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Design of Magnetic Core to Harvest Energy in Smart Grid

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ABSTRACT: Wireless sensors are utilized to monitor devices with substantial current running through them in the power system. Monitoring ensures dependable power transmission and prevents cascading power failures. This work presents the design and optimization of a dumbbell-shaped magnetic core for the purpose of harvesting magnetic flux in proximity to bus bars and transformers within electrical substations. The gathered energy powers wireless sensors, rendering them self-sustaining. The proposed core can generate 17.63mW of output power with 40000 turns when situated in a magnetic field of 9 μ T rms. The proposed core is straightforward to assemble and can generate power to supply monitoring sensors in the smart grid.

1. INTRODUCTION

To prevent malfunctions and ensure reliable power transmission, energy providers have started using wireless sensors to monitor voltage equipment and transmission lines in recent years [1]. Due to their lower power consumption and simplicity of installation in difficult-to-reach areas, wireless sensors have gained importance in recent years. The power grid uses wireless sensors to measure temperature, partial discharge, voltage, and current. To get localized information about air quality, atmospheric sensors are placed next to electricity networks. Condition monitoring is aided by line sensors and vibration sensors. However, the batteries that power wireless sensors are expensive to replace on a regular basis [3]. One major issue is the sensor batteries' erratic lifespan [4]. The literature research suggests that the low-power sensor consumes roughly 500 μ W to 1 mW [5]. To mitigate this constraint, residual energy is used to power the sensors and guarantee their sustainability. The energy sources in the power grid include solar, wind, vibrational, electromagnetic, electric, and radio frequency energy. The employed sources must be free from climatic impacts and should not demonstrate temporal fluctuation [5]. Variable electromagnetic fields constitute a substantial energy source in electrical substations. J. Isokorpi et al. [8] proposed that the maximum electromagnetic field in a 400 kV switching station is 9.1 μ T rms. In 110/20kV switching substations, the peak measurement is 18.6 μ T at a height of 1m and 14.8 μ T at 0.5m. T. Keikko et al. [9] identified that the most significant electromagnetic field was produced at the junction of the bus bar and the outgoing feeder, particularly the 20kV conductor extending from the transformer to the 20kV switchgear. The reading is roughly 18.6 μ T at a height of 1 meter and 14.8 μ T at a height of 0.5 meters above the ground. Maja Grbic and colleagues measured the electromagnetic field intensity around 110kV/10kV substations. The 86.15 μ Trms measurement was taken beneath the 10kV busbar, at a height of 1.7 meters above the ground. S. Ozen et al. [11] identified the electromagnetic field intensity surrounding transformer substations within a medical facility with high-capacity 31.5kV/04kV transformers. The magnetic field intensity in the transformer room is 4.67 μ T, whereas in the control room, it varies from 1.74 μ T to 27 μ T. The measured field is approximately 1.5 meters above the ground level. M.N. Oltean et al. [12] asserts that the intensity of the electromagnetic field depends on the distance from the device and power lines, as well as the current flowing through them. The electromagnetic field is evaluated under a 400kV overhead transmission line. The electromagnetic field density measured at 0.65m is 5.284 μ T, but at 1.25m above ground, it is 5.160 μ T. Maja Grbić et al. [13] evaluated the electromagnetic field density adjacent to an apartment near the Belgrade Siberia 110kV/35kV substation. The peak magnetic flux density around the apartment is approximately 12 μ T to 20 μ T, recorded at a height of 1 meter above the ground. The research demonstrates that the electromagnetic field decreases as the distance from high voltage apparatus

increases. The busbar and transformer in the substation serve as the principal sources of electromagnetic field energy. Supplementary sources include ripple control systems, overhead transmission lines, and switchgear. This energy can be harnessed to make wireless sensors sufficient.

Electromagnetic harvesters are primarily classified into clamped and non-clamped categories. A clamped magnetic harvester encircles the transmission line. This leads to line sag and poses a considerable maintenance risk. Non-clamped harvesters, in contrast, can be positioned near high-voltage and high-current devices, enhancing their versatility; nevertheless, they produce less power than clamped harvesters [14]. N M Roscoe et al. [15] constructed a cast iron core with a radius of 1.2 cm and a length of 60 cm to harness the electromagnetic field in high voltage and current devices. The gadget produced 1mW of output power at a 4.5μT_{rms} flow rate. Nina M. Roscoe et al. [3] engineered an optimum iron cast cylindrical core that produces a power output of 300 μW in an 18 μT_{rms} electromagnetic field density. The core has a length of 50 cm and a diameter of 5 cm, displaying a cylindrical shape. The core delineated in [15] and [3] consists of iron and incurs eddy current losses, characterized by a high aspect ratio. Sheng Yuan et al. [16] propose a bow tie ferrite core. The aspect ratio of the core is 7.5 cm. The harvester delivers 360 μW to the load in 7 μT_{rms}. Sheng Yuan et al. [17] propose a helical core made of ferrite material. The core has a length of 15 cm and a radius of 12 cm. The power supplied to the load is 612 μW at 7 μT_{rms} flux. Constructing a helical core is a difficult task, comprising three components that are then assembled. This establishes an air gap within the system. The proposed core in this research study is both efficient and straightforward to create. The core's essential architecture promotes an augmentation of electromagnetic flux, hence improving power harvesting. Section 2 refers to the design of the electromagnetic core, Section 3 outlines the results and discussion, and Section 4 offers the conclusion.

2. ELECTROMAGNETIC FIELD HARVESTER DESIGN

A magnetic core encased in a coil is utilized to harness the electromagnetic field enveloping the electrical grid. Voltage is produced when a magnetic coil is placed within a varying magnetic field, as per the principle of electromagnetic induction. The induced voltage is detailed in (1).

$$E = \frac{\omega \pi D^2 B N \mu_E}{4} \quad (1)$$

E is induced voltage, ω represents angular frequency, μ_E denotes effective permeability, D indicates the core diameter, B signifies electromagnetic flux density, and N refers to the number of turns. The voltage across the load is one-half of the voltage produced in the coil when a matched load is employed.

$$V_{out} = \frac{E}{2} \quad (2)$$

Figure1. Gives the harvesting core approximation

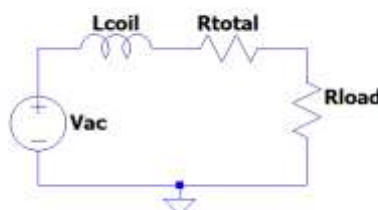


Figure 1. Core approximation

L_{coil} represents the inductance of the coil, whereas R_{total} denotes the total resistance presented by the magnetic core, which comprises both the core material and the copper coil.

The total impedance presented by the harvester is

$$Z = R_{total} + j\omega L + R_{Load} \quad (3)$$

If a compensating capacitor is connected to the receiving coil, the capacitive reactance at the resonant frequency cancels the inductive reactance of the coil. The circuit operates as a purely resistive network, as the reactive components of the impedance are eliminated under this circumstance.

$$R_{\text{total}} = R_{\text{core}} + R_{\text{coil}} \quad (4)$$

The out Power per unit volume can be calculated as below

$$\text{Volume} = \pi r^2 l \quad (5)$$

$$P_{\text{out}} = \frac{\pi^2 f^2 D^2 B^2 N^2 \mu_E^2}{16 R^2 l} \quad (6)$$

2.1 Core Material

Electrical conductivity, coercivity, saturation, and relative permeability (μ_R) are the fundamental characteristics of any magnetic core material. The core will be considerably magnetized in response to an external electromagnetic field when materials with a higher permeability are used. Manganese-zinc ferrite (Mn-Zn) is the primary material employed in this context. Soft magnetic cores are composed of ferrites. These cores demonstrate minimal core losses, high permeability, low electrical conductivity, and elevated electrical resistivity. Losses are reduced by the increased resistivity of ferrite [18]. Table 1 summarizes the μ_R of various core materials [19].

Table 1. The relative permeability (μ_R) of various core materials.

Sl.No	Core materials	μ_R	Operating frequency
1	Ferrite (NiZn)	200–2,000	1–100 MHz
2	Ferrite (MnZn)	1,500–15,000	20kHz–2 MHz
3	Soft Iron	2,000–5,000	DC–10 kHz
4	Permalloy	20,000–100,000	DC–500 kHz
5	Nanocrystalline	50,000-150,000	1kHz-1MHz

Iron possesses magnetic characteristics. It demonstrates low resistance and excellent permeability. Nonetheless, iron incurs significant Eddy current losses [18]. Nanocrystalline materials demonstrate an extraordinarily high level of permeability. Nevertheless, nanocrystalline materials exhibit more susceptibility to Eddy current losses compared to ferrite, owing to their reduced resistivity. The resistivity of Mn-Zn ferrite is approximately $1.1 \times 10^6 \Omega\text{m}$ [20]. Therefore Mn-Zn ferrite is regarded as the core material because of its relative permeability (μ_R) ranging from 1,400 to 15,000 and they exhibit little core losses. In the further section the relation between effective permeability and relative permeability is further explored.

The harvester's overall loss is attributable to copper and core losses.

The core loss arises from the alternating electromagnetic field. The core loss is comprised of hysteresis and Eddy current losses, while the copper loss is a result of the wound coil [21].

Core loss is composed of two primary components:

- Hysteresis loss: The frequency and electromagnetic field are the determining factors for hysteresis losses. Hysteresis losses are disregarded in this application due to the low frequency and magnetic field.
- Eddy current loss: It is influenced by the core's electrical resistivity. The power loss resulting from eddy current is denoted as [22].

$$P_{\text{Eddy}} = \frac{\pi^2 f^2 d^2 B^2}{16 \rho} \quad (7)$$

In this case, d stands for the rod's diameter, f for frequency, B for electromagnetic flux density, and ρ for core resistivity. The ρ of the ferrite material is extremely high. Because of its smaller diameter, the core created in this work exhibits low eddycurrent losses. As a result, it is ignored. Since the core resistance is insignificant in comparison, the coil resistance is the main source of the total loss.

2.2 Core shape

Effective permeability (μ_E) is the primary factor influencing the power that is extracted from the magnetic core. It is employed in the core when the magnetic material does not provide complete guidance for the flux. μ_E is contingent upon the demagnetization factor. A demagnetizing field is produced to neutralize the applied electromagnetic field whenever a cylindrical magnetic core is exposed to an external electromagnetic field. The demagnetization factor and the effective permeability of the core are related in (8). The effective permeability can be determined using the formula below [23].

$$\mu_E = \frac{\mu_R}{1 + N_d \mu_R} \quad (8)$$

N_d =Demagnetization factor. $\mu_E < \mu_R$

The demagnetization factor is variable upon the core's length, diameter, and material composition.

The effective permeability for various core geometries is computed as follows [23]

$$\mu_E = \frac{B_{in}}{B_x} \quad (9)$$

In order to optimize the length and diameter of the core, a uniform 9 μ Trms is generated using the Helmholtz coil in CST EM Studio. The magnetic core is immersed in the electromagnetic field, and the flux linkage within the core is quantified for various aspect ratios. The material's μ_R is 2300.

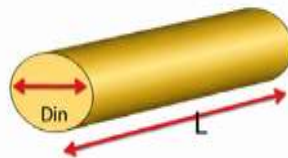


Figure 2. Cylindrical rod

The core's diameter is denoted by D_{in} , while its length is denoted by L . The optimized length and diameter of the solid cylindrical core in Figure 2 are determined by simulating it in the 9 μ Trms field with varying length-to-diameter ratios.

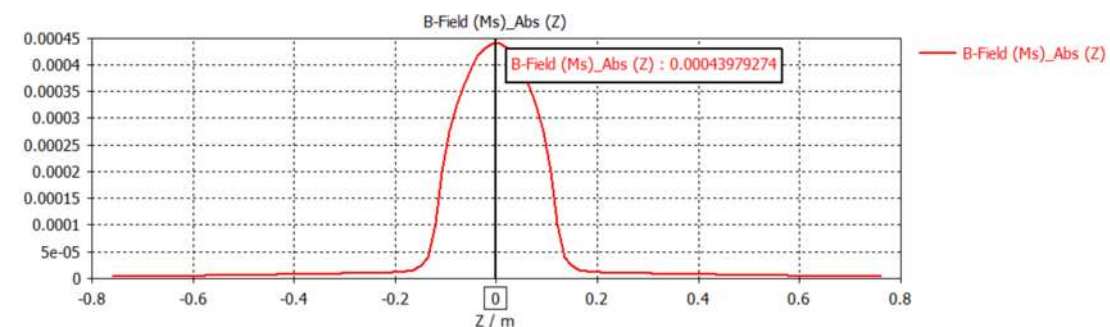


Figure 3 Flux density Simulation for the cylindrical rod with $D_{in}=3\text{cm}$, $l=25\text{cm}$, $\mu_R=2300$

Figure 3 indicates flux density induced in the cylindrical rod. The flux density in the center of the core is strongest. Cylindrical rods with identical lengths, diameter but varying Relative permeability is simulated using CST EM Studio and effective permeability is tabulated for different diameter of the cylindrical rod in table 2 to table 7.

Table 2. Parameters of the core with $D_{in}=2\text{cm}$. $N=200$, $L=25\text{cm}$.

μ_R	Bin (μT)	μ_E
100	456	50.66
500	705	78.38
1100	761	84.55
1700	779	86.55
2300	788	87.55
2900	793	88.11

Table 3. Parameters of the core with $D_{in}=2.5\text{cm}$. $N=200$, $L=25\text{cm}$.

μ_R	Bin (μT)	μ_E
100	374	41.55
500	526	58.44
1100	556	61.77
1700	568	63.11
2300	573	63.66
2900	576	64

Table 4. Parameters of the core with $D_{in}=3\text{cm}$. $N=200$, $L=25\text{cm}$.

μ_R	Bin (μT)	μ_E
100	313	34.77
500	415	46.11
1100	433	48.11
1700	439	48.77
2300	442	49.11
2900	443	49.22

Table 5. Parameters of the core with $D_{in}=3.5\text{cm}$. $N=200$, $L=25\text{cm}$.

μ_R	Bin (μT)	μ_E
100	269	29.88
500	339	37.66
1100	351	39
1700	355	39.44
2300	357	39.66
2900	358	39.77

Table 6. Parameters of the core with $D_{in}=4\text{cm}$. $N=200$, $L=25\text{cm}$.

μ_R	Bin (μT)	μ_E
100	240	26.66
500	286	31.77
1100	294	32.66
1700	297	33
2300	298	33.11
2900	299	33.22

Table 7. Parameters of the core with $D_{in}=4\text{cm}$. $N=200$, $L=25\text{cm}$.

μ_R	Bin (μT)	μ_E
100	240	26.66
500	286	31.77
1100	294	32.66
1700	297	33
2300	298	33.11
2900	299	33.22

Table 2,3,4,5,6 and 7 illustrate that the effective permeability increases with the rise in μ_R of the core up to a specific threshold, beyond which it becomes independent of μ_R .

Therefore, core material with very high permeability may not provide any significant rise in effective permeability. Nanocrystalline materials exhibit an exceptionally high degree of permeability. However, the resistivity of ferrite Mn-Zn is approximately $1.1 \times 10^{-6} \Omega \cdot m$ [20]. However, nanocrystalline is more susceptible to Eddy current losses than ferrite due to its lower resistivity. Therefore Mn-Zn ferrite is regarded as the core material because to its relative permeability (μ_R) ranging from 1,400 to 15,000. Ferrite exhibits little core losses.

The other parameter on which the effective permeability depends is the shape of the core. The effective permeability rises with an increase in aspect ratio. As the length-to-diameter ratio grows, the demagnetizing field diminishes. Maximum power is achieved when the core is longer and slender. Table 8 shows the relationship between the effective permeability of the core and the aspect ratio.

The core's aspect ratio is provided in (10).

$$\gamma = L/D \quad (10)$$

Demagnetization factor N_d as shown in (11) [23]

$$N_d = \frac{1}{\gamma^2 - 1} \left[\frac{\gamma}{\sqrt{\gamma^2 - 1}} \ln(\gamma + \sqrt{\gamma^2 - 1}) - 1 \right] \quad (11)$$

Table 8. Comparative analysis of effective permeability and demagnetization factor for varying aspect ratio

Aspect ratio	N_d	μ_E
5	0.055	17.77
10	0.020	48.26
15	0.0107	89.42
20	6.74×10^{-3}	139.2
25	4.67×10^{-3}	195.85
30	3.44×10^{-3}	257

Table 8 illustrates the relationship between the effective permeability of the magnetic core and the Length to Diameter (L/D) ratio. The effective permeability is noted to increase steadily as the L/D ratio rises from 5 to 30. This pattern indicates that a greater core length relative to the diameter provides a more effective pathway for magnetic flux, reducing demagnetization impacts and enhancing core magnetic strength. The observed nonlinear escalation indicates a significant reliance of the effective permeability on the geometric aspect ratio of the magnetic core. Elevated L/D ratios are advantageous for the confinement of magnetic fields and the minimization of magnetic resistance, both of which are important in harvesters. The relationship between demagnetization parameters and the aspect ratio of the core is illustrated in Figure 4. The demagnetization factor decreases as the aspect ratio of the core increases. The distance between the North Pole and the South Pole is increased by these cores, resulting in a reduction in demagnetization.

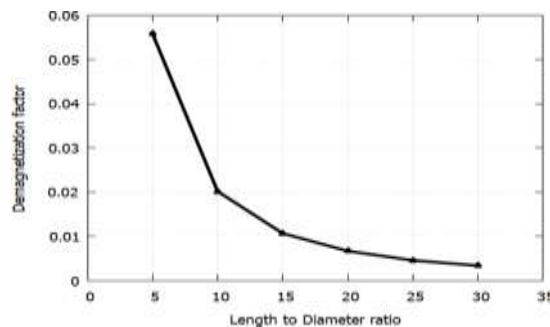


Figure 4 Demagnetization factor in relation to length-to-diameter ratio.

Nevertheless, cores with a smaller diameter and a longer length are more fragile and prone to damage. Consequently, the core's aspect ratio is optimized, and a core shape is developed to enhance the magnetic field that the core induces.

2.3 Design of core

The length-to-diameter ratio of the magnetic core can be raised to improve electromagnetic flux connection. As the length to diameter ratio increases the core becomes thin and lengthy, making it exceedingly brittle and prone to fracture. To improve the connection, magnetic plates are mounted to the cylindrical shaft. Figure 5 shows the dumbbell core, which is meant to improve the electromagnetic flux linkage

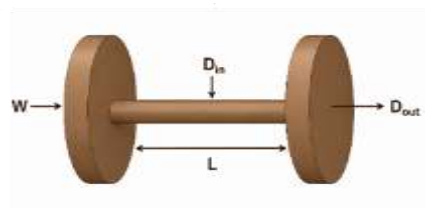


Figure 5. Designed Dumbbell core

The dumbbell core in Figure 6 is modeled with $D_{in}=2$ cm, $D_{out}=11$ cm, $W=2.8$ cm, and length $L=25$ cm and simulated in CST EM studio.

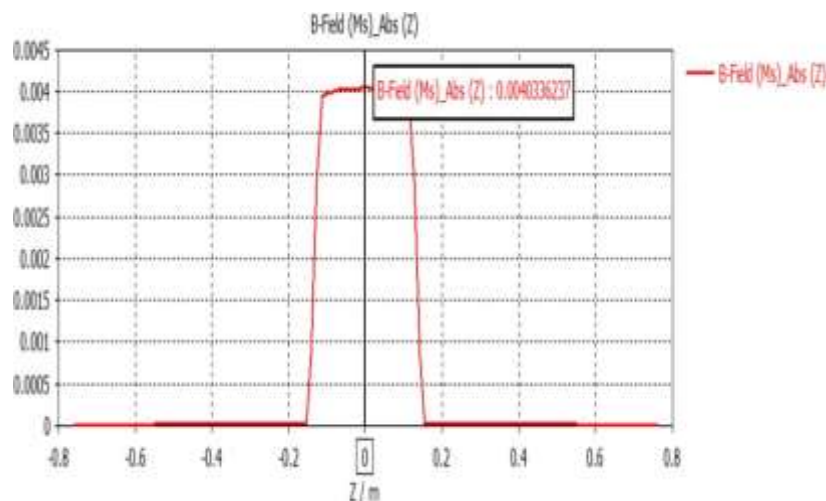


Figure 6 Magnetic flux linkage in the middle of the dumbbell core with $D_{in}=2$ cm, $L=25$ cm, $D_{out}=20$ cm, $W=2.6$ cm, $\mu R=2300$

The electromagnetic flux at the core's center is 4.03 mT_{rms} when compared to cylindrical rod which gives electromagnetic flux density is 689 μ T_{rms} for the same aspect ratio. Figure 6 shows that the addition of magnetic plates increases the

electromagnetic flux within the core, hence raising the induced voltage. As a result, a dumbbell-shaped core can provide more power than a cylindrical rod of similar length and diameter.

Optimizing dumbbell core: The inner diameter of the core is denoted by D_{in} , the outer diameter by D_{out} , the length is denoted by L , and the width of the plate affixed to the edges of the ferrite rod is denoted by W . Flux of $9\mu T_{rms}$ is employed to simulate a dumbbell core with varying inner diameter and outer diameter. Effective permeability for different D_{in} and D_{out} is tabulated in Table 9.

Table 9. Effective permeability for different core diameter when $\mu_r=2300$, $N=200$

D_{in} (cm)	μ_E Dout (10cm)	μ_E Dout (12cm)	μ_E Dout (14cm)	μ_E Dout (16cm)	μ_E Dout (16cm)	μ_E Dout (16cm)
2	252.2	288.8	328.8	366.6	400	447.7
2.2	211.1	244.4	277.7	311.1	344.4	377.7
2.4	181.1	208.8	238.8	267.7	298.8	328.8
2.6	156.6	181.1	205.5	232.2	258.8	286.6
2.8	136.6	157.7	180	203.3	226.6	251.1
3.0	120	138.8	158.8	178.8	200	221.1
3.2	106.6	123.3	140	158.8	177.7	197.7
3.4	95.2	110.1	125.5	142.2	158.8	175.5
3.6	85.4	98.7	112.2	127.7	142.2	158.8
3.8	77.2	88.8	102	115.5	128.8	143.3

Figure 7 depicts the relationship between the diameter of the magnetic plate and the resultant power output. It demonstrates that, with a fixed inner diameter and core length, a rise in D_{out} leads to a proportional increase in harvested power

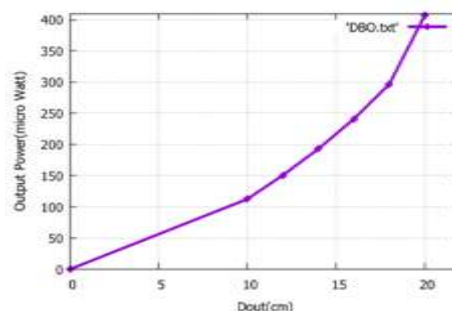


Figure 7. Power across the output as the function of diameter of magnetic plate of dumbbell core

Table 10 shows that a dumbbell core with a longer, narrow inner rod and a larger magnetic plate harvests more power.

Table 10. Harvested power for different core diameter when $\mu_r=2300$, $N=200$

D_{in} (cm)	$P_{out}(\mu W)$ (10cm)	$P_{out}(\mu W)$ (12cm)	$P_{out}(\mu W)$ (14cm)	$P_{out}(\mu W)$ (16cm)	$P_{out}(\mu W)$ (16cm)	$P_{out}(\mu W)$ (16cm)
2	113.5	148.9	193.03	239.9	285.6	357.8
2.2	105.7	141.7	183.07	229.6	281.5	342.2
2.4	101.2	134.6	176.1	221.3	275.6	333.8
2.6	96.1	128.5	165.5	211.3	262.6	322.8
2.8	91.4	121.8	158.6	202.3	251.5	308.7
3.0	86.7	116.1	152.07	192.7	240.9	294.5
3.2	83.1	111.2	143.3	184.5	231.4	286.03
3.4	79.6	106.5	138.4	177.6	221.7	270.7
3.6	76.02	101.6	131.20	169.8	210.7	262.9
3.8	73.07	96.8	127.4	163.6	203.5	251.7

A dumbbell-shaped rod with a diameter of 2 cm and a length of 25 cm is simulated and tabulated in Table 11. The value of N is 200, and the value of μ_r is 2300. The width of the outer plate w is varied, while the outer diameter D_{out} is 11 cm.

Table 11. Parameters of the cores when W is varied

$\mu_r=2300, N=200,$

Core	width (cm)	μ_E	Nd	Vcoil (mV)	VO(mV)	Rcoil(Ω)	Pout (μW)
Rod(a)	2	253.3	0.003	45	22.5	4.4	114.5
Rod(b)	2.5	265.5	0.0037	47.1	23.5	4.4	125.7
Rod(c)	3	278.8	0.0036	49.5	24.7	4.4	138.8
Rod(d)	3.5	298.8	0.0035	53	26.5	4.4	159.4
Rod(e)	4	303.3	0.0033	53.8	26.9	4.4	164.1
Rod(f)	4.5	316.6	0.0031	56.2	28.1	4.4	178.9

Table 11 depicts the relationship between output power and the width of the magnetic plate. The power experiences just a minimal enhancement with the enlargement of the magnetic plate. Consequently, augmenting the width of the magnetic plate has no considerable effect on the output power obtained.

The slender and long inner rod renders the core fragile. An increase in the outer diameter of the dumbbell core results in an increase in core volume. The results indicate that the total collected power increases as the core volume expands, because of the improvement magnetic flux linkage, effective permeability, and electromagnetic coupling. However, the increase in captured power is not proportional with the expansion of the core volume. The power density (i.e., harvested power per unit volume) decreases continuously as the core size increases, as the flux increase is less efficiently facilitated by the additional magnetic material, and magnetic saturation, demagnetization effects, and core losses become more apparent.

Power per unit volume is a more significant parameter for compact electromagnetic energy harvesters than total garnered power, as it indicates the efficient utilization of available space. the size, weight, and material cost of a high power density harvester can be reduced by utilizing a smaller magnetic core to produce the same output. Therefore, the fundamental dimensions must be optimized [25].

2.4 Coil Design

The electromagnetic core's power is dependent on both the copper coil twisted around it and the core itself. The number of rotations (N) and the harvested voltage are perfectly proportionate. Nevertheless, the coil's resistance rises as N does. Core resistance and coil resistance combine to form total resistance. Whereas core resistance causes eddy current and hysteresis losses, coil resistance causes copper losses. Because ferrite has a poor electrical conductivity and the operating frequency of 50 Hz, eddy current and hysteresis losses can be ignored. As the number of turns grows, copper loss greatly outweighs core loss. As a result, only copper loss is considered. Below is an analysis of the copper coil's properties. The resistance of a copper coil as a function of turn count for different core sizes is shown in Figure 8. More resistance is produced by the electromagnetic core with a larger inner diameter.

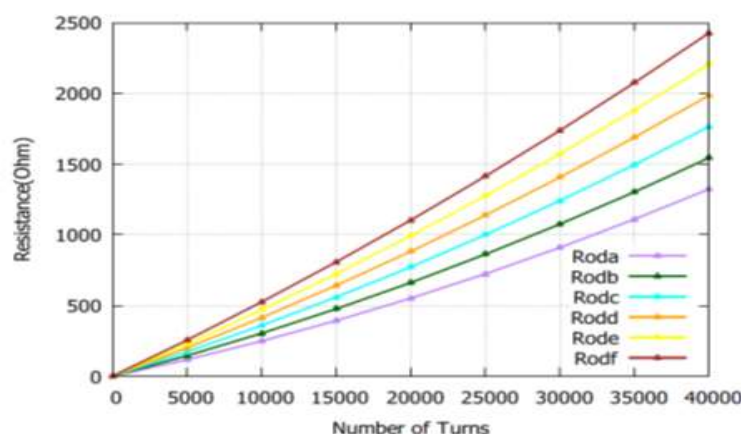


Figure 8. Coil Resistance as a function of Number of turns

The total wire length is given by [24]

$$L_{\text{wire}} = 2\pi N(D + (J_{\text{Layer}} * d)) \quad (12)$$

N represents the number of turns in the coil, d denotes the diameter of the wire, D signifies the diameter of the core, N indicates the number of turns, and J_{Layer} refers to the number of layers coiled.

$$J_{\text{Layer}} = \frac{N}{(W/d)} \quad (13)$$

W denotes the breadth of the copper coil. The diameter of the copper coil encircling the core is a crucial factor.

Table 12 demonstrates the relationship between wire diameter and resistance across different coil turns.

Table 12. Relationship between wire diameter and resistance across different coil turns R=Resistance of the coil

AWG	Wire diameter	R(Ω) N1=1000 turns	R(Ω) N2=2000 turns	R(Ω) N3=3000 turns	R(Ω) N4=4000 turns	R(Ω) N5=5000 turns
28	0.32	15	31	45	64	81
29	0.286	19	38	47.1	79	99
30	0.255	24	48	49.5	97	124
31	0.227	30	60	53	122	154
32	0.202	37	75	53.8	153	192
33	0.18	47	94	56.2	191	241

Table 12 demonstrates that a wire with a larger diameter exhibits reduced resistance; yet it occupies a greater area on the core, thereby decreasing the number of turns. The number of turns is proportional to the output voltage. Figure 9 illustrates the relationship between the number of turns and wire diameter. As the wire diameter grows, the number of twists decreases. This is due to its larger area on the core.

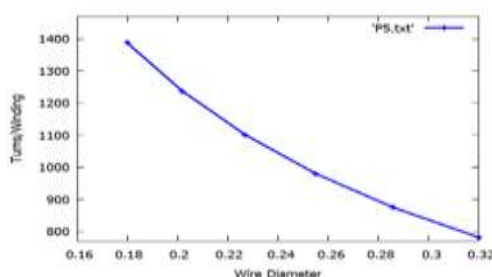


Figure 9. Number of turns/winding as the function of wire diameter.

The relationship between output power and AWG is seen in Table 13. The standard measurement for electrical cable diameter is the American Wire Gauge (AWG). A greater value in the American Wire Gauge indicates a thinner wire. The output power increases as the American Wire Gauge (AWG) increases. This is because a smaller diameter indicates higher number of twists because the wire with a smaller diameter takes up less space. Induced voltage increase as the number of turns increases.

Table 13. Relationship between wire diameter and output power

AWG	Wire diameter	N1=1000 turns	N2=2000 turns	N3=3000 turns	N4=4000 turns	N5=5000 turns
28	0.32	1.03mW	1.38mW	2.98mW	3.91mW	4.81mW
29	0.286	0.8mW	1.11mW	2.41mW	3.17mW	3.92mW
30	0.255	0.66mW	0.89W	1.93mW	2.56mW	3.14mw
31	0.227	0.52mW	0.7mW	1.54mW	2.03mW	2.51mW
32	0.202	0.41mW	0.56mW	1.22mW	1.62mW	2.01mW
33	0.18	0.33mW	0.45mW	0.98mW	1.299mW	1.60mW

3 RESULTS AND DISCUSSION

The proposed method improves the arrangement of the electromagnetic core to harness magnetic fields in power facilities. The dumbbell core is easy and rapid to construct. The essential structure promotes a rise in electromagnetic flux in the core, hence improving power extraction. Prior studies indicated the presence of a helical core. The helical core features an intricate design and is expensive to fabricate. Furthermore, fabricating a helical core as a singular unit is a demanding task. Three separate elements are generated and then combined, leading to an air void in the system. A ferrite core with different dimensions is modeled in a uniform electromagnetic field of $9 \mu\text{T}$. Uniform electromagnetic fields are generated by a Helmholtz coil. The boundary status is designated as open.

The Helmholtz coil is depicted in Figure 10 [26].

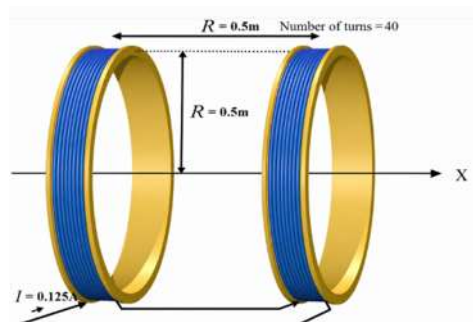


Figure 10. Helmholtz coil

R signifies the radius of the Helmholtz coil, expressed in meters. A Helmholtz coil consists of two identical magnetic coils separated by a distance R , equal to the coil's radius. The electromagnetic flux density generated by the Helmholtz coil is obtained from (15) [26].

Where μ_0 denotes the permeability of free space, N represents the number of turns coiled on the Helmholtz coil, and I signifies the current in amperes. The radius of each coil in this experiment is 0.5 meters, and the number of turns utilized is 40. The current flowing through each coil is 125 mA. The separation between the two coils is 0.5 meters. The generated electromagnetic flux density is $9 \mu\text{T}$

Figure 11 depicts the power throughout the load as a function of the number of turns for a dumbbell-shaped core.

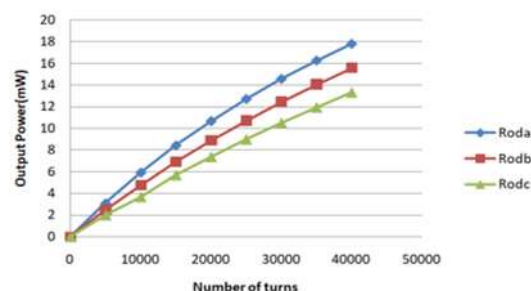


Figure 11. Output power as function of number of turns in dumbbell core.

$\{\text{Rod}(a), D_{in}=2\text{cm}\}, \{\text{Rod}(b), D_{in}=3\text{cm}\}, \{\text{Rod}(c), D_{in}=3\text{cm}\}, D_{out}=11\text{cm}, W=2.8\text{cm}$ is kept constant

Figure 11 illustrates that the output from the dumbbell core, the magnetic plate enhances electromagnetic flux coupling, hence increasing the flux density within the core and subsequently augmenting the output power. The suggested dumbbell core is engineered and modeled via CST Studio. A dumbbell core with an inner diameter of 2.2 cm, a length of 25 cm, an outer diameter of 11 cm, and a breadth of 2.8 cm has been built and simulated in an electromagnetic flux density of $9 \mu\text{T}$. The wire has a diameter of 0.255 mm and a resistance of $0.352 \Omega/\text{m}$. The output power is graphed for varying numbers of turns.

Table 14. Simulated output for different number of turns

N	Open circuit voltage	Power Output
200	49mV	0.12mW
2000	499mV	1.25mW
20000	4.99V	10mW
40000	9.98V	17.63mW

Increasing the number of turns increases output power. The proposed core has a length of 25 cm, an inner diameter of 2.2 cm, a magnetic plate diameter of 11 cm, and a breadth of 2.8 cm. Positioning the harvester near areas with high electromagnetic flux density allows for greater power extraction. Table 15 shows a comparison of several previous designs.

Table 15. Comparison with previous design

Parameters	Solenoid [3]	Bowtie [16]	Helical [17]	Dumbbell core
Flux density(μ T _{rms})	18	7	7	9
Length(cm)	50	15	15	25
Number of turns	40,000	40,000	400	2,000
wire diameter(mm)	-	0.14	0.4	0.255
Output power (mW)	0.3	0.36	0.6	1.25
Volume(cm ³)	981	188	292	627
Power density (μ W/cm ³)	1.86	0.85	2.10	1.99

Nina M. Roscoe et al. [3] developed an optimal iron cast cylindrical core that generates a power output of 0.3 mW in an 18 μ T_{rms} electromagnetic field density. The core measures 50 cm in length and 5 cm in diameter, exhibiting a cylindrical form. The proposed core [3] experiences Eddy current losses due to its iron composition and elevated aspect ratio. Sheng Yuan et al. [16] propose a bow tie ferrite core with an aspect ratio of 7.5 cm. The harvester supplies 0.36W to the load when positioned at 7 μ T_{rms}. Sheng Yuan et al. [17] suggest a helical core composed of ferrite material. The core measures 15 cm in length and has a diameter of 6 cm. The provided power is 0.6 mW in 7 μ T_{rms} flow. Constructing a helical core as a single entity is a labor-intensive endeavor, as it has three components that are then assembled. This creates an air gap within the system. The helical core possesses a complex structure and is costly to construct. The core presented in this research study is both efficient and straightforward to create.

The core design facilitates an increase in the electromagnetic flux within the core, hence capturing additional power. The study conducted here aims to harness the electromagnetic field within the electrical grid. Additional natural and residual energy may be evaluated, and hybrid harvesting techniques might be investigated.

4. CONCLUSION

The paper examines a dumbbell-shaped core designed to capture the electromagnetic field at electrical substations. The core suggested in this article is not affixed to the power line, allowing it to be positioned near high-voltage equipment. The magnetic plate is affixed to the cylindrical rod, enhancing flux coupling and hence increasing power generation. The basic design is straightforward and effective in comparison to the prior design. The results indicate that the output power of the dumbbell core with 40000 turns is 17.63mW, sufficient to power any low-power sensors. The output power can be augmented by increasing the number of revolutions on the core.

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AUTHOR CONTRIBUTIONS

Pavana H: Conceptualization, Investigation, Methodology, Laboratory Analysis, Data Curation

Sandhya B S Formal Analysis, Writing—Review & Editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Ethical approval was not required for this study.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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