THE UNIVERSITY OF ADELAIDE

School of Electrical and Electronic Engineering

# Investigation and Analysis of Decentralised Multilevel Modular Integrated Converters in Small Scale Grid-Tied PV Systems

A Thesis Submitted for the
Degree of Doctor of Philosophy

By

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*I dedicate this thesis to Yuli Chen.*

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# I. Abstract

This research focuses on the analysis of multilevel voltage interleaving for decentralised cascaded micro inverters in small scale photovoltaic (PV) grid tied applications. These decentralised cascaded micro inverters, otherwise known and modular integrated converters (MICs), have previously been implemented both with multilevel voltage interleaving (requires fast and reliable communications for PV power tracking) and without (requires no communications). The approach proposed by this research utilises a hybrid of both multilevel and non-multilevel switching, which reduces the communications requirement down to less than one system-wide update per second (whilst still allowing for a reduced filter size and lower switching frequency). In addition to the benefits of multilevel switching, the cascaded topology does not require a high gain DC-DC boost stage and maintains the ability to track the power of each PV panel independently.

It was found that the optimal number of MICs for a cascaded system should be between 4 and 8 and that such a system should utilise a 1$^{st}$ order inductive filter. Prototype MICs were developed and a comparison was made between a parallel and 2-MIC cascaded system that found an increase in both the efficiency (94.8% to 95.9%) and the total harmonic distortion (THD) (4.8% to 5.2%) for the cascaded system. Additionally, a grid zero-crossing detection error of just 4° in the cascaded system generated enough harmonics to exceed allowable THD limits. The implemented 4-MIC decentralised cascaded system utilised a round robin greedy sorting algorithm to sort power blocks for PV multilevel power tracking with an allocation error generally below 2%. Accounting for typical solar irradiance transient conditions and harmonic standards, it was found that a communications update rate of 0.7Hz is required. Additionally, it was found that grid-tied cascaded MICs have fundamental power sharing ratio limitations that restrict the maximum shading of one MIC to 74% in the 4-MIC system.

## II. Statement of Originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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**Signed**: David Scholten **Date**: 26/03/17

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## IV. Publications

[1] D. Scholten, N. Ertugrul, Wen L. Soong, "Micro-Inverters in Small Scale PV Systems: A Review and Future Directions", Australasian Universities Power Engineering Conference, (AUPEC 2013), 29th September, 2013.

[2] D. Scholten, N. Ertugrul, Wen L. Soong, "Analysis and Control of Decentralized PV Cascaded Multilevel Modular Integrated Converters", IEEE Energy Conversion Congress and Exposition (ECCE 2016).

Pending Publications:

[3] D. Scholten, N. Ertugrul, Wen L. Soong, "Detailed Analysis of Decentralised Multilevel Cascaded and Parallel Photovoltaic Converters", International Journal of Electrical Power & Energy Systems (2016).

[4] D. Scholten, N. Ertugrul, Wen L. Soong, "Analysis and Control of Decentralized PV Cascaded Multilevel Modular Integrated Converters", Journal of Emerging and Selected Topics in Power Electronics (2017).

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# VII. Abbreviations & Acronyms

| | |
|---|---|
| AC | Alternating Current |
| ADC | Analogue to Digital Converter |
| BOM | Bill Of Materials |
| CEC | California Energy Commission |
| CHB | Cascaded H-Bridge |
| DAC | Digital to Analogue Converter |
| DC | Direct Current |
| DMC | Decentralised Multilevel Cascaded |
| DIP | Dual In-line Package |
| DPP | Differential Power Processing |
| EOP | Ethernet Over Power |
| FC | Flying Capacitor |
| HF | High Frequency |
| HVDC | High Voltage Direct Current |
| IDE | Interactive Development Environment |
| IEEE | Institute of Electrical & Electronic Engineers |
| MIC | Modular Integrated Converter |
| MPP | Maximum Power Point |
| MPPT | Maximum Power Point Tracking |
| NPC | Neutral Point Clamped |
| PCB | Printed Circuit Board |
| PF | Power Factor |
| PLC | Power Line Communications |
| PV | Photo-Voltaic |
| PWM | Pulse Width Modulation |
| RMS | Root Mean Squared |
| SPWM | Sinusoidal Pulse Width Modulation |
| THD | Total Harmonic Distortion |

## VIII. Symbols

$C$ ........ Capacitance
$f$ ........ Frequency
$I_D$ ........ Diode Current
$I_{DC}$ ........ Average Current (DC)
$I_{MPP}$ ........ Maximum Power Point Current
$I_{photon}$ ........ Photon-Influenced Current
$I_{Ripple(pp)}$ ........ Peak-to-Peak Current (AC)
$I_{RMS}$ ........ Root Mean Squared Current
$I_{SC}$ ........ Short Circuit Current
$IV$ ........ Current-Voltage
$L$ ........ Inductance
$P_{Avg}$ ........ Average Power
φ ........ Phase Angle
$P_{Max}$ ........ Maximum Power
p-n ........ Positive-Negative
$R_s$ ........ Series Resistance
$R_{sh}$ ........ Shunt Resistance
$V_{DC}$ ........ Average Voltage (DC)
$V_{MPP}$ ........ Maximum Power Point Voltage
$V_{OC}$ ........ Open Circuit Voltage
$V_{Ripple(pp)}$ ........ Peak-to-Peak Voltage (AC)
$V_{RMS}$ ........ Root Mean Squared Voltage
ω ........ Angular Velocity
$Z_C$ ........ Capacitive Impedance
$Z_g$ ........ Grid Impedance
$Z_L$ ........ Inductive Impedance
$Z_{th}$ ........ Thevenin's Equivalent Impedance