MANAGEMENT OF HARMONIC DISTORTION FOR LARGE RENEWABLE ENERGY GENERATION

Project Summary

APQRC
AUSTRALIAN POWER QUALITY AND RELIABILITY CENTRE

UNIVERSITY
OF WOLLONGONG
AUSTRALIA

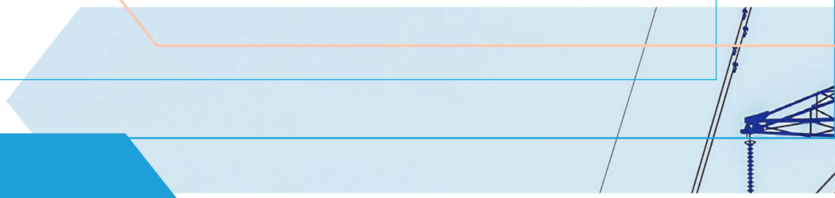
This project received funding from the Australian Renewable Energy Agency (ARENA) as part of ARENA's Advancing Renewables Program.

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



Introduction

The Australian electricity supply industry is experiencing an unprecedented paradigm shift. Traditional large centralised (often fossil fuel) generation is being replaced by renewable energy sources both small and large.

Transmission and distribution network operators are receiving numerous connection requests for renewable energy generators (REGs) ranging in size from a few megawatts to many hundreds of megawatts. Connection of these generators represents a significant change to the operation of transmission and sub-transmission networks due to: (a) there being a large number of them and hence there are many more connections; and (b) their interface to the network is predominately power electronics which may emit and/or be susceptible to power quality disturbances, especially harmonic distortion. The unprecedented increase in customer connections and power electronic interfaced devices has led to management of power quality, especially harmonic distortion, becoming of increasing importance to electricity network service providers.

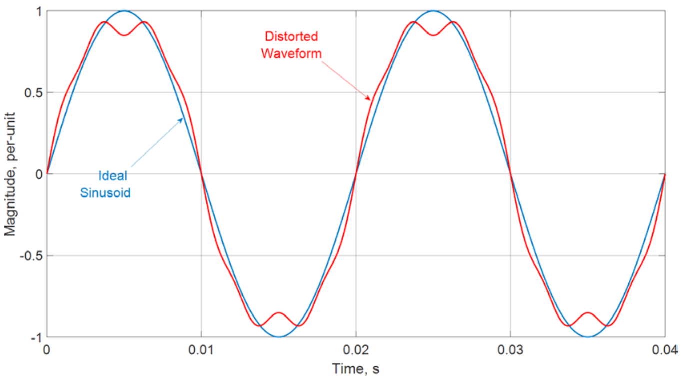
With support from ARENA, along with a number of network operators, renewable energy proponents and renewable energy technology vendors, the University of Wollongong has been investigating how to manage harmonic distortion in electricity supply networks with a particular emphasis on integration of large scale REGs. This project, which began in 2019 and concluded in early 2022, implemented a thorough investigation of the management processes used for harmonic distortion and the potential impacts of high penetration of power electronics interfaced REGs on electricity network harmonic distortion levels. The primary objective of the project was to compare the efficiency, efficacy and technical robustness of the harmonic allocation management strategies that are currently used with alternatives that may be simpler to apply and are potentially more technically robust. The project also sought to:

- Identify suitable aggregation methods for summation of harmonic current emissions from large-scale wind and/or solar farms in order to determine if application of diversity amongst identical devices is appropriate or whether direct arithmetic summation is more suitable.
- Provide preliminary assessment of the challenges related to assessing compliance of large-scale solar and wind farms with allocated harmonic emission levels.

This project summary presents the high level outcomes of the project and is designed to be explain the concepts and outcomes to a broad and not necessarily technical audience. More detailed technical information concerning the outcomes of the project can be found on the ARENA website.

What is Harmonic Distortion?

In electric power systems, harmonic distortion is defined as a periodic (repeating) change in the waveform shape from the ideal sinusoidal current or voltage. A primary source of voltage harmonic distortion is the interaction between devices which draw distorted current and the harmonic impedance of the network. Harmonic distortion introduces emissions that have frequency components that are multiples of the nominal supply frequency (50 Hz in Australia). Harmonic distortion is inherent in all electrical power systems and can be present in measurements of both voltage and current. An example of harmonic distortion is shown in the figure below.



Ideal sinusoid and distorted waveforms

One significant source of harmonic distortion within power systems is the operation of devices that use continuous switching of electronic components at frequencies well above the power system supply frequency to control their function. Examples of such devices include photovoltaic solar and wind turbine generator inverters, battery inverters, along with many other common device types found both in industry and households). High frequency switching leads to more efficient operation for the device but will introduce harmonic distortion into the power system.

Harmonic distortion reduces the efficiency of the power system by increasing losses, it can also decrease the longevity of some consumer products, interfere with control systems and in some cases has detrimental impacts on power system components, including reduced lifespan or failure. Harmonic distortion must therefore be appropriately managed within power systems to ensure that levels do not exceed limits above which equipment may not operate as intended or be damaged.

Management of Harmonic Distortion

The National Electricity Rules require that network operators limit the level of harmonic distortion in the power system by allocating allowed levels of emission to individual (large) customers. There is considerable evidence that the process of harmonic emission limit allocation commonly implemented in Australia often results in sub optimal outcomes for both network operators and network users.

The deficiencies of the present process have been found to be exacerbated by the prevalence of REGs. In many cases, present processes are leading to wide scale requirements for harmonic mitigation to be installed. The installation of this mitigation significantly increases costs to the REG proponent (and ultimately the electricity end-user) and may have significant impacts on the harmonic contribution from other nearby installations.

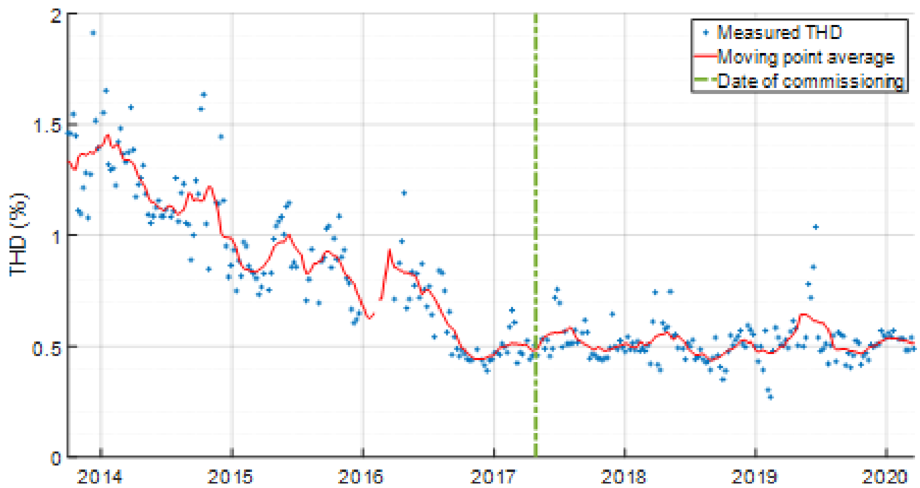
Global Harmonic Distortion Trends

Renewable energy generators interfaced to the electricity network through inverters are a known source of harmonic distortion and there is significant conjecture with respect to the implications of these additional harmonic sources. An initial project task involved reviewing historical harmonic distortion trends in power systems, nationally and internationally, with varying levels of REG penetration. This study provided an indication of the magnitude of impact that the connection of REG has had on power system distortion over long periods of time.

Data was obtained and analysed for five REG connections within Australia. The study also reviewed data publicly available for generator connections within the Netherlands which found in most cases, harmonic distortion reduced after the connection of large wind farms. An example of this is shown in the figure on page 7. for a substation in the Netherlands. Measurement data was analysed for approximately three years prior to the connection of a 600 MW offshore windfarm. As can be seen, harmonic distortion gradually decreases until the date of commissioning of the wind farm. Whilst the specifics of the site were not publicly available, correlation of the data with the windfarm project timeline suggests one or more factors are likely to be the cause, these include transmission network infrastructure upgrades, installation of harmonic mitigation (e.g. passive filtering), behaviour of harmonic distortion contributions from other sources, and/or other interactions such as phase cancellation with other harmonic sources.

Similar outcomes have been reported within Australia with harmonic distortion levels generally declining in recent years regardless of significantly more potential harmonic sources being connected to the network. This is important as the harmonic management and mitigation policies in use within Australia are designed so that harmonic distortion reaches an acceptable level once all expected customers are connected. The reduction of distortion levels suggest that the allocation process may be too stringent on connections leading to unnecessary investment being required for mitigation as well as underutilisation of the capacity of the network. Another possible impacting factor may be that modelling and design practices are perhaps inaccurate or not fit for purpose.

The literature review also found impacts of REG on harmonic distortion levels to be a primary concern of many European system operators. The concern however is less related to the injection of harmonic emissions but rather the impact of the connecting components (e.g. electrical cables, transformers, passive capacitor banks) that change the impedance of the network. This impact inherently alters underlying distortion levels throughout the network and is capable of introducing phenomena such as remote resonance, leading to significant amplification of distortion levels.



Average votage total harmonic distortion (THD) at
Eemshaven, Netherlands substation from 2014 through to 2020

Harmonic Allocation within Australia & Internationally

Network service providers in Australia and internationally generally follow a process in which connecting customers are allocated a maximum allowable harmonic emission limit, commonly termed a harmonic allocation. There are various processes used to calculate this emission limit. This project reviewed a number of allocation processes with the outcomes discussed below.

QUALITATIVE COMPARISON OF HARMONIC ALLOCATION PROCEDURES

There are currently many distinct harmonic allocation methodologies in use internationally. Analysis of reviewed methodologies found that they could be grouped into two specific categories which have been termed fixed and network forecast allocation methodologies. Without providing detailed information on the specifics of each methodology, some general advantages/disadvantages have been provided in the table below.

The most commonly implemented allocation methodology within Australia would be classed as a network forecast allocation method. Analysis of this allocation methodology identified many deficiencies with the process capable of significantly impacting the capability of NSPs to adequately manage harmonic levels, particularly in networks with long lines and a high penetration of REG.

It is important to note that there were no allocation methodologies which could be identified that adequately accounted for the identified impacts of REG. A number of proposed updates and changes to existing methodologies to address the impact of REG were observed, however, issues with the updates as they relate to uncertainty and conservativeness resulting in substantial limitations being applied to connections, were identified in all cases.

METHOD	ADVANTAGES	DISADVANTAGES
FIXED ALLOCATION	Simple to apply	Distortion limits may be exceeded
	Minimal input data required	Underlying assumptions not suitable for all network types
	Customer equity	REG not appropriately accounted for
NETWORK FORECAST ALLOCATION	Customer equity	Complex process
	Assumptions relevant to network under study	Various methods defined – scenario dependent
	Limited input data required	Requires forecast of final state of the network (assumptions)
	Network reaches distortion limit when at capacity*	Potentially increased likelihood of mitigation being required
		REG not appropriately accounted for

Advantages/disadvantages of fixed and network forcast based harmonic emission allocation methodologies

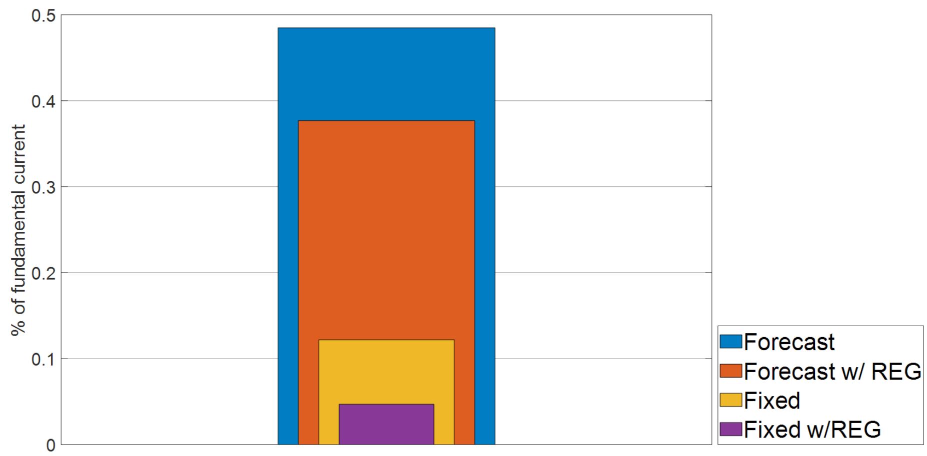
*In the event that all connected customers are meeting their allocated emission limit. The design of the process aims to maximise the use of the network capacity to absorb harmonic emissions. This may not always lead to distortion limits being maintained in practical applications.

QUANTITATIVE HARMONIC EMISSION LIMIT ALLOCATION COMPARISON

In order to visualise the impacts that adoption of different harmonic allocation methodologies have on the eventual emission limit a simple example is presented for a single customer. The figure below shows the allocated emission limits for a generic connection based on the two most common fixed and network forecast allocation methodologies. The figure suggests the existing network forecast methodology applied within Australia, without the consideration of REG allocates the largest emission limit to the example connection. The emission limit is reduced by approximately 17% when using the same methodology with assumptions included to account for REG. The most commonly applied fixed allocation method results in a significantly reduced allocation for the same connection, allocating between 9% and 26% of the network forecast allocation method. It can be shown that this is due to assumptions that are predefined within the fixed allocation methodology, suggesting that the method as it is currently defined is not suitable for all network types and scenarios and implements conservative assumptions in favour of requiring more detailed data.

The above findings are important as conservative allocations are more likely to lead to a requirement for harmonic mitigation to be installed which in turn significantly increases investment costs for REG proponents. The requirement for harmonic mitigation for REG is very common within Australia with many plants requiring some level of mitigation, even though harmonic distortion levels have been in decline in recent years, as discussed above.

The high level outcome is that existing harmonic emission allocation practices may be too conservative. This is further exacerbated with proposed updates to existing methods increasing conservative assumptions due to increased uncertainty. Ongoing assessments of existing and proposed methodologies and harmonic distortion trends is necessary to ascertain the efficacy of the management practices and ensure customers are not unduly restricted and that distortion levels are appropriately maintained.

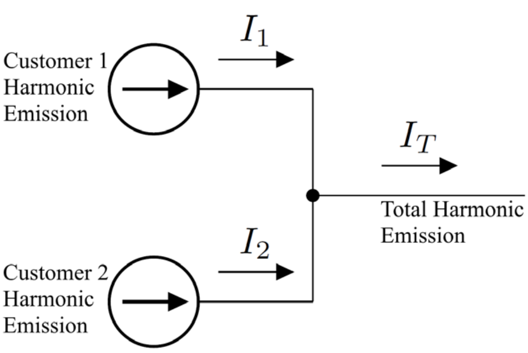


Visualisation of allocation comparison of fixed and network forecast based harmonic emission allocation methodologies with and without renewable energy generation

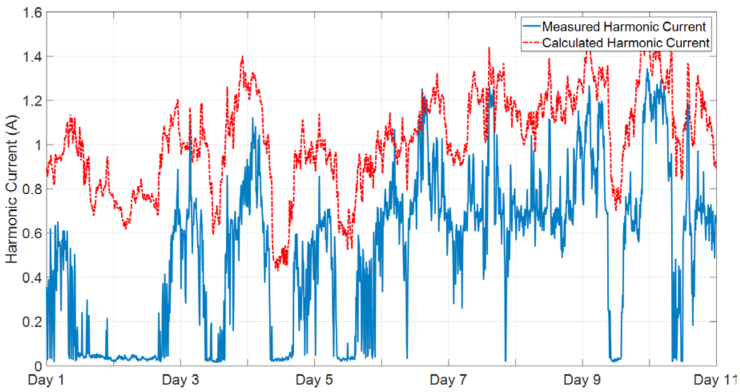
Harmonic Source Aggregation Impact on Assessment

A common concern with respect to harmonic management is how multiple harmonic sources interact with each other. Inherent variations (also known as diversity) between individual devices often result in the total harmonic emissions being less than the sum of each individual device and there are processes within allocation methodologies to account for this 'diversity'. For example, in the figure below, if the harmonic emissions of both Customer 1 (I_1) and Customer 2 (I_2) were connected to the power system through the same cable, the total measured harmonic emissions (I_T) may be less than the magnitude of ($|I_1| + |I_2|$) depending on phase angle relationships and time of operation. This is an important relationship that impacts the appropriate approach to allocation and assessment of the total harmonic emission contribution from individual customers. At present, existing practices for assessment of emissions from multiple REG inverters commonly assume worst-case scenarios, i.e. $|IT| = |I1| + |I2|$. This is a conservative approach and leads to an increased likelihood for harmonic mitigation being determined to be required for distorting installations during the design process.

Detailed analysis on data collected at a REG installation was undertaken in order to investigate how harmonic emissions from multiple inverters of the same type interact within a REG plant. This study found that it was most common for the total measured harmonic emissions to be substantially lower than the arithmetic sum of all measured emissions, an example of this is shown in the figure below. This suggests that there is diversity between sources and the currently applied method of arithmetically summating individual emissions is conservative.



Example aggregation of multiple harmonic sources



Time-series comparison of harmonic emission data as calculated and as measured to illustrate diversity of sources

Modelling REG to Forecast Harmonic Distortion Levels and Investigate Improved Mitigation Solutions

Existing practice within Australia (and many other countries internationally) requires proponents to mitigate (i.e. install harmonic filtering) within the connecting plant in order to limit the harmonic current that flows from the plant into the system if emissions are calculated to exceed the allocation at the planning stage. For example, if modelling studies for a proposed solar farm suggested that the plant is likely to exceed their allocated emission levels, the proponent would be required to install an onsite harmonic filter, which can increase capital costs by millions of dollars.

Modelling data from real networks has been used in order to estimate harmonic emission levels in a scenario of significantly increased penetration of REG. Once harmonic emission levels were understood, a revision of the present approach to harmonic mitigation for such scenarios was completed.

There were a number of significant outcomes from the study, see below.

A It was common for harmonic levels to exceed maximum allowable levels in remote areas due to a phenomenon known as remote resonance.

B A revision of the process to implement harmonic filtering found that it was potentially more economic for mitigation to be connected at the location of the network at which harmonic voltages were at their highest, rather than within offending plants.

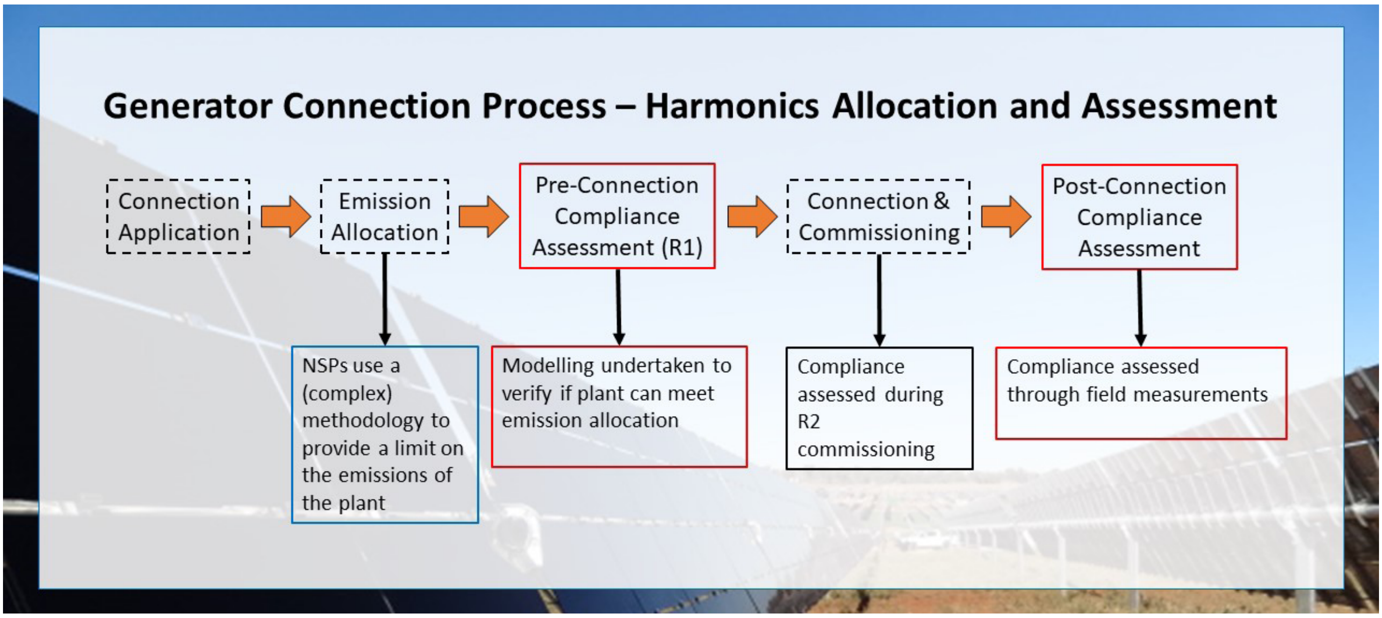
A comparative study found the revised approach reduced the size of the required harmonic filter by more than 98%. As such, this revised approach may significantly reduce costs to REG proponents and simplify the management of harmonic emissions for network service providers. This simplification is due to the reduced number of filters being connected to the network which inherently interact with each other, impacting the emissions of surrounding installations.

Further studies and work is required to develop a complete understanding of the possible implications of this revised approach to harmonic mitigation.

Evaluation of Compliance Assessment

Once an emission allocation for a plant has been calculated, the next step in the harmonic management process is assessing if the installation can meet the allocated emission limits. Whether or not an installation can meet emission allocations can have serious financial repercussions at both the planning and post connection stages. Failure to meet limits at the planning stage may require harmonic mitigation, typically in the form of harmonic filters before connection is approved.

Non-compliance at the post connection stage may again require mitigation which in this case may involve a shutdown of the plant and retrofit of a harmonic filter. The figure below shows an infographic which outlines the harmonic emission allocation and assessment process for a renewable energy generator. The aspects in the blue boxes are related to the topics discussed as part of this project, while the aspects in the red boxes are related to compliance assessment.



Harmonic allocation and assessment infographic

While general guidance for assessment of installation compliance with allocated harmonic emissions exists in Australian Standard AS/NZS 61000.3.6, 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 network operators 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 limits.

Challenges which exist related to compliance assessment of harmonic emissions of large loads and generators at both pre-connection and post-connection stages, and have been identified through interaction with stakeholders. Improper techniques for assessment of compliance can have significant implications for renewable energy connections as follows:

Underestimation of emissions may lead to higher than expected distortion levels, requiring design/retrofit of mitigation, and potentially curtailment/outages while being implemented.

Overestimation of emissions may lead to the requirement for costly mitigation, which ultimately may not be required.

Modelling of inverter based resources is currently inaccurate. Evidence from project partners identifies cases in which pre-connection compliance leads to mitigation being required, however post-connection measurements suggesting filtering not being necessary.

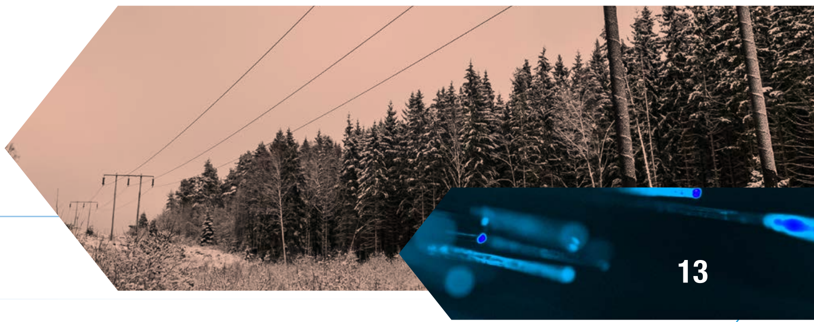
Whilst some methodologies have been presented in an effort to address some of these impacts, including those identified in the knowledge sharing outcomes of this project, the expected step change in renewable energy generator penetration is likely to exacerbate the identified issues and subsequently lead to harmonic distortion related issues on the network.

Measurement methodology and accuracy of instrumentation and transducers can have significant impacts on outcomes during post-connection assessments.

External network conditions and background distortion levels impact outputs of inverter based resources, potentially changing emission spectra. No conclusive work exists which identifies the scale of the impact. More work in the area is required if network-inverter interactions are to be appropriately identified within frequency domain modelling.

Australian standards and regulation presently lack a prescriptive and technically robust methodology for compliance assessment that can be applied consistently across all jurisdictions. Work needs be undertaken to avoid the mixed bespoke approaches. Outcomes of this work should include:

- 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 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'.
- Acknowledgment 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.
- 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 Project Outcomes

The following key project outcomes were identified during the above-mentioned project. The University of Wollongong will be continuing to investigate these in future research activities:

1

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.

2

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.

3

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.

4

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.

5

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.

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