

DESIGN AND ANALYSIS OF INTERFACE CIRCUITS AND SYSTEMS FOR HYBRID VIBRATIONAL ENERGY HARVESTERS

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DESIGN AND ANALYSIS OF INTERFACE CIRCUITS AND SYSTEMS FOR HYBRID VIBRATIONAL ENERGY HARVESTERS

by

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



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Dedicated to all my teachers

CERTIFICATE

This is to certify that the thesis titled **Design and Analysis of Circuits and Systems for Hybrid Vibrational Energy Harvesters**, submitted by **Pratibha Verma**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by her under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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अमन्त्रम् अक्षरम् नास्ति नास्ति मूलम् अनौषधम् ।
अयोग्यः पुरुषो नास्ति योजकस्तत्र दुर्लभः ॥

- Subhashita

Pratibha Verma

ABSTRACT

KEYWORDS: Energy Harvesting, Interface circuits, Triboelectric Generators, Hybrid Generators, Hybrid IC

The widespread growth of Internet of Things (IoT) technology has escalated the development of next generation electromechanical harvesting devices to fulfill the ever increasing energy requirements. The next generation electromechanical transducers include nanogenerators as well as hybrid transducers comprising more than one harvesting mechanism operating in synergy. However, the interface circuits (IC) available in the literature are generally designed only for conventional harvesting technologies (piezoelectric, electrostatic and electromagnetic). The efficiency of overall harvesting system is significantly diminished, if conventional harvesting architectures are used to individually interface each transducer in the hybrid harvesting system. Designed harvesters have their own distinct characteristics and come with their own set of challenges. For instance, triboelectric harvesters have a high peak-to-average ratio, high impedance, asymmetric output, and rectification losses associated with these devices. The resolution of these issues requires the development of novel systems and topologies that enhance the harvesting and sensing abilities of devices. Therefore, it is necessary to develop new and efficient interface electronics to extract energy from hybrid transducers and triboelectric harvesters. The primary aim of this thesis is to present the design of ICs that can efficiently interface new-age energy harvesters for powering up a wide array of applications.

In the first work, a miniaturized and integrated triboelectric harvesting system that overcomes the issues of high peak-to-average ratio, high impedance, asymmetric output, and rectification losses associated with conventional triboelectric harvesters. A mechanical switching approach is adopted to rectify the alternating output of the harvester, and it is integrated with a switched capacitor-based buck converter to lower the peak triboelectric output voltage. Using this approach, a conversion efficiency of 84.5% and the output voltage is improved by 4.1 times compared to a conventional AC triboelectric harvesting device [1].

Both piezoelectric and triboelectric transduction technologies convert the motion of an elastic layer into electrical output, albeit through different mechanisms. Their similar topological designs and complementary electrical characteristics make them ideal for pairing and developing hybrid piezoelectric-triboelectric generators. In the second work, the design and analysis of a biomechanical harvesting system consisting of a hybrid

piezoelectric-triboelectric generator and a suitable interface power management circuit (PMC) are presented. The piezoelectric and triboelectric outputs are interfaced using the proposed circuit architecture involving rectifiers and switched capacitor-based DC-DC converters. The implemented circuit replaces the conventional diodes with active diodes in the bridge rectifier of piezoelectric generator (PEG), thereby reducing power consumption and increasing efficiency. The interface circuit provides a peak efficiency of 77.33%, and the harvesting system can charge a 1 μ F load capacitor to 3.1 V in 20 s.

The third work presents an efficient hybrid energy-harvesting interface to simultaneously scavenge power from multiple transducers using a synchronous electrical charge extraction (SECE) converter. An energy injection scheme is proposed that involves multi-step energy harvesting mechanism, where charge from one transducer is first deposited onto the other transducer and eventually transferred to the output load. The combined power extracted simultaneously from both harvesters exceeds the power obtained from each individually. This scheme has been demonstrated using hybrid device consisting of piezoelectric/electromagnetic and piezoelectric/triboelectric pairs. This scheme results in an improved extracted power from a hybrid device for the same piezoelectric current excitation, which leads to a significant improvement of around 40x-80x increase in the extracted power compared to power obtained without energy injection [2].

In the end, an efficient design of a single-stage interface circuit, including rectification and buck regulation for triboelectric generators (TEG), is proposed. The proposed interface circuit adopts a distinct conditioning path for the positive and negative half-cycle outputs owing to the asymmetric nature of the TEG output. The implemented circuit also reduces the number of charge transfer stages and the power dissipation corresponding to the front-end bridge rectifiers and increases the peak efficiency of the circuit to the 75.1% at an external load of 7 M Ω compared to two-stage topology [3].

सारांश

संकेतशब्द: ऊर्जा संचयन, इंटरफ़ेस सर्किट, ट्राइबोइलेक्ट्रिक जनरेटर, हाइब्रिड जेनरेटर, हाइब्रिड आईसी

इंटरनेट ऑफ थिंग्स (आईओटी) तकनीक की व्यापक वृद्धि ने लगातार बढ़ती ऊर्जा आवश्यकताओं को पूरा करने के लिए अगली पीढ़ी के इलेक्ट्रोमैकेनिकल हार्वैस्टिंग उपकरणों के विकास को बढ़ावा दिया है। अगली पीढ़ी के इलेक्ट्रोमैकेनिकल ट्रांसड्यूसर में नैनोजेनरेटर के साथ-साथ हाइब्रिड ट्रांसड्यूसर भी शामिल हैं, जिसमें तालमेल में काम करने वाले एक से अधिक हार्वैस्टिंग तंत्र शामिल हैं। हालाँकि, साहित्य में उपलब्ध इंटरफ़ेस सर्किट (आईसी) आमतौर पर केवल पारंपरिक हार्वैस्टिंग प्रौद्योगिकियों (पीजोइलेक्ट्रिक, इलेक्ट्रोस्टैटिक और इलेक्ट्रोमैग्नेटिक) के लिए डिज़ाइन किए गए हैं। यदि हाइब्रिड हार्वैस्टिंग सिस्टम में प्रत्येक ट्रांसड्यूसर को व्यक्तिगत रूप से इंटरफ़ेस करने के लिए पारंपरिक हार्वैस्टिंग आर्किटेक्चर का उपयोग किया जाता है, तो समग्र हार्वैस्टिंग सिस्टम की दक्षता काफी कम हो जाती है। डिज़ाइन किए गए हार्वैस्टर की अपनी विशिष्ट विशेषताएं होती हैं और वे अपनी चुनौतियों के साथ आते हैं। उदाहरण के लिए, ट्राइबोइलेक्ट्रिक हार्वैस्टर में उच्च शिखर-से-औसत अनुपात, उच्च प्रतिबाधा, असममित आउटपुट और इन उपकरणों से जुड़े सुधार नुकसान होते हैं। इन मुद्दों के समाधान के लिए नवीन प्रणालियों और टोपोलॉजी के विकास की आवश्यकता है जो उपकरणों की कटाई और संवेदन क्षमताओं को बढ़ाती हैं। इसलिए, हाइब्रिड ट्रांसड्यूसर और ट्राइबोइलेक्ट्रिक हार्वैस्टर से ऊर्जा निकालने के लिए नए और कुशल इंटरफ़ेस इलेक्ट्रॉनिक्स विकसित करना आवश्यक है। इस थीसिस का प्राथमिक उद्देश्य आईसी के डिज़ाइन को प्रस्तुत करना है जो अनुप्रयोगों की एक विस्तृत श्रृंखला को सशक्त बनाने के लिए नए युग के ऊर्जा हार्वैस्टर को कुशलतापूर्वक इंटरफ़ेस कर सकता है।

पहले काम में, एक लघु और एकीकृत ट्राइबोइलेक्ट्रिक हार्वैस्टिंग प्रणाली जो उच्च शिखर-से-औसत अनुपात, उच्च प्रतिबाधा, असममित आउटपुट और पारंपरिक ट्राइबोइलेक्ट्रिक हार्वैस्टर से जुड़े सुधार नुकसान के मुद्दों पर काबू पाती है। हार्वैस्टर के वैकल्पिक आउटपुट को सुधारने के लिए एक यांत्रिक स्विचिंग दृष्टिकोण अपनाया जाता है, और इसे पीक ट्राइबोइलेक्ट्रिक आउटपुट वोल्टेज को कम करने के लिए एक स्विचड कैपेसिटर-आधारित बक कनवर्टर के साथ एकीकृत किया जाता है। इस दृष्टिकोण का उपयोग करते हुए, पारंपरिक एसी ट्राइबोइलेक्ट्रिक हार्वैस्टिंग डिवाइस की तुलना में 84.5% की रूपांतरण दक्षता और आउटपुट वोल्टेज में 4.1 गुना सुधार होता है।[1]

पीजोइलेक्ट्रिक और ट्राइबोइलेक्ट्रिक ट्रांसडक्शन दोनों प्रौद्योगिकियां विभिन्न तंत्रों के माध्यम से, एक लोचदार परत की गति को विद्युत आउटपुट में परिवर्तित करती हैं। उनके समान टोपोलॉजिकल डिज़ाइन और पूरक विद्युत विशेषताएँ उन्हें हाइब्रिड पीजोइलेक्ट्रिक-ट्राइबोइलेक्ट्रिक जनरेटर की जोड़ी बनाने और विकसित करने के लिए आदर्श बनाती हैं। दूसरे कार्य में, एक हाइब्रिड पीजोइलेक्ट्रिक-ट्राइबोइलेक्ट्रिक जनरेटर और एक उपयुक्त इंटरफ़ेस पावर मैनेजमेंट सर्किट (पीएमसी) से युक्त बायोमैकेनिकल हार्वैस्टिंग सिस्टम का डिज़ाइन और विश्लेषण प्रस्तुत किया गया है। पीजोइलेक्ट्रिक और ट्राइबोइलेक्ट्रिक आउटपुट को रेक्टिफायर और स्विचड कैपेसिटर-आधारित डीसी-डीसी कन्वर्टर से जुड़े प्रस्तावित सर्किट आर्किटेक्चर का उपयोग करके इंटरफ़ेस किया जाता है। कार्यान्वित सर्किट पीजोइलेक्ट्रिक जनरेटर (पीईजी) के ब्रिज रेक्टिफायर में पारंपरिक डायोड को सक्रिय डायोड से बदल देता है, जिससे बिजली की खपत कम हो जाती है और दक्षता बढ़ जाती है। इंटरफ़ेस सर्किट 77.33% की चरम दक्षता प्रदान करता है, और हार्वैस्टिंग सिस्टम 1 μF लोड कैपेसिटर को 20 s में 3.1 V तक चार्ज कर सकता है।

तीसरा कार्य एक सिंक्रोनस इलेक्ट्रिकल चार्ज एक्सट्रैक्शन (एसईसीई) कनवर्टर का उपयोग करके कई ट्रांसड्यूसर से एक साथ बिजली निकालने के लिए एक कुशल हाइब्रिड ऊर्जा-संचयन इंटरफ़ेस प्रस्तुत करता है। एक ऊर्जा इंजेक्शन योजना प्रस्तावित है जिसमें बहु-चरण ऊर्जा संचयन तंत्र शामिल है, जहां एक ट्रांसड्यूसर से चार्ज पहले दूसरे ट्रांसड्यूसर पर जमा किया जाता है और अंततः आउटपुट लोड में स्थानांतरित किया जाता है। दोनों हार्वैस्टर से एक साथ निकाली गई संयुक्त बिजली प्रत्येक हार्वैस्टर से अलग-अलग प्राप्त बिजली से अधिक है। इस योजना को पीजोइलेक्ट्रिक/इलेक्ट्रोमैग्नेटिक और पीजोइलेक्ट्रिक/ट्राइबोइलेक्ट्रिक जोड़े से युक्त हाइब्रिड डिवाइस का उपयोग करके प्रदर्शित किया गया है। इस योजना के परिणामस्वरूप समान पीजोइलेक्ट्रिक करंट उत्तेजना के लिए एक हाइब्रिड डिवाइस से बेहतर निकाली गई शक्ति प्राप्त होती है, जिससे ऊर्जा इंजेक्शन के बिना प्राप्त शक्ति की तुलना में निकाली गई शक्ति में लगभग $40\times-80\times$ की वृद्धि होती है। [2]

अंत में, ट्राइबोइलेक्ट्रिक जनरेटर (टीईजी) के लिए सुधार और बक कनवर्टर सहित एकल-चरण इंटरफ़ेस सर्किट का एक कुशल डिजाइन प्रस्तावित है। प्रस्तावित इंटरफ़ेस सर्किट टीईजी आउटपुट की असममित प्रकृति के कारण सकारात्मक और नकारात्मक आधे-चक्र आउटपुट के लिए एक अलग कंडीशनिंग पथ अपनाता है। कार्यान्वित सर्किट चार्ज ट्रांसफर चरणों की संख्या और फ्रंट-एंड ब्रिज रेक्टिफायर के अनुरूप बिजली अपव्यय को भी कम करता है और दो-चरण टोपोलॉजी की तुलना में $7\text{ M}\Omega$ के बाहरी भार पर सर्किट की चरम दक्षता को 75.1 % तक बढ़ा देता है। [3]

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ABBREVIATIONS

| | |
|--------------------------|--|
| IoT | Internet of Things |
| M2M | Machine-to-Machine |
| WSNs | Wireless Sensor Networks |
| TEGs | Triboelectric Generators |
| PEGs | Piezoelectric Generators |
| ESGs | Electrostatic Generators |
| HEGs | Hybrid Energy Generators |
| AC | Alternating Current |
| DC | Direct Current |
| DC-TEG | Direct-Current Triboelectric Generator |
| 3D | 3-Dimensional |
| VEHs | Vibrational Energy Harvesters |
| TEH | Triboelectric Harvester |
| PEH | Piezoelectric Harvester |
| EMH | Electromagnetic Harvester |
| MEH | Mechanical Energy Harvesting |
| PMC | Power Management Circuit |
| IC | Interface Circuit |
| PAR | Peak-to-average ratio |
| PET | Polyethylene Terephthalate |
| PDMS | Polydimethylsiloxane |
| CNTs | Carbon nanotubes |
| PTFE | Polytetrafluoroethylene |
| PVDF | Polyvinylidene fluoride |
| BaTiO₃ | Barium titanate |
| LiTaO₃ | Lithium Tantalate |
| AlN | Aluminum Nitride |
| PZT | lead zirconate titanate |
| ZnO | Zinc oxide |
| Al | Aluminium |
| EMF | Electromotive force |
| SEM | Scanning electron microscopy |
| FE | Frictional electrode |
| CCE | Charge collecting electrode |

| | |
|--------------|---|
| AFM | Atomic force microscope |
| Cu | Copper |
| ode | Ordinary differential equations |
| DSO | Digital storage oscilloscope |
| FEM | Finite Element Method |
| LED | Light emitting diode |
| MOS | Metal oxide semiconductor |
| TL | Top layer |
| BL | Bottom layer |
| PCB | Printed Circuit Board |
| CMOS | Complementary Metal-Oxide-Semiconductor |
| BCD | Bipolar-CMOS-DMOS |
| SC-BC | Switched capacitor buck converter |
| SOI | Silicon on Insulator |
| NVC | Negative Voltage Converter |
| FET | Field Effect Transistor |
| FBR | Full Bridge Rectifier |
| VD | Voltage Doubler |
| SSHI | Synchronous switch harvesting on inductor |
| SECE | Synchronous electric charge extraction |
| EI | Energy Injection |
| PWM | Pulse Width Modulation |

NOTATIONS

| | |
|------------------|------------------------------------|
| $V_{surface}$ | Surface potential difference |
| e | Elementary charge |
| ϵ_0 | Permittivity of free space |
| S | Mechanical strain |
| s | Compliance |
| T | Mechanical stress |
| E | Electric field |
| D | Electric displacement field |
| P | Polarization field density |
| P_S | Surface polarization field density |
| x | Displacement |
| F_e | Electrostatic force |
| Q | Charge |
| V | Voltage |
| I | Current |
| V_{OC} | Open-Circuit Voltage |
| V_{TE} | TEG open-Circuit Voltage |
| C_{TEG} | TEG Capacitance |
| C_{TEG} | TEG Capacitance |
| σ_0 | Surface charge density |
| d | Dielectric layer thickness |
| p | Pressure |
| F | Applied Force |
| F' | Effective Force |
| F_e | Electrostatic force |
| m | Mass |
| k | Stiffness |
| c | Damping coefficient |
| K_o | PEG damping coefficient |
| v | Velocity |
| $C_{P,PZ}$ | PEG Capacitance |
| R_L | Load Resistance |
| $C_{dielectric}$ | Dielectric layer capacitance |
| C_{air} | TEG air gap capacitance |
| C_{max} | Maximum TEG capacitance |
| C_{min} | Minimum TEG capacitance |
| C_s | storage Capacitor |
| C_i | Intermediate Capacitor |
| C_L | Load Capacitor |
| $D_{1,2}$ | Diodes |

| | |
|------------|-----------------------------------|
| $MN_{1,2}$ | NMOS |
| $MP_{1,2}$ | PMOS |
| V_d | Voltage drop across Diode |
| V_{ds} | Drain to Source voltage of MOSFET |
| w | Width |
| l | Length |
| P_{TEG} | TEG Power |
| P_{PEG} | PEG Power |
| P_{out} | Output Power |
| η | Efficiency |