

**PIEZOELECTRIC ENERGY HARVESTING
THROUGH LOW-FREQUENCY NON-SINUSOIDAL
VIBRATIONS OF CIVIL STRUCTURES**

SUMIT BALGUVHAR



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

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by

SUMIT BALGUVHAR

Department of Civil Engineering

Submitted

in fulfilment of the requirements of the degree of

Doctor of Philosophy

to the



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Dedicated to My Spiritual Master

H.H. Gopal Krishna Goswami Maharaj



CERTIFICATE

This is to certify that the report titled “**PIEZOELECTRIC ENERGY HARVESTING THROUGH LOW-FREQUENCY NON-SINUSOIDAL VIBRATIONS OF CIVIL STRUCTURES**” which is being submitted by **Mr. SUMIT BALGUVHAR** for the fulfilment of the requirements for the award of degree of **Doctor of Philosophy**, is a record of the student’s own work carried out at **Indian Institute of Technology Delhi** under my supervision and guidance. The matter embodied in this report has not been submitted elsewhere for the award of any other degree or diploma.

New Delhi
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Prof. Suresh Bhalla
Professor
Department of Civil Engineering
Indian Institute of Technology (IIT) Delhi

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ABSTRACT

Over the past two decades, advances in microelectronics and micro-electrical mechanical system (MEMS) technology have led to development of miniature devices for various applications which can run on micro to nano-watt power. This has ushered a growing interest in the field of energy harvesting using piezoelectric devices, which can convert dynamic mechanical strain into electric power in this range. In this connection, vibrations generated from civil structures, such as long/short-span bridges, city flyovers and elevated metro corridors, which are constantly under dynamic loads, are of special interest to researchers owing to the continuous availability of vibrations, unlike the solar power. The piezoelectric energy harvesters can work as sustainable and green power sources for ultra-low power consuming MEMS based portable electronic devices, such as wireless sensor nodes (WSNs), employed in automation systems, transportation networks, environmental monitoring, implanted medical devices and structural health monitoring (SHM). These can substitute batteries, which not only suffer from a finite lifespan but also pose environmental issues during disposal. Today, piezoelectric energy harvesting (PEH) represents a promising emerging technology to achieve autonomous, self-powered, and maintenance-free operation of WSNs and similar devices. However, several practical impediments still hinder the real-life deployment of PEH devices on civil infrastructures, such as low-frequency of the available vibrations (typically < 5 Hz) encountered there, coupled with low levels of voltage generation and the erratic nature signals.

The vast majority of PEH-related studies so far have only focused on the configurations and geometries of the harvester, often entailing secondary structures. d_{31} mode, which is the most

natural mode of excitation, has not been investigated in depth for piezo-patches directly bonded to the main structure. Such studies, which have focused on electronic conditioning circuitry for energy extraction, have been typically restricted to high sinusoidal voltages (>10 V) and high frequency (>20 Hz) signals or when the piezoelectric energy harvester is continuously excited in resonance conditions. However, very limited research has been carried out for low-frequency (<5 Hz) and low-voltage scenarios (<2 V) or where changes in excitation frequencies and voltage magnitudes are frequent, such as in case of real-life structural vibrations. Therefore, a successful industrial-scale deployment of PEH technology on civil-structures is still not operationally realized. The other important aspect is storage, which is problematic in civil-structures, again owing to their low-frequencies and erratic nature of vibrations.

This doctoral thesis aims to address these challenges and investigate power electronic interface circuits to enhance the power output and storage of the piezoelectric energy harvesters from civil infrastructure. Firstly, the experiments were carried out on a real-life city flyover to facilitate a first-hand measurement of the frequency range and the possible voltage range generated from surface-bonded Lead zirconate titanate (PZT) patches. This helped in understanding gaps between the lab and a typical real-life structure. With this information, further experiments were conducted in laboratory simulating real-life conditions of frequency and voltage pattern to perform a parametric study for investigating the influence of factors such as vibration frequency, voltage and circuit components like diodes on the harvestable power, otherwise not possible in real-life situations. Two standard bridge rectifier circuits: one using silicon diodes and the other using schottky diodes, were employed to charge a capacitor. From these experiments, it was established in principle that it is possible to harvest vibration power of the order of nano-watts

from a typical city flyover characterized with natural low-frequency. The schottky diode was found to perform better as compared to the silicon diode. Some power was also lost due to the voltage drop in the diodes of the rectifier.

The next set of experimental studies focused on evaluating various passive rectifier circuit topologies and zero on the best off the chip topology for the bridge rectifier circuits. The experiments were conducted using diode-based bridge rectifier circuit (DBRC) and metal-oxide semiconductor field effect transistor (MOSFET) based bridge rectifier circuit (MBRC). DBRC comprised of two different Schottky-type diodes (a) Model BAT1000 (b) Model IN-5819. MBRC comprised of a pair n-channel MOSFET (NMOS) and p-channel MOSFET (PMOS) in three different configurations, namely diode tied MOSFET (DMOS), gate cross-coupled MOSFET (GCMOS) and gate fully cross-coupled MOSFET (GFCMOS) connections in order to reduce the voltage drop during operations. The vibration signals were generated from a macro fiber composite (MFC) piezo patch bonded on a glass fibre composite cantilever beam. The cantilever was in-turn subjected under different excitation frequencies, but constant voltage amplitude, and vice-versa, to find each circuit's suitability for harvesting energy in real-life sources such as civil structures, where signals are characterized by low-frequency and low-voltage amplitude. The rectifier circuits were fully implemented using discrete components without involving any other external components and other associated start-up subsystems, as required in many of the previous reported studies.

Experimental results show that from PEH considerations, best performance is exhibited by D1000, a diode-based rectifier circuit, for the entire range of frequencies (5-15 Hz), which are

most dominant in civil-structures. The possible reason could be the lower forward bias voltage associated with D1000. Charging efficiency of about 81.33% has been achieved for 1 V open-circuit piezoelectric voltage excited at 5 Hz. The MOSFET based rectifier circuits, on the contrary, underperforms at 1 V, the possible reason could be the threshold voltage of the MOSFET is higher. Power in nano-watts range can be achieved across the capacitor from D1000 rectifier circuit at 5 Hz and 1 V open circuit voltage.

Next, an experimental laboratory investigation of the optimized D1000 rectifier circuit was carried out for charging a rechargeable battery from the energy harvested using piezoelectric element in simple d_{31} configuration. Lastly, field evaluation of the optimized circuit from the vibrations of the real-life city flyover and wind-based vibrations was carried out and storage of energy in the capacitor and battery was successfully demonstrated. A power of 0.17 mW was achieved from the MFC patch bonded directly to the girder and operating in d_{31} .

The main original contributions of this research have been to investigate and derive solutions for the practical issues related to PEH from low-frequency ambient vibrations of the civil-structures, which are otherwise good potential sources of vibrations. In this connection, the first contribution is the detailed investigation on circuit topologies by performing experiments under low-frequency and low-voltage scenarios typically encountered in real-life civil-structures. The second significant contribution is the proof-of-concept demonstration of PEH on real-life structures for the purpose of energy storage. It is expected that the study presented in this thesis can serve as a guideline for industrial scale design and manufacture of the piezoelectric energy harvesters for civil-infrastructure.

सार

पिछले दो दशकों में, माइक्रोइलेक्ट्रॉनिक्स और माइक्रो-इलेक्ट्रिकल मैकेनिकल सिस्टम (एमईएमएस) प्रौद्योगिकी में प्रगति के कारण विभिन्न अनुप्रयोगों के लिए लघु उपकरणों का विकास हुआ है जो माइक्रो से नैनो-वाट पावर पर चल सकते हैं। इसने पीजोइलेक्ट्रिक उपकरणों का उपयोग करके ऊर्जा संचयन के क्षेत्र में बढ़ती रुचि का सूत्रपात किया है, जो इस रेंज में गतिशील यांत्रिक तनाव को बिजली में परिवर्तित कर सकता है। इस संबंध में, लंबे/कम अवधि के पुलों, शहर के फ्लाईओवर और एलिवेटेड मेट्रो गलियारों, जो लगातार गतिशील भार के तहत हैं, जैसे नागरिक संरचनाओं से उत्पन्न कंपन सौर ऊर्जा के विपरीत कंपन की निरंतर उपलब्धता के कारण शोधकर्ताओं के लिए विशेष रुचि रखते हैं। पीजोइलेक्ट्रिक एनर्जी हार्वेस्टर अल्ट्रा-लो पावर खपत करने वाले एमईएमएस आधारित पोर्टेबल इलेक्ट्रॉनिक उपकरणों, जैसे वायरलेस सेंसर नोड्स (डब्ल्यूएसएन) के लिए टिकाऊ और हरित बिजली स्रोतों के रूप में काम कर सकते हैं, जो स्वचालन प्रणालियों, परिवहन नेटवर्क, पर्यावरण निगरानी, प्रत्यारोपित चिकित्सा उपकरणों और संरचनात्मक स्वास्थ्य निगरानी (एसएचएम) में नियोजित हैं। ये बैटरी को प्रतिस्थापित कर सकते हैं, जो न केवल एक परिमित उम्र से पीड़ित हैं बल्कि निपटान के दौरान पर्यावरणीय मुद्दे भी पैदा करते हैं। आज, पीजोइलेक्ट्रिक एनर्जी हार्वेस्टिंग (पीईएच) डब्ल्यूएसएन और इसी तरह के उपकरणों के स्वायत्त, स्व-संचालित और रखरखाव मुक्त संचालन को प्राप्त करने के लिए एक आशाजनक उभरती हुई तकनीक का प्रतिनिधित्व करता है। हालांकि, कई व्यावहारिक बाधाएं अभी भी सिविल अवसंरचनाओं पर पीईएच उपकरणों की वास्तविक जीवन तैनाती में बाधा डालती हैं, जैसे कि उपलब्ध कंपन की कम आवृत्ति (आमतौर पर < 5 हर्ट्ज) का सामना करना पड़ा, जो वोल्टेज उत्पादन के निम्न स्तर और अनियमित प्रकृति संकेतों के साथ मिलकर होता है।

पीईएच से संबंधित अधिकांश अध्ययनों ने अब तक केवल हार्वैस्टर के विन्यास और ज्यामिति पर ध्यान केंद्रित किया है, अक्सर माध्यमिक संरचनाओं को शामिल किया है। d31 मोड, जो उत्तेजन का सबसे प्राकृतिक तरीका है, पीजो-पैच सीधे मुख्य संरचना से बंधुआ के लिए गहराई में जांच नहीं की गई है। इस तरह के अध्ययन, जो ऊर्जा निष्कर्षण के लिए इलेक्ट्रॉनिक कंडीशनिंग सर्किटरी पर ध्यान केंद्रित किया है, आम तौर पर उच्च साइनसॉयडल वोल्टेज (> 10 वी) और उच्च आवृत्ति (> 20 हर्ट्ज) संकेतों या जब पीजोइलेक्ट्रिक ऊर्जा हार्वैस्टर लगातार प्रतिध्वनि की स्थिति में उत्साहित है करने के लिए प्रतिबंधित किया गया है। हालांकि, कम आवृत्ति (< 5 हर्ट्ज) और लो-वोल्टेज परिदृश्यों (< 2 V) या जहां उत्तेजन आवृत्तियों और वोल्टेज परिमाण में परिवर्तन अक्सर होते हैं, जैसे कि वास्तविक जीवन संरचनात्मक कंपन के मामले में बहुत सीमित शोध किए गए हैं। इसलिए, नागरिक संरचनाओं पर पीईएच प्रौद्योगिकी की एक सफल औद्योगिक पैमाने पर तैनाती अभी भी परिचालन रूप से साकार नहीं हुई है। दूसरा महत्वपूर्ण पहलू भंडारण है, जो नागरिक-संरचनाओं में समस्याग्रस्त है, फिर से उनकी कम आवृत्तियों और कंपन की अनियमित प्रकृति के कारण।

इस डॉक्टरेट थीसिस का उद्देश्य इन चुनौतियों का समाधान करना और सिविल बुनियादी ढांचे से पीजोइलेक्ट्रिक ऊर्जा हार्वैस्टर के बिजली उत्पादन और भंडारण को बढ़ाने के लिए पावर इलेक्ट्रॉनिक इंटरफेस सर्किट की जांच करना है। सबसे पहले, यह प्रयोग एक वास्तविक जीवन शहर फ्लॉराओवर पर किया गया था ताकि आवृत्ति रेंज के पहले हाथ के माप और सतह-बंधुआ लीड जिरकोनेट टाइटेनेट (पीजेडटी) पैच से उत्पन्न संभावित वोल्टेज रेंज की सुविधा प्रदान की जा सके। यह प्रयोगशाला और एक ठेठ वास्तविक जीवन संरचना के बीच अंतराल को समझने में मदद की। इस जानकारी के साथ, प्रयोगशाला में आगे के प्रयोग किए गए, जो कंपन आवृत्ति, वोल्टेज और सर्किट घटकों जैसे कटाई योग्य शक्ति पर डायोड जैसे कारकों के प्रभाव की जांच करने के लिए एक पैरामेट्रिक अध्ययन करने के लिए आवृत्ति और वोल्टेज पैटर्न

की वास्तविक जीवन की स्थितियों का अनुकरण करते हैं, अन्यथा वास्तविक जीवन की स्थितियों में संभव नहीं है। दो मानक पुल सुधारक सर्किट: एक सिलिकॉन डायोड का उपयोग करके और दूसरा शॉटकी डायोड का उपयोग करके, एक कैपेसिटर चार्ज करने के लिए नियोजित किया गया था। इन प्रयोगों से, यह सिद्धांत रूप में स्थापित किया गया था कि प्राकृतिक कम आवृत्ति के साथ विशेषता वाले एक विशिष्ट शहर फ्लाइंग ओवर से नैनो-वाट के क्रम की कंपन शक्ति को फसल करना संभव है। सिलिकॉन डायोड की तुलना में शॉटकी डायोड बेहतर प्रदर्शन करने के लिए पाया गया। सुधारक के डायोड में वोल्टेज की गिरावट के कारण कुछ बिजली भी चली गई।

प्रायोगिक अध्ययनों का अगला सेट विभिन्न निष्क्रिय सुधारक सर्किट टोपोलॉजी का मूल्यांकन करने और पुल सुधारक सर्किट के लिए चिप टोपोलॉजी से सर्वश्रेष्ठ पर शून्य पर केंद्रित था। यह प्रयोग डायोड आधारित पुल सुधारक सर्किट (डीबीआरसी) और मेटल-ऑक्साइड सेमीकंडक्टर फील्ड इफेक्ट ट्रांजिस्टर (एमओएफईटी) आधारित पुल सुधारक सर्किट (एमबीआरसी) का उपयोग करके किया गया। डीबीआरसी में दो अलग-अलग शॉटकी-प्रकार डायोड (ए) मॉडल BAT1000 (ख) मॉडल इन-5819 शामिल थे। एमबीआरसी में तीन अलग-अलग विन्यासों में एक जोड़ी एन-चैनल MOSFET (एनएमओ) और पी-चैनल MOSFET (पीएमओएस) शामिल थे, नामत डायोड बंधे MOSFET (DMOS), गेट क्रॉस-युग्मित MOSFET (GCMOS) और गेट पूरी तरह से पार युग्मित MOSFET (GFCMOS) कनेक्शन के लिए आपरेशनों के दौरान वोल्टेज ड्रॉप को कम करने के लिए। कंपन संकेतों को एक मैक्रो फाइबर कंपोजिट (एमएफसी) पीजो पैच से उत्पन्न किया गया था जो ग्लास फाइबर कंपोजिट कैटिलीवर बीम पर बंधा था। कैटिलीवर को विभिन्न उत्तेजन आवृत्तियों के अधीन किया गया था, लेकिन लगातार वोल्टेज आयाम, और इसके विपरीत, नागरिक संरचनाओं जैसे वास्तविक जीवन स्रोतों में ऊर्जा संचयन के लिए प्रत्येक सर्किट की उपयुक्तता को खोजने के लिए, जहां संकेतों को कम

आवृत्ति और कम वोल्टेज आयाम की विशेषता होती है। सुधारक सर्किट को किसी अन्य बाहरी घटकों और अन्य संबद्ध स्टार्ट-अप उप-उप-सभी को शामिल किए बिना असतत घटकों का उपयोग करके पूरी तरह से लागू किया गया था, जैसा कि पिछले रिपोर्ट किए गए कई अध्ययनों में आवश्यक था।

प्रायोगिक परिणाम बताते हैं कि पीईएच विचारों से, सर्वश्रेष्ठ प्रदर्शन D1000 द्वारा प्रदर्शित किया जाता है, जो एक डायोड-आधारित सुधारक सर्किट है, आवृत्तियों (5-15 हर्ट्ज) की पूरी श्रृंखला के लिए, जो नागरिक-संरचनाओं में सबसे अधिक प्रमुख हैं। संभावित कारण कम आगे पूर्वाग्रह D1000 के साथ जुड़े वोल्टेज हो सकता है। 5 हर्ट्ज पर उत्साहित 1 वी ओपन-सर्किट पीजोइलेक्ट्रिक वोल्टेज के लिए लगभग 81.33% की चार्जिंग दक्षता हासिल की गई है। MOSFET आधारित सुधारक सर्किट, इसके विपरीत, 1 वी पर अंडरपरफॉर्म करता है, संभावित कारण MOSFET की दहलीज वोल्टेज अधिक हो सकता है। नैनो-वाट रेंज में पावर 5 हर्ट्ज और 1 वी ओपन सर्किट वोल्टेज पर D1000 सुधारक सर्किट से कैपेसिटर में प्राप्त किया जा सकता है।

इसके बाद, अनुकूलित D1000 सुधारक सर्किट की एक प्रायोगिक प्रयोगशाला जांच सरल d31 विन्यास में पीजोइलेक्ट्रिक तत्व का उपयोग करके काटी गई ऊर्जा से एक रिचार्जेबल बैटरी चार्ज करने के लिए की गई थी। अंत में, वास्तविक जीवन शहर फ्लाइओवर और हवा आधारित कंपन के कंपन से अनुकूलित सर्किट का क्षेत्र मूल्यांकन किया गया था और कैपेसिटर और बैटरी में ऊर्जा के भंडारण को सफलतापूर्वक प्रदर्शित किया गया था। 0.27 एमडब्ल्यू की शक्ति हासिल की गई।

इस शोध का मुख्य मूल योगदान सिविल-संरचनाओं के कम आवृत्ति परिवेश कंपन से पीईएच से संबंधित व्यावहारिक मुद्दों की जांच और समाधान प्राप्त करना रहा है, जो अन्यथा कंपन के अच्छे संभावित स्रोत हैं। इस संबंध में, पहला योगदान कम आवृत्ति और कम वोल्टेज परिदृश्यों के तहत प्रयोगों का प्रदर्शन करके सर्किट topologies पर विस्तृत जांच आम तौर पर वास्तविक जीवन नागरिक संरचनाओं में सामना करना पड़ता है। दूसरा महत्वपूर्ण योगदान ऊर्जा भंडारण के उद्देश्य के लिए वास्तविक जीवन संरचनाओं पर पीईएच का प्रूफ-ऑफ-कॉन्सेप्ट प्रदर्शन है। यह उम्मीद की जाती है कि इस थीसिस में प्रस्तुत अध्ययन औद्योगिक पैमाने पर डिजाइन और नागरिक-बुनियादी ढांचे के लिए पीजोइलेक्ट्रिक ऊर्जा हार्वेस्टर के निर्माण के लिए एक दिशानिर्देश के रूप में काम कर सकता है।

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LIST OF ACRONYMS

AC	Alternative Current
ADC	Analogue-to-Digital Converter
ASSH	Adaptive synchronized Switch Harvesting
CVS	Concrete Vibration Sensor
DBRC	Diode based rectifier circuit
DC	Direct Current
DCM	Discontinuous Conduction Mode
DMOS	diode connected MOSFET
DSSH	Double synchronized Switch Harvesting
FFT	Fast Fourier Transformation
GCMOS	gate cross-coupled rectifier
GFCMOS	fully gate cross-coupled rectifier
IC	Integrated Circuit
IoT	Internet of Things
MBRC	Metal-Oxide Semiconductor Field Effect Transistor based rectifier circuit

MEMS	Micro-Electro-Mechanical Systems
MFC	Micro fibre composite
MOSFET	Metal-Oxide Semiconductor Field Effect Transistor
nMOS	n-channel Metal-Oxide Semiconductor Field Effect Transistor
PCH	Piezoelectric cantilever harvester
PEH	Piezoelectric Energy Harvester
p-SSHI	Synchronized Switch Harvesting on Inductor (placed in parallel)
pMOS	p-channel Metal-Oxide Semiconductor Field Effect Transistor
PVDF	Polyvinylidene Fluoride
PZT	Lead Zirconate Titanate
RC	Reinforced Concrete
RFID	Radio Frequency Identification
ScD	Schottky Diode
SECE	Synchronous Electric Charge Extraction
SHM	Structural Health Monitoring
SiD	Silicon Diode
SSDL	Smart Structures and Dynamic Laboratory

SSHI	Synchronous Switch Harvesting on Inductors
s-SSHI	Synchronized Switch Harvesting on Inductor (placed in series)
TRL	Technology Readiness Level
WSNs	Wireless Sensor Nodes

LIST OF SYMBOLS

a	Acceleration of the bridge
C	Capacitance of the capacitor
E_3	Electric field in the “3” direction
E_c	Energy stored in capacitor
E_h	Energy stored in capacitor in one hour
f	Frequency of the bridge
d	Displacement
D_1 to D_4	Diodes
D	depth of girder
D_3	Charge density
$\overline{\varepsilon_{33}^T}$	Complex electric permittivity (in direction “3”) at constant stress
h	Thickness of PZT patch
MP	p-channel Metal-Oxide Semiconductor Field Effect Transistor
MN	n-channel Metal-Oxide Semiconductor Field Effect Transistor
η	Mechanical loss factor of the PZT material
S	Strain of Piezoelectric Device

SSV	Steady state voltage across capacitor
T_3	Stress in direction “3” (thickness of patch)
T_c	Charging time of capacitor
V	Voltage across PZT patch
V_s	Supply input voltage
V_d	Diode threshold voltage
V_{OC}	Open circuit voltage of piezoelectric device
V_{DC}	DC voltage
Y	Young’s Modulus of elasticity
$\overline{Y^E}$	Complex Young’s modulus of elasticity of the PZT patch at constant electric field
δ	Dielectric loss factor of PZT material