ANALYSIS, MODELING AND CONTROL OF QUADRATIC TYPE WIDER STEP-DOWN GAIN DC-DC CONVERTERS

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MAY 2022

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by

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Submitted

in fulfilment of the requirements for the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2022

CERTIFICATE

This is to certify that the thesis entitled "**ANALYSIS, MODELING AND CONTROL OF QUADRATIC TYPE WIDER STEP-DOWN GAIN DC-DC CONVERTERS**" being submitted by **Mr. Shrikant Mohan Misal** 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.

Mr. Shrikant Mohan Misal has worked under my supervision and fulfilled the requirement for the submission of this thesis, which to my knowledge has reached the requisite standards. The embodied matter in this thesis has not been submitted to any other university or institute for the award of any degree.

Date: May, 2022

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ACKNOWLEDGEMENTS

This Ph.D. thesis is a compilation of research work carried out by me in the Electrical Engineering Department, IIT Delhi. It gives me immense pleasure to express heartfelt gratitude for my esteemed supervisor, **Prof. Mummadi Veerachary**, whose valuable guidance, profound advice and encouragement has led to the successful completion of this research work.

I would also like to extend my cordial thanks to all the SRC members: **Prof. Shaunak Sen**, **Prof. Ramkrishan Maheshwari**, **Prof. Amit Kumar Jain** and **Prof. T. S. Bhatti** for their valuable suggestions and constant motivation during the course of this work. I express a deep sense of indebtedness to **Prof. Jayadeva**, present Head of the Department and **Prof. Bhim Singh**, **Prof. S. D. Joshi** (previous Heads) as well as other faculty members for their constant motivation throughout my tenure at IIT Delhi. I am extremely grateful to **Visvesvaraya Ph.D. Scheme for Electronics & IT**, Government of India as well as **IIT-Delhi** for providing me financial assistance to carry out this project.

My sincere thanks to **Mr. Amit Kumar Prajapati**, **Mr. Vikas Mittal** and **Mr. Sagar Burla** for their utmost co-operation in rendering laboratory equipments and facilities all the time. I also want to extend the appreciation towards my beloved colleagues: Mr. Nikhil Kumar, Mr. Ambuj Sharma, Mr. Varun Chitransh, Ms. Jyoti Prakash, Mr. Punit Kumar, Mr. Priyabrata Shaw, Mr. Amarendra Reddy, Mr. Vargil Kumar and other fellow labmates, for their useful discussions, kind support and friendship. My special thanks to **Mr. Ambuj Sharma**, **Mr. Pradyumna Ranjan Ghosh**, **Mr. Nikhil Kumar** for their extended help and motivation in tough times. At this juncture, I derive immense pleasure in acknowledging all those people who directly or indirectly helped me to complete this research work successfully. Also, I take this opportunity to thank **Dr. B. P. Divakar**, Professor, REVA ITM Bangalore, whose constant motivation and guidance has made my journey to IIT Delhi possible.

Last but not the least, I would like to thank my parents, my wife, my elder sister and my brother in-law, for their unconditional love as well as moral support always. I am indebted to all the sacrifices made by them during the course of this research work.

Date: May, 2022 **Shrikant Mohan Misal**

ABSTRACT

Low voltage, high current functionalities are rapidly proliferating in modern point-of-load applications like microprocessors, battery chargers, LED ballasts, automotive drivetrains, portable electronic gadgets etc. To meet these supply requirements, traditional DC-DC buck converter suffers from switch under-utilization, constricted range of control, high device power stress and associated ripple current losses. Isolated DC-DC step-down converter topologies can provide wider conversion ratios, but they make substantial compromise on switching voltage/current surges, system volume, cost, transformer magnetizing losses and efficiency. As a result, development of non-isolated higher-order step-down converter topologies has garnered significant attention in recent years.

Through this thesis, such advanced transformerless topologies namely: sixth-order step-down converter, fifth-order step-down converter and fourth-order step-down converter, are introduced for point-of-load applications. Having quadratic type of wider voltage gain, these topologies facilitate an optimal trade-off between system order, switching elements and imposed voltage/current stress on the components. Their time domain analysis is carried out to anticipate steady-state behaviour and establish *L-C* design equations.

State-space averaged model for each topology is obtained and linearized transfer functions are evaluated, to subsequently design a fixed-frequency indirect sliding mode controller. The equivalent control law presented in this scheme is duly constituted from source side inductor current dynamics and load voltage error information, thus it provides simple realization as well as better transient response. Salient operational characteristics of the proposed topologies are analytically studied with simulation tools and subsequently validated using experimental outcomes of laboratory prototypes.

सार

माइक्रोप्रोसेसर, बैटरी चार्जर, एलईडी बलास्टस, ऑटोमोटिव ड्राइवट्रेन, पोर्टेबल इलेक्ट्रॉनिक गैजेट्स आदि जैसे आधुनिक पॉइंट-ऑफ-लोड अनुप्रयोगों में कम वोल्टेज, उच्च करेंट कार्यात्मकता तेजी से बढ़ रही है। इन आपूर्ति आवश्यकताओं को पूरा करने के लिए, पारंपरिक डीसी-डीसी बक कनवर्टर को झेलना पढता है – स्विच की काम उपयोगिता, सीमित नियंत्रण की सीमा, उच्च उपकरण शक्ति तनाव और रिप्पल करंट से सम्बंधित होनेवाले नुकसान। पृथक डीसी-डीसी स्टेप-डाउन कनवर्टर टोपोलॉजियाँ व्यापक रूपांतरण अनुपात प्रदान कर सकते हैं, लेकिन वे स्विचिंग वोल्टेज/करंट सर्ज, सिस्टम वॉल्यूम, महंगाई, ट्रांसफॉर्मर मैग्नेटाइजिंग लॉसेस और दक्षता पर पर्याप्त समझौता करते हैं। नतीजतन, हाल के वर्षों में गैर-पृथक उच्च-क्रम स्टेप-डाउन कनवर्टर टोपोलॉजियो के विकास ने महत्वपूर्ण ध्यान आकर्षित किया है।

इस थीसिस के माध्यम से, ऐसी बिना ट्रांसफॉर्मर वाली उन्नत टोपोलॉजियाँ जिनका नाम है : छठे-क्रम का चरण-डाउन कनवर्टर, पांचवें क्रम का चरण-डाउन कनवर्टर और चौथे क्रम का चरण-डाउन कनवर्टर, पॉइंट-ऑफ-लोड अनुप्रयोगों के लिए पेश कि गयी हैं। द्विघात प्रकार के व्यापक वोल्टेज लाभ होने के कारण, ये टोपोलॉजी सिस्टम ऑर्डर, स्विचिंग तत्वों और घटकों पर लगाए गए वोल्टेज/करंट तनाव के बीच एक इष्टतम व्यापार-बंद की सुविधा प्रदान करते हैं। उनका समय क्षेत्र विश्लेषण स्थिर-अवस्था व्यवहार का अनुमान लगाने और एल-सी डिजाइन समीकरण स्थापित करने के लिए किया गया है।

स्टेट-स्पेस औसत मॉडल प्रत्येक टोपोलॉजी के लिए प्राप्त किया गया है और रेखीयकृत स्थानांतरण कार्यों का मूल्यांकन हुआ है, बाद में एक निश्चित आवृत्ति अप्रत्यक्ष स्लाइडिंग मोड नियंत्रक को डिजाइन करने के लिए। इस योजना में प्रस्तुत समकक्ष नियंत्रण कानून विधिवत आपूर्ति की तरफ से आनेवाले इंडक्टर करंट की गतिशीलता और लोड वोल्टेज त्रुटि जानकारी से गठित है, इस प्रकार यह सरल प्राप्ति के साथ-साथ बेहतर क्षणिक प्रतिक्रिया प्रदान करता है। प्रस्तावित टोपोलॉजीयो की मुख्य परिचालन विशेषताओं का विश्लेषणात्मक रूप से सिम्युलेशन उपकरणों के साथ अध्ययन किया गया है और बाद में प्रयोगशाला प्रोटोटाइप के प्रयोगात्मक परिणामों का उपयोग करके सत्यापित किया गया है।

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LIST OF ABBREVIATIONS

DC	Direct Current
TBC	Traditional Buck Converter
EMI	Electromagnetic Interference
CCM	Continuous Inductor Current Mode
DCM	Discontinuous Inductor Current Mode
QBC	Quadratic Buck Converter
SOSDC	Sixth-Order Step-Down Converter
FSDC	Fifth-Order Step-Down Converter
FOSDC	Fourth-Order Step-Down Converter
KVL	Kirchoff's Voltage Law
KCL	Kirchoff's Current Law
RMS	Root Mean Square
ESU	Effective Switch Utilization
DPS	Device Power Stress
ESR	Equivalent Series Resistance
SMPS	Switch Mode Power Supply
TF	Transfer Function
LHP	Left Half of s-Plane
RHP	Right Half of s-Plane
PWM	Pulse Width Modulation
SMC	Sliding Mode Control
FFSMC	Fixed Frequency Sliding Mode Control

LIST OF SYMBOLS

f_s	Switching Frequency
V_g	Average supply voltage
v_o , V_o	Instantaneous and average load voltages
i_o , I_o	Instantaneous and average load currents
v_n , i_n	Instantaneous voltage and current quantities, with subscript '*n*' denoting the circuit elements
V_n	Peak voltage stress, with subscript '*n*' denoting the circuit elements
I_n , I_{nRMS}	Average and RMS current quantities, with subscript '*n*' denoting the circuit elements
M	Voltage conversion ratio for CCM operation
M_{DCM}	Voltage conversion ratio for DCM operation
A_{ON} , A_{OFF}	System Matrices for switch-ON and OFF case
B_{ON} , B_{OFF}	Input Matrices for switch-ON and OFF case
E_{ON} , E_{OFF}	Output Matrices for switch-ON and OFF case
D	Equilibrium switch duty signal
$\hat{v}_o$	Load voltage perturbation
$\hat{d}$	Duty ratio perturbation
$G_{vd}(s)$	Control-to-output transfer function
σ	Sliding surface
d_{eq}	Equivalent control signal
e	Load voltage error

X_{eq}	Equilibrium matrix of state variables in sliding dynamics
x_{cl}	Matrix for closed-loop sliding dynamics
A_{cl}	Linearized closed-loop system or Jacobian matrix