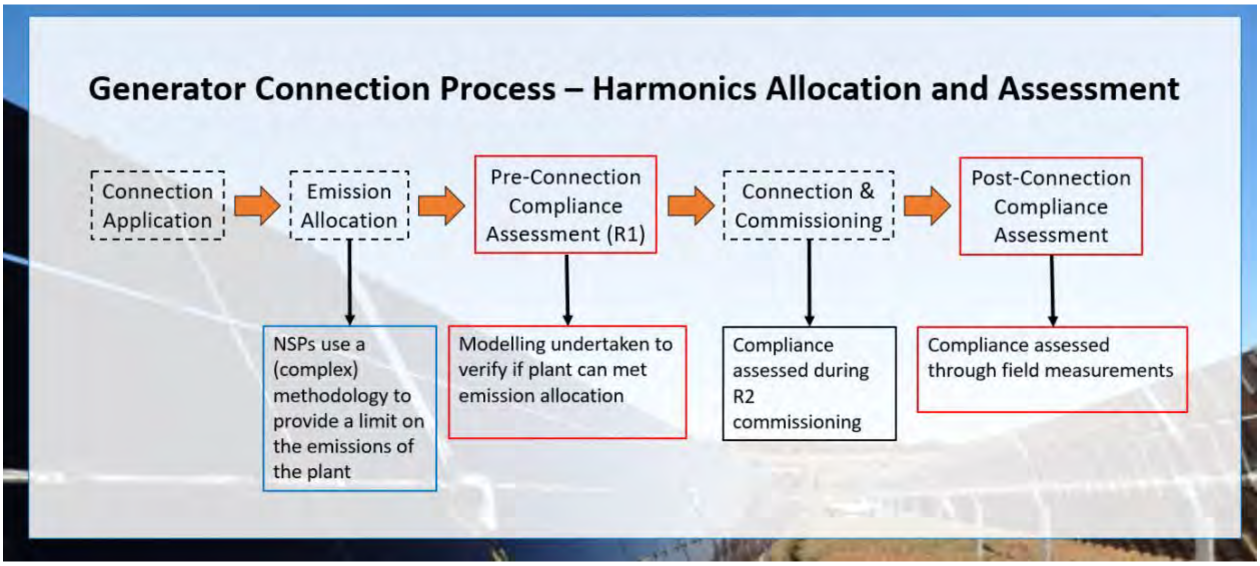
Further, a review of existing approaches to harmonic mitigation was undertaken which found that current practices are potentially inefficient leading to unnecessary increased costs and further issues due to shifting resonant frequencies. A revised, network-centric methodology was presented that was found to be capable of significantly reducing the reactive power requirement of the mitigation solution and also limiting the impact on the network spectrum and simplifying the application of harmonic management in general.

Consideration with respect to cost optimisation apportionment of financial responsibilities and modelling requirements with respect to the revised mitigation methodology were discussed. Such aspects require further studies and collaboration with stakeholders to adequately understand and determine sensitivity. As such the studies would benefit from further industry input and collaboration.

6 Preliminary Evaluations of Methods for Determining Harmonic Emission Compliance of Large Renewable Energy Generators

6.1 INTRODUCTION

The first step in the management of harmonic voltages for large installations, whether they be loads or generators, is allocation of a limit on the amount by which the installation can contribute to network distortion (emission allocation). Consideration of this allocation process is the key focus of this project. Once an emission allocation has been determined, the next step in the harmonic management process is determining whether the installation as designed can meet the allocated emission limits. Whether or not an installation can meet emission allocations can have serious financial repercussions at both the planning (pre) and post connection stages. Failure to meet emission limits at the planning stage may require harmonic mitigation, typically in the form of harmonic filters to be designed before the connection is approved. The cost of harmonic filters is not insignificant and can be up to several million dollars for a large solar or wind farm. Non-compliance at the post connection stage may again require mitigation. In this case installation of mitigation may require a shutdown of the plant and retrofit of a harmonic filter. This retrofit will likely be more costly than integrating the filter at the design stage and may result in the plant being idled for an extended period of time while the mitigation solution is designed and retrofit is undertaken. Figure 6-1 shows an infographic which outlines the harmonic allocation and assessment process for a renewable energy generator. The aspects in the blue boxes are the topic of this project (allocation) while the aspects in the red boxes are related to compliance assessment.



Generator Connection Process – Harmonics Allocation and Assessment

Connection Application

Emission Allocation

Pre-Connection Compliance Assessment (R1)

Connection & Commissioning

Post-Connection Compliance Assessment

NSPs use a (complex) methodology to provide a limit on the emissions of the plant

Modelling undertaken to verify if plant can met emission allocation

Compliance assessed during R2 commissioning

Compliance assessed through field measurements

Figure 6-1 - Harmonic Allocation and Assessment Infographic

While general guidance for assessment of installation compliance with allocated harmonic emissions exists in AS/NZS 61000.3.6 [71], the methodology is not sufficient or satisfactory to deal with the complexity of the situations being encountered in practice. As a consequence, at present, individual NSPs are implementing their own compliance assessment methodologies some of which vary markedly between jurisdictions. One of the outcomes of the lack of prescriptive guidance is the adoption of strategies that may be considered to be highly conservative with respect to ensuring that network harmonic voltage levels are maintained below harmonic voltage planning levels.

This section provides a preliminary evaluation of the present challenges for assessment of harmonic compliance for large loads and/or generators. The content of this section has been developed based on findings of previous sections of this report and capture interactions with a range of renewable energy stakeholders including renewable energy generation proponents, renewable energy generation equipment manufacturers, expert consultants and network service providers.

6.2 KEY CHALLENGES OF DETERMINING COMPLIANCE

6.2.1 IEC Technical Reports

Before discussion of other aspects of compliance assessment, it is worthwhile to explore the nature of IEC Technical Reports. There are three tiers of IEC document. Ranked in order of technical merit and consensus (with 1 being best) these are:

1. Standard
2. Technical Specification
3. Technical Report

As can be seen, Technical Reports are the lowest level of IEC document and have failed to achieve international consensus. The IEC definition of a technical report is as follows:

> *"Technical Reports (TR) focus on a particular subject and contain for example data, measurement techniques, test approaches, case studies, methodologies and other types of information that is useful for standards developers and other audiences. They are never normative."*

In spite of the known limitations of Technical Reports, IEC TR 61000-3-6:1996, which deals with allocation of harmonic emissions and to a lesser extent compliance assessment, was adopted as Australian standard AS/NZS 61000-3-6:2001 [76]. Reference to this standard in the national electricity rules render it normative. Another Technical Report, IEC TR 61400.21.3 is presently being used to evaluate the harmonic emission spectra of renewable energy plant. Notwithstanding any other challenges related to compliance assessment, the use of Technical Reports means that there is little prescriptive guidance and significant limitations associated with the technical robustness of any of the methodologies applied.

6.2.2 Pre-Connection Compliance Assessment

Pre-connection compliance for loads and generators is undertaken by means of numerical modelling most often implemented by computer software. In simple terms, the current emission of the installation is injected into the impedance of the network and the resulting distortion levels are compared to the allocated emission limit. The pre-connection compliance assessment process requires an understanding of network impedance and load/generator emission characteristics, both of which may be required to consider large numbers of operational scenarios including network operating states and generator output levels. As is the case with any studies undertaken using large volumes of data, the accuracy of the outcomes is impacted by the accuracy of the input data.

A prescriptive methodology for undertaking pre-compliance assessment does not presently exist in any Australian standard, regulation or guideline. As such, bespoke approaches have been adopted by network operators, which vary considerably in their application across different NSPs. The following have been identified as areas of uncertainty with respect to pre-connection compliance assessment that:

1. Determination of network harmonic impedance.
2. Accuracy of harmonic emission spectra models for power electronic devices and/or harmonic emission spectra provided by equipment manufacturers/suppliers.
3. Application of AS/NZS 61000.3.6 Stage 3 which, in its present form provides an option for conditional connection but little further detail.

Each of the above is discussed in detail below.

6.2.2.1 DETERMINATION OF NETWORK IMPEDANCE

The network impedance utilised for pre-connection compliance studies is critical as it is these values which are used in compliance assessment modelling. Under estimation of network impedance may result in higher than expected harmonic emissions once the plant is connected while over estimation may lead to pre-connection non-compliance and the requirement for design of mitigation before the plant is allowed to connect. As such, the implications of improperly determining the network impedance are significant.

The method used to specify the network impedance values used for pre-connection compliance studies is not consistent across all network operators. At transmission level, network impedance is often represented as an impedance polygon while a number of distribution network operators choose to supply only a single impedance value representative of the most common operating scenario for the network. A discussion of the technical limitations of each method of determining network impedance is detailed below.

6.2.2.1.1 Single Impedance Value

The single impedance method of determining network impedance generally involves supply of a single value calculated using the fundamental fault level value for the network at the point of connection. This impedance is generally inductive (the resistive component generally being ignored in high voltage networks). The uncertainty related to this method of specifying impedance is reasonably straightforward, that is, the single impedance value is based on only one network operating scenario and may not represent scenarios under which the network may be operated for extended periods of time. Under or over estimation of the single impedance value may either result in underutilisation of the harmonic absorption capacity of the network or non-compliance at the pre-connection stage that will not be observed once the installation is commissioned.

In addition to the above, a single network impedance value is not capable of incorporating any complex frequency dependent network behaviour. Scaling a single network impedance value to include the frequency dependence of components generally involves multiplying the impedance by the harmonic order. As such, the network impedance increases linearly and it is not possible to represent any network resonance conditions.

6.2.2.1.2 Harmonic Impedance Polygon

Harmonic impedance polygons remove some of the uncertainty related to single impedance values as the impedance polygon can include many network operating scenarios and will generally allow for understanding of the frequency dependence of the network (as a polygon is generated for each harmonic order). Figure 6-2 shows an example of an actual harmonic impedance polygon. Each of the markers on the impedance plane shown represents a network operating scenario (it can be seen that a very large number of network operating scenarios are represented). The dark lines shown encapsulate the polygon (in this case, the polygon encapsulated by ten points). It can also be seen that 5% of the values have been omitted from the polygon (the values that exist outside of the surrounding polygon).

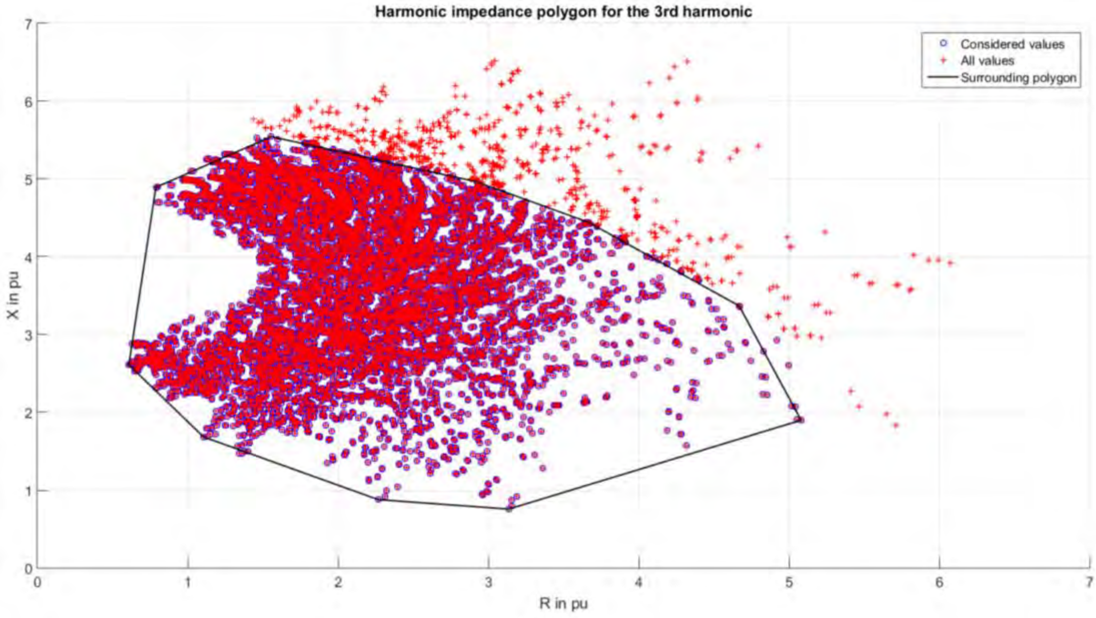


Figure 6-2 - Example Harmonic Impedance Polygon

While harmonic impedance polygons may provide a superior representation of the network impedance compared to a single network impedance value they require complex studies to generate. Further, a range of issues have been encountered related to the generation of harmonic impedance polygons including:

- A general lack of understanding or information with respect to the most likely operating scenarios for networks especially concerning:
  - Service status and appropriate modelling data for reactive plants (e.g. power factor correction capacitor banks). This reactive plant can have significant implications for the frequency response of the network.
  - Service status of *N-1* components (e.g. redundancy of transformers and transmission/distribution lines)
  - Understanding of harmonic emissions damping due to network loading
- A general lack of guidance with respect to the extent to which the network should be modelled. For example, is modelling the network up to several nodes away from the connection point of an installation suitable or is a more comprehensive model required? It is common for NSPs to require modelling of very large networks. This increases model complexity and associated time to develop and implement with uncertain benefit to accuracy.
- Harmonic polygons represent the network at the time when they are generated. In some cases, the polygons may also omit parts of the network, e.g. harmonic filters or committed installations, i.e. installations that are yet to physically connect to the system but have the appropriate connection agreements in place. The polygons do not reflect future network conditions and as such, installations may be assessed as being compliant at the planning stage only to be assessed as non-compliant post-connection.

The current methodology for harmonic impedance polygon generation usually involves considering a large number of different network operating scenarios for large networks with little or no weighting given to the likelihood of any particular scenario occurring (each marker in Figure 6-2 is given equal weighting). In many cases, the least likely operating scenario is concurrent with the largest impedance. Including these unlikely high impedance network operating scenarios increases the likelihood of harmonic emission mitigation being required by the proponent. Consideration must also be given to the fact that post-connection compliance is generally assessed using 95th percentile values of measurements. In this case, it may not be reasonable to include impedance values that will not likely exist for more than 5% of the time. A number of NSPs have taken this into account by omitting the largest 5% of impedances in generated impedance polygons (as indicated in Figure 6-2). However, it has been shown that the most likely network operating scenario can on occasion exist within the largest 5% of impedances and as such, arbitrary exclusion of the highest 5% of impedance values must be carefully reviewed.

6.2.2.2 MODELLING OF RENEWABLE ENERGY PLANT

Accurate modelling of the emission of power electronic devices is a key requirement for accurate pre-connection compliance assessment. As discussed in Section 2, a significant volume of research has been completed that identifies the impact of operational conditions on the harmonic emissions of a power-electronic device [2, 23, 148] Impacts of both internal and external conditions are capable of significantly varying the emissions of a device, however, these variations are often ignored in pre-connection compliance studies in favour of a single set of harmonic emissions which are generated based on an unknown combination of network characteristics and with an uncertain/non-standardised measurement methodology. OEMs of large inverters have specifically identified characterisation of inverter emissions as being highly challenging especially as the rating of the inverter increases. Operational conditions of networks that have been shown to vary the harmonic current emissions of power electronic devices include, but may not be limited to:

- Magnitude and order of background harmonic voltage levels
- Magnitude of fundamental voltage levels
- Magnitude of network unbalance

Operational conditions of power-electronic devices themselves that have been shown to vary the harmonic current emission include, but may not be limited to:

- Inverter operational set point, i.e. active and reactive power output
- Operational state of the device controller, i.e. Constant P/Q/V, Volt/VAr, Volt/Watt

The variables discussed above are considered in IEC TR 61400.21.3 [121], which is the international technical report currently being used to determine the emission characteristics of inverters via laboratory testing, time-domain simulation, converter impedance calculation or a combination of some or all of these approaches. This technical report provides general guidance in the development of harmonic models for wind turbines only, although it is suggested in [2] that the process can be extended to all devices using power-electronic converters. At present, the onus is placed on the device manufacturer to decide the conditions for which the emission models are developed and in general, only a single set of emission spectra, based on a single representation of network operating conditions, are provided. A request for more detailed information from OEMs often results in updated data with little to no explanation of how the updated results were obtained or for what conditions the model remains valid. It is obvious that inaccuracies in data for harmonic emissions can impact pre- and post-connection compliance. Underestimating emissions at the pre-connection stage may result in higher than expected impact post-connection while overestimating emissions at the pre-connection stage my result in pre-connection non-compliance requiring harmonic mitigation for the installation that is ill-designed, oversized or may not be required at all. Similar to other technical reports, IEC TR 61400.21.3 lacks a prescriptive method which can be followed to achieve a standardised outcome, in this case, a harmonic spectra emission model for the purposes of conducting pre-connection compliance assessment.

In addition to the above, the assumption that inverters behave as current sources across all harmonic orders has been shown to be too simplistic and lead to incorrect deductions from inverter laboratory measurements and unnecessarily conservative assessments of pre-connection compliance. Alternative models need to be robust, accurate and implementable. Available modelling approaches include time domain modelling [1, 150] and more complex frequency domain models, such as frequency dependent Norton impedances [151, 152] although difficulties have been identified with both approaches. Time-domain modelling is the most complex and therefore computationally intensive approach to harmonic modelling [12, 23, 50, 105]. Time constraints and complexity of development reduce the practicality of this approach and increase the time required to undertake the assessment. Issues have also been identified in [30] with relation to the accuracy of

EMT models for harmonic emissions studies. Frequency domain modelling reduces the complexity of modelling by representing harmonic sources as simple linear components such as Norton equivalents [108]. However, the validity of this simplification has been shown to be affected by a range of impacts as previously discussed. Non-representative simplified models are also capable of resulting in improper harmonic filter design.

6.2.2.2.1 Correlation of Emissions and Operational Conditions

A brief preliminary study has been undertaken on the data that was analysed in Section 4 to determine if the operational state of generators provide any indication to the expected emissions for each harmonic order, this is a commonly discussed topic when considering harmonic emissions of large REG plants and the development of harmonic models of IBR devices. The importance of the topic is related to the identification of worst-case expected harmonic emissions. It is common practice to assume that generators are operating in identical conditions resulting in harmonic emissions with no diversity. If correlation of harmonic emissions with fundamental power flow, or any other parameter exist, it may simplify the emissions analysis procedure as specific periods in which operational conditions of interest do not exist may be removed from consideration.

To analyse the correlation of harmonic orders with multiple characteristics (i.e. active/reactive power and fundamental voltage level), the correlation coefficient of each operational parameter with all harmonic orders was calculated. For example, the correlation coefficient of the total active power and fundamental current, as shown in Figure 6-3 is 0.92. Intuitively, the coefficient would be expected to be close to 1 for a well-balanced system.

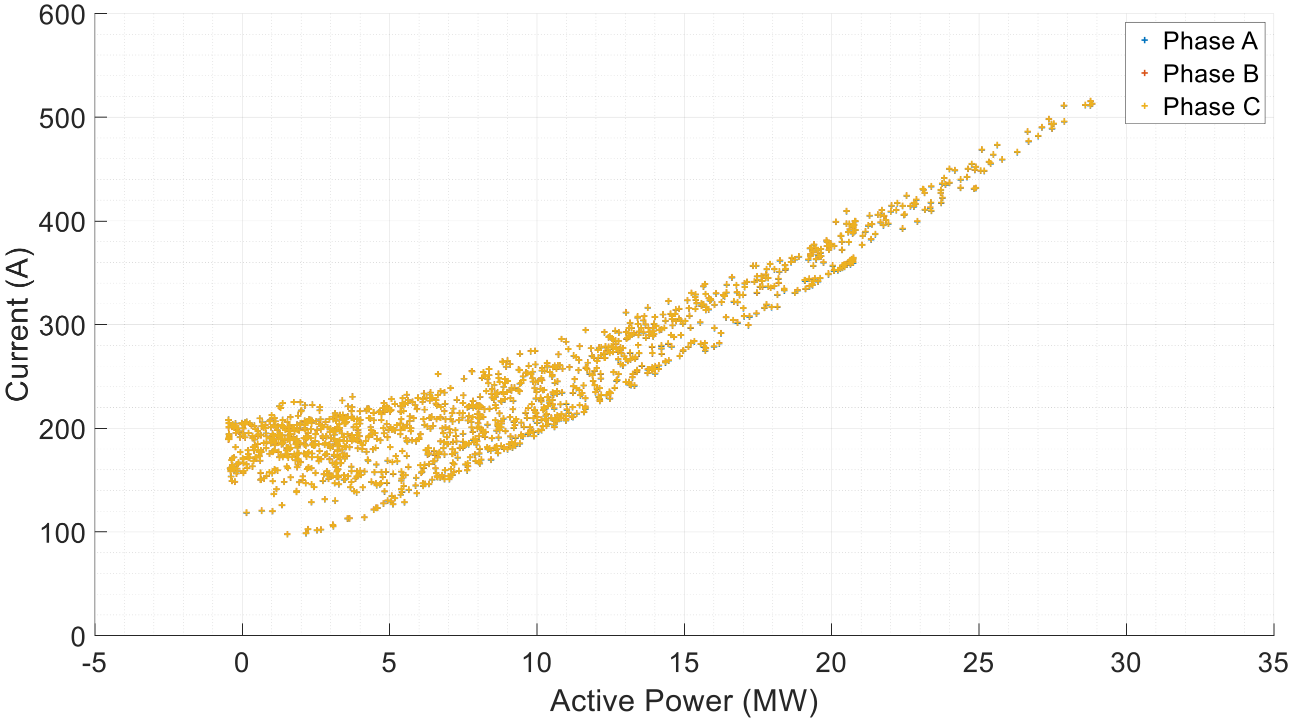


Figure 6-3 – Scatter graph of fundamental current and active power

Alternatively, the correlation coefficient of active power and the 5th order harmonic emission levels was calculated to be 0.07, suggesting no signs of correlation between 5th order harmonic emissions with the active power of the generators, as shown in Figure 6-4.

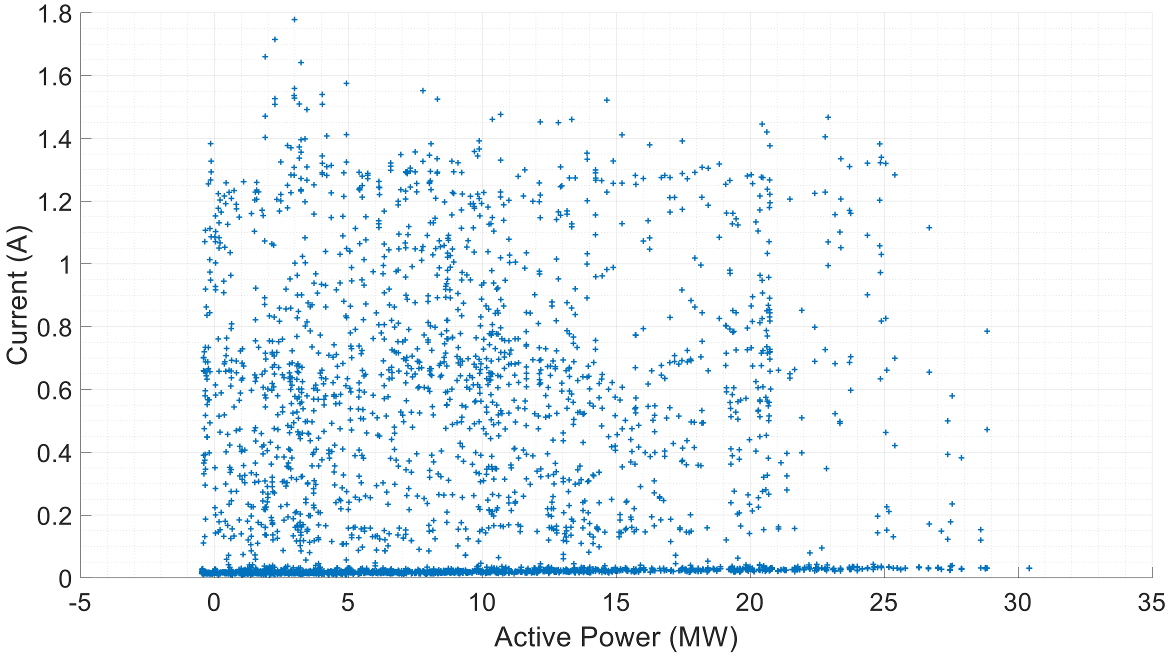


Figure 6-4 – Scatter graph of 5th harmonic current and active power

The correlation coefficients were calculated for all harmonic orders with measurements above the minimum threshold of the collector group (i.e. $0.15\ A$) when considering harmonic emissions against active power, reactive power and the fundamental voltage. The results are provided in Table 6.1. The analysis performed used the following metrics to qualify the level of correlation, based on [153]:

Strong: $|\boldsymbol{r}| \geq \mathbf{0.7}$, indicating approx. 50% or more value pairs are correlated

Moderate: $\mathbf{0.5} \leq |\boldsymbol{r}| < \mathbf{0.7}$, indicating approx. 25-50% of value pairs are correlated.

Weak: $\mathbf{0.25} \leq |\boldsymbol{r}| < \mathbf{0.5}$, indicating approx. 5-25% of value pairs are correlated.

Minimal/no correlation: $|\boldsymbol{r}| < \mathbf{0.25}$, indicating little or no correlation exists between values.

Table 6.1 - Correlation values of harmonic emissions and fundamental components

	r_i			
h	**P**	Q	V	I
1	0.92	0.24	0.00	1.00
2	0.04	-0.32	-0.02	0.13
3	-0.19	-0.53	-0.15	-0.03
5	0.01	0.15	0.06	-0.03
7	0.11	0.18	0.1	-0.02
11	-0.05	0.18	-0.09	-0.10
13	0.37	-0.02	-0.04	0.40
15	0.20	-0.04	-0.05	0.35

The values in Table 6.1 show a range of correlation values for harmonic orders with measurements above the minimum threshold. As can be seen, there exists very little correlation between fundamental components and harmonic emissions, i.e. for $h > 1$. The outcome of this study indicates that it is not appropriate to assume maximum emissions occur, for example, when $P = P_{max}$, and that specific operating states or operational conditions of the network such as fundamental voltage magnitude can be used to estimate worst-case operating scenarios. This is exemplified in Figure 6-4 where it is observed that maximum harmonic emissions of the 5th order are capable of occurring when the active power output of the feeder ranges from 0 – 30 MW. Such a result leads to all measurement periods being equally important.

6.2.2.3 APPLICATION OF AS/NZS 61000.3.6 STAGE 3

If pre-connection assessment fails, under the auspices of AS/NZS 61000.3.6, a call for mitigation of emissions is only one of the options available to the NSP. Another option is to allow acceptance of a connection under the provisions of AS/NZS 61000.3.6 Stage 3. These provisions allow the installation to be connected in the short term to assess the actual operating performance and/or allow a longer time period to finalise mitigation measures. The specific wording from AS/NZS 61000.3.6 is as follows:

> *"Under special circumstances, a consumer may require acceptance to emit disturbances beyond the basic limits allowed in stage 2. In such a situation, the consumer and the utility may agree on special conditions which facilitate connection of the distorting load. A careful study of the actual and future system characteristics has to be carried out in order to determine these special conditions."*

While Stage 3 connection is provided as an option in AS/NZS 61000.3.6, there is no guidance as to how it should be applied nor for how long. In addition, present regulation and the processes used to draft connection agreements make use of the Stage 3 connection concept difficult to implement. As such, Stage 3 connections are rarely implemented.

6.2.3 Post-Connection Compliance Assessment

Assessment of post-connection compliance with allocated emission levels undertaken through field measurements is another area where there is no clear consensus with regard to the methodology for measurement-based compliance assessment despite there being much research over at least a decade [133, 154-157]. Part of the problem has been incorrect or poor understanding of the concept of harmonic emission (or the meaning of harmonic voltage emission). The following questions have been developed and considered as key uncertainties in relation to post-connection compliance assessment requiring further investigation:

- What is the customer's responsibility? Should it be defined in terms of voltage, current or some other concept? Is the concept of "customer's share" rigorous and is it unambiguously measurable?
- Plant operating conditions - renewable energy plant operation depends on uncontrollable and sometimes unforeseeable atmospheric conditions. What are the allowable conditions for reasonable compliance measurement?
- Power system operating conditions - should checks be made as to the operational scenario(s) during the test period? Are all scenarios equally useful for assessing customer compliance?
- Measurement quantities - large plants generally contain transformers giving a range of internal voltage levels and possibly shunt filters and capacitors. Should voltage and current measurements be taken only at the point of connection or at other voltage levels as well?
- Measurement duration - can compliance be assessed over a day or is a longer period required? When seasonal effects are important in renewable generation, how should these be allowed for?
- Signal processing - can assessment be based on raw data or some processed quantity? Are there tests that need to be implemented for the suitability of data for compliance determination?
- What are the ongoing installation requirements with respect to discharging compliance obligations? For example, is ongoing assessment required or is periodic assessment appropriate?

More definitive processes are a necessity that result in fair, technically robust post-connection compliance solutions and are the focus of future work activities.

6.2.3.1 ASSESSMENT OF MONITORED DATA

Both AS/NZS 61000-3-6 and ENA Doc 033 [102] provide guidelines for the assessment of plant emission levels for determination of compliance with allocated emission levels. It is important to note that the methodologies described in both documents are informative as opposed to normative.

In the case of AS/NZS 61000-3-6:2001 (the version referred to in the NER), the document states that "At each (inter) harmonic frequency, the emission level from a distorting load is the (inter) harmonic voltage (or current) which would be caused by the load into the power system if no other distorting load was present". Most importantly the phrase "if no other distorting load was present" must be carefully considered. In practice it is almost impossible to undertake measurements with no other distorting load present. Taking this statement to its logical conclusions it is effectively stating that measurements are only valid if any voltage waveform distortion is only due to the interaction of the load being assessed and the network impedance (i.e. no background distortion is present). The document acknowledges this limitation as follows:

> *"In practice, these levels are generally assessed from the available data concerning the load and the system; their direct measurement is made difficult by the presence of numerous other distorting loads"*

ENA Doc 033 provides more detailed methodologies for assessment of plant emissions as well as criteria under which measurement values above the allocation may be accepted by the network service provider under special dispensation. However, the methodologies and guidelines are not robustly prescriptive and much of the application of concepts remains at the discretion of the NSP.

6.2.3.2 INSTRUMENT AND TRANSDUCER ACCURACY

It is reasonably well known that transducers used for measurement of harmonic frequencies have limitations with respect to their frequency response [158, 159]. This is particularly the case for voltage transformers (VTs). The frequency response of the transducers used for measurement of harmonics may have significant implications for compliance assessment. In the case of VTs, the maximum harmonic order that can be measured accurately decreases as the nominal voltage rating increases. At present these limitations of measurement systems are generally not considered when assessments of compliance are undertaken. Figure 6-5 and Figure 6-6 provide examples of the limitations of voltage transducers for harmonic measurement. In the case of Figure 6-5, it can be seen that only approximately 50% of voltage transducers would be suitable for measurement of 50th harmonic at voltages below 33 kV. This figure drops to less than 20% for voltages up to 100 kV and 0% once the nominal voltage reaches 400 kV. Figure 6-6 shows the measured frequency response (expressed as the correction factor required to 'scale' the VT response back to 1) for a 26 kV VT. Here it can be seen that this VT is likely only suitable for measurement of harmonics up to approximately the 20th order. Two resonances are observed at approximately the 31st and 62nd orders. Measurements close to these resonances will be amplified or attenuate to very large degrees.

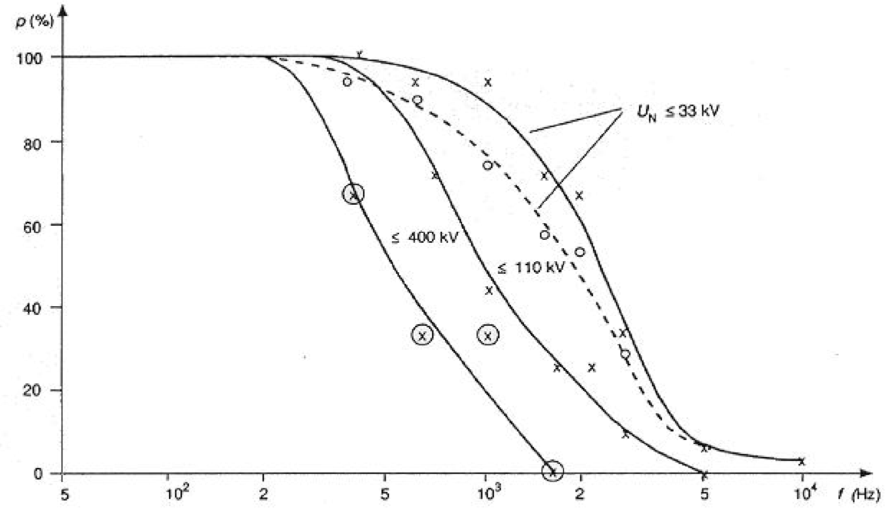


Figure 2 – Percentage p of inductive voltage transformers, the transfer ratio of which has a maximum deviation (from the normal value) of less than 5% or 5° up to the frequency f

Number of measured VT's: 41
――――― maximum error 5%
-------- maximum error 5°

Figure 6-5 - Number of Voltage Transducers Complying with IEC 61000-4-7:2002 Accuracy Requirements [160]

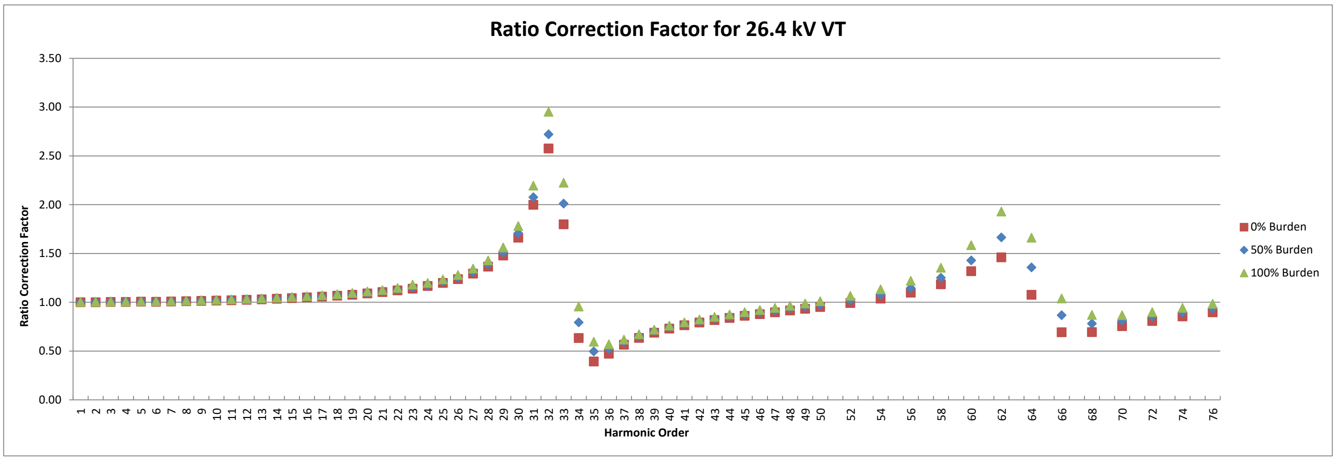


Figure 6-6 - Ratio Correction Factors for 26.4 kV VT Measured at the University of Wollongong

6.3 SUMMARY

This section has provided an overview of the challenges related to compliance assessment of the harmonic emissions of large loads and generators. These challenges have been identified through project activities and interaction with stakeholders. It is clear that a significant range of challenges exist in this subject matter area and that challenges exist at both the pre-connection and post-connection stages. Improper techniques for assessment of compliance can have significant implications for renewable energy connections including:

- Underestimation of emissions at the planning stage may lead to higher-than-expected distortion levels on plant commissioning. This in turn may lead to the requirement for design and retrofit of mitigation and curtailment or outages while this is being implemented.
- Overestimation of emissions at the planning stage may lead to the requirement for costly mitigation, which ultimately may not be required.
- Modelling of inverter-based resources (IBR) has been shown to be very inaccurate. Evidence from project partners identifies cases in which pre-connection compliance assessment leads to mitigation

being required however post-connection measurements and analysis leads to filtering not being necessary for the plant to meet its allocated emission limit.

- The external network also impacts the appropriate representation of the IBRs in the frequency domain. Operational conditions, background levels of harmonic voltage distortion and other parameters have all been identified to change the emission spectrum of IBRs, however, no conclusive work exists with respect to identifying the scale of the impact and how best to address this in pre-connection compliance assessment studies. Much more work in this area is required to appropriately identify necessary processes to improve accuracy of IBRs frequency domain modelling.
- With respect to measurements, the measurement methodology and accuracy of instrumentation and transducers can have significant impacts on outcomes. Network operating conditions and the presence of other distorting loads are other factors, which can influence the outcomes of assessment.

Australian standards and regulation presently lack a prescriptive and technically robust methodology for compliance assessment that can be applied consistently across all jurisdictions. In the absence of this methodology, NSPs have been applying bespoke procedures, which lack peer review and are not consistent across jurisdictions. It is recommended that work be undertaken to develop a prescriptive and technically robust set of procedures for assessment of compliance of harmonic emissions. The outcomes of this work should include:

- A prescriptive and consistent method for specifying network impedance.
- A prescriptive and consistent method for development of the harmonic emission spectra of plant. This should include concise guidance with respect to the network conditions that should be considered when determining the emission spectra of devices experimentally.
- Guidance with respect to application of AS/NZS 61000.3.6 Stage 3 connections and quantification of the impact of allowing non-complying connections, based on the level of margin(s) above compliance and the available headroom between existing harmonic levels on networks and established limits.
- A prescriptive methodology for field monitoring that can be used to determine if an installation is complying with the emission limits allocated at the planning stage. This should include a robust methodology for determination of the ‘customer contribution’.
- Acknowledgement that the accuracy of transducers can have significant implications with respect to the accuracy of harmonic measurements and this should be taken into account when undertaking compliance assessment procedures. Further, detailed prescriptive information related to the actual effectiveness of transducers when used for harmonic measurement (e.g. the highest practical order that could be measured and assessed at any particular nominal voltage level) should be provided.
- An investigation into harmonic voltage planning limits needs to be undertaken to ensure they are not too restrictive and correlation with network and equipment immunity needs to be established.

7 Conclusion and Recommendations

Present-day power systems are expecting to continue to connect large-scale renewable energy generators (REGs) that are known sources of harmonic distortion. If not adequately managed, harmonic distortion can result in deleterious effects on power system components and customer installations. The impacts of harmonic distortion are wide-ranging and include increased losses within the system and unwanted interaction with power electronic controller components. Given the implications of harmonic distortion, a pragmatic approach to managing power system harmonic distortion levels is a necessary practice.

With respect to REG, a range of connection technology types exist, each with unique topologies and controller strategies. The literature suggests that it is common for solar PV and Type III and IV WTGs to be sources of emission of non-characteristic and interharmonic orders. Further, the impacts of a range of factors on harmonic emission levels lead to generalised harmonic models which are unable to be verified through field measurements. In addition, equipment such as long cables, transformers and/or passive harmonic filters, commonly forming part of REG plants, are capable of interacting with existing harmonic sources within the network by introducing and shifting harmonic resonances.

7.1 HARMONIC DISTORTION

A review of harmonic distortion levels in Australian and international power systems was undertaken using long-term power quality monitoring data in order to evaluate the impact of ongoing connection of REG on the magnitude of network harmonic distortion. This review identified that experiences varied widely across NSPs and network operators internationally. For a considerable number of NSPs harmonic levels were found to be increasing with REG connections whilst others have detected a reduction in overall distortion. Reports of increased emissions were generally attributed to a combination of increased emissions along with the impacts of passive components of large REG plants interacting with existing harmonic sources. Instances of decreased distortion levels may be attributed to one or more of the following:

- Improved harmonic management processes
- Increased investment in transmission infrastructure
- Improved power electronic design and control
- Installation of mitigation

Other possible mechanisms for reduced network harmonic distortion levels include instances of phase cancellation or installations operating as a harmonic sink for particular harmonic orders. Of most importance is the finding that REG technologies are capable of significantly impacting harmonic emission levels which provides evidence that pragmatic approaches to ensuring appropriate harmonic levels are maintained in an efficient manner is prudent.

7.1.1 Recommendation

Based on the findings of this project, it is proposed that distortion levels be more closely monitored throughout the Australian power system, particularly in networks with high penetration of REG and in which resonance may be a factor of concern. Having the ability to track and monitor the trend of distortion levels allows NSPs and stakeholders to take a pro-active approach to the mitigation and management of harmonic distortion. Further, improved visibility of network-wide distortion allows for further investigations to be undertaken to assess and benchmark existing practices with respect to pre-connection compliance assessment and emission limit allocation.

7.2 HARMONIC EMISSION LIMIT ALLOCATION

Studies presented in this report identified that approaches to harmonic allocation and management vary significantly between countries and network operators. A significant number of network and country standards/regulations were reviewed in relation to technical performance and power quality. This qualitative review identified the similarities and differences between the most commonly implemented allocation methodologies. The key objective of the allocation process is to maintain harmonic voltage distortion below predefined levels. However, the review also showed that an overly conservative use of the network absorption capacity increases the likelihood of expensive mitigation being required. This mitigation, which is typically implemented as a passive harmonic filter, also potentially varies the harmonic resonance of the system which can have wider impacts.

The harmonic allocation methods reviewed were categorised based on the fundamental principles used to calculate emission limits for connecting customers. All reviewed methods can be grouped into two broad categories; fixed harmonic allocation methodologies and network forecast methodologies. Fixed allocation methodologies were found to implement assumptions that were generally too restrictive to be broadly applied across a broad range of network types. Whereas network forecast methods were found in many cases to result in conservative allocation limits due to the influence of future uncertainties. Whilst some updates have been proposed or implemented by NSPs internationally, such processes are shown to remain insufficient for uncertainties related to REG penetration levels, concentration and future system harmonic impedance.

A numerical comparison of some of the qualitatively reviewed harmonic allocation processes was undertaken, notably the IEEE and IEC methods (including derivations of the IEC method based on the scenario in which it is being applied). This comparison exemplifies the extent to which the IEC method is capable of being significantly impacted by future uncertainties such as REG penetration, concentration and system loading. Further, suggested variations to the IEC methodology to facilitate the integration of REG have been shown to be theoretically sound but the full implications are yet to be well understood due to the present lack of industry experience.

The IEEE method was also evaluated using to a simple system. The results of the study highlight the simplicity of the method but also its conservativeness. The example in which the IEEE method was applied to a long feeder resulted in the IEEE method only allocating 41% of the value allocated using the IEC method. Written caveats in the IEEE method also suggest generating installations are to receive the lowest allowable allocation limit, regardless of any other factors such as network strength. If this methodology is applied, the IEEE method allocates only 9% of the IEC method when considering an REG example. Based on the outcomes of the studies undertaken within this report, fixed allocation methodologies such as the IEEE method of allocation are generally not suitable for Australian networks particularly in the case of networks with long feeders.

7.2.1 Recommendation

The review of the various emission limit allocation processes identified use of the IEC method as the most appropriate for Australian networks, although substantial revisions and considerations may be necessary to account for the impacts of REG. A number of revised processes were developed and considered throughout this project, it is suggested that these be further developed and considered for application in appropriate scenarios. These revisions were compiled to address the impacts of REG on the management of harmonic distortion. Further socialisation and pilot application of these revisions would be necessary to determine level of efficacy, sensitivity and appropriate (and inappropriate) network conditions in which to apply the processes.

Harmonic emission limit allocation is a complex process. Application of any methodology requires a comprehensive understanding of the potential implications when applied to various network types and scenarios. Continuing dissemination and education of the impacts identified in this project should be prioritised to ensure industry professionals are aware of the impacts and challenges and how they may be mitigated.

7.3 HARMONIC MODELLING AND EMISSION DIVERSITY

The harmonic modelling of power electronic devices has evolved over time although the impacts of internal and external factors are yet to be adequately captured in frequency domain modelling practices. Further, the continued propagation of REG and non-linear devices has increased the complexity of determining a statistical representation of harmonic sources and subsequent interactions that accurately reproduce impacts witnessed on the network.

Standards for the management of harmonic emissions have mechanisms to allow for diversity in emissions. These diversity factors have traditionally always been applied to loads. However, present practice for REG connections has been to ignore diversity in emissions based on the fact that the harmonic sources within the plant are generally from identical plant (e.g. a solar farm may have multiple instance of the same inverter). Ignoring diversity in emissions represents a worst-case scenario for magnitudes. A case study of harmonic data from a REG plant has been analysed to investigate whether diversity exists between emissions form identical plant. The results of the case study indicate that significant diversity exists in the harmonic emissions from identical sources (i.e. inverters), at many harmonic orders, and for considerable intervals of the measurement period. Periods where arithmetic summation could reasonably be applied only occurred for short intervals and for a small number of harmonic orders.

7.3.1 Recommendation

The case study presented within this project identified substantial levels of diversity exist between identical inverters across the harmonic orders examined. This case study only examined a restricted part of a single REG. As such, it is recommended that further work be undertaken to appropriately identify aggregation of harmonic sources both within plants, and across the wider network. Understanding the diversity between harmonic sources has a significant implication on harmonic emission allocations and pre-connection compliance assessment outcomes. The present approach of applying no consideration to diversity in harmonics emission during planning studies may be overly conservative and lead to significant mitigation requirements in design, but perhaps not in practice.

7.4 HARMONIC MANAGEMENT AND MITIGATION

Simulation studies have been undertaken to exemplify the difficulties of harmonic management processes using both simplified and detailed network studies. These studies implemented a more complete analysis of the IEC allocation methodology and found that:

- The present allocation methodology of AS/NZS 61000.3.6 remains valid for very restricted scenarios only. Impacts due to long-line effects and uncertainty in load and REG connections were found to have significant effects on the capability of the methodology to efficiently and effectively manage harmonic emissions.
- Existing responsibilities related to the mitigation of harmonic currents lead to substantial inefficiencies and are capable of increasing the complexity of the harmonic management process in general.

The study examined multiple models with the same outcome; harmonic mitigation in networks with long lines and resonances is most efficient when connected at the point of the network which experiences the highest harmonic voltage as opposed to at the connection point of any individual plant. While existing practice requires REG proponents to install harmonic filtering locally to ensure current emissions do not exceed allocated emission limits the study found that the proposed revised approach was able to substantially decrease the required rating of the filtering (a simple example suggesting it may reduce required rating by 98 %), thereby decreasing costs.

7.4.1 Recommendations

The studies undertaken to investigate appropriate mitigation techniques in systems with long-line effects and resonance identified the efficiencies that may be gained with network-led approaches. Further work is recommended in order to investigate the efficiency and efficacy of this revised approach to harmonic mitigation for Australian networks with long lines and high penetration of REG. It is proposed that such an approach to mitigation would be well-suited in scenarios such as REZs. Impacts of future connections and regulatory requirements are examples of challenges to be overcome and require broader industry feedback to appropriately account for in the application of a revised mitigation practice.

7.5 COMPLIANCE ASSESSMENT

Australian standards and regulation presently lack a prescriptive and technically robust methodology for assessing for pre- and post-connection compliance for both loads and REG that can be applied consistently across all jurisdictions. In the absence of prescriptive methodologies, NSPs have been adopting bespoke approaches to compliance assessment that may vary considerably across jurisdictions. This project has undertaken a preliminary review in order to identify the most significant challenges to robust compliance assessment.

7.5.1 Recommendation

Based on the review undertaken for this project, it is recommended that future work be undertaken to provide consistent, prescriptive and technically robust techniques for compliance assessment. The aims of any future work should be to provide:

- Consistent methods for specifying network impedance and development of plant harmonic emission spectra - including guidance on network conditions that should be considered.
- Guidance with respect to the application of AS/NZS 61000.3.6 Stage 3 connections and quantification of the impact of allowing non-complying connections, based on the level of margin above compliance and the available headroom of existing harmonic levels.
- A prescriptive methodology for field monitoring that can be used to determine if an installation is complying with the emission limits allocated at the planning stage. This should include a robust methodology for determination of the 'customer contribution'.
- Acknowledgement that transducers can have significant implications on the accuracy of harmonic measurements and should be taken into account when undertaking compliance assessment procedures. Prescriptive information related to accuracy of transducers to be determined, e.g. the highest practical order at each nominal voltage level.

7.6 AN INVESTIGATION INTO PLANNING LEVELS NEEDS TO BE UNDERTAKEN TO ENSURE THEY ARE NOT TOO RESTRICTIVE AND CORRELATION WITH NETWORK AND EQUIPMENT IMMUNITY NEEDS TO BE ESTABLISHED.KEY OUTCOMES

The key outcomes of this project identify that a number of the existing practices for the management of harmonic distortion within electricity supply networks, particularly with respect to increasing proliferation of large REG are leading to inefficient harmonic emission limit allocation, potentially increasing investment requirements from proponents and making the management of power system distortion in general more complex than is necessary. The following is a summary of the key outcomes of this project:

- With respect to the impact of increasing penetration of REG on harmonic distortion in electricity networks and review of Australian and international literature on this subject indicates that **the impact is highly varied** with harmonic distortion in some networks increasing as the number of REG plants increase while in other network distortion levels appear to be decreasing as the number of REG plants increases.

- An assessment of a range of the most common methodologies for determining an emissions allocation for harmonic distortion has shown that while subject to a range of limitations that require addressing, **the IEC methodology** appears to remain the most valid approach for Australian networks, although challenges have been investigated with its application in networks with long feeders and high levels of REG penetration and uncertainty.

- A case study has indicated that **diversity exists for all harmonic orders between the harmonic emissions from identical inverters** within a wind farm. This challenges the conservative approach of arithmetically summating emissions which is presently applied with important consequences for pre-connection compliance assessment.

- Outcomes of modelling undertaken to investigate the impact of increasing REG penetration into a proposed renewable energy zone **challenges the efficiency and efficacy of the present methods of assessing impact and implementing mitigation**. These preliminary studies indicate that an **approach which is network focussed as opposed to plant focussed** will be better able to detect areas where harmonic distortion levels are problematic and also provide more efficient and targeted mitigation.

- A preliminary assessment of the challenges related to pre- and post-connection compliance assessment has identified that significant work is required to **develop prescriptive and technically robust methodologies for network and plant modelling as well as assessment of compliance through the use of field measurements.**

7.7 PROPOSED NEXT STEPS

While this project has provided some clarity with respect to a number of the questions related to management of electrical power system harmonic in the presence of increasing levels of REG, it has also identified that many challenges remain. As a response to these challenges, the following two activities provide a summary of the proposed next steps to maintain the momentum of this project with a view to achieving robust technical solutions to the remaining issues:

1. Continued research into aspects which have investigated by this project but still lack comprehensive evidence and broad industry acceptance. These aspects include:
    a. Review of both national and international literature reveals that the impact of increasing REG on overall network harmonic distortion levels remains unclear. An ongoing watch will be placed on this topic, including both literature review as well as proactive collection and analysis of data, in order to determine if trends emerge.
    b. Applicability of the summation law to emissions from multiple plant of the exact same type. The case study detailed in this report demonstrated that consideration should be given to inclusion of factors to account for diversity in emissions, however, further case studies are required before this can be stated unequivocally.
    c. Studies in this project have identified that a network based approach to mitigation of harmonic emissions may be significantly more efficient (from a technical and economic perspective) than requiring mitigation at the plant level. Many further studies are required before this method can be considered as a viable alternative. Work to be done concerning this subject includes assessment of both technical and regulatory factors.
2. It is clear that there are significant challenges in relation to assessment of compliance at both the pre- and post-connection phases for REG and that these challenges are providing significant barriers to ongoing REG connections. A project will be developed which will focus on compliance assessment.

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