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GEOMETRIC OPTIMIZATION OF MAGNETIC FIELD ENERGY HARVESTERS UNDER PRACTICAL WEIGHT CONSTRAINTS FOR RAILWAY CATENARY SYSTEMS

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Abstract

The deployment of IoT sensor nodes for predictive maintenance in modern railway infrastructure requires reliable and sustainable power sources. Magnetic field energy harvesting (MFEH) offers a promising self-powered solution by capturing stray magnetic fields from catenary systems. However, practical implementation on messenger wires is constrained by the low operating current (10–50 A) and strict mechanical safety regulations that limit the total harvester weight. Under such fixed-weight constraints, conventional magnetic-core scaling is no longer a viable strategy for enhancing power output. Furthermore, a critical design trade-off exists because decreasing the outer-to-inner diameter ratio enhances magnetizing inductance but increases the core height, leading to longer winding lengths and higher copper loss. To address these challenges, this paper proposes a two-dimensional geometric optimization method tailored for railway installation constraints. By simultaneously varying the core's inner diameter and height while dynamically updating the parallel impedance-matching condition, the proposed method mitigates electrical detuning and enables direct evaluation of geometric effects on harvested power. The results identify a distinct turning point beyond which copper loss counteracts inductance gains. Under a practical minimum inner diameter constraint of 35.0 mm, the optimized design achieves a maximum output power of 14.14 W at a core height of 88.0 mm. These findings provide essential design guidelines for self-powered monitoring systems in railway applications.

Keywords: magnetic core, IoT sensors, magnetic field energy harvesting (MFEH), railway catenary, smart maintenance

1 Introduction

The rapid advancement of the Internet of Things (IoT) has enabled the extensive deployment of wireless sensor nodes in modern power and railway infrastructures, primarily for real-time condition monitoring and predictive maintenance. For instance, the IoT-based tension adjustment device condition monitoring system was recently implemented in Korea [1]. Beyond catenary-specific applications, the proposed harvester can support a broader range of railway infrastructure monitoring. Notable examples include catenary-mounted IoT thermal sensors for hot-spot detection, as well as a data acquisition device designed for railway trackside facility maintenance and worker safety [2]. While these sensors significantly enhance operational safety, their long-term autonomy is severely constrained by the finite lifespan of conventional batteries and the environmental limitations of solar panels.

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To address these limitations, magnetic field energy harvesting (MFEH) has emerged as a practical self-powered solution that harvests electrical energy from the stray magnetic fields of high-current power lines [3–7] and railway systems [8–10]. In railway catenary systems, the messenger wire serves as an ideal location for MFEH installation, as it avoids direct contact with the pantograph while remaining in close physical proximity to existing trackside IoT sensors, as shown in figure 1. However, unlike standard utility power lines, the current available for energy harvesting on the messenger wire is significantly lower. While a high-speed train draws a large total current, this current is divided between the contact wire and the messenger wire. Field measurement data from the South Korean 25 kV AC catenary system indicate that the maximum current flowing specifically through the messenger wire is approximately 10 A for conventional passenger trains (e.g. Mugunghwa) and about 50 A for high-speed trains (e.g. KTX) [11, 12]. Therefore, the harvester must be designed to operate reliably within this 10–50 A range. This significantly lower primary excitation current results in a relatively weak magnetic field, making it difficult to generate sufficient voltage for IoT sensor operation.

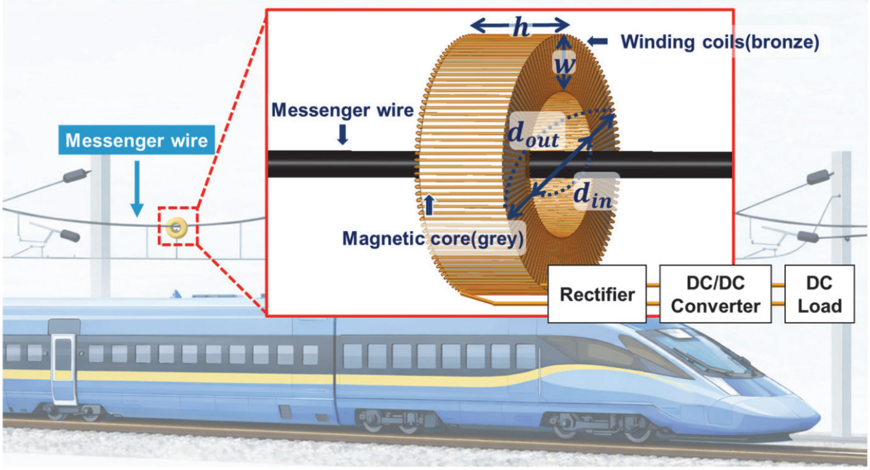

Figure 1 Concept of the magnetic energy harvesting from a railway catenary system

A straightforward solution to compensate for this weak magnetic field would be to increase the volume of the magnetic core. However, in practical railway catenary systems, attaching auxiliary equipment to the messenger wire is strictly regulated by mechanical safety standards to withstand environmental stressors. These stringent safety regulations inherently limit the maximum allowable weight of the energy harvester, which makes the conventional approach of increasing the core size impractical. Designing an efficient harvester within this strict physical limit introduces a complex geometric trade-off. Under a fixed-volume constraint, structurally modifying the core to enhance magnetic induction inevitably induces a geometric distortion that increases the internal winding length, thereby causing severe parasitic copper losses. While recent literature [13] has effectively addressed the circuit-level challenge by developing a parallel impedance matching framework tailored for low-current environments, the fundamental structural optimization to resolve this geometric trade-off remains unexplored.

To address this gap, this paper proposes a two-dimensional geometric optimization method for railway MFEHs under a fixed core-mass constraint. The inner diameter and core height are jointly optimized, while the load and parallel capacitance are updated at each design point using the analytical matching framework, so that the simulated output power reflects the geometric trade-off. The remainder of this paper is organized as follows.

Section 2 details the material selection, physical weight constraints imposed by railway standards, and the analytical formulation of the geometric trade-offs. Section 3 presents the 2D geometric-optimization simulation results and discusses the trade-off between inductance gain and parasitic losses. Finally, section 4 concludes the paper.

2 Design constraints and geometric modeling

2.1 Material selection and physical constraints

Before defining the design variables, it is essential to establish the material properties and physical constraints governing the harvester structure. Various soft magnetic materials, such as ferrite, silicon steel, and nanocrystalline alloys, can be considered for MFEH cores. In this study, silicon steel was selected because of its high magnetic permeability and cost-effectiveness. The proposed design methodology can also be extended to other magnetic materials by appropriately modifying their material properties, such as the saturation flux density and core loss characteristics. Practical deployment in the Korean railway environment is subject to strict weight and safety requirements. Auxiliary equipment installed on the messenger wire must satisfy structural safety standards under environmental stresses such as wind loading and mechanical vibration. In particular, the safety factor of the catenary system must be maintained above 2.2. According to the Korea Railway Standard [14], this requirement limits the maximum allowable additional load to approximately 3 kg. Considering the weight of the mounting clamps and protective housing, the magnetic core itself was limited to 1 kg in this study. This weight limit serves as the primary design constraint, determining the allowable volume and dimensions of the harvester core.

2.2 Analytical formulation of geometric trade-offs

In MFEH, the magnetizing inductance is a key parameter governing the induced voltage and plays a critical role in enhancing harvested energy. The magnetizing inductance can be expressed as follows:

$$L_m = \mu_{diff} \cdot \frac{N^2 A}{l} \tag{1}$$

where μ_{diff} is the differential permeability of the core, N is the number of coil turns, A is the cross-sectional area of the magnetic core, and l is the magnetic flux path length. As indicated in equation (1), the physical dimensions of the magnetic core are fundamental to the harvesting output. In particular, the inner diameter (d_{in}) of the core is a decisive parameter because it is intrinsically linked to both the cross-sectional area ($A = h \cdot w$, where h and w denote the height and width of the magnetic core, respectively) and the magnetic path length ($l_e = \pi(d_{in} + d_{out})/2$). Furthermore, the maximum number of turns ($N_{\max}$) that can be wound around the core is determined by the inner circumference divided by the coil diameter (d_{wire}), expressed as $N_{\max} \approx (\pi d_{in})/d_{wire}$. The induced voltage V_{th} at the harvester terminal is given by:

$$V_{th} = \omega B_{\max} A N \tag{2}$$

where $B_{\max}$ is the maximum magnetic flux density, ω is angular frequency. Specifically, both A and N are formulated as functions of the inner diameter d_{in} under a fixed-weight constraint of 1 kg. Since the total volume of the core is kept constant to meet safety requirements, any change in d_{in} necessitates a geometric trade-off in the outer diameter and height, which in turn determines the cross-sectional area (A).

Simultaneously, the maximum number of turns $N_{\max}$ is directly proportional to the inner circumference. Consequently, as $B_{\max}$ is a material-dependent constant for silicon steel, the harvested power is ultimately determined by the selection of d_{in}, which balances the magnetic induction capacity and winding constraints. While an increase in N enhances the induced voltage, it simultaneously leads to a longer total wire length, thereby increasing the parasitic resistance (R_S) of the coil. This increase in R_S results in higher copper losses, which can degrade the overall harvesting efficiency. Therefore, the structural design must balance the gain in induced voltage against the increase in internal resistance.

To analytically demonstrate this structural trade-off, the magnetizing inductance in equation (1) can be reformulated using the constant core volume constraint ($V_0 = A \cdot l$). By substituting $A = V_0 / l$ and the winding constraint $N_{\max} \approx (\pi d_{in})/d_{wire}$, L_m can be expressed independently of the core height h:

$$L_m \approx \frac{4\mu_{diff} V_0}{d_{\text{wire}}^2} \left(\frac{d_{\text{in}}}{d_{\text{in}} + d_{\text{out}}} \right)^2 = \frac{4\mu_{diff} V_0}{d_{\text{wire}}^2} \frac{1}{(1+k)^2} \tag{3}$$

where $k = d_{out}/d_{in}$ is defined as the outer-to-inner diameter ratio. This mathematical relationship reveals a critical insight: under a fixed-weight constraint, L_m is maximized when k approaches 1 (i.e., a radially thin core geometry).

However, maintaining the 1 kg core volume with a reduced radial width inevitably forces the core to elongate vertically, leading to a significant increase in height (h). As h increases, the wire length per turn ($2h + d_{out} - d_{in}$) extends significantly, triggering an exponential surge in the parasitic resistance R_S. Consequently, the theoretical voltage gain achieved by decreasing the ratio k is strictly offset by severe copper losses. To address this trade-off, a two-dimensional geometric optimization - simultaneously sweeping d_{in} and h, must be conducted to locate the global maximum power point.

3 Verification through simulation

3.1 Simulation setup

To verify the proposed two-dimensional geometric optimization methodology, comprehensive circuit-level simulations were conducted under practical railway catenary operating conditions. As validated in recent literature [13], a parallel-connected matching topology was uniformly applied across all simulation cases to ensure sufficient voltage gain under the low-source-current environment. The primary objective of the simulations is to locate the global maximum power point by navigating the structural trade-off between the magnetizing inductance and parasitic copper losses. To achieve this, a 2D grid sweep was performed, simultaneously varying the inner diameter (d_{in}) and the core height (h). Throughout the sweep, the total mass of the silicon-steel magnetic core was strictly maintained at 1 kg to comply with the mechanical safety constraints of the railway messenger wire. Furthermore, deploying the MFEH in practical railway catenary systems imposes a strict lower bound on its internal geometry. The messenger-wire diameter, insulation bobbin thickness, and vibration clearance together set the minimum feasible inner diameter. Therefore, the sweep range for the inner diameter was practically constrained to a minimum of 35.0 mm.

To minimize the effects of electrical mismatches and to evaluate structural variables more directly, the optimal parallel capacitance and load resistance were dynamically calculated and applied at each geometric iteration using the analytical framework discussed in section 2.2. This dynamic compensation allows the simulated power to more directly reflect the geometric effect, independent of circuit-level detuning. The key parameters used in the circuit simulation are summarized in table 1.

Table 1 Parameters of circuit simulation

Symbol	Parameter	Value
f_s	Power frequency	60 Hz
I_1	Primary current	50 A
d_{in}	Inner diameter of core	35-55 mm
d_{out}	Outer diameter of core	51-77.6 mm
h	Height of core	55-120 mm
B_{max}	Maximum magnetic flux density	1.75 T
H_{max}	Maximum magnetic field strength	400 A/m

3.2 2D Geometric optimization results and trade-off analysis

Figure 2 illustrates the comprehensive 2D grid-sweep results, showing the maximum harvested power across the practically constrained geometric range (inner diameters $d_1 \geq 35.0$ mm and varying core heights) under the strict 1 kg weight constraint. As shown in the surface plot, the output power shows a clear gradient of optimization. The theoretical derivation in section 2.1 suggests that the system tends to favor a lower outer-to-inner diameter ratio ($k = d_{out}/d_{in}$) to maximize the magnetizing inductance (L_m). Consequently, the power tends to increase as the geometry approaches the minimum permissible inner diameter ($d_{in} = 35.0$ mm).

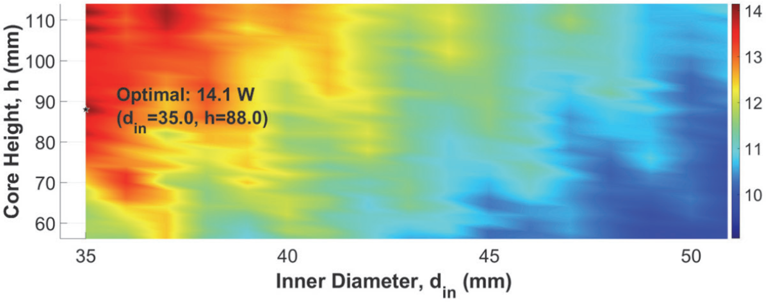

Figure 2 Simulated dutput power distribution over the geometric optimization space under 1 kg weight constraint ($d_{in} \geq 35.0$ mm)

Based on equation (3), it might theoretically appear that continuously decreasing the outer diameter (d_{out}) and correspondingly increasing the core height (h) under the fixed-mass constraint would yield a continuous increase in output power. However, aggressively elongating the core height (h) to further reduce the ratio under the fixed-volume constraint introduces a severe penalty: a drastic increase in the internal winding wire length and parasitic resistance (R_S). By balancing this trade-off between theoretical voltage gain and parasitic copper losses, the global practical optimum was identified. A maximum harvested power of 14.14 W was achieved at the boundary condition of $d_{in} = 35.0$ mm coupled with an optimal core height of $h = 88.0$ mm, ensuring both maximum electrical performance and mechanical reliability for trackside IoT sensors.

3.3 Power trade-off as a function of outer-to-inner diameter ratio

To further validate the geometric trade-off mathematically, figure 3 shows the power variation as a function of the outer-to-inner diameter ratio (*k*) with the inner diameter fixed at the practical minimum of 35.0 mm. As *k* decreases towards 1, the magnetizing inductance increases rapidly, leading to a steep rise in output power. However, to maintain the 1 kg core volume constraint, decreasing *k* inevitably elongates the core height (*h*), which in turn significantly increases the internal winding wire length and the parasitic resistance (R_S).

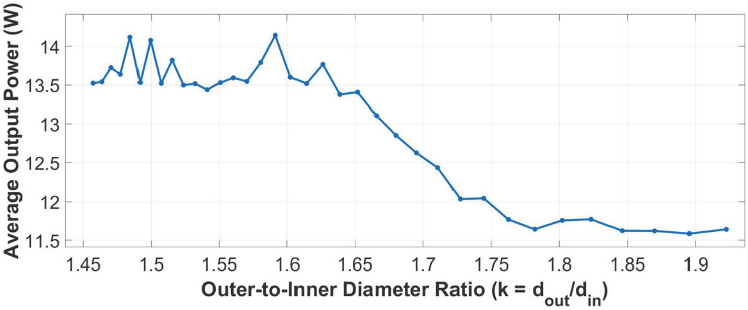

Figure 3 Variation of average output power with respect to outer-to-inner diameter ratio (*k*) at fixed practical inner diameter boundary (d_{in} = 35.0 mm)

The simulation results clearly show this turning point. The harvested power reaches its peak of 14.14 W at $k \approx 1.59$ (corresponding to $d_{out} \approx 55.7$ mm and $h \approx 88$ mm). In the inductance-driven region ($k > 1.59$), as the ratio decreases from 1.9, the core becomes relatively thinner. Under the fixed-volume constraint, this geometric shift significantly improves the magnetizing inductance (L_m). In contrast, entering the trade-off saturation region ($k < 1.59$), decreasing the ratio further forces the core to become excessively tall to maintain the 1 kg mass limit. While the theoretical magnetizing inductance continues to rise, extreme elongation significantly increases the internal winding wire length and its associated parasitic resistance (R_s). In this region, the increase in copper loss offsets the additional inductance gain, causing the extracted power to plateau and fluctuate around 13.5–14.0 W. This result confirms that the proposed 2D optimization prevents the system from entering this inefficient geometric saturation, identifying the exact boundary where electrical gain and physical penalties are balanced.

4 Conclusion

This paper proposed a two-dimensional geometric optimization method for magnetic field energy harvesters for railway catenary systems under a fixed core-mass constraint. By recalculating the optimal matching condition at each design point, the effect of core geometry on harvested power was evaluated more directly. The results showed that reducing the outer-to-inner diameter ratio improves magnetizing inductance, but excessive core elongation increases winding resistance and eventually reduces output power. Under the practical minimum inner diameter of 35.0 mm, the optimum geometry was obtained at an outer diameter of 55.7 mm and a height of 88.0 mm, yielding a maximum output power of 14.14 W. These results provide a practical design guideline for self-powered railway monitoring sensors, ultimately contributing to the reliable and sustainable implementation of predictive maintenance in smart railway infrastructures.

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