Proceeding Paper

Maximizing Electromagnetic Energy Harvester Efficiency Through Optimized Magnetic Configurations for Wireless Sensor Networks †

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Abstract: Wireless and battery-less sensor nodes are pivotal in the future of technology, particularly for continuous monitoring and minimizing maintenance costs. These nodes are especially critical in large-scale agricultural systems, where they enable tasks such as detection, identification, and fertilization, so it is important that self-powered wireless sensors operate reliably. This paper presented an electromagnetic generator within a novel energy harvester to investigate how the power density and efficiency can be improved by optimizing the magnet arrangement and orientation. Four designs are proposed with different magnets orientations and iron steel plate for flux concentrating. The finite element magnetic method (FEMM) is mainly used to simulate the fine-tuning of the magnet arrangement, combined with MATLAB and some mathematical methods to find a suitable magnet arrangement. The results show that by increasing the number of magnets to nine, adding a pure iron wall and using a Halbach array, the magnetic flux density can be increased by 1.92 times.

Keywords: electromagnetic energy harvester; finite element simulation; wireless sensor network; magnetic arrangement; energy efficiency

1. Introduction

Wireless sensors are extensively utilized across various applications, with multiple methods available for energy harvesting, including electromagnetic [1], piezoelectric [2], and triboelectric technologies [3]. Agriculture, being a critical driver of economic, commercial, and technological development in any emerging nation, has increasingly benefited from cutting-edge technological advancements and innovations aimed at improving both the quality and yield of agricultural products [4]. The expansion of wireless sensor networks (WSNs) has made it easier to monitor large-scale modern farms. In a smart irrigation system, various sensors, such as temperature monitors and flow meters, can be powered through renewable energy sources harvested from the environment. By employing WSN technology, a hybridized energy harvester driven by rotating waterpower can be incorporated to create a self-sufficient, intelligent agricultural monitoring system.

Despite these advancements, significant challenges remain, particularly in remote areas, where regularly replacing batteries or installing and maintaining power lines for electronic devices is both labor-intensive and costly [5]. This research primarily focuses on maximizing the power harvested using various methods that exploit water flow motion and temperature differences within an irrigation pipe. The water flow harvesting component employs a turbine with strategically positioned magnets, which efficiently convert the turbine's rotational energy into electrical energy via coils [6]. This paper

specifically examines an electromagnetic energy harvester, investigating how to optimize the magnetic arrangement within the generator using finite element analysis. The goal is to enhance power density and efficiency, enabling more effective powering of wireless sensors in agricultural applications.

2. Design

The electromagnetic generator consists of groups of coils, magnets, and a turbine. Faraday's Law states that a fluctuating magnetic field induces voltage in a circuit [6]. When the turbine rotates, the magnets and coils rotate with it, causing a change in magnetic flux that could convert the energy of the water flow into electrical energy. To maximize the magnetic flux concentrated on the magnet arrangements, many factors such as the number of the magnets need to be considered. Four main designs are proposed as shown in Figure 1.
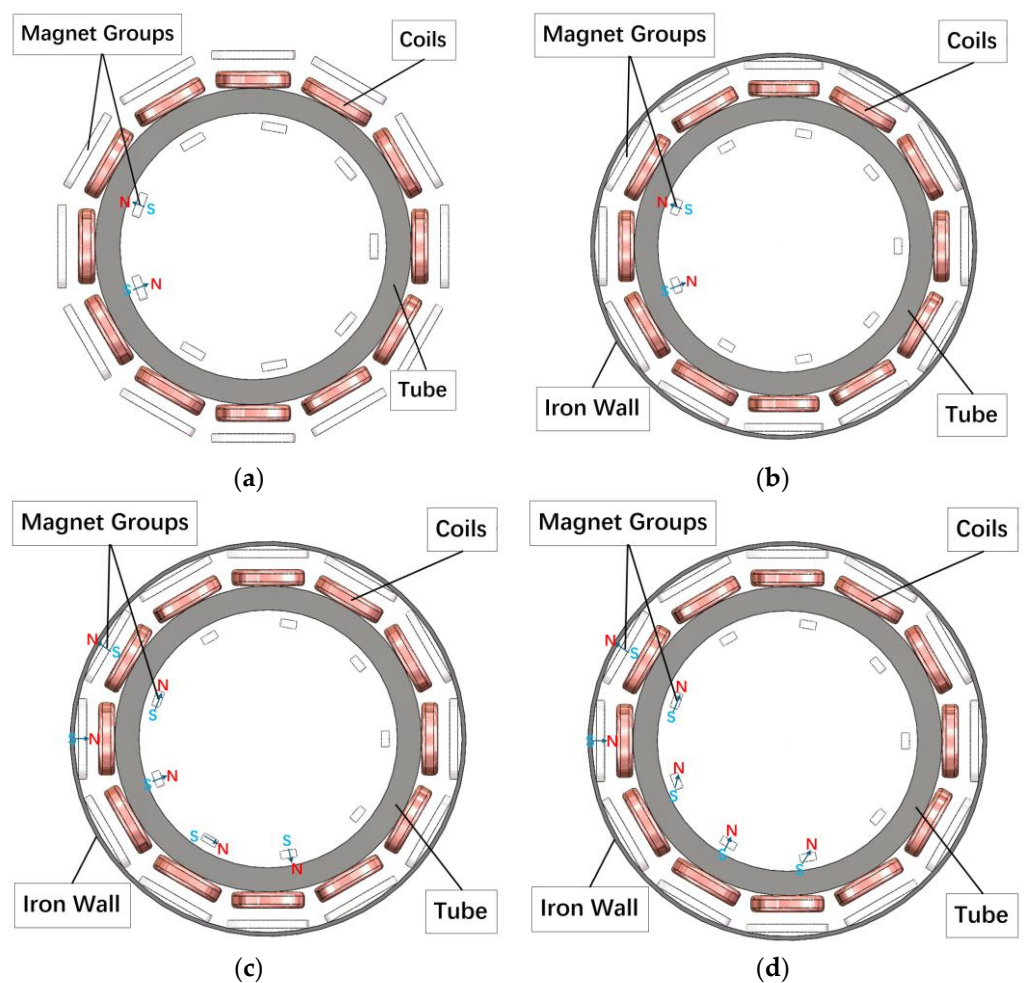

Figure 1. Model of the designs: (**a**) Design1; (**b**) Design 2; (**c**) Design 3.1; (**d**) Design 3.2.

2.1. Design 1: Increase the Number of Magnets

Research indicates that odd blade designs are more common and efficient, while even symmetrical blade arrangements can result in an unbalanced fan and increased resonance [7]. According to preliminary evaluations, fans usually have seven or nine blades, with diameters limits. The design of the inner ring magnets has also been optimized from 3 mm diameter to 2 mm diameter, which reduces the gap and allows denser arrangement. The thickness of the coils is also adjusted for increasing the coils, and the design also introduces many larger diameter outer coil magnets.

Figure 1a shows that the total of nine cylindrical magnets inside the tube located around the circle with the diameter of 28 mm, whose lower circular diameter is 2 mm, and the thickness of the cylinder is 1 mm (ϕ 2 mm × 1 mm). And outside the tube, around the circle with a diameter of 38 mm, there is a group of twelve coils of ϕ 9 mm × 2 mm and cor-responding with twelve cylindrical outer magnets of ϕ 10 mm × 1 mm arranged around the circle with a diameter of 44 mm.

2.2. Design 2: Add an Outer Pure Iron Ring Wall

Add a pure iron ring to the outermost part of the magnet as shown in Figure 1b. Due to the high permeability of the pure iron ring, which means that they can channel magnetic lines of force more easily [8], when the magnetic lines of forces pass through the pure iron ring, they are able to be concentrated, creating a stronger magnetic field inside it. Reducing the likelihood of the lines of force leaking out of the system is another important advantage, thus retaining more of the lines of force in the useful working area.

In this design, a pure iron ring wall with the thickness of 0.5 mm is added at the position that the circle diameter is 49 mm, together forming the whole structure of 50 mm.

2.3. Design 3: Magnet Arrangement in Halbach Array

The Halbach Array uses a special arrangement of magnets to enhance the field strength per unit direction, aiming to produce the strongest magnetic field with the small-est number of magnets [9]. Two simplest Halbach Array detailed arrangements and their intended effects are shown in Figure 1c,d.

Halbach Array is applied in the inner magnets' arrangement, with a 90-degree and a 45-degree rotation in each magnet direction. Outer magnets follow the reverse direction arrangement which is consistent with all of the above.

3. Result Analysis

Finite element magnetic method (FEMM) was used in conjunction with the MATLAB to conduct the analysis. After drawing the entire magnetic field simulation, the entire de-vice is operating under rotating motion, make it rotate 360 times to cover one revolution. To acquire a more accurate magnetic flux density produced by the magnet's rotation in the coil, each coil's magnetic flux density can be determined by taking the absolute aver-age value after scanning the coil area multiple times, which Figure 2. shows the FEMM pattern on the coil.
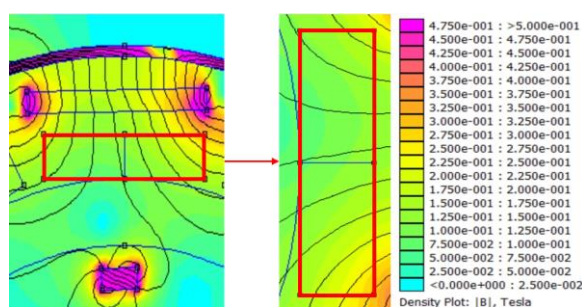

Figure 2. FEMM simulation results for coil regions.

Results Analysis

The data from Table 1 shown that the magnetic field strength can be effectively mod-ulated by altering the number of magnets, incorporating metallic materials, or adjusting the magnet configuration, and the FEMM simulation results diagrams are shown in Fig-ure 3.

Table 1. Design and the FEMM simulation results.

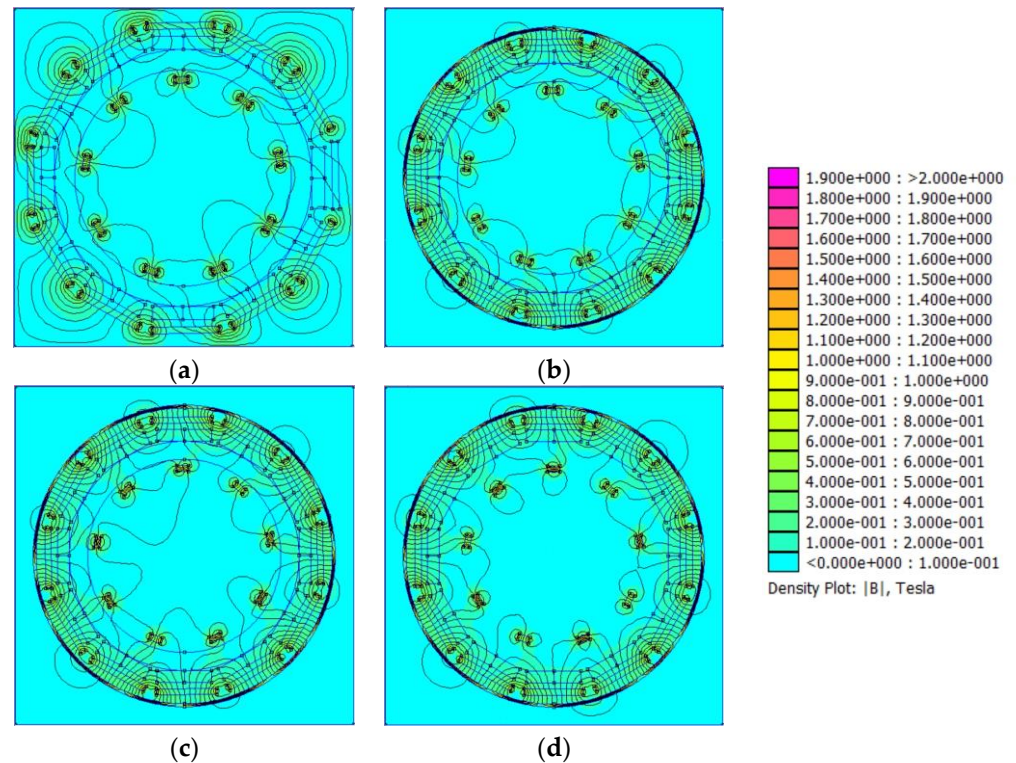| Design No.	Detailed Design	Magnetic Flux Density (T)
Design 1	Increase Magnets Number	0.0991
Design 2	Add Pure Iron Wall	0.1886
Design 3.1	Halbach Array Arrangement 1 (90°)	0.1902
Design 3.2	Halbach Array Arrangement 2 (45°)	0.1883

Figure 3. FEMM simulation results diagrams with materials and detailed arrangements: (**a**) Design1; (**b**) Design 2; (**c**) Design 3.1; (**d**) Design 3.2.

Among these the design adding a pure iron wall stands out as the most effective, achieving the highest growth. While there is a negligible difference between Designs 3, this could be attributed to the similar arrangements. Design 3.1 achieved a substantive enhancement to 0.1902 T which is increased by 1.92 times compared to the Design 1.

However, despite the improvement, Design 3.1 remains a conceptual idealization based on the original setup. For practical implementation, a comprehensive evaluation of additional factors such as cost, feasibility, and operational stability must be conducted alongside magnetic flux density considerations. Among the designs, the Halbach Array might present unprocurable, it only offers tiny improvements through too difficult operation. This array was considered in the idealized designs but has not been fully realized beyond the theoretical phase.

4. Conclusions

This design based on the improvement of the electromagnetic part of the energy harvester designed to support the application of wireless sensor networks. The results show that the flux density is improved by increasing the number of magnets, adding pure iron walls and applying Halbach Array. However, the ideal design requires further

considerations, and future work will aim to address these with a view to achieving more efficient and practical energy harvesting systems.

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