Capacitor-Centric Approaches for Size Reduction and Efficiency Improvement in Electric Vehicle Chargers

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submitted by

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under the guidance of

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of

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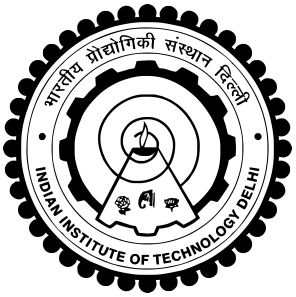

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THESIS CERTIFICATE

This is to certify that the thesis titled **Capacitor-Centric Approaches for Size Reduction and Efficiency Improvement in Electric Vehicle Chargers**, submitted by **Muhammad Zarkab Farooqi (2018EEZ8566)**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Muhammad Zarkab Farooqi

ABSTRACT

Power electronics play a crucial role in industrial applications, with electric vehicles (EVs) being one of the most prominent examples. EVs rely on battery chargers to replenish their battery packs, making features like efficiency, high power density, and reliability essential in such systems. Traditional grid-connected EV chargers typically use an AC-DC-DC architecture. However, this design often involves bulky electrolytic capacitors in single-phase converter systems, contributing to a larger overall footprint. A promising alternative to these capacitors is the use of active power buffers (APBs). APB converters enable the use of low-capacitance DC-port capacitors by either transferring the ripple from the DC port to another component within the circuit or by generating a counter-ripple waveform to cancel it out. These converters offer significant advantages, such as enhanced power density, improved reliability, and better input/output power quality. Due to these benefits, APBs were prominently utilised by participants in the Google Little Box Challenge, an industry-level competition aimed at advancing the power density of AC-DC converters.

Although APBs offer several advantages, their industrial application has been limited. This is mainly due to the considerable efficiency loss compared to passive solutions, the increased system complexity from adding switches and sensors, and their lack of robustness. While some challenges have been addressed through research, others remain under investigation, particularly regarding their practical implementation. This thesis focuses on the design and development of converters and techniques aimed at reducing capacitor requirements in single-phase and single-phase-derived converters. It presents novel and enhanced modulation and control strategies for APB converters, with a focus on improving performance and reducing complexity. To minimize ripple at the load end while using low-value capacitance, two types of APB topologies are examined: non-integrated and integrated APBs. The unique challenges of each category are addressed, and their suitability for EV chargers is analyzed in this thesis.

Non-integrated APBs are commonly explored topologies for reducing capacitor ripple in AC-DC systems due to their independent control and plug-and-play operation. Based on their power processing capabilities, non-integrated APBs can be further classified into two categories: complete-power processing APBs and partial-power processing APBs. Complete-

power processing APBs, which are most commonly used, tend to have higher efficeicny drop. Many researchers have proposed control and modulation techniques to improve the efficiency of these APBs, bringing their losses closer to those of passive solutions, such as electrolytic capacitors (E-caps). Although operating these APB converter in a critical-conduction mode can reduce switching losses, this technique is not beneficial at high power levels. This thesis addresses enhanced modulation and control strategies for complete-power processing APBs, aimed at further improving efficiency across a wide range of operating conditions and optimizing performance during dynamic periods. Furthermore, partial-power processing APB converters, which exhibit efficiency comparable to passive solutions, have the drawback of an increased sensor count. This issue is tackled by introducing an adaptive non-linear control strategy to reduce reliance on sensors, thereby enhancing reliability and reducing system complexity. All modulation techniques and control algorithms are developed in the MATLAB/Simulink environment, followed by magnetic and thermal simulation validation in COMSOL Multiphysics. Finally, experimental verification is conducted on various two-layer PCB prototypes of different APB converters, as well as a conventional front-end AC-DC converter, using the Texas Instruments TMS320F28379D microcontroller.

To enable power decoupling with minimal or no additional semiconductor switches, the adoption of integrated APB converters has been proposed in the literature. These converters have gained attention in the research community in recent years due to their reduced cost and lower system complexity. This thesis also investigates the potential of integrating a secondary-stage DC-DC converter with the APB, thereby maintaining the front-end H-bridge-based AC-DC converter structure and paving the way for the use of integrated APBs in multilevel converters. Furthermore, the thesis explores the possibility of repurposing the decoupling circuitry of integrated APBs to add multifunctional capabilities in EVs. The integrated APB converters are first validated conceptually through simulations in MATLAB/Simulink and Ansys MAXWELL, followed by experimental verification using SiC MOSFET-based hardware prototypes.

सारांश

पावर इलेक्ट्रॉनिक्स औद्योगिक अनुप्रयोगों में एक महत्वपूर्ण भूमिका निभाता है, जिसमें इलेक्ट्रिक वाहनों (EVs) को सबसे प्रमुख उदाहरणों में से एक माना जाता है। EVs अपनी बैटरी पैक्स को फिर से चार्ज करने के लिए बैटरी चार्जर्स पर निर्भर करते हैं, जिससे इस प्रकार के सिस्टम्स में दक्षता, उच्च पावर डेंसिटी और विश्वसनीयता जैसी विशेषताएँ आवश्यक हो जाती हैं। पारंपरिक ग्रिड-के कनेक्टेड EV चार्जर्स सामान्यतः एक AC-DC-DC आर्किटेक्चर का उपयोग करते हैं। हालांकि, यह डिज़ाइन अक्सर सिंगल-फेज कन्वर्टर सिस्टम्स में भारी इलेक्ट्रोलाइटिक कैपेसिटर्स का उपयोग करता है, जो पूरे सिस्टम का आकार बढ़ाने में योगदान करता है। इन कैपेसिटर्स के एक आशाजनक विकल्प के रूप में सक्रिय पावर बफर्स (APBs) का उपयोग किया जा सकता है। APB कन्वर्टर्स, DC पोर्ट कैपेसिटर्स के लिए कम कैपेसिटेंस का उपयोग करने की अनुमति देते हैं, या तो DC पोर्ट से रिपल को सर्किट के किसी अन्य घटक में ट्रांसफर करके, या एक काउंटर-रिपल वेवफॉर्म जनरेट करके इसे रद्द करने के द्वारा। ये कन्वर्टर्स महत्वपूर्ण लाभ प्रदान करते हैं, जैसे कि बेहतर पावर डेंसिटी, बेहतर विश्वसनीयता और बेहतर इनपुट/आउटपुट पावर क्वालिटी। इन लाभों के कारण, APBs का प्रमुख रूप से उपयोग किया गया था गूगल लिटिल बॉक्स चैलेंज में, जो एक उद्योग-स्तरीय प्रतियोगिता है जिसका उद्देश्य AC-DC कन्वर्टर्स की पावर डेंसिटी को बढ़ाना है।

हालांकि APBs कई लाभ प्रदान करते हैं, उनके औद्योगिक अनुप्रयोग सीमित रहे हैं। इसका मुख्य कारण यह है कि वे पासिव समाधानों की तुलना में काफी दक्षता हानि करते हैं, स्विचेस और सेंसर जोड़ने से सिस्टम की जटिलता बढ़ जाती है, और उनकी मजबूतता की कमी होती है। जबकि कुछ चुनौतियों को शोध के माध्यम से हल किया गया है, अन्य अभी भी जांच के अधीन हैं, विशेष रूप से उनके व्यावहारिक कार्यान्वयन के संबंध में। यह शोध सिंगल-फेज और सिंगल-फेज-व्युत्पन्न कन्वर्टर्स में कैपेसिटर की आवश्यकता को कम करने के लिए डिज़ाइन और तकनीकों के विकास पर केंद्रित है। यह APB कन्वर्टर्स के लिए नवीन और उन्नत मॉडुलन और नियंत्रण रणनीतियाँ प्रस्तुत करता है, जिनका उद्देश्य प्रदर्शन को सुधारना और जटिलता को कम करना है। लोड के अंत पर रिपल को कम करने के लिए और कम मूल्य वाले कैपेसिटेंस का उपयोग करते हुए, दो प्रकार की APB टॉपोलॉजीज की जांच की जाती है: नॉन-इंटीग्रेटेड और इंटीग्रेटेड APBs। प्रत्येक श्रेणी की विशिष्ट चुनौतियों को संबोधित किया जाता है, और EV चार्जर्स के संदर्भ में उनकी उपयुक्तता का विश्लेषण किया जाता है।

नॉन-इंटीग्रेटेड APB कन्वर्टर्स को AC-DC सिस्टम्स में कैपेसिटर रिपल को कम करने के लिए सामान्यत: अन्वेषित टॉपोलॉजीज माना जाता है, क्योंकि इनमें स्वतंत्र नियंत्रण और प्लग-एंड-प्ले ऑपरेशन होता है। इनके पावर प्रोसेसिंग क्षमताओं के आधार पर, नॉन-इंटीग्रेटेड APBs को दो श्रेणियों में और विभाजित किया जा सकता है: पूर्ण-पावर प्रोसेसिंग APBs और आंशिक-पावर प्रोसेसिंग APBs पूर्ण-पावर प्रोसेसिंग APBs, जो सामान्यत: उपयोग किए जाते हैं, उच्च कन्वर्टर हानि के लिए प्रवृत्त होते हैं। कई शोधकर्ताओं ने इन APBs की दक्षता को सुधारने के लिए नियंत्रण और मॉडुलन तकनीकों का प्रस्ताव किया है, जिससे उनकी हानियाँ पैसिव समाधानों, जैसे कि इलेक्ट्रोलाइटिक कैपेसिटर्स (E-caps), के समान हो जाती हैं। हालांकि,

कन्वर्टर को क्रटिकिल-कंडक्शन मोड में चलाने से स्वचिगि हानयिों को कम कयिा जा सकता है, यह तकनीक उच्च पावर स्तरों पर लाभकारी नहीं होती है। यह शोध पूर्ण-पावर प्रोसेसगि APBs के लएि उन्नत मॉडुलन और नयिंत्रण रणनीतयिों को संबोधति करता है, जनिका उद्देश्य ऑपरेटगि स्थतियिों की वस्तृित श्रृंखला में दक्षता को और सुधारना और गतशिील अवधयिों के दौरान प्रदर्शन को अनुकूलति करना है। इसके अलावा, आंशकि-पावर प्रोसेसगि APB कन्वर्टर्स, जो पैसवि समाधानों के समान दक्षता प्रदर्शति करते हैं, उनके पास एक अतरिक्ति सेंसर की आवश्यकता का नुकसान होता है। यह शोध इस समस्या का समाधान एक अनुकूलनशील नॉन-लनियिर नयिंत्रण रणनीतद्वारा करता है, जो सेंसर पर नर्भिरता को कम करता है, इस प्रकार वश्विसनीयता को बढ़ाता है और सस्टिम की जटलिता को घटाता है। सभी मॉडुलन तकनीकें और नयिंत्रण एल्गोरदिम MATLAB/Simulink वातावरण में वकिसति की जाती हैं, इसके बाद COMSOL Multiphysics में मैग्नेटकि और थर्मल समिुलेशन सत्यापन कयिा जाता है। अंत में, वभिन्नि APB कन्वर्टर्स के वभिन्नि दो-परत पीसीबी प्रोटोटाइपों पर और एक पारंपरकि फ्रंट-एंड AC-DC कन्वर्टर पर, Texas Instruments TMS320F28379D माइक्रोकंट्रोलर का उपयोग करके प्रयोगात्मक सत्यापन कयिा जाता है।

पावर डकिपलगि को सक्षम बनाने के लएि न्यूनतम या बनिा अतरिक्ति सेमीकंडक्टर स्वचि के, एकीकृत APB कन्वर्टर्स को अपनाने का प्रस्ताव दयिा गया है। इन कन्वर्टर्स ने हाल के वर्षों में अपनी कम लागत और कम सस्टिम जटलिता के कारण शोध समुदाय में ध्यान आकर्षति कयिा है। इस शोध में APB के साथ एक द्वतीियक-चरण DC-DC कन्वर्टर को एकीकृत करने की संभावना की भी जांच की गई है, ताकफ्रिंट-एंड H-ब्रजि आधारति AC-DC कन्वर्टर संरचना बनाए रखते हुए, एकीकृत APBs को मल्टीलेवल कन्वर्टर्स में उपयोग के लएि मार्ग प्रशस्त कयिा जा सके। इसके अलावा, यह कार्य एकीकृत APBs के डकिपलगि सर्कटिरी का पुनः उपयोग करने की संभावना का अन्वेषण करता है ताकि EVs में बहु-कार्यात्मक क्षमताएँ जोड़ी जा सकें। एकीकृत APB कन्वर्टर्स को पहले MATLAB/Simulink और Ansys MAXWELL में समिुलेशन के माध्यम से अवधारणात्मक रूप से सत्यापति कयिा जाता है, और फरि SiC MOSFET-आधारति हार्डवेयर प्रोटोटाइप का उपयोग करके प्रयोगात्मक सत्यापन कयिा जाता है।

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ABBREVIATIONS

AC	Alternating Current
ADC	Analog-to-Digital
APB	Active Power Buffer
BES	Battery Energy Storage
BSF	Band Stop Filters
CC	Constant Current
CCM	Continuous Conduction Mode
CEC	California Energy Commission
CHB	Cascaded H-Bridge
CRM	Critical Conduction Mode
CV	Constant Voltage
DAB	Dual Active Bridge
DC	Direct Current
DCM	Discontinuous Current Mode
DHB	Dual Half Bridge
DLFR	Double-Line Frequency Ripple
E-caps	Electrolytic DC-Port Capacitor
EV	Electric Vehicles
EMI	Electromagnetic Interference
GaN	Gallium Nitride
GPIO	General Purpose Input/Output
HF	High Frequency
HFIT	High Frequency Isolation Transformer
HPF	High Pass Filters
IAPB	Integrated Active Power Buffer
IGBT	Insulated Gate Bipolar Transistor
IOBEV	Integrated On-Board EV
LF	Low Frequency
LPF	Low Pass Filters

MMC	Modular-Multilevel Converters
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
MPPT	Maximum Power Point Tracking
MPC	Model Predictive Control
MV	Medium-Voltage
MUT-MPC	Modified Unit Template Based Model Predictive Control
PET	Power Electronic Transformers
PI	Proportional Integral
PMSM	Permanent Magnet Synchronous Motor
PR	Proportional Resonant
PV	Solar Photovoltaic
PWM	Pulse Width Modulation
SiC	Silicon-Carbide
SOC	State of Charge
SSB	Series-Stacked Buffers
TCM	Triangular Current Mode
THD	Total Harmonic Distortion
ZCD	Zero-Crossing-Detection
ZVS	Zero Voltage Switching

NOMENCLATURE

C_{DC1}	Split DC-link or DC-port Capacitances
C_{DC2}	Split DC-link or DC-port Capacitances
C_{DC}	DC-link or DC-port Capacitance
C_b	APB converter's Capacitor
C_{oss}	Switch-node equivalent capacitance
ΔV_{dc}	DC-link or DC-port low-frequency voltage variation
d_b	Duty of APB
E_{off}	Turn-off transition energy loss
E_{on}	Turn-on transition energy loss
f_{line}	Line frequency
f_{sw}	Switching frequency
$f_{2\omega}$	Twice-Line frequency
$f_{loss(\chi)_N}$	Normalized loss function w.r.t variable χ
$f_{volume(\chi)_N}$	Normalized volume function w.r.t variable χ
H	Magnetic field intensity
h_{t,C_b}	Height of APB Capacitor
h_{t,L_b}	Height of APB inductor
I_{th}	Thresh-hold current
i_b	APB converter's Inductor Current
$i_{b,HF}$	High-frequency triangular component in i_b
$i_{b,LF}$	Twice-line frequency sinusoidal component in i_b
$i_{b,\max}$	Maximum i_b for soft-switching
$i_{b,\min}$	Minimum i_b for soft-switching
i_{ga}, i_{gb}, i_{gc}	Three-phase Grid Currents
i_g	Single-phase Grid Current
i_o	Output Load Current
l_e	Magnetic path length
L_b	APB converter's Inductor
L_{dd}	Self inductances in PMSM
L_{ga}, L_{gb}, L_{gc}	Interfacing Inductors in Three-phase system
L_g	Grid interfacing Inductor

L_{lk}	Leakage Inductor in isolated DC-DC converter
L_{qd}	Mutual inductance in PMSM
L_{qq}	Self inductances in PMSM
N_{C_b}	Number of parallel APB capacitors
p	Number of poles in PMSM
P_{BES}	Power flowing through each split-Battery Energy Storage
$P_{C,DC1}$	Power in split- DC-link or DC-port Capacitors
$P_{C,DC2}$	Power in split- DC-link or DC-port Capacitors
P_{gL}	Grid interfacing Inductor Power
P_{max}	Maximum output power
P_o	Output Power
$P_{o,i}$	Output power $i = \{20\%, 40\%, 60\%, 80\%, 100\%\}P_{max}$
$P_{Tloss,i}$	Total Loss at i^{th} power level
ϕ	Phase-difference between pulses in isolated DC-DC converter
ψ_d	Flux linkage in PMSM
Q_{max}	Total charge to be removed when $i_b < 0$
Q_{min}	Total charge to be removed when $i_b > 0$
$R_{ds,ON}$	SiC MOSFET's ON-state resistance
S_b	Apparent power
T_{dt}	Dead-time between switches M_1 & M_2
τ_e	Torque developed in PMSM
θ	Temperature dependency factor of $R_{ds,ON}$
V_{dc}	DC-link or DC-port Voltage
V_{dc1}, V_{dc2}	Split DC-link or DC-port Voltages
V_{MUT}	Modified Unit-template
V_{UT}	Unit-template
v_b	APB converter's Capacitor Voltage
v_{ga}, v_{gb}, v_{gc}	Three-phase Grid Voltages
v_g	Single-phase Grid Voltage
ω	Grid Frequency in rad/s
ξ	Damping Factor