Design of circular inductive pad couple with magnetic flux density analysis for wireless power transfer in EV

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ABSTRACT

As the population grows, people will consume more natural resources. This issue will lead to a low petrol supply for all land transportation, especially supplies for car consumption. Therefore, the electric vehicle (EV) has been introduced to overcome this issue. Currently, wired charging of EVs has been implemented in most of the developed country, including Malaysia. However, some drawbacks have been found from this technology. Therefore, wireless charging comes into the picture to solve this issue. Charging pad on the road and at the car are required for both wired and wireless charging. Various designs of charging pad are available. However, this paper will only focus on the circular design. There is many software that can be used to design the coil pad. Each software has a different procedure and steps to design the coil pad. In this paper, JMAG Designer software will be used to design the circular coil pad. Then, three coil pair were simulated using JMAG Designer to investigate the magnetic flux density between primary and secondary coil when varying the misalignment of 0 cm, 4 cm and 8 cm. From the simulation, there is no specific trend in the relationship between magnetic flux density and misalignment.

Keywords:
Circular coil pad
Electric vehicle (EV)
JMAG Designer
Magnetic flux density
Misalignment
Wireless charging

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1. INTRODUCTION

The consumption of oil after the year 2010 is higher than the production of oil. This situation is very critical because oil production is not being able to meet the demand of the consumers starting from 2010. Therefore, the use of a fuel car will be irrelevant in the future. Government has introduced electric vehicle (EV) as one of the ways to solve this issue. Electric vehicle (EV) has been introduced in 2012 due to public awareness of the effect of gas emission from the traditional car and the extinction of petroleum natural resources [1]. Besides, EV and plug-in hybrid EV can improve air quality. This ability is because 22% of the carbon dioxide gas in the air is emitted from transportation [2]. In Malaysia, there are six models of electric car available in the market. Among the models are nissan leaf, mitsubishi motors i-MiEV, BMW i8 and volvo XC90. The use of EV has been implemented in many foreign countries such as China, Canada, Western Europe, Japan and the United States [3]-[5].

There are two ways of charging the EV, which is wired and wireless charging. Wired technique is a traditional way of charging the electric vehicle. Whilst wireless charging of EV offers compactness and safety without any use of a cable due to charging competence [6]-[9]. However, there are some risk and
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Hazards when using wireless charging pad. Large power levels from the charging pad will potentially cause electric shock, fire hazards and magnetic field exposure hazards [10]-[12]. Therefore, the charging pad designs have to meet the safety standard set by the international groups before it can be used commercially.

In wireless charging of EV, the coil pad design is among the crucial factors that need to be considered. Good coil pad design will reduce the loss of power to surrounding due to misalignment and air gap. The designs that have been discussed actively among researchers are circular, rectangular, double-D (DD), double-D quadrature (DDQ). Among many pad designs, the circular pad is the most functional design because of their magnetic properties [13]-[16]. There are various designs of the coil, and each of the designs has its benefit for its specific requirements and applications [17]-[21].

The primary and secondary coil pad system can be represented as the circuit shown in Figure 1 below. The circuit consists of the primary side, where primary inductance (Lp) is the primary coil pad while Ls is the secondary coil pad. This is the series-series compensation topology, the simplest compensation topology among all available compensation topologies [22]-[26].

![Figure 1. Inductive pad coupler schematic circuit](image)

Before producing the prototype of the circular coil pad, the coil pad was designed using specific software for the simulation process. Among the software that can be used is Solidwork, COMSOL Multiphysics and JMAG Designer. Different software has different ways to draw the coil pad.

In this paper, the simulation of coil pad using JMAG Designer software and the magnetic flux density were explained. The remaining section of this paper comprises of few main parts. Section 2 will be explaining about the methodology, while section 3 will lay out the simulation results from JMAG Designer software. As a conclusion, the last section will conclude the paper.

2. METHODOLOGY

This section will discuss the proposed methodology that is used to design a circular pad. In this section, there will be four subsections; overview design on coil pad, geometric parameters calculation, pad coupler design and simulation in JMAG Designer and evaluation. Subsection 2.1 will discuss the overall process to simulate the coil pad, including calculation and simulations. Whilst subsection 2.2 shows the formula and calculation needed for geometric parameters. Subsection 2.3 describes the flow of the coil design in JMAG Designer software. Lastly, subsection 2.4 is about the simulation and evaluation which will be explained more in section 3.

2.1. Overview design on coil pad

This section will discuss the steps needed to design and simulate the circular coil pad to identify the geometric parameters used. The followings are geometric parameters considered in this project; the number of turns (N), inner diameter (Di), and outer diameter (Dout) of coils. Figure 2 shows the step needed in designing geometric properties. Firstly, the geometric parameters are calculated and will be used in designing the pad coupler in JMAG. Later, the completed design of the pad coupler is simulated in the JMAG Designer software. Finally, the evaluation process consists of a magnetic flux density between the two coils were investigated.

![Figure 2. Steps needed to design the geometric properties](image)
2.2. Geometric parameters calculation

The coil pad parameters are calculated using (1) [13], [27]. \( D_i, D_{out}, L \) and \( N \) in that equation represents inner diameter, outer diameter, inductance and number of turns of the coil respectively.

\[
L = \frac{N^2(D_{out}+D_{in})^2}{8(15D_{out}-7D_{in})2.54}
\]

Where \( D_{in} \) is the inner diameter (in cm), \( D_{out} \) is the outer diameter (in cm), \( L \) the inductance (in \( \mu \)H) and \( N \) is the number of turns of coil. Equation on is applied to both primary and secondary inductance calculation in accordance with the parameters involved. Misalignment is calculated horizontally from the centre of the primary coil to the centre of the secondary coil. Whilst air gap distance is measured vertically from the surface of the primary coil to the surface of the secondary coil.

In this project, the value of primary and secondary inductance is 333.9 \( \mu \)H and 37 \( \mu \)H. Table 1 below displays the value for calculated and measured inductance (\( L \)), number of turns of coil (\( N \)), inner diameter (\( D_{in} \)) and outer diameter (\( D_{out} \)). The values of calculated and measured inductance are almost the same and in the acceptable range.

| Calculated inductance | Measured inductance | No. of turns calculated | No. of turns fabricated | Inner diameter (cm) | Outer diameter (cm) |
|-----------------------|---------------------|-------------------------|-------------------------|---------------------|---------------------|
| 333.9 \( \mu \)H      | 324.6 \( \mu \)H    | 45.93                   | 43                      | 5.5                 | 32.5                |
| 37.09 \( \mu \)H      | 33.3 \( \mu \)H     | 8.86                    | 8                       | 22.0                | 6.96                |
| 37.09 \( \mu \)H      | 35.4 \( \mu \)H     | 7.86                    | 8                       | 27.5                | 32.5                |
| 37.09 \( \mu \)H      | 36.1 \( \mu \)H     | 6.96                    | 7                       | 33.0                | 37.0                |

Then, the diameter of the coil pad is set for each pair. The size of the circular pad for the primary coil is fixed for all coil pairs. However, the secondary coil’s diameter is varied. There are three coil pair designs in this project which are P-S1, P-S2, P-S3. P represents the primary coil, while S represents the secondary coil. The subscript 1, 2 and 3 are the three different circular coil design. Table 1 above also shows the geometric parameter of the coil pad. The primary coil is design with 5.5 cm inner diameter (\( D_{in} \)) and 32.5 cm outer diameter (\( D_{out} \)).

- **Coil pair P-S1**: The inner diameter of the secondary coil (\( D_{in,S} \)) is bigger than the primary coil (\( D_{in,P} \)), whilst the outer diameter of secondary coil (\( D_{out,S} \)) is smaller than primary coil (\( D_{out,P} \)); \( D_{in,S} > D_{in,P}, D_{out,S} < D_{out,P} \).
- **Coil pair P-S2**: The outer diameter of secondary coil (\( D_{out,S} \)) and primary coil (\( D_{out,P} \)) is the same whilst the inner diameter of secondary coil (\( D_{in,S} \)) is bigger than primary coil (\( D_{in,P} \)); \( D_{in,S} > D_{in,P}, D_{out,S} = D_{out,P} \).
- **Coil pair P-S3**: The outer diameter of secondary coil (\( D_{out,S} \)) is bigger than the primary coil (\( D_{out,P} \)) while the inner diameter of secondary coil (\( D_{in,S} \)) is bigger than primary coil (\( D_{in,P} \)); \( D_{in,S} > D_{in,P}, D_{out,S} > D_{out,P} \).

The misalignment for this simulation is varied between 0 cm, 4 cm and 8 cm whilst the air gap is fixed to 4 cm. Figure 3 shows the P-S1 coil pair design without misalignment condition. Whilst, Figure 4 illustrates the top view of the coil design with 4 cm misalignment. This figure is the top view of the coil. The red coil in the Figure below represents the primary coil while brown represent secondary coil.
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Figure 3 has no misalignment because the centre of the primary coil is aligned with the secondary coil. However, from Figure 4, the centre of the primary coil is not aligned with the centre of the secondary coil. The distance from the centre of the primary coil to the centre of the secondary coil is 4 cm. The horizontal distance between them is measured and called as misalignment. These two designs of misalignment and without misalignment were used for the simulation in JMAG Designer. Table 2 below shows all the design (P-S1, P-S2, P-S3) for 0 cm, 4 cm and 8 cm misalignment in JMAG Designer.

| Misalignment (cm) | P-S1 | P-S2 | P-S3 |
|------------------|------|------|------|
| 0                | ![Image](image1) | ![Image](image2) | ![Image](image3) |
| 4                | ![Image](image4) | ![Image](image5) | ![Image](image6) |
| 8                | ![Image](image7) | ![Image](image8) | ![Image](image9) |

Table 2. Coil pair design at 0 cm, 4 cm and 8 cm misalignment

2.3. Pad coupler design

There are three main steps in designing the coil pad coupler in JMAG Designer software. The steps are sketching, revolving and circuit construction as shown in Figure 5.

![Image](image5)

Figure 5. Steps needed to design the circular coil pad in JMAG Designer

2.3.1. Sketching of circular coil pad

Based on the information in Table 1 above, the next step is to design these coils based on the $D_{in}$ and $D_{out}$ using the JMAG Designer software. The first step in order to design these coils (P, S1, S2, S3) is to sketch a line that represents the inner radius of the coil ($R_{in}$), and outer radius of the coil ($R_{out}$) are drawn in the ‘Geometry editor’ section as illustrated in Figure 5 below. The value of $R_{in}$ is taken as $\frac{D_{in}}{2}$, whilst $R_{out}$ is considered as $\frac{D_{out}}{2}$. Thus, the value of $R_{in}$ is 165 mm and $R_{out}$ is 185 mm. Figure 6 represents the secondary coil, S3 and the unit used in this sketching is in millimeter (mm).

These steps of designing the coil pad are repeated for primary coil except that the value of the sketch line that represents the inner radius of the coil ($R_{in}$) and outer radius of the coil ($R_{out}$) is now based on Table 1 under primary coil (P) ’s parameters [28].
2.3.2. Revolving the sketch

Now, the secondary coil’s sketch is revolved 0° about z-axis as indicated in the blue line shown in Figure 7. In this 0°, the secondary coil is just a line. This initial step is crucial to produce a circular shape. Then, Figure 8 illustrates the secondary coil revolved at 360° about the z-axis. This step will produce a complete circle and a full design of the coil. After completing the design for each primary and secondary pad, both pads will appear as display in Figure 9. The red colour represents the primary coil \( P \) while blue colour represents the secondary coil \( S_3 \).

![Figure 7. Secondary coil, S_3 revolved 0°](image7.png)

![Figure 8. Secondary coil, S_3 revolved 360°](image8.png)

![Figure 9. Coil design in the geometry editor of JMAG Designer](image9.png)

2.3.3. Construct circuit in JMAG Designer

After completing the sketching process, the model will be imported to the JMAG Designer to study the magnetic properties. Then, a circuit as in Figure 10 which represents both primary and secondary coil will be constructed in this software to state the coil’s parameter such as the number of turns, capacitance, load resistor and voltage source. The value for each parameter has been mentioned in Table 1 previously.

![Figure 10. Circuit constructed in JMAG Designer](image10.png)
2.3.4. Simulation in JMAG Designer and evaluation

After completing the parameters calculation and coil design, the simulation will then be initiated. JMAG Designer will run the simulation between coil pad (primary and secondary coil) to study the relationship between each coil design and misalignment towards the magnetic flux density produced. In summary, there are 4 steps which comprise of geometric parameters calculation, pad coupler design, simulation using the JMAG Designer software and evaluation. The results for the magnetic flux density simulation will be explained in section 3.

3. SIMULATION RESULTS

In JMAG Designer, the designed coil pairs are simulated to observe and measure the value of magnetic flux density. For each pair, the simulations are fixed to 4 cm air gap and varying the misalignment from 0 cm, 4 cm and 8 cm. Design 1 in Table 3 shows the magnetic flux density for P-S1 pair at 0 cm, 4 cm and 8 cm misalignment position respectively. The colour legend provided on the right of the simulated coil indicates the magnetic flux density distribution in a coil. Even though the highest magnetic flux value in the colour legend is represented by red colour, but the optimum magnetic flux density for this condition is between orange and red region (5.3333E-04 T to 6.0000E-04 T). This orange region value is written as the maximum magnetic flux density of 5.8004E-04 T written below the colour legend. The red colour may indicate the highest, but it is not optimum because the fluxes are too saturated, thus not ideal for power transfer.

| Design | Misalignment | 0 cm | 4 cm | 8 cm |
|--------|--------------|------|------|------|
| 1      |              | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| 2      |              | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| 3      |              | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |

From design 1 for all misalignments in Table 3, it can be seen that the magnetic flux density value for P-S1 pair is different at different misalignment condition. At 0 cm misalignment, the magnetic flux density value at the primary coil is low, which is 5.008E-04 T. However, as the misalignment between primary and secondary coil increases, the magnetic flux density increases as well until it reaches 1.733E-03 T at 8 cm misalignment.
Design 2 is P-S2 coil pair was sketched and simulated in J MAG Designer. This design has a similar outer diameter \( (D_{o1}) \) value for the primary and secondary coil, which is 32.5 cm. The simulated results at 0 cm, 4 cm and 8 cm misalignment are shown in Table 3. P-S2 pair has high magnetic flux density around 2.4396E-03 T at 0 cm misalignment. However, as the misalignment between primary and secondary coil increases, the magnetic flux density decreases as well until it reaches 1.6629E-03 T at 8 cm misalignment.

Design 3 is P-S3 coil pair where the outer diameter \( (D_{o1}) \) secondary coil is 37cm whilst primary coil is 32.5cm. P-S1 pair has low magnetic flux density around 1.2784E-03 T at 0 cm misalignment. However, as the misalignment between primary and secondary coil increases, the magnetic flux density decreases as well until it reaches 1.2407E-03 T at 8 cm misalignment. A graph that compares the maximum magnetic flux density for all three designs \((P-S_1, P-S_2, P-S_3)\) are expressed in Figure 11.

Figure 11 shows that misalignment affects the magnetic flux density value. When comparing P-S1 coil pair and P-S2 coil pair at 0 cm misalignment, P-S2 pair has higher magnetic flux density. The trend of magnetic flux density value over misalignment for P-S2 design is different comparing to P-S1, where the trend is increasing in contrast to P-S1. Furthermore, P-S3 design gives a lower value of magnetic flux density than P-S2 pair but higher than P-S1 pair at 0 cm misalignment. The magnetic flux density value for P-S2 at 0 cm misalignment is 1.278E-03 T which is the second-highest after P-S2. Therefore, these simulation results show that the magnetic flux density distribution at P-S1 coil is the lowest among the other two design \((P-S_2, P-S_3)\).

![Figure 11. Magnetic flux density for all three coil pairs design for air gap 4cm](image)

4. CONCLUSION

This paper has successfully investigated the magnetic flux density value for each coil pair \((P-S_1, P-S_2, P-S_3)\) under different misalignment condition at fix air gap. The coil pairs were design and simulated using J MAG Designer software. Overall, there are no specific trend in the relationship between magnetic flux density and misalignment. The above results were due to the different design of the coil pair used in this project which give the different effect of the magnetic flux distribution in a coil. Low magnetic flux will be produced between two coils when the primary and secondary coil gets further apart, and the surface area of these coils are not aligned. Therefore, the low value of magnetic flux density between the coils will then induced low current, which then gives low power transfer. Thus, P-S2 is the best design in terms of magnetic flux density from this simulation following by P-S3 and P-S1.

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