DEVELOPMENT, DESIGN AND ANALYSIS OF SWITCHING CAPACITOR BASED BUCK-BOOST CONVERTERS

VASUDHA KHUBCHANDANI

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

VASUDHA KHUBCHANDANI

Department of Electrical Engineering

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CERTIFICATE

This is to certify that the thesis entitled **“Development, Design and Analysis of Switching-Capacitor Based Buck-Boost Converters”** is submitted by **Ms. Vasudha Khubchandani** in fulfillment of the requirements for the degree of **Doctor of Philosophy** in the Department Electrical Engineering of Indian Institute of Technology Delhi, New Delhi.

Ms. Vasudha Khubchandani has worked under my supervision and fulfilled the requirement for submission of the thesis, which to my knowledge 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.

Date:

Prof. Mummadi Veerachary
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi-110016

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ABSTRACT

This thesis focusses on developing buck-boost dc-dc converter topologies by utilizing a switching-capacitor cell offering a variety of voltage gains. Firstly, a switching-capacitor cell buck-boost converter (SCBBC) Type-1 which has gain same as that of conventional buck-boost converter (CBBC) is evolved. Though its gain is same as that of CBBC i.e. $D/(1-D)$, it overcomes many limitations such as non-inverted load voltage polarity, common ground and non-pulsating source current. With the degree of freedom associated with two controllable switches, switching schemes are implemented to enable its multi-mode operation capability. With its primary feature of providing buck-boost conversion, realization of standalone buck as well as standalone boost functionality happens through simple gate control. The transition from buck mode to boost mode and vice-versa also happens seamlessly. Despite being operational under multi-mode, it exhibits low source current ripple. Detailed steady-state as well as small-signal analysis of the converter in all modes of operation is formulated. Exhaustive investigations pertaining to small-signal transfer functions revealed that it behaves as a minimum-phase system in buck-boost mode. In an attempt to reduce its source current ripple while keeping the voltage gain feature intact, the load side capacitor is shifted into the bypass path leading to formulation of SCBBC Type-2 topology. Detailed analysis is established for the SCBBC topologies (Type-1 and Type-2) and is validated through simulation and experimental measurements.

SCBBC Type-1 and Type-2 topologies voltage gain is identical to the buck-boost converter gain, wherein 0~50 % is the duty ratio range for bucking operation and the remaining duty ratio range (50~100 %) is for boosting. This voltage gain varies highly non-linearly with duty ratio and thus posing controlling issues particularly at higher duty ratios due to switching capacitor (C_1) action which exhibits gain $1/(1-D)$. To minimize this non-linear trend in gain variation, the duty ratio range for bucking operation is increased while reducing the duty ratio for boosting operation by replacing the switching-capacitor with a split capacitor cell. This split capacitor cell embedded SCBBC topology is named as modified switching-capacitor cell buck-boost converter (MSCBBC). Extensive mathematical analysis is established for the three MSCBBC topologies. Though these topologies are effective in extending the duty ratio range, they however need more number of components.

With an attempt to increase the voltage gain in the bucking range with reduced number of components, alternative topologies named as extended switching-capacitor based buck-boost converter (ESCBBC) topologies are evolved. This evolution is formulated by employing a switching-capacitor cell with an additional charge-pump cell. Two topologies are identified under this ESCBBC family i.e. ESCBBC Type-1 and Type-2. Both of them have identical voltage gain i.e. $1/2(1-D)$. Due to this, these converters offer fine-tuned duty-ratio feature in the buck range. A comparison of ESCBBC Type-1 and Type-2 converter showed that ESCBBC Type-2 inherits the features of ESCBBC Type-1 converter but also exhibits reduction in source current ripple close to 50 %. The converter also exhibited minimum-phase behaviour. Its steady-state analysis is followed by state-space model formulations. Analytical findings are validated with experimental observations. Although ESCBBC Type-2 converter may provide slight restrictions on account of voltage gain adaptability, it can reliably be employed in applications where higher variations occur in the battery voltage.

सारांश

यह थीसिस बक-बूस्ट डीसी-डीसी कनवर्टर टोपोलॉजीज़ के विकास पर केंद्रित है जिसमें एक स्विचिंग-कैपेसिटर सेल का उपयोग कर वोल्टेज गेन की विभिन्नता प्रदान की जाती है। पहले, एक स्विचिंग-कैपेसिटर सेल बक-बूस्ट कनवर्टर (SCBBC) Type-1 विकसित किया गया है जिसका गेन कनवेंशनल बक-बूस्ट कनवर्टर (CBBC) के समान है। इसके गेन CBBC के समान होने के बावजूद $D/(1-D)$, इसने गैर-उलटे लोड वोल्टेज पॉलारिटी, सामान्य ग्राउंड और गैर-पल्सेटिंग सोर्स करंट जैसी कई सीमाओं को दूर किया। दो नियंत्रणीय स्विचेज के साथ स्वतंत्रता के स्तर के साथ, स्विचिंग योजनाएँ को कार्यान्वित करने से इसकी मल्टी-मोड संभावना का संचालन संभव होता है। इसके प्राथमिक विशेषता बक-बूस्ट परिवर्तन प्रदान करने के साथ, सीधे गेट नियंत्रण के माध्यम से स्टैंडअलोन बक के साथ स्टैंडअलोन बूस्ट कार्यक्षमता का साक्षात्कार होता है। बक मोड से बूस्ट मोड और उल्टे की ओर भी स्वतंत्र रूप से होता है। मल्टी-मोड के तहत भी संचालन करने के बावजूद, इसमें कम सोर्स करंट रिप्पल प्रदर्शित होता है। स्टेडी-स्टेट और स्मॉल-सिग्नल विश्लेषण का विस्तृत अध्ययन, सभी संचालन मोड में कनवर्टर का सृजन होता है। स्मॉल-सिग्नल ट्रांसफर फंक्शन के संबंध में व्यापक अन्वेषणों ने बताया कि यह बक-बूस्ट मोड में एक मिनिमम-फेज सिस्टम के रूप में व्यवहार करता है। स्रोत करंट के रिप्पल को कम करने के प्रयास में, वोल्टेज गेन सुविधा को बरकरार रखते हुए, लोड साइड कैपेसिटर को बाईपास पथ में स्थानांतरित किया गया है जिससे SCBBC Type-2 टोपोलॉजी का निर्माण हुआ है। SCBBC टोपोलॉजियों (Type-1 और Type-2) के लिए विस्तृत विश्लेषण स्थापित किया गया है और इसे सिमुलेशन और प्रायोगिक मापनों से सत्यापित किया गया है।

एससीबीबीसी टाइप-1 और टाइप-2 टोपोलॉजी वोल्टेज गेन बक-बूस्ट कन्वर्टर गेन के समान है, जिसमें बकिंग ऑपरेशन के लिए 0~50 % ड्यूटी रेशियो रेंज है और शेष ड्यूटी रेशियो रेंज (50~100%) बूस्टिंग के लिए है| यह वोल्टेज गेन ड्यूटी रेशियो के साथ अत्यधिक गैर-रैखिक रूप से बदलता है और इसलिए उच्च ड्यूटी रेशियो पर नियंत्रण समस्याएँ पैदा कर सकती है, खासकर स्विचिंग कैपेसिटर (C_1) के कार्रवाई के कारण जो गेन $1/(1-D)$ प्रदर्शित करता है। इस गेन विविधता में अनियमित रुझान को कम करने के लिए, बकिंग ऑपरेशन के लिए ड्यूटी रेशियो रेंज को बढ़ाया गया है जबकि बूस्टिंग ऑपरेशन के लिए ड्यूटी रेशियो को कम किया गया है स्विचिंग-कैपेसिटर को एक विभाजित कैपेसिटर सेल से बदलकर। इस विभाजित कैपेसिटर सेल सम्मिलित SCBBC टोपोलॉजी को संशोधित स्विचिंग-कैपेसिटर

सेल बक-बूस्ट कनवर्टर (MSCBBC) के नाम से जाना जाता है। इन तीन MSCBBC टोपोलॉजियों के लिए व्यापक गणितात्मक विश्लेषण स्थापित किया गया है। ये टोपोलॉजी ड्यूटी रेशियो रेंज को बढ़ाने में प्रभावी होती हैं, हालांकि इन्हें अधिक संख्या में कॉम्पोनेंट्स की आवश्यकता होती है।

बकिंग रेंज में वोल्टेज गेन को बढ़ाने के साथ संख्या में कमी करने के प्रयास के साथ, वैकल्पिक टोपोलॉजियां विस्तारित स्विचिंग-कैपेसिटर आधारित बक-बूस्ट कनवर्टर (ESCBBC) टोपोलॉजियां विकसित की गई हैं। इस विकास को एक अतिरिक्त चार्ज-पंप सेल के साथ स्विचिंग-कैपेसिटर सेल का उपयोग करके फॉर्म्यूलेट किया गया है। इस ESCBBC परिवार के तहत दो टोपोलॉजियां पहचानी गई हैं, जैसे ESCBBC Type-1 और Type-2। दोनों में वोल्टेज गेन समान होता है, अर्थाता $1/2(1-D)$। इसके कारण, ये कनवर्टर्स बक रेंज में ड्यूटी-रेशियो विशेषता प्रदान करते हैं। ESCBBC Type-1 और Type-2 कनवर्टर की तुलना में पाया गया कि ESCBBC Type-2 ESCBBC Type-1 कनवर्टर की विशेषताओं को अनुसरण करता है, लेकिन सोर्स करंट रिप्पल में 50 % की कमी भी प्रदर्शित करता है। इस कनवर्टर में मिनिमम-फेज व्यवहार भी दिखाया गया। इसका स्थिर-स्थिति विश्लेषण के पश्चात राज्य-स्थान मॉडल फॉर्म्युलेशन किया गया है। विश्लेषणात्मक फिंडिंग्स को प्रायोगिक अवलोकनों से सत्यापित किया गया है। हालांकि ESCBBC Type-2 कनवर्टर वोल्टेज गेन अनुकूलन के कारण थोड़ी सी प्रतिबंधितता प्रदान कर सकता है, लेकिन यह विशेषताओं के साथ उपयोगी हो सकता है जहां बैटरी वोल्टेज में अधिक विविधता होती है।

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V_g	Source voltage
V_o	Load voltage
I_g	Source current
I_o	Load current
V_c	Average voltage across capacitor
I_L	Average current through inductor
P_g	Input Power
P_o	Output Power
η	Efficiency
i	Instantaneous current through inductor
Δi	Ripple in inductor
v_c	Instantaneous voltage across capacitor
Δv_c	Ripple in capacitor voltage
v_D	Voltage across diode
v_s	Voltage across switch
r	ESL of inductor
r_c	ESR of capacitor
r_{DS}	On-state resistance
R_F	Diode forward resistance
V_F	Diode forward voltage drop
X_{ss}	Steady-state Solution
D	Duty-ratio
f_s	Switching-frequency
T_s	Time-period
S	Sensitivity
T	Complimentary sensitivity
M_s	Maximum Sensitivity

LIST OF ABBREVIATIONS

SC	Switching-capacitor
SL	Switching-inductor
CD	Capacitor-diode
PCS	Power conversion system
KVL	Kirchoff’s voltage law
KCL	Kirchoff’s current law
CCM	Continuous conduction mode
DCM	Discontinuous conduction mode
EMI	Electro-magnetic interference
CBBC	Conventional buck-boost converter
TSBBC	Two switch buck-boost converter
NIBB	Non-inverting buck-boost converter
GM	Gain margin
PM	Phase margin
RHPZ	Right half of s-plane zero
SCR	Source current ripple
PWM	Pulse width modulation
RMS	Root mean square
PV	Photovoltaic
SCBBC	Switching-capacitor based buck-boost converter
MSCBBC	Modified switching-capacitor based buck-boost converter
ESCBBC	Extended switching-capacitor based buck-boost converter