EXPLORING MODULAR MULTILEVEL CONVERTER FOR RENEWABLE ENERGY APPLICATIONS

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INSTITUTE OF TECHNOLOGY DELHI

June 2026

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by

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DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING

Submitted

In fulfillment of the requirements of the degree of Doctor of Philosophy to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2026

Dedicated to

Eternal Energy

CERTIFICATE

This is to certify that the thesis entitled, "**Exploring Modular Multilevel Converter for Renewable Energy Applications**", being submitted by **Mr. Nikilesh Vinayak Wanjari** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy, is a record of bonafide research work carried out by him**. He has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which, to my knowledge, has reached the requisite standard.

The results reported in the dissertation have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

I take this opportunity to thank my supervisor, Prof. Sumit Kumar Chattopadhyay, for his intellectual support, moral support, enthusiasm, and patience. He has given me the freedom and support to learn and develop skills that I wanted to have, and also to carry out research to the extent possible by me in my areas of interest. It was a great opportunity for me to work under the supervision of Prof. Chattopadhyay, who has not only guided me in my doctoral research but also supported me in all spheres of life.

I would also thank him for teaching me the art of writing technical papers, answering reviewer queries, and making fine presentations. My research life would have been void without his guidance. Apart from the research life, he has helped me in developing interpersonal skills, and professional ethics. I am also glad to have them guiding me with the research processes through online meets during the pandemic situations. I owe him a lot.

I sincerely thank all the members of my SRC committee, Prof. K. A. Subramanian, Prof. Ashu Verma, and Prof. Amit Kumar Jain for giving their valuable time to attend my seminars and evaluate my work. Their critical feedback has improved the quality of this thesis.

I am thankful to former heads Prof. K. A. Subramanian and present head Prof. Vamsi Krishna for their encouragement and support. Sincere gratitude goes on to the staff and all of the other faculty members at IIT Delhi for their assistance with the administrative work. As a result, I was able to devote sufficient time to doing research. I also want to thank Mr. Navneet Kumar for helping me in many ways like procuring components for my experimental prototype. The complicated things have become way easier because of him.

Thanks are due, to my lab-mates who turned my lab into home. The list is quite long. I would like to thank Neha Tak, Mohsin Krim Ansari, Rishabh Sharma, Neethi S. Pillai, Yamini Chakrala, Gaurav Thote, Nikita, Surya Kiran, Gaurav Prit, Chinmay Das, Ayush Chauhan, Aqib Qureshi, Adiba, Bevin KC, Satyaveer Singh Rawat, Mohit Murarka and Saumya not only for helping me with my work but also for making the lab lively. I could ask for any amount of help from any of them and they were always ready. I am really honored and proud to be a member of this lab where the students not only grow themselves but also wholeheartedly help others grow thus making the entire lab stronger. I am likewise thankful to those who have directly or indirectly helped me to finish my dissertation study.

I would also like to thank other research scholars and my hostel mates Kripa Tiwari, Shukrasish Sarkar, Zarkaab, and Narayan for the company and discussions. I heartfully thank my friends, Vikas

Raghuvansi, Tomson Laishram, Kalash Srivastava, Shashank Sahu for their valuable help and suggestions in directing my life and career.

Finally, I acknowledge the encouragement, dedication, blessings, prayers and continuous selfless support of my parents Mr. Vinayak Wanjari & Mrs. Lata Wanjari. Without their blessings, unconditional love & affection, and relentless support despite all odds, particularly during rough patches of my life, it would not have been possible for me to achieve whatever I have achieved, in my life. I dedicate this thesis to them, though this is not worthy enough in comparison to their sacrifices, love and support.

Finally, thanks to the almighty for being generous enough to usher me with great strength and valor to overcome the challenges that bothered me.

Nikilesh Vinayak Wanjari

Abstract

The rapid penetration of renewable energy and the electrification of transportation demand power electronic systems that are efficient, modular, scalable, and grid-friendly. Traditional two-level converters face limitations at higher power and voltage levels due to bulky filters, increased switching losses, and limited fault tolerance. In this context, multilevel converters, with their modular structure, high-quality waveform generation, and inherent redundancy, emerge as a promising platform for next-generation energy systems.

This thesis investigates multilevel converter-based solutions across three interconnected domains. The first part presents a modular dc–dc converter derived from cascaded half-bridge submodules. The topology minimizes passive component requirements, achieves stable operation at high duty ratios, and inherently balances distributed storage units. Simulation results validate its compact design, high efficiency, and adaptability for dc microgrid and storage integration.

The second part develops a battery-integrated modular multilevel converter (MMC) inverter for photovoltaic (PV) systems. By embedding batteries at the submodule level, the converter enables distributed storage management, state-of-charge (SoC) equalization, and seamless bidirectional energy flow between PV, storage, and grid. Both simulation and experimental validation confirm low-distortion grid currents, high efficiency at low switching frequencies, and stable operation under dynamic conditions.

The third part proposes a multilevel converter-based charging station for electric bus fleets. A cascaded H-bridge (CHB) rectifier ensures clean grid interfacing with multiple isolated dc outputs, while MMC-based on-board chargers (OBCs) within each bus handle both charging and propulsion. Simulation studies demonstrate balanced battery charging, reduced ripple, near-unity

power factor, and the capability to supply ancillary services to the grid.

The findings collectively establish that modular and multilevel converter architectures are well-suited for high-power applications where efficiency, reliability, and flexibility are essential. Beyond addressing current challenges, the proposed systems pave the way for integration with renewable sources, smart grids, and vehicle-to-grid (V2G) technologies. The research concludes that CHB and MMC topologies can form the backbone of future sustainable infrastructures, enabling large-scale electrified mobility and net-zero energy systems.

Key Words: - Electric Vehicle Charging Station, Grid-Connected Inverters, Modular dc-dc Converter, Modular Multilevel Converter, Photovoltaic Solar Inverter.

सारांश

नवीकरणीय ऊर्जा की तीव्र बढ़ती हुई पैठ और परिवहन के विद्युतीकरण के कारण ऐसे शक्ति इलेक्ट्रॉनिकी तंत्रों की आवश्यकता बढ़ रही है, जो दक्ष, मॉड्यूलर, विस्तारयोग्य और ग्रिड-अनुकूल हों। पारंपरिक द्वि-स्तरीय परिवर्तक उच्च शक्ति और उच्च वोल्टता स्तरों पर भारी छनित्रों, बढ़ी हुई स्विचिंग हानियों और सीमित फॉल्ट टॉलरेंस के कारण सीमाओं का सामना करते हैं। इस संदर्भ में, बहुस्तरीय परिवर्तक अपनी मॉड्यूलर संरचना, उच्च-गुणवत्ता तरंगरूप उत्पादन और अंतर्निहित अतिरिक्तता के कारण अगली पीढ़ी की ऊर्जा प्रणालियों के लिए एक आशाजनक यंत्र के रूप में उभरते हैं।

यह शोध-प्रबंध तीन परस्पर संबंधित क्षेत्रों में बहुस्तरीय परिवर्तक-आधारित समाधानों का अध्ययन करता है। पहला भाग कैस्केडेड अर्ध-सेतु उपमॉड्यूलों से व्युत्पन्न एक मॉड्यूलर दिष्ट धारा-दिष्ट धारा परिवर्तक प्रस्तुत करता है। यह टोपोलॉजी निष्क्रिय घटकों की आवश्यकता को न्यूनतम करती है, उच्च कर्तव्य अनुपातों पर स्थिर प्रचालन प्राप्त करती है, और वितरित ऊर्जा भंडारण इकाइयों का स्वाभाविक संतुलन करती है। अनुकरण परिणाम इसके संकुचित अभिकल्प, उच्च दक्षता, तथा दिष्ट धारा सूक्ष्मग्रिड और ऊर्जा भंडारण एकीकरण के लिए इसकी उपयुक्तता को सत्यापित करते हैं।

दूसरा भाग प्रकाशवैद्युत प्रणालियों के लिए बैटरी-एकीकृत मॉड्यूलर बहुस्तरीय परिवर्तक प्रतिलोमक विकसित करता है। उपमॉड्यूल स्तर पर बैटरियों को समाहित करके, यह परिवर्तक वितरित ऊर्जा भंडारण प्रबंधन, आवेश-अवस्था समानीकरण, तथा प्रकाशवैद्युत स्रोत, ऊर्जा भंडारण और ग्रिड के बीच निर्बाध द्विदिशीय ऊर्जा प्रवाह को सक्षम बनाता है। अनुकरण और प्रायोगिक सत्यापन दोनों कम-विकृति ग्रिड धाराओं, कम स्विचिंग आवृत्तियों पर उच्च दक्षता, और गतिशील परिस्थितियों में स्थिर प्रचालन की पुष्टि करते हैं।

तीसरा भाग विद्युत् बस बेड़ों के लिए बहुस्तरीय परिवर्तक-आधारित आवेशन केंद्र प्रस्तावित करता है। कैस्केडेड एच-सेतु दिष्टकारी अनेक पृथक दिष्ट धारा निर्गमों के साथ स्वच्छ ग्रिड अंतःसंबंध सुनिश्चित करता है, जबकि प्रत्येक बस के भीतर मॉड्यूलर बहुस्तरीय परिवर्तक-आधारित वाहनस्थ आवेशक आवेशन और प्रणोदन दोनों को संचालित करते हैं। अनुकरण अध्ययन संतुलित बैटरी आवेशन, कम तरंगिलता, लगभग एकक शक्ति गुणांक, और ग्रिड को सहायक सेवाएँ प्रदान करने की क्षमता प्रदर्शित करते हैं।

ये निष्कर्ष सामूहिक रूप से स्थापित करते हैं कि मॉड्यूलर और बहुस्तरीय परिवर्तक संरचनाएँ उन उच्च-शक्ति अनुप्रयोगों के लिए उपयुक्त हैं, जहाँ दक्षता, विश्वसनीयता और बदलती प्रचालन स्थितियों के प्रति अनुकूलता आवश्यक होती है। वर्तमान चुनौतियों का समाधान करने के साथ-साथ, प्रस्तावित तंत्र नवीकरणीय स्रोतों, स्मार्ट ग्रिडों और वाहन-से-ग्रिड तकनीकों के साथ एकीकरण का मार्ग प्रशस्त करते हैं। यह शोध निष्कर्ष निकालता है कि कैस्केडेड एच-सेतु और मॉड्यूलर बहुस्तरीय परिवर्तक टोपोलॉजियाँ भविष्य की सतत अवसंरचनाओं की आधारशिला बन सकती हैं, जो बड़े पैमाने पर विद्युतीकृत गतिशीलता और शुद्ध-शून्य ऊर्जा प्रणालियों को सक्षम बनाती हैं।

मुख्य शब्द: विद्युत् वाहन आवेशन केंद्र, ग्रिड-संबद्ध प्रतिलोमक, मॉड्यूलर दिष्ट धारा-दिष्ट धारा परिवर्तक, मॉड्यूलर बहुस्तरीय परिवर्तक, प्रकाशवैद्युत सौर प्रतिलोमक.

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List of Abbreviations

BES	Battery Energy Storage
BMS	Battery Management System
CHB	Cascaded H-Bridge
DOD	Depth of Discharge
DAB	Dual Active Bridge
DVRs	Dynamic Voltage Restorers
EV	Electric Vehicle
EMI	Electromagnetic Interference
ESS	Energy Storage System
ESR	Equivalent Series Resistance
FCS	Fast Charging Station
FC	Flying Capacitor
GaN	Gallium Nitride
HVDC	High Voltage DC Transmission
HEV	Hybrid Electric Vehicle
HESS	Hybrid Energy Storage Systems
IGBT	Insulated Gate Bipolar Transistor
IC	Integrated Circuit
LED	Light Emitting Diode
LVDC	Low-Voltage DC
MVDC	Medium-Voltage DC
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MMC	Modular Multilevel Converter
MLCs	Multilevel converters
MWT	multi-winding transformers (MWT)
NZEBs	Net-Zero Energy Buildings
NPC	Neutral Point Clamped
OBC	On-Board Charger
PD-PWM	Phase-Disposition Pulse-Width Modulation
PLL	Phase-Locked-Loop
PV	Photovoltaic
PCC	Point of Common Coupling
PCB	Printed Circuit Board
PI	Proportional-Integral
P-Res	Proportional-Resonant
PWM	Pulse Width Modulation
RCMCs	Reconfigurable Cascaded Multilevel Converters
RES	Renewable Energy Resources
SOGI	Second-Order Generalized Integrator
SiC	Silicon Carbide
SST	Solid-State Transformer
SoC	State-of-Charge
SOH	State-of-Health
SRM	Switched Reluctance Motor
THD	Total Harmonic Distortion

V2G	Vehicle-to-Grid
WBG	Wide-Bandgap
XFC	Xtreme Fast Charging