

**DESIGN AND DEVELOPMENT OF HIGH-VOLTAGE SOLID-
STATE PULSED POWER GENERATORS**

DEVESH MALVIYA



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

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STATE PULSED POWER GENERATORS**

by
DEVESH MALVIYA

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

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

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CERTIFICATE

This is to certify that the thesis entitled “**DESIGN AND DEVELOPMENT OF HIGH-VOLTAGE SOLID-STATE PULSED POWER GENERATORS**” being submitted by **Mr. Devesh Malviya** for the award of the degree of **Doctor of Philosophy** is a record of a bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi, New Delhi. Mr. Devesh Malviya worked under my guidance and supervision and has fulfilled the requirement for the submission of the thesis, which to my knowledge has reached the requisite standards. The matter embodied in this thesis has not been submitted to any other University or Institute for the award of any Degree or Diploma.

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Dr. M. Veerachary

Professor

Department of Electrical Engineering

Indian Institute of Technology Delhi

New Delhi-110016

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Devesh Malviya

Abstract

The induction of solid-state technology in pulsed power generators (PPGs) has significantly improved the generators in terms of size, weight, and performance. Furthermore, this technology has enhanced the system's controllability over critical pulse parameters such as amplitude, width, polarity, shape, and repetitiveness. However, considering the usefulness of the PPGs in a wide variety of applications, several other factors such as the 'pulsed output to input voltage conversion ratio (PO-IVCR)' of the PPGs, the number of semiconductors and passive devices required by them, and utilization of a single generator for different applications have substantial importance and need to be addressed. This thesis investigates the solid-state pulsed power generator technology with the motivation to design and develop PPGs that can offer enhanced PO-IVCR and that too by requiring fewer semiconductors and passive components. Moreover, it is desired that the developed PPG should exhibit the features such as precise pulse reproducibility, better controllability over pulse specifications, generation of high repetitive bipolar pulses, and the ability to drive different types of loads. The primary attention has been given to the development of bipolar pulse generators, which have become an attractive research topic because of their usability in medical applications. With the above motivations, the research work has been carried out, and the outcomes are exhaustively discussed in this thesis.

This thesis presents two novel bipolar pulsed power generators, namely Bipolar High-Voltage Pulsed Power Supply (BHVPPS) and Modular Bipolar Pulse Generator (MBPG).

BHVPPS is an inductor-based PPG that utilizes the energy-storing capability of the inductor and thus can be classified as an inductive energy storage system. BHVPPS controls the flow of energy into its inductor as a boost converter does and follows the parallel charging concept like the Marx generator. BHVPPS is found to achieve high PO-IVCR by utilizing less number of semiconductors and passive devices. Moreover, BHVPPS is suitable for driving various load types such as plasmas, biological cells, gases, etc. The thesis extensively discusses the principle of operation of the BHVPPS and establishes an exhaustive mathematical analysis to explain the BHVPPSs' working. Further, it presents a detailed design procedure for the selection of passive components. The thesis also validates the claims and advantages of the BHVPPS through simulations and experiments.

Another bipolar pulsed power generator, i.e., MBPG presented in the thesis, is an inductor-less PPG or, in other words, is a capacitive energy storage PPG system and consists of only capacitors and switches. It makes MBPG suitable for a wide range of operations. Conventionally, two capacitor charging mechanisms, i.e., parallel charging and sequential charging, are employed in the inductor-less PPGs. Both have their own merits and demerits, but a common issue associated with both of them is the requirement of a large number of capacitors and associated switching devices for achieving a large PO-IVCR, and at such PO-IVCRs, PPGs become vulnerable to several challenges. To mitigate these challenges, a charging mechanism for the capacitors of the PPGs, i.e., sequential cum parallel capacitor charging (S+P-CC), is proposed in this thesis. As the name suggests, "S+P-CC" involves the concept of sequential as well as parallel charging. The working of the "S+P-CC" is simple, and it supports a very high PO-IVCR. The proposed MBPG utilizes this charging mechanism and effectively supports a relatively higher PO-IVCR. Moreover, it requires fewer switches and capacitors than its peers. In addition to it, MBPG is modular, has the ability to produce pulses at high repetitiveness, and provides flexibility in the adjustment of pulse parameters such as

amplitude, polarity, and width. The thesis extensively establishes the steady-state and transient analysis to explain the behaviour of the MBPG and derives the energy expressions and the design methodology. The thesis also provides the simulation and experimental results in support of the claims made by the MBPG. Furthermore, the thesis provides an exhaustive comparative study between the reported PPGs and the proposed MBPG to prove the feasibility and relevance of the proposed PPG.

The above-discussed PPGs are intended to generate bipolar pulses, which are of utmost importance in electroporation-based cancer therapies. But, several other applications, such as food treatment and particle accelerators, also require high voltage pulses but of unipolar nature. Food sterilization requires multipulse output, whereas the particle accelerator industry requires PPGs, which give low-voltage droop long high-voltage pulses. Considering these requirements, a multipulse/ unipolar PPG is designed. This PPG supports a high PO-IVCR and is, given the name: HVMG, i.e., high-voltage multipulse generator. A detailed discussion on the working of the HVMG is provided in the thesis, and to verify the claims made in the thesis, simulation and experiments have been carried out. Further, this thesis proposes a voltage droop compensation technique that effectively compensates the pulsed voltage droop. To verify the effectiveness of this technique, it is implemented on the HVMG. The proposed approach is tested through exhaustive simulations and experiments, and the results, thus obtained, are found in close agreement.

सार

पल्सड पावर जेनेरेटर्स (पी.पी.जी.) में सॉलिड-स्टेट टेक्नोलॉजी को शामिल करने से आकार, वजन और प्रदर्शन के मामले में जेनेरेटर्स में काफी सुधार हुआ है। इसके अलावा, इस तकनीक ने आयाम, चौड़ाई, ध्रुवता, आकार और दोहराव जैसे महत्वपूर्ण पल्स मापदंडों पर सिस्टम की नियंत्रणीयता को बढ़ाया है। हालांकि, विभिन्न प्रकार के अनुप्रयोगों में पी.पी.जी की उपयोगिता पर विचार करते हुए, कई अन्य कारक जैसे 'पल्सड आउटपुट टू इनपुट कन्वर्जन रेश्यो (पीओ-आईवीसीआर)', अर्धचालकों की संख्या और उनके लिए आवश्यक पैसिव उपकरण, और विभिन्न अनुप्रयोगों के लिए एकल जेनेरेटर के उपयोग का पर्याप्त महत्व है और इन्हें संबोधित करने की जरूरत है। यह थीसिस ऐसे पी.पी.जी की रचना और विकास करने की प्रेरणा के साथ सॉलिड-स्टेट पल्सड पावर जेनेरेटर तकनीक की जांच करती है जो कि उच्च पीओ-आईवीसीआर की पेशकश कर सके और वह भी कम अर्धचालक और पैसिव घटकों की आवश्यकता के द्वारा। इसके अलावा, यह वांछित है कि विकसित पी.पी.जी में सटीक पल्स रिप्रोड्यूसिबिलिटी, पल्स विनिर्देशों पर बेहतर नियंत्रणीयता, उच्च दोहराव वाले द्विध्रुवी पल्सों का उत्पादन और विभिन्न प्रकार के भार को चलाने की क्षमता जैसी विशेषताएं प्रदर्शित होनी चाहिए। प्राथमिक ध्यान द्विध्रुवी पल्सों को उत्पन्न करने वाले पी.पी.जी के विकास पर दिया गया

है, जो चिकित्सा अनुप्रयोगों में उनकी उपयोगिता के कारण अनुसंधान का एक आकर्षक विषय बन गए हैं।

उपरोक्त प्रेरणा के साथ, शोध कार्य किया गया है, और इस थीसिस में परिणामों की विस्तृत चर्चा की गई है।

यह थीसिस दो नवीन द्विध्रुवी पल्स जेनेरेटर, अर्थात् द्विध्रुवी उच्च-वोल्टेज स्पंदित विद्युत आपूर्तिकर्ता (बी.एच.वी.पी.पी.एस.) और मॉड्यूलर द्विध्रुवी पल्स जेनेरेटर (एम.बी.पी.जी.) प्रस्तुत करती है। बी.एच.वी.पी.पी.एस. एक इंडक्टर आधारित पी.पी.जी. है जो इंडक्टर की भंडारण क्षमता का उपयोग करता है और इस प्रकार बी.एच.वी.पी.पी.एस. को एक इंडक्टिव ऊर्जा भंडारण प्रणाली के रूप में वर्गीकृत किया जा सकता है। बी.एच.वी.पी.पी.एस. अपने इंडक्टर में ऊर्जा के प्रवाह को नियंत्रित करता है जैसाकि एक बूस्ट कनवर्टर करता है और मार्क्स जनरेटर की तरह समानांतर चार्जिंग अवधारणा का पालन करता है। यह पाया गया है की बी.एच.वी.पी.पी.एस. अर्धचालकों और पैसिव उपकरणों की कम संख्या का उपयोग करके उच्च पीओ-आईवीसीआर प्राप्त करता है। इसके अलावा, बी.एच.वी.पी.पी.एस. विभिन्न प्रकार के लोड जैसे प्लाज्मा, जैविक कोशिकाओं और गैसों आदि का प्रसंस्करण करने के लिए उपयुक्त है। यह थीसिस बी.एच.वी.पी.पी.एस. के संचालन के सिद्धांत पर व्यापक रूप से चर्चा करती है और बी.एच.वी.पी.पी.एस. के कामकाज की व्याख्या करने के लिए एक विस्तृत गणितीय विश्लेषण स्थापित करती है। इसके अलावा, यह पैसिव घटकों के चयन के लिए एक विस्तृत डिजाइन प्रक्रिया भी प्रस्तुत करती है। थीसिस सिमुलेशन और प्रयोगों के माध्यम से बी.एच.वी.पी.पी.एस. के दावों और लाभों को भी मान्य करती है।

यह थीसिस एक अन्य द्विध्रुवी पल्स जेनेरेटर, यानी, एम.बी.पी.जी., जो कि एक इंडक्टर-रहित पी.पी.जी. है या, दूसरे शब्दों में, एक कैपेसिटिव ऊर्जा भंडारण पी.पी.जी. सिस्टम है, इस थीसिस में प्रस्तावित है और इसमें केवल कैपेसिटर्स और स्विचेस होते हैं। यह इसे संचालन की विस्तृत श्रृंखला के लिए उपयुक्त बनाता है। परंपरागत रूप से, दो कैपेसिटर चार्जिंग मैकेनिज्म, यानी समानांतर चार्जिंग और अनुक्रमिक चार्जिंग, इंडक्टर-रहित पी.पी.जी.

में कार्यरत हैं। दोनों के अपने गुण और दोष हैं, लेकिन इन दोनों से जुड़ी एक आम समस्या यह है कि इन्हे उच्च पीओ-आईवीसीआर को प्राप्त करने के लिए बड़ी संख्या में कैपेसिटर्स और संबंधित स्विचिंग उपकरणों की आवश्यकता होती है और फिर ऐसे पीओ-आईवीसीआर पर, पी.पी.जी. कई चुनौतियों के प्रति संवेदनशील हो जाते हैं। इन चुनौतियों को कम करने के लिए, पी.पी.जी. के कैपेसिटर्स के लिए एक नया चार्जिंग सिद्धांत, यानी अनुक्रमिक सह समानांतर कैपेसिटर चार्जिंग (एस+पी-सीसी), इस थीसिस में प्रस्तावित है। जैसा कि नाम से पता चलता है, "एस+पी-सीसी" में अनुक्रमिक और समानांतर चार्जिंग की अवधारणा शामिल है। "एस+पी-सीसी" का कार्य सरल है, और यह बहुत अधिक पीओ-आईवीसीआर का समर्थन करता है। प्रस्तावित एम.बी.पी.जी. इस चार्जिंग तंत्र का उपयोग करता है और प्रभावी रूप से अपेक्षाकृत उच्च पीओ-आईवीसीआर प्राप्त करता है। इसके अलावा, इसे अन्य पी.पी.जी. की तुलना में कम स्विचेस और कैपेसिटर्स की आवश्यकता होती है। इसके अलावा, एम.बी.पी.जी. मॉड्यूलर है, उच्च दोहराव पर पल्सों का उत्पादन करने की क्षमता रखता है, द्विध्रुवी और साथ ही एकध्रुवीय पल्सों को उत्पन्न करता है, और आयाम, ध्रुवता और चौड़ाई जैसे पल्स मापदंडों के समायोजन में लचीलापन प्रदान करता है। थीसिस व्यापक रूप से एम.बी.पी.जी. के व्यवहार की व्याख्या करने के लिए स्थिर-अवस्था और क्षणिक-अवस्था का विश्लेषण स्थापित करती है और ऊर्जा अभिव्यक्ति और रचना पद्धति की व्युत्पत्ति करती है। थीसिस एम.बी.पी.जी. द्वारा किए गए दावों के समर्थन में अनुकरण और प्रयोगात्मक परिणाम भी प्रदान करती है। इसके अलावा, थीसिस प्रस्तावित पी.पी.जी. की व्यवहार्यता और प्रासंगिकता को साबित करने के लिए प्रतिवेदित पी.पी.जी. और प्रस्तावित एम.बी.पी.जी. के बीच एक विस्तृत तुलनात्मक अध्ययन प्रदान करती है।

उपर्युक्त चर्चा किए गए पी.पी.जी. का उद्देश्य द्विध्रुवी पल्सों को उत्पन्न करना है, जो इलेक्ट्रोपोरेशन-आधारित कैंसर उपचारों में अत्यंत महत्वपूर्ण हैं। लेकिन, कई अन्य अनुप्रयोगों, जैसे कि खाद्य उपचार और कण त्वरक के लिए भी उच्च वोल्टेज पल्सों की आवश्यकता होती है लेकिन एकध्रुवीय प्रकृति की। खाद्य उपचार के

लिए मल्टीपल्स आउटपुट की आवश्यकता होती है, जबकि कण त्वरक उद्योग को ऐसे पी.पी.जी. की आवश्यकता होती है, जो लो-वोल्टेज ड्रूप लॉन्ग हाई-वोल्टेज पल्स देते हैं। इन आवश्यकताओं को ध्यान में रखते हुए, एक मल्टीपल्स/एकध्रुवीय पी.पी.जी. डिज़ाइन किया गया है। यह पी.पी.जी. उच्च पीओ-आईवीसीआर का समर्थन करता है और इसे नाम दिया गया है: एच.वी.एम.जी., यानी, उच्च वोल्टेज मल्टीपल्स जेनेरेटर। एच.वी.एम.जी. की कार्यशैली पर एक विस्तृत चर्चा थीसिस में की गई है, और थीसिस में किए गए दावों को सत्यापित करने के लिए, सिमुलेशन और प्रयोग किए गए हैं। इसके अलावा, यह थीसिस वोल्टेज ड्रूप को कम करने की एक तकनीक प्रस्तावित करती है जो प्रभावी रूप से पल्सड वोल्टेज ड्रूप की भरपाई करती है। इस तकनीक की प्रभावशीलता को सत्यापित करने के लिए, इसे एचवीएमजी पर लागू किया गया है। प्रस्तावित दृष्टिकोण का परीक्षण विस्तृत सिमुलेशन और प्रयोगों के माध्यम से किया गया है, और सभी परिणामों के बीच घनिष्ठ समानता पायी गयी है।

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List of Symbols

n	Number of stages
L	Inductor of the BHVPPS
D	Diode of the BHVPPS
S_B	Boost stage switch of the BHVPPS
S_{Pi}	Positive pulse generating switches of the BHVPPS
S_{Ni}	Negative pulse generating switches of the BHVPPS
S_{Ci}	Capacitor charging switches of the BHVPPS
δ_P	Positive pulse duration
δ_N	Negative pulse duration
δ_T	Total width of the bipolar pulse
I_{max}	Maximum current of the BHVPPS inductor
I_{Dmax}	Maximum current of the BHVPPS diode
V_{Cimax}	Maximum voltage of the BHVPPS capacitors
$C_1, C_2, \dots, C_n$	Capacitors of the BHVPPS
C	Capacitance of the BHVPPS's capacitors and MBPG's module capacitors
R	Purely resistive load
τ	Time constant of the n -stage BHVPPS R - C circuit
V_{in}	DC Input voltage
k	Time duration

v_L	Voltage across the inductor of the BHVPPS
v_C	Voltage across the capacitor of the BHVPPS
i_L	Current through the inductor of the BHVPPS
i_C	Charging current of the capacitor of the BHVPPS
ω	Natural frequency of the BHVPPS circuit
$t_1, t_2, \dots, t_6$	Instantaneous times of a periodic cycle of the BHVPPS
R_L	Load resistance
C_L	Load capacitance
v_{RL}	Voltage across the load resistance
v_{CL}	Voltage across the load resistance
v_o	Output pulse voltage of the BHVPPS
q	Ratio of the capacitor's voltage at t_1 and the maximum capacitor voltage
V_{omax}	Peak of the output pulse voltage
L_C	Critical inductance
V_{Cimax}	i^{th} capacitor's maximum charging voltage
V_{Cimin}	i^{th} capacitor's minimum charging voltage
E_{output}	Energy in the pulsed output
T_s	Time duration of the single cycle of the BHVPPS
f	Pulse repetition rate
x	Number of SM
y	Number of SS
V_{pulse}	Output pulse voltage of the HGPPM
C_{SM}	Capacitors of the sub-modules of the HGPPM
C_1	Capacitance of the capacitors of the HGPPM's sub-module
C_{SS}	Capacitors of the sub-stages of the HGPPM
C_2	Capacitance of the capacitors of the HGPPM's sub-stage
T	Time duration of the single cycle of the HGPPM
V_s	DC source voltage for the HGPPM
r_{limit}	Limiting resistor
β	Permissible per unit dip in each SM capacitor's voltage
γ	Permissible per unit dip in each SS capacitor's voltage
$v1, v2$	SM capacitors' voltage levels

v_3, v_4	SS capacitors' voltage levels
m	Number of modules
S_{Ai1}	Upper-side switches of the modules of the MBPG
S_{Ai2}	Lower-side switches of the modules of the MBPG
C_{Ai}	Capacitors of the modules of the MBPG
$V_{CA1}, V_{CA2}, \dots, V_{CAm}$	Voltage across the module capacitors of the MBPG
C_{Bj}	Capacitors of the stages of the MBPG
C'	Capacitance of the MBPG's stage capacitors
$V_{CB1}, V_{CB2}, \dots, V_{CBm}$	Voltage across the stage capacitors of the MBPG
S_{main}	Source side switch of the MBPG
S_{Bj1} and S_{Bj2}	MBPG's stage capacitor's charging switches
S_{Bk}^+	Positive pulse generating switches of the MBPG
S_{Bk}^-	Negative pulse generating switches of the MBPG
V_{Cmax}	Maximum voltage up to which the MBPG's module capacitor charges
V_{Cmid}	MBPG's module capacitor's voltage after a unipolar pulse discharge
V_{Cmin}	Minimum voltage up to which the MBPG's module capacitor discharges
$V_{C' max}$	Maximum voltage up to which the MBPG's stage capacitor charges
$V_{C' min}$	Minimum voltage up to which the MBPG's stage capacitor discharges
$i_{CA1}, i_{CA2}, \dots, i_{CAm}$	Current through the MBPG's module capacitors
$i_{C'}$	Current through the MBPG's stage capacitors
V_o	MBPG's pulsed output voltage
I_o	MBPG's load current
E_{pulse}	Energy in each pulse delivered by the MBPG to the load
p, q, r	Permitted fall in the MBPG's module and stage capacitor's voltage
r_C	ESR of the MBPG's module capacitors
$r_{C'}$	ESR of the MBPG's stage capacitor
$t_{p.w.}$	Width of the MBPG's bipolar pulsed output
f_{sw}	Switching frequency of the MBPG
t_C	Time required by the MBPG's module capacitor to reach 99 % of the source voltage

$t_{C'}$	Time required by the MBPG's stage capacitors to get charged to $V_{C'_{max}}$ from $V_{C'_{min}}$
$P_{capacitor,loss}$	Power loss through the capacitors
$P_{switch,loss}$	Power loss through the switches
$P_{diode,loss}$	Power loss through the diodes
$V_{CE_{sat}}$	Collector-emitter saturation voltage of the IGBT
$V_{CE_{OFF}}$	OFF state voltage across the collector and emitter of the IGBT
t_r	Rise-time of the IGBT
t_f	Fall- time of the IGBT
$I_{switch,avg}$	Average collector current of the IGBT
V_F	Forward voltage drop of the diode
I_F	Average forward current through the diode
$i_{C,rms}$	RMS current through the capacitor
T_j	Junction temperature of the switch
T_A	Ambient temperature
$R_{\theta jc}$	Thermal resistance between junction and case
$R_{\theta cs}$	Thermal resistance between case and sink
$R_{\theta sa}$	Thermal resistance between sink and ambience

List of Abbreviations

PPGs	Pulsed Power Generators
PFN	Pulse Forming Network
EM	Electromagnetic
EMI	Electromagnetic interference
MMC	Modular multilevel converter
SCC	Switch-Capacitor Cells
HB	Half Bridge
SM	Sub Module
LCD	Liquid Crystal Display
RE	Reversible Electroporation
IRE	Irreversible Electroporation
PEF	Pulsed Electric Field
PO-IVCR	Pulsed Output to Input Voltage Conversion Ratio
BHVPPS	Bipolar High Voltage Pulsed Power Source
DCM	Discontinuous Conduction Mode
S+P-CC	Sequential cum parallel capacitor charging
HVMG	High Voltage Multipulse Generator
SS	Sub Stage
TSV	Total Standing Voltage
IBPPS	Inductor-Based Pulsed Power Supply
ILPPS	Inductor-Less Pulsed Power Supply

CCM	Continuous Conduction Mode
MBPG	Modular Bipolar Pulse Generator
ESR	Equivalent Series Resistance
ESL	Equivalent Series Inductance
PCB	Printed Circuit Board
HVDC	High Voltage Direct Current
SiC	Silicon Carbide
GaN	Gallium Nitride
PSIM	Powersim
Tp	Topologies
kV	Kilo-volt
kHz	Kilo-Hertz
RMS	Root Mean Square
Bi.	Bipolar
Uni.	Unipolar