Impedance-Source Network Power Converters

by

Yam P. Siwakoti

B. Tech. (*1st*), M.E. (*magna-cum-laude*)

Dissertation submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

Department of Engineering

Faculty of Science and Engineering

Macquarie University

Australia

December, 2014

Acknowledgements

I would like to thank my supervisor Professor Graham E. Town for his continuous encouragement, support and guidance throughout my PhD.

I would also like to express my profound gratitude to my adjunct supervisor Professor Frede Blaabjerg and mentor Professor Poh Chiang Loh from the Department of Energy Technology (DET), Aalborg University, Denmark, for their support, encouragement and guidance during my offsite research. They stood by me whenever I encountered any difficulties during my research.

A special thank you goes to Professor F. Z. Peng and Assistant Professor Shuitao Yang at the Department of Electrical and Computer Engineering, Michigan State University, USA for all the input on collaborative publications.

I would also like to extend my appreciation to Dr Keith Imrie for his thorough grammatical editing of some of my publications and thesis.

It was a great pleasure to work at DET during the summer of 2013. I would like to thank Mr Cam Pham and Mr Walter Neumayr and Associate Professor Søren Juhl Andreasen for delightful discussions and support.

I sincerely appreciate the financial support from the International Macquarie University Research Excellence Scholarships (iMQRES), Maquarie University Postgraduate Research Fund (MQ PGRF), the Australian Research Council (ARC) and ARC linkage industry partner TriQuint Semiconductor Inc. USA, which made this research and my stay in Australia possible.

I am truly and deeply indebted to Ms Anki Khurana for her kind help and support during my undergraduate studies. I would like to thank all my school teachers from

Sikkim (India) and also like to thank my undergraduate supervisor Professor Raj Kumar Jarial (NIT Hamirpur, India), my first mentor in power electronics. This journey would not have been possible without their help, support and encouragement.

Family is extremely important to me in all likelihood because I am blessed to have such a wonderful one. I want to thank my brothers, sisters, sister-in-laws, my father-in-law and brother-in-law for their help, encouragement and understanding during various ups and downs of my life. It is a pity my father passed away in 1997 and mother in 2013 and did not see this day. At least they lived long enough to know that I would get here. Their intelligence, compassion and love are deep within me and provide a lifelong inspiration. I miss them.

With deepest love, I would like to thank my wife Ramala and little son Kishan. They are always there with me with their love, support, understanding and encouragement in every endeavour, which enhanced my life to a larger extent.

Finally, let me express my deepest gratitude to God for His blessings.

Statement of Candidate

I certify that the work presented in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree to any other university or institution other than Macquarie University.

I also certify that the thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged.

In addition, I certify that all information sources and literature used are indicated in the thesis.

Yam P. Siwakoti

December, 2014

Abstract

The research described in this thesis covers the analysis and design of impedance-source networks for a wide range of electric power conversion applications (dc-dc, dc-ac, ac-dc, ac-ac). Various impedance networks, circuit topologies and modulation techniques were analysed, designed and tested in the laboratory to improve the performance (efficiency, reliability and power density) of the converter. To achieve this, three distinct approaches were taken in this research, which include: i) investigate and implement a new modulation technique, ii) retrofit existing topologies to get an improved hybrid topology, and iii) investigate a novel converter topology with desired performance.

In the first approach, a new modulation technique called "*optimised PWM control with shoot-through during zero-states*" was developed to improve the performance of any impedance-network-based dc-dc converter with an intermediate H-bridge switching topology. Compared to classical modulation techniques, the new modulation technique minimises the number of switching commutations of the power switches and reduces the switching losses of the converter whilst achieving Zero Voltage Switching (ZVS). This improves efficiency of the converter specially working at higher frequency. Further, the digital implementation of the proposed technique is simple and requires fewer resources (comparators, registers, logic gates, memory *etc.*) available within the digital platforms, *e.g.* FPGA, DSP and microcontroller.

In the same context, a modified space vector pulse-width-modulation technique (Odd SVPWM) with a reduced number of commutations of the power switches was investigated and analysed to minimise the common-mode voltage and leakage current

of a 3-phase quasi-Z-source inverter. The modulation technique is useful in a transformerless grid-connected inverter for solar photovoltaic system, which has strict safety requirements. The modulation technique was also implemented in a transformerless 3-phase quasi-Z-source inverter for ac drives to reduce the common-mode voltage and common-mode currents.

The second approach was accomplished by amalgamation of a quasi-Z-source impedance network with a push-pull switching topology. The resulting new dc-dc converter uses fewer switches, has a smaller common duty cycle and a smaller turns ratio of the transformer compared to existing topologies. This converter has improved power density, efficiency and reliability, making it suitable for applications which demand a wide range of voltage gain such as distributed generation and dc power supplies found in telecommunication, aerospace and electric vehicles.

Finally, a versatile Y-shaped impedance network was invented for applications in converters requiring a very high voltage gain. To achieve that, the proposed network uses a tightly coupled three-winding inductor. The obtainable voltage gain of this converter is presently not matched with any other impedance network-based converter operated at the same duty ratio. The proposed impedance network also has more degrees of freedom for varying its gain, and hence provides more design freedom to meet its requirements. These advantages are more prominent when applied to inverter design. The inverter can produce a very high voltage gain while simultaneously operating at a higher modulation index, which minimises the switching device stress, better utilises the input voltage (dc-link voltage) and produces better output waveforms compared to classical impedance-network-based inverters. The incommensurate properties of this network open a new horizon to researchers and engineers to explore, expand and modify the circuit to suit a wide range of power conversion applications.

List of Original Publications

This is a thesis by publication and includes 17 publications that have undergone the peer review process. Unlike a traditional thesis, in a thesis by publication the involvement of collaborators is required to be clarified.

Unless otherwise stated, I had the primary responsibility for the work contained in each of these publications, which included initial conception of the work, the development of the idea into a working theory, the analysis and design of a system from this theory, and the actual writing up of the work for publication. The order of authors indicates the level of contribution to each work. The second co-author typically indicates that they had provided the initial idea for the research that I have pursued, reviewed and offered valuable support and guidance during the publication process.

The following list (not in temporal order) summarises my contributions as author of this thesis by publication. Numbering reflects the chapter and order in which the work is presented.

Chapter 1:

[P1.1] **Yam P. Siwakoti**, F. Z. Peng, F. Blaabjerg, P. C. Loh and Graham E. Town, "Impedance Source Network for Electric Power Conversion – Part I: A Topological Review," *IEEE Transaction on Power Electron.*, vol. 30, no. 2, pp. 699-716, Feb. 2015.

[P1.2] **Yam P. Siwakoti**, F. Z. Peng, F. Blaabjerg, P. C. Loh, G. E. Town and S. Yang, "Impedance Source Network for Electric Power Conversion – Part II:

Review of Control and Modulation Techniques," *IEEE Transaction on Power Electron.*, vol. 30, no. 4, pp. 1887-1905, Apr. 2015.

[P1.3] **Yam P. Siwakoti** and G. E. Town, "Design of FPGA-controlled Power Electronics and Drives using MATLAB Simulink," in *Proc. 5th IEEE Annual International Energy Conversion Congress and Exhibition (ECCE) Asia 2013 Downunder*, Melbourne, Australia, pp. 571-577, June 3-6, 2013.

Chapter 2:

[P2.1] **Yam P. Siwakoti** and G. E. Town, "Improved Modulation Technique for Voltage Fed Quasi-Z-Source DC/DC Converters," in *Proc. Twenty-Ninth Annual IEEE Applied Power Electronics Conference and Exposition (APEC 2014)*, Fort Worth, TX, pp. 1973-1978, March 16-20, 2014.

[P2.2] **Yam P. Siwakoti** and G. E. Town, "Three-phase Transformerless Grid Connected Quasi Z-Source Inverter for Solar Photovoltaic Systems with Minimal Leakage Current," in *Proc. 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Aalborg, Denmark, June 25-28, 2012, pp. 368-373.

[P2.3] **Yam P. Siwakoti** and G. E. Town, "Common-Mode Voltage Reduction Techniques of Three-Phase Quasi Z-Source Inverter for AC Drives," in *Proc. Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Long Beach, CA, March 17-21, 2013, pp. 2247-2252.

Chapter 3:

[P3.1] **Yam P. Siwakoti**, F. Blaabjerg, P. C. Loh and G. E. Town, "A High Voltage Gain Quasi-Z-Source Isolated DC/DC Converter," in *Proc. IEEE International*

Symposium on Circuits and Systems (ISCAS), Melbourne, Australia 1-5 June 2014, pp. 2441-2444.

[P3.2] **Yam P. Siwakoti**, F. Blaabjerg, P. C. Loh and G. E. Town, “A High Gain Quasi-Z-Source Push-Pull Isolated DC/DC Converter,” *IET Power Electron.,* vol. 7, iss. 9, pp. 2387–2395, 2014.

Chapter 4:

[P4.1] **Yam P. Siwakoti**, P. C. Loh, F. Blaabjerg and G. E. Town, “Y-Source Impedance Network,” in *Proc. Twenty-Ninth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Fort Worth, TX, March 16-20, 2014, pp. 3362-3366.

[P4.2] **Yam P. Siwakoti**, P. C. Loh, F. Blaabjerg and G. E. Town, “Y-Source Impedance Network,” *IEEE Trans. Power Electron. (Letter),* vol. 29, no. 7, pp. 3250-3254, Jul. 2014.

[P4.3] **Yam P. Siwakoti**, P. C. Loh, F. Blaabjerg, S. J. Andreasen and G. E. Town, “Y-Source Impedance Network Based Boost DC/DC Converter for Distributed Generation,” *IEEE Trans. Ind. Electron.,* DOI: 10.1109/TIE.2014.2345336.

[P4.4] **Yam P. Siwakoti**, P. C. Loh, F. Blaabjerg and G. E. Town, “Y-Source Impedance Network Based Isolated Boost DC/DC Converter,” in *Proc. IEEE International Power Electronics Conference, IPEC-Hiroshima 2014-ECCE Asia*, 18-21 May, 2014, pp. 1801-1805 **[INVITED PAPER]**.

[P4.5] **Yam P. Siwakoti**, P. C. Loh, F. Blaabjerg and G. E. Town, “Magnetically Coupled High Gain Y-Source Isolated DC/DC Converter,” *IET Power Electron.,* vol. 7, iss. 11, pp. 2817–2824, 2014.

[P4.6] **Yam P. Siwakoti**, P. C. Loh, F. Blaabjerg and G. E. Town, "Y-Source Inverter," in *Proc. IEEE PEDG2014 Conference*, NUI Galway, Ireland, pp. 1-6, 24-27 June 2014.

Chapter 5:

[P5.1] **Yam P. Siwakoti**, P. C. Loh, F. Blaabjerg and G. E. Town, "Effects of Leakage Inductances on Magnetically-Coupled Impedance-Source Networks," in *Proc. EPE-ECCE Europe 2014,* pp. 1-7, 26-28 August 2014.

[P5.2] **Yam P. Siwakoti**, P. C. Loh, F. Blaabjerg and G. E. Town, "Effects of Leakage Inductances on Magnetically-Coupled Y-Source Network," *IEEE Tran. Power Electron. (Letter)*, vol. 29, no. 11, pp. 5662-5666, Nov. 2014.

Chapter 6:

[P6.1] **Yam P. Siwakoti** and G. E. Town, "Performance of Distributed DC Power System Using Quasi Z-Source Inverter Based DC/DC Converters," in *Proc. Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC),* Long Beach, CA, March 17-21, 2013, pp. 1946-1953.

This thesis is dedicated to my late parents.

For their endless love, support and encouragement

Table of Contents