

DESIGN AND IMPLEMENTATION OF HIGH-POWER CONVERTERS FOR MEDIUM VOLTAGE INDUCTION MOTOR DRIVES

ROHIT KUMAR



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
FEBRUARY 2025**

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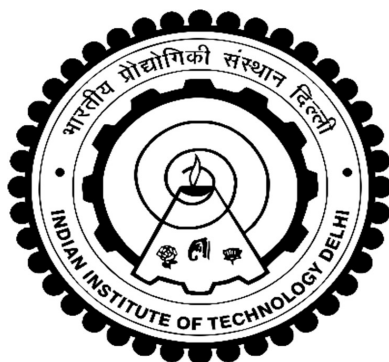
Rohit Kumar

Department of Electrical Engineering

Submitted

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

to the



Indian Institute of Technology Delhi

February 2025

CERTIFICATE

This is to certify that the thesis entitled, “**Design and Implementation of High Power Converters for Medium Voltage Induction Motor Drives**” being submitted by **Mr. Rohit Kumar** for the award of the degree of Doctor of Philosophy is a record of bona fide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Rohit Kumar 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 obtained herein have not been submitted to any other University or Institute for the award of any degree.

Dated:

Place: New Delhi

(Prof. Bhim Singh)
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi-110016, India

ACKNOWLEDGEMENTS

I wish to express my deepest gratitude and indebtedness to **Prof. Bhim Singh** for providing me guidance and consistent supervision to carry out the Ph.D. work. Working under him, has been a wonderful experience, which has provided a deep insight to the world of research. Determination, dedication, innovativeness, resourcefulness, and discipline of **Prof. Bhim Singh** have been the inspiration for me to complete this work. His consistent encouragement, continuous monitoring and commitments to excellence have always motivated me to improve my work and use the best of my capabilities. Due to his blessing, I have earned various experiences other than research, which will help me throughout my life. My sincere thanks and deep gratitude are to **Prof. S. S. Nag, Prof. Sumit Pramanick** and **Prof. T. C. Kandpal**, all SRC members for their valuable guidance and consistent support during my research work. I wish to convey my sincere thanks to **Prof. Piyus Kant (IIT Kanpur)** and **Prof. Shimi S. L (PEC Chandigarh)**, for providing valuable guidance and necessary support during this work, which made the foundation for my research work.

I wish to express my sincere thanks to the government of India for helping financially under the FIST project (RP03195) and J.C. Bose fellowship (RP03128). Thanks are due to Sh. Puran Singh, Mr. Amit Kumar, Mr. Anurag Singh, Mr. Sumit and Mr. Jitendra of PG Machines Lab, UG Machines Lab and Power Electronics Lab, IIT Delhi for providing me facilities and assistance during this work.

I would like to give special thanks to my batch mates Mrs. Kripa Tiwari, Mr. Muhammad Zarkab Farqooi, and Mr. Vipin Kumar Singh, for their valuable time, motivation, co-operation and support during my research work.

I am thankful to all my seniors, Dr. Shailendra Kumar, Dr. Anshul Varshney, Dr. Radha Kushwaha, Dr. Souvik Das, Mr. Gaurav Modi, Mr. Utsav Sharma, Mrs. Shalvi Tyagi, Mr. Sandeep Sahoo, Mr. Sudip Bhattacharya, and Mr. Syed Bilal Qaiser Naqvi, Dr. Jitendra Gupta, Mr. Gurmeet, Mr. Debasish Mishra, Mr. Aryadip Sen, Mr. Yalavarthi Amarnath, Ms. Hina Parveen, Mrs. Rashmi Rai, Mrs. Yashi Singh, Mr. Sayandeve Ghosh, Mr. Saran Chaurasiya, Dr. Vivek Narayanan, Mr. Suri Rama Naga Praneeth, Mr. Priyvratt Vats, Mr. Rahul Kumar, Mr. Sharankumar Shastri, Mr. Deepak Saw, Mr. Shivam Kumar Yadav, Mrs. Kousalya V, Ms. Sanjenbam Chandrakala Devi, Mr. Junaid Khan, Dr. Subir Karmakar and Mr. Saurabh Mishra, for their valuable aid and cooperation and informal support during this period.

Moreover, I would like to thank my juniors and colleagues, Mr. Madan Gopal Sharma, Mr. Arjun Kumar, Mr. Biswajit Saha, Ms. Farha Siddique, Mr. Sumit Kumar, Mr. Gaurav Kumar, Mr. Himansu Sahoo, Mr. Adnan Farooq Khan, Mr. Chetan Shashank Matwankar, Mr. Nishant Kumar Singh, Ms. Smita Mohanty, Mr. Siddharth Ghosh, Mr. Praveen Kumar Singh, Mr. Suvom Roy, Mrs. Gauri Chandra, Mr. Subhadip Chakraborty, Mr. Purusharth Semwal, Mr. Abhishek Abhinav Nanda, Mr. Aswin Dilip Kumar, and Mrs. Sunaina Singh and all PG Machines lab group for their valuable support.

I would like to extend my heartfelt thanks to my friends Mr. Nirbhay Soam, Mr. Anil Gaur, Mr. Ritesh Gupta, Mr. Shailendra Choudhary, Mr. Piyush Bajpai, Mr. Prabhat Bajaj, Mr. Ritesh Soni, Mr. Tushar Yadav, Mr. Ankur Sharma, Mr. Ashish Yadav, Mr. Sukrashis Sarkar, Dr. Surbhi Aggarwal and Dr. Nitesh Yadav for their encouraging words and support. I would like to thank my roommates Mr. Anurag Choudhary and Mr. Ankit Kumar Singh, who supported and inspired me during my stay in ‘Munirka’, Delhi.

I would also like to thank Mr. Yatindra, Mr. Satish, Mr. Sandeep and all other Electrical Engineering office staff for being supportive throughout. I am likewise thankful to those who have directly or indirectly helped me to finish my dissertation study.

I would like to thank my grandfather Late Shri. Bajani Yadav, grandmother Late Mrs. Hanso Devi, Maternal grandfather Late Shir Dambar Yadav, Maternal grandmother Late Mrs. Suraj Muki Yadav, my mother Mrs. Meena Yadav and my father Mr. Birpal Yadav for their dreams, blessings and constant encouragement. I would like to thank my younger sister Ms. Ritu Rani, younger brother Mr. Mohit Yadav, Sister-in-law Mrs. Pragati Yadav and my finace Kumari Shalini Yadav for their continuous support and encouragement. Their trust in my capabilities had been a key factor to all my achievements. At last, I am beholden to almighty for their blessings to help me to raise my academic level to this stage. I pray for their benediction in my future endeavours. Their blessings may be showered on me for strength, wisdom and determination to achieve in future.

Dated:

Place: New Delhi

(Rohit Kumar)
Research Scholar
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi-110016, India

ABSTRACT

This thesis work deals with the design and development of high-performance medium voltage induction motor drive systems for the variable speed operation so that these drive systems can be effectively utilized for the various applications of industries. Initially, this work develops various multi-pulse AC-DC converters to overcome the challenges and mitigate the harmonics components at the grid end of the drive system. In this work, the winding arrangement of the transformers are comprehensively analyzed, and accordingly, different techniques like phase displacement and multi-phase conversion are presented for developing various AC-DC converters. Few of the grid side converters (18-pulse, 30-pulse, 36-pulse, and 54-pulse AC-DC converters) are designed and implemented with single unit of the multi winding transformer. Phase displacement technique has been implemented among the secondary windings of transformers to develop these 18-pulse, 30-pulse, 36-pulse, and 54-pulse AC-DC converters. Although these power converters adhere to the power quality successfully at the grid end but the manufacturing of the transformer units for these converters becomes complex due to very small phase displacement among the secondary windings. Consequently, multi-unit multi-winding transform architectures are developed in this research work. Here, these multi winding transformers are designed for 24-pulse, 36-pulse, and 54-pulse AC-DC converters. The phase displacement technique is implemented not only secondary winding as well in primary windings also. Due to this, the windings of transformers are designed with a large phase displacement angle, which overcomes the manufacturing challenges of the transformer unit for higher pulse converter. Three-phase system based 36-pulse and 54-pulse AC-DC converters significantly impact power quality of those drive systems, which have utilized high levels of multilevel inverters like symmetric/asymmetric 7-level, 9-level...N-level. Another major issue of power quality occurs when drive systems are designed with 3-level or 4-level inverter configurations. Hence, a high pulse converter is required to sustain the power quality standard of a medium-voltage system when a drive operates with a low-level inverter. Therefore, this research works focuses on developing a high-pulse converter (30-pulse, 50-pulse and 60-pulse AC-DC converter) by implementing multi-phase conversion as well as phase displacement technique on multi winding transformer. Further, this work does not focus only on the grid side as well as it focuses on drive-side challenges also. In this research work, conventional cascaded H-bridge 5-level, 7-level, 13-level symmetric as well as asymmetric configuration is presented. The structure conventional H-bridge requires huge number of sources, to reduces the number of sources multi-level

inverter configurations designed with different type circuit arrangement among the isolated and non-isolated leg based two-level inverter. Through these circuit arrangements, 4-level, 5-level, 6-level, and 7-level inverter structures are developed. Apart from this, to overcome the number of components at the drive side converters, novel inverters configurations are designed with the cascaded arrangement of the unit cell and h-bridge. The symmetric and asymmetric reduced switches based multi-level inverter structure are designed for developing 5-level, 7-level, 9-level, and 11-level inverter. In the last, hybrid configurations of multi-level inverter are also designed.

After effectively developing the various power converter for both end of the drive system, this research work deals with the modulation technique to operates the drive side converter effectively for make variable speed operation and high-power quality performance. This research work presents modified level shifted pulse width modulation, flag type-pulse width modulation and carrier overlapped pulse width modulation for 4-level, 5-level, 6-level and maximum 7-level inverter. Moreover, fundamental switching frequency based selective harmonic elimination, nearest level control and area equalization modulations technique are presented for higher level inverters like 7-level, 9-level, 11-level, 13-level inverters.

Notably, all the proposed power converters based medium voltage induction motor drive configurations are designed and developed to realize improved power quality performance at the supply side as well as drive side and strictly comply with set national/international standards while operating under defined operating conditions. Each medium voltage induction motor drive configuration's operational analysis, design, and control are analyzed comprehensively, considering wide operating conditions. The performance of the presented configurations of medium voltage induction motor drive configuration's and the associated control techniques is analyzed by performing simulation on MATLAB/Simulink platform. Additionally, the laboratory prototype of the system undergoes an experimental validation of all the described topologies, and the corresponding test results are reported.

सारांश

यह थीसिस कार्य परिवर्तनीय गति संचालन के लिए उच्च-प्रदर्शन मध्यम वोल्टेज इंडक्शन मोटर ड्राइव सिस्टम के डिजाइन और विकास से संबंधित है ताकि इन ड्राइव सिस्टम का उद्योगों के विभिन्न अनुप्रयोगों के लिए प्रभावी ढंग से उपयोग किया जा सके। प्रारंभ में, यह कार्य चुनौतियों पर काबू पाने और ड्राइव सिस्टम के ग्रिड अंत में हार्मोनिक घटकों को कम करने के लिए विभिन्न मल्टी-पल्स एसी-डीसी कन्वर्टर विकसित करता है। इस कार्य में, ट्रांसफार्मर की घुमावदार व्यवस्था का व्यापक रूप से विश्लेषण किया जाता है, और तदनुसार, विभिन्न एसी-डीसी कनवर्टर को विकसित करने के लिए चरण विस्थापन और बहु-चरण रूपांतरण जैसी विभिन्न तकनीकों को प्रस्तुत किया जाता है। कुछ ग्रिड साइड कन्वर्टर (18-पल्स, 30-पल्स, 36-पल्स, और 54-पल्स एसी-डीसी कन्वर्टर) को मल्टी वाइंडिंग ट्रांसफार्मर की एकल इकाई के साथ डिजाइन और कार्यान्वित किया जाता है। इन 18-पल्स, 30-पल्स, 36-पल्स और 54-पल्स एसी-डीसी कनवर्टर को विकसित करने के लिए ट्रांसफार्मर की द्वितीयक वाइंडिंग के बीच चरण विस्थापन तकनीक लागू की गई है। हालाँकि ये पावर कन्वर्टर ग्रिड के अंत में बिजली की गुणवत्ता का सफलतापूर्वक पालन करते हैं, लेकिन सेकेंडरी वाइंडिंग के बीच बहुत छोटे चरण विस्थापन के कारण इन कन्वर्टर के लिए ट्रांसफार्मर इकाइयों का निर्माण जटिल हो जाता है। नतीजतन, इस शोध कार्य में मल्टी-यूनिट मल्टी-वाइंडिंग ट्रांसफॉर्म आर्किटेक्चर विकसित किए गए हैं। यहां, ये मल्टी वाइंडिंग ट्रांसफार्मर 24-पल्स, 36-पल्स और 54-पल्स एसी-डीसी कनवर्टर के लिए डिज़ाइन किए गए हैं। चरण विस्थापन तकनीक न केवल द्वितीयक वाइंडिंग के साथ-साथ प्राथमिक वाइंडिंग में भी लागू की जाती है। इसके कारण, ट्रांसफार्मर की वाइंडिंग को बड़े चरण विस्थापन कोण के साथ डिज़ाइन किया गया है, जो उच्च पल्स कनवर्टर के लिए ट्रांसफार्मर इकाई की विनिर्माण चुनौतियों पर काबू पाता है। तीन-चरण प्रणाली आधारित 36-पल्स और 54-पल्स एसी-डीसी कन्वर्टर उन ड्राइव सिस्टमों की बिजली की गुणवत्ता को महत्वपूर्ण रूप से प्रभावित करते हैं, जिन्होंने सममित/असममित 7-स्तर, 9-स्तर....एन-स्तर जैसे बहुस्तरीय इनवर्टर के उच्च स्तर का उपयोग किया है। बिजली की गुणवत्ता का एक और प्रमुख मुद्दा तब होता है जब ड्राइव सिस्टम को 3-स्तरीय या 4-स्तरीय इन्वर्टर कॉन्फ़िगरेशन के साथ डिज़ाइन किया जाता है। इसलिए, जब कोई ड्राइव निम्न-स्तरीय इन्वर्टर के साथ संचालित होती है, तो मध्यम-वोल्टेज प्रणाली के बिजली गुणवत्ता मानक को बनाए रखने के लिए एक उच्च पल्स कनवर्टर की आवश्यकता होती है। इसलिए, यह शोध कार्य बहु-चरण रूपांतरण के साथ-साथ मल्टी-वाइंडिंग ट्रांसफार्मर पर चरण विस्थापन तकनीक को लागू करके एक उच्च-पल्स कनवर्टर (30-पल्स, 50-पल्स और 60-पल्स एसी-डीसी कनवर्टर) विकसित करने पर केंद्रित है। इसके अलावा, यह कार्य केवल ग्रिड पक्ष पर ही केंद्रित नहीं है बल्कि यह ड्राइव-साइड चुनौतियों पर भी ध्यान केंद्रित करता है। इस शोध कार्य में, पारंपरिक कैस्केड एच-ब्रिज 5-स्तर, 7-

स्तर, 13-स्तरीय सममित और साथ ही असममित विन्यास प्रस्तुत किया गया है। संरचना पारंपरिक एच-ब्रिज को बड़ी संख्या में स्रोतों की आवश्यकता होती है, स्रोतों की संख्या को कम करने के लिए पृथक और गैर-पृथक पैर आधारित दो-स्तरीय इन्वर्टर के बीच विभिन्न प्रकार के सर्किट व्यवस्था के साथ डिज़ाइन किए गए बहु-स्तरीय इन्वर्टर कॉन्फ़िगरेशन। इन सर्किट व्यवस्थाओं के माध्यम से, 4-स्तर, 5-स्तर, 6-स्तर और 7-स्तरीय इन्वर्टर संरचनाएं विकसित की जाती हैं। इसके अलावा, ड्राइव साइड कन्वर्टर्स पर घटकों की संख्या को दूर करने के लिए, यूनिट सेल और एच-ब्रिज की कैस्केड व्यवस्था के साथ नवीन इन्वर्टर कॉन्फ़िगरेशन डिज़ाइन किए गए हैं। सममित और असममित कम स्विच आधारित मल्टी-लेवल इन्वर्टर संरचना 5-लेवल, 7-लेवल, 9-लेवल और 11-लेवल इन्वर्टर विकसित करने के लिए डिज़ाइन की गई है। अंत में, मल्टी-लेवल इन्वर्टर के हाइब्रिड कॉन्फ़िगरेशन भी डिज़ाइन किए गए हैं।

ड्राइव सिस्टम के दोनों सिरों के लिए विभिन्न पावर कन्वर्टर को प्रभावी ढंग से विकसित करने के बाद, यह शोध कार्य चर गति संचालन और उच्च-शक्ति गुणवत्ता प्रदर्शन के लिए ड्राइव साइड कन्वर्टर को प्रभावी ढंग से संचालित करने के लिए मॉड्यूलेशन तकनीक से संबंधित है। यह शोध कार्य 4-स्तर, 5-स्तर, 6-स्तर और अधिकतम 7-स्तर इन्वर्टर के लिए संशोधित स्तर स्थानांतरित पल्स चौड़ाई मॉड्यूलेशन, ध्वज प्रकार-पल्स चौड़ाई मॉड्यूलेशन और वाहक ओवरलैप्ड पल्स चौड़ाई मॉड्यूलेशन प्रस्तुत करता है। इसके अलावा, 7-लेवल, 9-लेवल, 11-लेवल, 13-लेवल इन्वर्टर जैसे उच्च स्तरीय इन्वर्टर के लिए मौलिक स्विचिंग आवृत्ति आधारित चयनात्मक हार्मोनिक उन्मूलन, निकटतम स्तर नियंत्रण और क्षेत्र समीकरण मॉड्यूलेशन तकनीक प्रस्तुत की जाती है।

विशेष रूप से, सभी प्रस्तावित पावर कन्वर्टर्स आधारित मध्यम वोल्टेज इंडक्शन मोटर ड्राइव कॉन्फ़िगरेशन को आपूर्ति पक्ष के साथ-साथ ड्राइव पक्ष पर बेहतर बिजली गुणवत्ता प्रदर्शन का एहसास करने और परिभाषित परिचालन स्थितियों के तहत संचालन करते समय निर्धारित राष्ट्रीय / अंतर्राष्ट्रीय मानकों का सख्ती से अनुपालन करने के लिए डिज़ाइन और विकसित किया गया है। प्रत्येक मध्यम वोल्टेज इंडक्शन मोटर ड्राइव कॉन्फ़िगरेशन के परिचालन विश्लेषण, डिज़ाइन और नियंत्रण का व्यापक परिचालन स्थितियों पर विचार करते हुए व्यापक रूप से विश्लेषण किया जाता है। मीडियम वोल्टेज इंडक्शन मोटर ड्राइव कॉन्फ़िगरेशन और संबंधित नियंत्रण तकनीकों के प्रस्तुत कॉन्फ़िगरेशन के प्रदर्शन का विश्लेषण MATLAB/Simulink प्लेटफ़ॉर्म पर सिमुलेशन करके किया जाता है। इसके अतिरिक्त, सिस्टम का प्रयोगशाला प्रोटोटाइप सभी वर्णित टोपोलॉजी के प्रयोगात्मक सत्यापन से गुजरता है, और संबंधित परीक्षण परिणाम रिपोर्ट किए जाते हैं।

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LIST OF ABBREVIATIONS

MLI	Multi-level Inverter
MPC	Multi-pulse converter
PWM	Pulse Width Modulation
MV	Medium Voltage
MVIMD	Medium Voltage Induction Motor Drive
IM	Induction Motor
DBR	Diode Bridge Rectifier
NPC-VSC	Neutral-Point-Clamped-Voltage Source Converter
HNPC	H-bridge Neutral-Point-Clamped
CHB	Cascaded H-bridge
IGBT	insulated-gate bipolar transistor
ASD	Adjustable Speed Drive
IPT	Interphase Transformer
ZSBT	Zero-Sequence Blocking Transformers
IFOC	Indirect Field Oriented Control
GA- SHE	Genetic Algorithm- Selective Harmonic Elimination
NLC	Nearest Level Control
AEMS	Area Equalization Modulation Scheme
SVM	Space Vector Modulation
MLSPWM	Modified Level Shifted Pulse Width Modulation
ST-MLI	Stairs type Multi-level Inverter
CMLI	Cascaded Multi-level Inverter
FVSI	Floating Voltage Source Inverter
MWT	Multi Winding Transformer
FT-LSPWM	Flag Type Level Shifted Pulse Width Modulation
SFO-NLC	Switching Frequency Optimal-Nearest Level Control
BU-HB MLI	Basic Unit H- Bridge Multi-level Inverter
RS-HB MLI	Reduced Switch H- Bridge Multi-level Inverter
IEEE	Institute of Electrical and Electronics Engineers
THD	Total Harmonic Distortion

LIST OF SYMBOLS

U_m	Stator terminal voltage (V)
U_{dc}	DC-link voltage (V)
m	Modulation index
N	Number of levels
N_{dc}	Number of DC sources
N_s	Number of secondary windings
N_T	Number of Transformer
θ_{sec}	Phase displacement in secondary windings
θ_{pri}	Phase displacement in primary windings
N_{pulse}	Number of diode bridge pulse
U_L	Secondary winding line voltage(V)
U_{NS}, U_{NL}	Small and large winding voltage of delta-polygon winding(V)
U_{k1}, U_{k2}	windings voltage of epitaxial-delta winding
u_r, u_g, u_b	Modulating signals produced from indirect vector control
ω_r	actual speed(rad/s)
ω_r^*	reference speed (rad/s)
ω_{sl}	slip speed (rad/s)
T_e	Reference torque (Nm)
I_{ref_d}	direct axis reference current (A)
I_{ref_q}	quadrature axis reference current(A)
I_{act_d}	direct axis actual current (A)
I_{act_q}	quadrature axis actual current (A)
L_{lr}	rotor leakage inductance(H)
L_m	magnetizing inductance (H)
i_r, i_g, i_b	Stator currents(A)
i_{sr}, i_{sg}, i_{sb}	Grid current (A)
$G_{l(r/g/b)}$	IGBT switches of r,g,b-phases
$i_{s1}, i_{s2} \dots i_{sn}$	Secondary windings currents(A)
$i_{p1}, i_{p2} \dots i_{pn}$	Primary windings currents (A)
U_{p1}, U_{p2}, U_{pn}	Pole Voltage of VSI (V)