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# Harmonic impact of photovoltaic inverters on low voltage distribution systems

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## Abstract

The number of installations of photovoltaic solar panels and associated inverter systems within residential premises is increasing. As these systems incorporate a power electronics front end, they will have an influence on the quality of supply in regards to voltage harmonics. This paper investigates the harmonic impact on an LV distribution feeder due to the installation of residential type grid connected photovoltaic inverter systems. To undertake the study an aggregated current source model is proposed for the photovoltaic inverter systems based on measurement data from available literature and the relevant international standards. A typical LV distribution feeder including load arrangements is selected for the study. Conventional harmonic modelling methods are applied to determine harmonic emissions and resulting harmonic voltage levels for various penetration levels of photovoltaic inverter systems. Based on this study, a recommendation is made for acceptable penetration levels to limit the harmonic impact of grid connected photovoltaic inverter systems.



## Keywords

inverters, photovoltaic, low, impact, harmonic, systems, voltage, distribution

## Disciplines

Physical Sciences and Mathematics

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# Harmonic Impact of Photovoltaic Inverters on Low Voltage Distribution Systems

A.A. Latheef, D.A. Robinson, V.J. Gosbell, *Member, IEEE,* and V. Smith

***Abstract*— The number of installations of photovoltaic solar panels and associated inverter systems within residential premises is increasing. As these systems incorporate a power electronics front end, they will have an influence on the quality of supply in regards to voltage harmonics. This paper investigates the harmonic impact on an LV distribution feeder due to the installation of residential type grid connected photovoltaic inverter systems.**

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***Index Terms*— photo-voltaic, power quality, harmonics, LV distribution, distributed generation.**

## I. Introduction

As residential customers become more energy conscious and environmentally aware, the installation of grid connected photovoltaic solar panels for small-scale electricity generation is expected to grow [1]. For developing countries, where there may be limited resources for large scale electricity generation, implementation of photovoltaic solar panels also offer a method of demand management during periods of peak energy consumption by supplying residential dwelling loads, or part thereof, directly within the customers premises [2], [3].

To enable energy from dc producing photovoltaic cells to be utilised for small-scale electricity generation within residential dwellings an inverter system incorporating power electronics is required to synchronise with the ac mains supply. Based on existing conversion techniques, inverter inherent non-linearities result in harmonics being injected into the mains supply during operation. This may result in a significant increase in harmonic voltage distortion levels on the power system if inverter system numbers are extensive. Thus, concerns for the systems power quality arises as a major issue for electricity network service providers attempting to meet regulatory standards and for customers connected to the power system wishing to minimise malfunction of sensitive equipment. However, the implementation of photovoltaic inverter systems (PVIS) allows residential customers to contribute to their own energy demand and also provides the opportunity to export energy to the grid. Consequently, guidelines for inverter operation and installation have been issued and are generally accepted by the manufactures and users.

In relation to PVIS installations the relevant equipment standards to which manufacturers and users must comply with in Australia include AS 4777.1 to AS 4777.3 [4–6]. International guidelines are also available including IEEE Std 929 [7]. For harmonic disturbances the network service provider should maintain harmonic voltage levels within the limits recommended in standards and guidelines such as AS/NZS 61000.3.6 [8] (an adaptation of IEC 61000-3-6 [9]) and IEEE Std 519 [10]. For the work in this paper recommended limits from Handbook 264 [11], an application guide for AS/NZS 61000.3.6, are utilised to establish acceptable harmonic voltage levels. The Handbook HB264 [11] is widely accepted in Australia for planning the harmonic voltage levels of the power systems.

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

$$P_{level}(\%) = \frac{n_{pvis} n_{dist} S_{INV}}{S_{TX}} \times 100\% \qquad (1)$$

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

Finally, a sensitivity study is performed in order to determine the influence of various factors (e.g. conductor impedance) on the distortion levels of the system, including the Voltage Total Harmonic Distortion ($V_{THD}$).

## II. Methodology

Fig. 1 illustrates a simplified block diagram of a typical grid connected residential type PVIS [12]. The first module of the PVIS includes a dc control system which regulates the energy flow and voltages produced by the photovoltaic cells for the inverter system. The inverter is then connected to the grid via a filter module which provides both circuit isolation

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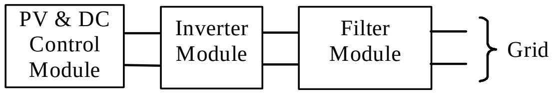


Fig. 1. Simplified block diagram of a photovoltaic inverter system

and the filtering operation to reduce harmonic disturbances. The preference of some residences to have a back-up system to charge batteries for energy storage is not shown in Fig. 1. Although several individual elements of the PVIS exhibit non-linearity, the operation of the inverter module provides the most significant contribution to harmonic distortion emissions, essentially acting as a harmonic source. The mathematical modelling of the non-linear inverter module undertaken for this study is based on the work in [13] using superimposed current source models combined with frequency domain techniques. Frequency domain modelling techniques have shown acceptable accuracy within the scope of this type of study, although alternative models of PVIS are also available for more detailed time domain studies [12].

Nodal analysis is utilised to determine the magnitude of the individual harmonic voltages arising on the network due to the harmonic emissions of the connected PVIS using

$$[V_h] = [Z_h][I_{h,PVIS}] \tag{2}$$

where $V_h$ is the harmonic voltage matrix representing the voltages at the monitoring points within the study system, $I_{h,PVIS}$ the harmonic current matrix due to the PVIS operating at their maximum rated current, and $Z_h$ is the harmonic impedance matrix of the study system (including LV distributor, loads, transformer impedances and the upstream MV impedance). Each node represents the location of the aggregated, or lumped, current source models for the connected PVIS. The resulting $V_{THD}$ is determined by superimposing the individual harmonic voltages.

The model is used to investigate the fraction of PVIS that would be allowed to inject their full rated power into the grid before the $V_{THD}$ or individual harmonic voltage planning levels recommended in [11] are violated at the most extreme location on the LV distribution network. This is referred to as the acceptable penetration level of the system.

### A. Aggregated PVIS Model

A typical inverter rating of 2kW selected for this study was based on the mean rating of a total of 200-400 residential home installations, most of which consisting of 1-3kW inverters, from a project compiled in [14]. For this study it is assumed for a given distributor the PVIS units operates at its maximum power output and the failure rates as detailed in [15] are considered negligible, resulting in insignificant power diversity among them.

Harmonic current emission magnitudes typical to the types of inverters used in PVIS for the $2^{nd}$ to $40^{th}$ harmonics were obtained from [16] and [17]. The data from [16] and [17] included measurements of emissions from six different inverter manufacturers, with inverter ratings of 0.6kW, 0.7kW, 0.8kW, 1.3kW, 2.25kW, 2.5kW, 3.0kW and 3.2kW. The magnitudes of harmonic emissions from each of the inverter types needed to be scaled to provide an estimation of the harmonic emission of a representative 2kW inverter. It is noted that for this study only the inverter output harmonic current magnitudes were considered.

Normalising the harmonic current magnitudes from each inverter type allowed a direct comparison of the harmonic emission from each type. From the modeling perspective it was deemed acceptable that a less than half the total number of inverter types may exceed the $I_{THD}$ and/or $I_h$ magnitude/s recommended limits from [4], with a consistency in the existence of a particular harmonic to the rating of the inverter and the manufacturer. The reason for having such a scheme is for the model to produce current harmonic magnitudes within the recommended limits and have magnitudes slightly higher than the average inverter available on the market. In selecting the exact current harmonic magnitude to represent the 2kW inverter model three choices were proposed

1) A statistical approach using the $95^{th}$ percentile of the available normalised harmonic magnitudes from each inverter manufacturer,
2) The average value of the normalised harmonic magnitudes from each inverter manufacturer, or
3) The $2^{nd}$ highest of the normalised harmonic magnitudes from each inverter manufacturer.

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

It is the intention that the model complies with the appropriate standard. On this basis a filtering mechanism was implemented to bound the magnitudes of $I_h$ and $I_{THD}$ by the recommended limits of harmonic emissions from [4]. The resulting magnitudes of $I_h$ and $I_{THD}$ using this method are provided in Table I. The selected method has three main advantages;

i) The outcome is an existing harmonic magnitude,
ii) Although current magnitude does not reflect the average or the $95^{th}$ percentile value it still maintains a relatively high value on most of the harmonics, and
iii) Model reflects all the manufacturers' inverter current harmonic behavior.

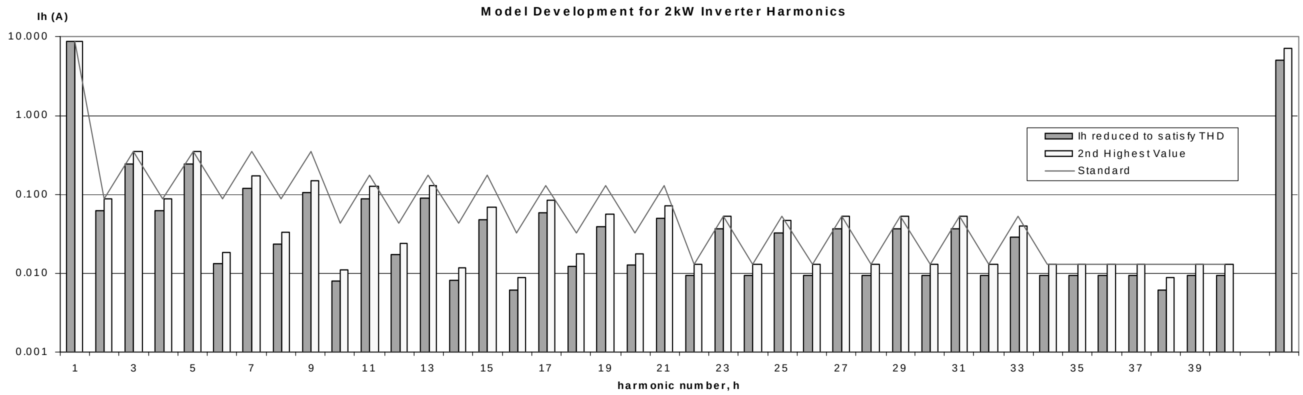


Fig. 2. Harmonic current magnitudes of a representative 2kW inverter and recommended emission limits from [5]

TABLE I
MODELLED HARMONIC CURRENT EMISSION SPECTRUM OF A REPRESENTATIVE 2KW INVERTER

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

It is clearly seen from the $I_h$ spectrum of Fig. 2 that most of the low order harmonic current magnitudes from the representative inverter are well within the recommended limits. Consequently adopting the limits within the harmonic standard as the magnitude of harmonic current emissions for the required model would not reflect the true acceptable penetration levels of the PVIS, leading to an overly pessimistic result. Thus, the model developed using the $2^{nd}$ highest value from the available data was implemented for the required current source model.

### *B. LV Distribution Network Model*

For this study a typical LV distribution system is modelled using data provided in [11] consisting of a 350kVA MV/LV distribution transformer with two overhead conductor type distributors of length 350m each, as shown in Fig. 3. In order to complete the calculation of the harmonic contribution of the residential type PVIS, it was assumed that the distributors were assigned specifically to residential use and the residential dwellings were uniformly distributed (or tapped uniformly on the distributor). It was also assumed that the two distributors reflect similar operational characteristics, i.e. homogeneity, without loss of accuracy for this study. This means that the penetration level is shared between the two distributors, each possessing the same loading figures. In addition, for the calculation of the distributors harmonic voltage, the following assumptions were made:

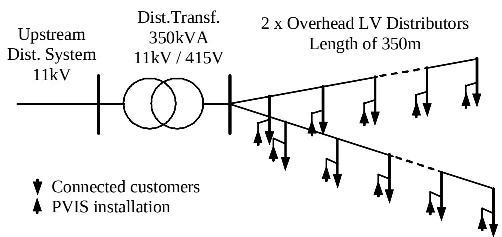


Fig. 3. Typical LV distribution system

1) Based on the voltage drop of the distributor remaining within 0.06pu at the end of the distributor under loaded conditions, fundamental voltage change is considered negligible for the purpose of calculations.
2) Background distortions at LV can be considered significant to cause an impact on the penetration levels, as the study [18] shows the contribution from a large building dedicated to residential use can cause radical voltage distort at the transformer bus. Hence, background distortions are included.
3) Diversity among the PVIS along the distributors has been considered insignificant, as the geographical areas covered by the two distributors are relatively small based on surface area [12]. This leads to constant sunlight intensity for all the residential loads on the studied distributors. This is true for the lower frequency harmonics but requires further investigation for the high frequency harmonics.
4) Harmonic current magnitudes from the PVIS are in proportion to the rating to the inverter system (as per Section II-A).

On the basis of distributor homogeneity, voltage harmonic distortion levels were calculated using a lumped impedance parameter model as shown in Fig. 4. For this study the residential loads and current sources representing the PVIS are lumped at three pre-assigned locations; the distribution transformer LV

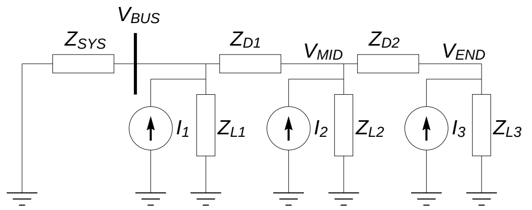


Fig. 4. Schematic of system model including harmonic impedance of customer loads and current sources representing lumped PVIS are represented on one of the identical distributors

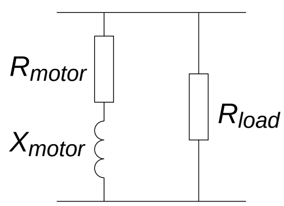


Fig. 5. Residential type load model used in the study

busbar ($V_{BUS}$), the middle of the LV distributor ($V_{MID}$), and the end of the LV distributor ($V_{END}$), at defined ratios of 1:2:1 respectively. The resulting harmonic impedance matrix $Z_h$ of the system shown in Fig. 4 is given by

$$\begin{bmatrix} Z_{SYS} + n_d Z_{D1} + n_d Z_{L1} & -n_d Z_{D1} & 0 \\ -Z_{D1,h} & Z_{D1} + Z_{D2} + Z_{L2} & -Z_{D2} \\ 0 & -Z_{D2,h} & Z_{D2} + Z_{L3} \end{bmatrix} \quad (3)$$

where $Z_{SYS}$ is the transformer and upstream harmonic impedance, $Z_{L1}$, $Z_{L2}$, and $Z_{L3}$ are the shunt harmonic impedances representing lumped load, $Z_{D1}$ and $Z_{D2}$ are distributor harmonic impedances, $I_1$, $I_2$ and $I_3$ are lumped injected harmonic currents from PVIS installations and $n_d$ is the number of identical distributors connected at bus point.

The study was undertaken for three types of LV distribution systems; overhead conductor (OH) type (default study), a similar system utilising aerial bundled conductors (ABC), and an LV system using underground cabling (UG). Each type of distributor was based on a multiple earth neutral (MEN) configuration. The significance of MEN systems is that the resulting zero sequence harmonic impedance of the LV distributor is approximately three times the positive sequence phase sequence impedance. For a balanced system this has a considerable bearing on all triplen harmonic voltages (zero sequence harmonics).

### C. Residential Load Model

To incorporate the loading effect of residential loads on the harmonic voltage levels within the LV distribution system a load impedance ($Z_{L1}$, $Z_{L2}$, etc.) is included in the study. The load model attempts to reflect the domestic appliances in daily usage. The model was adopted on justification from [13], [19], and [20] using a passive component model with a series resistance and inductance (representing small motor type equipment), and a parallel resistor (representing heat and lighting elements), as shown in Fig. 5. The components $R_{motor}$ and $X_{motor}$ are determined using the locked rotor impedance as per [13] and proportioned to match to the equivalent loading being applied. $R_{load}$ is also proportioned to match the required loading assuming a residential customer load rating of 6kVA and a power factor of approximately 0.9 lagging at peak load. The proportion of the $R_{load}$ was an extremely large impedance compared to $R_{motor}$ and $X_{motor}$ consequently absorbing insignificant harmonic current, hence with this understanding $R_{load}$ was eliminated from the simulation. Skin effect, which tends to increase the harmonic impedance of resistive elements with increasing frequency, is incorporated as per recommendations in [20]. It is noted that the load impedance is relatively large compared to the power system impedance at harmonic frequencies, implying that virtually all the $I_h$ from the inverter source flow into the upstream system. Thus the effect on the acceptable penetration level will be negligible, however the load model is included for completeness.

### D. Background Harmonic Distortion

The allocation of allowable $V_h$ contributions from PVIS ($L_{PVIS}$) is based on the planning levels for LV systems less the contribution from loads within the same LV distribution system and upstream. The contribution from upstream is assumed to be equal to the MV planning level as per [11]. It is assumed there will be considerable diversity between the upstream and PVIS harmonic contribution, thus the "summation law" approach in accordance with [8] is utilised.

Typical harmonic contributions from residential loads ($L_{OLV,h}$) can be estimated using (4) based on results from [21] where $\beta_h$ is a scaling factor adopted from measurement results from actual systems ($\beta_h = 0.025$ per unit for the $5^{th}$ harmonic), and $x_{tx}$ is the transformer impedance.

$$L_{OLV,h} = \beta_h x_{tx} h \quad (4)$$

Combining the contributions from upstream ($L_{MV,h}$), the LV loads ($L_{OLV,h}$) and the available LV limit ($L_{LV,h}$) using the summation law where alpha is the summation exponent for harmonics given by [8], the allowable $V_h$ contribution from the PVIS ($L_{PVIS}$) can be determined using

$$L_{PVIS,h} = \sqrt[\alpha]{L^{\alpha}_{LV,h} - L^{\alpha}_{MV,h} - L^{\alpha}_{OLV,h}} \quad (5)$$

The harmonic impedance of the LV distributor system is used to determine the allowable harmonic current emission from the PVIS based on the available PVIS voltage contribution. The allowable harmonic current contributions are proportional to the acceptable penetration levels.

## III. Results

The results of the harmonic voltage calculations using the methods and models outlined in Section II were completed using a various simulation packages, based on system details given in Table II. The acceptable penetration level is based on two factors; $V_{THD}$ within recommended limits and individual voltage harmonics within recommended limits. The acceptable penetration level for PVIS installations is relatively high when considering only $V_{THD}$ but is considerably lower when based

TABLE II
LV SYSTEM PARAMETERS

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

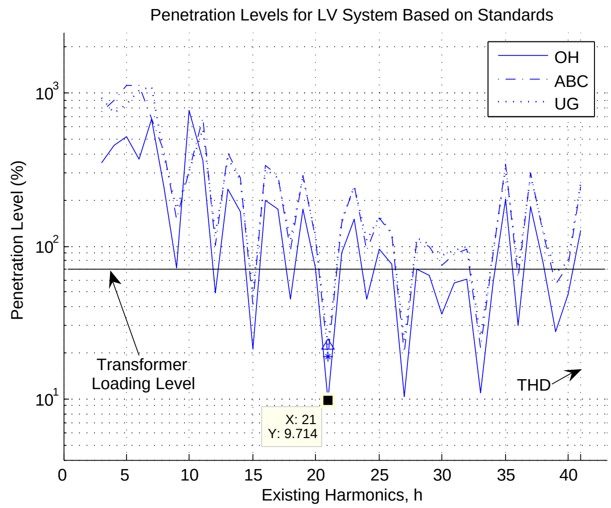


Fig. 6. Penetration levels based on recommended limits [11]

on the individual harmonic voltage levels. It was found that with no harmonic contributions from LV loads considered the $21^{st}$ harmonic exceeds the limits recommending in [11], suggesting an acceptable penetration level of approximately 9.7% for OH type distributor, as seen in Fig. 6. These results show that it is necessary to investigate the individual voltage harmonics for significance before the acceptable penetration level can be decided.

When the distortion due to LV loads is included, as shown in Fig. 7, a significant impact on the acceptable penetration levels is apparent. The acceptable penetration level of the $21^{st}$ harmonic is reduced to approximately 4.5% on OH, 8.6% on ABC and 10% on UG distributors, corresponding to 7, 13 and 18 PVIS units as the critical number for the LV system not to exceed its voltage harmonics at the most susceptible location. Fig. 8 shows the penetration levels along the distributor, indicating the significance of the penetration levels from the bus location to the end of the distributor. Additional studies were conducted on the effects of reducing the harmonic emissions of the PVIS, i.e. reducing the $I_h$ magnitudes. It is assumed this could be achieved through improving filtering or inverter switching techniques. A reduction of $I_h$ results shows that the system with the lowest impedance distributors will be allowed to have approximately 25 units of PVIS, if current harmonic emissions are reduced by 30%. Significant improvements seen over the studied distributor types are provided in Table III.

Overall results of the study illustrated that a particular harmonic ($21^{st}$) has the tendency to exceed the acceptable voltage harmonic limits on LV systems, rather than overall

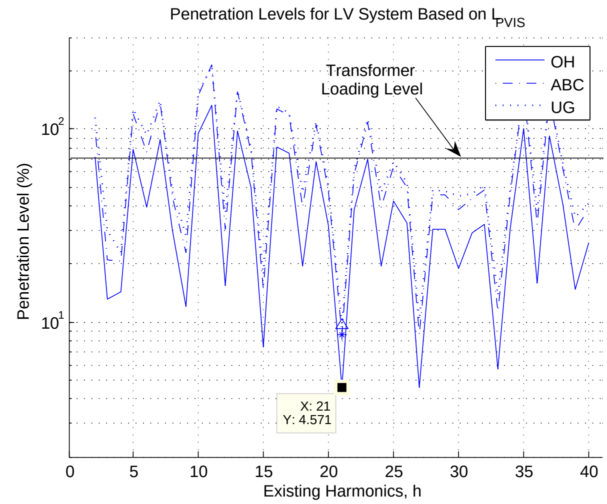


Fig. 7. Penetration levels based on $L_{PVIS}$

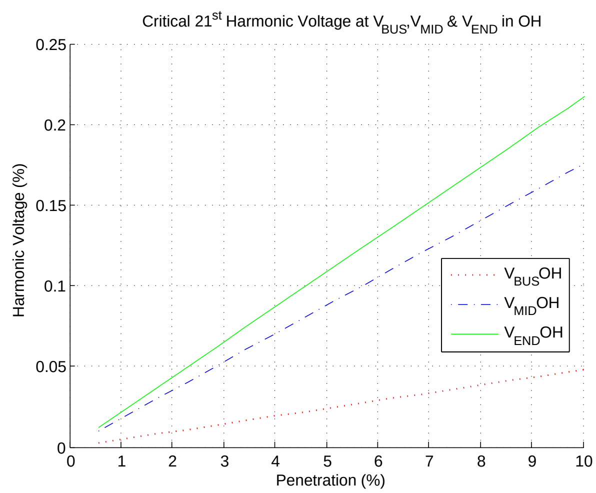


Fig. 8. Penetration levels along the Overhead type distributor

TABLE III
THE EFFECT OF $I_h$ REDUCTION ON PENETRATION LEVELS BASED ON $L_{PVIS}$

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

$V_{THD}$, regardless of the distributor type. However, the distributor type used on LV systems has a significant effect on the acceptable penetration levels due to the large variation in harmonic impedance. when comparing the common distributor types, UG was found to be the distributor type which allowed the highest acceptable penetration of PVIS based on harmonic voltage levels.

## IV. CONCLUSION

This paper proposes a method for calculating the acceptable penetration level of residential grid connected photovoltaic inverter system installations based on $V_{THD}$ and individual harmonic voltage limits recommended in the relevant Australian harmonic standards.

The Possibilities of having a reduced inverter current harmonic magnitude and the impact of using common distributor types were studied in order to understand the variation of acceptable penetration levels for grid connected photovoltaic inverter systems.

To allow the calculation to be performed, mathematical models for the aggregated harmonic current emissions from a typically sized inverter have been established. This model is based on the relevant harmonic standards and measurement data obtained from available literature.

A typical LV distribution system consisting of an MV/LV distribution transformer and two LV distribution feeders has been investigated. With the possibility of better filtering, $I_h$ could be reduced by 30% giving acceptable penetration levels of PVIS installations of approximately 6%, 12% and 14% on overhead conductor, aerial bundled conductors and underground cabling of LV distribution feeder types respectively. Correspondingly, the acceptable penetration levels for such a reduction in $I_h$ leads to a distribution of approximately 22kW, 42kW and 50kW of energy along their respective LV systems. The results are based on the inclusion of significant contributions from background distortion from both upstream and LV distributor distorting loads.

Future work required for this study includes the analysis of the resulting harmonic voltage distortion within the MV distribution network due to the PVIS installation on the LV System.

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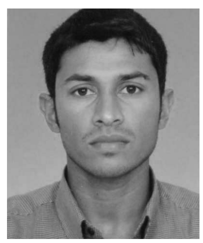

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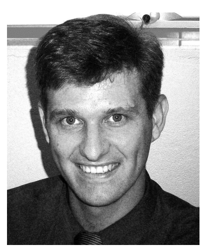

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