

**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**

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by

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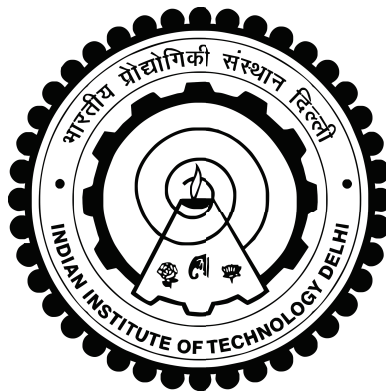
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Submitted

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to the



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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. Priyvrats 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. Priyvrats 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.

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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 डिजाइन 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 डिजाइन 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 हैं।

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 है, जिससे ये डिजाइन रेलगन और अन्य विद्युत चुम्बकीय प्रमोचन प्रणाली जैसे उच्च-शक्ति अनुप्रयोगों के लिए उपयुक्त हो जाता है। यह अध्ययन अत्याधुनिक कंपल्सेटर के विकास में तकनीकी प्रगति और व्यावहारिक विचारों का व्यापक अवलोकन प्रदान करता है।

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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 ($H/turn.s^2$)
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 Gradient 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 Gradient (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