DESIGN AND PERFORMANCE ANALYSIS OF INTEGRATED ROTATING MACHINE BASED PULSED POWER SUPPLY FOR ELECTROMAGNETIC LAUNCH APPLICATIONS

PRIYVRAT VATS

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
MAY 2025

DESIGN AND PERFORMANCE ANALYSIS OF INTEGRATED ROTATING MACHINE BASED PULSED POWER SUPPLY FOR ELECTROMAGNETIC LAUNCH APPLICATIONS

by

PRIYVRAT VATS

Department of Electrical Engineering

Submitted

in fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

INDIA

MAY 2025

Dedicated

to

*my **Family***
*and **Teachers***

CERTIFICATE

This is to certify that the thesis entitled, **" Design and Performance Analysis of Integrated Rotating Machine Based Pulsed Power Supply for Electromagnetic Launch Applications"** being submitted by **Mr. Priyvrat Vats** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Priyvrat Vats 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 here in have not been submitted to any other University or Institute for the award of any degree.

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

ACKNOWLEDGMENT

I feel incredibly fortunate to have been born and raised in **India**. Words cannot express my gratitude to my nation **India** and the **Government of India** for the exceptional education and upbringing I've received. I owe a tremendous debt to all my academic institutions, particularly the **Indian Institute of Technology Delhi**, for the substantial resources they have invested in my education. I am also deeply thankful to the **Ministry of Defence**, **Ministry of Education**, **Defence Research and Development) Organization**, **DRDO - IIT Delhi Joint Advanced Technology Centre (DRDO-IITD JATC)** and the **Anusandhan National Research Foundation (Formerly Science and Engineering Research Board)** for their generous support through scholarships, travel grants, conference fees, and other expenses over the years. I also owe a profound sense of gratitude to the my birth place **Mehada Shahapur** and its communities that have shaped my journey, providing a foundation of values and support that have been integral to my achievements. It is my sincere hope to give back at least as much as I have received from my country in my lifetime.

I would like to take this opportunity to express my heartfelt gratitude and respect for my supervisor, **Prof. Bhim Singh**, whose guidance and consistent supervision have been invaluable throughout my Ph.D. journey. I consider myself extremely fortunate to have had the privilege of working under his mentorship for the longest duration among his Ph.D. students, tackling one of the most challenging issues in the Indian context together. From day one at IIT Delhi, he has been a constant source of inspiration due to his vast knowledge, technical expertise, and quick wittedness, which have a remarkable way of diffusing even the most serious situations. His innovative ideas and technical suggestions have been instrumental in helping me navigate complex problems and situations during my Ph.D. His continuous motivation, encouragement, and constructive advice have significantly contributed to my growth, making me a much better version of myself over the past few years. He has always shown exceptional kindness to all his students, often providing resources at his own expense. I feel truly blessed to have been trained under his guidance and am committed to carrying forward his legacy.

I want to express my gratitude and appreciation to Prof. Nilanjan Senroy, Prof. T. C. Kandpal, Prof. Anandarup Das, Prof. G. Bhuvaneswari and Prof. Ramkrishan Maheswari for their invaluable support and constructive critiques throughout my research. Their insightful feedback has given me new perspectives on tackling research problems, significantly enhancing the quality of my work.

I would like to extend my heartfelt thanks to the Prof. Bhim Singh, Prof. Sukumar Mishra, Prof. Mummadi Veerachary, Prof. Ramkrishan Maheswari and Prof. Amit Kumar Jain for their invaluable contributions during my coursework. Their guidance laid a strong foundation for my research work, for which I am deeply grateful.

I extend my heartfelt gratitude to our Project PI Prof. Jitendra Prasad Khatait and Co-PI Prof. Bhim Singh, Prof. G. Bhuvaneswari, Prof. Sudipto Mukherjee and Prof. Shouri Chatterjee for granting me the opportunity to contribute to this remarkable project. Your guidance and support have been invaluable, and I am truly honored to be part of this team. Thank you for believing in my potential. I also extend my heartfelt thanks to the Dr. M. H. Rahaman, and Dr. A. K. Tripathi for their support for execution of project .

I sincerely thank my undergraduate supervisor Prof. Provas Kumar Roy and postgraduate supervisor Prof. Yash Pal for giving me the opportunity to work and grow under your mentorship. Your guidance and encouragement have been instrumental in my academic and professional development. I am deeply grateful for your unwavering support and belief in my abilities.

I extend my heartfelt thanks to my school teachers and mentors Prof. R. P Singh, Prof. Srinivas Singh, Ashok Kumar, Ram Naresh Chaudhary, Shushma Kumari, Kumari Asha Sinha, Binay Kumar, Vijay Kumar Pathak, Sanjay Kumar Singh, Vivekanand Nand Sharma, Dr. Bhagwan Prasd Sinha, Prof. Jitendra Pathak (IIT Kharagpur), Prof. Dashrath Prasad Singh (IIT Bombay), Late Prof. Janardan Prasad Singh (SCERT Bihar), Prof. Ramji Singh, Ramjivan Singh (Ex. Agriculture Minister, Govt. of Bihar), Brajesh Kumar (VP Think Gas), Dr. Gautam Goswami (Sc.G, TIFAC, DST), Gulab Pathak, Nawal Kishore Prasad Singh, Late Suresh Pathak, Sambhu Pathak, Shambhu Prasad for giving me the opportunity to understand, work and develop a fundamental understanding of various subjects. Your dedication and encouragement have laid a strong foundation for my academic and personal growth. I am truly grateful for your unwavering support and belief in my potential.

I am deeply grateful to IIT Delhi for providing the research facilities that have been crucial for my work. I would like to extend my sincere thanks to Sh. Srichand, Sh. Puran Singh, Mr. Amit Kumar, Mr. Jitendra, Mr. Anurag, Mr. Sagar, Mr. Vivek Vikash Satpati and Mr. Rahul from the UG & PG Machines Lab, Power Electronics Lab and Mechatronics Lab for their invaluable assistance and support. I am also indebted to Mr. Yatindra, Mr. Satish, Mr. Sandeep, Ms. Shashikala Chauhan, Mrs. Pushpa Ji and the entire Electrical Engineering, Mechanical Engineering and DRDO-IITD JATC office staff for their continuous support. Additionally, I want to express my gratitude to everyone who has directly or indirectly helped me complete my dissertation.

I would like to extend my heartfelt thanks to my seniors, Dr. Iqlakh Hussain, Dr. Aniket Anand, Dr. Shailendra Kumar, Dr. Sachin Devassy, Dr. Nishant Kumar, Dr. Saurabh Sukla, Dr. Anjanee Kumar Mishra, Dr. Shadab Murshid, Dr. Priyank Shah, Dr. Radha Kushwaha, Dr. Piyush Kant, Dr. Nidhi Mishra, Dr. Seema, Dr. Anjeet Kumar Verma, Dr. Utkarsh Sharma, Dr. Srijeet R, Dr. Anshul Varshney, and Dr. Satakshi Sharma, for their valuable advice and suggestions during my research. My PhD journey would have been incredibly dull without the companionship of Mr. Pushpendra Yadav, Mr. Suri Praneeth, Mr. Amarnath Yalavarthi, Mr. Debashish Mishra, and Mr. Saran Chaurasiya, who have been a constant source of support and motivation during difficult times. I would also like to thank Mr. Gurmeet Singh, Ms. Heena Praveen, Ms. Rashmi Rai, Mr. Aryadip Sen, Mr. Sayan Dev Ghosh, Dr. Vivek Narayan, Dr. Jitendra Gupta, Dr. Souvik Das, Mr. Gaurav Modi, Mr. Syed Bilal Qaiser Naqvi, Ms. Shalvi Tyagi, Mr. Sharankumar Shastri, Mr. Shivam Kumar Yadav, Mr. Vipin Singh, Mr. Sumit Kumar, Mr. Biswajit Saha, and Ms. Farah Siddiqi, Amanpreet Singh, Rajesh Kumar, Vivek Chaudhary, Rajendra Bahadur, Gaurav Goyal, Nagendra Kumar Mehta, Niraj Kumar for their valuable support.

I would like to thank my friends for helping me out during all these years of hardwork with their mental and emotional support. I wish to thank especially Prof. Avinash Kumar (IIT Roorkee), Abhinav Vatsh, Pushpendra, Som Prakash, Rajni, Madhukar Kumar, Priyanka Kumari, Nistha, Mohit, Diksha, Anand, D. Swati, Dr. Anad Kumar, Prof. Roshni Agnihotri, Varun Sharma, Dr. Rajiv, Hitesh and Dr. Arnav. They have become a support system for me during my PhD duration.

The hardships and sacrifices of my grandparents, the Late **Gauri Shankar Singh**, Late **Harinandan Chaudhary**, Late **Shevya Devi**, Late **Kaushalya Devi**, have enabled my family to enjoy the opportunities and comforts I have today. I would like to express my deepest gratitude to my parents, **Rajesh Kumar** and **Pushpa Kumari** for their unwavering support and encouragement throughout my academic journey. Your endless patience, love, and belief in me have been my greatest source of strength. This thesis is a testament to his guidance and sacrifices. Their encouragement has allowed me to pursue research without worrying about my other responsibilities.

Despite not having had the opportunity to pursue a PhD himself, my father possesses a strong scientific temperament. Although circumstances prevented him from achieving this academic milestone, his unwavering support and encouragement have enabled me to reach these heights in the next generation. I would like to express my profound gratitude to my brother, **Subrat**, who has been a constant guide in enhancing my technical understanding. His expertise, patience, and unwavering support have been invaluable in navigating complex concepts and challenges.

I extend my heartfelt gratitude to my wife, **Dr. Kashish Bhardwaz** for her unwavering support, patience, and encouragement throughout this journey. Her understanding and sacrifices have been instrumental in my success. I also wish to thank my father-in-law and mother-in-law **Sunil Kumar Singh** and **Nisha Kumari** for their constant support and belief in my endeavors. Your collective love and encouragement have made this achievement possible.

I also take this opportunity to thank my family members Dr. Ramashish Singh, Dr. Sobha Kumari, Shambhu Chaudhary, Vijay Chaudhary, Sudhir Prasad Singh, Sunita Kumari, Sunil Singh, Sangeeta Kumari, Pankaj Singh, Navendu Priyadarshi, Dr. Smita Singh, Priyanka Priyadarshani, Praveen Kumar, Shivangi, Shambhavi, Alankar Kumar, Pranav Kumar, Sonam, Shakshi Kumari, Amiyavrat, Yogesh, Mona, Raja, Subham, Sujal, Aman, Aayush, Tanya, Shagun, Divit, Arjita, Tejas, Priyanka Kumari (MS Manjaul), Bindu Devi, Santosh Kumar, Laxmi Kumari, Kanchan Kumari, Rammilan Singh, Babita Devi. I also want to thank Sravan Tanti, Sitaram Pandit and his family for continuous support.

I am deeply grateful to the almighty for granting me a life where I could make meaningful choices and pursue the path of higher knowledge and wisdom. This divine guidance has blessed me with the strength and clarity to achieve my goals and dreams.

May 15, 2025

New Delhi

Priyvrat Vats

ABSTRACT

The research work focuses on the design and development of various types of compulsators, including the Halbach compulsator, multi-layer compulsator, dual armature compulsator, and axial flux compulsator. Each design aims to enhance the performance and efficiency of electromagnetic launch systems by addressing specific technical challenges. The Halbach array configuration is utilized for its superior magnetic field properties, while the multi-layer winding technique increases produced voltage to self-inductance and increases energy delivery. The dual armature design incorporates two sets of windings to improve energy discharge, and the axial flux configuration optimizes power and energy density and enhances the energy utilization factor.

Additionally, the research delves into the design of a thyristor stack and gate drive circuit, which are crucial for managing the high-power switching required in compulsator applications. The thyristor stack design ensures reliable and efficient switching, while the gate drive circuit provides the necessary control signals to operate the thyristors effectively.

A significant aspect of this work is the study of synchronization of multiple compulsators. Synchronization is critical to ensure that the compulsators discharge their energy simultaneously, maximizing the overall power delivered to the electromagnetic launcher. This involves precise timing and control mechanisms to coordinate the operation of multiple units.

Through extensive simulation and analysis, the research demonstrates the feasibility and benefits of these advanced compulsator designs. The findings highlight improvements in energy density, power density, and overall system efficiency, making these designs suitable for high-power applications such as railguns and other electromagnetic launch systems. The study provides a comprehensive overview of the technical advancements and practical considerations in the development of state-of-the-art compulsators.

सारांश

यह शोध कार्य विभिन्न प्रकार के कंपल्सेटर्स के डिजाइन और विकास पर केंद्रित है, जिसमें हालबैक कंपल्सेटर, बहु-परत कंपल्सेटर, द्वि-आर्मेचर कंपल्सेटर और अक्षीय चुंबकीय प्रवाह कंपल्सेटर शामिल हैं। प्रत्येक डिजाइन का उद्देश्य विशिष्ट तकनीकी चुनौतियों का समाधान करके विद्युत चुम्बकीय प्रक्षेपण प्रणालियों के प्रदर्शन और दक्षता को बढ़ाना है। हालबैक व्यूह का उपयोग इसके बेहतर चुंबकीय क्षेत्र गुणों के लिए किया जाता है, जबकि बहु-परत घुमावदार तकनीक उत्पादित वोल्टेज और स्व-प्रेरकत्व के अनुपात और ऊर्जा वितरण को बढ़ाती है। दोहरे आर्मेचर डिज़ाइन में ऊर्जा निर्वहन के सुधार के लिए वाइंडिंग के दो सेट शामिल हैं और अक्षीय प्रवाह कंपल्सेटर विन्यास शक्ति और ऊर्जा घनत्व को अनुकूलित करता है, साथ ही ऊर्जा उपयोग को बढ़ाता है।

इसके अतिरिक्त, यह शोध कार्य एक थाइरिस्टर स्टैक और गेट ड्राइव सर्किट के डिजाइन पर प्रकाश डालता है, जो कंपल्सेटर अनुप्रयोगों में आवश्यक उच्च-शक्ति स्विचिंग के प्रबंधन के लिए महत्वपूर्ण हैं। थाइरिस्टर स्टैक डिज़ाइन विश्वसनीय और कुशल स्विचिंग सुनिश्चित करता है, जबकि गेट ड्राइव सर्किट थाइरिस्टर को प्रभावी ढंग से संचालित करने के लिए आवश्यक नियंत्रण संकेत प्रदान करता है।

इस काम का एक महत्वपूर्ण पहलू कई कंपल्सेटर के तादात्म्य का अध्ययन है। तादात्म्य यह सुनिश्चित करने के लिए महत्वपूर्ण है कि कंपल्सेटर अपनी ऊर्जा को एक साथ निर्वहन करते हैं, जिससे विद्युत चुम्बकीय लांचर को वितरित समग्र शक्ति अधिकतम हो जाती है। इसमें कई इकाइयों के संचालन को समन्वित करने के लिए सटीक समय और नियंत्रण तंत्र शामिल है।

व्यापक सिमुलेशन और विश्लेषण के माध्यम से, यह अनुसंधान इन उन्नत कंपल्सेटर डिजाइनों की व्यवहार्यता और लाभों को प्रदर्शित करता है। इस कार्य का निष्कर्ष ऊर्जा घनत्व, बिजली घनत्व और समग्र प्रणाली के दक्षता में सुधार को उजागर करता हैं, जिससे ये डिजाइन रेलगन और अन्य विद्युत चुम्बकीय प्रमोचन प्रणाली जैसे उच्च-शक्ति अनुप्रयोगों के लिए उपयुक्त हो जाता हैं। यह अध्ययन अत्याधुनिक कंपल्सेटर के विकास में तकनीकी प्रगति और व्यावहारिक विचारों का व्यापक अवलोकन प्रदान करता है।

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ac	Alternating Current
AFCPA	Axial Flux Compulsator
CPA	Compensated Pulsed Alternator
CPPS	Compulsator based Pulse Power Supply
CAD	Computer Aided Design
CO_2	Carbon Dioxide
DACPA	Dual Armature Compensated Pulsed Alternator or Compulsator
dc	Direct Current
DESI	Defence and Security Equipment International
DEW	Directed Energy Weapons
EM	Electromagnetic
EMALS	Electromagnetic Aircraft Launch Systems
EML	Electromagnetic Launcher / Electromagnetic Launch System
ELS	Excitation Loop Suppression
EMP	Electromagnetic Pulse
EMF	Electromotive Force
EPP	Explosive Pulsed Power
FEA	Finite Element Analysis
HCPA	Halbach Array Compulsator
HPM	High Power Microwave
IGBT	Insulated-Gate Bipolar Transistor
PPS	Pulse Power Supply
MEA	More Electric Aircraft
MCPA	Multi-layer Halbach Array Compulsator
MTBF	Mean Time between Failures
NdFeB	Neodymium Iron Boron (Neodymium magnets)
PA	Pulsed Alternator
PFN	Pulse Forming Network

PM	Permanent Magnet
PT	Pulse Transformer
RF	Radio Frequency
RFC	Radial Flux Compulsator
rpm	Revolution Per Minute
VCCS	Voltage Controlled Current Source
2-D	Two Dimensional

LIST OF SYMBOLS

A	Unit of Current (A)
a	Number of Parallel Path
A_e	Cross-sectional Area of Core (m^2)
A_l	Inductance Factor ($H/turns^2$)
A_C	Area of Capacitor Plate (m^2)
A_L	Cross-sectional Area of Inductor Core (m^2)
α_a	Temperature Coefficient of Material (K^-1)
B	Magnetic Flux Density (T)
$B_{ag,r}$	Radial Flux Density (T)
B_m	Maximum or Peak Flux Density (T)
B_r	Remanent Flux Density (T)
B_{sat}	Saturation Flux Density (T)
B_c	Core Magnetic Flux Density (T)
C	Capacitance (F)
C_s	Snubber Capacitors (F)
C_p	Specific Heat Capacity ($J/kg - K$)
d	Derating of Thyristor for Reliable Operation
D	Diode
D_{avg}	Average Diameter of Armature Windings (m)
D_{ish}	Inner Diameter of Electromagnetic Shield (m)
D_{iso}	Outer Diameter of Inner Stator Core (m)
D_{oc}	Rotor Outer Diameter (m)
D_{osh}	Outer Diameter of Outer Electromagnetic Shield (m)
D_{osi}	Inner Diameter of Outer Stator Core (m)
D_{oso}	Outer Diameter of Outer Stator Core (m)
D_r	Diameter of Airgap (m)
D_{ri}	Airgap Diameter for Inner Armature or Diameter of Inner Airgap (m)
D_{ro}	Airgap Diameter for Outer Armature or Diameter of Outer Airgap(m)
D_s	Outer Diameter of Stator Core (m)
D_{sh}	Outer Diameter of Shaft (m)
E	Electric Field Intensity (V/m)
E_c	Kinetic Energy Storage in Rotor Core (J)
E_{KE}	Total Kinetic Energy Storage in Rotar (J)
E_{sh}	Total Kinetic Energy Storage in Electromagnetic Shield (J)

E_C	Energy Stored in Capacitor (J)
$E_{g,max}$	Maximum Generated EMF per Phase (V)
E_L	Energy Stored in Inductor (J)
E_{pm}	Kinetic Energy Storage in Permanent Magnet (J)
E_ρ^V	Volumetric Energy Density (J)
F	Lorentz Force (N)
f	Frequency of Operation (Hz)
J_r	Moment of Inertia of Rotor ($kg - m^2$)
L'	Inductance Gardiant of Electromagnetic Launcher (H/m)
L_e	Effective Length of Coil Side (m)
L_m	Stator Mutual-Inductance (H)
L_r	Rotor Core Length (m)
L_{rr}	Rotor Self-Inductance (H)
$L_{rr'}$	Rotor Self-Inductance Referred to Stator (H)
L_s	Effective Length of Stator Core (m)
L_{ss}	Stator Self-Inductance (H)
L_s	Effective Length of Stator Core (m)
μ	Magnetic Permeability (H/m)
μ_o	Permeability of Free Space ($4\pi \times 10^{-7} H/m$)
μ_r	Relative Permeability
N_p	Number of Turns in Primary Winding
N_{ph}	Number of Turns per Phase
ω_s	Electrical Angular Frequency (rad/sec)
ω_r	Rotor Speed (rad/sec)
p	Number of Pole Pair
R'	Resistance Gradiant (Ω/m)
R_s	Snubber Resistance (Ω)
R_{scr}	Thyristor Resistance (Ω)
ρ_a	Density of Armature Winding Material (kg/m^3)
ρ_c	Density of Rotor Core Material (kg/m^3)
ρ_{pm}	Density of Magnet Material (kg/m^3)
ρ_{sh}	Density of Electromagnetic Shield Material (kg/m^3)
S_a	Cross-sectional Area of Armature Conductor (m^2)
σ_a	Conductivity of Armature Winding Material (S/m)
σ_s	Conductivity of Electromagnetic Shield Material (S/m)
T_m	Mechanical Torque (m)

t_{ipm}	Thickness of Inner PM (m)
t_{opm}	Thickness of Outer PM (m)
t_{pm}	Thickness of PM Excitation (m)
t_{sh}	Thickness of Electromagnetic Shield (m)
θ_f	Final Winding Temperture (K)
θ_i	Initial Winding Temperture (K)
θ_m	Magnetization Angle (rad)
θ_p	Polarization Angle (rad)
V_{tip}	Tip Velocity (m/sec)
V_m	Muzzel Velocity (m/sec)
W_{pm}	Weight of PM material (kg)
ε	Dielectric Constant