DESIGN AND CHARACTERIZATION OF TEXTILE BASED TRIBOELECTRIC NANOGENERATORS FOR MONITORING APPLICATIONS

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by

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Submitted

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

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

DEDICATED TO MY PARENTS

In loving memory of my

Mother (Late Smt. Vandana Somkuwar)

and

Grandmother (Late Smt. Sonabai)

CERTIFICATE

This is to certify that the thesis entitled **"Design and Characterization of Textile based Triboelectric Nanogenerators for Monitoring Applications"**, submitted by **Mr. Viraj Uttamrao Somkuwar** to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Textile and Fibre Engineering, is a record of bonafide research work carried out by him. Mr. Viraj Uttamrao Somkuwar diligently pursued his research work under my guidance and supervision and has fulfilled the requirements for the submission of the thesis, which, to my knowledge, aligns with the requisite standards for a Ph.D. degree from this institute.

The results contained in the thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.

Place: New Delhi

Date:

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(Viraj Uttamrao Somkuwar)

ABSTRACT

Triboelectricity, a phenomenon where certain materials become electrically charged after coming into frictional contact with a different material, has garnered significant interest for its potential in energy harvesting applications. Textile-based triboelectric nanogenerators (TENGs) are popular due to their ability to seamlessly integrate with clothing, providing a constant source of friction. Textile fabrics are particularly favourable due to their ubiquitous use in daily life and ability to conform to various shapes and movements. However, existing textile TENG technologies primarily utilize textiles as substrates for coatings or involve complex fabrications with metallic coatings, which can negatively impact comfort and other textile properties. Additionally, the use of multiple materials on a single layer by coating, sandwiching, and stitching increases the thickness, stiffness and weight of the TENG. To address these gaps, the current research proposes an all-textile integrated TENG fabricated using industrial knitting technologies.

Henceforth, the present research focuses on studying the influence of triboelectric textile material, fabric structure, contact separation frequency, and pressure on the performance of the textile TENG using a vertical, lateral sliding, bending, and stretching contact separation mechanism. Textile materials such as cotton, polyester, nylon, and PP are explored for their triboelectric potential on woven and knitted fabric platforms. The nylon and PP have demonstrated the highest output voltage and current among all the analyzed textile materials due to their better dielectric properties and higher surface roughness. The comparison of woven and knitted structures has shown that the knitted textile TENG has a significant increase in output voltage, current, and

power. The optical profile analysis revealed that the 3D configuration of the knitted loop creates higher roughness than the repeat unit of woven fabric; hence, the contact area improved significantly with the knitted fabric, increasing the output of textile TENG.

Further, integrated knitted textile TENGs are developed using an industrial knitting machine, and their ability to harvest biomechanical energy is demonstrated. Four different structures namely 1R1C, pocket, plating, and ridge were developed with varying knitting components, and their performance is evaluated under lateral sliding and vertical contact separation modes. The plated and ridge structures demonstrated superior performance, generating peak power densities of 45 $\mu W/m^2$ and 110 $\mu W/m^2$, respectively. Their enhanced performance is attributed to the enhanced surface roughness and increased contact area. The sliding mode exhibited higher output compared to the vertical contact separation mode, owing to prolonged friction and multiple micro contact separations. The structures displayed impressive long-term stability, enduring a stable output until 12,000 cycles of contact separation and 30 washing cycles.

The knitted textile fabric, with its excellent confirmability, follows the close proximity of the human body limbs; the textile TENG can harvest the electrical energy from mechanical energy generated during the various contact separation movements during sliding, tapping, bending and stretching motions. To exploit the potential of textile TENG further, the performance of ridge and plated knit TENG are evaluated in bending and stretching contact separation mode. The results depict that stretching and bending movements change the surface profile, which contributes to the change in the electrical output when the intensity of bending and stretching is altered. The results

show the ridge structure achieved a peak power density of 0.27 μW/m² in the stretching mode and 0.36 μW/m² in the bending mode. The knit TENG, integrated into an arm sleeve, was tested for its potential in monitoring movements during exercise rehabilitation and analyzing output voltage waveforms to assess and optimize recovery exercises.

To ensure the practical application of textile TENGs, testing conditions, such as the impact of ambient temperature and humidity, are analyzed to evaluate the stability of textile TENG devices. A significant decrement in voltage and current of the TENG device has been observed, along with an increase in relative humidity. As the moisture in the environment increases at high humidity, the short circuit charge shows a reduction of 70 % in short circuit charge (Q_{sc}). The interaction between moisture and textile causes surface conduction, resulting in charge dissipation at high humidity. The impact of different temperatures showed a pronounced reduction of 80 % in voltage and 64 % in current as the temperature increased to 20 °C from 70 °C. The temperature-induced thermal energy enables electrons to overcome energy barriers and escape via thermionic emission into the atmosphere, reducing the Q_{sc}. This research provides a pathway for advancing wearable energy-harvesting technologies, emphasizing the importance of material selection and structural design in achieving efficient and stable energy outputs.

सार

ट्राइबोइलेक्ट्रिसिटी, एक ऐसी घटना जहां कुछ पदार्थ एक अलग पदार्थ के साथ घर्षण संपर्क में आने के बाद विद्युत रूप से चार्ज हो जाती है, इस तकनीक ने ऊर्जा संचयन अनुप्रयोगों में अपनी क्षमता के लिए महत्वपूर्ण रुचि पैदा की है। कपड़ा-आधारित ट्राइबोइलेक्ट्रिक नैनोजेनरेटर (टीईएनजी) कपड़ों के साथ सहजता से एकीकृत होने और घर्षण का निरंतर स्रोत प्रदान करने की अपनी क्षमता के कारण लोकप्रिय हैं। कपड़े दैनिक जीवन में उनके सर्वव्यापी उपयोग और विभिन्न आकृतियों और गतिविधियों के अनुरूप होने की क्षमता के कारण विशेष रूप से अनुकूल हैं। हालाँकि, मौजूदा कपड़ा टीईएनजी प्रौद्योगिकियाँ मुख्य रूप से कोटिंग्स के लिए आधार के रूप में वस्त्रों का उपयोग करती हैं या धातु कोटिंग्स के साथ जटिल निर्माण शामिल करती हैं, जो आराम और अन्य कपड़ा गुणों पर नकारात्मक प्रभाव डाल सकती हैं। इसके अतिरिक्त, कोटिंग, सैंडविचिंग और सिलाई द्वारा एक ही परत पर कई सामग्रियों के उपयोग से टीईएनजी की मोटाई, कठोरता और वजन बढ़ जाता है। इन अंतरालों को संबोधित करने के लिए, वर्तमान शोध औद्योगिक बुनाई प्रौद्योगिकियों का उपयोग करके निर्मित एक संपूर्ण कपड़ा एकीकृत टीईएनजी का प्रस्ताव करता है।

इसके बाद, वर्तमान शोध ऊर्ध्वाधर, पार्श्व स्लाइडिंग, मुड़ना और संपर्क पृथक्करण तंत्र को खींचकर ट्राइबोइलेक्ट्रिक कपड़ा सामग्री, कपड़े की संरचना, संपर्क पृथक्करण आवृत्ति और कपड़ा टीईएनजी के प्रदर्शन

पर दबाव के प्रभाव का अध्ययन करने पर केंद्रित है। कपास, पॉलिएस्टर, नायलॉन और पॉलीप्रोपाइलीन जैसी कपड़ा सामग्री को बुने हुए और बुने हुए कपड़े के प्लेटफार्मों पर उनकी ट्राइबोइलेक्ट्रिक क्षमता के लिए खोजा जाता है। नायलॉन और पॉलीप्रोपाइलीन ने अपने बेहतर ढांकता हुआ गुणों और उच्च सतह खुरदरापन के कारण सभी विश्लेषणित कपड़ा सामग्रियों के बीच उच्चतम आउटपुट वोल्टेज और करंट का प्रदर्शन किया है। बुने हुए और बुने हुए ढांचों की तुलना से पता चला है कि बुने हुए कपड़ा टीईएनजी में आउटपुट वोल्टेज, धारा और शक्ति में उल्लेखनीय वृद्धि हुई है। ऑप्टिकल प्रोफाइल विश्लेषण से पता चला कि बुने हुए लूप का 3डी कॉन्फ़िगरेशन बुने हुए कपड़े की दोहराई गई इकाई की तुलना में अधिक खुरदरापन पैदा करता है; इसलिए, बुने हुए कपड़े के साथ संपर्क क्षेत्र में उल्लेखनीय सुधार हुआ, जिससे कपड़ा टीईएनजी का उत्पादन बढ़ गया।

इसके अलावा, एकीकृत बुना हुआ कपड़ा टीईएनजी एक औद्योगिक बुनाई मशीन का उपयोग करके विकसित किया जाता है, और बायोमैकेनिकल ऊर्जा का उत्पादन करने की उनकी क्षमता का प्रदर्शन किया जाता है। चार अलग-अलग संरचनाएं अर्थात् 1R1C, पॉकेट, प्लेटिंग और रिज अलग-अलग बुनाई घटकों के साथ विकसित की गईं, और उनके प्रदर्शन का मूल्यांकन पार्श्व स्लाइडिंग और ऊर्ध्वाधर संपर्क पृथक्करण मोड के तहत किया जाता है। प्लेटेड और रिज संरचनाओं ने बेहतर प्रदर्शन किया, जिससे क्रमशः 45 $\mu W/m^2$ और 110 $\mu W/m^2$ की चरम शक्ति घनत्व उत्पन्न हुआ। उनके बेहतर प्रदर्शन का श्रेय बढ़ी हुई सतह

खुरदरापन और बढ़े हुए संपर्क क्षेत्र को दिया जाता है। लंबे समय तक घर्षण और कई सूक्ष्म संपर्क पृथक्करणों के कारण, स्लाइडिंग मोड ने ऊर्ध्वाधर संपर्क पृथक्करण मोड की तुलना में उच्च आउटपुट प्रदर्शित किया। संरचनाओं ने प्रभावशाली दीर्घकालिक स्थिरता प्रदर्शित की, संपर्क पृथक्करण के 12,000 चक्रों और 30 धुलाई चक्रों तक स्थिर आउटपुट को सहन किया।

बुना हुआ कपड़ा, अपनी उत्कृष्ट पुष्टि के साथ, मानव शरीर के अंगों की निकटता का अनुसरण करता है; कपड़ा टीईएनजी स्लाइडिंग, टैपिंग, झुकने और खींचने की गति के दौरान विभिन्न संपर्क पृथक्करण आंदोलनों के दौरान उत्पन्न यांत्रिक ऊर्जा से विद्युत ऊर्जा का संचयन कर सकता है। टेक्सटाइल टीईएनजी की क्षमता का और अधिक दोहन करने के लिए, रिज और प्लेटेड निट टीईएनजी के प्रदर्शन का मूल्यांकन झुकने और संपर्क पृथक्करण मोड में किया जाता है। नतीजे बताते हैं कि खींचने और झुकने की गतिविधियां सतह प्रोफ़ाइल को बदल देती हैं, जो झुकने और खींचने की तीव्रता में बदलाव होने पर विद्युत उत्पादन में बदलाव में योगदान देती है। नतीजे बताते हैं कि रिज संरचना ने स्ट्रेचिंग मोड में 0.27 $\mu W/m^2$ और झुकने वाले मोड में 0.36 $\mu W/m^2$ की अधिकतम पावर घनत्व हासिल की है। आर्म स्लीव में एकीकृत निट टेंग का व्यायाम पुनर्वास के दौरान गतिविधियों की निगरानी करने और पुनर्प्राप्ति अभ्यासों का आकलन और अनुकूलन करने के लिए आउटपुट वोल्टेज तरंगों का विश्लेषण करने की क्षमता के लिए परीक्षण किया गया था।

कपड़ा टीईएनजी के व्यावहारिक अनुप्रयोग को सुनिश्चित करने के लिए, कपड़ा टीईएनजी उपकरणों की स्थिरता का मूल्यांकन करने के लिए परिवेश के तापमान और आर्द्रता के प्रभाव जैसी परीक्षण स्थितियों का विश्लेषण किया जाता है। सापेक्षिक आर्द्रता में वृद्धि के साथ-साथ, टीईएनजी डिवाइस के वोल्टेज और करंट में महत्वपूर्ण कमी देखी गई है। जैसे ही उच्च आर्द्रता पर वातावरण में नमी बढ़ती है, शॉर्ट सर्किट चार्ज शॉर्ट सर्किट चार्ज (क्यूएससी) में 70% की कमी दर्शाता है। नमी और कपड़ा के बीच परस्पर क्रिया सतह के संचालन का कारण बनती है, जिसके परिणामस्वरूप उच्च आर्द्रता पर चार्ज का अपव्यय होता है। विभिन्न तापमानों के प्रभाव से वोल्टेज में 80% और करंट में 64% की कमी देखी गई क्योंकि तापमान 70 डिग्री सेल्सियस से बढ़कर 20 डिग्री सेल्सियस हो गया। तापमान-प्रेरित थर्मल ऊर्जा इलेक्ट्रॉनों को ऊर्जा बाधाओं को दूर करने और वायुमंडल में थर्मिओनिक उत्सर्जन के माध्यम से भागने में सक्षम बनाती है, जिससे क्यूएससी कम हो जाता है। यह शोध पहनने योग्य ऊर्जा-संचयन प्रौद्योगिकियों को आगे बढ़ाने के लिए एक मार्ग प्रदान करता है, जो कुशल और स्थिर ऊर्जा आउटपुट प्राप्त करने में सामग्री चयन और संरचनात्मक डिजाइन के महत्व पर जोर देता है।

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Terms	Abbreviations
Triboelectric nanogenerator	TENG
Electronic textiles	E-Textiles
Direct current	DC
Polydimethylsiloxane	PDMS
Poly (methyl methacrylate)	PMMA
Polyimide	PI
Relative humidity	RH
Polyaniline	PANI
Polyvinyl chloride	PVC
Polypropylene	PP
Silver	Ag
Aluminium nanoparticle	Al NP
Multiwall carbon nanotube	MWCNT
Fluorinated ethylene propylene	FEP
Open circuit voltage	V_{OC}
Contact separation	C-S
Short circuit current	I_{SC}
Short circuit charge	Q_{SC}
Polyethylene terephthalate	PET
Polyacrylonitrile	PAN

Water vapour transmission rate	WVTR
Atomic force microscopy	AFM