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Enhancing efficiency of magnetic energy by implementing square-shaped materials adjacent to induction machine windings

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Abstract

This study provides a worthwhile method for increasing the magnetic field energy and induction machine (IM) effectiveness. The coupling between the transmitter and receiver windings in the IM system can be improved by creating materials with specific electromagnetic properties. This added material has altered the magnetic flow as well as the energy of the magnetic field. Eventually, it is possible to calculate the efficiency of the magnetic field, or the ratio of primary to secondary magnetic energy. With the use of two-dimensional finite element analysis, numerical results on five cases with various configurations of a magnetic substance have been produced. This material, which varies in length or breadth, is positioned close to the windings of the transmitter, receiver, or both. Case 3, in which the transmitter generates a magnetic field on the receiver side with a minimum energy of 0.05 J and a maximum energy of 0.015 J, is the ideal material configuration for DC current. Currently, the system efficiency is 0.29 on average. A 1 kHz transmitter's energy is constant under all conditions, but its counterpart's energy fluctuates significantly, with case 5 receiving the most energy. Therefore, case 5 turns into the optimal structural arrangement. It can be inferred that case 5 similarly dominates the other with an efficiency of 0.0026, which is much greater than that of 1 kHz efficiency, while the windings are operating at 1 MHz. This leads to stronger magnetic field coupling and increased power transfer effectiveness.

Keywords: energy efficiency; inductive coupling; magnetic flux density; non-linear magnetic field; solenoid winding.

I. Introduction

As workhorses for transforming electrical energy into mechanical effort, induction machines (IM) are employed elements in many industries. The strength and management of the magnetic field within these machines' windings have a significant impact on their effectiveness and performance. A thorough knowledge of the underlying theories and different methods is necessary to increase the magnetic energy in induction machine windings. This backdrop examines crucial ideas and approaches for achieving this objective [1].

In induction machines, the stator windings provide the dual functions of field and armature windings. Synchronous speed is the set speed at which flux is created in the air gap when stator windings are coupled to an AC supply. Both the rotor and stator windings experience voltage induction as a result of this rotating flux [2]. Torque is produced when current enters the rotor winding and interacts

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with the rotating flux when the rotor circuit is closed [3]. The synchronous speed and the rotor's steady-state speed are quite near. The rotor winding may resemble the stator winding or it may resemble a cage-type winding. The latter is created by inserting copper or aluminum bars into the rotor slots and using rings to shorten the ends of the bars.

Selecting the right core material, winding design, insulation, and cutting-edge control methods are all part of the interdisciplinary effort to increase the magnetic energy in induction machine windings. In order to satisfy the rising expectations for energy efficiency and sustainability in contemporary industry, improved magnetic energy is important [4][5][6].

Altering the rotor slot profile minimizes windage losses caused by drag forces in induction machines. computational fluid dynamics (CFD) optimizes airflow dynamics to reduce these losses [7]. Notably, while CFD is used, it doesn't involve finite element analysis (FEA) for estimating magnetic energy. The focus is on improving efficiency by adjusting the rotor slot design. CFD enables detailed airflow analysis, aiming to cut drag-related losses, but FEA isn't applied to evaluate magnetic energy in this context.

Alternating current (AC) passing through the machine's windings produces them. Rotor conductors experience voltages as a result of magnetic fields, and this mechanical torque is what drives the machine [8][9][10]. Magnetic energy is significantly influenced by the magnetic core material used in the stator and rotor. Magnetic flux is frequently concentrated using high-permeability materials like steel or iron laminations [11][12]. Unfortunately, magnetic energy coming from the transmitter is still not concentrated on the receiver winding.

Optimizing magnetic energy in induction machines relies heavily on the winding design, with strategies like scattered windings and varied coil layers enhancing magnetic field dispersion. Slot and pole design play crucial roles in maximizing magnetic energy [13][14]. However, induction machines encounter limitations such as constrained torque at low speeds and lower power factors, leading to inefficiencies and higher energy consumption. Addressing these issues necessitates adjustments in torque and power factor. A holistic approach to improve magnetic energy involves core material selection, winding design, insulation, and advanced control techniques, significantly enhancing effectiveness and performance in various industrial applications [15][16][17][18]. Despite limitations in starting torque for induction machines remain popular due to their reliability, simplicity, and affordability. Special designs or additional equipment may be required to overcome these limitations. Overall, improving magnetic energy is pivotal to meet rising expectations for energy efficiency and sustainability in modern industries.

Waveguides are structures that are used in the resonant waveguide technique to steer electromagnetic waves. By accurately structuring the waveguide and adjusting material properties, this technology enables higher-efficiency power transmission over greater distances than prior systems. This creative research offers a method to increase the energy of the magnetic field and induction devices' overall efficiency. The coupling between the system's transmitter and receiver windings can be improved by using specially made materials with certain electromagnetic characteristics. It is feasible to "trap" or "guide" the magnetic field by utilizing these materials to create magnetic resonators.

II. Materials and Methods

The efficiency of IM systems can be considerably impacted by the transmitter and receiver winding designs [19]. The magnetic coupling and energy transfer efficiency are influenced by elements including winding size, shape, number of turns, and winding material. The total efficiency may be increased by optimizing the winding design to the unique demands of the IM system, including the necessary power levels, distance, and frequency [20].

The efficiency of IM can be increased by making sure that the resonance frequency is suitably matched to that of the transmitter and receiver windings [21]. By modifying the load's impedance to match that of the windings, load matching techniques can reduce energy reflections and system losses. It is possible to use sophisticated electronics, such as control algorithms and power electronics [22][23][24].

A. Research objectives

Researchers and engineers are continually coming up with new methods to increase the strength and effectiveness of IM as technology develops [25]. Resonant waveguide is a method for induction machines that makes use of waveguides, which are structures that can direct electromagnetic waves. In comparison to conventional IM techniques, it is feasible to achieve high-efficiency power transfer over greater distances by carefully engineering the waveguide's shape and material characteristics.

This study offers a special technique for enhancing magnetic field energy as well as the energy efficiency of IM. It is possible to create materials with certain electromagnetic characteristics that will enhance the coupling between the transmitter and receiver windings in the IM system. For instance, magnetic resonators that can "trap" or "guide" the magnetic field can be made using these materials. Stronger magnetic field coupling and improved power transfer efficiency are the result of this.

B. Problem limitations

A linear connection between the applied magnetic field and the resultant magnetization does not apply to the characteristics of nonlinear magnetic materials. As opposed to being proportional to the applied field, their magnetization response may instead display complicated phenomena including hysteresis, saturation, and nonlinear susceptibility.

Strong magnetism and hysteresis behaviour are characteristics of ferromagnetic materials including iron, nickel, and cobalt. Their magnetic behaviour exhibits saturation effects and hysteresis loops, and their magnetization response is very nonlinear [26].

With the benefits of simplicity, safety, design freedom, and improved user experiences, these considerations have helped wireless power transmission gain appeal across a range of applications [27][28]. IM still has issues with efficiency, standardization, and cost, and its uptake will vary based on the particular application or sector.

Magnetic ions having opposing magnetic moments make up ferrimagnetic materials, such as ferrites as shown in Figure 1. Due to the intricate magnetic interactions between the ions, they display nonlinear magnetization behaviour that leads to hysteresis and nonlinear susceptibility.

Colour scales are frequently used in finite element analysis (FEA) to display and depict simulation results, such as stress, strain, temperature, or other physical parameters, on a colour map. The amount or intensity of the simulated values at various places or components of the FEA model is shown using colour scales. A rainbow colour scale is a collection of hues that extend from red to violet and cover the whole visible spectrum. Although this kind of colour scale is frequently employed for its aesthetic appeal, it has some drawbacks since it might give the wrong impression of magnitude. The perception and comprehension of simulation results can be significantly impacted by the choice of colour scale used in FEA.

C. Biot-Savart's law

Based on the tests conducted in about two centuries ago by the French scientists Jean-Baptiste Biot and Félix Savart, the Biot-Savart law is a basic quantitative connection between an electric current $\vec{I}$ and the magnetic field $\vec{B}$ it generates.

Magnetic field lines $\vec{B}$ that form loops around the current are produced by a current in a loop. The Biot-Savart law expresses the partial $d\vec{B}$ field contribution of the total $\vec{B}$ field from a tiny conductor segment. The partial $d\vec{B}$ field when the conductor segment of length and orientation dl conducts a current of direction I, is given in equation (1).

$$d\vec{B} = \mu_0 \vec{I} dl \times \hat{a}_R / 4\pi R^2 \tag{1}$$

where μ_0 represents the permeability of empty space in this equation and has a value of $4\pi \times 10^{-7}$ newtons per square ampere, while dl is a vector element of length and it has a component $\hat{a}_R$ which is a base vector along x-axis. Then, R is the distance between a tiny conductor segment and an observation point.

Considering the vector character of the field, the magnetic field of a current in a loop or winding is created by adding up the individual partial contributions of each circuit segment.

$$\vec{B} = \mu_0 \mathrm{I} \hat{a}_\varphi / 2\pi r^2 \tag{2}$$

Equation (2) is the formula for the magnetic field at a distance r from a long, straight wire carrying current, where r is the distance from the wire, and $\hat{a}_\varphi$ is a unit vector pointing in the direction of the wire. In other words, the perpendicular distance r from the wire to the provided location, r, and the value of the magnetic field $\vec{B}$ at a nearby point, are exactly proportional to each other.

D. Magnetic field energy

In delicate situations, shielding and electromagnetic interference (EMI) mitigation techniques could be required. These phenomena lead researchers to study and improve the magnetic field distribution within the machine FEA techniques. A capacitor stores its energy in the electric field that exists between its plates. An inductor also has the capacity to store energy, but it does so in the form of its magnetic field. The magnetic energy density u_{m} can be integrated to find this energy at an excessive volume.

$$u_{\mathrm{m}} = B^2 / 2\mu_0 \tag{3}$$

Equation (3) comes from the long - cylindrical solenoid. It should assume that the magnetic field is

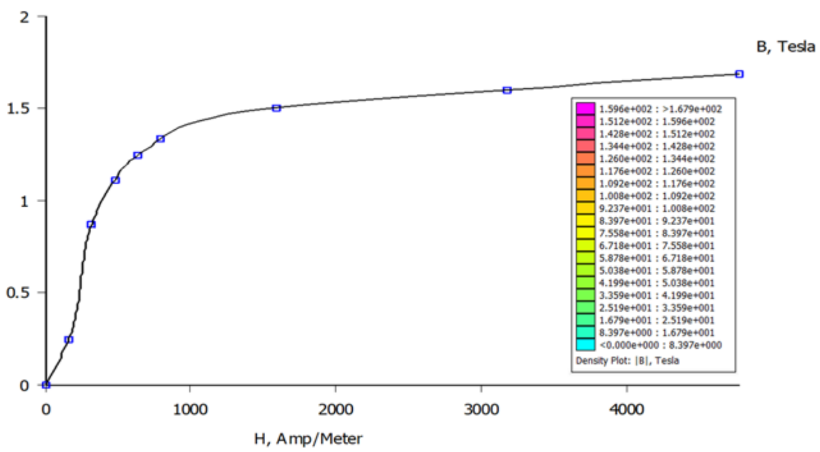

Figure 1. Non-linear magnetic field on the iron core and its colour scale

largely constant and provided by $B = \mu_0 \mathrm{nI}$ everywhere inside the solenoid by again utilizing the infinite solenoid approximation. As a result, the magnetic energy density times volume is identical to the amount of energy stored in a solenoid, which is expressed as equation (4).

$$U = u_{\mathrm{m}}\mathrm{V} = (\mu_0 nI)^2 (Al)/2\mu_0 = \frac{1}{2}(\mu_0 n^2 Al) I^2 \quad (4)$$

If the number of turns per unit length of the solenoid $\mathrm{n} = \mathrm{N/L}$, the self-inductance L of a long solenoid, in a volume of the solenoid $V = Al$, can be addressed as equation (5).

$$L = \mu_0 \mathrm{n}^2 Al = \mu_0 \mathrm{n}^2 V \quad (5)$$

Substituting equation (5) in equation (4), the stored energy becomes equation (6).

$$U = L\mathrm{I}^2/2 \quad (6)$$

III. Results and Discussions

Let us consider a couple of windings that have wire diameter = 0.5 mm, number of turns = 100, and distance = 2.5 mm. The examination consists of five different cases which vary in size and location of the added material.

A. Case 1: Normal winding

The simplicity of locating and aligning the transmitter and reception windings can also be impacted by the size of the transmitter winding. It is simpler to obtain correct alignment and placement for effective power transmission with bigger transmitter windings because they give the receiver winding a broader target area to align with. A couple of winding is tested by an electric power supply with zero frequency, 1 kHz, and 1 MHz respectively since they show significant features of magnetic energy instead of 10 or 100 multipliers of frequency.

The efficiency of the induction machine system can be impacted by the winding's size. It can be seen from Figure 2 that larger windings in the transmitter enable more power input and a stronger magnetic field, which enhances the effectiveness of wireless power transmission to the reception winding. This is so that the coupling coefficient between the transmitter and receiver windings can be increased. Bigger windings often have more turns and a wider surface area.

Table 1.
Numerical results on Case 1

Frequency (Hz)	Magnetic Field Energy (J)		Efficiency (%)
	Primary Winding	Secondary Winding	
0	0.048345	0.013166	27.2338023
1 k	2714.910	0.136464	0.0050265
1 M	6.903600	0.006674	0.0966743

Table 1 shows that DC current produces the lowest magnetic field energy but has good efficiency which is 27 %. Instead of generating the highest energy on both transmitter and receiver at 1 kHz, IM that works on 1 MHz yields moderate magnetic field energy as well as better efficiency than that at 1 kHz.

B. Case 2: Placing a 0.5 mm x 3.5 mm non-linear magnetic material behind the receiver

The selection of the magnetic material, its characteristics, and its right integration into the IM system design are significant aspects in attaining increased efficiency, it is depicted in Figure 3. Higher efficiency and improved performance in induction machine applications can be achieved by carefully taking into account the unique needs of the IM system and selecting the proper magnetic materials. The result in Table 2 is a little different from the result in Case 1 in that there are a few reductions on both, transmitter and receiver, magnetic energy eventually the efficiency decreases slightly. This happened because the material is thick and should be made thinner.

C. Case 3: Placing a 0.25 mm x 2.5 mm non-linear magnetic material behind the receiver

High permeability magnetic material, as shown in Figure 4, can aid in concentrating and guiding the magnetic field lines through the receiver winding, minimizing losses brought on by magnetic field leakage and enhancing the amount of power delivered to the winding.

Table 3 asserts that magnetic energy increases whether in the transmitter or receiver. This makes the ratio between energy in the receiver and transmitter better than that in either Cases 1 or 2. The added material is shorter and thinner than in Case 2. Additionally, magnetic materials can increase the efficiency of energy transfer by enhancing the

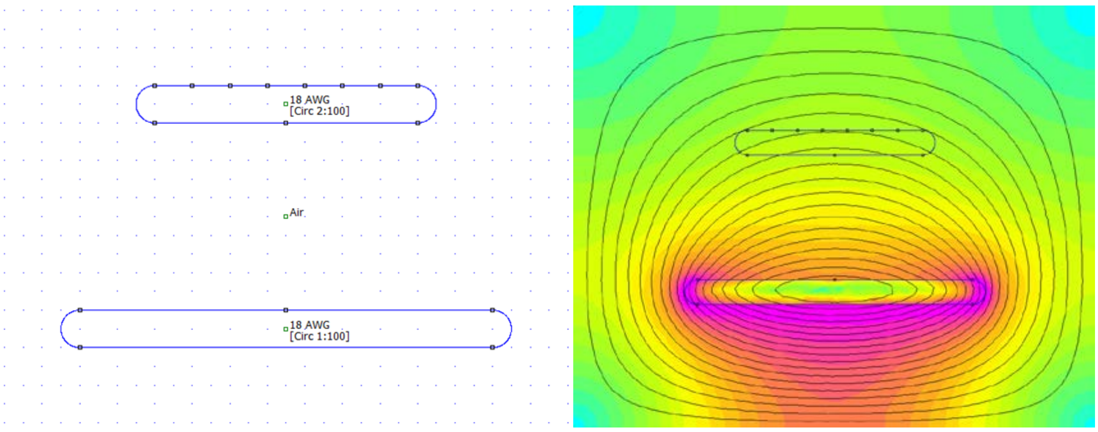

Figure 2. The two-dimensional FEA result of Case 1

magnetic field's penetration into the receiving winding.

D. Case 4: Placing a 0.25 mm x 3.5 mm non-linear magnetic material behind the receiver

The magnetic losses in IM windings can be decreased with the use of magnetic materials, drawn in Figure 5 Eddy current losses in conducting materials and hysteresis losses in magnetic materials are only two examples of the causes of these losses. By containing and directing the magnetic flux along a specified route, magnetic materials with high magnetic permeability, such as ferrite cores, can assist in minimizing these losses and increase system effectiveness [29]. Table 4 are not better than the results in Table 1, Table 2, and Table 3 since it has a little reduction in its efficiency. Because magnetic materials assist in focusing the magnetic field and make windings smaller, they can also enable the creation of winding designs that are more compact. This enables smaller and more practical IM solutions, which can be especially helpful in situations where space is at a premium, as in portable electronic devices or implanted medical equipment.

E. Case 5: Placing the 0.25 mm x 3.5 mm material behind the receiver and the 0.25 mm x 5.5 mm material behind the transmitter

Figure 6 implies that a linear connection between the applied magnetic field and the resultant magnetization does not apply to the characteristics of nonlinear magnetic materials. As opposed to being proportional to the applied field, their magnetization response can instead display complicated phenomena including hysteresis, saturation, and nonlinear susceptibility. The size of the transmitter

Tabel 2.
Numerical results on Case 2

Frequency (Hz)	Magnetic Field Energy (J)		Efficiency (%)
	Primary Winding	Secondary Winding	
0	0.05300	0.013036	24.5950199
1 k	2714.92	0.136398	0.0050240
1 M	6.90596	0.006606	0.0956627

Table 3.
Numerical results on Case 3

Frequency (Hz)	Magnetic Field Energy (J)		Efficiency (%)
	Primary Winding	Secondary Winding	
0	0.05096	0.015002	29.4375166
1 k	2714.92	0.137407	0.0050612
1 M	6.90493	0.007617	0.1103054

Table 4.
Numerical results on Case 4

Frequency (Hz)	Magnetic Field Energy (J)		Efficiency (%)
	Primary Winding	Secondary Winding	
0	0.05255	0.012790	24.3401659
1 k	2714.92	0.136286	0.0050199
1 M	6.90574	0.006494	0.0940393

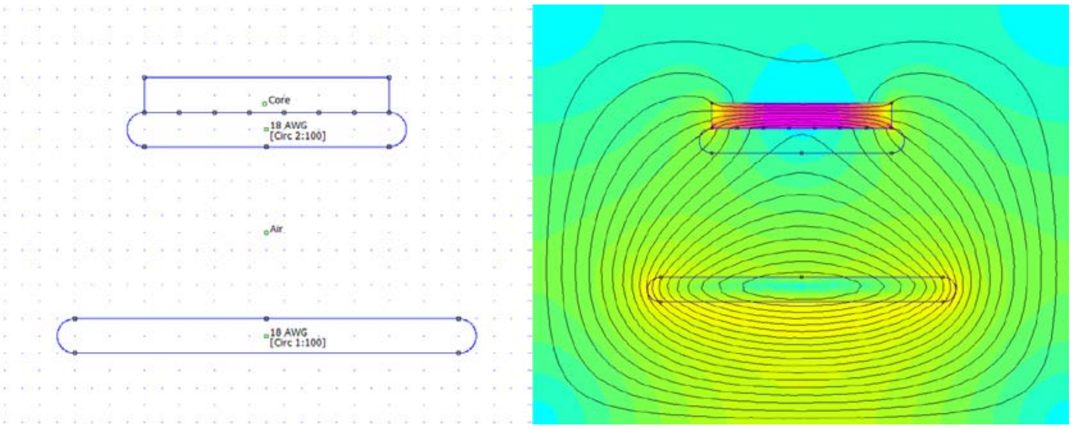

Figure 3. The FEA simulation in Case 2

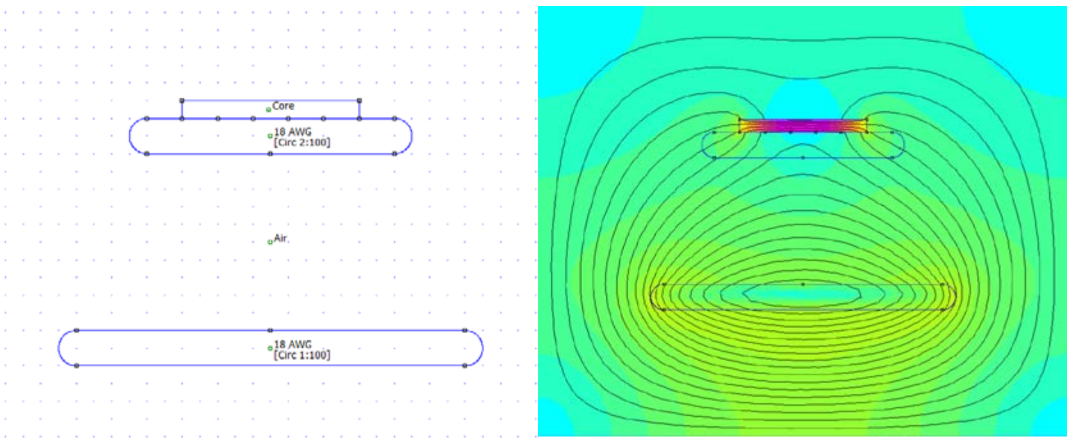

Figure 4. The magnetic distribution of Case 3 with FEA

winding might also be influenced by the application's power needs. Larger transmitter windings may be necessary for applications that call for higher power levels in order to accommodate the higher power input and output.

When the materials are given behind the transmitter and receiver as seen in Table 5, not only do the energies increase significantly but the efficiency is the best among others, except for the DC current case. It can be noticed that the electromagnetic field can be guided or trapped between the distance with special arrangements of materials.

F. Results comparison

The choice of the magnetic material, its properties, and its proper integration into the IM winding system are important factors in achieving higher efficiency. For DC current in Table 6, the best arrangement of material is case 3, because the transmitter generates the lowest magnetic field energy which is 0.05 Joules while the field energy on the receiver side is the biggest around 0.015 Joules. This makes the system efficiency highest at about 0.29.

Table 7 notes that the 1 kHz transmitter has the same energy in all cases, while on the counterpart, it has slight variations of energy with Case 5 receiving the highest energy. This makes Case 5 become the best structure arrangement. Whereas Table 8 operated in 1 MHz, it can be inferred that case 5 also dominates the other with an efficiency of 0.0026 which is much better than the efficiency stated in Table 7.

Steering the produced magnetic fields to cause currents in the rotor, which produces its magnetic field, is the process of capturing and directing

Table 5.
Numerical results on Case 5

Frequency (Hz)	Magnetic Field Energy (Joules)		Efficiency (%)
	Primary Winding	Secondary Winding	
0	0.21967	0.035980	16.3792593
1 k	2715.00	0.148296	0.0054621
1 M	6.99179	0.018509	0.2647248

Table 6.
Comparison of all cases in DC current3

Case	Magnetic Field Energy (Joules)		Efficiency (%)
	Primary Winding	Secondary Winding	
1	0.0483447	0.0131661	27.2338023
2	0.0530026	0.0130360	24.5950199
3	0.0509615	0.0150018	29.4375166
4	0.0525473	0.0127901	24.3401659
5	0.2196650	0.0359795	16.3792593

[a] f = 0 Hz, I = 1 A, Windings = 100, d = 2.5 mm

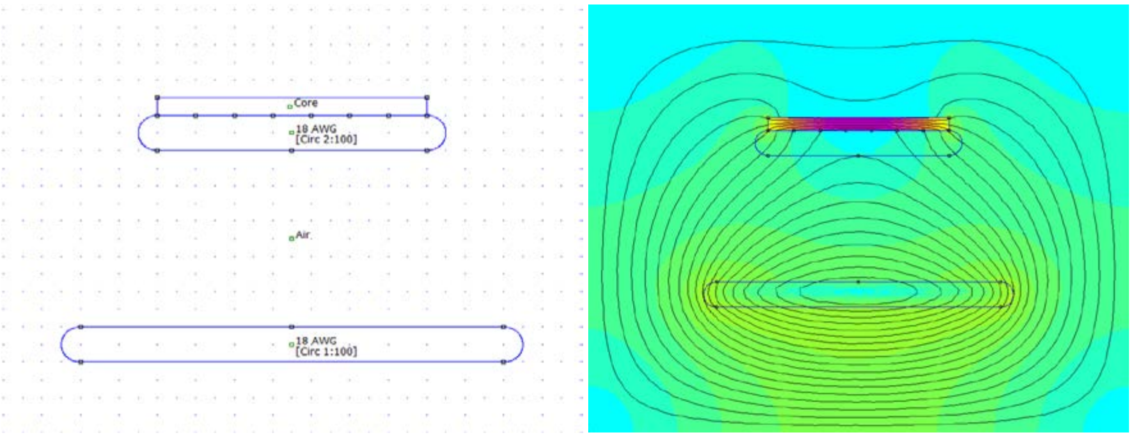

Figure 5. Case 4's FEA simulation result

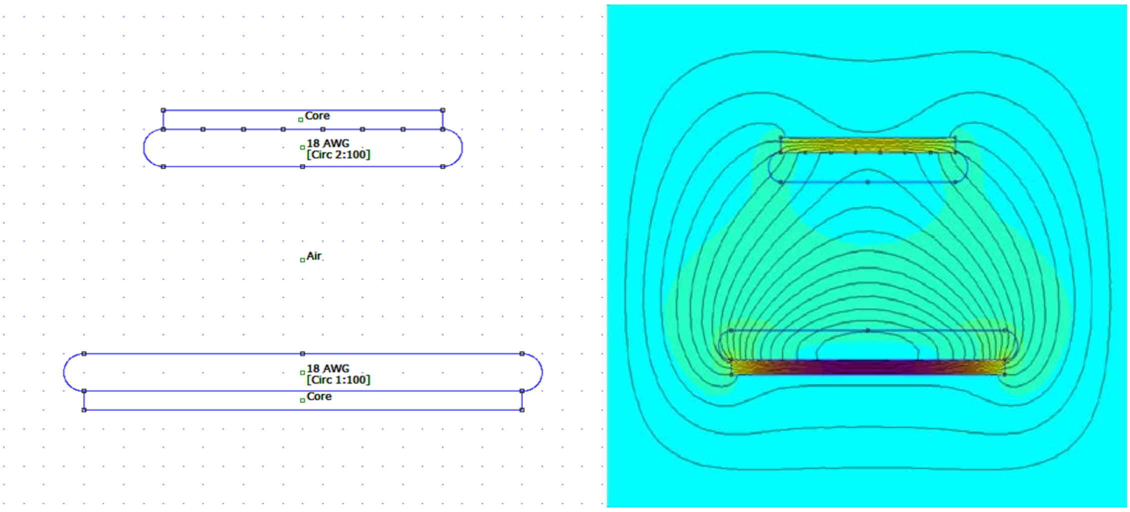

Figure 6. The Case 5's magnetic distribution with FEA simulation

Table 7.
Comparison of all cases in 1 kHz AC current

Case	Magnetic Field Energy (Joules)		Efficiency (%)
	Primary Winding	Secondary Winding	
1	2714.91	0.136464	0.0050265
2	2714.92	0.136398	0.0050240
3	2714.92	0.137407	0.0050612
4	2714.92	0.136286	0.0050199
5	2715.00	0.148296	0.0054621

b. f = 1 kHz, I = 1 A, Windings = 100, d = 2.5 mm

Table 8.
Comparison of all cases in 1 MHz AC current

Case	Magnetic Field Energy (Joules)		Efficiency (%)
	Primary Winding	Secondary Winding	
1	6.90360	0.00667401	0.0966743
2	6.90596	0.00660643	0.0956627
3	6.90493	0.00761651	0.1103054
4	6.90574	0.00649411	0.0940393
5	6.99179	0.01850900	0.2647248

c. f = 1 MHz, I = 1 A, Windings = 100, d = 2.5 mm

magnetic energy within an induction machine. The torque produced by this reaction causes the rotor to rotate. Higher efficiency and improved performance in induction machine applications can be achieved by considering the unique needs of the IM winding system and selecting the proper magnetic materials.

IV. Conclusion

Numerical results on five cases with distinct arrangements of magnetic material have been done with two-dimensional finite element analysis. This material, which is different either in length or width, is placed near the transmitter, receiver, or both windings. Not only magnetic flux but also magnetic field energy has changed because of this additional material. Eventually, the efficiency of the magnetic field, that is the ratio between secondary and primary, can be estimated. The optimal material arrangement for DC current is case 3, where the transmitter produces a magnetic field with a minimum energy of 0.05 Joules and a maximum energy of 0.015 Joules on the receiver side. The system efficiency now stands at 0.29 on average. The energy of a 1 kHz transmitter is constant in all circumstances, but the energy of its counterpart varies slightly, with case 5 receiving the maximum energy. As a result, case 5 becomes the ideal structural configuration. While the windings operate at 1 MHz, case 5 likewise dominates the other with an efficiency of 0.0026, which is significantly higher than that of 1 kHz efficiency. Improving the magnetic energy of induction devices has an essential impact on how well IMs work. The electromagnetic induction concept underpins the operation of induction machinery, including induction motors. More magnetic energy has the potential to improve motor performance. An increased magnetic field strength causes the induction motor to run more efficiently overall by reducing energy loss and increasing output power. Another benefit is increasing magnetic energy can result in an increase in the induction machine's torque and power output. The motor can withstand heavier loads or run more effectively at the same load when there is a larger magnetic field around it. Better starting torque with more magnetic energy is especially helpful in implications when more torque is needed to start the machinery or in circumstances where the motor must start under load. Increased magnetic energy influences the induction machine to operate more steadily and effectively. This can lead to higher performance overall, less vibrations, and smoother operation–especially with changing load situations. Raising the magnetic energy yields the machine running cooler and losing less heat. A more effective magnetic field will result in fewer resistive losses and heat generation in the motor.

Declarations

Author contribution

As this paper's primary contributors, M.A. Habibi, S.N. Mustika, Aripriharta, and C.A.A. Izhar each contributed equally. The final manuscript was reviewed and approved by all authors.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

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