

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

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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

by

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Department of Electrical Engineering

Submitted

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



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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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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 बलास्ट्स, ऑटोमोटिव ट्राइबंदेन, पोर्टेबल इलेक्ट्रॉनिक गैजेट्स आदि जैसे आधुनिक पॉइंट-ऑफ-लोट अनुप्रयोगों में कम वोल्टेज, उच्च करंट कार्यात्मकता तेजी से बढ़ रही है। इन आपूर्ति आवश्यकताओं को पूरा करने के लिए, पारंपरिक डीसी-डीसी बक कनवर्टर को छेदना पड़ता है – स्विच की काम उपयोगिता, सीमित नियंत्रण की सीमा, उच्च उपकरण शक्ति तनाव और रिपल करंट से सम्बंधित होनेवाले नुकसान। पृथक डीसी-डीसी स्टेप-डाउन कनवर्टर टोपोलॉजियाँ व्यापक रूपान्तरण 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 टोपोलॉजियों 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-लोट अनुप्रयोगों के लिए पेश कि गयी हैं। डिप्लॉट 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 डिज़ाइन समीकरण स्थापित करने के लिए किया गया है।

स्टैट-स्पेस औसत मॉडल प्रत्येक टोपोलॉजी के लिए प्राप्त किया गया है और रेखीयकृत स्थानांतरण कार्यों का मूल्यांकन हुआ है, बाद में एक निश्चित आवृत्ति अग्रयुक्त स्लाइडिंग मोड नियंत्रक को डिज़ाइन करने के लिए। इस योजना में प्रस्तुत समकक्ष नियंत्रण कानून विधिवत आपूर्ति की तरफ से आनेवाले इंटकर्ट करंट की गतिशीलता और लोट वोल्टेज वुटि जानकारी से गठित है, इस प्रकार यह सरल प्राप्ति के साथ-साथ बेहतर क्षणिक प्रतिक्रिया प्रदान करता है। प्रस्तावित टोपोलॉजीयों की मुख्य परिवालन विशेषताओं का विश्लेषणात्मक रूप से सिमुलेशन 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_n, V_n	Instantaneous and average load voltages
i_n, I_n	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_{RMS}	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}_n	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