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Dual-Rotor Electromagnetic Energy Harvester Using PCB Coils for Shaft-Mounted Wireless Sensor Applications

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ABSTRACT: Supplying battery-free power to wireless sensor systems (WSSs) mounted on rotating shafts remains a major challenge due to limited installation space, low rotational speed, and the requirement for long-term autonomous operation. This paper presents a compact dual-rotor energy harvester (EH) based on multilayer printed circuit board (PCB) sheets, designed for powering WSSs installed on ship propulsion shafts. Stacked multilayer PCB coils forming a three-dimensional structure are arranged on both the inner and outer rotors to enhance magnetic flux linkage and power density. The experimental results show that the EH generates power levels up to 959 mW at a shaft speed of 300 rpm. The output power improved nonlinearly with increasing rotational speed, demonstrating its suitability for real-time monitoring applications. The proposed EH offers a promising solution for powering WSS in autonomous driving technologies, with the potential for further optimization and integration into various mobility systems.

1. INTRODUCTION

Recent advancements in information and communication technology (ICT), including light detection and ranging (LiDAR) sensors, satellite communications, and artificial intelligence (AI) [1], are driving significant changes across the mobility industry, spanning land, sea, and air.

Core technologies for autonomous vehicles (AVs), maritime autonomous surface ships (MASSs), and unmanned aerial vehicles (UAVs) are rapidly advancing, driven by significant global investments aimed at commercialization.

Real-time monitoring of critical components and systems, which enables remote control, is one of the core technologies for autonomous driving. The propulsion shaft, a key component in AVs, UAMs, and MASSs, transmits propulsion power from the engine or electric motor to wheels or propellers. Consequently, vibrations are inevitable and may lead to bearing abnormalities. To address this, a wireless sensor system (WSS) for real-time remote monitoring and control of shaft conditions is essential. However, one of the main challenges in implementing WSS [2] on rotating shafts is the power supply technology, as electric power must be delivered to the system without relying on batteries [3].

To overcome this issue, wireless power transfer (WPT) and energy harvesting technologies have been explored. Although advancements in WPT, such as the development of new structures, coils, and coupling methods, have been made [4, 5], the technology still requires an external power source. Similarly, energy harvesters (EHs) using principles such as electromagnetic (EM), triboelectric, electrostatic, and piezoelectric effects have been widely studied for capturing rotational energy in various applications. However, integrating EHs into wireless sensing systems (WSSs) requires high power generation and simple designs for practical use. Various EM EH designs have been previously explored. A dual Halbach array EH [6] demonstrated an increased electromotive force and power generation by concentrating the magnetic flux, although it had a limited output power of 1.093 mW. Similarly, EHs utilizing rolling magnets [7] showed an improved magnetic flux rate and captured an average power of 1.02 mW, but faced limitations in cycling motions. Another EH design based on a tunable magnetic-spring structure [8] achieved a power output of 10.66 mW from swing motion. A frequency upconverted EH [9] yielded an average power of 2.15 mW, albeit with complexity in design and dependence on various parameters.

To enhance the output power of frequency up-conversion structures, a variable reluctance EM EH utilizing a periodic arrangement of magnets and teeth was reported in [10], achieving a power output of 726 mW. In addition, the monostable EM EH described in [11] produced approximately 0.7 mW, relying on carefully arranged magnetic configurations. A novel curved EH design in [12] generated 5.185 mW, whereas a curved-structure EH reported in [13] achieved 3.13 mW. A high-performance contra-rotating EH combining a contra-rotating mechanism and friction pendulum was presented in [14], delivering a maximum output power of 712 mW.

Furthermore, a shaft-mounted EM EH employing 12 rotor coils, each with 3,000 wire turns, was reported in [15], achieving an average output power of 5,124 mW at a rotational speed of 300 rpm under laboratory conditions. While this result demonstrates the potential for high power generation, it relies on bulky wire-wound coils with extremely high turn counts and a structurally complex configuration, which differs fundamentally from compact multilayer PCB-based coil architectures and poses challenges for scalable integration in practical marine propulsion systems.

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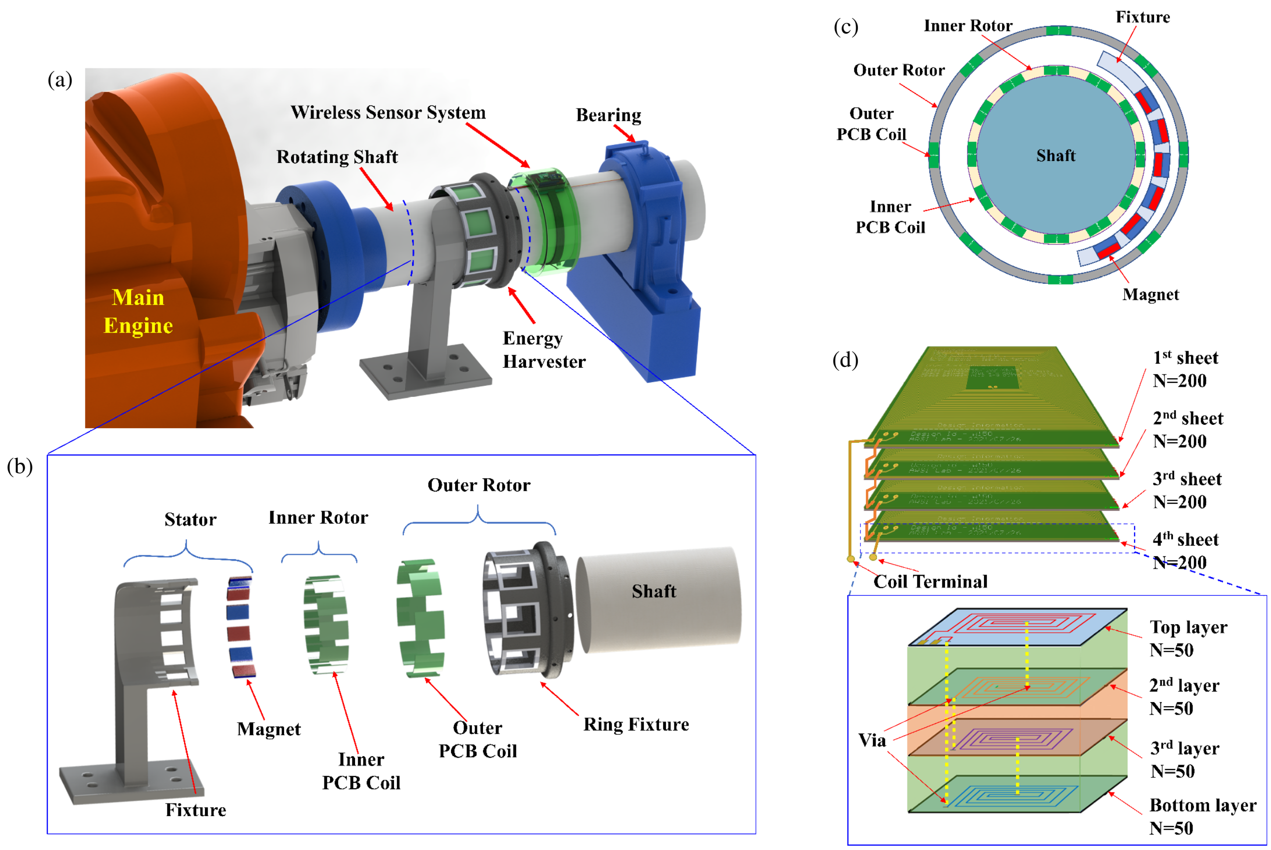

FIGURE 1. (a) The 3D structural overview of the EH for powering the WSS, (b) the 3D exploded schematic view of the proposed EH, (c) the cross-sectional view, and (d) the configuration of the coil bundle integrated into four PCB sheets, with each PCB sheet formed by laminating four layers.

Despite notable progress in EM EH designs, many reported systems exhibit limited output power or rely on structurally complex and bulky coil configurations, restricting their applicability to propulsion-shaft-mounted WSS. Because the output power of EM EHs strongly depends on the number of coil turns, increasing the power within a limited installation space typically necessitates highly intricate wire-wound coils, leading to increased manufacturing complexity and poor scalability.

In contrast, the core innovation of this study lies in the integration of a dual-rotor architecture with multilayer PCB-based three-dimensional coils. By stacking planar PCB windings and placing coil bundles on both the inner and outer rotors, the proposed design significantly enhances magnetic flux utilization and power density within a compact and manufacturable structure. This approach fundamentally differs from conventional wire-wound coil-based energy harvesters and enables practical, battery-free power generation for shaft-mounted wireless sensor systems operating under low-speed rotational conditions.

Consequently, a key challenge in compact, high-performance EM EH development is the realization of a simple, manufacturable, and space-efficient coil structure that is capable of delivering sufficient electrical power under realistic rotational speeds. To address this challenge, this paper proposes a compact dual-rotor EM EH employing multilayer PCB-integrated three-dimensional coils, and presents its structural design, fabrication, and experimental performance evaluation.

2. DESIGN OF A COMPACT DUAL-ROTOR EH

2.1. EH Structure Based on the Dual-Rotor Configuration

The energy harvesting system proposed in this study is designed to power a WSS installed on a ship's propulsion shaft. The conceptual design is illustrated in Fig. 1. The inductor integration technology used in radio frequency integrated circuits (RFICs) [16] enables the design of ultra-small, thin three-dimensional (3D) rotor coils by stacking 2D windings. This approach simplifies the coil structure for compact energy harvesting applications. A 3D exploded view of the proposed EH is shown in Fig. 1(b). To enhance the power output, a dual-rotor structure is proposed, with coils positioned on both sides of the magnet array, as shown in Fig. 1(c). The coils were stacked on a multilayer PCB substrate to form a compact 3D coil, as shown in Fig. 1(d).

A key innovation in this study is the use of multilayer PCB coils on both sides of the rotating magnetic array, which boosts the power output by increasing flux linkage and optimizing magnetic field use. Additionally, PCB coils simplify the integration with onboard electronics by eliminating the need for multiple external physical connections to other components. This design reduces the mechanical complexity and enhances reliability, making it particularly suitable for marine applications.

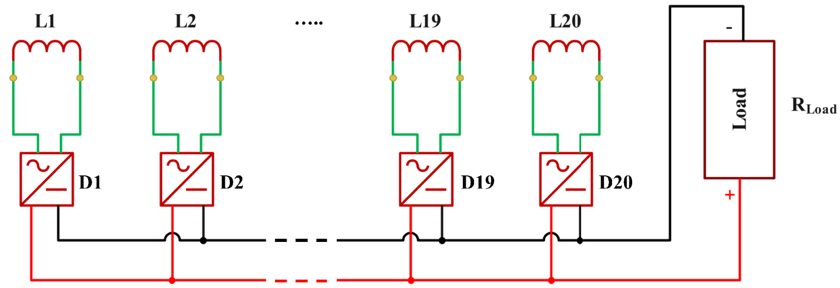

FIGURE 2. Equivalent circuit of the dual-rotor coil consisting of the coil bundles and rectifiers.

2.2. Design of the 3D Coil and the Dual-Rotor Structure

The operating power of the WSS, which integrates a power module, four sensors, a control and processing unit, and a wireless data transmission module, ranges from 800 mW to 1.5 W [3, 15, 17]. These systems include sensors for monitoring rotational speed, vibration, temperature, and other mechanical parameters, as well as wireless transmission modules for data communication and control units for system management. The dual-rotor EH proposed in this study was designed to meet these power requirements, ensuring continuous operation of the WSS without the need for external power sources. Therefore, the target power level of the EH was set to exceed 800 mW within a speed range of 100–300 rpm. Fig. 1(c) shows the coil bundle creation process using four stacked PCB sheets interconnected in series, forming a coil with 800 turns. Each PCB sheet has four layers, with 200 turns (50 turns per layer), separated by an FR-4 substrate, and interconnected through vias. The dual-rotor system consists of inner and outer coil bundles. The inner rotor contains 12 evenly spaced coil bundles mounted on the shaft, while the outer rotor includes eight coil bundles attached to an outer ring fixture, as shown in Fig. 1(c). The outer ring fixture ensured that the coil bundles rotated consistently with the shaft. The dual-rotor design uses 20 coil bundles connected in parallel to reduce the resistance and efficiently harness the generated power, as shown in Fig. 2.

2.3. Stator and Power Generation

The stator includes seven block magnets arranged to create alternating magnetic fields. The magnets were positioned with opposing polarities to ensure proper magnetic interactions. The fixture had rectangular holes to secure magnet alignment. The EH generates power by inducing a voltage in a coil bundle through relative motion between the magnets and coils, following Faraday's law of induction [10]. The total induced voltage is determined by the combined contributions of the inner and outer rotors.

3. EXPERIMENTAL SETUP AND PERFORMANCE OF THE EH

3.1. Fabrication and Experimental Setup of the EH

The fabricated EH, as shown in Fig. 3, features N40-grade sintered NdFeB magnets with a nickel coating ($46 \times 30 \times 10$ mm). The fixture was made from polylactic acid (PLA) using 3D

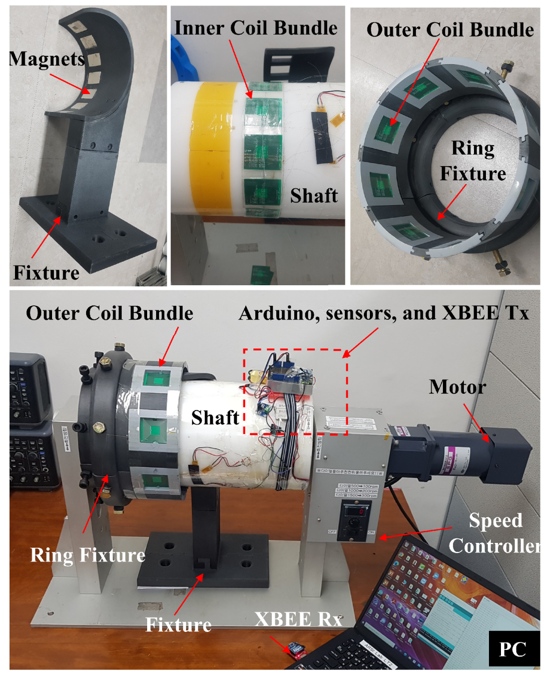

FIGURE 3. The fabrication of the EH and experimental setup for testing the characteristics of the fabricated EH prototype.

printing, with holes matching the magnet sizes and arranged in an alternating polarity configuration. The shaft was made of polyethylene (PE), whereas the ring fixture used acrylonitrile butadiene styrene (ABS) and PLA, with uniformly arranged square holes. The multilayer PCB sheets consisted of an FR-4 substrate and 1 oz copper, with coil bundles attached using adhesive and insulating. Each coil bundle had a resistance of 287.8 Ω.

The EH components were assembled on a laboratory test bench to evaluate power generation under controlled conditions using the WSS. The EH prototype was mounted on a test bench shaft and driven by an electric motor. The proposed EH has an outer diameter of 287 mm, an inner shaft diameter of 200 mm, and an axial length of 180 mm. These compact dimensions enable practical integration onto propulsion shafts without significantly affecting mechanical balance. The induced voltage and power were measured using the WSS. Considering that the total resistance of 20 coils connected in parallel is approximately 15 Ω, the power characteristics were measured with a load resistance of 15 Ω and an MB10F bridge rectifier. The wireless

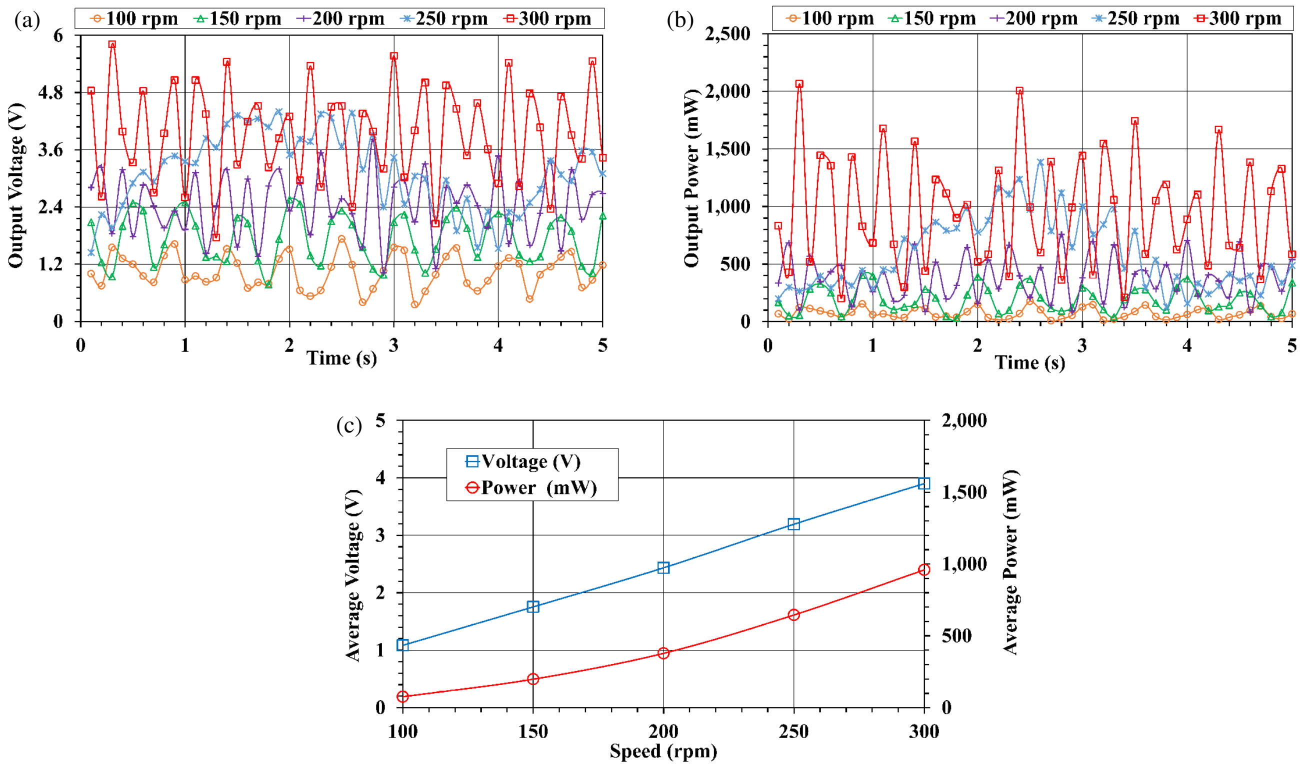

FIGURE 4. Measurement results: (a) output voltage and (b) output power waveforms when the EH operates at speeds ranging from 100 rpm to 300 rpm, and (c) average voltage and power performance measured as functions of the rotational speed of the shaft, ranging from 100 rpm to 300 rpm.

transmission of sensed signals was enabled by the XBee transmitter (Tx) and receiver (Rx) modules. The shaft speed, controlled by a motor speed controller, ranged from 100 to 300 rpm to evaluate the performance of the EH.

3.2. Performance of the EH

Figure 4 shows the EH output performance under a 15 Ω external load at different speeds. The peak voltage of the EH with the six magnets fluctuated, and the peak output power varied with the shaft speed. The experimental results in Figs. 4(a) and (b) show that the output voltage amplitudes of approximately 1.09, 1.75, 2.43, 3.19, and 3.9 V after rectification at shaft speeds of 100, 150, 200, 250, and 300 rpm, respectively. After obtaining the induced voltage and current, the average values were calculated, as shown in Fig. 4(c). As the shaft speed increases, the EH output power also rises, achieving average power levels of 76.3, 198.5, 378.51, 645.57, and 959.93 mW for the respective speeds. The results indicate that the output power increases with speed, thereby demonstrating the potential of the proposed EH for WSS applications. The power output follows a nonlinear trend that is approximately proportional to the square of the shaft speed, aligning with Faraday's law. The EH generates over 800 mW within the 100–300 rpm range, making it suitable for WSS applications. A shaft rotational speed of approximately 300 rpm corresponds to typical operating conditions in large marine propulsion systems employing reduction gearboxes, where low-speed, high-torque shaft motion is required. Such conditions are common in trawlers, tugboats, and heavy transport vessels. Therefore, the investigated speed range is particularly relevant for evaluating shaft-mounted WSSs under realistic marine operating environments. The minor fluctuations observed in the output voltage and power waveforms are mainly attributed to practical experimental factors, including mechanical vibration of the rotating shaft, non-uniform magnetic field distribution, and rectifier-induced voltage ripple. In addition, the wireless sensor system samples the electrical signals at a sampling rate of 10 Hz, which may contribute to small variations in the instantaneous waveforms. Nevertheless, this sampling rate is sufficient to accurately capture the overall power generation trend and average output performance, and it does not affect the validity of the reported results.

The electrical power generation characteristics of the proposed EH are influenced by coil design, magnetic field interaction, and load conditions. As the shaft speed increases, larger induced voltages and currents are generated, leading to a higher output power; however, this is accompanied by increased resistive losses in the coil windings and rectifier circuitry, which scale with the square of the current ($P_{\text{loss}} = I^2R$). At higher rotational speeds, additional loss mechanisms, such as eddy current effects and magnetic saturation, may also affect electrical performance.

In this study, a 15 Ω external load was selected to approximately match the equivalent resistance of the parallel-connected coil bundles, thereby achieving near-optimal electrical power extraction in accordance with the maximum power transfer theorem. This load-matching condition enables the efficient utilization of the generated electrical power while minimizing the losses associated with resistance mismatch.

4. CONCLUSIONS

In this study, a compact dual-rotor EM EH based on multilayer PCB sheets is proposed for powering a WSS mounted on ship propulsion shafts. The EH was designed to satisfy the power requirements of the shaft-mounted WSS, and experimentally demonstrated to achieve a maximum output power of 959 mW at a rotational speed of 300 rpm. The measured results confirmed that the electrical power output increased with the shaft speed, indicating the feasibility of the proposed EH for real-time monitoring of propulsion systems. The proposed dual-rotor architecture demonstrates that multilayer PCB-based EM harvesters can overcome the conventional power limitations associated with compact EHs for rotating machinery while maintaining a structurally simple and integrable design. This architecture provides a practical and battery-free solution for shaft-mounted wireless sensing applications by directly converting rotational mechanical energy into electrical power without relying on external power sources. Further optimization of the coil configuration, magnetic arrangement, and system integration is expected to enhance performance and facilitate practical deployment in marine propulsion systems.

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