

**MODELING AND ANALYSIS OF PREDICTIVE  
CURRENT CONTROLLED HIGHER ORDER DC-DC  
CONVERTERS**

by

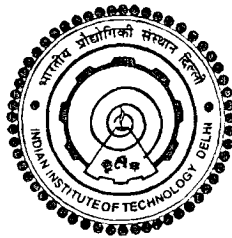
**SUDHAKARABABU CHAKKIRALA**

**DEPARTMENT OF ELECTRICAL ENGINEERING**

Submitted

In fulfillment of the requirements of the degree of Doctor of Philosophy

to the

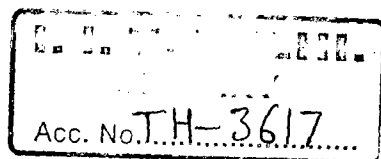
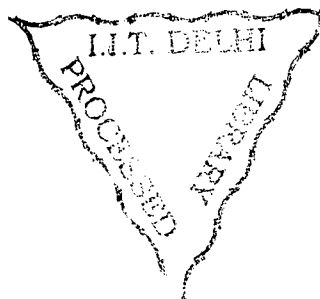


**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**JUNE 2008**

DC-DC Conversion  
Predictive Control

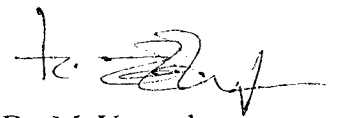
TH  
621.314.1  
CHA-M



## CERTIFICATE

This is to certify that the thesis entitled "*Modeling and Analysis of Predictive Current Controlled Higher Order DC-DC Converters*" being submitted by **Sudhakarababu Chakkirala** for the award of the degree of **Doctor of Philosophy** is a record of the original and bonafide research work carried out by him in the Electrical Engineering Department of Indian Institute of Technology Delhi.

Mr. Sudhakarababu Chakkirala worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results contained in it have not been submitted in part or full to any other University or Institute for award of any degree/diploma.



Dr. M. Veerachary

Department of Electrical Engineering

Indian Institute of Technology Delhi

New Delhi - 110 016

India

Date: 03/10/2008

## ACKNOWLEDGMENTS

I would like to express my most sincere gratitude and appreciation to my advisor, Dr. M. Veerachary, for his continuous support, guidance, and encouragement throughout the course of this work. His valuable expertise, extensive vision, and advice made this work possible.

Especially, I would like to thank Prof. J. K. Chatterjee, Prof. T. S. Bhatti and Dr. G. Bhuvaneshwari for their helpful suggestions and comments regarding this work.

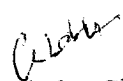
I would also like to extend my gratitude to Mr. Gurucharan Singh (Senior Technical Superintendent) and Mr. S.S. Negi (Lab Technician) for their outmost cooperation rendered in providing with the lab equipment and components at all times.

I am grateful to Mr. Tirath Khiara, R&D Head of Delta Energy Systems (India) Pvt. Ltd, and my colleagues in Delta for their encouragement and support during my thesis writing.

It has been a great pleasure associating with the excellent faculty, staff, and students at the Power Electronics Laboratory (PEL), Electrical Engineering Department, IIT Delhi. Working at PEL has been really an enriching experience, with an exciting and immensely supporting environment, and the overall atmosphere have made my stay at IIT Delhi pleasant and enjoyable. I can never forget the numerous helps from my friends K.S. Phani Kiranmi, Sihnoy, Mr. Anmol Saxena, Mr. T. Chandra Shekar and M.Tech students.

I would like to especially thank my friends at IIT Delhi, Dr. Vijay Krishna, Dr. Ranga Rao, Murali, Dr. Raghvendra kumar, and Navneet kumar Pandey, for their constant encouragement and co-operation throughout my stay in IIT Delhi.

I express my heart full thanks to my family for making me exhilarated with their moral support throughout this work. Without their love and support it would not have been possible to complete this thesis. I would like to thank for their enormous patience levels they have shown.

  
Sudhakarbabu Chakkirala

## ABSTRACT

As the domain of interest, in the field of dc-dc conversion, is increasing in the direction of digital solutions, both in power management and controllers design, exploring suitability and evolving advanced digital controllers is very much needed. Further, dynamic performance improvement of the dc-dc converters, includes variety of topologies simple to complex system, is the major concern of the designer. This motivates the need for proposing the digital predictive controller's solution to the dc-dc converters. In this direction the thesis develops certain predictive current control strategies for higher order dc-dc converters. The work presented in this thesis addressed mainly the following aspects: (i) dc-dc converters discrete modeling and then proposed generalized small-signal models, (ii) predictive current control schemes for higher order dc-dc converters, and (iii) stabilization of current control schemes through proper selection of pulse-width-modulation strategy.

Basic dc-dc converters are widely used in many applications but they present certain limitations such as high ripple currents and EMI problems, etc. Adding filter stage can able to rectify the problem, but they effect the dynamical properties. To overcome some of the disadvantages of the second order topologies, fourth order buck, boost and interleaved boost converter circuits are introduced and their operation, modeling aspects are closely investigated. Several different control strategies, in analog domain, have been introduced for stable operation of the converter and dynamic performance improvement. Current mode control scheme is one such scheme that results in better dynamic performance but, however, this scheme may become unstable for certain operating conditions. This unstable phenomenon, sub-harmonic oscillations, is also problematic even in digital current mode control

schemes. The control algorithms implemented in digital domain are mostly based on the principles of analog control schemes and hence digital controllers also exhibit similar kind of stability issues. However, in digital controllers these issues need to be handled in a different manner and one such strategy is modulation scheme selection.

This thesis investigates the digital predictive controller's stability (i) based on the magnitude of current to be controlled: average, peak and valley current control, together with different modulation schemes: trailing, leading and triangle modulation, and (ii) fixed and variable frequency current control schemes. These investigations show that appropriate selection of modulation technique together with predictive current control scheme capable of avoiding subharmonic oscillations irrespective of its operating duty ratios. All these controllers are realized, in digital domain, based on single sample per switching cycle.

The source voltage or load perturbations have an impact on the load voltage and hence there is a need to design a closed-loop controller to ensure load voltage regulation together with better dynamic response. The controller design as well its performance mainly governed by the converter system models. Particularly, in the digital controller design the accuracy is depends on the discrete state-space equation solution and approximations used in it. In this thesis a modified bilinear discrete modeling method, its accuracy is almost equivalent to the exact discrete modeling, is established. Small-signal models, based on modified bilinear discrete modeling method, are established and then used in the subsequent digital controller designs. Predictive current controller's dynamic performance compared with the digital average current mode and voltage mode control techniques. Predictive current control shows faster dynamic response as compared to other digital control schemes reported

in this thesis. The performance improvement of the converter, both steady-state and dynamic, is studied by including the coupling among the inductors.

Variable frequency predictive current control stability aspects under different modulation techniques are analyzed. This analysis shows that the system is stable, irrespective of the modulation strategy used, for average, peak and valley current control schemes. Further, variable frequency control schemes yields better dynamic performance than the fixed frequency control schemes. All the above theoretical predictions have been validated through simulation and experimental investigations.

# TABLE OF CONTENTS

	<b>Page No</b>
ABSTRACT	i
Table of Contents	iv
List of Figures	viii
List of Tables	xii
List of Acronyms	xiii
Nomenclature	xiv
<b>Chapter I</b>	
Introduction	
1.1 General Introduction	1
1.2 Review of the Past Work	5
1.3 Scope and Objectives of the Thesis	10
1.4 Organization of the Thesis	12
1.5 Salient Contributions of the Thesis	14
<b>Chapter II</b>	
Second and Higher Order DC-DC Converters	
2.1 Introduction	17
2.2 Second and Higher order DC-DC converters	17
2.2.1 Buck Converter	17
2.2.2 Buck Converter with Input Filter	19
2.2.3 Fourth Order Buck Converter	21
2.2.4 Fourth Order Buck Converter with Integrated Inductor	23
2.2.5 Boost Converter	25
2.2.6 Boost Converter With Output Filter	26
2.2.7 Fourth Order Boost Converter	28
2.2.8 Coupled Inductor Fourth order boost converter	31
2.2.9 Interleaved Boost Converter	32
2.3 Conclusions	35
<b>Chapter III</b>	
Modeling of Higher Order Converters	
3.1 Introduction	36
3.2 Fourth Order Buck Converter	37
3.3 Fourth Order Boost Converter	39
3.4 Interleaved Boost Converter	41
3.5 Discrete-Time Modeling and Comparative Analysis of Different Modeling Techniques	44
3.6 Small-Signal Model Development for the Modified Discrete Modeling Method	50
3.7 Conclusions	53
<b>Chapter IV</b>	
Generalized Analysis of Predictive Current Control Schemes and their Stability Aspects	
4.1 Introduction	54
4.2 Modulation Techniques	55

4.3	Current Mode Control scheme	56
4.4	Predictive Current Control Law	57
4.5	Predictive Current Control under Trailing Edge Modulation	58
4.5.1	Valley Current Control under Trailing Edge Modulation	59
4.5.2	Peak Current Control under Trailing Edge Modulation	61
4.5.3	Average Current Control under Trailing Edge Modulation	64
4.6	Predictive Current Control under Leading Edge Modulation	67
4.6.1	Peak Current Control under Leading Edge Modulation	68
4.6.2	Valley Current Control under Leading Edge Modulation	69
4.6.3	Average Current Control under Leading Edge Modulation	72
4.7	Predictive Current Control under Trailing Triangle Edge Modulation	75
4.7.1	Average Current Control under Trailing Triangle Edge Modulation	76
4.7.2	Valley Current Control under Trailing Triangle Edge Modulation	78
4.7.3	Peak Current Control under Trailing Triangle Edge Modulation	80
4.8	Predictive Current Control under Leading Triangle Edge Modulation	83
4.8.1	Average Current Mode Control under Leading Triangle Edge Modulation	84
4.8.2	Valley Current Control under Leading Triangle Edge Modulation	86
4.8.3	Peak Current Control under Leading Triangle Edge Modulation	88
4.9	Conclusions	91

## Chapter V

	Predictive Current Control of Fourth Order Converters	
5.1	Introduction	94
5.2	Predictive Current Control of Fourth order Buck Converter	94
5.3	Predictive Current Control Law under Trailing Edge Modulation	95
5.3.1	Valley Current Control	96
5.3.2	Peak Current Control	97
5.3.3	Average Current Control	98
5.3.4	Signal Flow Graph	98
5.3.5	Simulation Results	100
5.4	Predictive Current Control under Leading Edge Modulation	104

5.5	Predictive Current Control under Leading Triangle Edge Modulation	108
5.6	Predictive Current Control under Trailing Triangle Edge Modulation	112
5.6.1	Simulation Results	114
5.7	DSP Based Real-Time Implementation	118
5.7.1	Introduction to Analog DSP Admc401	118
5.7.2	Overview of Real-Time Controller Implementation	118
5.7.3	Experimental Results and Discussions	121
5.8	Predictive Current Control of Fourth order Boost Converter	123
5.9	Predictive Current Control Laws under Trailing Edge Modulation	124
5.9.1	Stability Analysis in Frequency Domain	125
5.9.2	Simulation Results	126
5.9.3	Experimental Results	132
5.10	Predictive Current Control under Leading Edge Modulation	135
5.10.1	Stability Analysis in Frequency Domain	135
5.11	Predictive Current Control under Leading Triangle Edge Modulation	139
5.11.1	Stability Analysis in Frequency Domain	139
5.12	Predictive Current Control under Trailing Triangle Edge Modulation	142
5.12.1	Stability Analysis in Frequency Domain	143
5.13	Conclusions	148
<b>Chapter VI</b>	<b>Compensator Design for Fourth Order Converters</b>	
6.1	Introduction	149
6.2	Digital Compensators Design Methodologies	149
6.3	Compensator Design for Fourth Order Buck Converter	150
6.4	Compensator Design for Fourth Order Boost Converter	159
6.5	Conclusions	169
<b>Chapter VII</b>	<b>Predictive Current Control of Interleaved Boost Converter</b>	
7.1	Introduction	170
7.2	Interleaved Boost Converter	170
7.3	Predictive Current Control	172
7.3.1	Predictive Average Current Control	174
7.3.2	Predictive Peak Current Control	175
7.3.3	Predictive Valley Current Control	175
7.3.4	Stability Analysis	176
7.3.4.1	Predictive Average Current Control	177
7.3.4.2	Predictive Peak Current Control	179
7.3.4.3	Predictive Valley Current Control	180
7.3.5	Experimental Results and Discussions	181
7.4	Conclusions	190

<b>Chapter VIII</b>	<b>Variable frequency Predictive Current Control of Fourth Order Boost Converter</b>	
8.1	Introduction	192
8.2	Conventional Variable Frequency Digital Current Control	193
8.3	Fixed Frequency Predictive Current Control	195
	8.3.1 Fixed Frequency Predictive Average Current Control	197
	8.3.3 Fixed Frequency Predictive Valley Current Control	198
	8.3.2 Fixed Frequency Predictive Peak Current Control	199
8.4	Variable Frequency Predictive Current Control	201
	8.4.1 Variable Frequency Predictive Average Current Control	201
	8.4.2 Variable Frequency Predictive Peak Current Control	203
	8.4.3 Variable Frequency Predictive Valley Current Control	203
8.5	Stability Analysis of Current Control Loop	205
	8.5.1 Predictive Fixed Frequency Control	206
	8.5.2 Predictive Variable Frequency Control	208
8.6	Discussion on Simulation Results	210
8.7	Experimental Results	214
	8.7.1 Stability Analysis	214
	8.7.2 Load Voltage Regulation	218
8.8	Conclusions	221
<b>Chapter IX</b>	<b>Conclusions and Future Scope of Work</b>	
9.1	Conclusions	223
9.2	Future Scope of Work	225
References		227
Appendix I		235
Appendix II		238
Appendix III		239
Appendix IV		240
Bio-Data		242