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High-performance, Wind-driven Triboelectric-Electromagnetic Hybrid Nanogenerator for Self-powered Wireless Transmission and Wind Speed Sensing in the Internet of Things

Dr.C P Jawahar[1] and Anup Kumar Jana[2]

Abstract

Wind energy is becoming more crucial in addressing the scarcity of fossil fuel due to the development of promising technologies like Electromagnetic Generators (EGs), Triboelectric Nanogenerators (TNs), and their hybrid nanogenerators. However, only a portion of wind energy can be efficiently converted into electricity. By integrating 5G technology with the Internet of Things (IoT) and expanding the deployment of wireless sensor networks, vulnerable areas may be effectively monitored for potential disasters. Nevertheless, substituting conventional chemical batteries with new ones in IoT devices poses a substantial difficulty, particularly in distant regions. This article presents a hybrid energy harvester explicitly designed for wind energy harvesting. This work introduces the High Performance, Wind-driven Triboelectric-Electromagnetic Hybrid Nanogenerator (HPW-TEHN) as a solution for self-powered Wireless Transmission (WT) and Wind Speed Sensing (WSS) in the Internet of Things (IoT). Here, we present a High-Performance Wind Turbine with a wide operational range of wind speeds, allowing for efficient harnessing of wind energy across different levels, including gentle breezes and moderate and severe winds. The gadget comprises a spinning body and a sliding body. The power-producing mechanism consists of the EGs in the rotating body and the TNs in the sliding body. All created units are fully enclosed within the device box, effectively insulated from challenging environmental conditions. This research comprehensively analyzes the impact of dielectric material kinds and sizes on the output performance of TNs. Additionally, it investigates the output performance of this device under various wind speeds. The performance of HPW-TEHN improves as the wind speed increases. At a wind speed of 10 m/s, the TN, EG, and HPW-TEHN generate an output power of 0.19 mW, 0.38 mW, and 1.4 mW, respectively.

Keywords: *Electromagnetic Generators, Triboelectric Nanogenerators, Triboelectric-Electromagnetic Hybrid Nanogenerator, Wind Speed Sensing, Internet of Things, Wireless Transmission.*

Introduction

With the continuous maturation of 5G technology, the prevalence of IoT increases. The Internet of Things (IoT) is information technology that enables the connection between different items and users through sound, light, heat, energy, mechanics, chemistry, biology, location, and other forms of information. It improves the widespread link between items and individuals, enabling the detection, identification, and control of objects and operations through network connectivity. This transforms ordinary operations into elements of an

[1] Professor, Department of Mechanical, Kalinga University, Naya Raipur, Chhattisgarh, India. ku.cpjawahar@kalingauniversity.ac.in

[2] Assistant Professor, Department of Mechanical, Kalinga University, Naya Raipur, Chhattisgarh, India. ku.anupkumarjana@kalingauniversity.ac.in

"intelligent" network. Enabling the operation of hundreds of millions of sensors will pose a significant difficulty with the widespread adoption of the IoT.

Currently, sensors mostly rely on batteries for power. Due to the limited lifespan of conventional batteries and their negative impact on the environment, they are no longer suited for powering sensors in the IoT [3]. To address these issues, scientists are actively developing eco-friendly energy sources, including wind, sun, mechanical vibration, water, and other alternatives. Due to its great energy output potential and natural availability, wind is widely recognized as a significant energy source. Harnessing wind energy offers a viable solution to address the issue of sensor energy supply in the IoT [4].

The need for independent and self-sufficient systems in the IoT has generated enthusiasm for energy-harvesting devices that can gather energy from the surroundings. Traditional energy sources face difficulties in fulfilling dispersed IoT devices' power demands, especially in rural or hard-to-reach areas [5]. The proposed Triboelectric Energy Harvesting Network (TEHN) utilizes the triboelectric effect and electromagnetic induction to transform wind energy effectively into electrical power. Triboelectric materials provide electric charge by contact electrification, while the electromagnetic component amplifies power output through induced currents.

Incorporating the EG and TN tackles several obstacles linked to traditional energy-gathering techniques. The nanogenerator utilizes wind energy to provide a sustainable and scalable power source for IoT devices [6]. Moreover, the autonomous wireless transmission capability obviates the necessity for external power sources, facilitating deployment in distant areas or in times of crisis. Adding wind speed sensing capability improves the nanogenerator's adaptability, offering useful ecological information for weather tracking, maintenance forecasting, and climate study.

The emergence of the IoT has driven the advancement of creative energy-collecting solutions for the sustainable powering of wireless sensor networks. Out of these options, nanogenerators have emerged as viable contenders for transferring mechanical energy from the surroundings into electrical power. The combination of triboelectric and electromagnetic processes in a hybrid nanogenerator has attracted interest in this particular situation due to its ability to capture energy from wind, which is both widespread and sustainable. This study examines the design, production, and effectiveness of an EG-TN, with a specific emphasis on its use in self-powered WT.

The main goals of this project are to create, construct, and analyze an HPW-TEHN specifically designed to harness wind energy. The study aims to examine the energy conversion efficiency and power output of the nanogenerator, as well as its potential use in self-powered wireless transmission and wind speed monitoring within the IoT framework. The research contributes to advancing sustainable and self-sufficient energy solutions for IoT installations by attaining these objectives.

Related Works

This review explores research on using wind-driven hybrid nanogenerators for self-powered wireless transmission and wind speed detection in the Internet of Things (IoT) framework. The survey examines existing research to gain a thorough knowledge of high-performance nanogenerators' techniques, implementations, and outcomes. This will give insights into how these nanogenerators might contribute to sustainable and self-sufficient IoT applications.

Shi et al.'s research explores the use of Triboelectric Nanogenerators (TENGs) and hybridized systems to further the development of IoT applications. The technique encompasses the creation and execution of energy harvesting devices based on TENG technology, specifically emphasizing their incorporation into IoT frameworks [7]. The study seeks to offer significant insights into the effectiveness and practicality of TENGs in promoting IoT technology.

Lu et al. conducted a study that examines the combined use of energy harvesting and signal detection utilizing a single TENG for intelligent self-powered wireless sensing devices [8]. The study uses TENG technology to harness energy from the surrounding environment and assesses the resulting parameters, such as voltage, current, and power density. The benefit arises from the combined capability of energy harvesting and sensing in a single device, enhancing the effectiveness of self-powered wireless sensing systems.

Wang et al. suggest a hybrid energy harvesting system that utilizes a high-performance TENG specifically designed for smart agricultural purposes. The implementation entails the integration of TENG technology with a high-efficiency level, while the study investigates the output characteristics and performance measures pertinent to agricultural environments [9]. This study makes a valuable contribution to advancing sustainable energy solutions specifically designed for precision agriculture.

Li et al. present a Triboelectric-Electromagnetic Hybrid Wind-Energy Harvester specifically developed for self-powered sensing applications in metropolitan areas [10]. The suggested technology entails the creation of a device that can harness energy from urban wind currents, even at low wind speeds. The research assesses the performance attributes and highlights the device's use as an autonomous wind speed sensor in urban settings.

Li et al. investigated using hybrid wind energy nanogenerators to create self-powered forest environmental monitoring microsystems [11]. The study examines the integration of TENGs with wind energy collecting techniques to create environmentally friendly power solutions in forest settings. An evaluation is conducted on the performance measures and the practicality of these systems for monitoring the environment in real-time, contributing to developing environmentally friendly sensor solutions.

Dang et al. introduce a hybrid generator that combines triboelectric and electromagnetic principles to gather wind energy. The generator utilizes an inertia-driven conversion mechanism with a scale warning feature [12]. The approach incorporates the integration of an inertia-driven mechanism to optimize the extraction of energy from wind. This work investigates the output characteristics and applications of scale warning to provide a deeper understanding of the adaptability of TENGs for harvesting wind energy.

Zou et al. introduce a self-regulation technique for TENGs and self-powered wind-speed sensors [13]. The research aims to improve the efficiency of TENGs by implementing a self-regulation mechanism, hence boosting their performance in different situations. The work offers useful insights into self-regulation mechanisms to enhance the flexibility and efficiency of TENGs in wind energy collecting.

Yong et al. provide an innovative environmental self-adaptive wind energy harvesting method that combines a triboelectric and electromagnetic nanogenerator. The study investigates a dual-channel power management system for adaptive energy harvesting [14]. An assessment is conducted on the performance and flexibility of the suggested technology for autonomous systems, focusing on improvements in its capacity to function in various environmental conditions to promote sustainable energy solutions.

The combination of triboelectric and electromagnetic principles provides a synergistic method for harvesting energy, offering a practical option for sustainable power generation of IoT devices. The survey uncovers a wide range of approaches, executions, and measures of performance linked to TEHNGs, showcasing their efficacy in various applications. The survey findings provide valuable information for future advancements in energy-efficient and self-powered IoT ecosystems, showcasing the potential of high-performance nanogenerators to meet the energy requirements of connected devices. This highlights the significance of the expanding IoT environment.

The Structural Configuration of TEHN

Fig. 1 illustrates that the power generating units, namely TEHN (TN+EG), are enclosed inside the body frame of the appliance. A copper wind cup, positioned at the structure's apex, gathers wind energy and delivers spinning mechanical energy to the power generation units. The core structure of the body frame consists of a sliding element and a spinning component. The circular motion resulting from ambient mechanical activity may be converted into a linear movement by combining the spinning component with the sliding component. This concept utilizes a sliding portion to provide regular interaction and detachment between two distinct triboelectric components: aluminum foil and silicone rubber. The interaction between two substances via proximity and separation may transform mechanical energy into electric energy due to triboelectrification and electrostatic induction. Simultaneously, the movement of magnets and coils may transform rotational mechanical energy into electrical energy.

The spinning component consists of a trio of beams and two studded discs with magnets. The three intersecting beams are coplanar, forming an angle of 120º. To minimize friction between the sliding element and the beam, a bearing with an internal diameter of 0.3 cm and an exterior diameter of 0.7 cm is affixed to the end of each beam. EGs comprise revolving discs with magnets and coils securely attached to the body frame. Every EG device consists of 6 coils and six magnets. Magnets are evenly placed over the revolving discs, with switching magnetic polarizations. Six coils are securely attached to the body frame's lower and upper halves. The coils are interconnected in a series configuration to amplify the output voltage. The bottom disc and the three beams form a cohesive unit, whereas the top disk is detachable. The objective of this design is to streamline the process of installation.

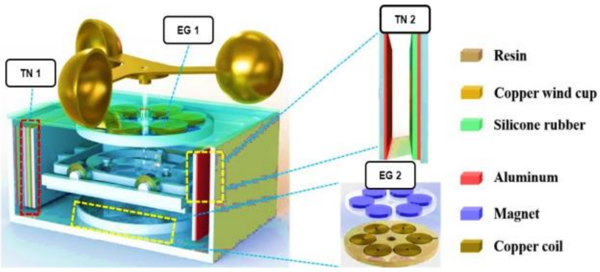


Figure 1: Structure of HPW-TEHN

The sliding element comprises two detachable resin panels, four bearings, and an elliptical frame. The resin layer is coated with aluminum, which functions as an electrode layer and a positive friction material for the TN. Four bearings, with an interior diameter of 0.6 cm and an exterior diameter of 1.7 cm, are positioned on each side of the sliding structure. These bearings convert sliding friction into rolling friction, lowering the resistance between the moving structure and the moving tracks.

Figure 2: The structure of the HPW-TEHN for wideband wind energy extraction in the ship and port

The HPW-TEHN is a power source combining the benefits of TNs at low frequencies and EGs at high frequencies. It is particularly useful for powering electronic equipment in isolated regions. A carefully designed hybridized nanogenerator ensures superior performance, long-term viability, and a wide range of power generation. Fig. 2 visually represents the framework and demonstrates its standard usage situations. The all-in-one design allows straightforward integration with a light pole in ports and can also be fitted on ships for harnessing wind power from the ocean.

Working of HPW-TEHN

Fig. 3 illustrates the operational concept of EG and TN. Faraday's inductive electromagnetic principle states that a shift in the magnetic field through coils, triggered by the mutual rotation among the magnet cluster and the coils in the revolving EG, produces an electric current.

Fig. 3 demonstrates that the sliding component undergoes a back-and-forth movement when the rotary section spins clockwise. In step I, the sliding portion is positioned centrally, with the spacing between the middle point and the silicone resistance layers remaining constant. When beam B1 reaches a certain location in stage II, the aluminum layer collides with the silicone rubber surface. The triboelectrification phenomenon causes the generation of identical concentrations of opposing charges on the exteriors of two distinct friction substances. The Al layer surface is populated with positive charges, whereas the silicone rubber film has negative charges. Currently, there is no closed circuit established in the external circuit. As beam B2 undergoes rotation, it imparts a lateral motion to the sliding component towards the right (stage III), detaining the two resistance levels on the left side. As the distance between the two surfaces rises, the electrons move from the silicone rubber electrode to the Al layer through a separate circuit. This continues until the two frictional layers on the right come into contact, and the separation gap between the frictional stages on the left reaches its optimum level (stage IV). As the rotating component continues to revolve, beam B3 propels the sliding component towards the left (stage V), causing the movement of electrons from the Al surface to the electrode of the silicone rubber film. With each complete rotation of the spinning component, both TN 1 and TN 2 experience three such phases.

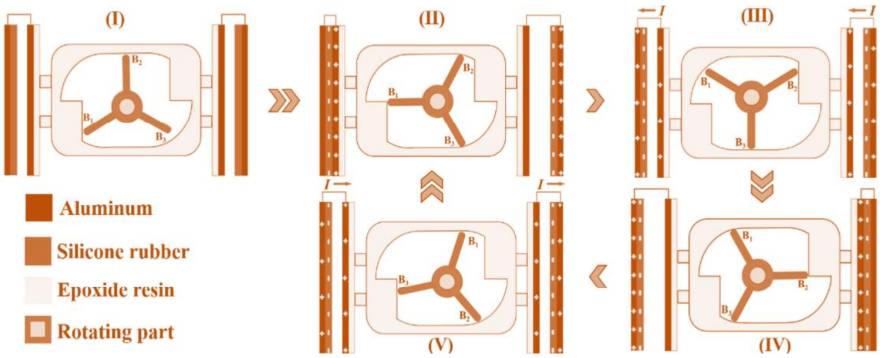
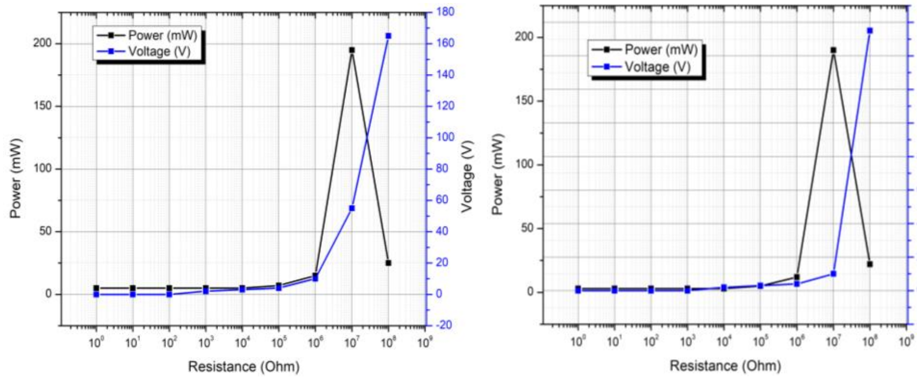


Figure 3: Power generation from HPW-TEHN using the revolving motion of TNs

Output and Results

A comprehensive study was conducted to investigate the impact of several types of triboelectric materials and surface areas (ranging from 2500 mm2 to 4500 mm2) on the output performance of TN. The negative triboelectric materials employed in this investigation are polytetrafluoroethylene (PTFE) and silicone rubber sheets. A wind speed of 10 m/s is employed in this experiment to provide the necessary kinetic energy for the rotating aspect. Individually, the performance of the silicone rubber film surpasses that of PTFE. Hence, the studies employ a silicone rubber sheet measuring 4500 mm2 in size, with a length of 8.5cm and a width of 5.5cm.

The impact of wind speed on the performance of the TN and the EG is then examined comprehensively. The findings of this examination are presented in Fig. 4. Within this particular segment; a blower is employed to generate wind speeds ranging from 4 to 15 meters per second, which can be likened to wind speeds often observed in nature between grades 3 and 8.

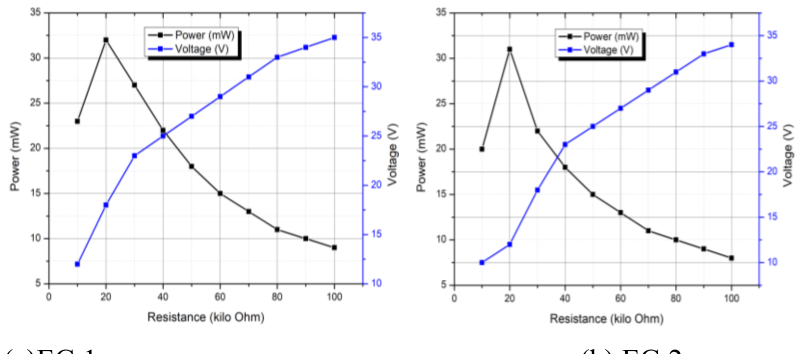


(a)TN 1 (b) TN 2

Figure 4: Output power (mW) and voltage (V) of TNs in the proposed HPW-TEHN for varying resistances (Ω)

Fig. 4(a) depicts the output power (mW) and voltage (V) of TN 1 in the proposed HPW-TEHN for varying resistances (Ω). The output power constantly maintains a level of 5mW when the resistance is below or equal to 10^3 Ω, demonstrating a steady performance even with lower resistive loads. Nevertheless, when the resistance escalates, there is a significant augmentation in both power and voltage. Significantly, when the resistance is increased to 10^6 Ω and 10^7 Ω, the output power experiences a large rise to 15mW and 195mW, respectively. This increase in power is accompanied by equivalent voltages of 10 V and 55 V.

Fig. 4(b) depicts the output power (mW) and voltage (V) of TN 1 in the proposed HPW-TEHN for varying resistances (Ω). At lower resistances (1 Ω, 10 Ω, 100 Ω, and 10^3 Ω), the output power stays consistent at 3 mW, with no voltage produced. This suggests that the device performs well even when subjected to lighter loads. As the resistance rises, a significant enhancement is evident. For resistances of 10^4 Ω and 10^5 Ω, the power output rises to 3 mW and 5 mW, respectively. This increase is followed by voltages of 2 V and 3 V. Also, when the resistance is set to 10^6 Ω and 10^7 Ω, the output power increases significantly to 12 mW and 190 mW, respectively. The equivalent voltages for these power levels are 4 V and 10 V. The results indicate that the suggested HPW-TEHN performs well when subjected to increased resistive loads, highlighting its potential for effective energy harvesting in various applications.



(a)EG 1 (b) EG 2

Figure 5: Output power (mW) and voltage (V) of EGs in the proposed HPW-TEHN for varying resistances (Ω)

Fig. 5(a) depicts the output power (mW) and voltage (V) of EG 1 in the proposed HPW-TEHN for varying resistances (Ω). A steady pattern is noticed when the resistance increases from 10 kΩ to 100kΩ. The power output of EG 1 gradually diminishes from 23 milliwatts to 9 milliwatts, coinciding with a fall in voltage from 12 volts to 35 volts. The negative correlation between resistance, power, and voltage demonstrates the load-dependent nature of EG 1.

Fig. 5(b) depicts the output power (mW) and voltage (V) of EG 2 in the proposed HPW-TEHN for varying resistances (Ω). As the resistance grows from 10kΩ to 100kΩ, a noticeable pattern emerges in the behavior of EG 2. The power output of EG 2 shows a fluctuating pattern, starting at 20 mW, peaking at 31 mW at a resistance of 20kΩ, and gradually decreasing to 8 mW at a resistance of 100kΩ. Simultaneously, the voltage exhibits a parallel pattern, commencing at 10 V, reaching a peak of 12 V, and ultimately stabilizing at 34 V. The versatility of EG 2 inside the HPW-TEHN for diverse operational situations and load needs is highlighted by its sensitivity to fluctuations in resistive loads.

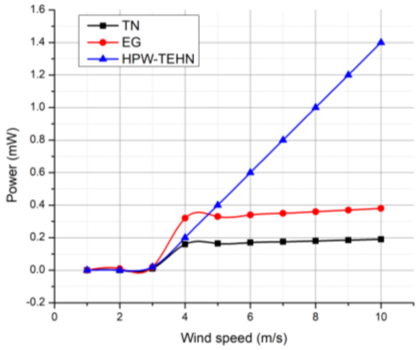


Figure 6: Power output of TN, EG, and HPW-TEHN at varying wind speeds

Fig. 6 depicts the power output of TN, EG, and HPW-TEHN at varying wind speeds. As the wind speed rises from 1 m/s to 10 m/s, the TN first produces little electricity, gradually reaching 0.19 mW at 10 m/s. The EG, engineered explicitly to harvest wind energy, begins power generation at 0.01 mW when the wind speed reaches 2 m/s and progressively escalates to 0.38 mW when the wind speed reaches 10 m/s. The HPW-TEHN showcases an improved performance by synergistically merging the outputs of TN and EG. The power output increases from 0 milliwatts at lower wind speeds to 1.4 milliwatts at 10 meters per second. The chart highlights the efficacy of the suggested hybrid nanogenerator in gathering and converting wind energy into electrical power, demonstrating its potential for self-sustained wireless transmission and wind speed monitoring in the Internet of Things.

Conclusion

This article introduces a hybrid energy harvester specially engineered for harnessing wind energy. This study presents the High Performance, Wind-driven Triboelectric-Electromagnetic Hybrid Nanogenerator (HPW-TEHN) as a viable option for generating power for WSS in the IoT. This work provides a High-Performance Wind Turbine with a broad operational range of wind speeds, enabling optimal wind energy utilization across various intensities, including soft breezes, strong winds, and even violent gusts. The device consists of a rotating component and a moving component. The power generation mechanism comprises the EGs positioned within the rotating body and the TNs installed on the sliding body. The device efficiently encloses all generated units from demanding environmental conditions. This study thoroughly investigates how different types and sizes of dielectric materials affect the output performance of TNs.

Furthermore, it examines the efficiency of this device's output across different wind velocities. The efficiency of HPW-TEHN rises with higher wind speeds. The TN, EG, and

HPW-TEHN provide power outputs of 0.19mW, 0.38mW, and 1.4mW, respectively, when exposed to a wind speed of 10 m/s.

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