

**DESIGN AND DEVELOPMENT OF
SOFT-TRANSITION NETWORKS FOR CHARGE-PUMP BASED
INTERLEAVED BOOST CONVERTERS**

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SOFT-TRANSITION NETWORKS FOR CHARGE-PUMP BASED
INTERLEAVED BOOST CONVERTERS**

by

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Submitted

**in fulfilment of the requirements of the degree of Doctor of Philosophy
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CERTIFICATE

This is to certify that the thesis entitled “**Design and Development of Soft-Transition Networks for Charge-Pump Based Interleaved Boost Converters**” is being submitted by **Ms. Jyoti Prakash** in fulfillment of the requirements for the degree of **Doctor of Philosophy** in the Department of Electrical Engineering of Indian Institute of Technology Delhi, New Delhi.

Ms. Jyoti Prakash has worked under my supervision and fulfilled the requirement for 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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ABSTRACT

Charge-pump based boost converters are effective in realizing high voltage boosting at moderate duty ratios while interleaved operation of individual boost topologies effectively reduces the ripples in the source current. Furthermore, due to interleaved operation the source current ripple frequency is double that of the individual cells switching frequency. Thereby, charge-pump based interleaved boost converters not only yield a high voltage gain but also exhibit improved source current ripple profile. With this motivation, this thesis investigates the performance improvement aspects of charge-pump based interleaved boost converters. Here, the attention is primarily on reduction of switching losses by reshaping the switch electrical quantities (voltage across the switch and current flowing through the switch) so that losses within the switching devices are either minimized or eliminated during transitions (i.e. switch-OFF to ON transition, switch-ON to OFF transition). Though the reshaping of voltage and current flowing through switch is possible in many ways, but this thesis has paid attention only to design and develop auxiliary transition networks which are feasible for fixed-frequency of operation.

The existing soft-switched interleaved boost converters invariably uses stand-alone zero-voltage and zero-current transition networks. Here, each switch has its associated auxiliary transition network. Although these schemes are shown to be effective in terms of soft-switching performance but the corresponding system power density is low on account of more number of components involved in the soft-switching networks. Moreover, the requirement of multiple active switches and the associated gate driver circuitry also adds to the control complexity of the interleaved boost converters. With the aim to reduce the number of auxiliary transition networks, firstly investigation pertaining to development of common soft-switching network for multi-phase interleaved boost converters is carried out. This is possible in interleaved converter topologies because the turn-ON/turn-OFF instants of the switches are phase-shifted by $360/N$, where 'N' is the number of interleaved boost cells and there is presence of sufficient time delay between any two turn-ON/turn-OFF instants. Use of common soft-switching network effectively reduces the number of resonating inductors, active switches and the associated gate driving circuit requirement. Based on this concept, a capacitor assisted zero-voltage zero-current transition network (ZVZCTN) is proposed for a charge-pump based dual boost converter (CPBBC). Here,

only one transition network is present but it ensures soft-transitions of two main switches with appropriate gating scheme. This transition network (composed of two diodes, an auxiliary switch, and a resonating inductor) ensures zero-voltage turn-ON and zero-current turn-OFF of the main switching devices; also ensures zero-current turn-OFF of the main diodes without imposing any extra voltage stresses on the devices. The auxiliary-capacitors which are connected across the diodes of the soft-switching network effectively controls the rate of fall of currents during turn-OFF of the main switches.

The above-mentioned capacitor-assisted soft-switching scheme ensures soft-switching during both turn-ON and turn-OFF transitions of the main switches; soft turn-OFF of the main diodes and ZCS turn-ON of the auxiliary switch. However, current sharing between the two switch branches during the transition zones may not be equal. Therefore, to resolve this issue, an auxiliary transformer based zero-voltage zero-current transition scheme is developed for dual-phase interleaved converters. This transition network is simple in structure and yet achieves effective soft-transitions (zero-voltage turn-ON as well as zero-current turn-OFF) for the main switches. It facilitates zero-current turn-OFF of all the diodes along with zero-current turn-ON of the auxiliary switch. Additionally, the auxiliary transformer self-adjusts the current in the auxiliary network depending upon the loading conditions and thus the reactive energy during the soft-switching is low for the entire range of loads. A detailed theoretical analysis is presented by considering a high step-up dual-phase interleaved boost converter as an example. The feasibility of the proposed soft-switching scheme is implemented on the same and its effectiveness is demonstrated through experimental results which are obtained on a 400 W converter prototype.

The two soft-transition networks mentioned above are effective in terms of soft-switching of the main switches both during turn-ON and turn-OFF transitions along with the ZCS turn-OFF of the main diodes. However, the auxiliary switch turns-OFF in hard-switched manner. To overcome this issue, a coupled inductor assisted zero-voltage transition network is proposed for dual-phase interleaved converters. It includes a dedicated auxiliary switch, a diode, and a coupled inductor for each phase of the interleaved converter. This proposed soft-transition network ensures complete

soft transitions to the main as well as the auxiliary devices. To ensure turn-ON of the primary switches with zero-voltage transition, the additional switches are activated before the gating signal is applied to their respective primary switch. The presence of coupled inductor in series with a voltage multiplier capacitor facilitates zero-current switching of all the diodes, thereby suppressing the reverse recovery associated losses. Detailed steady-state analysis, principle of operation and design considerations are discussed. A 24 - 200 V, 100 W converter, working at a frequency of 100 kHz is constructed to validate the theoretical studies. The transition loss reduction obtained through the proposed ZVZCT network is demonstrated through sample temperature measurements of heat-sinks associated with the switching devices. The measurements of the soft-switched prototype circuit demonstrated a $2 \sim 4$ % efficiency improvement over the hard-switched converter. Furthermore, all the proposed transition networks resulted in soft-transitions over a wide range of loads at a fixed frequency of operation.

सारांश

चार्ज-पंप आधारित बूस्ट कन्वर्टर मध्यम शुल्क अनुपात में उच्च वोल्टेज बूस्टिंग को साकार करने में प्रभावी होते हैं जबकि व्यक्तिगत बूस्ट टोपोलॉजी का इंटरलीव्ड ऑपरेशन प्रभावी रूप से स्रोत में तरंगों को कम करता है। इसके अलावा, इंटरलीव्ड ऑपरेशन के कारण सोर्स करंट रिपल फ्रीक्वेंसी अलग-अलग सेल स्विचिंग फ्रीक्वेंसी से दोगुनी होती है। इस प्रकार, चार्ज-पंप आधारित इंटरलीव्ड बूस्ट कन्वर्टर न केवल एक उच्च वोल्टेज लाभ प्राप्त करते हैं, बल्कि बेहतर स्रोत करंट रिपल प्रोफाइल भी प्रदर्शित करते हैं। इस प्रेरणा के साथ, यह थीसिस चार्ज-पंप आधारित इंटरलीव्ड बूस्ट कन्वर्टर के प्रदर्शन सुधार पहलुओं की जांच करती है। यहां, मुख्य रूप से स्विच विद्युत मात्रा (स्विच के पार वोल्टेज और स्विच के माध्यम से बहने वाली धारा) को बदलकर स्विचिंग नुकसान को कम करने पर ध्यान दिया जाता है ताकि स्विचिंग उपकरणों के भीतर नुकसान या तो कम से कम हो या संक्रमण के दौरान समाप्त हो (यानी स्विच-ऑफ से चालू हो) संक्रमण, स्विच-ऑन से ऑफ संक्रमण)। हालांकि वोल्टेज और स्विच के माध्यम से बहने वाले प्रवाह को फिर से आकार देना कई तरीकों से संभव है, लेकिन इस थीसिस ने केवल सहायक संक्रमण नेटवर्क को डिजाइन और विकसित करने पर ध्यान दिया है जो ऑपरेशन की निश्चित आवृत्ति के लिए व्यवहार्य हैं।

मौजूदा सॉफ्ट-स्विच्ड इंटरलीव्ड बूस्ट कन्वर्टर हमेशा स्टैंड-अलोन जीरो-वोल्टेज और जीरो-करंट ट्रांजिशन नेटवर्क का उपयोग करते हैं। यहां, प्रत्येक स्विच का अपना संबद्ध सहायक संक्रमण नेटवर्क होता है। यद्यपि इन योजनाओं को सॉफ्ट-स्विचिंग प्रदर्शन के मामले में प्रभावी दिखाया गया है, लेकिन सॉफ्ट-स्विचिंग नेटवर्क में शामिल घटकों की अधिक संख्या के कारण संबंधित सिस्टम पावर घनत्व कम है। इसके अलावा, कई सक्रिय स्विच और संबंधित गेट ड्राइवर सर्किटरी की आवश्यकता भी इंटरलीव्ड बूस्ट कन्वर्टर की नियंत्रण जटिलता को जोड़ती है। सहायक ट्रांजिशन नेटवर्क की संख्या को कम करने के उद्देश्य से, सबसे पहले मल्टी-फेज़ इंटरलीव्ड बूस्ट कन्वर्टर के लिए सामान्य सॉफ्ट-स्विचिंग नेटवर्क के विकास से संबंधित जांच की जाती है। इंटरलीव्ड कन्वर्टर टोपोलॉजी में यह संभव है क्योंकि स्विच के टर्न-ऑन / टर्न-ऑफ इंस्टैंट्स को 360°/एन द्वारा चरण-स्थानांतरित किया जाता है, जहां 'एन' इंटरलीव्ड बूस्ट सेल की संख्या है और किसी के बीच पर्याप्त समय विलंब की उपस्थिति है। दो टर्न-ऑन / टर्न-ऑफ इंस्टैंट। सामान्य सॉफ्ट-स्विचिंग नेटवर्क का उपयोग प्रभावी रूप से गूंजने वाले इंडक्टर्स, सक्रिय स्विच और संबंधित गेट ड्राइविंग सर्किट की आवश्यकता को कम करता है। इस अवधारणा के आधार पर, चार्ज-पंप आधारित डुअल बूस्ट कन्वर्टर (CPBBC) के लिए एक कैपेसिटर असिस्टेड जीरो-वोल्टेज जीरो-करंट ट्रांजिशन नेटवर्क (ZVZCTN)

प्रस्तावित है। यहां, केवल एक ट्रांज़िशन नेटवर्क मौजूद है, लेकिन यह उपयुक्त गेटिंग स्कीम के साथ दो मुख्य स्विचों के सॉफ्ट-ट्रांज़िशन को सुनिश्चित करता है। यह संक्रमण नेटवर्क (दो डायोड, एक सहायक स्विच, और एक अनुनाद प्रारंभ करनेवाला से बना) मुख्य स्विचिंग उपकरणों के शून्य-वोल्टेज टर्न-ऑन और शून्य-वर्तमान टर्न-ऑफ सुनिश्चित करता है; उपकरणों पर कोई अतिरिक्त वोल्टेज तनाव लगाए बिना मुख्य डायोड के शून्य-वर्तमान टर्न-ऑफ को भी सुनिश्चित करता है। सहायक कैपेसिटर जो सॉफ्ट-स्विचिंग नेटवर्क के डायोड से जुड़े होते हैं, मुख्य स्विच के टर्न-ऑफ के दौरान धाराओं के गिरने की दर को प्रभावी ढंग से नियंत्रित करते हैं।

उपर्युक्त कैपेसिटर-असिस्टेड सॉफ्ट-स्विचिंग स्कीम मुख्य स्विच के टर्न-ऑन और टर्न-ऑफ ट्रांज़िशन दोनों के दौरान सॉफ्ट-स्विचिंग सुनिश्चित करती है; मुख्य डायोड का सॉफ्ट टर्न-ऑफ और सहायक स्विच का ZCS टर्न-ऑन। हालाँकि, संक्रमण क्षेत्रों के दौरान दो स्विच शाखाओं के बीच वर्तमान साझाकरण समान नहीं हो सकता है। इसलिए, इस समस्या को हल करने के लिए, दोहरे चरण इंटरलीव्ड कन्वर्टर के लिए एक सहायक ट्रांसफार्मर आधारित शून्य-वोल्टेज शून्य-वर्तमान संक्रमण योजना विकसित की गई है। यह संक्रमण नेटवर्क संरचना में सरल है और फिर भी मुख्य स्विच के लिए प्रभावी सॉफ्ट-ट्रांज़िशन (शून्य-वोल्टेज टर्न-ऑन के साथ-साथ शून्य-वर्तमान टर्न-ऑफ) प्राप्त करता है। यह सहायक स्विच के शून्य-वर्तमान टर्न-ऑन के साथ-साथ सभी डायोड के शून्य-वर्तमान टर्न-ऑफ की सुविधा प्रदान करता है। इसके अतिरिक्त, सहायक ट्रांसफार्मर लोडिंग स्थितियों के आधार पर सहायक नेटवर्क में करंट को स्व-समायोजित करता है और इस प्रकार सॉफ्ट-स्विचिंग के दौरान प्रतिक्रियाशील ऊर्जा लोड की पूरी श्रृंखला के लिए कम होती है। एक उदाहरण के रूप में एक उच्च चरण-अप दोहरे चरण इंटरलीव्ड बूस्ट कनवर्टर पर विचार करके एक विस्तृत सैद्धांतिक विश्लेषण प्रस्तुत किया गया है। प्रस्तावित सॉफ्ट-स्विचिंग योजना की व्यवहार्यता उसी पर लागू की जाती है और इसकी प्रभावशीलता प्रयोगात्मक परिणामों के माध्यम से प्रदर्शित की जाती है जो 400 डब्ल्यू कनवर्टर प्रोटोटाइप पर प्राप्त होते हैं।

ऊपर बताए गए दो सॉफ्ट-ट्रांज़िशन नेटवर्क मुख्य डायोड के ZCS टर्न-ऑफ के साथ-साथ टर्न-ऑन और टर्न-ऑफ ट्रांज़िशन के दौरान मुख्य स्विच के सॉफ्ट-स्विचिंग के मामले में प्रभावी हैं। हालाँकि, सहायक स्विच हार्ड-स्विच तरीके से बंद हो जाता है। इस समस्या को दूर करने के लिए, दोहरे चरण इंटरलीव्ड कन्वर्टर के लिए एक युग्मित प्रारंभ करनेवाला सहायता प्राप्त शून्य-वोल्टेज संक्रमण नेटवर्क प्रस्तावित है। इसमें इंटरलीव्ड कनवर्टर के प्रत्येक चरण के लिए एक समर्पित सहायक स्विच, एक डायोड और एक युग्मित प्रारंभ करनेवाला शामिल है। यह प्रस्तावित सॉफ्ट-ट्रांज़िशन नेटवर्क मुख्य के साथ-साथ सहायक उपकरणों के लिए पूर्ण सॉफ्ट

ट्रांज़िशन सुनिश्चित करता है। शून्य-वोल्टेज संक्रमण के साथ प्राथमिक स्विच का टर्न-ऑन सुनिश्चित करने के लिए, उनके संबंधित प्राथमिक स्विच पर गेटिंग सिग्नल लागू होने से पहले अतिरिक्त स्विच सक्रिय हो जाते हैं। एक वोल्टेज गुणक संधारित्र के साथ श्रृंखला में युग्मित प्रारंभ करनेवाला की उपस्थिति सभी डायोड के शून्य-वर्तमान स्विचिंग की सुविधा प्रदान करती है, जिससे रिवर्स रिकवरी से जुड़े नुकसान को दबा दिया जाता है। विस्तृत स्थिर-राज्य विश्लेषण, संचालन के सिद्धांत और डिजाइन विचारों पर चर्चा की जाती है। सैद्धांतिक अध्ययनों को मान्य करने के लिए 24 - 200 वी, 100 डब्ल्यू कनवर्टर, 100 किलोहर्ट्ज़ की आवृत्ति पर काम कर रहा है। प्रस्तावित ZVZCT नेटवर्क के माध्यम से प्राप्त संक्रमण हानि में कमी को स्विचिंग उपकरणों से जुड़े हीट-सिंक के नमूना तापमान माप के माध्यम से प्रदर्शित किया जाता है। सॉफ्ट-स्विच किए गए प्रोटोटाइप सर्किट के मापन ने हार्ड-स्विच कनवर्टर पर 2 ~ 4% दक्षता सुधार का प्रदर्शन किया। इसके अलावा, सभी प्रस्तावित संक्रमण नेटवर्क के परिणामस्वरूप संचालन की एक निश्चित आवृत्ति पर भार की एक विस्तृत श्रृंखला पर नरम-संक्रमण हुआ।

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LIST OF ABBREVIATIONS

ZV	Zero-Voltage
ZC	Zero-Current
QR	Quasi-Resonant
ZVS	Zero-Voltage Switching
ZCS	Zero-Current Switching
QRC	Quasi Resonant Converters
QSW	Quasi Square Wave
RCD	Resistor-Capacitor-Diode
RLD	Resistor-Inductor-Diode
IGBT	Insulated Gate Bipolar Transistor
DCM	Discontinuous Conduction Mode
CRM	Critical Conduction Mode
CCM	Continuous Conduction Mode
IBC	Interleaved Boost Converter
ZVT	Zero -Voltage Transition
ZCT	Zero -Current Transition
PWM	Pulse Width Modulation
ZVZCT	Zero-Voltage Zero-Current Transition
RAC	Resonant Auxiliary Circuit
DPIBC	Dual-Phase IBC
ZVZCTN	Zero-Voltage Zero-Current Transition Network
CPBBC	Charge-Pump Based Dual Boost Converter
MZVZCTN	Modified Zero-Voltage Zero-Current Transition Network
CPIBC	Charge-Pump Based Interleaved Boost Converter
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
LSCIBC	Low Source Current Ripple Interleaved Boost Converter
ZVZCDBC	Zero-Voltage Zero-Current Transition Charge-Pump Based Dual Boost Converter
PWM	Pulse Width Modulation
ZVZCS	Zero-Voltage Zero-Current Switching
PTG	Peripheral Trigger Generator

ATN	Auxiliary Transition Network
TZ	Transition Zone

LIST OF SYMBOLS

V_g	Source voltage (V)
V_o	Load voltage (V)
f_s	Switching frequency (Hz)
D	Duty Ratio
D_{eff}	Effective Duty Ratio
L_1, L_2	Main inductors
S_1, S_2	Main Switches
D_1, D_2, D_3, D_4	Main diodes
C_1, C_2, C_3, C_4	Main Capacitances
S_a, S_{a1}, S_{a2}	Auxiliary switches
D_{r1}, D_{r2}	Auxiliary diodes
C_{Dr1}, C_{Dr2}	Auxiliary capacitances
C_{S1}, C_{S2}	Net capacitance across S_1, S_2
L_r	Resonant inductance
A_{Tr}	Auxiliary transformer
$n_1:n_2$	Transformer turns ratio
L_{kp}, L_{ks}	Leakage Inductances
L_m	Magnetizing Inductance
L_{eq}	Equivalent Inductance
L_p	Primary inductance of coupled inductor
L_{s1}, L_{s2}	Secondary inductance of coupled inductor