PULSED POWER CIRCUIT DESIGN TECHNIQUES FOR ELECTROMAGNETIC LAUNCHERS

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PULSED POWER CIRCUIT DESIGN TECHNIQUES FOR ELECTROMAGNETIC LAUNCHERS

by

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To,

My mother *Shila Saha Chaudhuri* and my father *Gurupada Chaudhuri*

who have lived all the highs and lows of this journey with me.

Certificate

This is to certify that the thesis entitled **"Pulsed Power Circuit Design Techniques for Electromagnetic Launchers"**, being submitted by **Dipta Chaudhuri** for the award of the degree of **Doctor of Philosophy** to the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of bonafide work done by her under our supervision and guidance. The matter embodied in this thesis has not been submitted to any other University or Institute for the award of any other degree or diploma.

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Dipta Chaudhuri

Abstract

The railgun, an electromagnetic launcher, is a powerful weapon that can propel projectiles to very high velocities (Mach 6-7) without the use of any explosive materials. Nowadays it is being extensively explored and in use due to these advantages. It requires a very high pulsed current of the order of hundreds of kA with a rise time of a few milliseconds.

This research work is motivated by the challenges in the design, implementation and improvements of these high-current pulsed power supplies (PPS). PPS circuits are switched-*RLC* circuits. Traditionally, the switches used in PPS are spark-gap switches. Despite having high voltage and high current ratings, spark-gap switches have a short lifetime. Comparatively, semiconductor switches are modular, have a longer lifespan, and are now an attractive alternative to spark-gap switches in PPS design. However, they have lower ratings. They may have to be stacked in series-parallel due to the very high voltage and current requirement in railguns. Further, they have to be well-protected with snubbers to withstand sudden voltage transients, as well as with series and parallel resistors to force fairly equal sharing of voltages and currents among the stacked switches to prevent any damage. A 400 kJ capacitive PPS (CPPS) unit is designed that uses off-the-shelf thyristors and diodes and addresses all these issues. Also, a general methodology is proposed for designing fully-protected semiconductor switch-stacks suitable for CPPS.

To turn-ON the thyristors in a CPPS, a gate current of high magnitude and high rising-rate is required, and the gate-drive circuit has to be isolated from the high-power PPS circuit. Also, all the thyristors used in a switch-stack have to be triggered simultaneously

to avoid transient voltage spikes. A circuit suitable for simultaneously triggering all the thyristors of the 400 kJ CPPS is designed using load line analysis.

Another class of PPS is the inductive pulsed power supply (IPPS). Current maintainable meat grinder (CMMG), a type of IPPS, is suitable for velocity control during railgun launch. A 400 kJ CMMG is compared with the 400 kJ CPPS using a combination of circuit simulations and 3-D electromagnetic-mechanical coupled simulations, and it is seen that for all practical inductance values, the muzzle velocity of the CPPS-driven-railgun is significantly lesser than the CMMG-driven-railgun.

Although CMMG is suitable for replacing CPPS, there is a substantial wastage of energy in it due to the residual current, which also results in muzzle arcing. A new topology of IPPS, the current maintainable meat grinder with energy recovery (CMMGER), is proposed in which this residual current reduces just before the projectile reaches the muzzle, reducing the possibility of muzzle arc, as well as a substantial portion of the residual energy is restored to be reused.

To summarize, the major contributions of this thesis work are (i) Electromagnetic- mechanical coupled simulation of an electromagnetic railgun along with circuit simulation of the PPS has been carried out to assess its dynamic performance (ii) A generalized methodology has been proposed to design a thyristor switch stack and diode stack (along with all protection circuits) to replace the spark-gaps used in a PPS (iii) A suitable firing circuit has been designed for the thyristor stack to fire all the devices in the stack simultaneously with proper isolation between the power and firing modules (iv) A comparison between an

IPPS and CPPS has been presented that emphasizes the superiority of the IPPS over CPPS, especially in imparting higher velocities to the projectile. And finally, (v) an IPPS in the form of a CMMG has been designed with a capability to recover part of the energy so that it can be reused to improve the overall efficiency of the electromagnetic launcher apart from reducing arcing considerably when the projectile exits the barrel.

सार

रेलगन, एक विद्युत चुम्बकीय लांचर, एक शक्तिशाली हथियार है जो किसी भी विस्फोटक सामग्री के उपयोग के बिना प्रक्षेप्य को बहुत उच्च वेग (मच 6-7) तक चला सकता है। इन फायदों के कारण आजकल इसे बड़े पैमाने पर खोजा और उपयोग में लाया जा रहा है। इसके लिए कुछ मिलीसेकंड के उदय समय के साथ सैकड़ों kA के क्रम की बहुत उच्च स्पंदित करंट की आवश्यकता होती है।

यह शोध कार्य इन उच्च-वर्तमान पल्स पावर सप्लाई (पीपीएस) के डिजाइन, कार्यान्वयन और सुधार में चुनौतियों से प्रेरित है। पीपीएस सर्किट स्विच किये जाने वाले आरएलसी सर्किट हैं । परंपरागत रूप से, पीपीएस में उपयोग किए जाने वाले स्विच स्पार्क-गैप स्विच होते हैं। उच्च वोल्टेज और उच्च वर्तमान रेटिंग होने के बावजूद, स्पार्क-गैप स्विच का जीवनकाल छोटा होता है। तुलनात्मक रूप से, सेमीकंडक्टर स्विच मॉड्यूलर होते हैं, उनका जीवनकाल लंबा होता है, और अब ये हैं पीपीएस डिज़ाइन में स्पार्क-गैप स्विच का एक आकर्षक विकल्प। हालाँकि, उनकी रेटिंग कम है।

रेलगनों में बहुत अधिक वोल्टेज और करंट की आवश्यकता के कारण उन्हें सीरीज - पैरेलल में स्टैक् करना पड़ सकता है। इसके अलावा, उन्हें अचानक वोल्टेज परिवर्तन का सामना करना पड सकता है इसीलिए स्नबर्स के साथ अच्छी तरह से संरक्षित किया जाना चाहिए । किसी भी क्षति को रोकने के लिए स्टैक्ड स्विचों के बीच वोल्टेज और धाराओं को समान रूप से साझा करने के लिए सीरीज और पैरेलल रेजिस्टेंस डालना ज़रूरी है ।

एक 400 किलोजूल कैपेसिटिव पीपीएस (सीपीपीएस) डिज़ाइन की गई है जो ऑफ-द-शेल्फ थाइरिस्टर और डायोड का उपयोग करती है और इन सभी मुद्दों का समाधान करती है। इसके अलावा, सीपीपीएस के लिए उपयुक्त पूरी तरह से संरक्षित अर्धचालक स्विच-स्टैक को डिजाइन करने के लिए एक सामान्य पद्धति प्रस्तावित है।

सीपीपीएस में थाइरिस्टर को चालू करने के लिए, उच्च परिमाण और उच्च बढ़ती दर के गेट करंट की आवश्यकता होती है, और गेट-ड्राइव सर्किट को उच्च-शक्ति पीपीएस सर्किट से आइसोलेशन करना पड़ता है। साथ ही, स्विच-स्टैक में उपयोग किए जाने वाले सभी थाइरिस्टर को एक साथ चालू करना होगा क्षणिक वोल्टेज स्पाइक्स से बचने के लिए। 400 किलोजूल सीपीपीएस के सभी थाइरिस्टर को एक साथ ट्रिगर करने के लिए उपयुक्त सर्किट को लोड लाइन विश्लेषण का उपयोग करके डिज़ाइन किया गया है। पीपीएस का एक अन्य वर्ग इंडक्टिव पल्स पावर सप्लाई (आईपीपीएस) है। करंट मेंटेनेबल मीट ग्राइंडर (सीएमएमजी), एक प्रकार का आईपीपीएस, रेलगन लॉन्च के दौरान वेग नियंत्रण के लिए उपयुक्त है। सर्किट सिमुलेशन और 3-डी इलेक्ट्रोमैग्नेटिक-मैकेनिकल युग्मित सिमुलेशन के संयोजन का उपयोग करके 400 किलोजूल सीएमएमजी की तुलना 400 किलोजूल सीपीपीएस से की गयी है, और यह देखा गया है कि सभी व्यावहारिक अधिष्ठापन मूल्यों के लिए, सीपीपीएस-चालित-रेलगन का थूथन वेग सीएमएमजी-चालित-रेलगन से काफी कम है। यद्यपि सीएमएमजी सीपीपीएस को बदलने के लिए उपयुक्त है, लेकिन अवशिष्ट करंट के कारण इसमें ऊर्जा की काफी बर्बादी होती है, जिसके परिणामस्वरूप थूथन में जलन भी होती है। आईपीपीएस की एक नई टोपोलॉजी, एनर्जी रिकवरी करने वाला करंट मेंटेनेबल मीट ग्राइंडर (सीएमएमजीईआर) का प्रस्ताव है, जिसमें प्रक्षेप्य के थूथन तक पहुंचने से ठीक पहले यह अवशिष्ट करंट कम हो जाती है, जिससे थूथन चाप की संभावना कम हो जाती है, साथ ही अवशिष्ट एनर्जी का एक बड़ा हिस्सा पुन: उपयोग के लिए बहाल हो जाता है।

संक्षेप में, इस थीसिस कार्य के प्रमुख योगदान हैं:

(i) इसके गतिशील प्रदर्शन का आकलन करने के लिए पीपीएस के सर्किट सिमुलेशन के साथ एक विद्युत चुम्बकीय रेलगन का विद्युत चुम्बकीय-यांत्रिक युग्मित सिमुलेशन किया गया है। (ii) पीपीएस में प्रयुक्त स्पार्क-गैप को बदलने के लिए थाइरिस्टर स्विच स्टैक और डायोड स्टैक (सभी सुरक्षा सर्किट के साथ) को डिजाइन करने के लिए एक सहज पद्धति प्रस्तावित की गई है। (iii) थाइरिस्टर स्टैक के लिए एक उपयुक्त फायरिंग सर्किट डिजाइन किया गया है ताकि स्टैक में सभी उपकरणों को एक साथ बिजली और फायरिंग मॉड्यूल के बीच उचित आइसोलेशन के साथ फायर किया जा सके। (iv) आईपीपीएस और सीपीपीएस के बीच एक तुलना प्रस्तुत की गई है जो सीपीपीएस पर

आईपीपीएस की श्रेष्ठता पर जोर देती है, खासकर प्रक्षेप्य को उच्च वेग प्रदान करने में। और अंत में, (v) सीएमएमजी के रूप में एक आईपीपीएस को एनर्जी के हिस्से को पुनर्प्राप्त करने की क्षमता के साथ डिजाइन किया गया है ताकि जब प्रक्षेप्य बैरल से बाहर निकलता है तो आर्किंग को काफी कम करने के अलावा विद्युत चुम्बकीय लॉन्चर की समग्र दक्षता में सुधार किया जा सके।

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PPS	Pulsed Power Supply
CPPS	Capacitive Pulsed Power Supply
IPPS	Inductive Pulsed Power Supply
EMRG	Electromagnetic Railgun
EML	Electromagnetic Launcher
CMMG	Current Maintainable Meat Grinder
CMMGER	Current Maintainable Meat Grinder with Energy Recovery
ICCOS	Inverse Current Commutation with Semiconductor
STRETCH	Slow Transfer of Energy Through Capacitive Hybrid
SECT	Self-charged Capacitor and Thyristors
MTBF	Mean Time Between Failure
PFN	Pulse Forming Network
PFU	Pulse Forming Unit
CPFU	Capacitive Pulse Forming Unit
SPICE	Simulation Program with Integrated Circuit Emphasis

FEM	Finite Element Method
LED	Light Emitting Diode
BJT	Bipolar Junction Transistors
OPAMP	Operational Amplifier
FET	Field Effect Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PT	Pulse Transformer
BCSC	Bridge Current Switching Circuit
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor