I. INTRODUCTION

Audio frequency injection control (AFIC) signals, otherwise known as ripple injection control signals, are high frequency voltage waveforms that are superimposed onto the supply voltage at distribution level, usually 11 kV or 22 kV, in order to control loads. The AFIC signals are detected by receiving relays which then switch connected loads such as off-peak hot water systems or street lights. There is anecdotal evidence and industry concern that solar PV inverters are having an impact on AFIC levels either through attenuation or amplification. Further evidence is given by the fact that some DNSPs require inverter manufacturers to provide inverter impedance measurements at AFIC signalling frequencies.

Through the use of comprehensive measurements and analysis procedures, this paper presents an investigation into the interaction between solar inverters and AFIC signalling. Measurements were taken on systems of various sizes and then modelled within a computer simulation environment to determine the cause of the witnessed phenomena.

The remainder of this paper is organised as follows: Section II presents background material on AFIC signalling along with a review of similar projects investigating interactions between signalling and PV inverter systems. Section III introduces the three procedures that are reported in the current research; field measurements reported in Section IV, laboratory measurements reported in Section V and the computer simulation and analyses reported in Section VI. Finally, future work and conclusions are presented in Sections VII and VIII respectively.

II. BACKGROUND

AFIC control signals are applied to the network through the use of high frequency generators, which inject a binary coded format through superposition of a high frequency waveform (typically in the range 175 Hz – 1500 Hz) onto the sinusoidal fundamental waveform. AFIC receiving relays are programmed to interpret each coded pulse and switch on or off as appropriate.

The Australian standard for energy systems connected to the grid via inverters, AS 4777.2 [1], obliquely suggests that solar PV inverters may have an impact on AFIC (ripple) control signals stating that;

‘The inverter should not significantly radiate or sink frequencies used for ripple control by the local electrical distributor. The distributor should be consulted to determine which frequencies are used. Fitting of additional filtering components may be required in some grid areas.’ [1]

This is the only mention of AFIC signals in the standard, suggesting that it is understood the signals may be affected but fails to specify the level at which action should be taken. This leaves the onus on the installation owner and network operator to determine whether any action is required.

Further evidence that inverters may impact AFIC signalling levels is given by the fact that a DNSP in France, Électricité Réseau Distribution France (ERDF), now ENEDIS, which injects signals at 175 Hz requires manufacturers to supply the impedance of their inverters at this frequency, measured across the grid connection terminals [2]–[4]. It should be noted that the measurements found in [2] were able to be measured during the laboratory measurement section of the current research only when the inverter was completely disconnected and powered down (all of the measured inverters exhibited very different impedance measurements once they were switched on and supplying power).
A study performed in 2007 investigated the direct impact that solar inverters have on 175 Hz control signals [5]. This was a simulated study performed in the MATLAB environment. The research confirmed that inverter front-end filters are likely to have an impact on ripple control signal levels but does not confirm the result with physical measurements. Whilst the project was novel for the time, a more considered approach, including physical measurements is required due to the continued growth of solar installations.

Based on the current lack of research related to the topic, significant work is required including direct measurements of various sized installations followed by comprehensive analysis procedures to better understand the phenomena.

III. Procedure

In order to investigate the possible interaction between solar inverters and AFIC signal magnitudes an analysis involving three different methods of investigation was undertaken. The three stages of investigation were as follows:

1) Field measurements;
2) Laboratory measurements;
3) Computer simulation and analysis.

IV. Field Measurements

The first stage of investigation involved field measurements of AFIC signal levels measured at a commercial sized solar installation (160 kWp). Field measurements were conducted at the Sustainable Buildings Research Centre (SBRC), a research facility located on the Innovation Campus of the University of Wollongong. The building is a 6-star Green Star Education Design v1 installation, and includes a 160 kWp solar installation.

A two-stage approach to evaluating the interaction between the solar installation and AFIC signal magnitudes was adopted. Initial measurements were made simply by connecting a power quality (PQ) monitor to a wall outlet and taking 10-minute interval measurements of the voltage magnitudes over a period of approximately 100 hours. In this location, the electricity provider uses an AFIC signalling frequency of 746 Hz which can be detected by a PQ monitor measuring the 15th harmonic voltage.

Fig. 1 which shows the 15th harmonic voltage magnitude during the day and night displays the results of this measurement campaign. A clear step reduction in the 15th harmonic voltage level can be observed during the day, at a time which corresponds with the period during which the solar inverters will be operating. One of the major differences between day time and night time operation of the building is that the solar system will only supply power during the day. Another large factor is the variation in load between day and night. It was hypothesised that operation of the solar system was the leading factor in the observed reduction in 15th harmonic voltages associated with AFIC signalling, with the variation in load not having a significant impact. In order to investigate this hypothesis, a second phase of testing was completed which involved measurement of AFIC signals over a short period of time during the day with the inverters in one of three scenarios, displayed in Table I.

The following steps were taken to reduce variability of AFIC levels during the test period:

- Testing was undertaken on a sunny day to ensure that there would be solar generation and with little cloud, the variation in solar generation was assumed to be small.
- Arrangements were made with the local electricity distributor to inject AFIC signals on demand. This allowed testing to be undertaken over a short time frame, thus negating the impact of load changes on AFIC magnitudes and also allowed precise identification of signal presence.

The results of the second phase of measurements taken at the SBRC over the course of approximately 90 minutes can be seen in Fig. 2 for the scenarios that are defined in Table I. The measurements shown in Fig. 2 clearly display the impacts that the inverters have on AFIC signal magnitudes. Referring to Fig. 2 two outcomes may be surmised:

- Firstly, it appears clear that the impact on the harmonic

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Isolated from the Grid</td>
</tr>
<tr>
<td>2</td>
<td>Connected to the grid, DC panels isolated</td>
</tr>
<tr>
<td>3</td>
<td>Connected to the grid and generating power</td>
</tr>
</tbody>
</table>

Fig. 2. Harmonic voltage measurement with AFIC signals applied on demand
voltage levels is due to the presence of the inverters. This is demonstrated by the large step change in harmonic voltage levels for Scenario 3. As these measurements were taken over a short period of time, external parameters such as load variation which may impact AFIC signal magnitudes are mitigated.

• Secondly, it can be suggested that with no DC power being supplied to the inverter, the interacting circuitry that significantly impacts the AFIC signal magnitudes remains disconnected from the grid. This is derived from the similarity of the voltage levels between Scenarios 1 and 2 and the significant step change noticed for Scenario 3.

It should be noted that the second outcome is in support of the research defined in [5]. Stating that the front-end filter circuitry may be significantly interacting with the signalling voltages.

V. LABORATORY MEASUREMENTS

Given the results of field measurements detailed in Section IV showed strong indication that solar inverters generating power can have an impact on AFIC signal magnitudes, further investigation was performed within a controlled environment in order to investigate the exact mechanism by which inverters impact AFIC signal magnitudes. This second stage of the study investigated the effect that a single, residential sized (<5 kWp) installation could have on AFIC signals present on the supply voltage. Laboratory testing was undertaken in the Power Quality and Renewable Energy Laboratory at the University of Wollongong. The devices under test comprised of four residential size solar inverters. Ratings of the inverters tested are shown in Table II. To simulate normal operating conditions, the inverters were connected in the configuration shown in Fig. 3. As can be seen, the test circuit contains a line impedance representing a short section of a typical LV feeder. The inverter was connected to the end of this line impedance, in parallel with a passive load designed to resemble a typical residential household load of ≈3.3 kVA with a 0.9 lagging power factor. The following measurements were made:

• Voltage at the PCC, \( V_a \)
• Line current, \( I_a \)
• Current measured flowing from (or to) the inverter, \( I_b \)

The inverters under test were supplied by a solar array simulator which mimics the performance of solar panels. The supply voltage \( (V_{in}) \) was provided by an arbitrary waveform generator at 230 V RMS. If sinusoidal conditions are requested, this device has a low distortion output. In order to simulate AFIC signals, the 15th harmonic at 5% of the fundamental supply was superimposed onto the voltage waveform. The inverters supplied approximately half of the required power to the passive load and the test circuit remained identical for each test case with the only variable being the inverter under test.

A. 15th Harmonic Voltage Level Comparison

In order to examine the impact of different inverters on the 15th harmonic voltage levels, in the first instance the 15th harmonic voltage levels at \( V_a \) were recorded and compared for all four inverters individually. The results of these measurements are presented in Fig. 4. It can be seen that the magnitude of the 15th harmonic voltage at \( V_a \) varies significantly depending on the inverter under test. Most notable is the increase in 15th harmonic voltage for Inverter 1 and the noticeable decrease for Inverter 2. Inverter 3 and Inverter 4 appear to have much less of an impact on the 15th harmonic voltage levels.

B. Current Phasor Measurements

In order to better understand the mechanism behind the changes in 15th harmonic voltage levels due to the presence of the various inverters, the current phasors \( I_{a,15} \) and \( I_{b,15} \) were measured relative to \( V_{a,15} \), with the inverters present and generating power. These phasors define the complex current flowing between the waveform generator and the connected inverter. The magnitude and phase of these currents assist in determining the real and reactive components present due to the inverter’s connection. It should be noted that for clarity, the current sensor measuring \( I_b \), as shown in Fig. 3, was reversed. It was found that the inverter was not injecting active power

![Fig. 3. Laboratory Measurement Test Circuit](image_url)

<table>
<thead>
<tr>
<th>Inverter</th>
<th>Rated Output (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter 1</td>
<td>2.5</td>
</tr>
<tr>
<td>Inverter 2</td>
<td>2.6</td>
</tr>
<tr>
<td>Inverter 3</td>
<td>3.0</td>
</tr>
<tr>
<td>Inverter 4</td>
<td>3.6</td>
</tr>
</tbody>
</table>

![Fig. 4. 15th Harmonic voltage magnitude at \( V_a \) for all inverters under test](image_url)
at the 15th harmonic but instead consuming it. Each current sensor was oriented to measure positive current as the flow of current from the source to the load. Fig. 5 and Fig. 6 show the voltage and current phasor diagrams for Inverters 1 and 2, the two inverters that affected the 15th harmonic voltage levels most significantly. Of particular note in these two figures is the difference in phase angle of the current relative to the voltage. Fig. 5 displays a phasor with leading current (capacitive) at the 15th harmonic whilst Fig. 6 shows a lagging current (inductive). This result indicates that the impact on 15th harmonic voltage levels is due to the passive impedance of the inverters as opposed to the inverter actively injecting harmonic current.

C. Investigation of Inverter Frequency Response

Given the varied performance observed across inverters when supplied with ripple control signals, it was decided to perform a frequency response analysis of each inverter in order to investigate the characteristics of the inverter impedance at different frequencies. This frequency response assessment was achieved by supplying each inverter with a range of harmonic voltages at 5% of the fundamental, in 100 Hz steps from 150 Hz to 1.35 kHz. Equation (1) can then be used to determine each inverter’s measured impedance over this range.

\[ Z = \frac{V}{I} \]  

(1)

Fig. 7 displays the frequency response profile for Inverter 1. Presenting essentially an exponential approach to the horizontal crossing in the form of (2), this inverter does not appear inductive to the grid over the measured frequency range.

\[ X = 1 - e^\frac{1}{f} \]  

(2)

The frequency response of Inverter 2 can be seen in Fig. 8. Most notable about this graph is the presence of two zero crossings, one at 400 Hz and the other at \( \approx 1220 \) Hz. This result leads to the inverter appearing as a capacitive or inductive impedance, depending on the frequency of the distortion present. These measurements were also completed for the remaining two inverters, the results have been omitted in favour of brevity.

VI. COMPUTER SIMULATION & ANALYSIS

The frequency response curves obtained for the inverters during laboratory measurements suggest that it is the impedance of the inverter’s filtering circuits that have the dominant impact on inverter impedance. This was also observed in Section IV and is supported by [5]. In order to further investigate this, computer simulation and analysis was performed in order to verify the impedance model that best represented each inverter and to investigate the implications of different
filter design topologies. Computer simulation was performed using the PSCAD/EMTDC package with the inverter modelled as a unity power factor fundamental current source, with no additional harmonic distortion and connected to the supply voltage through a passive filter, shown in Fig. 9. The component values shown in Fig. 9 represent the front end of the inverter as a dual component passive load at the 15th harmonic. This represents the filter as a resistor in series with a capacitor or inductor, however, it is more likely that the inverter is connected through an LC, LCL or similar filter design [6].

A. Use and Impact of Filters

1) LC and LCL Filters: The choice and design of a filter can have significant impacts on how the inverter interacts with the grid. A common choice of filter for grid connected inverters is the LC or LCL filter [6]. Placed in the correct configuration, these filters provide a low impedance path for low frequencies and, present a higher impedance path as the frequency increases.

The characteristics of LC and LCL filters have been examined using frequency sweep testing of filter models in the PSCAD simulation environment. The model used the ideal forms of these filters and calculated the complex impedance of the filters across a range of frequencies from 0 - 4000 Hz. The results of this can be seen in Fig. 10. Whilst the discrete values of the reactance have been omitted, as this has been completed with inferred values for each of the components, the profile of the response is of considerable interest. Noticeably, the LC filter could be directly compared to the measured frequency response of Inverter 1 further verifying that it is the impedance of the filter that has the dominant impact on inverter impedance.

2) Pi Filters: While the frequency response of the LCL filter shown in Fig. 10 has some resemblance to the frequency response of Inverter 2, one would need to omit the second sharp drop at \( \approx 1220 \text{ Hz} \) seen in Fig. 8. After further research, another common filter type was investigated, the Pi filter. This can also be placed in a low-pass configuration and yields the frequency response profile shown in Fig. 11. It can be seen that the frequency response is similar to that of the LCL filter but with an additional zero crossing. Comparing the frequency response of the Pi filter to the frequency response profile of Inverter 2, it could be suggested that Inverter 2 employs a filter configuration similar to that of the Pi filter. One could envisage the curve of Fig. 11 being ‘stretched-out’ along the x-axis to closer resemble the Inverter 2 frequency response profile as shown in Fig. 8.

B. Filter Choice

Filter choice and design involves balancing advantages and disadvantages to obtain an optimal result. The filters investigated in Section VI-A are far from an exhaustive review however are commonly used components within grid tied inverters, all with unique advantages and disadvantages. A simple comparison of the transfer impedance Bode plots with the transfer function of (3) highlights the differences as shown in Fig. 12.

\[
H(\omega) = \frac{V_o(\omega)}{I_i(\omega)} \quad (3)
\]

The Pi filter exhibits the greatest impedance at high frequencies however a noticeable a spike is present within the response and can result in multiple resonant frequencies. The LC filter has a smooth response over the frequency range however the
impedance is far less compared to that of the Pi filter at high frequencies. The LCL filter splits the difference of impedance without added resonance issues however inductors are bulky and expensive components.

Filter design is a complex and well documented practice, a broad overview has been included as a suggestion of the potential impacts that may arise between the different choices made by manufacturers.

VII. FUTURE WORK

This study addresses an issue that is still yet to be fully understood. Whilst modelling and calculations suggest that significant interaction between inverters and AFIC signalling is possible, whether it is likely to occur or will have detrimental effects on equipment requires further investigation. The field measurement results of the study presented here are specific to a particular installation. Due to the high number of variables present on networks at any given time, for example loading levels, types of inverters, and network resonances, it is difficult to determine if and when adverse interaction between inverters is likely to occur. Better understanding of this requires further investigation. Such investigations could include:

- Field measurements at other locations and distribution networks.
- Laboratory measurements of the impedance characteristics of a large number of inverters ranging from legacy models to more current, popular models.

- Simulation of distribution networks including varying levels of inverter penetration and varying numbers of inverters supplied by different manufacturers. Such a study would also investigate whether inverter filtering components can contribute to network resonance.
- Investigation into the effect of inverters on ripple control signal levels placed at various distances along a typical LV feeder.
- Measurement on the impact of passive filters for problematic inverters.
- Further research to determine other mitigating techniques and at which point to apply them.

VIII. CONCLUSION

The work completed in this study presents initial measurements and simulations aimed at identifying the potential impacts that solar inverters may have on AFIC signal magnitudes. Whilst the results presented led to an investigation of filter design, the overall result confirms that the inverters can interact with AFIC signals and that the interaction is primarily a result of the impedance of the inverter filtering. Depending on the type of filter used and the components selected, the impact could be significant or go unnoticed. Whether attenuation or amplification is experienced appears dependent on the individual inverter as different manufacturers employ various filter types and hence influence overall impact.

This project focused on single inverters operating within a localised site. It is believed that further work must be completed in order to investigate the impact that multiple inverters connected along a feeder may have on the network. This will provide insight and information towards creating a representative model that is able to highlight areas that may be having issues with amplified or attenuated AFIC signals.

IX. ACKNOWLEDGMENT

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REFERENCES