Chapter 9
Finite Element Analysis on Enhancement of Contactless Power Transfer by Using Metamaterials—A Review

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9.1 Introduction

Wireless power transfer can be defined as the transmission of energy from one place to another without using wires. It started by Nikola Tesla in the late 1890s. Wireless technology has provided us the ability to have long-range communications that would not normally happen if wires were needed. The most common wireless power transfer technologies are electromagnetic induction and microwave power transfer (Rahman et al. 2014).

There are different types of the wireless power transfer systems. It can be categorized into the capacitive coupling and inductive coupling (Asheer et al. 2013). Capacitive coupling is usually used in the lower range of power transfer whereas inductive coupling is used in high power transmission. Inductive power is used widely compared to capacitive power because it has more advantages than capacitive. Inductive power transfer carries a lower risk of electric shock because there are no exposed conductors (Asheer et al. 2013).

In general, a wireless power system consists of a transmitter connected to a source of power such as a main power line, which converts the power to a time-varying electromagnetic field, and one or more receiver devices that receive the power and convert

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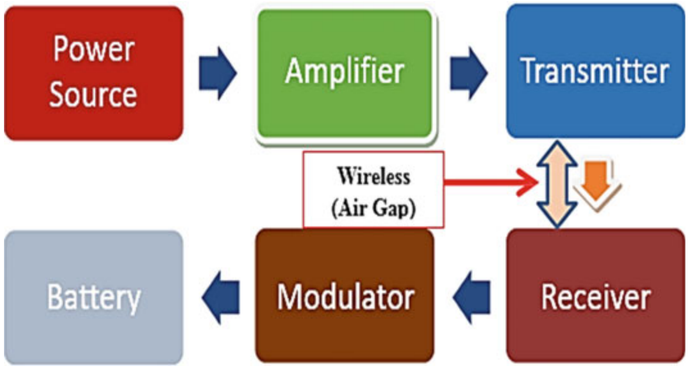


Fig. 9.1 The basic principle of contactless power transfer

it back to DC or AC electric current which is utilized by an electrical load (Shinohara 2014; Sun et al. 2013). Figure 9.1 shows the basic principle of contactless power transfer. This paper will review the finite element analysis method for contactless power transfer systems.

9.2 Finite Element Analysis

Finite element analysis (FEA) is a computer-based method of simulating or analyzing the behavior of engineering structures and components under a variety of conditions. It is the latest engineering tool that has been used to replace the old way which is by experimenting. FEA is widely accepted in almost all engineering disciplines. The process of analysis involves subdividing the complex structure or component into smaller more manageable (finite) elements. Figure 9.2 shows a simple explanation of how FEA works.

Like any other approximate numerical method, the solution produced by finite element analysis contains a certain amount of error. It is highly dependent on the parameter design in terms of size, type of use, and the similarity of the design with actual hardware. Validation of a FE model is carried out by comparison of the results with measured test data or by values obtained by other independent means such as hand calculations or other FEA programs (Nuttall 2011).

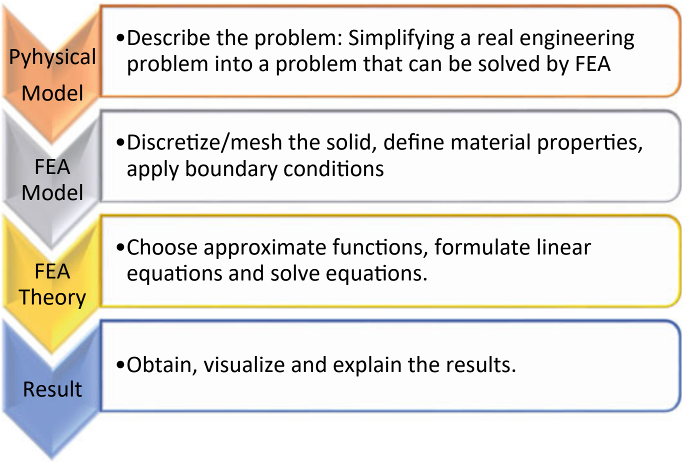


Fig. 9.2 How does FEA work (Bong 2004)

9.3 Finite Element Analysis of Enhancement Contactless Power System by Using Metamaterials

9.3.1 What is a Metamaterial

One of the earliest demonstrations of wireless energy transfer was the use of microwave radiation to power a small helicopter in 1964 (Brown 1984). Until now, there is still undergoing an evolution and many efforts have been made to improve this technology as well as its efficiency. There is much research on how to increase the efficiency of WPT.

One way to improve the efficiency of the WPT is by using metamaterials (Nishimura et al. 2014). In Nishimura et al. (2014), Yu (2014), Greegor et al. (2008), Wang et al. (2011, 2010), Chabalko et al. (2015), Wang and Teo (2012), there has been discussed the use of metamaterials in contactless power transfer. Due to their unique electromagnetic properties such as negative permeability, metamaterials can be used to enhance the evanescent waves of the near-field (Yu 2014). Metamaterials are engineered structures usually much smaller than the working wavelength whose electromagnetic properties are obtained from their structure rather than their chemical composition (Pendry et al. 2006).

Metamaterials are a new class of artificial material composed of man-made structures. Figure 9.3 shows how the setup of the circuit is done using metamaterials. The blocks of the metamaterial are much smaller in size than their working wavelength. Like other electromagnetic materials, the electromagnetic properties of metamaterials are described by macroscopic parameters such as permittivity ε and permeability μ (Yu 2014). When evanescent waves propagate in the air or other dielectric media, they can be enhanced (Greegor et al. 2008).

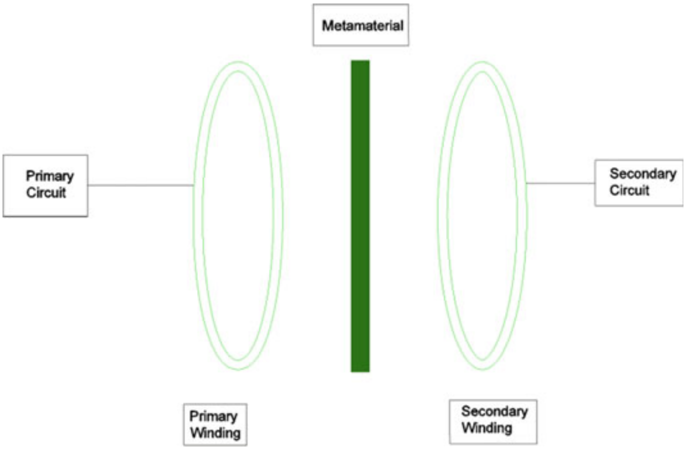


Fig. 9.3 Circuit setup using metamaterial

9.3.2 Finite Element Analysis Setup and Result

The metamaterial is placed between the two coils. Metamaterials are supposed to act as a magnetic super lens that concentrates the evanescent magnetic field around the slab enhancing the inductive. The result for secondary voltage with and without metamaterial in Nishimura et al. (2014) showed the difference.

Usually, the electromagnetic induction that was produced by the transmitter coil will spread randomly in the air medium. But using metamaterials can guide or focus the electromagnetic induction to increase the range of interactions between the receiver coil and electromagnetic induction produced by the transmitter coil. The result in Nishimura et al. (2014) shows that at the same transmitter and receiver gap, the efficiency of wireless transfer that uses metamaterials is higher compared to the efficiency of wireless transfer that does not use metamaterials.

It shows that the usage of the metamaterial in a system will improve the magnetic coupling strength. When using a metamaterial, the magnetic flux generated in the primary coil will focus on the secondary coil thus will increase the efficiency of the transfer. In Wang et al. (2011) the researchers have done a simulation on the effect of different distances of metamaterials from the windings. The simulation setup is shown in Fig. 9.4.

The position ‘P’ is shown as the distance between the transmitting coil and the metamaterial slab. The researchers changed the distance of ‘P’ in some different values. Figure 9.7 shows the simulation result of contactless power transfer with metamaterial with a different distance of ‘P’.

There were five different distances of ‘P’ which are 5 cm, 10 cm, 15 cm, center between transmitter and receiver, and finally original which means no metamaterial was used. The result shows that the efficiency is highest when the metamaterial was placed at the center between the primary winding and secondary winding and the

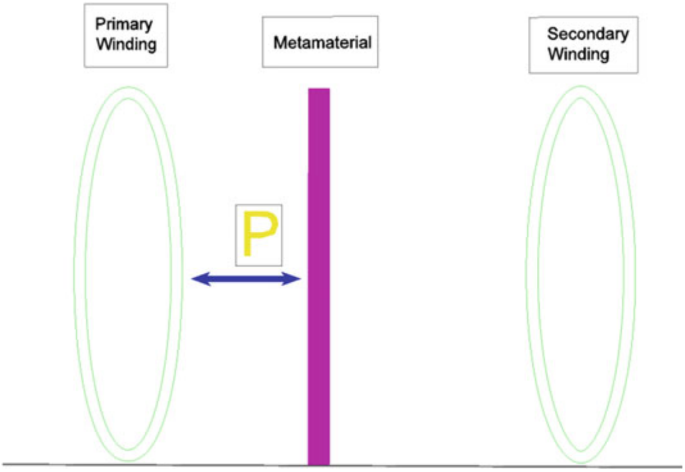


Fig. 9.4 Simulation setup for contactless power transfer with a different distance of metamaterial

second highest is when the distance of metamaterial is 15 cm. The lowest efficiency is when there is no use of metamaterial during the transfer process. This is because the field strength at metamaterial is lowest at the center, so power loss due to the metamaterial is lower compared to other positions, so more power is delivered (Wang et al. 2011). Thus, more magnetic flux was induced to the secondary winding or transmitter coil.

9.4 Finite Element Analysis of Contactless Power Transfer and Its Losses in Air Gaps

9.4.1 Effect on Mutual Inductance and Coupling Coefficient

Some different types of losses occur during the contactless power transfer process that has been discussed in Nguyen et al. (2014), Sibue et al. (2012), Tang and McDannold (2014). One of the main reasons for these losses to occur is because of an air gap that happens during the power transfer process. The air gap in wireless power transfer (WPT) cannot be avoided and will always happen in the WPT system. This is because in the basic concept of WPT, there is no contact between the power transmitter and power receiver during the transmission process. So, this air gap will influence the WPT system.

One of the effects that can be seen or measured is an inductance value or output power. The inductance value usually will influence the value of mutual inductance and coupling coefficient. Mutual inductance is the basic operating principle of the transformer, motors, generators, and any other electrical component that interacts with another magnetic field. Mutual inductance can also be defined as a leakage inductance from a coil that can interfere with the operation of another adjacent component through electromagnetic induction. The mutual inductance (M) between the primary winding and secondary winding produce can be calculated by:

$$M = L_m(N_2/N_1) \tag{9.1}$$

or

$$M = \left(|L_{ser} - L_{par}|\right)/4 \tag{9.2}$$

where L_m is the magnetizing inductance, N_1/N_2 is the turn ratio between the primary and secondary winding, L_{ser} is the inductance in series and L_{par} is the inductance in parallel.

The value of mutual inductance produced depends on the positioning or gap between the two coils or windings. If the distance between two coils is small, so nearly all of the magnetic flux generated by the first coil will interact with the second coil turns inducing a relatively large electromagnetic force (emf) and therefore producing a large mutual inductance value. Otherwise, the amount of magnetic flux interacting between two coils will be weaker if the distance or gap between the coils is large. So it will produce a much smaller induced emf and therefore a much smaller mutual inductance value. The maximum efficiency of wireless power transfer depends on the value of mutual inductance (Nguyen et al. 2014).

Besides that, the coupling coefficient value also will influence the mutual inductance. The coupling coefficient can be derived as:

$$K = \frac{M}{L_1 L_2} \tag{9.3}$$

The coupling coefficient will be maximum when the entire flux in one coil links with the other. The maximum value of k is unity. Thus when k = 1, the coupled coils will be perfectly connected. The mutual inductance between the two coils will be maximum with k = 1. So the formula of mutual inductance with a maximum value of K will become:

$$M = \sqrt{(L_1 L_2)} \tag{9.4}$$

where L_1 is the self-inductance at primary circuit and L_2 is the self-inductance at secondary circuit.

When the distance or gap between the coils is larger, the value of k is very small. So the connection will be called a loosely coupled coil. In Zainol et al. (2016), the researchers have done the finite element analysis on a contactless battery charger. The simulation will be based on the magnetic field distributions of contactless battery chargers with different air gaps. Then the results were focused on the mutual inductance and coupling coefficient effect on the various air gap. Figures 9.5 and 9.6 show the result of mutual inductance and coupling coefficient on the different air gaps by using the finite element analysis solution. The researchers were using the ANSOFT MAXWELL software as a method to get the result. The distance of air gap was tested at four different distances which were 1, 2, 3, and 4 cm. The parameter of the primary and secondary winding for experiment and simulation is the same to verify the data.

It is shown that as the gap becomes larger the mutual inductance and coupling coefficient of wireless power transfer will be small. This is because the existence of a large air gap between the primary coil and the secondary coil will weaker the mutual coupling inductance within the contactless power transfer.

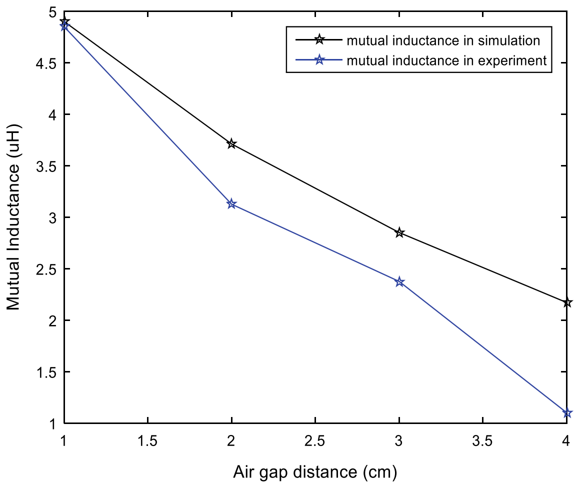


Fig. 9.5 Mutual inductance with different distances (Zainol et al. 2016)

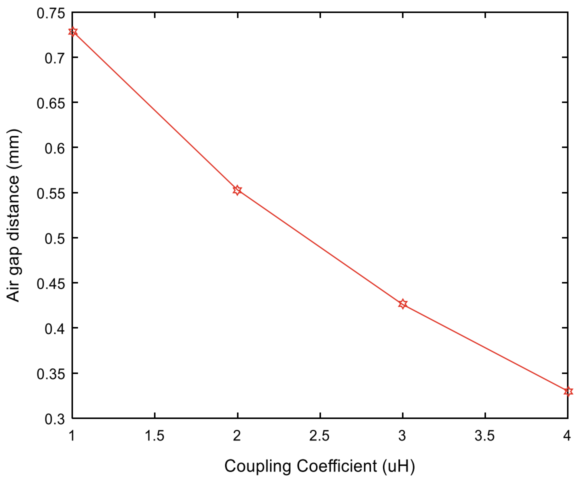


Fig. 9.6 Coupling coefficient with different distances (Zainol et al. 2016)

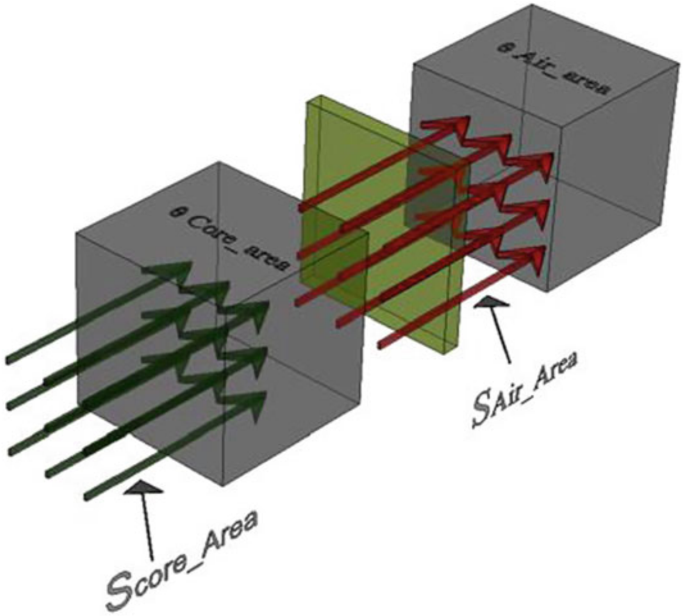


Fig. 9.7 Factor of flux ratio of magnetic core with air-gap

9.4.2 Effect on Magnetic Flux Distribution Ratio

In Jez and Polit (2014) the researchers have done a study about the effect of air gap on the magnetic flux distribution ratio by using the finite element analysis method. Due to the increasing distance of the air gap, the magnetic flux will spread out to the air medium and will cause an effect called the fringing effect. The fringing effect was discussed in Jez and Polit (2014), Nysveen and Hernes (1993), Fletcher et al. (2005). The best design of a contactless power system is when the fringing flux is at minimum and flux lines occupy the same cross-section in the air-gap area as in the magnetic core (Jez and Polit 2014). The situation is shown in Fig. 9.7.

Based on Fig. 9.10, the flux ratio formula can be derived as:

$$\mathrm{F_{FR}} = \frac{\phi air\_area}{\phi core\_area} \tag{9.5}$$

where $\mathrm{F_{FR}}$ is the factor of magnetic fluxes ratio, Φ air_area is the magnetic flux in an air-gap area with a cross-section like in a magnetic core and Φ core_area is themagnetic flux in a core area with a cross-section of a magnetic core.

Then finite element analysis is done by researchers by using the COMSOL software to get the result of magnetic flux ratio with a different air gap. The simulation model is shown in Fig. 9.8.

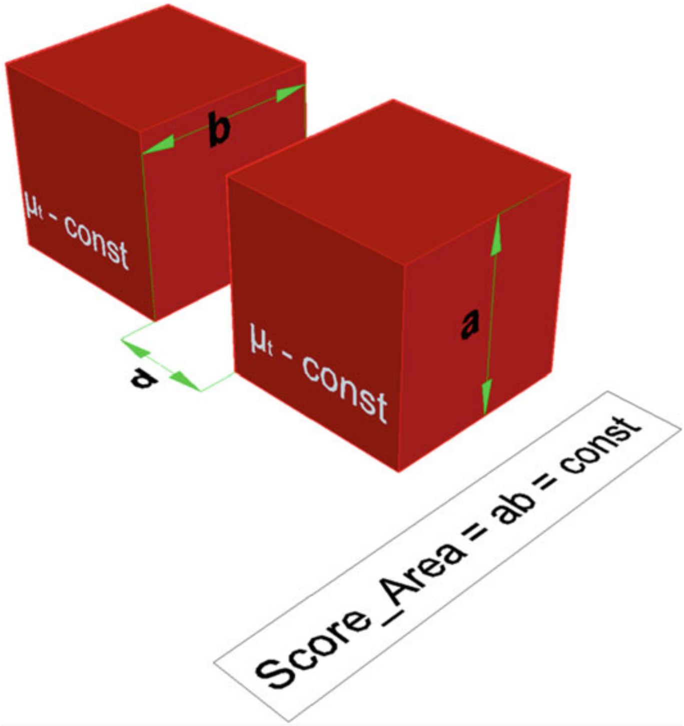


Fig. 9.8 Basic model of simulation analyses

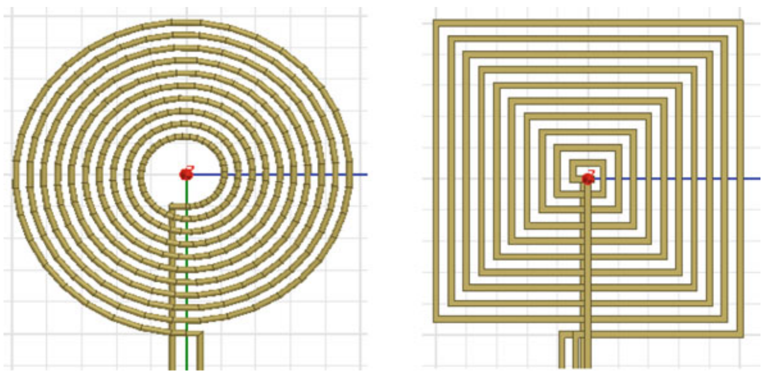
Dimension ratio for ‘a’ and ‘b’ and the distance of air gap is changed. The gap distances (d) was tested on 1, 5, 10, 30, 70 and 90 mm. The result shows that factor of magnetic fluxes ratio is highest when the air gap is nearest which means at 1 mm. Its mean, the fringing effect is minimum when the air gap between the coils is close. But if the distance of gap is constant but only the dimension ratio for ‘a’ and ‘b’ is changed, the magnetic flux ratio is highest when the dimension ratio is nearer to one. Its mean, at dimension ratio 0.8, the factor of magnetic fluxes ratio (F_{FR}) was highest at each gap 1, 5, 10, 70 and 90 mm. That is because flux lines occupy the same cross-section in the air-gap area as in the magnetic core. As a result, the fringing effect will decrease the reluctance of the magnetic path and thus increases inductance of the winding so more magnetic flux will be transferred to the secondary winding.

9.5 Finite Element Analysis of Contactless Power with Different Types of Coils and Shapes

One of the most important things that need to be considered in designing a contactless power transfer system is the type of coil and the shape design of the coil. The effect of different types of coil and parameters of coil design on contactless power transfer systems has been discussed in Horigome et al. (2014), Ongayo and Hanif (2015), Kava et al. (2015), Sampath et al. (2014), Fincan and Üstün (2015). Rectangular coil and circular coil are the two most popular types that are usually used in a contactless power circuit system. The effect of using these two types of coils has been discussed in Ongayo and Hanif (2015) by using the finite element analysis method. Figure 9.9 shows the design of the coil that has been used in the simulation.

The efficiency between these two types of coils can be determined in many ways and one of them is by determining the value of mutual inductance and coupling coefficient for each coil under the same parameter experiment process. Figures 9.10 and 9.11 show the magnetic field density plot in circular coreless coil and rectangular coreless coil. The model design has been simulated using Ansys Maxwell from a 240 V, 20 kHz AC sinusoidal voltage (Ongayo and Hanif 2015).

The magnetic field density plot scale shows the range of the strength of the magnetic field density with the bottom blue representing the lowest value and the top red the highest value. That shows the induction is highest near the coil and becomes weaker when it moves further from the coil. The field density plot between the two coils has the same pattern. In order to determine which type of coil gives the better performance or efficiency, the researchers have done a simulation on both coils to get the value of inductance for each coil. Figure 9.12 shows the simulation result on the mutual inductance value for both coils.



(a) Circular coil (b) Rectangular coil

Fig. 9.9 Design of coil in ANSOFT MAXWELL simulation

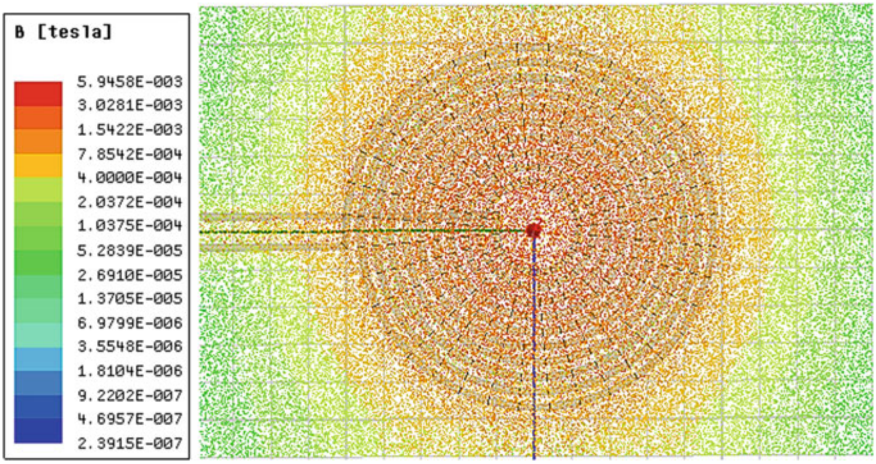


Fig. 9.10 Magnetic field density plot for circular coil

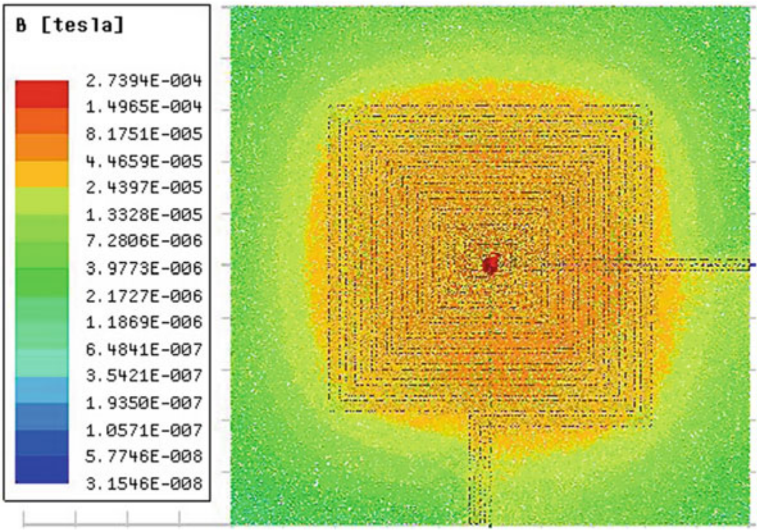


Fig. 9.11 Magnetic field density plot for rectangular coil

The result shows that mutual inductance in circular winding was higher than the mutual inductance in rectangular winding. This is because the rectangular coil geometry results in a longer conducting path as compared to circular coil (Ongayo and Hanif 2015). Therefore, the circular winding is more efficient to use in contactless power transfer systems compared to the rectangular winding because it can induce more power compared to rectangular winding.

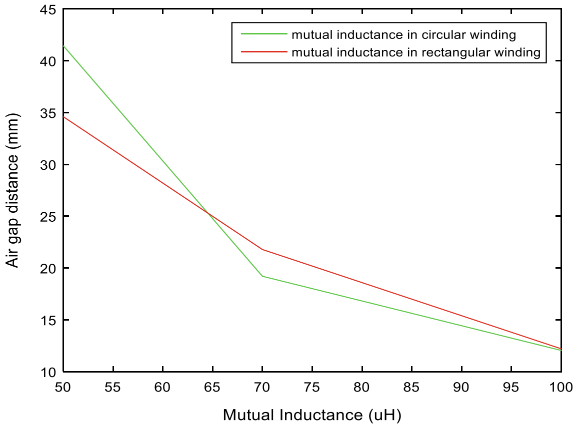


Fig. 9.12 Value of mutual inductance for circular and rectangular coil for 50–100 mm air gap (Ongayo and Hanif 2015)

9.6 Latest Research Development

Currently, the enhancement of contactless power transfer using metamaterials have been developed widely. The displacement distributions on two typical plate-type structures have been introduced by Ma et al. (2017). The guidelines to design the optimal metamaterial with efficient power transfer, low cost, and high capability have been discussed in Dong et al. (2017). A metamaterial slab and the superconducting coil had been used in Sharma (2018) for electric vehicle charging to obtain a higher coupling coefficient of around 0.9. The challenges and opportunities for contactless power transfer using metamaterials have been explored in their properties (Bhattacharya et al. 2018) and design solutions (Lee et al. 2018). Two kinds of dual-band metamaterials were integrated to achieve negative and near zero permeability (Lu et al. 2020). A triplex layer with low metamaterial resulted in an efficiency enhancement of 26.8% (Liu et al. 2020). The metamaterial inclusion is investigated after using the evolutionary algorithm to optimize the design and geometry of the coil (Corrêa et al. 2019; Khafaga et al. 2022). The design is constructed with anisotropic Z magnetic metamaterials (Z-MM) to enhance the efficiency of contactless power transfer (Lu et al. 2021). In Adepoju et al. (2022) the finite element analysis of proposed metamaterials coupled with an equivalent circuit model is performed in ANSYS and validated in an experimental prototype.

9.7 Conclusion

In conclusion, this paper has reviewed the finite element analysis method for the enhancement of contactless power systems by using metamaterials. Then the paper evaluates the effect of air on the mutual inductance, coupling coefficient, and magnetic flux ratio. It is found that the effect of mutual inductance is very much dependent upon the relative positions of the two coils. The position between the two coils also will create the air gap that will influence the magnetic field ratio. The simulation results have shown that a circular coil has relatively better coupling and gives better efficiency as compared to a rectangular one with more or less similar dimensions. All these situations have been verified by the finite element analysis method. The results of recent finite element analysis have proven the effectiveness of metamaterials for contactless power transfer enhancement. Hence, it can be concluded that metamaterials can be a potential material to enhance the contactless power transfer system.

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