

CERTAIN INVESTIGATIONS ON IMPEDANCE SOURCE INVERTERS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI**

APRIL 2016

CERTAIN INVESTIGATIONS ON IMPEDANCE SOURCE INVERTERS

by

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Department of Electrical Engineering

Submitted in fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

APRIL 2016

CERTIFICATE

This is to certify that the thesis entitled “**CERTAIN INVESTIGATIONS ON IMPEDANCE SOURCE INVERTERS**” being submitted by **Mr. Chandra Shekar Thelukuntla** for the award of degree of **Doctor of Philosophy** is a record of a bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi, New Delhi. Mr. Chandra Shekar Thelukuntla, worked under my guidance and supervision and has fulfilled the requirement for the submission of the thesis, which to my knowledge has reached the requisite standards. The matter embodied in this thesis has not been submitted to any other University or Institute for the award of any Degree or Diploma.

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ACKNOWLEDGEMENTS

It gives me immense pleasure in expressing regards and deep sense of gratitude to my esteemed supervisor Prof. M. Veerachary, Department of Electrical Engineering, Indian Institute of Technology - Delhi, India, for introducing the methodology to do research. He has been teaching and guiding me about self-discipline in laboratory work and in written scientific communication. I would like to thank him for his invaluable guidance and constant encouragement throughout the period of doctoral program.

I would like to thank my fellow research scholars in Power Electronics Lab Anmol Ratna Saxena, R. Kalpana, B. Amarendra Reddy, Vargil Kumar E., Sudhakar Ch., Priyesh, Shikha and Swati. I would also like to thank M. Tech students Suresh, Kamlesh, Krishna Mohan, Satish, Prashant, Sachin, Firehun, Lokesh, V. Praveen, Mallesham, Madan Mohan, Dileep Ganta, Krishna Mohan, Srinath N., Amar Singh, M.N.V. Bhavana, for their helpful discussions, support and friendship. I am also thankful to R&D colleagues at Sukam Power Systems Pvt., Limited for their support.

I would like to express my deep sense of gratitude to my S.R.C. members, Dr. Nilanjan Sen Roy, Dr. Bijaya Ketan Panigrahi, Associate Professors, Department of Electrical Engineering, and Dr. T. S. Bhatti, Professor, Centre for Energy Studies, IIT Delhi, for their constructive remarks, useful and timely suggestions and guidance.

I would like to thank Prof. Bhim Singh, Head of the Department, Prof. J.K. Chatterjee, Prof. G. Bhuvaneswari, Prof. K.R. Rajagopal, Dr. Amit Jain, of Department of Electrical Engineering, for their encouragement and support.

I would also like to express my sincere thanks to Sri. Gurcharan Singh, Sr. Technical Superintendent, Mr. Amit Kumar, Jr. Technical In-charge, and Sri. S.S. Negi, Lab technician, of Power Electronics lab, for their help during my research work.

Last but not least, I am highly indebted to my beloved wife Mrs. T. Laxmi, son T. Kedar, beloved mother Mrs.T. Dhanamma, father Sri. T. Narasimha, , Sri. K.

Keshavulu, Smt. K. Chandrakala, brother T. Ramlingam, brother-in-law K. Suman and other family members for their unconditional support and sacrifice without which, it would not have been possible to complete the PhD.

While writing this page of my thesis, I express my immense pleasure in acknowledging all those who directly and indirectly helped me in completing the work successfully.

Chandra Shekar Thelukuntla

ABSTRACT

Multi-stage power processing is widely used in dc-ac conversion. However, to achieve higher efficiencies, reduction in number of stages as well as switching devices is desirable. In this context, single-stage dc-ac inverters are better from the efficiency point of view. Moreover, single-stage power conversion topologies require lesser number of control-loops that are sufficient to ensure stable and reliable power conversion. On account of lesser control-loops the degree of freedom is reduced, from control point of view, and imposes duty ratio limitations. Its impact can easily be minimized through an appropriate controller structure, where-in the control-loops has to act in such a way to give optimal pulse width pattern to the single-stage inverter. Therefore, investigations in this thesis are mainly targeted to address the following issues of impedance source inverters: (i) modeling and analysis of impedance source inverters: (a) Z-source inverter, (b) Quasi Z-source inverters, and (c) X-source inverter. (ii) design and optimization of controllers to ensure dc and ac side regulation, (iii) Direct and indirect control of dc-link voltage in the impedance source inverters, (iv) Control of Z-source inverter with constant, adaptive shoot-through duty ratio and modulation indices.

The present work focuses on single-phase single-stage inverter topologies, that are formed by cascade connection of impedance source network with H-bridge inverter. These topologies have embedded buck-boost feature, ease of control, and fewer number of switching devices. The boosting of the dc-link voltage in such topologies is achieved through the impedance source network by controlling the duty ratio termed as shoot-through duty ratio (STDR). This STDR is integrated within the zero state of

inverter switching cycle and does not affect the volt-sec balance of the downstream inverter. Since, the modulation index corresponding to the inverter load voltage unaltered the dc-link voltage; boost control is independent of pulse width modulation associated with the ac-side load voltage regulation. However, at each operating point the sum of shoot-through duty ratio, required for boost control, and the duty ratio determined by the modulation index for load voltage regulation should be maintained constant. Exhaustive investigations on control of Z-source inverters with constant shoot-through duty ratio and modulation index limits are made and in certain cases the Z-source inverter found to be working with saturated limits of duty ratios leading to either insufficient boosting or ac load voltage droop or distortion. In order to overcome these limitations, an algorithm is proposed in this thesis for adaptive selection of saturation limits. Its effectiveness is demonstrated through simulation studies and then prototype experimental measurements.

Although, impedance source topologies belong to single stage conversion systems, but they need suitable controllers to: (i) meet load demand, (ii) handle source and load side variations, (iii) achieve better regulation, and (iv) yield reliable and stable power processing. The reliability of impedance source inverters not only depends on its steady-state design but depends on the controller design as well. In this direction, this thesis makes an attempt to design control schemes ensuring the above stated requirements. Mathematical models of impedance source inverters are formulated through signal flow-graphs. A proportional plus resonant controller is designed to attain the ac load voltage regulation. A design procedure is established to identify all possible proportional plus integral controller parameters to directly control the dc-link voltage. Since, the dc-link voltage in impedance source topologies is of

pulsating nature an appropriate sensing scheme is required. To avoid these limitations, due to the sensing, an indirect dc-link voltage control through Z-source capacitor voltage regulation is proposed. Although, the capacitor voltage sensing is not a difficult task but the simple proportional plus integral controller, used in direct dc-link voltage, is not suitable on account of control-to-Z-source capacitor transfer function. In order to achieve Z-source capacitor voltage control, a proportional plus integral plus derivative controller structure is proposed in this thesis. Stabilizing regions of the three controller parameters (k_p , k_i , and k_d) are generated by solving a set of non-linear inequality equations, after enforcing Hermite-Biehler theorem satisfying the interlacing property. An important property of these regions is that all admissible controller combinations, easily identifiable without needing trial and error tuning, ensures closed-loop system stability and also closely satisfies the design specifications. A manual selection of optimal and yet feasible controller parameters from these stabilizing regions is a challenging task. In view of this, a particle swarm optimization based search technique is used in this thesis to identify the optimal controller parameters, from the known stabilising regions, based on the minimisation of integral time absolute error (ITAE) performance index subject to the relative stability constraints. The developed models are used in design of controllers and their feasibility is demonstrated on a Z-source inverter to ensure dc and ac side regulation. The theoretical predictions have been validated through experimental investigations.

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LIST OF SYMBOLS AND ABBREVIATIONS

$G_{pid}(s)$	PID controller transfer function
$H_z(s)$	Sensor gain transfer function
$G_{v_o d_m - o - I}^t(s)$	terminated Control-to-load voltage transfer function
$G_{v_{dclink} d_s - o - Z}^u(s)$	Unterminated Control-to-dc-link voltage transfer function
$G_{v_c d_s}^u(s)$	Unterminated Control-to-Z-source capacitor voltage transfer function
AST	Active-state
$DCLV$	DC-link voltage
$DDCL$	Direct dc-link voltage
DG	Distributed Generation
D_s	Shoot-through duty ratio
EMI	Electromagnetic interference
f_s	Switching frequency
GM	Gain margin
$IDCL$	Indirect dc-link voltage
I_{dclink}	DC-link current
i_L	Instantaneous inductor current
I_L	Average Inductor current
i_o	Instantaneous load current
I_o	Load current
$ITAE$	Integral time absolute error
m	Modulation Index
MI	Modulation index
$MRPWM$	Modified reference Pulse width modulation
NST	Non Shoot-through state
$PI\ controller$	Proportional plus integral controller
$PID\ controller$	Proportional plus integral plus derivative controller
PM	Phase margin

<i>PR controller</i>	Proportional plus resonant controller
<i>PSO</i>	Particle Swarm Optimization
<i>QZCIC</i>	Quasi Z-source inverter with continuous input current
<i>QZDIC</i>	Quasi Z-source inverter with discontinuous input current
r_1/r_2	Inductor-1, 2 dc resistance
r_{c1}/r_{c2}	Capacitor-1, 2 equivalent series resistance
RHPZ	Right half s-plane zero
SFG	Signal flow graph
<i>SPWM</i>	Sinusoidal Pulse width modulation
<i>ST</i>	Shoot-through state
<i>STDR</i>	Shoot-through duty ratio
<i>SVPWM</i>	Space Vector Pulse Width Modulation
<i>THD</i>	Total harmonic distortion
T_s	One switching time period
V_o	Load voltage
V_c	Average Capacitor Voltage
v_C	Instantaneous capacitor voltage
V_{dc}	Source voltage
V_{dclink}	DC-link Voltage
v_{L1}/v_{L2}	Voltage across inductor-1, 2
v_{c1}/v_{c2}	Voltage across capacitor-1, 2
v_o	Instantaneous load voltage
<i>XSI</i>	X-Source Inverter
<i>ZCV</i>	Z-Source Capacitor voltage
<i>ZS</i>	Zero-state
<i>ZSI</i>	Z-Source Inverter
Δv_c	Peak-to-peak capacitor voltage ripple
Δi_L	Peak-to-peak inductor current ripple
ζ	Damping factor
ω_o	Inverter output voltage frequency in rad/sec