Harmonic Impact of Residential Type Photovoltaic Inverters on 11kV Distribution System

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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 11kV distribution system due to the installation of residential type grid connected photovoltaic inverter systems (PVIS). To characterise the aggregated harmonic current spectrum contributed from the low voltage system, a typical inverter spectrum is utilised. Conventional harmonic modelling techniques are applied to determine a medium voltage system model and resulting network wide harmonic voltages for various penetration levels of residential type 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.

1. INTRODUCTION

This paper is a continuation of the study [1] completed on determination of the harmonic impact of PhotoVoltaic Inverters Systems (PVIS) on low voltage distribution systems. To undertake the study an aggregated current source model was proposed for the photovoltaic inverter systems (Appendix, Table 5) based on measurement data from available literature [2] [3], the relevant international standards [4] and appropriate modelling techniques [5] [6]. A typical LV distributor including load arrangements was 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. A method was developed in determining the maximum acceptable number of PVIS that can be connected to the grid for LV distribution networks without harmonic limits being exceeded.

This study proposes a method to determine the acceptable number of LV residential type PVISs that can be connected to the grid without exceeding the MV distribution networks harmonic limits. To undertake this study a residential distribution system model was developed, which includes a residential feeder model consisting of aggregated distribution transformers represented as harmonic current sources characterised by the PVISs harmonic current spectrum. Continuing from the system modelling, this study proposes an appropriate method of determining a background distortion level for the medium voltage system which will be used in allocating a harmonic voltage distortion level for LV PVIS in MV system.

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

$$[V_h] = [Z_h][I_{aggr,PVIS,h}] \quad (1)$$

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

A method to determine the acceptable penetration levels of LV PVIS was incorporated as suggested by reference [1], where by the acceptable level is measured as a percentage of the distribution transformer rating, given by equation (2).

$$P_{level}(\%) = \frac{n_{pvis} n_{dist} S_{INV}}{S_{TX}} \times 100\% \quad (2)$$

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. Details of the LV systems are given in Table 1.

Table 1: LV System Parameters [1]

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

To determine the acceptable level of penetration the harmonic voltage distortion of the MV system was found for several values of penetration level and a comparison was made to the recommended harmonic distortion limits. This study analyses four sets of recommended harmonic voltages arising from the MV distribution system in order to represent a suitable acceptable penetration level of PVIS, namely acceptable penetration levels based on comparing network wide harmonic voltages contributed from LV PVIS with:

i. Standard harmonic voltage planning levels for 11kV distribution systems excluding phase and time magnitude diversity
ii. Standard harmonic voltage planning levels for 11kV distribution systems including phase and time magnitude diversity
iii. Harmonic voltage distortion levels allocated for PVIS, based on background distortion excluding phase and time magnitude diversity
iv. Harmonic voltage distortion levels allocated for PVIS, based on background distortion including phase and time magnitude diversity

2. MEDIUM VOLTAGE DISTRIBUTION NETWORK MODEL

Figure 1 shows the complete medium voltage and low voltage system under study. The system consists of two distributors per 350kVA distribution transformers, seven overhead feeders and substation transformers rated at 25MVA with (n-1 redundancy). The system is based on a dedicated residential purpose distribution, hence MV loads are excluded in the system. For the purpose of calculation, the feeders are assumed to be electrically homogenous, i.e. similar conductor parameters among feeders, same length feeders and each feeder reflects distribution transformers of similar characteristics. A typical medium voltage system of overhead open-wire system was adopted from reference [7]. In addition to the aforementioned feeder characteristics, system wide assumptions are believed to be necessary for the calculation of the harmonic voltages around the network given by:

i. The distribution transformers are believed to be spread out evenly along the feeder as seen in Figure 1.
ii. The low voltage distribution system is represented by an aggregated LV residential type PVIS [1].
iii. Based on the voltage drop of the feeder to remain within 0.05pu at the end of the feeder under loaded condition, fundamental voltage drop is considered negligible for the purpose of calculations.
iv. The sun's illumination level on the MV voltage network span will be considered uneven, resulting in phase and time magnitude diversity among the PVISs on the entire network. Hence, corresponding harmonic voltages will be calculated based on related diversity factors as suggested by [7] [8].
v. The harmonic current absorbed by the residential load is believed to have an insignificant impact on the MV network wide distortion levels [1].

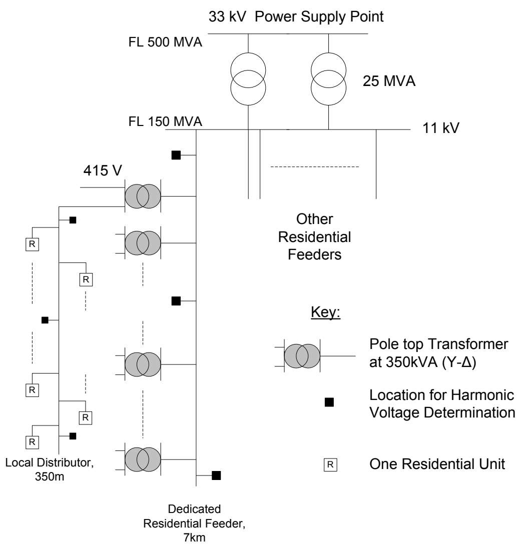

Figure 1: Shows the complete residential distribution system under study

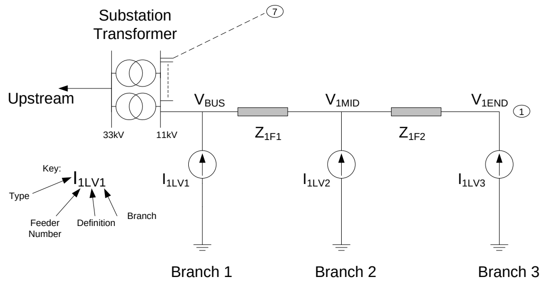

Figure 2: Schematic of system model including the feeder impedance and representation of the aggregated distribution transformers as harmonic current sources

On the basis of feeder homogeneity, harmonic voltage distortion levels around the network were calculated based on a lumped impedance model as shown in Figure 2. For this study the distribution transformers per feeder are lumped at three pre-assigned locations; substation transformers busbar V_{BUS}, middle of the MV feeder V_{MID} and the end of the MV feeder V_{END}, at defined rations of 1:2:1 [1]. The resulting harmonic impedance matrix Z_h of the system shown in Figure 2 is given by matrix (3).

$$\begin{bmatrix} Z_{SYS,h} + n_f Z_{f1,h} & -n_f Z_{f1,h} & 0 \\ -Z_{f1,h} & Z_{f1,h} + Z_{f2,h} & -Z_{f2,h} \\ 0 & -Z_{f2,h} & Z_{f2.h} \end{bmatrix} \quad (3)$$

Where $Z_{SYS,h}$ is the transformer and upstream impedance, n_f is the total number of feeders, $Z_{f1,h}$ and $Z_{f2,h}$ corresponds to feeder impedances and I_{1LV1}, I_{1LV2} and I_{1LV3} are the lumped harmonic currents from the distribution transformers subjected to PVIS.

The study was undertaken for overhead open wires system feeders based on the understanding that the highest impedance type feeder (overhead conductor type) will contribute to lowest acceptable penetration levels of PVIS [1]. Hence, it is believed that any portion of the feeder subjected to underground cabling or aerial bundled cable conditions will be bound by the overhead conductors acceptable penetration levels of PVIS.

3. BACKGROUND DISTORTION

The allocation of allowable MV harmonic voltage distortion limits for the LV PVIS ($L_{11,PVIS,h}$) is based on the planning levels of MV system less the total contribution from distorting loads. The total contribution from distorting loads include loads in the existing MV system and the downstream (LV system) equipments. Since the contribution from the MV distorting loads in a dedicated residential feeder will be considered negligible, the term $L_{O,11,h}$ in equation (5) will be considered insignificant as shown in Figure 3. The contribution from upstream is assumed to be equal to the 33kV planning levels as per [7]. 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.

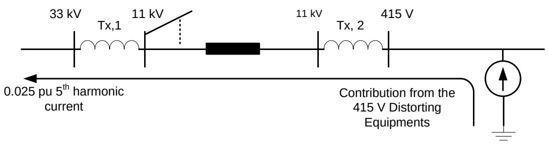

Figure 3: Simplified diagram to show the cause of the harmonic voltage distortion levels in MV system

Typical harmonic contributions from residential loads in the MV system ($L_{11,415,h}$) can be estimated for the range of harmonics under study using (4), based on the suggestion from [9] where β_h is a scaling factor adopted from measurement results from actual systems ($\beta_h = 0.025$ per unit for the 5^{th} harmonic), and $x_{tx,s}$ is the substation transformer impedance.

$$L_{11,415,h} = \beta_h x_{tx,s} h \tag{4}$$

Combining the contributions from upstream ($L_{33,h}$), the LV loads ($L_{11,415,h}$) and the available MV limit ($L_{11,h}$) 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 equation (5). Corresponding results of $L_{11,PVIS,h}$ is provided in Table 2.

$$L_{11,PVIS,h} = \sqrt[\alpha]{L^{\alpha}_{11,h} - L^{\alpha}_{33,h} - L^{\alpha}_{11,415,h} - L^{\alpha}_{O,11,h}} \tag{5}$$

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

4. RESULTS

The results of the harmonic voltage calculations using the methods and models outlined in Section 2 and Section 3 were completed using various simulation packages, based on system details given in Figure 1 and Figure 2.

Table 2: Harmonic voltage distortion levels in 11kV system for PVIS as a percentage

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

However, a simple method for estimating the acceptable penetration levels of harmonic current sources (PVIS) is proposed by equation (6) based on Figure 4.

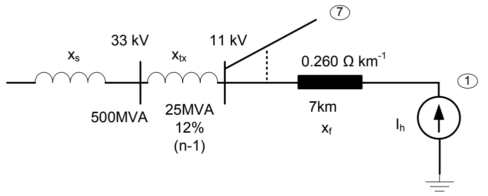

Figure 4: Estimating the acceptable penetration level of PVIS, based on estimated 5^{th} harmonic parameters

$$\begin{aligned} V_{h,std} &= 5.1\% \rightarrow 5^{th} harmonic \\ I_{h,inv} &= 2.82\% \rightarrow 5^{th} harmonic \\ P_{max} &= \frac{V_{h,std}}{(x_f + x_{tx} + x_s) I_{h,inv}} \\ P_{max} &= \frac{0.051}{(0.05 + 0.06 + 0.0268)0.0282} \\ P_{max} &= 268\% \end{aligned} \tag{6}$$

where $V_{h,std}$ is the recommended harmonic voltage planning level [7], $I_{h,inv}$ represents the modelled inverters' harmonic current magnitude, P_{max} represents the maximum acceptable penetration level based on system parameters and x_f, x_{tx} and x_s are the corresponding impedances of the system.

The derived acceptable penetration levels of PVIS exclusive of background distortions revealed a significantly higher numbers (a difference of approximately 17 units of PVIS) compared to inclusive of background distortion levels, as seen in Table 3. Hence, inclusion of background distortion is essential when determining the acceptable penetration levels of PVIS in MV systems.

Table 3: The summary of results representing the four comparison conditions in determining the acceptable penetration levels of PVIS

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

(1) * – Harmonic voltage to compare
(2) ** – Including diversity as suggested [7] [8]
(3) 40^{th},31^{st} – Format of results based on two distinct harmonics

The acceptable penetration level study of PVIS without diversity but including the background distortion in the

MV system has shown that the 40^{th} harmonic exceeds the limits at approximately 18% acceptable penetration levels (approximately 32 PVIS units) and the limiting odd harmonic was the 31^{st} harmonic, exceeding the harmonic voltage limit at 23% acceptable penetration level (approximately 41 PVIS units), as shown in Figure 6. However as suggested in [7], the MV harmonic

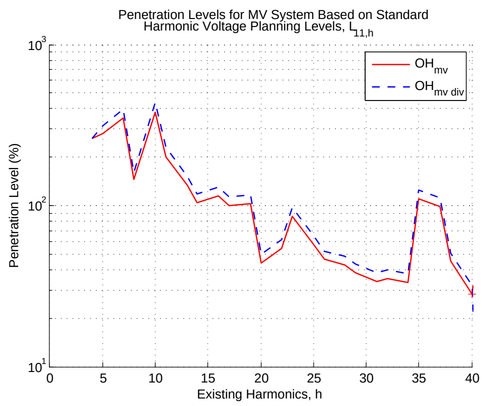

Figure 5: Penetration levels of LV PVIS on MV system with limiting voltages as harmonic voltage planning levels [7] on long overhead open wire distribution feeders

distortion levels are better expressed with phase and time magnitude diversity among the distortion contributors. The acceptable penetration level study of PVIS with diversity including the background distortion in MV system has shown that the 40^{th} harmonic exceeds the limits at approximately 20% acceptable penetration levels (approximately 36 PVIS units), and the limiting odd harmonic was the 31^{st} harmonic, exceeding the harmonic voltage limit at 27% acceptable penetration level (approximately 47 PVIS units), as shown in Figure 6. Individual harmonic magnitudes corresponding to the number of acceptable PVIS units are provided as additional detail in Appendix, Table 6.

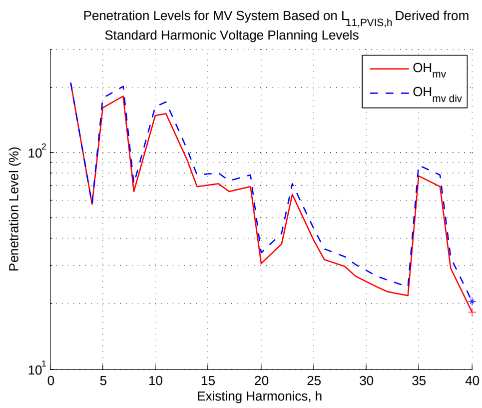

Figure 6: Penetration levels of LV PVIS on MV system with limiting voltages as harmonic voltage limits given by Table 2 on long overhead open wire distribution feeders

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

Table 4: The effect of I_h Reduction on Penetration Levels (%)

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

(1) * – Including Diversity among the Distortive Sources [7] [8]
(2) $31^{st}(40^{th})$ – Results based on two distinct harmonics

achieved through improving filtering or inverter switching techniques. For a reduction of I_h by 30% the results showed that for the to 40^{th} harmonic, the limits were exceeded at approximately 29% acceptable penetration levels (approximately 51 PVIS units), and the limiting odd harmonic was the 31^{st} harmonic, exceeding the harmonic voltage limit at 38% acceptable penetration level (approximately 67 PVIS units) with inclusion of background and appropriate diversity as given by Table 4.

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

5. Conclusion

This paper proposes a method for calculating the acceptable penetration levels of low voltage residential type photovoltaic inverter systems in medium voltage distribution systems based on limits recommended in the relevant Australian harmonic standards.

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

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

The acceptable penetration levels from the residential type photovoltaic systems injecting their full rated current at LV system was shown to be approximately 21% for the even harmonic (40^{th}) and 27% for the odd harmonic (31^{st}) corresponding to approximately 72kW and 94kW of energy, respectively.

With the possibility of better filtering where I_h is reduced by 30%, the acceptable penetration levels of residential type photovoltaic systems reached 29% for the 40^{th} harmonic and 38% for the 31^{st} harmonic corresponding to approximately 100kW and 133kW of energy, respectively.

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

Future work required for this study includes the analysis of the resulting acceptable penetration levels of LV PVIS in power distribution network configurations consisting of common feeder types.

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6. APPENDIX

Table 5: Modelled Harmonic Current Emission Spectrum of a Representative 2kW Inverter [1]

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

Table 6: Shows the acceptable penetration level of PVIS units in MV system before exceeding the voltage limits given in Table 2 for individual harmonics

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