

2006

Harmonic impact of photovoltaic inverter systems on low and medium voltage distribution systems

Ahmed Ahsan Latheef
University of Wollongong

Follow this and additional works at: <https://ro.uow.edu.au/theses>

University of Wollongong

Copyright Warning

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site.

You are reminded of the following: This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author. Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material.

Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Latheef, Ahmed Ahsan, Harmonic impact of photovoltaic inverter systems on low and medium voltage distribution systems, M.Eng. thesis, School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, 2006. <http://ro.uow.edu.au/theses/627>

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Harmonic Impact of Photovoltaic Inverter Systems on Low and Medium Voltage Distribution Systems

A thesis submitted in fulfilment of the
requirements for the award of the degree

Masters of Electrical Engineering

from

UNIVERSITY OF WOLLONGONG

by

Ahmed Ahsan Latheef
Bachelor of Engineering (Hons)

SCHOOL OF ELECTRICAL, COMPUTER
AND TELECOMMUNICATIONS ENGINEERING
2006

Abstract

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 increase. However, the issue of quality of the electrical supply is as equally important as adopting sustainable energy. This thesis proposes a method to determine the quality of electrical supply based on the acceptable level of harmonic current that can be injected from a typical grid connected residential type photovoltaic inverter system (PVIS). The acceptable number of PVISs is based on not exceeding the recommended harmonic voltage levels in medium voltage (MV–11kV) and low voltage (LV–415V) distribution systems given in standard AS/NZS 61000.3.6-2001 and its application guide HB 264-2003.

To undertake this study, an acceptable frequency domain model of a typical power system is developed, an appropriate model of a typical inverter spectrum is proposed and a method for allocating harmonic voltage distortion levels for PVIS in MV and LV systems by incorporating background distortion is suggested. The harmonic voltage distortion levels caused by the residential type PVIS are calculated based on conventional methods such as nodal analysis applied over the distribution network.

A typical residential power system is adapted from the available literature. The LV distributors of the power system were modelled based on residential load and PVIS aggregation, and MV feeders are modelled based on distribution transformer aggregation. The distributors selected for LV systems study are based on overhead

open–wire conductor, aerial bundled conductor and underground cabling types and the MV system feeders are based on an open–wire overhead conductor system. Residential load for harmonic studies is modelled based on the duration of equipment usage (with typical household ratings) during the power generation (active time) of the PVIS. Active time of the PVIS is estimated from field measurement data.

Since the LV system is of multiple earth neutral (MEN) construction, an additional system study is required to investigate the effective neutral harmonic impedance. This study revealed the significance of the zero sequence impedance of the system to show the importance of representing the neutral current within the study. Consequently, the acceptable number of PVIS units is limited by triplen harmonic voltage magnitudes suggested by recommended harmonic voltage levels.

Studying the available literature revealed that the development of a harmonic current spectrum to represent a typical photovoltaic inverter's line current is required. Hence, an adequate harmonic current spectrum was developed being selected from three distinct methods. The PVIS spectrums were modelled up to 40th harmonic, and an appropriate model was selected from among the three proposed models based on their compliance to recommended harmonic current emission levels, both individual and total, as suggested by standards. Examining the harmonic range up to 40th revealed that recent LV distribution network harmonic studies associated with PVIS are not wide enough in harmonic range to show some important network wide harmonic issues.

Allocation of harmonic voltage distortion levels for the LV PVIS was based on the background distortion level and recommended harmonic voltage planning levels and the suggestion in standards to incorporate sufficient diversity for the MV and LV distribution systems contribution. Background harmonic voltage distortion levels were calculated based on published data related to field measurements from dedicated residential feeders in distribution systems.

This study has proposed and identified a method to assess the harmonic distortion levels in MV and LV distribution systems, and related key issues, to assist the harmonic management of these systems due to grid connected PVIS.

Statement of Originality

This is to certify that the work described in this thesis is entirely my own, except where due reference is made in the text.

No work in this thesis has been submitted for a degree to any other university or institution.

Signed

Ahmed Ahsan Latheef

December, 2006

Acknowledgments

I would like to thank my parents for their constant support given to me throughout the time of my studies, their encouragement for me to move forward with my studies during the most depressed times is invaluable. I would also like to thank my wife and my son for their patience and understanding, when long hours were spent on studies instead of being with them.

I am very grateful to those who assisted me in this work; my supervisor Dr Vic Smith for constant support and his contribution to publications from this study, Prof Vic Gosbell for his continuous technical support and guidance from the early stage of this work to the submission of this thesis, Dr Duane Robinson for his supervision during the initial stage of this work and Integral Energy for their assistance in providing with technical data. I am honoured to have worked with a team of extremely high technical knowledge and experience in the field.

Contents

1	Introduction	1
1.1	Thesis Statement	1
1.2	Thesis Objective	1
1.3	Methodology	2
1.4	Thesis Layout	3
1.5	Publications Based on Work Performed for this Thesis	5
2	Literature Review	6
2.1	Introduction	6
2.2	Introduction to Solar Power	6
2.3	Main Systems of Solar Power Generation	8
2.4	Power Quality Issues Related to PVIS	17
2.5	Literature Review Summary	19
3	Standards Overview	21
3.1	Introduction	21
3.2	Standards for Regulating Harmonic Distortion Levels in Electrical Power Systems	22
3.2.1	IEEE std 519	22
3.2.2	IEC 61000-3-6	23

CONTENTS	viii
3.2.3 Application of Summation Law in IEC 61000-3-6	25
3.2.4 Comparison between the IEEE std 519 and IEC 61000-3-6 on Harmonic Assessing	26
3.3 Other Standards Related to Connection of Energy Sources with the Electrical Power System	28
3.3.1 AS 4777–2002 Family	29
3.3.2 IEEE 1547–2003 and IEEE std 929-2000	30
3.4 Chapter Summary	31
4 Inverter Current Harmonic Spectrum Modelling	32
4.1 Introduction	32
4.2 Proposed Approach for Representing I_h Spectrum	33
4.3 Modelling Methodology	35
4.3.1 Data Preparation	35
4.3.2 Details of Modelling Methods	36
4.3.3 Modelling Method Using Statistical Approach based on 95 th Percentile	37
4.3.4 Modelling Method based on Average Harmonic Magnitude .	38
4.3.5 Modelling Method Based on Selecting an Existing Harmonic Magnitude	39
4.4 Proposed Model	41
4.5 Limitation on I_h Manufacturer Data	44
4.6 Chapter Summary	44
5 Medium and Low Voltage System Modelling	46
5.1 Introduction	46
5.2 Selecting a Medium and Low Voltage System	47
5.2.1 Transformer Details	48

CONTENTS	ix
5.2.2 Low Voltage System	50
5.2.3 Open wire Overhead Bare Conductor type	54
5.2.4 Aerial Bundled Conductor type	54
5.2.5 Underground Cable type	55
5.2.6 Medium Voltage System	60
5.3 Determination of Acceptable Penetration Levels of PVIS	63
5.4 Limitation on the representation of system impedance	64
5.5 Chapter Summary	64
6 Multiple Earth Neutral Grounding in Residential Areas	65
6.1 Introduction	65
6.2 Methodology	67
6.3 Results	70
6.4 Chapter Summary	73
7 Harmonic Voltage Distortion Levels for PVIS in 11kV and 415V Distribution Systems	74
7.1 Introduction	74
7.2 Vulnerability of Systems to Standard Harmonic Current Spectra . .	76
7.2.1 Determining Inverter Spectra for Vulnerability Study	76
7.2.2 Determining an Effective Magnitude to Represent the Critical harmonic	78
7.3 Harmonic Voltage Distortion Levels for PVIS in the 415V System .	80
7.3.1 Representing an Existing Distortion Level For 415V Systems	80
7.3.2 Representing the Upstream (11kV) System Distortion in the 415V System	85
7.3.3 Proposed Harmonic Voltage Distortion Levels for PVIS in the 415V System	86

CONTENTS	x
7.4 Harmonic Voltage Distortion Levels for PVIS in the 11kV System	86
7.4.1 Representing the Distortion Contribution in the 11kV System Due to Existing 415V System Equipment	88
7.4.2 Representing Distortion in the 11kV System due to the Upstream (33kV) System	89
7.4.3 Proposed Harmonic Voltage Distortion Levels for PVIS in 11kV System	89
7.5 Limitations on Modelling the background V_{THD} distortion levels	90
7.6 Chapter Summary	90
8 Presentation of Results	92
8.1 Introduction	92
8.2 Results from Vulnerability of Systems to Standard Harmonic Spectra, from Section 7.2	93
8.3 Impact of LV PVIS on Harmonic Voltage Distortion Levels for 11kV and 415V Systems, from Chapter 5	95
8.3.1 Penetration Level of PVIS Results for 415V System, (from Section 5.2.2	95
8.3.2 Penetration Level of LV PVIS Results for 11kV System, (from Section 5.2.6	99
8.4 Results from Additional Studies	103
8.4.1 Study 1: Penetration Levels of LV PVIS when Shunt Load Component " R_{load} " becomes Significant Relative to System Impedance, (Appendix F	104
8.4.2 Study 2: Implementation of Harmonic Voltage Limits from IEEE Std 519, Chapter 3, (Section 3.2.1)	104
8.4.3 Study 3: Comparison of I_h Model with Field Measurements, Appendix H	105
8.5 Chapter Summary	107
9 Conclusions and Recommendations for Future Work	109

CONTENTS	xi
9.1 Introduction	109
9.2 Penetration levels of residential type photovoltaic systems on 415V Systems	110
9.3 Penetration levels of residential type photovoltaic systems on 11kV Systems	111
9.4 Additional Studies	112
9.5 Recommendations for Future Work	113
Bibliography	115
A Methodology	122
B Related Calculations	123
B.1 Distributor Parameter Calculations	123
B.1.1 LV Distributor Parameters	123
B.1.2 MV Feeders Parameters	124
B.2 Load Parameter Related Calculations	125
B.3 Example of Voltage Drop Calculation	128
B.3.1 Voltage Drop Across a LV Distributor	128
B.3.2 Voltage Drop Across an MV Feeder	129
B.4 Substation Transformer Impedance Calculation	129
B.5 Underground Cable Model	130
C Inverter Data	133
C.1 Raw Data from Literature	133
C.2 Normalised Data, $\bar{I}_{i,j}$	134
C.3 Additional Results Related to Section 4.3.4	135
D Domestic Equipment Contribution to LV System Distortion	136

E	Harmonic Spectra for Vulnerability study	139
F	Additional Study on the Significance of the Shunt Component in Residential Load Model	140
F.1	Introduction	140
F.2	Results	141
F.3	Conclusion	143
G	Additional details on Acceptable Penetration Levels	144
G.1	Additional Details related to 415V system	144
G.2	Additional Details related to 11kV system	145
H	Harmonic Current Spectrum Field Measurements	147
H.1	Introduction	147
H.2	Measuring Instrument	147
H.3	Acquired Graphs from the Measurements	148

List of Figures

2.1	Major building blocks of a typical solar powered system, conditions for grid synchronisation is achieved from the characteristics of inverter block in combination with filter block, on fundamental frequency and the harmonic limits that can be injected to the grid . . .	8
2.2	(Left) A mono crystalline solar panel of 175W and (Right) A polycrystalline solar panel of 165W, available ratings of solar panel can be used with manufacturers details to estimate the amount of roof area required to generate 2kW [1]	9
2.3	Equivalent Circuit of a PV module showing the diode and ground leakage currents [2]	10
2.4	The behaviour of the i-v characteristics at different illumination levels, adopted from [3]	10
2.5	The characteristics of the power output due to different illumination levels related to Figure 2.4, adopted from [3]	11
2.6	(Top) A transformer-less PVIS with line-commutated inverter designed to operate as a central system, adopted from [4]. (Bottom) A transformer-less design showing the filter connected (L-C-L) to grid, model developed to study different grid conditions [5]	14
2.7	A PVIS with boost converter, adopted from [4]	15
2.8	A PVIS design incorporating a transformer at the front end, adopted from reference [6]	15
2.9	(a) an LC filter and (b) LCL filter, as required for PVIS harmonic filtering in line currents	16
4.1	Resulting current harmonic magnitudes based on the statistical approach based on 95 th percentile	38

4.2	The variation in 3^{rd} , 5^{th} & 7^{th} harmonics and the resulting standard deviations for the observed range of harmonics in the study	40
4.3	Resulting current harmonic magnitudes based on the average harmonic current magnitude among the observed manufacturers	41
4.4	Current harmonic magnitudes based on selecting the highest magnitude method	42
4.5	Harmonic current magnitudes of a representative 2kW inverter and recommended emission limits from [7]	43
5.1	The single line diagram of the complete MV/LV system to be used in the study	48
5.2	The equivalent circuit of a typical practical transformer. Ideal transformation is represented by “T” with turns ratio of N_1 and N_2 corresponding to primary and secondary side respectively.	49
5.3	Typical LV distribution system	51
5.4	A typical method of lumping loads on the center of the distributor	52
5.5	The aggregated loads on three branches, representing a typical distribution system	53
5.6	The aggregated residential loads at the distributor level	57
5.7	Proposed load model	58
5.8	Schematic of system model including the feeder impedance and representation of the aggregated distribution transformers as harmonic current sources	62
6.1	a) The available physical distance of the phase plane b) The complex depth and the earth return plane [8] and c) The 4-wire power system layout and their return paths	68
6.2	Carson’s Line, representing a unit length of an overhead power line with ground return [9]	68
6.3	Four wire Low Voltage system under study, showing mutual impedance for phase ‘a’	70
6.4	The change in zero-sequence impedance over the range of harmonics	71

6.5	a) Zero-sequence impedance b) The earth impedance in parallel with neutral impedance	72
6.6	The phasor representation of the earth current and neutral current with reference to Figure 6.3	72
7.1	The modelled harmonic spectrum from the standard current harmonic magnitudes [7] of a 2kW inverter system	79
7.2	Current Harmonic Spectrum of a 36W Fluorescent Lamp	81
7.3	Current Harmonic Spectrum of an 11W CFL	82
7.4	Current Harmonic Spectrum of a SMPS on a Personal Computer	83
7.5	Current Harmonic Spectrum of a 1000W Microwave oven at steady state	84
7.6	Simplified diagram of the system to show the cause of the harmonic voltage distortion levels due to 415V distorting equipment	87
8.1	[TOP] Three graphs represent the effective magnitude (addressed in Section 7.2.2, page 78) of selected models from the standard harmonic emission levels, and [BOTTOM] Graph represents the effective magnitude of the current harmonic spectrum from the standard [7] and the modelled spectrum	94
8.2	The allowable harmonic voltage distortion levels for PVIS	96
8.3	Penetration levels as a percentage of distribution transformer rating of PVIS on LV systems with limiting voltages as harmonic voltage planning levels [10] with common types of low voltage distribution feeders	97
8.4	Penetration levels as a percentage of distribution transformer rating of PVIS in LV systems with harmonic voltage limits derived from [10] inclusive of background distortion levels ($L_{415,PVIS,h}$) with common types of low voltage distribution feeders	98
8.5	Penetration levels along the overhead type distributor	98
8.6	Estimating the acceptable penetration level of PVIS, based on estimated 5 th harmonic parameters	99

8.7	Penetration levels of LV PVIS as a percentage of distribution transformer rating on MV system with limiting voltages as harmonic voltage planning levels [10] on long overhead open wire distribution feeders	101
8.8	Penetration levels of LV PVIS as a percentage of distribution transformer rating on MV system with limiting voltages as harmonic voltage limits given by Chapter 7, Table 7.4 on long overhead open wire distribution feeders	102
8.9	Penetration levels of PVIS on 415V systems with harmonic voltage limits derived from IEEE std 519 [11].	105
8.10	Comparison of the standard [7], field measurement and developed model	106
A.1	A comprehensive understanding of the major building blocks in achieving the main objective of this study	122
B.1	(a) A typical LV distribution system and (b) Shows the impedance diagram of Figure (a)	128
B.2	(a) Adopted model to represent the UG cable (b) The selected UG model is modified to allow an accessible mid-point on the cable for harmonic voltage calculation (c) The proposed model for the UG cable to be used in this study	131
D.1	Current Wave Form of a 1000W Microwave at start up	137
D.2	Current Harmonic Spectrum of a 1000W Microwave at start up	137
D.3	Current Harmonic Spectrum of TV	138
F.1	Changing impedance of system and load against frequency	141
F.2	Changing impedance of the load over loading level of the transformer	142
H.1	Hioki 3196, used for power quality analysis	148
H.2	The daily 95 th percentile value of harmonic current for phases A, B and C	148
H.3	The maximum I_h of the daily 95 th percentile value for harmonic current from phases A, B and C	149

H.4	The rms value of the current in phase A, B and C taken over the period of monitoring	149
H.5	The fundamental current magnitude in phase A, B and C taken over the period of monitoring	150
H.6	The third harmonic current magnitude in phase A, B and C taken over the period of monitoring	150
H.7	The fifth harmonic current magnitude in phase A, B and C taken over the period of monitoring	151
H.8	The seventh harmonic current magnitude in phase A, B and C taken over the period of monitoring	151

List of Tables

3.1	Harmonic voltage limits, IEEE 519 [11]	22
3.2	Harmonic Current Distortion limits as a percent of I_L (first row in Table 10.3, IEEE std 519 [11])	23
3.3	Recommended Harmonic Voltage Planning levels for 415V, 11kV and 33kV Australian distribution Systems [10]	24
3.4	Summation exponents for the application of Second Summation law [10]	26
3.5	Standard harmonic current limits for grid connected energy systems via inverters rated <10kVA, [7]	29
4.1	Modelled Harmonic Current Emission Spectrum of a Representative 2kW Inverter	43
5.1	Table showing the insignificance of the typical per-unit shunt impedance of practical transformers in the range 3kVA to 250kVA [12]	50
5.2	Some of the residential equipment electrical characteristics. It should be noted that the definition of distorting equipment is relative to how much harmonic current is taken from the system in comparison to other equipment. Chapter 7 provides typical residential equipment harmonic current spectra that contributes to background distortions.	56
7.1	Existing distortion $L_{O,415,h}$ levels scaled based on β_h	85
7.2	Harmonic Voltage levels in 415V systems for PVIS, reference to equation (7.3)	87
7.3	Existing distortion $L_{11,415,h}$ levels scaled for 11kV system based on β_h	88

7.4	Harmonic Voltage levels in 11kV system for PVIS, referred to equation (7.5)	90
8.1	LV System Parameters	96
8.2	The effect of I_h Reduction on Penetration Levels Based on $L_{415,PVIS,h}$	99
8.3	The summary of results representing the four comparison conditions in determining the acceptable penetration levels of PVIS	100
8.4	The effect of I_h Reduction on Penetration Levels (%)	103
C.1	Raw Data from [13], [14] and [15] as published	133
C.2	All inverter harmonic currents rated to 2kW and standardised to [7], $\bar{I}_{i,j}$	134
C.3	Shows the variation and the standard deviation for the observed harmonics related to Figure 4.2 Section 4.3.4, Modelling Method based on Average Harmonic Magnitude	135
C.4	The I_h magnitudes produced by three analysed methods, without THD adjustment	135
E.1	Categorised three harmonic spectra from the standard [7] satisfying the total harmonic distortion condition of 5%. The I_h is reduced by 15% for use in the system vulnerability to harmonic spectra study. .	139
F.1	Shows the harmonics which limit the acceptable penetration levels of PVIS for different system loading levels, subjected to the emission of the current harmonic spectrum modelled in Chapter 4	143
G.1	Shows the maximum number of units that can be connected to 415V system with OH, ABC and UG distribution type feeders before exceeding the voltage planning levels given in [10] Table 3.3 for individual harmonics	144
G.2	Shows the maximum number of units that can be connected to 415V system with OH, ABC and UG distribution type feeders before exceeding the voltage limits incorporating background distortion levels given in Table 7.2 for individual harmonics	145

-
- | | | |
|-----|--|-----|
| G.3 | Shows the maximum number of units that can be connected within the 415V systems before exceeding the 11kV system's harmonic voltage planning levels given in [10] Table 3.3 for individual harmonics | 145 |
| G.4 | Shows the acceptable penetration level of PVIS units in 11kV system before exceeding the voltage limits given in Chapter 7, Table 7.4 for individual harmonics | 146 |

List of Abbreviations

PV	Photovoltaic
PVIS	Photo-Voltaic Inverter System
MV	Medium Voltage
LV	Low Voltage
THD	Total Harmonic Distortion
V_h	Harmonic voltage
V_{THD}	Voltage Total harmonic Distortion
PQ	Power Quality
I_h	Inverter Harmonic Current
h	Represents the harmonic number (Multiple of the fundamental, 50Hz)
$L_{415,h}$	Harmonic Voltage Planning Level for 415V system [10]
$L_{11,h}$	Harmonic Voltage Planning Level for 11kV system [10]
$L_{33,h}$	Harmonic Voltage Planning Level for 33kV system [10]
$L_{O,415,h}$	Distortion contribution due to existing 415V system equipment
$L_{415,PVIS,h}$	Allowable V_h contribution to PVIS for the 415V system
$L_{11,PVIS,h}$	Allowable V_h contribution to PVIS for the 11kV system
$L_{11,415,h}$	Distortion contribution due to existing 415V system equipment in 11kV system
$x_{s,tx,h}$	Impedance of the Transformer and Upstream at h^{th} harmonic
x_{tx}	Transformer impedance
α	Harmonic Summation exponent [10]
β_h	Background Harmonic allocation factor at h^{th} harmonic
GMD	Geometric Mean Distance

L_{PVIS}	Allowable distortion Limit for the PVIS
PCC	Point of Common Coupling
IEEE	Institute of Electrical and Electronics Engineers, Inc
IEC	International Electrotechnical Commission
ABC	Aerial Bundled Conductor system voltage feeder type
OH	Overhead open wire system voltage feeder type
UG	Underground system voltage feeder type
S_{INV}	Rating of the inverter
V_{INV}	Voltage at the point of grid connection of the inverter system
AAC	Aluminum Alloy Conductor
UG	Underground Cabling
ABC	Aerial Bundled Conductor
V_{BUS}	Voltage at the transformer side of a MV feeder or LV distributor
V_{MID}	Voltage at the mid-point of a MV feeder or LV distributor
V_{END}	Voltage at the end of a MV feeder or LV distributor
Z_{load}	Residential load impedance